

EUV Sources for Lithography

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Vivek Bakshi

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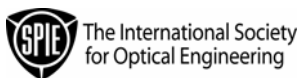
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Back cover images: Top: HEIGHTS simulation of the density evolution near plasma pinching in XTREME technologies' DPP EUV source, courtesy of Ahmed Hassanein, Argonne National Laboratory. Bottom: Iso-contour of the conversion efficiency for Sn LPP, courtesy of Katsunobu Nishihara, Osaka University.

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*I dedicate this book to my parents,
wife, and daughter*

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Preface

Until recently, EUV source power was the number one challenge to implementing EUV lithography (EUVL) in the high-volume manufacturing of computer chips. But due to the dedicated efforts of a few dozen research groups around the world, EUV source technology continues to advance. Today, with tremendous improvements in source power and other characteristics, source power is no longer the leading challenge. EUV sources have evolved from a laboratory concept to reality, with alpha-level EUV sources being delivered for integration in alpha-level EUV scanners.

This reference book contains 38 chapters contributed by leading researchers and suppliers in the field of EUV sources for EUVL. The chapter topics are intended to cover the needs of practitioners of the technology as well as readers who want an introduction to EUV sources. The book begins with in-depth coverage of EUV source requirements and the status of the technology, followed by a review of fundamental atomic data and descriptions of theoretical models of discharge-produced plasma (DPP) and laser-produced plasma (LPP) based EUV sources, prominent DPP and LPP designs, and alternative technologies for producing EUV radiation. Also covered are topics in EUV source metrology, EUV source components (collectors, electrodes), debris mitigation, and mechanisms of component erosion in EUV sources.

As EUV source technology has progressed, researchers and commercial suppliers around the world have published more than 100 papers per year, and the amount of technical data on EUV source technology continues to increase. My effort as volume editor has been to produce an authoritative reference book on EUV source technology, which has not existed until now. In the future one may need to consult the proceedings of SEMATECH's EUV Source Workshops and SPIE's Microlithography conference for the most recent performance improvements in EUV sources, but this text will still deliver the in-depth technical background information on particular technical approaches and on EUV source technology in general.

The primary strength of this book is that the contributions came from leading experts. The choice of having many authors per section has produced a comprehensive and true reference book, covering a range of technical options and opinions. I have done my best to make each chapter a complete reference in itself, though some sections—usually the introductory sections of chapters—inevitably overlap. For example, although each chapter mentions the requirements for a source, the

reader is encouraged to consult Chapter 2 to understand the details of EUV source requirements. Likewise, many authors refer to certain issues such as debris generation in their chapters; however, the reader is directed to Chapter 37 for a comprehensive reading on the fundamentals of debris generation and mitigation.

This project has been successful due to the dedication and hard work of many technologists worldwide. Therefore, I would like to acknowledge and thank the authors who have worked very hard to produce a reference chapter on their technical work. Their quality manuscripts made my job as an editor much easier. This book is essentially the fruit of their labor.

I would like to thank my colleagues at SEMATECH's member companies, as well as the authors in this volume who took the time to review the chapters by their colleagues. I would especially like to thank some of the referees who reviewed multiple chapters: Vadim Banine, Vladimir Borisov, Peter Choi, Akira Endo, Igor Fomenkov, Samir Ellwi, Björn Hansson, Ahmed Hassanein, Lennie Klebanoff, Konstantin Koshelev, Thomas Krücken, Hans J. Kunze, Rainer Lebert, Malcolm McGeoch, Katsunobu Nishihara, Gerry O'Sullivan, Joseph Pankert, Martin Richardson, David Ruzic, Uwe Stamm, Yusuke Teramoto, and Sergey Zakharov.

I would also like to acknowledge the contributions of my family, whose influence, encouragement, and support have allowed me to undertake such a project. First of all, my father, Mr. Om Prakash Bakshi, MA, set a very high standard for written communication and the pursuit of excellence, which still today I can only strive to meet. My mother, Mrs. Pushpa Bakshi, MA, retired lecturer of the Punjabi language, always set the example of hard work and taught me a pragmatic approach toward solving everyday problems, which still guides me. My wife, Laura Coyle, encouraged me to undertake this intellectual pursuit and has always been an example of innovation and uncompromising attention to quality and detail for achieving perfection, as evident in her own achievements. Laura's and my daughter Emily's encouragement have allowed me to continue and complete this project. For these reasons, I have dedicated this book to my parents and my wife and daughter.

I would like to thank SPIE acquisitions editor Timothy Lamkins, with whom I worked to generate the concept of this book. I would also like to thank SPIE editor Margaret Thayer, who made one of the largest book projects ever undertaken by SPIE Press a very smooth process. I very much appreciate her support and hard work for making this book project a reality.

Finally, I would like to thank my former manager, Kevin Kemp, for his guidance and support in this project, and my employer, SEMATECH, which exemplifies industry cooperation in the semiconductor community. SEMATECH has created a global platform to facilitate consensus on the direction of technology and to promote cooperative work in the pre-competitive arena of computer chip manufacturing. Hopefully, this book will set an example of how a large number of experts and competitors can cooperate to produce a reference work to benefit an entire industry.

Vivek Bakshi
December 2005

Introduction

In semiconductor manufacturing, progress is measured in terms of the industry's continued ability to adhere to Moore's Law, which states that the number of transistors on a chip doubles about every two years. The *International Technology Roadmap for Semiconductors* (ITRS) dictates expected performance specifications for chip manufacturing technology to ensure continued adherence to this law. Accomplishing these specifications in turn requires the development and perfection of new technologies at a pace that is unmatched by any other industry. No single company can hope to do this alone: The increasing complexity of the technical challenges and the rising cost of development call for an unprecedented level of resource and risk sharing among semiconductor manufacturers, tool and materials suppliers, and research institutions and consortia.

Among the technical challenges facing the semiconductor industry, lithography presents some of the most formidable problems, particularly the search for a next-generation lithography solution that can provide for high-volume manufacturing of computer chips at the 32 nm node and beyond. Extreme ultraviolet lithography (EUVL) is the leading candidate to succeed optical lithography at the currently used wavelength of 193 nm. However, the technical challenges of source power, source component and optics lifetime, resist performance, and mask defectivity still must be addressed to ensure the cost-effective and timely implementation of EUVL. Furthermore, the industry infrastructure in these key areas needs to be developed rapidly to support planned manufacturing at the 32 nm generation.

Source power and associated source component lifetime are among the most critical of all the EUVL challenges. The amount of available source power translates directly to the wafer throughput that can be achieved by an EUV exposure tool. Source component lifetime affects the cost of maintaining the tool, including the amount of time that a tool must be taken out of productive service for maintenance. Both these factors in turn drive the per-wafer processing cost for the technology. The past four to six years have seen a concerted effort on the part of suppliers and researchers to achieve the power levels and component lifetimes required to produce commercial EUV sources for lithographic applications. This volume celebrates the successes along this path and provides a reference for practitioners in the field and other interested readers.

SEMATECH is a consortium of the world's leading semiconductor manufacturers, and is a powerful catalyst for accelerating the commercialization of technology

innovations into manufacturing solutions for the semiconductor industry. Its lithography division conducts targeted research projects to accelerate technology and infrastructure development to meet the lithography requirements of the ITRS. It also organizes numerous technical workshops and symposia involving technologists and decision-makers from around the world to foster global, pre-competitive cooperation and to drive consensus solutions for future semiconductor manufacturing technology. Continued progress in the development of EUVL is a prime example of SEMATECH's efforts in this regard, and this book is a direct result of such collaboration.

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List of Abbreviations

AA	average atom
ACR	absolute cryogenic radiometer
ADM	angular distribution monitor
AEM	Auger electron microscopy
AES	Auger electron spectroscopy
AFM	atomic force microscopy
AIM	aerial-image microscope
ALS	Advanced Light Source (U.S.)
ANL	Argonne National Laboratory (U.S.)
AO	acousto-optical
arb.	arbitrary
ASD	axially symmetrical discharge
a.u.	arbitrary units
BCA	binary collision approximation
BW	bandwidth
CBM	carbon-based materials
CBS	collision-based spectroscopy
CCD	charge-coupled device
CE	conversion efficiency
CES	charged-exchange spectroscopy
CF	ConFlat
CFC	carbon-fiber composite
CI	configuration interaction
CM	collisional mixing
CO	condenser optic
CoO	cost of ownership
COR	condenser-optic region
CR	collisional radiative
CRE	collisional radiative equilibrium
CRM	collisional radiative mode
CTE	coefficient of thermal expansion
cw	continuous wave
CXRO	Center for X-ray Optics (at LBNL, U.S.)
DCA	direct configuration accounting

DCU	dual-crystal unit
DF	Dirac-Fock
DL	diffraction limit
DLC	diamondlike carbon
DMD	defect-mediated desorption
DPF	dense plasma focus
DPP	discharge-produced plasma
DPSS	diode-pumped solid state
DRT	discrete-ordinate method
DTA	detailed term accounting
DUV	deep ultraviolet
DWA	distorted-wave approximation
EBIT	electron-beam ion trap
EDX	energy dispersive x-ray spectroscopy
EM	electromagnetic
EO	electro optical
EOS	equation of state
ES	electrostatic analyzer
ESA	spherical-sector electrostatic energy analyzer
ESIEA	electrostatic ion energy analyzer
ESR	electrical substitution radiometer
ETS	Engineering Test Stand
EUV	extreme ultraviolet
EUVA	Extreme Ultraviolet Lithography System Development Association (Japan)
EUVL	extreme ultraviolet lithography
EUV LLC	EUV Limited Liability Corporation
FAC	Flexible Atomic Code
FC	Flying Circus
FDWG	Fundamental Data Working Group (of SEMATECH)
FFS	flat-field spectrograph
FMEA	failure-mode and effect analysis
FOM	Fundamenteel Onderzoek der Materie (The Netherlands)
FT	foil trap
FWHM	full width at half maximum
GA	Gibbsian adsorption
GDPP	gas-discharge produced plasma
GEA	gridded energy analyzer
GIM	grazing-incidence mirror
HCI	highly charged ions
HCT	hollow-cathode triggered
HEDP	high-energy-density physics
HEW	half energy width
HF	Hartree-Fock

HFR	Hartree-Fock approximation with relativistic extensions
HFS	Hartree-Fock-Slater
HLI	Helmholtz-Lagrange invariant
HULLAC	Hebrew University Lawrence Livermore Atomic Code
HV	high voltage
HVE	high-voltage electrode
HVM	high-volume manufacturing
IBA	inverse bremsstrahlung absorption
IC	integrated circuit
ICE	intrinsic conversion efficiency
IDEA	interferometric data evaluation algorithms
IDEAL	Illinois Debris-Mitigation for EUV Applications Laboratory (U.S.)
IEA	ion energy analyzer
IEUVI	International EUV Initiative
IF	intermediate focus
IGBT	insulated gate bipolar transistor
IMPACT	Interaction of Materials with charged Particles And Components Testing
IP	ion probe
IR	infrared
IRD	International Radiation Detectors
ISMT	International SEMATECH
ITRS	<i>International Technology Roadmap for Semiconductors</i>
KIAM	Keldysh Institute of Applied Mathematics (Russia)
LBNL	Lawrence Berkeley National Laboratory (U.S.)
LEISS	low-energy ion scattering spectroscopy
LER	line edge roughness
LLNL	Lawrence Livermore National Laboratory (U.S.)
LPL	Laser Plasma Laboratory (U.S.)
LPP	laser-produced plasma
LTE	local thermodynamic equilibrium
MCDF	multiconfiguration Dirac-Fock
MCHF	multiconfiguration Hartree-Fock
MCP	microchannel plate
MCRT	Monte Carlo radiation transport
MCS	multicomponent system
MET	microexposure tool
METI	Ministry of Economy, Trade, and Industry (Japan)
MHD	magnetohydrodynamics
MHRDR	magnetohydroradiative-dynamic research
ML	multilayer
MLM	multilayer mirror
MO	master oscillator

MOPA	master oscillator–power amplifier
MPC	magnetic pulse compression
MSEM	modified semiempirical method
Mo/Si	molybdenum on silicon
MTBF	mean time between failure
MTTR	mean time to repair
NA	numerical aperture
NEDO	New Energy and Industrial Technology Development Organization (Japan)
NGC	Northrop Grumman Corporation (U.S.)
NGL	next-generation lithography
NIST	National Institute of Standards and Technology (U.S.)
NLTE	non-local thermodynamic equilibrium
NSLS	National Synchrotron Light Source (U.S.)
OOB	out-of-band
ORNL	Oak Ridge National Laboratory (U.S.)
PBN	pyrolytic boron nitride
PE	potential energy
PMMA	poly(methyl methacrylate)
PO	projection optics
POM	polyacetal
POPA	power-oscillator–power-amplifier
PREUVE	PRoject Extreme Ultraviolet (France)
PS	preferential sputtering
PSPDI	phase-shifting point-diffraction interferometer
PTB	Physikalisch-Technische Bundesanstalt (Germany)
PV	peak to valley
PVD	physical vapor deposition
PZT	lead zirconium titanate
QCM	quartz crystal microbalance
QCM-DCU	quartz crystal microbalance–dual-crystal unit
RAL	Rutherford Appleton Laboratory (U.K.)
RC	radiative collapse
RC	resistive capacitance (time constant)
RDE	rotating-disk electrode
RED	radiation-enhanced diffusion
RES	radiation-enhanced sublimation
rf	radio frequency
RGA	residual gas analyzer
RIS	radiation-induced segregation
RMDU	rotating multidischarge unit
RMHD	radiative magnetohydrodynamics
RTE	radiation transport equation
SBS	stimulated Brillouin scattering

SCDF	single-configuration Dirac-Fock
SCO	superconfiguration code
SCOPE	Surface Cleaning of Optics by Plasma Exposure (U.S.)
SEM	scanning electron microscopy
SHG	second-harmonic generator
SHM	screened hydrogenic model
SIMS	secondary-ion mass spectroscopy
slm	standard liters per minute
SOSA	spin-orbit split array
SPF	spectral purity filter
SRC	Semiconductor Research Corporation (U.S.)
SRIM	Stopping and Range of Ions in Matter
STA	supertransition array
STE	self-trapped exciton
STM	scanning tunneling microscope
SURF II	Synchrotron Ultraviolet Radiation Facility (at NIST)
TBD	to be determined
TDLDA	time-dependent local density approximation
TE	thermal equilibrium
TEM	transmission electron microscopy
TF	Thomas-Fermi
TGS	transmission grating spectrograph
TMP	turbomolecular pump
TOF	time-of-flight
TPS	Thomson parabola spectrometer
TRINITI	Troitsk Institute of Innovation and Fusion Research (Russia)
TRIM	Transport of Ions in Matter
TVD	total variation diminishing
TWG	Technical Working Group
UHV	ultrahigh vacuum
UTA	unresolved transition array
VNL	Virtual National Laboratory (U.S.)
VUV	vacuum ultraviolet
WDS	wafer dose sensor
WS	working standard
XPS	x-ray photoelectron spectroscopy

Chapter 1

EUV Source Technology: Challenges and Status

Vivek Bakshi

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1.1 Introduction

Extreme ultraviolet lithography (EUVL) is the leading technology being considered for printing circuits at the 32-nm node¹ and below in a high-volume manufacturing (HVM) environment fab. In EUVL, a 13.5-nm-radiation wavelength generated by an EUV source is used to print circuits. Because light radiation is strongly absorbed at this wavelength, the entire EUVL scanner system must be in a vacuum environment, and all optics must be reflective, not refractive. Based on the HVM requirements of 100-wafer/h throughput and other system requirements for optics, resist sensitivity, and overhead (Table 1.1), a power requirement of 115 W has been specified for HVM EUVL scanners. Besides power, EUV sources must meet additional specifications. The production-level requirements in Table 1.1 have been jointly agreed upon by major scanner manufacturers.^{2,3}

Discharge-produced plasma (DPP) and laser-produced plasma (LPP) are the leading technologies for generating high-power EUV radiation at 13.5 nm. In both technologies, hot plasma of $\approx 20\text{--}50$ eV of the chosen fuel material is generated, which produces EUV radiation. In DPP, magnetic pinching of low-temperature plasma generates the high-temperature plasma. In LPP, the target material is heated by a laser pulse to generate high-temperature plasma. Xenon, tin, and lithium are the fuel materials of choice for EUV sources.

The cost-effective implementation of EUVL in HVM presents many technical challenges, of which the EUV source power has remained the greatest one until recently. In the fall of 2004, significant progress in EUV source power was reported at the EUVL Symposium in Miyazaki, Japan, making source power a lesser concern. The current challenges for implementing EUVL in HVM are listed in Table 1.2.

Today worldwide, more than eight suppliers and consortia are working to develop high-power EUV sources for EUVL. In addition, some suppliers are working to develop low-power EUV sources that are finding applications in metrology to support EUVL. This chapter presents the status of high-power EUV source technology and summarizes the technical challenges that must be overcome to meet the specifications for high-power EUV sources in HVM.

1.2 Conversion Efficiency of EUV Sources

1.2.1 DPP versus LPP

The conversion efficiency (CE) is the ratio of energy radiated by the EUV source in a 2% bandwidth (BW) around 13.5 nm to the input energy to the EUV source. The CE is used to estimate the utility requirements, choose the fuel, and understand the limits of power scaling. The fundamental CE for a fuel represents the upper limit of CE for that particular fuel.

For DPP, the input energy is the electrical energy consumed by the entire system (energy dissipated in the plasma plus energy lost in the electrical system). However,

Table 1.1 EUV source requirements and technology status.

EUV source specifications	Best reported values				Requirements		
	Xe DPP	Sn DPP	Xe LPP	Sn LPP	Alpha	Beta	Production
Status as of	Q1 2005	Q1 2005	Q1 2005	Q1 2005	2005	2007	2009
Wavelength (nm)	13.5	13.5	13.5	13.5	13.5	13.5	13.5
Throughput (wafers/h)					20	60	100
EUV power at intermediate focus (W)	25	50	2.3	3	10 ^a	30 ^a	115 ^b
Repetition frequency (kHz)	2	6.5	4.5		2 ^a	5 ^a	7–10 ^a
Integrated energy stability (%)	2		5		5 ^a	1 ^a	0.3 ^b
Source cleanliness					TBD	TBD	> 30,000 h
Collector lifetime (10 ⁹ pulses)	10	1	5	TBD	1 (1 month) ^a	10 (3 months) ^b	80 (12 months) ^c
Electrode lifetime (10 ⁹ pulses)	0.35	> 1	N/A	N/A	1 (1 month) ^a	10 (3 months) ^a	80 (12 months) ^b
Projection optics lifetime (h)							30,000
Etendue of source output (mm ² sr)			< 1		TBD ^a	TBD ^a	< 3.3 ^b
Max. solid angle to illuminator (sr)					TBD ^a	TBD ^a	0.03–0.2 ^b
Spectral purity, 130–400 nm					TBD	TBD	TBD ^c
Spectral purity, > 400 nm					TBD	TBD	TBD ^c
Spectral purity, 20–130 nm					TBD	TBD	TBD

^aNo problems.
^bChallenges remain.
^cPotential showstopper; significant technical challenges remain. TBD = to be determined.

Table 1.2 Challenges for Implementation of EUVL in HVM by 2009^a.

Ranked issues	
1	Availability of defect-free masks
2	Lifetime of source components and collectors
3	Resist resolution sensitivity and line edge roughness (LER)
Unranked issues	
	Reticle protection during storage handling and use
	Source power
	Projection and illuminator optics quality and lifetime

^aList generated by EUVL Symposium Organization Committee, November 2004, Miyazaki, Japan.

sometimes the CE values presented in the literature take into account only the energy deposited in the plasma. In DPP, some of the energy is lost in the electrical components; therefore, the reported CE will depend on system-specific details. Without those details, it is difficult to separate the CE from the fundamental CE limits for a given fuel. Reference 4 gives an example of the CE for the entire system as well as the fundamental CE. For a given fuel, it is possible to optimize the system operation to maximize its CE.⁵ One may note that many times the highest CE reported for a fuel and source design combination does not correspond to optimal operating conditions. In this situation, it is best to use the CE for optimal operating conditions to get a realistic utility consumption estimate and understand the limits of power scaling. For the LPP system, the laser power and EUV output in the 2% BW around 13.5 nm is used to estimate the CE. However, for LPP systems, the overall conversion for the entire system is much less than for DPP because of the low wall-plug-to-laser-light CE of a laser system, which is typically less than 10%.

1.2.2 Xe, Sn, and Li conversion efficiency

For Xe plasma, only the Xe¹⁰⁺ ionic stage is responsible for the emission in the 13.5-nm radiation bandwidth,⁶ which results in a 1% or less CE. Although Xe as a fuel has been favored for being a noble gas, its low CE requires a high energy input to meet HVM EUV source power requirements. Such inputs are prohibitive due to limits on thermal management for DPP, and due to lack of high-power lasers for LPP, precluding Xe as the fuel of choice for high-power EUV sources.

As suppliers learn to optimize their systems, measured CEs have continued to increase. Historical data for such an increase are not given in this section, but can be reviewed in the technology description of various source designs.⁷ Although modeling has predicted a wide range of fundamental CE limits for Xe (2–4%),⁸ experimentally only a 1% CE has been observed for Xe plasmas.

Today CEs for a Xe DPP system are reported in the ranges of 0.45%,⁴ 0.5%,¹⁰ and 1%.¹¹ One must be cautious in accepting high CE numbers, since (for example)

for a given DPP design they may require a source size larger than allowed by the etendue requirements of the system. Therefore, the maximum CE may correspond to the available power at the source and not to the acceptable power at the EUVL scanner.

In the case of LPP, the source size is smaller (on the order of $100 \times 100 \mu\text{m}$); thus, etendue mismatch is not a concern (see Sec. 1.3.2.5 for details on this topic). For Xe LPP, CEs of 0.7%,¹² 0.8%,¹³ and 0.8–1%¹¹ have been reported. It has been shown that for Xe LPP, the transient nature of the Xe^{+10} population may be limiting the CE, and pulse shaping and pulse trains may help increase it.¹⁴ The above values of the CE are for LPPs produced using Nd:YAG lasers. For LPP systems using pulsed CO_2 lasers, CEs of 0.7%¹⁵ and 0.8%¹² have been reported. For a given system, in the case of LPP, the CE weakly depends on the laser wavelength.¹⁶

For Sn, multiple ionic stages, Sn^{+8} to Sn^{+12} , contribute to emissions around 13.5 nm, resulting in a higher CE;¹⁷ much higher theoretical estimates for the CE for Sn (4–7.5%) have been reported.⁸ Recent work also predicts CEs of 3.5–6% for Sn-based EUV sources.¹⁸ A factor of 3–4 for Sn over Xe is usually quoted in the literature for experimental measurements of the CE.^{19,20} For Sn DPP EUV sources, 2% CE has been reported,^{10,21} with a goal of 3% CE on the supplier roadmap.¹¹ Such goals can be achieved by reducing the etendue mismatch and optimizing the system design.²² Higher CE values have been reported for Sn LPP: 2.5% using Sn-doped droplet targets,²³ and likewise 2.5% using a Sn tape with a 25% Sn concentration.^{13,24} Based on current experimental data, a 3% CE can be expected for mass-limited Sn targets.²³ Much higher CEs have been obtained using solid Sn targets (viz., 3%²⁵ and 5%²³). Note, however, that solid Sn targets are probably not practical for use as fuel in an EUV source, because they generate large amounts of debris. In fact, for all Sn-based EUV sources, debris mitigation continues to be a serious challenge.

Li is a third material of choice that was recently revisited by EUV source suppliers for both LPP⁹ and DPP systems.²⁶ In the past, very low CEs of 0.1% for capillary discharges²⁷ and 0.23% for dense plasma focus (DPF) systems²⁸ were reported. However, recently much higher CE measurements of 2.5–3% have been reported for Li-based LPP EUV sources,⁹ and 2.5% CE is expected for Li-based DPP EUV sources.²⁶

1.2.3 Utility requirements

Utility requirements for EUV sources and for a wafer manufacturing fab in general should be considered, since these requirements allow an understanding of why some potential EUV source technologies may not be cost-effective. Although firm numbers are not available for laser utility requirements and full-scale scanners, utility consumption estimates can still point out potential issues.

EUVL is expected to be implemented in a 300-mm HVM fab. Based on current data, the utility requirements in 300-mm fabs have been estimated.^{29,30} In a

HVM 300-mm fab (defined as 30,000–40,000 wafer starts per month), the average power requirement for the entire fab is 50 MW. For a typical fab, 40% of the energy consumed is used by tools. In today's fabs, 193-nm scanners are the leading-edge-technology scanners. On average in an HVM fab, 10 scanners of leading-edge technology are needed for patterning critical layers. The utilities for a 193-nm scanner are rated for 75 kW, which makes consumption by 10 scanners 750 kW, or 4% of the total tool power consumption. For this discussion, the power rating for equipment has been used for the actual power consumption by the tool. In reality, the actual power consumption is less; however, data on it are not readily available.

A 40-W, 193-nm laser used in a 193-nm scanner has utilities rated for 50 kW.³² An HVM Sn DPP EUV source is expected to consume 30 kW of power; therefore, for DPP EUV sources, no increase in utilities (power consumption or cooling requirements) is expected. Today's EUVL microsteppers are rated for 100 kW of power usage. Their Xe DPP EUV sources generate 1 W of power using ≈ 2 kW of power input (based on a 0.5% CE for Xe), or 2% of the energy. For an alpha-level EUVL scanner with 25 W of a Sn DPP source, utilities are rated for 150 kW. A good estimate assumes that for a production-level EUVL scanner, ≈ 150 kW of energy will be required, meaning only a modest increase in power consumption is expected in the HVM environment for one EUVL scanner, and ≈ 750 kW for 10 EUV scanners.

The utility estimate for EUVL scanners will be different if LPP-based EUV sources are used. The power scaling for DPP sources is limited due to thermal management limits on electrode cooling. If future applications of EUVL demand higher power, LPP can provide the needed power scaling. However, the utility requirements for LPP raise concern, depending on the type of laser employed by the EUV source.

For an Nd:YAG laser, the wall-plug-to-laser-light CE (*wall-plug efficiency*) is estimated to be 10%, which means 120 kW of power will be needed to generate 12 kW of laser light, which is the amount necessary to produce the required 115 W of power—hence increasing the power requirement for EUV sources by 70 kW over that of a light source for a 193-nm scanner. For 10 scanners this will mean an additional 700 kW of power, which, although a substantial increase, may be acceptable. However, high-power Nd:YAG lasers do not seem to be technically feasible or cost-effective.¹² Suppliers are looking at a pulsed CO₂ laser, which is expected to demonstrate $\approx 8\%$ wall-plug efficiency. The main concern for utility requirements, however, comes with excimer lasers. Present wall-plug efficiency estimates range from 0.5%³¹ to 2%,³² or a power input from 600 kW to 2.4 MW to generate 12 kW of laser power. This would mean additional power requirements of 550 kW to 2.35 MW per EUV source, or 5.5 to 23.5 MW for 10 such EUV sources, as compared to 193-nm light sources. Such estimates of additional utility requirements could render excimer-laser-driven LPP EUV sources not cost-effective.

1.3 EUV Source Power

1.3.1 Measurements

The EUV source requirements are specified at the intermediate focus (IF) in the 2% BW around 13.5 nm. However, most measurements are now performed by directly observing the EUV source. Consequently, the power estimated at the IF requires the estimation of losses between the source and IF. Metrology for measurements at IF is still being developed.^{33–35} Since measurements at IF are more cumbersome and IF metrology equipment is more expensive, power measurements are likely to continue to be taken directly at source.

Absolute EUV power is measured using one or more multilayer mirrors and EUV diodes, although absolutely calibrated charge-coupled devices (CCDs) combined with spectrometers can also perform these measurements. Both mirror and diodes are calibrated at beamline. SEMATECH has sponsored the Flying Circus (FC) project to independently assess source performance,⁴ cross-calibrate the suppliers' EUV sensors, and cross-calibrate other commercial EUV energy sensors.^{4,36,37} Such measurement campaigns have resulted in confidence in the source power measurements and source performance data. For FC, an accuracy of better than 3% is estimated for absolute EUV power measurements on a beamline.³⁸ These absolute accuracies are good for the Xe-based system only. For Sn-based EUV sources, because of varying spectral correction factors, an FC-type device with special 2%-BW mirrors has been used. The special multilayer mirrors, designed to simulate the performance of the 11-mirror system, allow one to estimate the EUV radiation in the 2% BW around 13.5 nm, without spectral feature information for the Sn source in a wide-spectral-range calibration.³⁹

1.3.2 Factors influencing effective EUV light collection

All of the EUV radiation emitted by sources cannot be collected and transmitted to IF. The following sections review various factors that affect the collection of EUV light at IF. Table 1.3 summarizes these discussions of EUV source technology limits.

1.3.2.1 Geometrical collector efficiency

Due to geometrical constraints, in today's system designs, a collector for a DPP EUV source collects less light than a collector for an LPP source. Currently, a 1.8-sr collector consisting of concentric hyperbolic-elliptical mirror shells (Wolter type 1 grazing-incidence optics) is being used for DPP EUV sources.^{40,41} For these collectors, EUV light undergoes two reflections before it is collected at IF. These collectors are produced by coating a nickel shell with palladium (Pd) or other materials like gold (Au), rhodium (Rh), or ruthenium (Ru); some new proprietary alloys are also proposed. For DPP EUV sources, suppliers have been proposing a collector of 3.14 sr, which will collect 50% of the light. However, no such design has yet

Table 1.3 EUV source technology limits.

	DPP			LPP		
	Xe		Sn	Xe		Sn
	Today	Ultimate	Today	Today	Ultimate	Today
Input power (W)	20000	30000	20000	2500	15000	1000
Conversion efficiency (%)	1.00	1.00	2.00	0.80	1.20	2.50
Power at the source (W)	200	300	400	20	180	25
Collection (sr, out of 2π sr)	1.8	3.14	1.8	3.14	5	3.14
Collection ability (% of 2π sr)	29	50	29	50	80	50
Collector transmission (%)	65	70	65	65	70	65
Debris mitigation transmission (%)	80	80	80	100	100	100
Gas transmission (%)	85	85	85	85	85	85
SPF transmission (%)	40	70	40	40	70	40
Etendue match (%)	75	100	75	100	100	100
Effective collection capability (%)	4	17	4	11	33	11
Power at intermediate focus (W)	8	50	15	2	60	3
						149

been realized, and doing so will be challenging. Separate studies are underway⁴² to investigate the collection limit of collectors. Carl Zeiss and Media Lario are the leading suppliers for these grazing-angle collectors.

For LPP, collectors are made from Mo/Si multilayers, which are protected by a thin coating layer (e.g., Ru). Today suppliers have demonstrated 3.14-sr collectors, and work is underway to design and manufacture a 5-sr collector, which will have 80% CE.¹¹

1.3.2.2 Collector reflectivity

Collector materials have limited reflectivity, contributing to loss of EUV light in the system. For Pd-coated shells used as collectors for DPP, the reflectivity at 13.5 nm decreases linearly from 85% to 65% for a grazing incidence angle of 5 to 15 deg.⁴⁰ Due to the finite size of plasma and the multishell collector design, the modeled effective reflectivity needs to be verified. Such measurements will become available as IF metrology is further developed. For now, a rough estimate of the upper limit of reflectivity of 70% is used. For LPP collectors based on multilayers, an upper limit of 70% is likewise projected. Note that, as the collector degrades, its effective reflectivity will decrease.

1.3.2.3 Gas transmission

Absorption of EUV light by a background gas such as Xe is expected in DPP and LPP systems. Although absorption-versus-pressure data are readily available,⁴³ suppliers do not provide pressure data because of pressure gradients and the proprietary nature of such data. From the FC2 experiment,³⁶ for 2.1 mTorr of Xe, a loss of 15% for a 900-mm distance in an EUV source can be expected. Suppliers usually expect a 15% loss, or 85% transmission, for Xe, which indicates the path length and gas pressure of EUV radiation to the IF.

For Sn-based DPP systems, the choice of carrier gas is not publicly known. Experiments with various Sn halides have shown that absorption by carrier gases can be a problem.⁴⁴ An 85% value is used in Table 1.3, but measurements need to be performed to assess the practical transmission for Sn-based DPP EUV sources.

1.3.2.4 Spectral purity filter transmission

EUV sources radiate over a range from the EUV to the infrared (IR). The multilayer optics in the EUVL scanner (Fig. 2.6) and grazing-angle collector also reflect in most wavelength regions. This combination of source emission and optics reflectivity will result in a wide spectrum of radiation being transmitted through the system and reaching the wafer. Radiation out of a 2% BW around 13.5 nm is called out-of-band (OOB) radiation. The main radiation bands of concern are 130–400 nm and >400 nm. In the 130–400-nm band, multilayers have significant reflectivity, transmitted radiation will cause flare at the wafer, and the longer-wavelength radiation will heat the optics, reticle, and wafers, causing overlay problems⁴⁵ and the

need to cool the optics. In addition, there is some concern about the ionization of environmental contamination by vacuum ultraviolet (VUV) light.⁴⁶

Today, complete source spectral purity requirements for OOB radiation are not agreed on among major scanner manufacturers. For 130–400 nm, spectral purity requirements are <3–7% (compare the power in this region with the power in the 2% BW around 13.5 nm), and spectral purity for the region >400 nm is not specified. The spectral requirements outside the 2% BW in 18–130 nm have not been addressed by scanner manufacturers, because the multilayer reflectivity in that range is very small. One of the scanner manufacturers has made public its estimate for the entire OOB requirements.⁴⁵ By assuming that a total OOB radiation at the wafer will need to be <10%, together with OOB radiation of <1% in the <400-nm region and total OOB radiation absorption by a single mirror of <10%, it is estimated that a specification of <3% OOB radiation will be needed in the region of 130–400 nm, 10% in 400–800 nm, and 0.2% in >800 nm to address flare and thermal issues. Remember that these specifications for OOB are at the IF, and not all of the OOB emitted at the source will be collected there, due to étendue limits and the finite reflectivity of optical elements between the source and IF.

Until recently, the potential need for a spectral purity filter (SPF) has not been widely acknowledged, causing the neglect of precise measurement of OOB radiation and development of SPF technology. In a recent industry panel discussion, all major scanner manufacturers publicly acknowledged the need for SPFs and agreed that even if they are not included in the final design, it is too risky to assume that SPFs will not be needed.⁴⁷ In a recent industry forum,⁴⁸ the majority of stakeholders (scanner manufacturers and source suppliers) agreed that SPFs will be needed.

The experimental data available for Xe DPP^{4,50} show that OOB radiation at the source is more than allowed by specifications at IF. It has been shown that in the 5–18-nm region 46%, and in the 18–80 nm region, 9.8% of the total radiation is expected,⁴⁹ which may not meet the OOB requirements for an EUV source. Measurements⁴ have shown that in the 130–400-nm region, the OOB radiation is 14%. For Sn LPP, data are available for a mass-limited droplet-based LPP system. OOB radiation in the 130–325-nm region was found to be negligible. However, in the 325–850-nm region it is 13%, compared to 9% measured for Xe DPP⁴ in the same region. Absolute spectral measurements of OOB radiation for various fuels are needed. The source operation parameters (temperature and density) will affect the OOB radiation; hence systematic measurements of OOB radiation are needed as a function of those parameters.

In today's EUVL microsteppers, a thin film is used as the SPF, which also doubles as a debris filter and vacuum barrier. Although such filters work well at lower EUV powers, they will not be able to tolerate the thermal load at high EUV power. Any SPF designed for high-power manufacturing will need to address the thermal load. Recent work has shown the experimental SPF efficiency based on the diffraction rating to be 55%, and the theoretical efficiency to be 60%.⁵⁰ Lawrence Berkeley National Laboratory (LBNL) has measured the efficiency of its multilayer SPFs to be 40%⁵¹ but predicts that an SPF efficiency >70% is well within reach

(see Refs. 50 and 51 and the references cited in the latter). Note that LBNL's SPF's are based on multilayer mirrors and the efficiency numbers refer to the percentage reflectivity of a multilayer, which is estimated to have an upper limit of absolute reflectivity of 70% at 13.5 nm. It is assumed that a multilayer SPF will replace one of the mirrors in the EUVL scanner, and its insertion will cause an additional loss factor of 30%.

1.3.2.5 Etendue mismatch

EUV sources have etendue limitations; there is an upper limit to the size of the source that can be accepted by the scanner. The current maximum acceptable etendue is 3.3 mm² sr, with a maximum solid angle of input to the illuminator of 0.03–1.2 sr. Because the acceptable source size specifications may vary among scanner manufacturers, the collectable source power for a given source will vary for different EUVL scanners.

Today a typical DPP source supplier expects for its source a 50–100% etendue match.^{11,15,52} The main problem for DPP is that the source size increases as the output power increases, limiting the maximum power that can be collected by a DPP source. It has been reported that the Sn pinch is smaller in size than the Xe pinch;¹⁹ however, Sn DPP sources will also have the problem of increasing source size with increasing source power.

The LPP source, in contrast, is small ($\approx 100 \times 100 \mu\text{m}$); for it, the source size should not be an issue.^{11,15,52} The full-spectrum source size and inband source size also raise some questions, and measurements are not conclusive. Measurements⁵³ have found 18% larger inband size than full-spectrum size for a Xe DPP source,⁵³ although for a Xe LPP source it was found that the inband source size could be smaller in size than the full-spectrum source size.⁵⁴

1.3.2.6 Other factors affecting source power requirements

Because the requirement for 115 W of power arises from a throughput model (see Table 2.3), the EUV source power requirements can increase, depending on how some of the requirements change. It is important to consider some of the major factors that may increase or decrease source power requirements.

1.3.2.6.1 Resist sensitivity. The EUVL scanner throughput model assumes an EUV resist sensitivity of 5 mJ/cm². Although this is the only characteristic mentioned in the throughput model, an EUV resist must meet many additional specifications [e.g., line edge roughness (LER) and resolution]. There is a trade-off between sensitivity, LER, and resolution.⁵⁵ For example, increasing absorption will improve the resist sensitivity but will worsen the profile and resolution. Because the resist sensitivity depends on how many times a resist molecule causes a reaction, more reaction means increased sensitivity but also higher LER. Today it appears that the alpha specification for resist sensitivity (5 mJ/cm²) for a given resolution cannot be met without sacrificing LER (see Table 1.4). Data 1 is for one

Table 1.4 EUV resist performance.

Parameter	Alpha specs	Data 1	Data 2	Data 3
Resolution 1:1 (nm)	45	50	48	48
Sensitivity (mJ cm ²)	<5	20	7.4	2.7
LER (nm)	<4	≈4	5.9	11.1

type of resist; data 2 and 3 are for another type. Resist performance needs to improve; otherwise, higher source power may be necessary to achieve the required throughput.

1.3.2.6.2 Mirror reflectivity. The current throughput model assumes 67.5% reflectivity for multilayers. It has been shown that a higher reflectivity of 70% is possible,⁵⁶ and a reflectivity >67% that can be obtained and sustained can reduce power requirements. At the same time, the reflectivity of collectors and mirrors decreases as they erode. Currently, a 10% reflectivity loss is accepted as the end of lifetime for optics; present lifetime estimates for mirrors are 1000 h.⁵⁷ Therefore, this factor can also weigh against the source power requirements. More source power can be demanded to compensate for loss of reflectivity in the mirrors and collector optics in an EUVL scanner.

1.3.2.6.3 Other factors. Other factors that can potentially affect power requirements are overhead time and number of mirrors. According to the EUVL scanner throughput model, out of a total of 36 s spent per wafer in the EUV scanner, 27 s is devoted to overhead time, and only 9 s is spent on exposing the photoresist on the wafer. Ota et al.² discuss the basis of the overhead time chosen in the throughput model. A small decrease in overhead time can mean a decrease in the required source power. Also, if the number of mirrors for certain scanner designs increases as EUVL is implemented at smaller nodes, more power will be needed.

1.3.3 Power for DPP sources

Table 1.3 shows the technology limits for various EUV source technologies. We should mention that a “showstopper” is defined as a technical problem that cannot be solved in a cost-effective and timely manner; a technical challenge, on the other hand, is one that can be so addressed. In many cases, one has to work on meeting a technical challenge to know that it is a showstopper.

Table 1.3 estimates the average value for sources of power loss between the source and IF. The actual values will depend on the source design and will need to be measured. In general, power values expected for today are conservative, and technology limit values estimate the upper limit for obtainable power from a given technology.

1.3.3.1 Xe DPP

EUV sources for existing EUV microsteppers are based on Xe DPP technology. They provide about 1 W of power at the IF.¹¹ However, the showstopper for Xe DPP is thermal extraction. It is now widely agreed that this technology cannot meet the power need for HVM sources, since the upper limit for thermal mitigation is expected to be 30 kW. All current Xe DPP projects^{10,11} are now focused on delivering a low-power source for an alpha-level scanner.

The current data for thermal extraction indicate that up to 20 kW^{10,11} of input power can be mitigated. The use of porous-metal cooling technology,⁵⁸ in which high-pressure water is forced through porous metal electrodes to cool them, has allowed increased power input to the sources. An additional increase in the thermal mitigation is expected from design changes and the new electrode cooling technologies. To reduce the thermal heat load on the electrodes, the distance between the plasma and electrode also needs to be increased to allow higher power generation.^{11,15,22} An electrode configuration called Star Pinch has been demonstrated to allow a higher thermal load than other DPP sources,⁵⁹ and for this electrode configuration a 10¹⁰-pulse lifetime has been predicted by the supplier. Input energy to a DPP source is dissipated in various components of the system, from which the heat must be extracted. According to calorimetric measurements for the Star Pinch configuration,⁵⁹ in the cathode 8%, anode 6%, foil comb 13%, and chamber 73% of the input power is dissipated. Electrode thermal extraction is therefore only part of the issue, but still the most important part, since rising temperatures can increase the erosion of electrodes and reduce their lifetime. Sputtering is the next leading cause of erosion of electrodes.

For Xe DPP, it is reasonable to expect that close to 1% can be achieved for the upper limit of the CE, something already seen with Xe LPP. Today most suppliers are working with 1.8-sr collectors and plan to integrate 3.14-sr collectors in the near future. In Table 1.3, the debris mitigation device transmission is simply an estimate; the same is true for SPF filters available today. With a 75% etendue match expected, a 4% effective collection can be expected today for Xe DPP, which can potentially increase to 17% as the SPF and collector efficiency improve. Since power measurements are made directly at the source, 200 W in 2 π sr with 4% collection will mean that a minimum of 8 W of power can be expected at the IF. With 30-kW power input and 17% collection, a maximum of 50 W of power at the IF can be expected for Xe DPP.

In summary, thermal extraction is the showstopper for Xe DPP technology, limiting it to 50 W of maximum power at IF. Remaining challenges for Xe DPP-based EUV sources are debris mitigation, collector lifetime, and collector cooling.

1.3.3.2 Sn DPP

For Sn DPP, a higher CE of 2.5% has been measured¹⁰ and up to 3% CE has been predicted.⁶⁰ The same constraints on collection efficiency for Xe DPP apply to Sn DPP systems. Current collection efficiency is estimated to be 4%, and 17% is expected in the near future. With 400 W of power measured in 2 π sr at the source,

a minimum of 15 W of power can be expected at IF. An upper limit of 150 W at IF is expected for a 30-kW power input.

In Sn DPP systems, debris mitigation is the potential showstopper. For a typical pinch, 1×10^{15} Sn atoms are needed.⁶¹ This means delivery and extraction of up to 500 g of Sn a day for a Sn DPP system. Unlike Xe, Sn will deposit on the collector and other optics, causing serious lifetime issues, and therefore must be mitigated. Because the collector lifetime is the most important component, success of debris mitigation is mainly reflected in the increased lifetime of Sn collectors. The current best estimate for the collector lifetime is 100 million to 10 billion pulses.²¹ The supplier that made these estimates has shown a 5% loss of reflectivity for a sample collector material over 100 million pulses for its debris mitigation system. The supplier has also shown that it can reclaim collector reflectivity, for up to 100 cleaning cycles, with only 4% loss in the reflectivity after 100 cycles. Thus, the supplier is expecting to demonstrate a collector lifetime of up to 10 billion pulses. Although such performance meets the needs for an alpha-level EUVL scanner, much work is still needed for a manufacturing scanner to meet the expected requirements of 80 billion pulses. In addition, debris mitigation techniques for a Sn DPP source may have lower transmission than for a Xe DPP source, lowering the overall collection efficiency. In summary, the critical issues being faced by Sn DPP are debris mitigation, collector lifetime, and collector thermal load.

1.3.3.3 Li DPP

Recently a high-power Li DPP system was proposed.²⁶ With the present estimate of a 2.5% CE for a Li DPP source, the collection efficiency and technology limits are expected to be similar to those of a Sn DPP system. However, no power performance data are currently available to assess the potential technical challenges or showstoppers.

1.3.4 Power for LPP sources

1.3.4.1 Laser power

High-power lasers are the key enablers of LPP EUV source technology. Consequently, their limitations must be fully understood to understand the limitations of LPP EUV sources. A high average power (15-kW range) and high peak power (hundreds-of-millijoules to 1-J pulses with a width of ≈ 10 ns)^{62–64} are needed. It is also believed that an ≈ 10 -ns pulse length may be needed for Xe LPP only, while large pulse lengths of ≈ 100 ns may be sufficient for Sn LPP.

No single laser module is expected to meet these laser power requirements. Laser modules will need to be multiplexed to deliver such power. Multiplexing high-power lasers has been demonstrated, in which three 1-kW lasers were spatially and temporally multiplexed.^{13,24} Although there is no hard technical basis for predicting how many chains can be used for multiplexing, it is a good estimate that up to 15 kW of laser power can be achieved. In principle, higher laser power

can be achieved by further multiplexing, thus giving this technology the scalability to enable higher EUV power than current specifications.

Nd:YAG lasers, CO₂ lasers, and excimer lasers are being considered for LPP-based EUV sources for HVM. Since a weak dependence of CE on laser wavelength has been shown,¹⁶ the ultimate choice will most probably be decided by the cost of ownership (CoO) of lasers.

A supplier developed a 1.5-kW Nd:YAG laser module using master oscillator–power amplifier (MOPA) architecture⁶² and demonstrated reliable operation of 1.5-kW lasers. The supplier was then able to combine up to three such chains and deliver 4.5 kW of power. Such laser power output is the current record for the high-power EUV source industry, but the system was not run long enough to obtain reliability data.⁶⁵ A second supplier has demonstrated Nd:YAG lasers with 2.5-kW power, 6 ns, and a 10-kHz system that yields 4 W of power at IF.¹² Plans exist to increase the power to 5 kW to demonstrate 10-W systems. However, because further increases in Nd:YAG laser power are not deemed feasible and cost-effective,¹² this supplier plans to use pulsed CO₂ lasers as drivers for high-power sources. A third supplier has demonstrated a 1.2-kW, 16.6-ns Nd:YAG pulse laser,¹¹ which gives a 1% CE and produces 12 W of power at IF. A fourth supplier¹³ has demonstrated operation of a 1-kW Nd:YAG laser module. It expects to increase the laser power per module to 1200 W. In addition, this supplier has demonstrated multiplexing of three lasers to realize 3 kW of laser power and believes that higher power can be achieved by multiplexing.

Reliable CO₂ lasers with continuous output of 10–20 kW are commercially available. However, they need to be switched to produce the desired pulse shapes. A 30–40% switching efficiency is expected for these lasers. Initial experiments have shown CEs of 0.6%¹² and 0.7%¹⁵ with targets for CO₂ laser pulses.

In addition, excimer lasers have been proposed as the driver for LPP sources for an HVM environment.^{16,32} The excimer drive laser in such a source uses a triple-harmonic Nd:YLF seed laser that has been frequency-shifted to match the XeF emission at 351 nm. Operation has been demonstrated at 4 kHz with a 100-mJ pulse energy per power amplifier, which provides output power of 800 W using a single laser frame with two excimer power amplifiers. With input power of 50 kW, it has a 1.6% wall-plug light efficiency. The supplier roadmap shows an increase to two laser frames and increased operation frequency to 8 kHz per amplifier or 32 kHz overall, with a pulse energy of 220 mJ to deliver 7 kW of power. Based on an output of 3.5 kW per frame with 150-kW input power, the supplier expects to achieve 2% wall-plug CE for its XeF excimer drive lasers. This supplier has also demonstrated the feasibility of a sub-100-μm Sn droplet delivery system operating at 36 kHz that can use its high-frequency laser system. There is, however, disagreement on the wall-plug efficiency for excimer lasers; estimates as low as 0.5% have been proposed as realistic.³¹

The laser power density of 1×10^{11} W/cm² is now believed to be the optimum for generating Sn LPP plasmas with Nd:YAG lasers. This was recently demonstrated in experiments⁶⁶ by scanning the Sn targets through the minimal focus of a

laser beam (with a maximum intensity of 1×10^{12} W/cm²) and seeing double peaks corresponding to CE maxima.⁶⁶ Experimental and modeling efforts are underway to understand these power density limits in order to develop ways to achieve the maximum CE for Sn LPP.⁶⁶ Experimental and modeling results¹⁶ indicate that the required optimum laser power density increases with decreasing laser wavelength.

1.3.4.2 Xe LPP

Today, for Xe LPP with 2.5-kW Nd:YAG lasers, Xe jet target, and 0.8% CE, a supplier has measured 9.1 W of power at the source and expects 2 W to be collected at the IF.¹² A second supplier, using a 1.2-kW Nd:YAG laser, a xenon droplet target, and 1% CE, has measured 12 W at the source. A third supplier, using a 1-kW Nd:YAG laser and xenon jet, has measured 0.8% CE and 8 W at the source. It has also demonstrated a combined laser system, with 0.5% CE and 3 kW, with 15 W measured at the source.^{13,24}

Assuming 15 kW to be the highest feasible laser power that can be made available, this technology has the potential of delivering a minimum of 60 W of power at IF. Due to the low CE of Xe fuel, similar to that in Xe DPP, this technology is not expected to deliver the power required for EUV sources for HVM.

1.3.4.3 Sn LPP

Due to its higher efficiency, Sn is also favored as a fuel in LPP EUV sources. In addition to high-power lasers, the potential technical challenges for Sn LPP are Sn delivery and Sn debris mitigation. In LPP, the geometrical arrangement allows for a large collection angle; however, this geometry also does not allow debris mitigation devices (e.g., a foil trap) between the source and the collector. For Xe LPP, progress has been made in mitigating debris (high-energy Xe ions) using gas curtains.^{15,49} However, for Sn, which is a metal, Sn debris mitigation may be a showstopper for LPP.

The most promising approach to addressing Sn debris is the use of an enclosed Sn source,⁶⁸ in which heated Sn is contained in a cavity, the laser beam enters through heated silicon windows, and EUV exits through other windows. In the past, development of such metal sources for EUV applications has been difficult for cadmium targets,⁶⁹ because silicon windows degraded and metal eventually leaked out.

At this time, the highest reported power is 25 W at the source, with a 2.5% CE for Sn tape-based targets.¹³ Other researchers have reported higher CEs for Sn LPP⁷⁰ but with much lower laser power. Today the expected collection efficiency is 11%, but progress in collector design and improved SPF will increase that to 33%. This means that for a 15-kW laser, up to 149 W of power can be obtained at the IF for Sn LPP. In summary, the remaining technical challenges for Sn LPP technology are laser power, debris mitigation, and collector lifetime.

1.3.4.4 Li LPP

Li LPP was recently chosen by a supplier as the technology for achieving high-power EUV sources.^{9,16,71} The supplier has demonstrated a 2.5% CE using a 351-nm excimer laser. The initial spectra have shown smaller OOB radiation than for Sn LPP. Due to their smaller atomic weight, Li ions cause less erosion of the collector mirrors, and the deposited Li metal can be removed by heating the mirrors to 400°C. The same supplier has also demonstrated a coating for collector mirrors that may be able to control the diffusion of Li into the mirrors. In addition, a Li droplet delivery system with droplets of 50- μm diameter and operation frequency of 48 kHz has been demonstrated. No EUV source power results have been yet reported.

Similarly to Sn LPP, 149 W of power can be estimated for a 15-kW power input. However, if SPFs are not necessary for Li LPP, higher EUV source power may be achieved. Remaining challenges for Li LPP technology are the laser power and additional system issues that may surface as the source performance data becomes available for Li LPP-based EUV sources.

1.4 Source Components and Their Lifetimes

An important factor in the viability of EUV sources is the lifetime of their components. Electrode lifetime is important for DPP, and collector lifetime is important for DPP and LPP.

The critical component lifetime is measured as the number of pulses that a component can accept without its performance degrading to an unacceptable level. For collectors, up to 10% loss of reflectivity is accepted.⁷² For electrodes, choosing lifetime measurement criteria is not straightforward. A loss of 10% power in the source has been proposed as a criterion for replacing electrodes.⁷³

Previously, scanner suppliers had lifetime requirements for components of 30,000 h tied to cleanliness requirements for sources. Recently, however,⁷² they have clarified this requirement to say that the lifetime of critical components will be decided by the CoO. This means that if collectors and electrodes can be cost-effectively replaced with an acceptable component cost, down time, and requalification time, the lifetime of the source components can be lower. This is good news for source suppliers, since the lifetime of 30,000 h could be a showstopper for EUV sources.⁷⁴ Since there are no widely accepted CoO models of EUV sources for EUV scanners today, an agreement was reached between scanner manufacturers and source suppliers in an industry forum on this topic.³ Currently, the general guideline for lifetime requirements (Table 1.1) sets the lifetime of an alpha tool operating at 2 kHz at 1 month or 10 billion pulses, of a beta tool operating at 5 kHz at 3 months or 10 billion pulses, and of a production tool at 12 months or 80 billion pulses.

Today, for Xe DPP for microsteppers, the electrode lifetime is >80 h or 300 million pulses.¹¹ A much higher electrode lifetime of 10 billion pulses was previously projected for another design of Xe DPP.⁶⁰ For Sn DPP, an electrode life-

time of >1 billion pulses has been reported.²¹ Thermal management and increased plasma-to-electrode distance will enable the collector lifetime to be improved. Recently an innovative electrode design involving rotating electrodes and a laser-triggered vacuum arc for tin delivery has been proposed to demonstrate >1 -billion-pulse lifetime for the electrodes, and this design can potentially allow the supplier to meet the lifetime specifications of electrodes in Sn DPP.²¹ The cost and time to replace electrodes are lesser issues than the lifetime of collectors.

Collector lifetime is generally measured with a sample made of collector materials using measurements of its reflectivity over time or a quartz crystal microbalance (QCM).¹¹ For Xe DPP, lifetimes of 500 million¹⁰ to 1 billion¹¹ pulses have been demonstrated, and a range of 5–10 billion is expected.¹¹

Collector lifetime for Sn DPP is a major challenge. Lifetimes of 10 million²¹ to 100 million¹¹ pulses have also been demonstrated by an *in situ* cleaning method to restore the reflectivity of collectors for up to 100 cycles with only 4% reflectivity loss. This means that a lifetime up to 10 billion pulses or longer can be achieved.

Compared to DPP, in the current designs the distance between the source and collector in LPP is larger. For Xe LPP, a lifetime of 5 billion pulses has been demonstrated. There are currently no data for the Sn LPP collector lifetime. It has been shown¹⁶ that for a Li LPP, a lifetime of 45 billion pulses can be expected, and the supplier hopes that its technology will also be applicable for Sn LPP. Although collector lifetime remains the second challenge for the implementation of EUVL, it appears that eventually this will be a CoO issue and not a potential showstopper for EUV sources.

1.5 Summary and Future Outlook

Today, Sn DPP technology is the leading technology for high-power EUV sources; sources based on this technology can deliver up to 400 W of EUV power at the source, and the estimated collectable power at the IF ranges from 15 to 50 W. The lower estimates correspond to the assumptions that SPF will be needed and that the current etendue match and capacity of collectors and SPF will be maintained. The highest estimate corresponds to a 100% etendue match with the performance of collectors and SPF expected in the future. Based on 30 kW of maximum input power and an increased CE of 3%, Sn DPP can be expected to deliver up to 150 W of power at IF. If the input power can be further increased, the source power at IF may also be increased. With present data on tin debris mitigation and an estimated collector lifetime of 10 billion pulses, we can expect that collector lifetime will be a CoO issue. The existing technical challenges facing Sn DPP EUV sources are the need for collector cooling, continued progress in debris mitigation, and development of suitable technology.

Xe as the fuel is not expected to deliver the required power for HVM by either DPP or LPP technology. However, we may see Xe DPP sources in alpha- or beta-level scanners. For LPP technology in general, high-power lasers are the leading

technical challenge and a potential showstopper. LPP technology has the advantage of potential power scaling; however, the current lack of high-power lasers has reduced confidence in this technology. Li is a new candidate fuel material. Demonstrating a 2.5% CE with the potential for low damage to the collector and *in situ* collector cleaning, Li LPP technology has the potential for success. However, the current lack of EUV source power data for Li LPP makes it difficult to predict the potential of Li as a fuel for EUV source technology. Although high-frequency Sn droplet targets are in operation today, debris mitigation is still a significant technical challenge for Sn LPP.

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Chapter 2

EUV Source Requirements for EUV Lithography

Kazuya Ota, Yutaka Watanabe, Vadim Banine, and Hans Franken

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2.1 Introduction and Background

2.1.1 Joint specifications

Joint specifications for EUV sources were first presented by ASML, Canon, and Nikon in February 2002 to accelerate source development by source suppliers, and the joint specifications have been updated periodically. The latest requirements are shown in Table 2.1, which was presented at the EUV Source Workshop in Miyazaki (Japan) on November 5, 2004.¹

These specifications are defined at/after the intermediate focus (IF), which is explained in the next subsection. Table 2.2 shows how major requirements changed from 2002 to 2004. Requirements for wavelength, EUV inband power, and etendue

Table 2.1 Joint requirements for EUV sources (February 2004).

Source characteristics	Requirements
Wavelength (nm)	13.5
EUV power (inband) (W)	115*
Repetition frequency (kHz)	>7–10 [‡]
Integrated energy stability (%)	±0.3, 3 σ over 50 pulses
Source cleanliness (hours)	>30,000 [†]
Etendue of source output (mm ² sr)	<3.3 [‡]
Max. solid angle input to illuminator (sr)	0.03–0.2 [‡]
Spectral purity:	
130–400 nm (DUV/UV) (%)	<3–7 [‡]
>400 nm (IR/visible) at wafer (%)	TBD [‡]

*At intermediate focus (IF).

[†]After IF.

[‡]Design dependent.

Table 2.2 Changes in joint requirements.

Source characteristics	Feb. 2002	Oct. 2002	Feb. 2003	Sept. 2003	Feb. 2004	Nov. 2004
Wavelength (nm)	13–14	13.5	13.5	13.5	13.5	13.5
EUV power (inband) (W)	47–120	80–120	115	115	115	115
Repetition frequency (kHz)	5	6	7–10	7–10	7–10	7–10
Etendue of source output (mm ² sr)	1	1–3.3	1–3.3	1–3.3	1–3.3	3.3
Max. solid angle input to illuminator (sr)	0.2	0.03–0.2	0.03–0.2	0.03–0.2	0.03–0.2	0.03–0.2

of source output were agreed on at the workshop, but requirements for repetition frequency and maximum solid angle input to illuminator are not yet agreed on, because they depend on the tool design.

2.1.2 Definition of EUV source

Two kinds of plasmas emit EUV light: laser-produced plasma (LPP) and gas-discharge plasma (GDP). There are various types of GDPs according to the arrangement of the electrodes. Furthermore, several materials (Xe, Sn, etc.) are used for the plasma. Thus, even if only the plasma is considered, there are many potential candidates for the EUV source to be used for high-volume manufacturing (HVM). Collector optics is used to collect EUV light that radiates from the plasma and to focus the light at the IF. There are two kinds of mirror for the collector: the normal-incidence multilayer mirror and the grazing-incidence total-reflection mirror. Furthermore, there are many types of collector that are being developed.

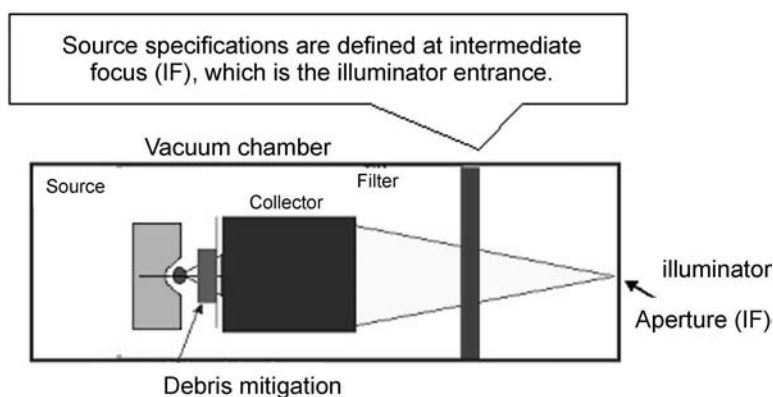


Figure 2.1 Definition of EUV source.

The EUV source is defined as the IF where the EUV light is focused, so that the appropriate exposure tool, and particularly its illuminator, does not depend on the variety of EUV source as described above. The IF is the illuminator entrance (see Fig. 2.1). The characteristics of EUV light at the IF should not depend on the method of generating the plasma or on its material, but must satisfy the overall joint requirements.

The lifetime of the source components, including the collector optics, is an important factor in the cost of ownership (CoO) of the EUV source. Debris shortens the lifetime of the collector. The material, size, energy, and state of the debris depend on the method of generating the plasma and on its material. Therefore, a debris mitigation system is an indispensable component, and its structure must be optimized for each EUV source.

Light emitted from a plasma has a wide-ranging spectrum, from EUV to IR. A spectral filter may be needed for the EUV source to satisfy the requirement of spectral purity for its application. It is known that the spectra of light from LPPs and GDPs are different. The spectral filters for LPP and GDP may therefore differ because they must be optimized.

2.2 Source Requirements

2.2.1 Choice of wavelength

The optics used in the EUVL tools is based on multilayer mirrors (MLMs). Different combinations of multilayer pairs are possible. The most common for the EUV region are Mo/Si and Mo/Be pairs. The Mo/Be mirrors' spectral range is larger than that of the Mo/Si mirrors. The cutoff wavelength for Mo/Si mirrors is about 12.5 nm in the shortwave region. No source, though, has been found so far that can make effective use of this fact. Strong emission in the 11-nm region has been demonstrated for LPP Xe sources; see Fig. 2.2. Nevertheless, because the spectral width of the ML mirror in the shorter wavelength region is narrower than in the

longer wavelength region, the total power at the wafer for Mo/Be mirrors does not exceed that of Mo/Si mirrors. Coupled with the manufacturing and safety problems of Mo/Be mirrors, that has led to a choice of wavelength in favor of Mo/Si mirrors.

A more quantitative choice relates to the final adjustment of the system wavelength within a given spectral window of the Mo/Si mirror. The source emission characteristics play a major role in that choice.

A number of sources have potential for EUVL.^{2–7} Due to their emission characteristics, the working materials that are used in those sources are usually Xe, Sn, and Li. Li, being a line emitter,^{7,8} is the most sensitive to the choice of operating wavelength of the lithographic tool. Li radiates at 13.50 nm with a linewidth of 0.03 nm. The choice of a central wavelength differing from 13.50 nm by even a small amount can eliminate the possibility of using Li as a working material in the source for EUVL. On the other hand, a nonoptimal choice of the wavelength of the sources with other radiators means loss of power as well. The amount of energy lost due to nonoptimal spectral alignment can be evaluated. This type of analysis has been done for a white-light source with a wavelength-independent spectrum.⁹ In this case, the integrated reflectivity of the system, with 10 mirrors, is only 5% lower for 13.5 nm than for 14.4 nm, as mentioned by Stuik et al. in Ref. 9. However, the final analysis has been done with a combination of the optical throughput and the light-source spectrum in Ref. 10.

Figure 2.2 presents a calculated near-normal-incidence reflectivity, based on the model of Ref. 11, for an 11-mirror reflective system. In contrast with a white spectrum, real Xe-, Sn-, and Li-based sources⁸ have a maximum near 13.5 nm. Alteration of the peak wavelength by 0.5 nm might cause light losses of 60%–100%. The light loss induced by placing the tool wavelength at 13.5 nm for Xe and Sn emitters does not exceed 5%–10%.

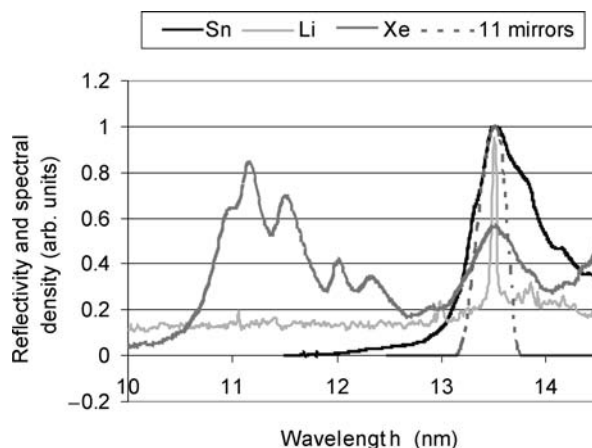


Figure 2.2 Calculated near-normal-incidence reflectivity of an 11-mirror system, based on the model of CXRO,¹¹ vs. spectra of Sn, Li, and Xe, as acquired in a joint investigation by ASML-ISAN.⁸

Thus, depending on the type of light source, it is possible to achieve only a 5%–10% increase in the optical throughput of a system by accurate spectral matching for emitters other than Li. The same shift for a Li-based source would make its use in EUVL impossible. That is not desirable at this early stage of development of EUVL. Currently, therefore, 13.5 nm is the wavelength of choice for EUVL.

2.2.2 Source power

The output power is the most important characteristic for EUV sources, because it affects the wafer throughput of EUV exposure tools directly. A typical EUV wafer throughput model is shown in Table 2.3. The energy required for exposing a wafer is obtained from field and wafer parameters. Assuming a field size of 25 mm × 25 mm and 89 fields in a wafer, 78.7% of the wafer area is exposed. A 25-mm field height is formed by masking a 26-mm field with an aperture, so 3.8% (= 1/26) of the light power is blocked. Assuming the resist sensitivity to be 5.0 mJ/cm², the energy needed to expose all fields in a wafer is 2.9 J.

On the other hand, the power at the wafer is obtained from the source power, illuminator conditions, reticle conditions, and projection optics (PO) box conditions.

Table 2.3 Typical wafer throughput model.

Throughput	wafers/h	100
Time per item		
Total time per wafer	sec	36.0
Stage overhead	sec	27.0
Exposure time	sec	9.0
Field and wafer parameters		
Wafer diameter	mm	300
Fraction of wafer exposed	%	78.7
Penalty for not using full field height	%	96.2
Resist sensitivity	mJ/cm ²	5.0
Intermediate derivatives at wafer		
Total energy per wafer	J	2.9
Power at wafer	W	0.321
PO box		
Reflectivity, mirror	%	67.5
Number of near-normal mirrors		6
Bandwidth mismatch loss	%	5.0
Polarization loss	%	5.0
Gas absorption PO	%	5.0
Total transmission PO	%	8.1
Reticle		
Reflectivity reticle	%	65.0
Power at reticle	W	6.1
Illuminator		
Total transmission	%	8.4
General		
Overall component degradation	%	37.0
Power: captured clean inband photons	W	115.2

The total transmission of the illuminator and that of the PO box are assumed to be 8.4% and 8.1%, respectively. The overall component degradation factor includes the collector reflectance degradation, MLM reflectance degradation, spectral purity transmission degradation, and so on. It is expected that 115-W light power will be attenuated to 0.321 W from the IF point to the wafer as a result.

The exposure time per wafer can be calculated by dividing the total exposure energy at the wafer by the exposure power at the wafer. The stage overhead time includes the scanning-stage acceleration and deceleration times, the wafer alignment time, the wafer exchange time, and so on. It should be noticed that the required scanning length for a reticle stage is longer than the 25-mm field size, because the 2-mm slit width and ≈ 3 -mm arc height are included. The time for running this 5-mm extra length might be counted as a part of the exposure time, but in this model it is included in the stage overhead.

Next, how to improve the wafer throughput is discussed. The source output power, the illuminator transmittance, the PO-box transmittance, and the resist sensitivity are all equivalent in affecting the exposure time. If the resist sensitivity is improved by a factor of 2, the required source power is reduced by half. The scanning-stage acceleration also affects the wafer throughput, but its contribution is not the same as that of the above-mentioned factors. How each factor affects the wafer throughput is reviewed here.

A simplified wafer throughput model, which is different from the model described above, is now introduced (see Fig. 2.3).¹³ The time required to process a wafer by a wafer scanner is described with the following expression:

$$\begin{aligned} T &= T_{\text{scan}}N + T_{\text{oh}} \\ &= N(t_{\text{acc}} + t_{\text{settle}} + t_{\text{exp}} + t_{\text{settle}} + t_{\text{dec}}) + T_{\text{oh}} \\ &= N \left[\frac{2P}{a_w WR} + 2t_{\text{settle}} + \frac{(L + H)WR}{P} \right] + T_{\text{oh}}, \end{aligned}$$

where T_{scan} = scanning time per field, N = field number per wafer, T_{oh} = overhead time (wafer exchange, wafer alignment, etc.), t_{acc} = acceleration time, t_{dec} =

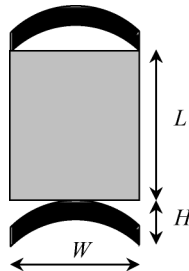


Figure 2.3 Exposure field and illumination ring-field.

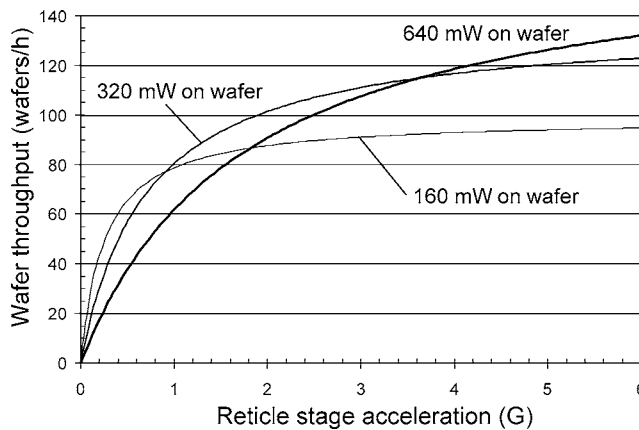


Figure 2.4 Relationship between wafer throughput and stage acceleration.

deceleration time, t_{exp} = field exposure time (even velocity), t_{settle} = stage settling time (after accelerating and before decelerating), P = EUV intensity on wafer, a_w = acceleration of wafer stage, W = field width, L = field height, H = arc height + slit width, and R = photoresist sensitivity.

In this model, the time for stepping between fields is not calculated, because the stepping movement is assumed to finish within the scanning deceleration and the acceleration time. The wafer throughput is obtained from the expression $3,600/T$, where T is in seconds. The relationship between the wafer throughput and the reticle stage acceleration is shown in Fig. 2.4. In this calculation, the photoresist sensitivity is 5 mJ/cm^2 , the stage settling time is 25 ms, and the overhead time is 11.5 sec. Results for EUV intensities on wafers of 160, 320, and 640 mW are shown, while 321 mW was assumed in the typical throughput model in Table 2.3. The field size is $25 \text{ mm} \times 25 \text{ mm}$, and the number of fields is 89.

Figure 2.4 shows that wafer throughputs of more than 100 per hour cannot be obtained if the EUV intensity on wafer is 160 mW, even if the reticle stage acceleration is higher than 6 G. If the EUV intensity is 640 mW, a reticle stage acceleration higher than 4 G is needed to take full advantage of the additional EUV power.

2.2.3 Repetition frequency

The repetition frequency is determined from a specification of dose uniformity. The dose uniformity depends not only on the integrated energy stability of the EUV source, but also on the control and measurement accuracy of the dose in the exposure tool.

The power at the wafer is 0.321 W in the typical wafer throughput model. The slit exposure area on the wafer is assumed to be $2 \times 25 \text{ mm}^2$. Therefore, the average EUV power in the slit is 642 mW/cm^2 . The exposure time is 7.8 ms at a point on a wafer if the resist sensitivity is 5 mJ/cm^2 .

In a case where the energy stability budget of the EUV source for dose control is 0.2% (3σ), 0.25% (3σ), or 0.3% (3σ), EUV light must expose the point with 112.5, 72, or 50 pulses, respectively, if the integrated energy stability over 50 pulses is 0.3% (3σ). To deliver more than those numbers of pulses in 7.8 ms, repetition frequencies more than 14.4, 9.2, and 6.4 kHz are needed, respectively. It is stated in the joint requirements that the repetition frequency must be higher than 7–10 kHz, depending on the design of the exposure tool.

The width of the slit is limited because the number of mirrors in the projection optics is limited. The width is assumed to be 2 mm in the typical wafer throughput model. If the width changes, the requirement of the integrated energy stability or the repetition frequency may change.

2.2.4 Imaging

The source-induced dose repeatability has a significant influence on the quality of the imaging (critical-dimension control). Figure 2.5 presents an example of a

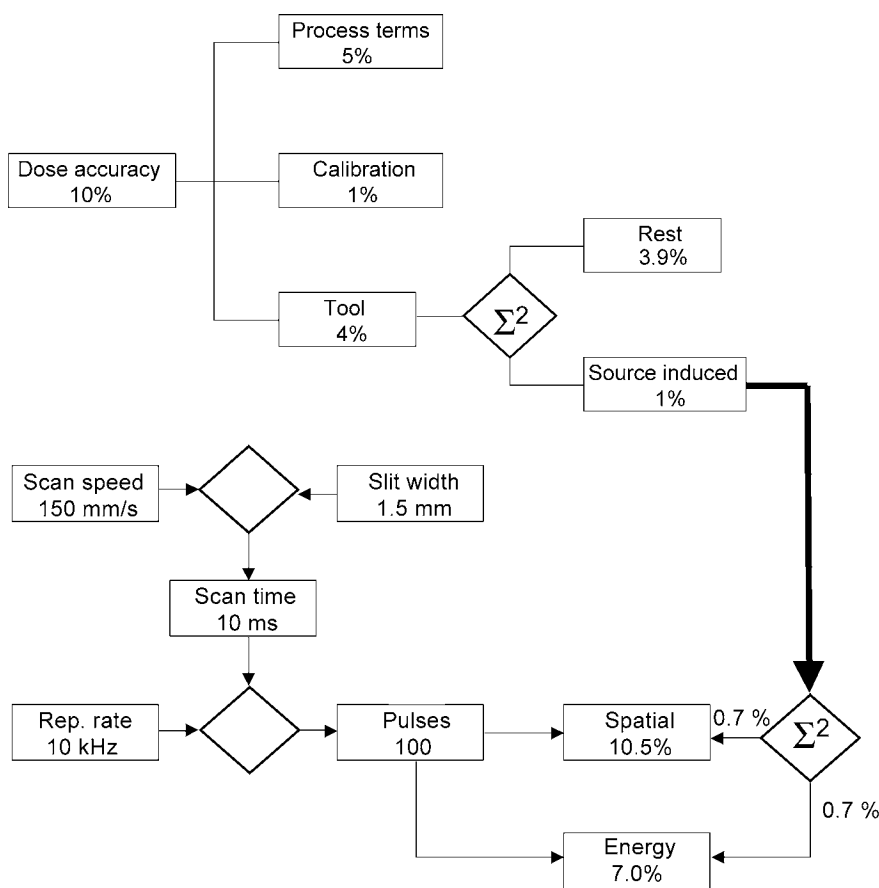


Figure 2.5 Source-induced repeatability diagram.

simplified model based on critical-dimension control, which is determined by the source repeatability.

If a dose accuracy of 10% is necessary from the critical-dimension-control point of view, then source-induced dose repeatability can contribute only 1% or less, as shown in Fig. 2.5. An accurate analysis of the nature of dose repeatability budgets is given in Ref. 9. The main components in the dose repeatability budget are:

- the intensity pulse-to-pulse repeatability, and
- the source pulse-to-pulse spatial stability.

The influence of pulse-to-pulse variation of intensity on the dose repeatability (D_i) depends on the number of pulses in the slit and the magnitude of this variation ($3\sigma_i$):

$$D_i = \frac{3\sigma_i}{\sqrt{N}}. \quad (2.1)$$

Depending on the illuminator design, every movement of the source leads to an intensity shift in the slit. This means that some parts of the slit may receive an incorrect amount of energy. The influence of the spatial stability on the dose repeatability (D_{sp}) depends on:

- the slit-related spatial stability factor f_2 (1/3 has been assumed here),
- the magnitude of this variation ($3\sigma_{sp}$), expressed as a percentage of the source size, and
- the number of pulses in the slit (in the case of random positional variation).

The dose repeatability for critical illumination is given by

$$D_{sp} = \frac{2 \times 3\sigma_{sp} f_2}{\sqrt{N}}. \quad (2.2)$$

The following equation can be used to calculate the number of pulses in the slit:

$$N = \frac{wfq}{v}, \quad (2.3)$$

where fq is the source repetition rate, w is the slit width, and v is the scan speed. In the case of a real optical design, the relations between these factors can be different. Table 2.4 summarizes the values used in Fig. 2.5.

Using Eq. (2.3), the number of pulses in the slit can be calculated to be 100. The dose-induced repeatability budget is split evenly between dose repeatability (induced by spatial pulse-to-pulse repeatability) and repeatability of the pulse-to-

Table 2.4 Values assumed in the example of Fig. 2.5.

W	1.5 mm
V	150 mm/s
f_q	10 kHz
Source-induced repeatability budget	1%

pulse intensity. The different contributions are summed quadratically, since they are independent. Using Eqs. (2.1) and (2.2), it is possible to calculate the restrictions on spatial stability and the variation of the intensity of the source. The numbers listed in Fig. 2.5 are the 3σ values.

It is apparent that the higher the repetition rate of the source, the better the dose repeatability. Thus, when choosing between two sources (other factors being the same), the source with a higher repetition rate and therefore lower energy per pulse is preferable.

2.2.5 Source cleanliness

Next to output, cleanliness is the most critical characteristic of an EUV source, because it affects the wafer throughput and the CoO directly. It is desirable to minimize debris from the target, nozzle, or electrode reaching the IF. Residual debris hits and damages illuminator mirrors, and the mirror reflectivity will drop in proportion to the amount of debris and its kinetic energy. It is anticipated that the collector mirror that faces the source emission point will be damaged by debris and will be replaced periodically. But other illuminator mirrors after the IF cannot be replaced easily, because they are integrated into a wafer exposure tool and aligned precisely with each other.

More than 30,000 light-on hours of source cleanliness after the IF is required to obtain a 10-year lifetime of the illuminator, where the exposure time is expected to be 1/3 of the wafer processing time. The amount of debris that is discharged through the opening between the source and the wafer exposure tool should be controlled. In addition, C_xH_y and H_2O , which flow into the wafer exposure tool through the opening, should be controlled because they contaminate the illuminator mirrors and the projection mirrors. In order to achieve the required source cleanliness, metrology and evaluation techniques are very important.

2.2.6 Etendue of source output and positioning stability

Etendue is an optical invariant and is called by many different names.¹⁴ One of the names is “light-gathering power.” As implied by this terminology, when light enters an optical system with smaller etendue from another optical system with larger etendue, the former optical system fails to transmit some part of the light. Thus, an illuminator cannot transmit all light from an IF with larger etendue than that of the illuminator. Therefore, a given EUV power with a larger etendue than

that of the requirement is substantially equivalent to a smaller EUV power with the etendue of the requirement. The light that cannot be transmitted through the illuminator becomes thermal energy, and extra cooling is needed. The etendue at the IF must be smaller than that of the requirement.

When area A on a wafer is exposed with uniform intensity and uniform numerical aperture, NA , the etendue, E_P , of the projection optics is obtained by

$$E_P = A2\pi(1 - \sqrt{1 - NA^2}) \approx \pi A \cdot NA^2.$$

This is the etendue of the light exposed on the wafer and is also the etendue of the light that is outgoing from the reticle and is transmitted through the projection optics. On the other hand, the etendue, E_I , of the light that impinges on the reticle is obtained by

$$E_I = \pi(Am^2) \left(\sigma \cdot \frac{NA}{m} \right)^2 = \pi\sigma^2 A \cdot NA^2,$$

where σ is the coherence factor and m is the magnification. When there is an integrator in the illuminator, E_I is the etendue of the light that is outgoing from the integrator and transmitted through a downstream part of the illuminator after the integrator. It is found that E_P is different from E_I unless σ is 1. This means that etendue is not necessarily conserved before and after the reticle. The zeroth-order diffraction light from the reticle is reflected at the same angle as incident light. However, the first-order diffraction light is reflected at a different angle from that of the zeroth order. Therefore, the etendue becomes bigger after the reticle.

Whether an integrator is necessary or unnecessary in an EUV illuminator depends on the characteristics of the EUV source (e.g., the spatial uniformity and angular uniformity) and their temporal stability. The required characteristics of the integrator also depend on the characteristics of the EUV source. When an integrator is used in the illuminator, the integrator enlarges the etendue.

If the area A is 50 mm², NA is 0.25, and σ is 0.6, then E_P is 9.8 mm² sr and E_I is 3.5 mm² sr. The coherence factor is changed for various device patterns and may become smaller. In such a case, E_I becomes smaller than 3.5 mm² sr. If an integrator is used, the etendue of the light that falls on the integrator (i.e., the etendue of the light that is outgoing from the IF and is transmitted through an upstream part of the illuminator before the integrator) may be much smaller than E_I ; it is 1 mm² sr in one optical design of the illuminator. It is shown in the joint requirements that the etendue must be smaller than 1–3.3 mm² sr.

If the center of gravity of EUV light at the IF moves, the movement results in both etendue enlargement and deterioration of illumination uniformity. If the range of the movement is less than 10% of the beam size, it seems to cause few problems. However, the required positioning stability has not yet been agreed on in the joint requirements.

2.2.7 Spectral purity

The DUV/VUV power output from the source is required to be weak, because it behaves as a flare at the wafer; namely, it exposes the photoresist everywhere and affects critical-dimension control. The critical-dimension error budget must be discussed in order to decide the allowance of DUV/VUV intensity at the wafer, but a provisional number, less than 1% of EUV, is established here. A wafer heated by IR/visible light expands thermally, and the overlay accuracy is degraded by the wafer expansion. The allowable IR/visible light intensity at the wafer is assumed to be less than 10% of EUV intensity here.

The allowable DUV/VUV power and IR/visible power at the IF can be calculated using the spectral transmittance of illumination and projection optics and the allowable intensity at the wafer, as is done above.

The spectral reflectivity of a multilayer coated mirror is shown in Fig. 2.6. The expected reflectivity at 13.5 nm is 67.5%, which is indicated by a horizontal solid line. The average reflectivity from 130 to 400 nm is about 60%, and it is much smaller than the EUV reflectivity (67.5%). But the reflectivity for some wavelengths is higher than 67.5%, and this band is dominant when the allowable DUV/VUV power is calculated.

The reflectivity for IR is very high; more than 90% is expected. IR light is transmitted from the IF point to the wafer with little attenuation. In order to keep the ratio of the IR/visible light intensity to EUV intensity below 10% at the wafer, the allowable IR/visible light power at the IF point may need to be 0.2% or less of the EUV inband power.

2.3 Component Degradation

The throughput of an exposure tool should meet the specification even at the end of life of every component. Table 2.5 shows the conditions for the component

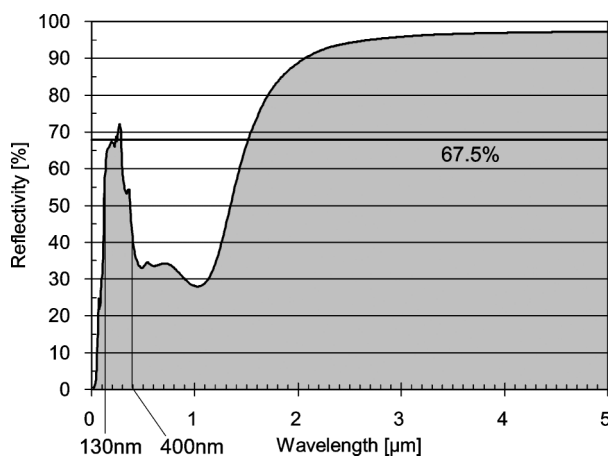


Figure 2.6 Spectral reflectivity of a multilayer coated mirror.

Table 2.5 Conditions of component degradation calculation.

Collector end-of-life transmission	90%
Electrode end-of-life efficiency	90%
ML end-of-life transmission	85%
Filter end-of-life transmission	95%
System end-of-life transmission	65%
Remarks:	
• End-of-life means replace or clean component	
• Anticipated required margin	90%

degradation calculation. The collector transmission, electrode efficiency, multi-layer transmission, and filter transmission are end-of-life degradation factors that are assumed to be 90%, 90%, 85%, and 95%, respectively. To obtain the multilayer transmission, it is assumed that the reflectivity of each MLM decreases by 1% on average. The system end-of-life transmission is the total degradation calculated from the other four degradation factors and is 65%. Besides the above conditions, there may be some unexpected component degradation. This anticipated required margin is thought to be 90%. In the typical wafer throughput model, we assumed the margin is 95%. Therefore, in the typical throughput model we concluded that intensity of EUV light is decreased 37% by overall component degradation.

Components must be replaced or cleaned and recovered at the end of their life. Multilayer mirrors, except the first few mirrors of the illuminator, are assumed not to be replaceable. The lifetimes of the other MLMs must be the same as that of the exposure tool itself. The collector and electrode must be easily replaceable, in view of their present achieved lifetimes.

The exchange time and cost of the electrode, the collector, debris mitigation, and the spectral purity filter should be included in the total maintenance time and cost. The mean time between failure (MTBF), the mean time to repair (MTTR), the scheduled downtime for routine maintenance, and the maintenance cost for the EUV source should be about the same as or modestly greater than those of present excimer ArF and KrF lasers for use in lithography.

The lifetime of source components has to be determined from not only the source power but also all other requirements: etendue, stability, etc.

2.4 Cost of Ownership

The purchase of photolithography equipment is a complex decision. Many aspects need to be weighed against one another in order to justify the preference for a specific supplier. In view of the ever-increasing purchasing cost per unit, this evaluation needs to be performed very accurately. One important parameter is the cost of ownership (CoO) of the exposure tool, to which the operating cost of the source is a considerable contributor. The cost of source operation involves many aspects. Roughly they can be split into operating costs, consumables, and clean-room area costs.

Examples of operating costs are those of wall-plug power, fuel material such as Xe or Sn, various gases, and cooling water. Consumables are parts that need to be exchanged due to operational wear or as part of preventive maintenance. Examples for DPP systems are the electrode set, collection optics, and parts of the mitigation system. For LPP systems parts of the drive laser must be exchanged on a regular basis, and within the discharge volume, the target delivery systems and collection optics must be considered as replaceable parts as well.

Looking at today's status of development, it is not possible to give an accurate estimate of what the CoO of the first tools will be. Large error bars will be there, and even some of the future spare parts are still in the definition phase right now.

A simplified model (2.4) similar to Ref. 12 can be used for the CoO of the source. It is apparent that the total CoO will depend on such quantities as the power of the source, optical system throughput, and resist sensitivity, and on the throughput as well. But once a certain throughput for certain system parameters is evaluated, the formula for the CoO per wafer level exposure can be written as

$$\text{CoO} = \frac{\text{size} \cdot (\text{price per m}^2)}{\text{throughput} \cdot (\text{hours/year})} + \frac{\text{initial cost}}{\text{throughput} \cdot (\text{hours/year})} \cdot \left(\frac{1}{5} + \frac{1}{10} + \frac{1}{25} \right) + \frac{\text{consumables}}{\text{throughput} \cdot (\text{hours/year})}. \quad (2.4)$$

Real values, which include detailed analyses of the system, should be used for this calculation. The throughput has a major influence on the CoO of the complete system; let us take it fixed at, say, 100 wafers/h and calculate an example CoO of the source as a function of initial source cost and source consumables cost. An example similar to that in Ref. 12 is considered, and the following values on a yearly basis are used in the calculation:

- \$500/m² has been assumed for the cost of the clean-room floor.
- The number of hours per year equals 24 × 365 × 65% utilization = 5700 h.
- The fraction 1/5 represents 5-year depreciation; 1/10, 10% interest; and 1/25, a 4% service cost.
- Footprint + service area: 20 m².
- Throughput: 100 wafers/h.

Figure 2.7 presents the results of these analyses. It is clear that the main driver of the CoO is the purchasing price of the source itself. At the same time one should not disregard the price of consumables in the evaluations.

The target consumables–spare-part cost should be optimized to a value where present photolithography tools are operational in the field.

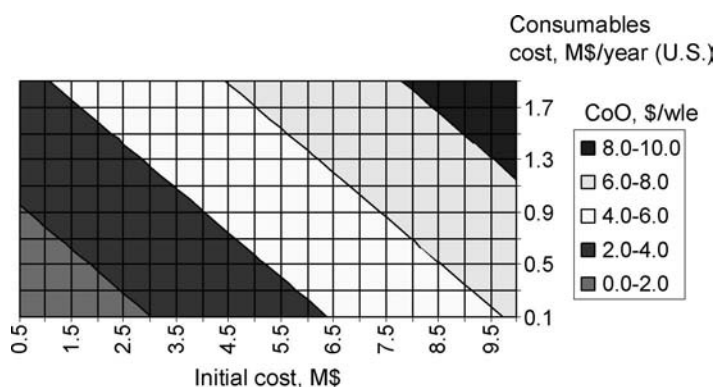


Figure 2.7 CoO of the source as a function of initial costs and consumables, where wle stands for wafer level exposure.

2.5 Conclusions

The joint requirements for EUV sources have been specified by exposure-tool manufacturers, and their bases have been explained above. They will be helpful for source developers and source suppliers. More detailed requirements or specifications for EUV sources are needed for exposure-tool manufacturers; many of them depend on both exposure-tool design and source design. Information exchange between exposure-tool manufacturers and source suppliers will be needed individually. However, source development is still the most critical issue for EUVL. The illuminator transmission and the sensitivity of the photoresist, which determine the required source power, need to be improved to relax the requirement for source power.

Acknowledgments

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Chapter 3

Atomic Xenon Data

John D. Gillaspy

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3.1 Introduction

The focus of this chapter is on fundamental *atomic* data; other sorts of fundamental data (related to the erosion of surfaces by plasma ions, for example) may be needed

as well. The key aspects of plasma modeling are shown in a block diagram in Fig. 3.1. Accurate fundamental input data (the left block of Fig. 3.1) are crucial to the success of this overall scheme. Toward the end of this chapter, the discussion turns to benchmarking the atomic physics aspects of the plasma model (right block of Fig. 3.1). Other chapters in this volume discuss the other blocks.

The necessary fundamental atomic data sets are typically very large because of the huge number (infinite, actually) of internal quantum states that even a single atom presents. By one estimate,¹ the subset of the atomic data set needed to accurately model an EUVL plasma is on the order of 1 million numbers (including the ionization energies, transition energies, and a large variety of cross sections). Due to the sheer magnitude of the problem, most of these data must be calculated rather than determined experimentally.

Because the EUVL plasmas are so hot that they produce highly charged ions (HCIs), and because few labs are equipped to study the atomic physics of HCIs, the reliability of the huge input data set (what I have called *type I data*¹) is largely untested. Therefore, it is important not only to begin testing as many of the input data as is practical, but also to jump ahead and begin benchmark-testing the predicted output spectra (what I have called *type II data*¹). These type II data can be used to assess the accuracy of the *overall* plasma model (including the accuracy and completeness of the type I input data). Both of these types of benchmarks are discussed further below.

In order to assess the availability of relevant data and to evaluate the issues discussed in this chapter, International SEMATECH formed a Fundamental Data Working Group (ISMT FDWG) in 2003. Since that time, this group has held a number of deliberations, and their input helped form the substance of this chapter. Notice of significant omissions would be gladly welcomed by the author.² The membership of the ISMT FDWG is listed in Appendix A.

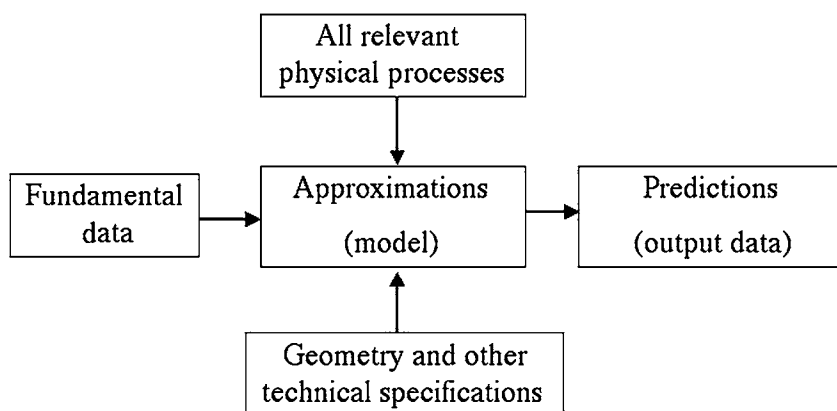


Figure 3.1 Key aspects of plasma modeling, showing the two types of data discussed in this chapter (left and right blocks).

3.2 Specification of the Subtypes of Fundamental Atomic Data Needed

Because of the huge volume of type I data needed, it helps to have some sort of scheme to organize it, think about it, and discuss it. This section presents one such scheme.

Each type I data point can be associated with a specific energy level, or levels, in the species and charge state of interest (if multiple levels are involved, the most deeply bound level can be used for the purposes of organizing the data). These energy levels, in turn, can be arranged in a large multidimensional array, $E(Z, q, i)$. Each element of the array contains one number, with the indices along the axis of the array specified as below.

The *first axis* of the energy array labels the atomic number (in the case of xenon, $Z = 54$). Future versions of this chapter may extend to Sn ($Z = 50$) or Li ($Z = 3$), as these are being considered as alternative emitters.

The early focus on Xe and Sn by the microelectronics industry appears to be based largely on a Livermore study carried out by Spitzer et al.³ in 1994 using parameters somewhat different than those that are the focus of the community today. The Livermore study used a 4% FWHM reflectivity bandwidth centered at 12.9 nm for selected elements, and then interpolated the findings for the range $Z = 13$ to $Z = 82$ using theory. The laser used to produce the plasma operated at 532 and 1064 nm, and had pulse lengths in the range of 7.5 to 30 ns. The targets were all solid slabs. An unexpected finding of this work was a lack of dependence on laser wavelength.

A reassessment of the “optimal emitter” using the best available modern atomic codes has been proposed by Feldman et al., but this has not been pursued. For now, we focus on atomic data for Xe because it was the consensus opinion of the FDWG that much of the understanding starting to emerge from Xe studies can be transferred to the case of Sn.

The *second axis* of the energy array gives the number of atomic electrons missing: the ion charge ($q = 0, 1, 2, \dots$).

For a complete description of Xe, one needs $q = Z + 1$ (including the neutral atom), or 55, different charge states. For EUVL, the focus is on 13.5-nm light emitted from plasmas around 30-eV temperature. In this case, the emitter has $q = 10$, and so clearly this is the most significant charge state of the 55 possible choices. Data from surrounding charge states are needed because the charge state of the emitter evolves from ionization from below ($q < 10$) and recombination from above ($q > 10$). The consensus of the FDWG is that $q = 1$ to $q = 18$ is needed in order to accurately model EUVL light sources, and that the range $q = 7$ to $q = 18$ is particularly crucial. The latter range is thus the focus of this chapter.

The *third axis* of the energy array gives the energy level within the ion that is specified by the first two axes.

To uniquely specify the energy level from a fundamental point of view, one needs a complete set of quantum numbers corresponding to the eigenvalues of the

exact Hamiltonian. Unfortunately, the latter is not available in practice. Typically, the quantum numbers are specified assuming *LS* coupling, and then the wave functions are “corrected” by mixing in small components of nearby *LS* eigenstates. For example,

$$\Psi = 0.98\Psi_1 + 0.02\Psi_2. \quad (3.1)$$

In the case of highly charged ions, however, the mixing can be so strong that the “dominant” state is ambiguous; for example,

$$\Psi = 0.32\Psi_1 + 0.32\Psi_2 + 0.07\Psi_3 + \dots \quad (3.2)$$

The mixing coefficients given in Eq. (3.2) are from an actual case that arose in the analysis of xenon spectra in the 13.5-nm wavelength band.⁴ Switching to *jj* coupling, which is appropriate for very highly charged ions, is not of much help in this case, as the leading *jj* term is only 15%. This underscores the fact that Xe^{10+} is in a “messy” intermediate regime that is problematic from a theoretical point of view. Even in cases where one term in an expansion like that illustrated in Eq. (3.2) is dominant, differences between calculations may result in uncertainties in the coefficients sufficient to make the level identification ambiguous. The need for good ties to clean experiments, therefore, is even greater than usual.

An alternative, operational approach is to delineate the energy levels by the values of their energies. One might hope to compare one calculation with another by comparing line lists. The spectrum of xenon near 13.5 nm is so dense, however, that this is of little value—the uncertainties in the calculations can be larger than the separations between the levels.

The fact that Xe^{10+} has an unusually large number of levels with separations that fall within the 2% specified bandpass of the 13.5-nm EUVL center wavelength is, in fact, one of the reasons that it is an efficient emitter. The dense spectrum is also one of the reasons that very few fully resolved spectroscopic data were available in this wavelength band until recently. Spectra taken at moderate resolution have led to talk of “the three strong xenon lines at 13.5 nm,” but in fact under higher resolution these three lines appear as dozens of very closely spaced lines (see Fig. 3.2).

Industry plasma modelers have already considered thousands of levels in their calculations, and are concerned that this may not be enough. In addition to the levels that directly lead to transitions in the desired wavelength band, other levels can be important because of their indirect influence on the desired radiation (radiative cascade from recombination into higher-lying levels, for example).

Appendix B lists the xenon energy levels tabulated by Saloman at NIST.⁷ Also listed in this appendix are the references to the original data sources from the period 1961 to 2003. A particularly recent paper⁴ provides more results than were contained in an earlier rapid report.⁶

The *ionization energy* can be considered to be the asymptotic limit of an energy level as n (the principle quantum number) approaches infinity. Table 3.1 lists the

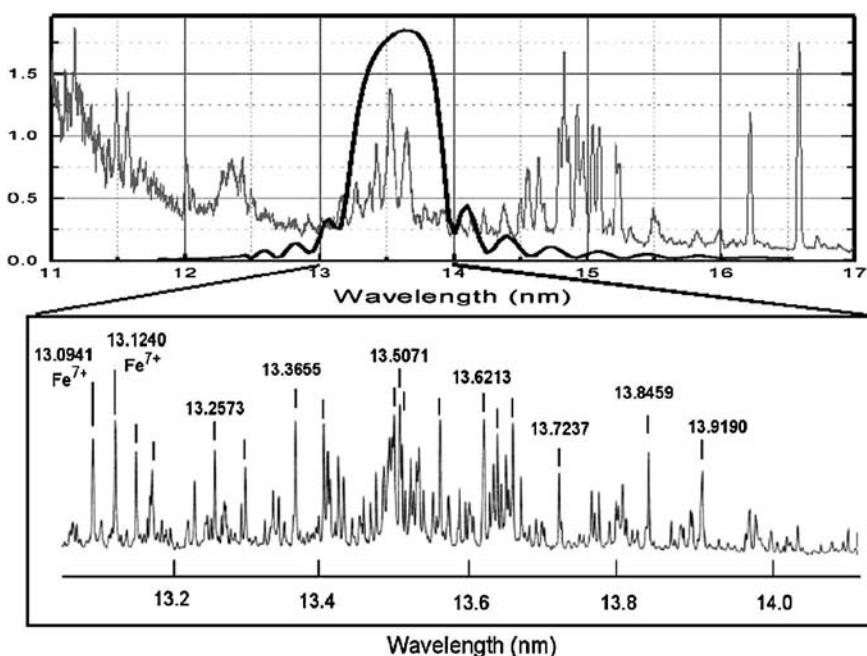


Figure 3.2 Xenon spectra near 13.5 nm in (upper graph) moderate resolution using a high-quality industrial spectrometer (reprinted from Ref. 5 with permission from Cymer Inc.); and (lower graph) ultrahigh resolution using the world's largest grazing-incidence spectrometer at NIST (reprinted from Ref. 6). The 2% bandpass window of a multilayer EUVL mirror array is shown overlaid in the upper spectrum.

ionization energies of the relevant charge states of xenon that were presented in Ref. 1.

The *transition energies* (emission wavelengths) are determined by the differences between the energy levels. For a large number of energy levels, N , there are approximately $\frac{1}{2}N^2$ unique transition energies. Which of these transition energies is important is determined not only by their correspondence with the desired wavelength of the emitted light (13.5 nm), but also by the selection rules that allow or forbid transitions between them.

In the case of highly charged ions, where many of the usual selection rules appear to be violated due to strong configuration interaction (level mixing), the question of which transition energies are significant is complex. In some cases, so-called “forbidden” transitions can be stronger than “allowed” ones.

Furthermore, which energy levels are negligible can depend on the details of the plasma processes. For example, dielectronic recombination can indirectly alter the light emitted at 13.5 nm by changing the amount of $q = 10$ charge state and/or by leading to excited states that then cascade down to the ground state through multiple steps. Because dielectronic recombination depends on the number of free electrons present at specific velocities that are determined by the energy levels, simply selecting those levels that directly give rise to transitions at 13.5 nm will lead to errors in the model predictions.

Table 3.1 Ionization energies of the first 18 stages of xenon. The column labeled EBIT refers to a tabulation of values that has been in use by the community of electron-beam ion-trap users during the past 10–15 years. The column labeled SCDF contains the results of a recent single-configuration Dirac–Fock calculation;⁸ the column labeled SC-EBIT shows the difference between the previous two columns.

Charge	# of e-	Roman	Config	Term	EBIT	SCDF	SC-EBIT	Literature
0	54	I	5p6	1S0	11.0	11.22673	0.22673	12.12984
1	53	II	5p5	2P3/2	20.1	19.85394	−0.24606	20.97502
2	52	III	5p4	3P2	30.1	29.60376	−0.49624	31.04564
3	51	IV	5p3	4S3/2	40.7	41.65659	0.95659	40.91478
4	50	V	5p2	3P0	53.9	53.87642	−0.02358	54.14389
5	49	VI	5p	2P1/2	65.9	65.71570	−0.1843	66.7030
6	48	VII	5s2	1S0	92.6	89.61138	−2.98862	91.59952
7	47	VIII	5s	2S1/2	106.7	104.1730	−2.52699	105.9761
8	46	IX	4d10	1S0	180.4	178.1859	−2.21412	179.8391
9	45	X	4d9	2D5/2	205.7	201.6382	−4.06176	
10	44	XI	4d8	3F4	231.7	227.5624	−4.13756	
11	43	XII	4d7	4F9/2	258.5	254.6778	−3.82221	
12	42	XII	4d6	5D4	286.1	280.6667	−5.43335	
13	41	XIV	4d5	6S5/2	314.3	314.2833	−0.01668	
14	40	XV	4d4	5D0	346.0	343.5413	−2.45869	
15	39	XVI	4d3	4F3/2	375.8	373.1942	−2.60579	
16	38	XVII	4d2	3F2	406.2	404.2271	−1.97295	
17	37	XVIII	4d	2D3/2	437.2	433.7355	−3.46445	
18	36	XIX	4p6	1S0	553.7	549.7384	−3.96157	
25					[at high q , agree with literature to $\ll 1\%$]			
26								

For each of the many levels in the energy array, there are a large number of associated fundamental data points associated with the variety of dynamical processes that can occur in the plasma (ultimately shifting the electronic occupation of this level). These processes can be written in terms of a cross section. The most important ones are delineated as follows:

- A. Ionization
 - A1. Electron impact
 - A2. Photoionization
- B. Recombination
 - B1. DR
 - B2. Three-body ($\text{Xe} + e + e$)
 - B3. RR
 - B4. Charge exchange (with every other possible charge state, and neutral)
- C. Excitation/relaxation
 - C1. Electron impact
 - C2. Photoabsorption (optical thickness issues; opacity)
 - C3. Spontaneous emission (interaction with vacuum fluctuations)

These are summarized schematically in Fig. 3.3.

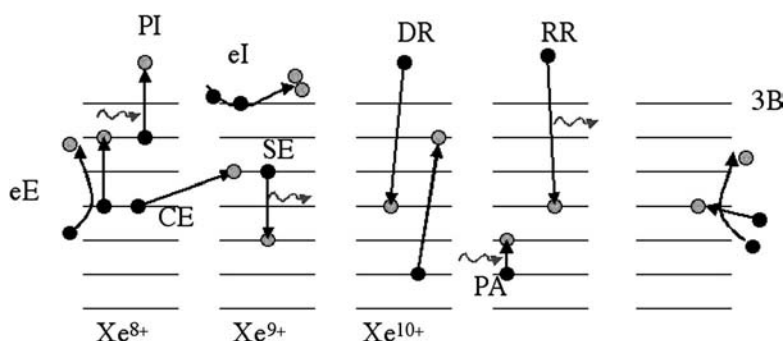


Figure 3.3 Schematic representation of the physical processes discussed in this chapter. eE = electron impact excitation, CE = charge exchange, PI = photoionization, eI = electron impact ionization, SE = spontaneous emission, DR = dielectronic recombination, PA = photoabsorption, RR = radiative recombination (two-body recombination), 3B = three-body recombination.

In summary, for each of the first 18 charge states of xenon, we need a large number of energy levels, which in turn determine an even larger number of transition energies. Furthermore, for each energy level we need a large number of cross sections corresponding to a variety of ionization, recombination, and excitation/relaxation mechanisms.

3.3 Overview and Current Status of Available Data for Xenon ($q = 7$ to $q = 18$)

The *ionization energies* are known quite well. Representative values are listed in Table 3.1 above and in Appendix B below. New ionization energies for all of the ion stages of all the elements were recently published.⁹

Significant progress has been made in determining the most important parts of the *energy-level* array, and the consequent *transition energies*, as summarized in Appendix B.

Almost no experiments are available to test the calculations of the relevant cross sections that are associated with each of the many energy levels. An important exception is described in the next paragraph.

The *electron-impact ionization cross section* has recently been measured for the case of xenon in a charge state $q = 10$ ($\text{Xe}^{10+} + e \rightarrow \text{Xe}^{11+} + 2e$) by the group of Alfred Mueller in Giessen,¹⁰ using the well-established techniques developed in their previous work. The result of this cross-section measurement is shown in Fig. 3.4.

Bizau et al.¹¹ present relative photoionization data on Xe up to $q = 7$. In collaboration with Ron Phaneuf's group at the University of Nevada at Reno and collaborators at the Advanced Light Source at Berkeley, we have recently measured high absolute photoionization cross sections of Xe^{4+} , Xe^{5+} , and Xe^{6+} .¹²

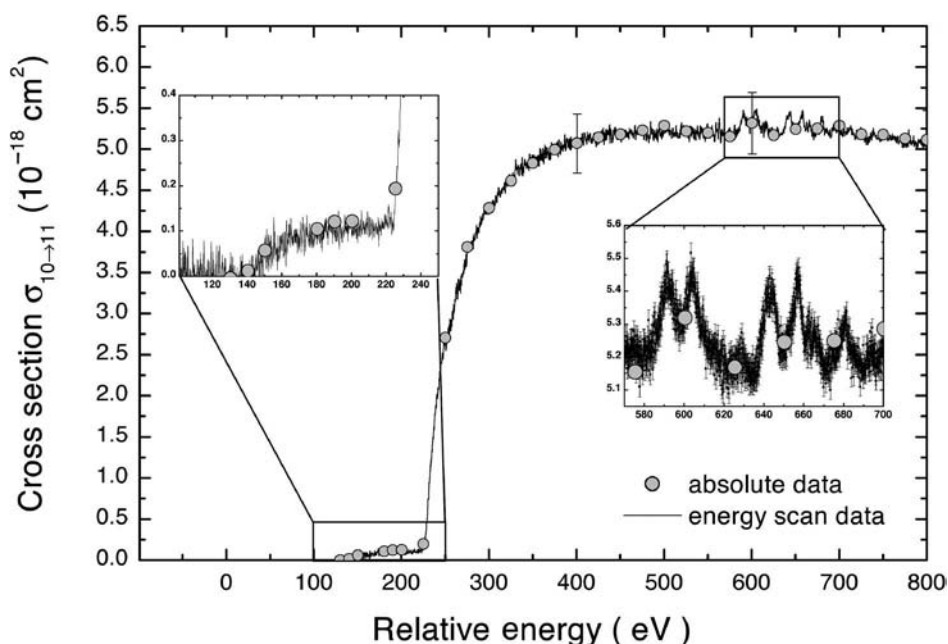


Figure 3.4 Electron-impact ionization cross section for Xe^{30+} going to Xe^{31+} .⁷ The sub-threshold rise in the cross section is due to metastable states in the beam. (Courtesy of Alfred Mueller.)

3.4 References to Data for the Less-Critical Charge States ($q < 7$ or $q > 18$) of Xenon

This section contains some references that may be of more general interest to the EUVL community than those listed elsewhere in this chapter.

Ionization energies of all the elements are given in Ref. 13, and are available on the Web.¹⁴ An alternative complete (but unpublished) electronic compilation of all of the energy levels of all of the charge states of all the elements from $Z = 1$ to $Z = 100$ has been informally circulated within the NIST electron beam ion trap (EBIT) community during the past 15 years and is available through contact with that community.

An expanded version of Appendix B (including data and literature references for all charge states of xenon) has been published elsewhere.⁷

The Oak Ridge National Laboratory (ORNL) cross-section database¹⁵ contains many references to work on electron-impact ionization, but at the time of this writing it contains nothing for $q > 6$ at energies under 80 eV.

3.5 Benchmarking Input Data

As shown by the comparison of the numbers in the last column in Table 3.1, the ionization energies are well known (to about 3%).

Calculated wavelengths sampled from the Argonne¹⁶ and Reno¹⁷ groups have been determined to be in good agreement with experimentally known values to within 0.1 nm (after adjustment, in one case,¹⁷ to the known ionization energies).

The calculated values for electron-impact ionization of Xe¹⁰⁺ (converting it to Xe¹¹⁺) from the Argonne group¹⁶ have been determined to be in good agreement with the Giessen experiments, as described above.

3.6 Benchmarking Output Data

These benchmarks fall into two classes. In what I call *type B* benchmarks, spectra from a plasma of unknown electron energy distribution are compared with model calculations. Either the model parameters or the experimental parameters are adjusted to optimize the agreement. In contrast, for what I call *type A* benchmarks the plasma electron energy distribution is well known and can be used as fixed input to the plasma model. The measured spectrum from the well-characterized plasma can then be compared with the calculated spectrum, with no (or relatively few) adjustable parameters. To my knowledge, no type A benchmark comparisons have been completed by the EUVL community.

At the request of Intel, my group at NIST has been producing type A benchmark data using the EBIT. The EBIT has the particular advantage of not only having a very *well-defined* electron energy distribution, but also a very *sharply peaked* (nearly delta-function) and *oriented* (unidirectional) distribution. This makes it possible to very selectively test various collision processes that contribute to the overall light output of the plasma, and to allow for the possibility of testing polarization effects. The NIST EBIT is described in detail elsewhere.^{18–20} By comparing plasma models (suitably modified to take into account the proper energy distribution and observation angle), one can avoid the key weakness of type B benchmarks, namely that various inaccuracies in the model are compensating for each other and producing a reasonably good fit to the observed spectra, albeit for the wrong reasons. The cancellation of errors in type B benchmarks can frequently be adjusted to give good agreement with observations, but it will hold up less frequently when extrapolated to new plasma conditions outside those in the fit. Type A benchmarking is highly desirable given that the main goals of EUVL modeling are extrapolative: (1) determining the ultimate efficiency limits of EUVL light sources, and (2) assisting in the discovery of new source designs that will change the plasma output sufficiently to meet the design specifications of the semiconductor industry. Both of these goals involve extrapolation to regimes that are considerably beyond those achieved to date.

A variety of NIST EBIT type A benchmark data are presently available for double-blind comparisons. An example of an EBIT EUV spectrum for Xe is shown in Fig. 3.5. More samples of EBIT data that can be used for benchmarking xenon models were published recently in a special cluster of articles on EUV light sources

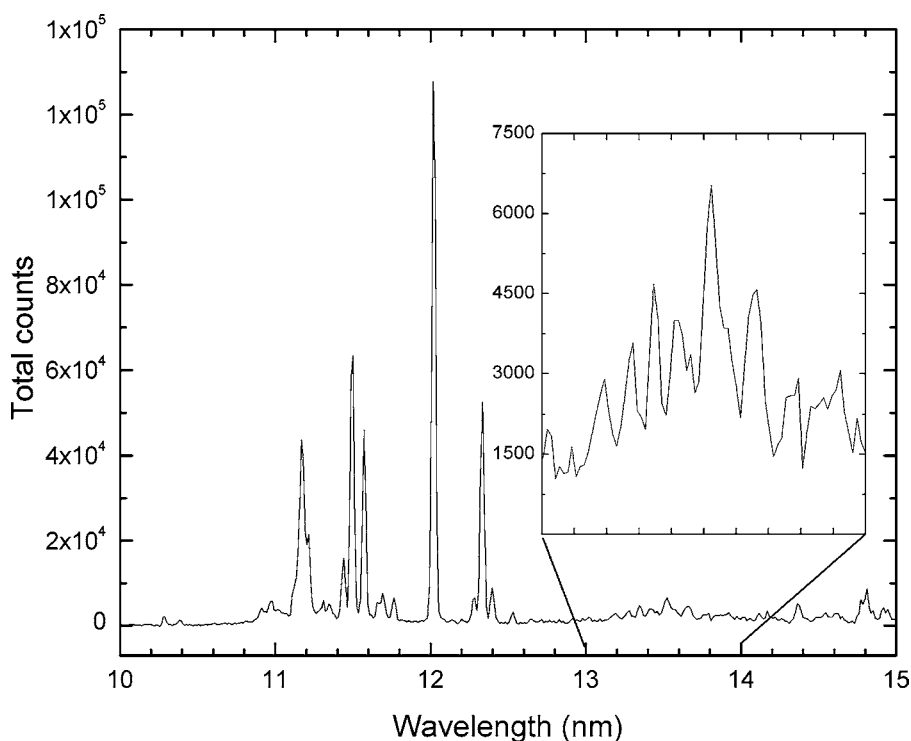


Figure 3.5 EUV spectrum of an optically thin Xe plasma produced in the NIST EBIT with an electron beam of density $1 \times 10^{11}/\text{cm}^3$. The observation angle was 90 deg to the beam direction, and the 210-eV electron energy is just above the ionization threshold needed to produce Xe^{10+} .

for semiconductor manufacturing.²¹ Additional data can be generated to suit the specific needs of particular modeling groups.

Type B benchmarks are important because they take place in plasmas that correspond more closely to those that will be used in real EUVL light sources. An example of such a type B benchmark has been published by researchers at Cymer.²² Although these calculations give good agreement with the experiments, they predict that even more light output could be achieved at somewhat longer wavelengths (just under 15 nm) and lower plasma temperatures (around 25 eV); this prediction is not in agreement with the model calculations of the Argonne group.¹⁶

Other type B benchmark tests have been completed by the Saclay group²³ and by Sasaki and collaborators.²⁴

3.7 Outlook and Future Data Needs

It should be clear from the above discussion that many more atomic data are needed in all categories in order to ensure that EUVL models are accurate. In Ref. 1, the

International SEMATECH Fundamental Data Working Group highlighted the particularly urgent need for electron-impact ionization, excitation, and recombination cross sections, due to the virtual lack of reference data there. Furthermore, it was subsequently recommended that a code comparison workshop be held in order to compare the predictions of various codes with each other for a well-defined test case.

Finally, it is perhaps worth emphasizing something that was discussed at the first EUV Source Modeling Workshop in 2003 in Antwerp: even if one shifts the source gas from xenon to tin, there is still a great deal to be learned about the physics of tin sources through additional fundamental work with xenon. This is due primarily to the similarities in the atomic structure and the utility of scaling laws. For example, what we learn about the xenon unresolved transition array (UTA) at just below 11 nm can tell us much about the emission in tin at 13.5 nm. This is described in more detail in a recent publication by Fahy et al.²¹

Acknowledgments

I thank Alfred Mueller, Carsten Brandau, and Holger Knopp for measuring the electron-impact ionization cross section, Alfred Mueller for permission to reproduce it here, Ed Saloman and Joe Reader for providing the results of their work to me prior to publication, Malcolm W. Chase [Editor, *Journal of Physical and Chemical Reference Data (JPCRD)*] for permission to reproduce the material in Appendix B, Alex Aguilar for preparing Fig. 3.5 and for leading the photoionization measurements, the ISMT FDWG for much advice, and the NIST EBIT team (<http://physics.nist.gov/MajResFac/EBIT/people.html>) for valuable assistance. Funding of this work was provided by ISMT under LITH152.

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Appendix A: International SEMATECH's Fundamental Data Working Group

Members of the International SEMATECH Fundamental Data Working Group in 2003 included John Gillaspay (NIST), chair; Vivek Bakshi, co-chair, ISMT Source Project leader; Howard Milchberg (University of Maryland); Ahmed Hassanein (Argonne National Laboratory); Martin Laming (U.S. Naval Research Laboratory); Yong-Ki Kim (NIST); Konstantin Koshelev (Institute of Spectroscopy, Troitsk); Gerry O'Sullivan (University College, Dublin); Roberto Mancini (University of Nevada, Reno); Martin Richardson (University of Central Florida); Bryan Rice (Intel); Jonathan Cobb (Motorola); and Martin Schmidt (CEA Saclay).

Replacements in 2004 to the above members: Michel Poirier replaced Martin Schmidt (CEA Saclay); Yuri Ralchenko replaced Yong-Ki Kim (NIST); and Shahid Rauf replaced Jonathan Cobb (Motorola).

Appendix B: Xenon Atomic Data

A compilation of the energy levels, spectral lines (wavelengths), intensities, and ionization energies for all charge states of xenon, as prepared by Dr. Edward Saelomon of NIST over the course of many years, was published while this book was in preparation⁷ (both in hardcopy and on the *JPCRD* Web site). A subset of that compilation for the most critical charge states for EUVL ($q = 7$ to $q = 18$) is reproduced at the end of this appendix with permission of Malcolm W. Chase, editor, *JPCRD*. In the second column of the energy tables, even parity is indicated with a "0" and odd parity is indicated with a "1."

Section B.1 contains the material for $q = 7$, Sec. B.2 contains the material for $q = 8$, and so on. Note that each of these sections has its own list of references.

B.1 Xe VIII ($q = 7$)

Ag isoelectronic sequence

Ground state $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 S_{1/2}$

Ionization energy $854,755 \pm 33 \text{ cm}^{-1}$ ($105.976 \pm 0.004 \text{ eV}$) [96WAN]

Partial analyses of the spectrum of seven times ionized xenon (Xe VIII), were published by several sources: [02CHU], [96WAN], [95LAR], [95DRU], [84KAU], [83BLA], [82OSU], [81KAU], [79ROB]. We use the levels determined by Wang et al. [96WAN] for the 8–9s, 8–9p, 7–9d, 5f $^2F_{7/2}$, 6–9f, 5–9g, 6–9h, 7–10i, 8–10k, and 9l levels. We use Churilov and Joshi [02CHU] for the $4d^9 5s 4f$ levels. We use Larsson et al. [95LAR] for the 7p, 6d, and 4f levels. We use Kaufman and Sugar [84KAU] for the $4d^9 5s 5p$ levels. We use Kaufman and Sugar [81KAU] for the 5–7s, 5–6p, 5d, and 5f $^2F_{5/2}$ levels. On the basis of the rejection by Kaufman and Sugar [84KAU] of Blackburn et al.'s [83BLA] results for the $4d^9 5s 5p$ levels, we have not included any of their levels or the related work of O'Sullivan [82OSU]

in this compilation. Note that Kaufman and Sugar [84KAU] labeled their levels with the leading term. As a result, two different levels are designated $4d^9 5s 5p$ ($3/2, {}^3P_0$) $_{3/2}^\circ$ (at 550,449 and 556,619 cm^{-1}). For consistency we maintain their designations. This only affects the lines 181.670 Å (with 550,449 cm^{-1} as its upper level) and 179.656 Å (with 556,619 cm^{-1} as its upper level). We quote the results presented in the Xe VIII level table to the indicated number of decimal places (zero) for levels with a decimal point. Levels without a decimal point have uncertainties in their tens place.

Xe VIII lines have been reported by several sources: [61FAU], [79ROB], [80KER], [81BAS], [81KAU], [82OSU], [83BLA], [84KAU], [95DRU], [95LAR], [96WAN], [02CHU]. The sources of the lines in our Xe VIII line table are summarized in the Xe VIII line source table.

Churilov and Joshi [02CHU] classified two Xe VIII resonance lines. They re-measured the spectrograms of Kaufman et al. [83KAU] using improved measurement techniques. Blackburn et al. [83BLA] classified 18 VUV lines. They used an LPP as their source. The quoted uncertainty of their wavelength measurements was 0.05 Å. However, due to the findings of Kaufman and Sugar [84KAU], none of their lines is used here. O'Sullivan [82OSU] classified 2 VUV lines using the experimental procedure of Blackburn et al. [83BLA]. These lines are also not used here.

Where duplicate lines exist, the priority order used for selection was [02CHU], [84KAU], [81KAU], [79ROB], [61FAW], [95LAR], [96WAN], [95DRU], [81BAS], and [80KER]. No [80KER] or [61FAW] lines are in our final list.

All candidate lines are passed through a program to determine if they correspond to a transition between the known Xe VIII levels. Only classifiable lines are included in our compilation.

Transition-probability calculations utilizing the Cowan codes [81COW] with adjusted configuration average energies are used to help in choices between multiple possible classifications of lines. Intensities reported are those given in the stated references and are not on a common scale. Intensities are not reported for the collision-based spectroscopy, charge-exchange spectroscopy, or beam-foil results.

The intensity codes given in the Xe VIII line table are taken from the specified sources. Their meanings are stated below:

<u>Symbol</u>	<u>Definition</u>
b	Blend
BF	Lines observed in beam-foil spectroscopy
CBS	Lines observed in collision-based spectroscopy
CES	Lines observed in charge-exchange spectroscopy
*	Two or more classifications of this line share the same intensity

The ionization energy was determined by [96WAN] by means of spectral analysis.

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- 81KAU V. Kaufman and J. Sugar, *Phys. Scripta* **24**, 738 (1981).
- 82OSU G. O'Sullivan, *J. Phys. B* **15**, L765 (1982).
- 83BLA J. Blackburn, P. K. Carroll, J. Costello, and G. O'Sullivan, *J. Opt. Soc. Am.* **73**, 1325 (1983).
- 83KAU V. Kaufman, J. Sugar, and J. L. Tech, *J. Opt. Soc. Am.* **73**, 691 (1983).
- 84KAU V. Kaufman and J. Sugar, *J. Opt. Soc. Am. B* **1**, 38 (1984).
- 95DRU M. Druetta and D. Hitz, *Nucl. Instrum. Methods B* **98**, 211 (1995).
- 95LAR M. O. Larsson, A. M. Gonzalez, R. Hallin, F. Heijkenskjöld, R. Hutton, A. Langereis, B. Nyström, G. O'Sullivan, and A. Wännström, *Phys. Scripta* **51**, 69 (1995).
- 96WAN M. Wang, A. Arnesen, R. Hallin, F. Heijkenskjöld, A. Langereis, M. O. Larsson, C. Nordling, and A. Wännström, *J. Opt. Soc. Am. B* **13**, 1650 (1996), **14**, 1516 (1997).
- 02CHU S. S. Churilov and Y. N. Joshi, *Phys. Scr.* **65**, 40 (2002).

B.2 Xe ix ($q = 8$)

Pd isoelectronic sequence

Ground state $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} {}^1S_0$

Ionization energy $1,450,500 \pm 1,000 \text{ cm}^{-1}$ ($179.85 \pm 0.10 \text{ eV}$) [02CHU_a]

An analysis of the spectrum of eight times ionized xenon, Xe ix (Pd-like xenon) was published by Churilov et al. [02CHU_b]. The uncertainty of their levels is about 20 cm^{-1} with respect to the ground state and 5 cm^{-1} relative to other levels. Five additional levels (those involving the $4d^9 6p$, $4d^9 7p$, and $4d^9 6f$ configurations) are from Churilov and Joshi [02CHU_a] with uncertainties of about 20 cm^{-1} for levels below $1,100,000 \text{ cm}^{-1}$ and 75 cm^{-1} for higher levels. We do not use the levels reported by Callegari et al. [02CAL], because they disagree with [02CHU_b] for most levels other than those belonging to the $4d^9 5p$ configuration. The LS designation for some levels has very little physical significance and may not even be the largest eigenvector component.

Churilov et al. [02CHU_b] was the source of 108 classified Xe IX lines in our Xe IX line list. They used a fast 40-kV capillary discharge with inductive storage as their source. The uncertainty of their wavelength measurements is 0.003 Å at wavelengths between 90 and 150 Å, and 0.007–0.010 Å at wavelengths between 300 and 800 Å.

Churilov and Joshi [02CHU_a] was the source of five Xe IX classified resonance lines in the list. They remeasured the spectrograms of [83KAU] using improved measurement techniques. The uncertainty of their wavelength measurements is 0.003 Å at wavelengths longer than 90 Å, and 0.006 Å at shorter wavelengths. [83KAU] used a modified triggered spark initiated by a puff of xenon gas as their source.

Callegari et al. [02CAL] was the source of 31 line classifications in our list. They classified 109 lines, but only 61 of them are consistent with the energy levels chosen above. They used a capillary pulsed discharge as their source. The uncertainty of their wavelength measurements is 0.02 Å.

Where duplicate lines exist, the priority order used for selection was [02CHU_b], [02CHU_a], then [02CAL]. Earlier work with greater wavelength uncertainty was carried out by [61FAW], [64FAW], [82SUG], [82OSU], [83BLA], [94KAM], and [96LEM]. Any lines from these references were superseded by those from the three above.

All candidate lines are passed through a program to determine if they correspond to a transition between the known Xe IX levels. Only classifiable lines are included in our compilation.

Transition-probability calculations utilizing the Cowan codes [81COW] with adjusted configuration average energies are used to help resolve choices between multiple possible classifications of lines. Intensities reported are those given in the stated references and are not on a common scale.

The intensity codes given in the Xe IX line table are taken from the specified sources. Their meanings are stated below:

<u>Symbol</u>	<u>Definition</u>
m	Masked line
b	Blend
?	Tentative classification
*	Two or more classifications of this line share the same intensity

The ionization energy was determined by Churilov and Joshi [02CHU_a] by means of spectral analysis.

Section B.2 References

- 61FAW B. C. Fawcett, B. B. Jones, and R. Wilson, *Proc. Phys. Soc. London* **78**, 1223 (1961).
- 64FAW B. C. Fawcett, A. H. Gabriel, B. B. Jones, and N. J. Peacock, *Proc. Phys. Soc. London* **84**, 257 (1964).

- 81COW R. D. Cowan, *The Theory of Atomic Structure and Spectra*, University of California Press, Berkeley (1981).
- 82OSU G. O'Sullivan, *J. Phys. B* **15**, L765 (1982).
- 82SUG J. Sugar and V. Kaufman, *Phys. Scripta* **26**, 419 (1982).
- 83BLA J. Blackburn, P. K. Carroll, J. Costello, and G. O'Sullivan, *J. Opt. Soc. Am.* **73**, 1325 (1983).
- 83KAU V. Kaufman, J. Sugar, and J. L. Tech, *J. Opt. Soc. Am.* **73**, 691 (1983).
- 94KAM P. van Kampen, R. Hallin, F. Heijkenskjöld, A. Langereis, M. O. Larsson, C. Nordling, B. Nyström, G. O'Sullivan, and A. Wännström, *Phys. Scripta* **49**, 198 (1994).
- 96LEM B. E. Lemoff, G. Y. Yin, C. L. Gordon III, C. P. J. Barty, and S. E. Harris, *J. Opt. Soc. Am. B* **13**, 180 (1996).
- 02CAL F. Callegari, M. Gallardo, M. Raineri, A. G. Trigueiros, and J. G. Reyna Almandos, *J. Quant. Spectrosc. Radiat. Transfer* **73**, 13 (2002).
- 02CHU_a S. S. Churilov and Y. N. Joshi, *Phys. Scripta* **65**, 40 (2002).
- 02CHU_b S. S. Churilov, A. N. Ryabtsev, W.-Ü. L. Tchang-Brillet, and J.-F. Wyart, *Phys. Scripta* **66**, 293 (2002).

B.3 Xe x ($q = 9$)

Rh isoelectronic sequence

Ground state $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^9 {}^2D_{5/2}$

Ionization energy $1,627,000 \text{ cm}^{-1}$ (201.7 eV) [70CAR]

A partial analysis of the spectrum of nine times ionized xenon, Xe x, was published by Churilov and Joshi [02CHU] based on experimental work of Kaufman et al. [83KAU]. They considered the transitions between the $4d^9$ ground configuration and the $4d^8 5p$, $4d^8 4f$, and $4p^5 4d^{10}$ levels. We tabulate the 62 levels they determined in the Xe x level table. The levels have an uncertainty of 10 cm^{-1} . The levels of the excited configurations are very mixed in LS notation, and we follow Churilov and Joshi [02CHU] in not specifying an LS designation but assigning them by specifying only the configuration, the integer value of the energy level, the J value, and the odd parity. See [02CHU] for the leading LS terms of each level. The “?” after the $672,762\text{-cm}^{-1}$ $J = 7/2$ level indicates that this level is tentative.

Churilov and Joshi [02CHU] classified 83 Xe x lines. They remeasured the spectrograms of [83KAU] using improved measurement techniques. The uncertainty of their wavelength measurements is 0.003 Å . These lines are listed in the Xe x line table.

Kaufman et al. [83KAU] classified 47 lines. They used a modified triggered spark initiated by a puff of xenon gas as their source. The quoted uncertainty of their wavelength measurements is 0.005 Å .

All candidate lines are passed through a program to determine if they correspond to a transition between the known Xe x levels. Only classifiable lines are included in our compilation.

Transition-probability calculations utilizing the Cowan codes [81COW] are used by Churilov and Joshi [02CHU] to help in choices between multiple possible classifications of lines. Intensities reported are those given in Churilov and Joshi [02CHU].

The intensity codes given in the Xe x line table are taken from the specified source. Their meanings are stated below:

<u>Symbol</u>	<u>Definition</u>
b	Blended line
m	Masked line
?	Listed as a tentative classification in reference
*	Two or more classifications of this line share the same intensity

The ionization energy was determined by Carlson et al. [70CAR] by means of a calculation based on a simple spherical-shell solution for neutral atoms.

Section B.3 References

70CAR	T. A. Carlson, C. W. Nestor, Jr., N. Wasserman, and J. D. McDowell, <i>At. Data</i> 2 , 63 (1970).
81COW	R. D. Cowan, <i>The Theory of Atomic Structure and Spectra</i> , University of California Press, Berkeley (1981).
83KAU	V. Kaufman, J. Sugar, and J. L. Tech, <i>J. Opt. Soc. Am.</i> 73 , 691 (1983).
02CHU	S. S. Churilov and Y. N. Joshi, <i>Phys. Scripta</i> 65 , 40 (2002).

B.4 Xe x₁ (*q* = 10)

Ru isoelectronic sequence

Ground state $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^8 \ ^3F_4$

Ionization energy $1,847,200 \pm 1600 \text{ cm}^{-1}$ ($229.02 \pm 0.20 \text{ eV}$) [03CHU_b]

A partial analysis of the spectrum of ten times ionized xenon, Xe x₁, was carried out by Churilov et al. [03CHU]_a, [03CHU]_b. They studied the transitions between the $4p^6 4d^8$ ground configuration and the $4p^6 4d^7 5p$, $4p^6 4d^7 4f$, and $4p^5 4d^9$ excited levels. We tabulate the 132 levels they determined in the Xe x₁ level table. The levels of the ground configuration have an estimated uncertainty of 10 cm^{-1} . The excited configuration levels have estimated uncertainties of 20–30 cm^{-1} . The levels of the excited configurations are very mixed in their term designations (and for several levels also in their configurations), so we do not specify an *LS* designation, but assign them by specifying only the configuration, the integer value of the energy level, the *J* value, and their odd parity. See Churilov et al. [03CHU]_b

for the leading *LS* terms of each level. A “?” after a level indicates that the level is tentative.

Churilov et al. [03CHU]_a classified 16 prominent Xe xI lines, and Churilov et al. [03CHU]_b classified 201 Xe xI lines. They used a low-inductance triggered spark initiated by a puff of xenon gas as their source. The uncertainty of their wavelength measurements is 0.003 Å. The lines listed in the Xe xI line table are taken from [03CHU]_b.

All candidate lines are passed through a program to determine if they correspond to a transition between the known Xe xI levels. Only classifiable lines are included in our compilation.

Transition-probability calculations utilizing the Cowan codes [81COW] are used by Churilov et al. [03CHU]_b to help in choices between multiple possible classifications of lines. Intensities reported are those given in Churilov et al. [03CHU]_b.

The intensity codes given in the Xe xI line table are taken from the specified source. Their meanings are stated below:

<u>Symbol</u>	<u>Definition</u>
bl	Blended line
m	Masked line
?	Listed as a tentative classification in reference
*	Two or more classifications of this line share the same intensity

The ionization energy was determined by Churilov et al. [03CHU]_b by means of semiempirical calculations.

Section B.4 References

- 81COW R. D. Cowan, *The Theory of Atomic Structure and Spectra*, University of California Press, Berkeley (1981).
- 03CHU_a S. S. Churilov, Y. N. Joshi, and J. Reader, *Opt. Lett.* **28**, 1478 (2003).
- 03CHU_b S. S. Churilov, Y. N. Joshi, J. Reader, and R. R. Kildiyarova, “Analysis of the $4p^6 4d^8 - (4d^7 5p + 4d^7 4f + 4p^5 4d^9)$ transitions in Xe xI ion,” *Phys. Scripta* **70**, 126 (2004).

B.5 Xe xII (*q* = 11)

Tc isoelectronic sequence

Ground state $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^7 4f_{9/2}$

Ionization energy $2,125,000 \text{ cm}^{-1}$ (263.5 eV) [70CAR]

The ground state of Xe xII was determined by means of a calculation using the Cowan codes [81COW]. No wavelengths or energy levels have been reported for this ion. Klosner and Silfvast [00KLO] have identified emission around 110 Å from a capillary-discharge plasma as being from Xe xII. The ionization energy was

determined by Carlson et al. [70CAR] by means of a calculation based on a simple spherical shell solution for neutral atoms.

Section B.5 References

- 70CAR T. A. Carlson, C. W. Nestor, Jr., N. Wasserman, and J. D. McDowell, *At. Data* **2**, 63 (1970).
 81COW R. D. Cowan, *The Theory of Atomic Structure and Spectra*, University of California Press, Berkeley (1981).
 00KLO M. A. Klosner and W. T. Silfvast, *J. Opt. Soc. Am. B* **17**, 1279 (2000).

B.6 Xe XIII ($q = 12$)

Mo isoelectronic sequence

Ground state $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^6 {}^5D_4$

Ionization energy $2,374,000 \text{ cm}^{-1}$ (294.4 eV) [70CAR]

The ground state of Xe XIII was determined by means of a calculation using the Cowan codes [81COW]. No wavelengths or energy levels have been reported for this ion. The ionization energy was determined by Carlson et al. [70CAR] by means of a calculation based on a simple spherical-shell solution for neutral atoms.

Section B.6 References

- 70CAR T. A. Carlson, C. W. Nestor, Jr., N. Wasserman, and J. D. McDowell, *At. Data* **2**, 63 (1970).
 81COW R. D. Cowan, *The Theory of Atomic Structure and Spectra*, University of California Press, Berkeley (1981).

B.7 Xe XIV ($q = 13$)

Nb isoelectronic sequence

Ground state $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^5 {}^6S_{5/2}$

Ionization energy $2,624,000 \text{ cm}^{-1}$ (325.3 eV) [70CAR]

The ground state of Xe XIV was determined by means of a calculation using the Cowan codes [81COW]. No wavelengths or energy levels have been reported for this ion. The ionization energy was determined by Carlson et al. [70CAR] by means of a calculation based on a simple spherical-shell solution for neutral atoms.

Section B.7 References

- 70CAR T. A. Carlson, C. W. Nestor, Jr., N. Wasserman, and J. D. McDowell, *At. Data* **2**, 63 (1970).
 81COW R. D. Cowan, *The Theory of Atomic Structure and Spectra*, University of California Press, Berkeley (1981).

B.8 Xe xv ($q = 14$)

Zr isoelectronic sequence

Ground state $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^4 \ ^5D_0$

Ionization energy $2,890,000 \text{ cm}^{-1}$ (358.3 eV) [70CAR]

The ground state of Xe xv was determined by means of a calculation using the Cowan codes [81COW]. No wavelengths or energy levels have been reported for this ion. The ionization energy was determined by Carlson et al. [70CAR] by means of a calculation based on a simple spherical-shell solution for neutral atoms.

Section B.8 References

- 70CAR T. A. Carlson, C. W. Nestor, Jr., N. Wasserman, and J. D. McDowell, *At. Data* **2**, 63 (1970).
 81COW R. D. Cowan, *The Theory of Atomic Structure and Spectra*, University of California Press, Berkeley (1981).

B.9 Xe xvi ($q = 15$)

Y isoelectronic sequence

Ground state $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^3 \ ^4F_{3/2}$

Ionization energy $3,142,000 \text{ cm}^{-1}$ (389.6 eV) [70CAR]

The ground state of Xe xvi was determined by means of a calculation using the Cowan codes [81COW]. No wavelengths or energy levels have been reported for this ion. The ionization energy was determined by Carlson et al. [70CAR] by means of a calculation based on a simple spherical-shell solution for neutral atoms.

Section B.9 References

- 70CAR T. A. Carlson, C. W. Nestor, Jr., N. Wasserman, and J. D. McDowell, *At. Data* **2**, 63 (1970).
 81COW R. D. Cowan, *The Theory of Atomic Structure and Spectra*, University of California Press, Berkeley (1981).

B.10 Xe xvii ($q = 16$)

Sr isoelectronic sequence

Ground state $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^2 {}^3F_2$

Ionization energy $3,395,000 \text{ cm}^{-1}$ (420.9 eV) [70CAR]

The ground state of Xe xvii was determined by means of a calculation using the Cowan codes [81COW]. No wavelengths or energy levels have been reported for this ion. The ionization energy was determined by Carlson et al. [70CAR] by means of a calculation based on a simple spherical-shell solution for neutral atoms.

Section B.10 References

- 70CAR T. A. Carlson, C. W. Nestor, Jr., N. Wasserman, and J. D. McDowell, *At. Data* **2**, 63 (1970).
 81COW R. D. Cowan, *The Theory of Atomic Structure and Spectra*, University of California Press, Berkeley (1981).

B.11 Xe xviii ($q = 17$)

Rb isoelectronic sequence

Ground state $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d {}^2D_{3/2}$

Ionization energy $3,647,000 \text{ cm}^{-1}$ (452.2 eV) [70CAR]

The ground state of Xe xviii was determined by means of a calculation using the Cowan codes [81COW]. Three classified lines have been reported by Sugar et al. [92SUG] from work using a tokamak source:

λ (Å)	I	Classification
109.521	30	$4p^6 4d {}^2D_{3/2} - 4p^5 4d^2 ({}^1G^o) {}^2F_{5/2}^o$
107.224	40	$4p^6 4d {}^2D_{5/2} - 4p^5 4d^2 ({}^1G^o) {}^2F_{7/2}^o$
108.005	60	$4p^6 4d {}^2D_{5/2} - 4p^5 4d^2 ({}^3F^o) {}^2D_{5/2}^o$

They quote an uncertainty of 0.005 Å for their wavelengths. The semiempirically corrected value (obtained by smoothing along the isoelectronic sequence) of the first of these lines gives a value of $913,000 \pm 42 \text{ cm}^{-1}$ for the energy of the $4p^5 4d^2 ({}^1G^o) {}^2F_{5/2}^o$ level with respect to the ground state. The value of the $4p^6 4d {}^2D$ splitting was not determined.

The ionization energy was determined by Carlson et al. [70CAR] by means of a calculation based on a simple spherical-shell solution for neutral atoms.

Section B.11 References

- 70CAR T. A. Carlson, C. W. Nestor, Jr., N. Wasserman, and J. D. McDowell, *At. Data* **2**, 63 (1970).
 81COW R. D. Cowan, *The Theory of Atomic Structure and Spectra*, University of California Press, Berkeley (1981).
 92SUG J. Sugar, V. Kaufman, and W. L. Rowan, *J. Opt. Soc. Am. B* **9**, 1959 (1992).

B.12 Xe XIX ($q = 18$)

Kr isoelectronic sequence

Ground state $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 \ ^1S_0$

Ionization energy $4,618,000 \text{ cm}^{-1}$ (572.5 eV) [70CAR]

A very partial analysis of the spectrum of 18 times ionized xenon, Xe XIX, was published by Sugar et al. [91SUG]. We use their energy levels, which are based on semiempirically smoothed wavelengths. The absence of decimal points for values in the energy-level table indicates that the values above zero, in order of increasing value, have uncertainties of about 30 and 40 cm^{-1} , respectively.

Sugar et al. [91SUG] classified two Xe XIX resonance lines. They used a tokamak as their light source. The estimated uncertainty of their wavelength measurements is 0.005 Å.

Breton et al. [88BRE] classified one line at 106.37 Å, which was a small structure on a broad band. They also used a tokamak as their light source. The quoted uncertainty of their wavelength measurements is 0.05 Å. They tentatively assigned the line to a transition between the ground state and a $4p^5 4d$ level. We did not include this line in the Xe XIX line table.

We use the two lines of Sugar et al. [91SUG]. Intensities reported are those given in this reference.

All candidate lines are passed through a program to determine if they correspond to a transition between the known Xe XIX levels. Only classifiable lines are included in our compilation.

The intensity code given in the Xe XIX line table is specified below:

<u>Symbol</u>	<u>Definition</u>
p	Perturbed by a close line

Crespo López-Urrutia et al. [02CRE] tentatively classify a line observed using an EBIT at $4363 \pm 4 \text{ Å}$ as the forbidden intraconfiguration transition $4p^5 4d \ ^3P_2 - ^3P_1$.

The ionization energy was determined by Carlson et al. [70CAR] by means of a calculation based on a simple spherical-shell solution for neutral atoms.

Section B.12 References

- 70CAR T. A. Carlson, C. W. Nestor, Jr., N. Wasserman, and J. D. McDowell, *At. Data* **2**, 63 (1970).
- 88BRE C. Breton, C. DeMichelis, W. Hecq, M. Mattioli, J. Ramette, B. Saoutic, C. Bauche-Arnoult, J. Bauche, and J. F. Wyart, *Phys. Scripta*. **37**, 33 (1988).
- 91SUG J. Sugar, V. Kaufman, D. H. Baik, Y.-K. Kim, and W. L. Rowan, *J. Opt. Soc. Am. B* **8**, 2026 (1991).
- 02CRE J. R. Crespo López-Urrutia, P. Beiersdorfer, K. Widmann, and V. De-caux, *Can. J. Phys.* **80**, 1687 (2002).

Table B.1 Energy levels of Xe VIII.

Energy level (cm ⁻¹)	Parity	Configuration	Term	<i>J</i>	Source of level
0.	0	5s	2S	1/2	81KAU
116467.	1	5p	2p ^o	1/2	81KAU
135052.	1	5p	2p ^o	3/2	81KAU
265161	1	4f	2F ^o	5/2	95LAR
265711	1	4f	2F ^o	7/2	95LAR
309888.	0	5d	2D	3/2	81KAU
312816.	0	5d	2D	5/2	81KAU
395497.	0	6s	2S	1/2	81KAU
443378.	1	6p	2p ^o	1/2	81KAU
450773.	1	6p	2p ^o	3/2	81KAU
497579.	1	5f	2F ^o	5/2	81KAU
498018.	1	5f	2F ^o	7/2	96WAN
527425	0	6d	2D	3/2	95LAR
528794	0	6d	2D	5/2	95LAR
541550.	1	4d ⁹ (² D _{5/2})5s5p(³ p ^o ₁)	(5/2, ³ p ^o ₁)	3/2	84KAU
550449.	1	4d ⁹ (² D _{3/2})5s5p(³ p ^o ₀)	(3/2, ³ p ^o ₀)	3/2	84KAU
555118.	1	4d ⁹ (² D _{5/2})5s5p(³ p ^o ₂)	(5/2, ³ p ^o ₂)	1/2	84KAU
556619.	1	4d ⁹ (² D _{3/2})5s5p(³ p ^o ₀)	(3/2, ³ p ^o ₀)	3/2	84KAU
562724.	1	4d ⁹ (² D _{3/2})5s5p(³ p ^o ₁)	(3/2, ³ p ^o ₁)	3/2	84KAU
564149.	1	4d ⁹ (² D _{3/2})5s5p(³ p ^o ₁)	(3/2, ³ p ^o ₁)	1/2	84KAU
568595.	1	4d ⁹ (² D _{3/2})5s5p(³ p ^o ₂)	(3/2, ³ p ^o ₂)	1/2	84KAU
574228.	1	4d ⁹ (² D _{3/2})5s5p(³ p ^o ₂)	(3/2, ³ p ^o ₂)	3/2	84KAU
585288.	1	4d ⁹ (² D _{5/2})5s5p(¹ p ^o ₁)	(5/2, ¹ p ^o ₁)	3/2	84KAU

Table B.1 (Continued).

Energy level (cm^{-1})	Parity	Configuration	Term	J	Source of level
599973.	1	$4d^9(^2D_{3/2})5s5p(^1P^o_1)$	$(3/2, ^1P^o_1)$	1/2	84KAU
565296.	0	7s	^2S	1/2	81KAU
570268	0	5g	^2G	7/2	96WAN
570268	0	5g	^2G	9/2	96WAN
589827	1	7p	$^2P^o$	1/2	95LAR
593781	1	7p	$^2P^o$	3/2	95LAR
616368	1	6f	$^2F^o$	5/2	96WAN
616708	1	6f	$^2F^o$	7/2	96WAN
634595	0	7d	^2D	3/2	96WAN
635355	0	7d	^2D	5/2	96WAN
655008	0	8s	^2S	1/2	96WAN
656891	0	6g	^2G	7/2	96WAN
656891	0	6g	^2G	9/2	96WAN
659228	1	6h	$^2H^o$	9/2	96WAN
659228	1	6h	$^2H^o$	11/2	96WAN
669948	1	8p	$^2P^o$	1/2	96WAN
672187	1	8p	$^2P^o$	3/2	96WAN
684635	1	7f	$^2F^o$	5/2	96WAN
684818	1	7f	$^2F^o$	7/2	96WAN
696304	0	8d	^2D	3/2	96WAN
696678	0	8d	^2D	5/2	96WAN
708690	0	9s	^2S	1/2	96WAN

Table B.1 (Continued).

Energy level (cm ⁻¹)	Parity	Configuration	Term	<i>J</i>	Source of level
709360	0	7g	2G	7/2	96WAN
709360	0	7g	2G	9/2	96WAN
711135	1	7h	2H ^o	9/2	96WAN
711135	1	7h	2H ^o	11/2	96WAN
711338	0	7i	2I	11/2	96WAN
711338	0	7i	2I	13/2	96WAN
717839	1	9p	2p ^o	1/2	96WAN
719277	1	9p	2p ^o	3/2	96WAN
727257	1	8f	2F ^o	5/2	96WAN
727403	1	8f	2F ^o	7/2	96WAN
735070	0	9d	2D	3/2	96WAN
735510	0	9d	2D	5/2	96WAN
743475	0	8g	2G	7/2	96WAN
743475	0	8g	2G	9/2	96WAN
744798	1	8h	2H ^o	9/2	96WAN
744798	1	8h	2H ^o	11/2	96WAN
744953	0	8i	2I	11/2	96WAN
744953	0	8i	2I	13/2	96WAN
744993	1	8k	2K ^o	13/2	96WAN
744993	1	8k	2K ^o	15/2	96WAN
755719	1	9f	2F ^o	5/2	96WAN
755757	1	9f	2F ^o	7/2	96WAN

Table B.1 (Continued).

Energy level (cm^{-1})	Parity	Configuration	Term	J	Source of level
766889	0	9g	$2G$	9/2	96WAN
767897	1	9h	$2H^o$	9/2	96WAN
767897	1	9h	$2H^o$	11/2	96WAN
768009	0	9i	$2I$	11/2	96WAN
768009	0	9i	$2I$	13/2	96WAN
768033	1	9k	$2K^o$	13/2	96WAN
768033	1	9k	$2K^o$	15/2	96WAN
768039	0	9l	$2L$	15/2	96WAN
768039	0	9l	$2L$	17/2	96WAN
784510	0	10i	$2I$	11/2	96WAN
784510	0	10i	$2I$	13/2	96WAN
784528	1	10k	$2K^o$	13/2	96WAN
784528	1	10k	$2K^o$	15/2	96WAN
811260	1	$4d^9 5s(3D)4f$	$2P^o$	1/2	02CHU
811400	1	$4d^9 5s(3D)4f$	$2P^o$	3/2	02CHU

Table B.2 Spectral lines of Xe VIII.

Observed vacuum wavelength (Å)	Observed wave number (10 ³ cm ⁻¹)	Intensity and comment	Classification				Uncertainty of observed wavelength (Å)	Source of line			
			Configuration	Term	J	Configuration			Term	J	
123.243	811.405	20	5s	2S	1/2	-	4d ⁹ 5s(3D)4f	2p ^o	3/2	0.003	02CHU
123.265	811.260	15	5s	2S	1/2	-	4d ⁹ 5s(3D)4f	2p ^o	1/2	0.003	02CHU
166.674	599.974	15	5s	2S	1/2	-	4d ⁹ (2D _{3/2})5s5p(1p ^o ₁)	(3/2, 1p ^o ₁)	1/2	0.005	84KAU
170.856	585.288	100	5s	2S	1/2	-	4d ⁹ (2D _{5/2})5s5p(1p ^o ₁)	(5/2, 1p ^o ₁)	3/2	0.005	84KAU
174.147	574.228	5	5s	2S	1/2	-	4d ⁹ (2D _{3/2})5s5p(3p ^o ₂)	(3/2, 3p ^o ₂)	3/2	0.005	84KAU
175.872	568.595	3	5s	2S	1/2	-	4d ⁹ (2D _{3/2})5s5p(3p ^o ₂)	(3/2, 3p ^o ₂)	1/2	0.005	84KAU
177.258	564.149	35	5s	2S	1/2	-	4d ⁹ (2D _{3/2})5s5p(3p ^o ₁)	(3/2, 3p ^o ₁)	1/2	0.005	84KAU
177.707	562.724	50	5s	2S	1/2	-	4d ⁹ (2D _{3/2})5s5p(3p ^o ₁)	(3/2, 3p ^o ₁)	3/2	0.005	84KAU
179.656	556.619	30	5s	2S	1/2	-	4d ⁹ (2D _{3/2})5s5p(3p ^o ₀)	(3/2, 3p ^o ₀)	3/2	0.005	84KAU
180.142	555.118	5	5s	2S	1/2	-	4d ⁹ (2D _{5/2})5s5p(3p ^o ₂)	(5/2, 3p ^o ₂)	1/2	0.005	84KAU
181.670	550.449	10	5s	2S	1/2	-	4d ⁹ (2D _{3/2})5s5p(3p ^o ₀)	(3/2, 3p ^o ₀)	3/2	0.005	84KAU
184.655	541.550	10	5s	2S	1/2	-	4d ⁹ (2D _{3/2})5s5p(3p ^o ₀)	(3/2, 3p ^o ₀)	3/2	0.005	84KAU
221.841	450.773	15	5s	2S	1/2	-	4d ⁹ (2D _{5/2})5s5p(3p ^o ₁)	(5/2, 3p ^o ₁)	3/2	0.005	81KAU
222.79	448.85	40b	5p	2p ^o	1/2	-	6p	2p ^o	3/2	0.005	81KAU
225.541	443.378	10	5s	2S	1/2	-	7s	2S	1/2	0.02	79ROB
232.426	430.244	1	5p	2p ^o	3/2	-	6p	2p ^o	1/2	0.005	81KAU
255.32	391.67	40	4f	2F ^o	5/2	-	7s	2S	1/2	0.005	81KAU
255.68	391.11	50	4f	2F ^o	7/2	-	6g	2G	7/2	0.02	79ROB
327.833	305.033	2	4f	2F ^o	5/2	-	6g	2G	9/2	0.02	79ROB
328.430	304.479	5	4f	2F ^o	7/2	-	5g	2G	7/2	0.005	81KAU
358.384	279.030	4	5p	2p ^o	1/2	-	5g	2G	9/2	0.005	81KAU
383.99	260.423	70b	5p	2p ^o	3/2	-	6s	2S	1/2	0.005	81KAU
499.8	200.08	CBS	6d	2D	3/2	-	6s	2S	1/2	0.02	79ROB
502.7	198.93	CBS	6d	2D	3/2	-	8f	2F ^o	5/2	0.4	96WAN
517.007	193.4210	50	5p	2p ^o	5/2	-	8f	2F ^o	7/2	0.4	96WAN
					1/2	-	5d	2D	3/2	0.005	81KAU

Table B.2 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10^3cm^{-1})	Intensity and comment	Classification				Uncertainty of observed wavelength (Å)	Source of line
			Configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>
525.3	190.37	CBS*	6d	$2D$	5/2	9p	$2p^0$	3/2
525.3	190.37	CBS*	6d	$2D$	3/2	9p	$2p^0$	1/2
532.791	187.6909	1	5d	$2D$	3/2	5f	$2F^0$	5/2
540.04	185.171	50	5d	$2D$	5/2	5f	$2F^0$	7/2
541.29	184.744	10	5d	$2D$	5/2	5f	$2F^0$	5/2
562.547	177.7629	50	5p	$2p^0$	3/2	5d	$2D$	5/2
571.894	174.8576	5	5p	$2p^0$	3/2	5d	$2D$	3/2
628.6	159.08	CES*	5f	$2F^0$	5/2	6g	$2G$	7/2
628.6	159.08	CES*	5f	$2F^0$	7/2	6g	$2G$	9/2
636.5	157.11	CBS	6d	$2D$	3/2	7f	$2F^0$	5/2
665.7	150.22	CBS	6f	$2F^0$	7/2	9g	$2G$	9/2
709.9	140.86	CBS*	5d	$2D$	3/2	6p	$2p^0$	3/2
709.9	140.86	CBS*	5g	$2G$	7/2	7h	$2H^0$	9/2
709.9	140.86	CBS*	5g	$2G$	9/2	7h	$2H^0$	11/2
724.96	137.939	10	5d	$2D$	5/2	6p	$2p^0$	3/2
740.458	135.0515	500	5s	$2S$	1/2	5p	$2p^0$	3/2
749.2	133.48	CBS	5d	$2D$	3/2	6p	$2p^0$	1/2
820.0	121.95	CBS	6p	$2p^0$	1/2	7s	$2S$	1/2
825.7	121.11	CBS	7d	$2D$	3/2	9f	$2F^0$	5/2
830.7	120.38	CBS	7d	$2D$	5/2	9f	$2F^0$	7/2
858.607	116.4677	500	5s	$2S$	1/2	5p	$2p^0$	1/2
870.3	114.90	CBS	7p	$2p^0$	3/2	9s	$2S$	1/2
873.0	114.55	CBS	6p	$2p^0$	3/2	7s	$2S$	1/2
919.3	108.78	CBS*	6h	$2H^0$	11/2	9i	$2I$	13/2
919.3	108.78	CBS*	6h	$2H^0$	9/2	9i	$2I$	11/2

Table B.2 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10 ³ cm ⁻¹)	Intensity and comment	Classification				Uncertainty of observed wavelength (Å)	Source of line
			Configuration	Term	J	Configuration	Term	J
934.7	106.99	CBS	7s	2S	1/2	–	2p ^o	3/2
1087.2	91.98	CBS	7d	2D	5/2	–	2F ^o	7/2
1124.1	88.96	CBS*	5g	2G	7/2	–	2H ^o	9/2
1124.1	88.96	CBS*	5g	2G	9/2	–	2H ^o	11/2
1124.1	88.96	CBS*	6d	2D	3/2	–	2F ^o	5/2
1166.7	85.71	CBS*	6h	2H ^o	9/2	–	2I	11/2
1166.7	85.71	CBS*	6h	2H ^o	11/2	–	2I	13/2
1190.0	84.03	CBS	6p	2p ^o	1/2	–	2D	3/2
1200.3	83.31	CBS	7d	2D	3/2	–	2p ^o	1/2
1251.0	79.94	CBS*	6f	2F ^o	7/2	–	2D	5/2
1251.0	79.94	CBS*	6f	2F ^o	5/2	–	2D	3/2
1281.7	78.02	CBS	6p	2p ^o	3/2	–	2D	5/2
1304.6	76.65	CBS	6p	2p ^o	3/2	–	2D	3/2
1363.1	73.36	CBS*	7h	2H ^o	9/2	–	2I	11/2
1363.1	73.36	CBS*	7h	2H ^o	11/2	–	2I	13/2
1365.4	73.24	CBS*	7i	2I	13/2	–	2K ^o	15/2
1365.4	73.24	CBS*	7i	2I	11/2	–	2K ^o	13/2
1375.9	72.68	BF	5f	2F ^o	5/2	–	2G	7/2
1384.1	72.25	BF	5f	2F ^o	7/2	–	2G	9/2
1418.8	70.48	CBS	6g	2G	9/2	–	2F ^o	7/2
1507.2	66.35	CBS	6d	2D	3/2	–	2p ^o	3/2
1535.4	65.13	CBS*	7p	2p ^o	1/2	–	2S	1/2
1535.4	65.13	CBS*	8p	2p ^o	1/2	–	2D	3/2
1538.6	64.99	CBS	6d	2D	5/2	–	2p ^o	3/2
1580.0	63.29	CBS	8p	2p ^o	3/2	–	2D	5/2

Table B.2 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10^3cm^{-1})	Intensity and comment	Classification				Uncertainty of observed wavelength (Å)	Source of line
			Configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>
1591.8	62.82	CBS	8s	$2S$	$1/2$	–	$2p^0$	$1/2$
1602.5	62.402	CBS	6d	$2D$	$3/2$	–	$2p^0$	$1/2$
1684.6	59.36	CBS	8d	$2D$	$3/2$	–	$2F^0$	$5/2$
1691.8	59.11	CBS	8d	$2D$	$5/2$	–	$2F^0$	$7/2$
1708.2	58.54	CBS*	7g	$2G$	$9/2$	–	$2H^0$	$11/2$
1708.2	58.54	CBS*	7g	$2G$	$7/2$	–	$2H^0$	$9/2$
1758.3	56.873	CBS*	7h	$2H^0$	$11/2$	–	$2I$	$13/2$
1758.3	56.873	CBS*	7h	$2H^0$	$9/2$	–	$2I$	$11/2$
1763.8	56.696	CBS*	7i	$2I$	$11/2$	–	$2K^0$	$13/2$
1763.8	56.696	CBS*	7i	$2I$	$13/2$	–	$2K^0$	$15/2$
1808.7	55.288	CBS	6s	$2S$	$1/2$	–	$2p^0$	$3/2$
1844.6	54.212	BF*	6g	$2G$	$7/2$	–	$2H^0$	$9/2$
1844.6	54.212	BF*	6g	$2G$	$9/2$	–	$2H^0$	$11/2$
1919.1	52.108	BF*	6h	$2H^0$	$9/2$	–	$2I$	$11/2$
1919.1	52.108	BF*	6h	$2H^0$	$11/2$	–	$2I$	$13/2$
1971.7	50.718	CBS	7f	$2F^0$	$7/2$	–	$2D$	$5/2$
1998.4	50.040	CBS	7d	$2D$	$3/2$	–	$2F^0$	$5/2$
2021.0	49.465	CBS	7d	$2D$	$5/2$	–	$2F^0$	$7/2$
2087.3	47.894	CBS	6s	$2S$	$1/2$	–	$2p^0$	$1/2$
2122.2	47.106	CBS	4f	$2F^0$	$7/2$	–	$2D$	$5/2$
2154.9	46.391	CBS	7g	$2G$	$9/2$	–	$2F^0$	$7/2$
2233.5	44.759	CBS	7p	$2P^0$	$1/2$	–	$2D$	$3/2$
2235.1	44.727	CBS	4f	$2F^0$	$5/2$	–	$2D$	$3/2$
2404.6	41.574	CBS	7p	$2P^0$	$3/2$	–	$2D$	$5/2$
2448.9	40.822	CBS	7p	$2P^0$	$3/2$	–	$2D$	$3/2$

Table B.2 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10^3cm^{-1})	Intensity and comment	Classification				Uncertainty of observed wavelength (Å)	Source of line
			Configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>
2467.6	40.513	CBS	6f	$2F^0$	5/2	—	$2G$	7/2
2487.8	40.184	CBS	6f	$2F^0$	7/2	—	$2G$	9/2
2516.8	39.721	CBS*	8h	$2H^0$	9/2	—	$2I$	11/2
2516.8	39.721	CBS*	8h	$2H^0$	11/2	—	$2I$	13/2
2526.4	39.570	CBS*	8i	$2I$	13/2	—	$2K^0$	15/2
2526.4	39.570	CBS*	8i	$2I$	11/2	—	$2K^0$	13/2
2710.6	36.881	CBS	7d	$2D$	5/2	—	$2p^0$	3/2
2737.9	36.514	CBS	8p	$2p^0$	3/2	—	$2S$	1/2
2821.0	35.438	CBS*	7g	$2G$	7/2	—	$2H^0$	9/2
2821.0	35.438	CBS*	7g	$2G$	9/2	—	$2H^0$	11/2
2829.0	35.338	CBS	7d	$2D$	3/2	—	$2p^0$	1/2
2953.2	33.852	bBF*	7h	$2H^0$	9/2	—	$2I$	11/2
2953.2	33.852	bBF*	7h	$2H^0$	11/2	—	$2I$	13/2
2970.7	33.652	BF*	7i	$2I$	11/2	—	$2K^0$	13/2
2970.7	33.652	BF*	7i	$2I$	13/2	—	$2K^0$	15/2
3229.8	30.953	CBS	8d	$2D$	3/2	—	$2F^0$	5/2
3248.4	30.776	CBS	5f	$2F^0$	7/2	—	$2D$	5/2
3253.7	30.725	CBS	8d	$2D$	5/2	—	$2F^0$	7/2
3351.2	29.831	CBS	5f	$2F^0$	5/2	—	$2D$	3/2
3511.6	28.469	CBS	7s	$2S$	1/2	—	$2p^0$	3/2
4079.0	24.509	CBS*	7s	$2S$	1/2	—	$2p^0$	1/2
4079.0	24.509	CBS*	8p	$2p^0$	3/2	—	$2D$	5/2
4093.5	24.422	CBS*	8g	$2G$	7/2	—	$2H^0$	9/2
4093.5	24.422	CBS*	8g	$2G$	9/2	—	$2H^0$	11/2
4307.1	23.211	CBS*	8h	$2H^0$	11/2	—	$2I$	13/2

Table B.2 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10^3cm^{-1})	Intensity and comment	Classification				Uncertainty of observed wavelength (Å)	Source of line
			Configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>
4307.1	23.211	CBS*	8h	2H°	9/2	–	2I	11/2
4331.6	23.080	CBS*	8i	2I	11/2	–	2K°	13/2
4331.6	23.080	CBS*	8i	2I	13/2	–	2K°	15/2
4337.9	23.046	CBS*	8k	2K°	13/2	–	2L	15/2
4337.9	23.046	CBS*	8k	2K°	15/2	–	2L	17/2
4423.7	22.599	CBS	8d	2D	5/2	–	2p°	3/2
4642.4	21.535	CBS	8d	2D	3/2	–	2p°	1/2
4841.4	20.649	CBS	9d	2D	3/2	–	2F°	5/2
4937.6	20.247	CBS	9d	2D	5/2	–	2F°	7/2
5819.5	17.179	CBS	8s	2S	1/2	–	2p°	3/2

Table B.3 Sources of Xe VIII lines.

Source	Number of classifications	Light source	Wavelength range (Å)	Uncertainty (Å)
79ROB	7	Theta pinch	223–725	0.02
81BAS	10	Beam-foil spectroscopy	1376–2971	0.5
81KAU	12	Modified triggered spark initiated by a puff of Xe gas	222–859	0.005
84KAU	10	High-voltage spark discharge	167–185	0.005
95DRU	2	Charge-exchange spectroscopy	629	0.5
95LAR	9	Collision-based spectroscopy	1282–2235	0.5
96WAN	83	Collision-based spectroscopy	500–5820	0.4–0.8
02CHU	2	Codified triggered spark initiated by a puff of Xe gas	123	0.003

Table B.4 Energy levels of Xe IX.

Energy level (cm ⁻¹)	Parity	Configuration	Term	J	Source of level
0.	0	4d ¹⁰	1S	0	02CHU _b
453468.	0	4d ⁹ 5s	3D	3	02CHU _b
456956.	0	4d ⁹ 5s	3D	2	02CHU _b
470048.	0	4d ⁹ 5s	3D	1	02CHU _b
473496.	0	4d ⁹ 5s	1D	2	02CHU _b
575438.	1	4d ⁹ 5p	3p ^o	2	02CHU _b
578986.	1	4d ⁹ 5p	3F ^o	3	02CHU _b
593154.	1	4d ⁹ 5p	3F ^o	2	02CHU _b
594522.	1	4d ⁹ 5p	3p ^o	1	02CHU _b
596854.	1	4d ⁹ 5p	3F ^o	4	02CHU _b
602541.	1	4d ⁹ 5p	1D ^o	2	02CHU _b
604877.	1	4d ⁹ 5p	1p ^o	1	02CHU _b
605410.	1	4d ⁹ 5p	3D ^o	3	02CHU _b
607906.	1	4d ⁹ 5p	3p ^o	0	02CHU _b
616157.	1	4d ⁹ 5p	1F ^o	3	02CHU _b
618269.	1	4d ⁹ 5p	3D ^o	1	02CHU _b
621147.	1	4d ⁹ 5p	3D ^o	2	02CHU _b
665447.?	1	4d ⁹ 4f	3p ^o	1	02CHU _b
696312.	1	4d ⁹ 4f	3D ^o	1	02CHU _b
832414.	1	4d ⁹ 4f	1p ^o	1	02CHU _b
780792.	0	4d ⁹ 5d	3S	1	02CHU _b
788522.	0	4d ⁹ 5d	3G	4	02CHU _b
790022.	0	4d ⁹ 5d	3D	2	02CHU _b
790742.	0	4d ⁹ 5d	3G	5	02CHU _b
790854.	0	4d ⁹ 5d	1P	1	02CHU _b

Table B.4 (Continued).

Energy level (cm ⁻¹)	Parity	Configuration	Term	<i>J</i>	Source of level
792488.	0	4d ⁹ 5d	3D	3	02CHU _b
795332.	0	4d ⁹ 5d	1F	3	02CHU _b
796070.	0	4d ⁹ 5d	3P	2	02CHU _b
797063.	0	4d ⁹ 5d	3F	4	02CHU _b
798896.	0	4d ⁹ 5d	3P	0	02CHU _b
803860.	0	4d ⁹ 5d	3P	1	02CHU _b
805240.	0	4d ⁹ 5d	3G	3	02CHU _b
807691.	0	4d ⁹ 5d	3D	1	02CHU _b
809314.	0	4d ⁹ 5d	1G	4	02CHU _b
810825.	0	4d ⁹ 5d	1D	2	02CHU _b
811675.	0	4d ⁹ 5d	3F	2	02CHU _b
813696.	0	4d ⁹ 5d	3F	3	02CHU _b
843962.	0	4d ⁹ 5d	1S	0	02CHU _b
963320.	1	4d ⁹ 6p	3p ^o	1	02CHU _a
972620.	1	4d ⁹ 6p	1p ^o	1	02CHU _a
995359.	1	4d ⁹ 5f	3H ^o	6	02CHU _b
995961.	1	4d ⁹ 5f	3H ^o	5	02CHU _b
998024.	1	4d ⁹ 5f	1D ^o	2	02CHU _b
998220.	1	4d ⁹ 5f	3F ^o	3	02CHU _b
998989.	1	4d ⁹ 5f	3F ^o	4	02CHU _b
999785.	1	4d ⁹ 5f	1G ^o	4	02CHU _b
1000432.	1	4d ⁹ 5f	3G ^o	5	02CHU _b
1001354.	1	4d ⁹ 5f	1F ^o	3	02CHU _b
1004493.	1	4d ⁹ 5f	3D ^o	1	02CHU _b
1012122.	1	4d ⁹ 5f	3H ^o	4	02CHU _b
1013161.?	1	4d ⁹ 5f	1H ^o	5	02CHU _b

Table B.4 (Continued).

Energy level (cm ⁻¹)	Parity	Configuration	Term	<i>J</i>	Source of level
1014147.	1	4d ⁹ 5f	3F ^o	2	02CHU _b
1015439.	1	4d ⁹ 5f	3D ^o	3	02CHU _b
1017029.	1	4d ⁹ 5f	3G ^o	4	02CHU _b
1017377.	1	4d ⁹ 5f	3G ^o	3	02CHU _b
1036821.	1	4d ⁹ 5f	1p ^o	1	02CHU _b
1130660	1	4d ⁹ 7p	3p ^o	1	02CHU _a
1142635 ?	1	4d ⁹ 7p	1p ^o	1	02CHU _a
1170685	1	4d ⁹ 6f	1p ^o	1	02CHU _a

Table B.5 Spectral lines of Xe IX.

Observed vacuum wavelength (Å)	Observed wave number (10^3 cm^{-1})	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
85.420	1170.69	3	4d ¹⁰	1S	0	—	4d ⁹ 6f	1p ^o	0.006	02CHU _a
87.517	1142.64	2	4d ¹⁰	1S	0	—	4d ⁹ 7p	1p ^o	0.006	02CHU _a
88.444	1130.66	5?	4d ¹⁰	1S	0	—	4d ⁹ 7p	3p ^o	0.006	02CHU _a
96.449	1036.82	35	4d ¹⁰	1S	0	—	4d ⁹ 5f	1p ^o	0.003	02CHU _b
99.553	1004.49	10	4d ¹⁰	1S	0	—	4d ⁹ 5f	3D ^o	0.003	02CHU _b
102.815	972.62	10	4d ¹⁰	1S	0	—	4d ⁹ 6p	1p ^o	0.003	02CHU _a
103.808	963.32	12	4d ¹⁰	1S	0	—	4d ⁹ 6p	3p ^o	0.003	02CHU _a
120.133	832.41	200	4d ¹⁰	1S	0	—	4d ⁹ 4f	1p ^o	0.003	02CHU _b
143.614	696.311	90	4d ¹⁰	1S	0	—	4d ⁹ 4f	3D ^o	0.003	02CHU _b
150.275	665.447	5	4d ¹⁰	1S	0	—	4d ⁹ 4f	3p ^o	0.003	02CHU _b
161.742	618.269	650	4d ¹⁰	1S	0	—	4d ⁹ 5p	3D ^o	0.003	02CHU _b
165.323	604.877	950	4d ¹⁰	1S	0	—	4d ⁹ 5p	1p ^o	0.003	02CHU _b
400.906	249.435	26	4d ⁹ 5p	3p ^o	1	—	4d ⁹ 5d	1S	0.007	02CHU _b
418.257	239.087	171	4d ⁹ 5p	1p ^o	1	—	4d ⁹ 5d	1S	0.007	02CHU _b
426.07	234.703	2	4d ⁹ 5p	3F ^o	3	—	4d ⁹ 5d	3F	0.02	02CAL
430.52	232.277	2	4d ⁹ 5p	3p ^o	2	—	4d ⁹ 5d	3D	0.02	02CAL
435.12	229.822	1	4d ⁹ 5p	3p ^o	2	—	4d ⁹ 5d	3G	0.02	02CAL
436.41	229.142	1	4d ⁹ 5d	3D	1	—	4d ⁹ 5f	1p ^o	0.02	02CAL
442.52	225.978	2	4d ⁹ 5d	1D	2	—	4d ⁹ 5f	1p ^o	0.02	02CAL
443.080	225.693	31	4d ⁹ 5p	3D ^o	1	—	4d ⁹ 5d	1S	0.007	02CHU _b
444.23	225.109	9	4d ⁹ 5d	3F	2	—	4d ⁹ 5f	1p ^o	0.02	02CAL
450.44	222.005	1	4d ⁹ 5d	1F	3	—	4d ⁹ 5f	3G ^o	0.02	02CAL
454.32	220.109	1	4d ⁹ 5d	1F	3	—	4d ⁹ 5f	3D ^o	0.02	02CAL
457.624	218.520	90	4d ⁹ 5p	3F ^o	2	—	4d ⁹ 5d	3F	0.007	02CHU _b
458.54	218.083	1*	4d ⁹ 5d	3p	2	—	4d ⁹ 5f	3F ^o	0.02	02CAL

Table B.5 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10 ³ cm ⁻¹)	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
458.54	218.083	1*	4d ⁹ 5p	3F ^o	3	—	4d ⁹ 5d	4	0.02	02CAL
459.407	217.672	99	4d ⁹ 5p	3F ^o	2	—	4d ⁹ 5d	2	0.007	02CHU _b
460.719	217.052	224	4d ⁹ 5p	3p ^o	2	—	4d ⁹ 5d	3	0.007	02CHU _b
462.229	216.343	102	4d ⁹ 5p	3F ^o	3	—	4d ⁹ 5d	3	0.007	02CHU _b
462.319	216.301	83	4d ⁹ 5p	3p ^o	1	—	4d ⁹ 5d	2	0.007	02CHU _b
464.19	215.429	4	4d ⁹ 5p	3p ^o	2	—	4d ⁹ 5d	1	0.02	02CAL
466.010	214.588	300m	4d ⁹ 5p	3p ^o	2	—	4d ⁹ 5d	2	0.007	02CHU _b
466.09	214.551	3	4d ⁹ 5p	3F ^o	2	—	4d ⁹ 5d	1	0.02	02CAL
468.386	213.499	223	4d ⁹ 5p	3F ^o	3	—	4d ⁹ 5d	3	0.007	02CHU _b
469.10	213.174	5	4d ⁹ 5p	3p ^o	1	—	4d ⁹ 5d	1	0.02	02CAL
470.64	212.477	4	4d ⁹ 5p	3F ^o	4	—	4d ⁹ 5d	4	0.02	02CAL
471.498	212.090	276	4d ⁹ 5p	3F ^o	2	—	4d ⁹ 5d	3	0.007	02CHU _b
473.864	211.031	66	4d ⁹ 5p	3F ^o	3	—	4d ⁹ 5d	2	0.007	02CHU _b
474.601	210.703	55	4d ⁹ 5p	3F ^o	2	—	4d ⁹ 5d	1	0.007	02CHU _b
475.12	210.473	1b	4d ⁹ 5d	3G	4	—	4d ⁹ 5f	4	0.02	02CAL
476.892	209.691	103	4d ⁹ 5d	3G	5	—	4d ⁹ 5f	5	0.008	02CHU _b
477.240	209.538	374	4d ⁹ 5p	3F ^o	3	—	4d ⁹ 5d	4	0.008	02CHU _b
477.685	209.343	115	4d ⁹ 5p	3p ^o	1	—	4d ⁹ 5d	1	0.008	02CHU _b
478.10	209.161	1	4d ⁹ 5p	1D ^o	2	—	4d ⁹ 5d	2	0.02	02CAL
480.08	208.299	4b*	4d ⁹ 5p	3D ^o	3	—	4d ⁹ 5d	3	0.02	02CAL
480.08	208.299	4b*	4d ⁹ 5p	1D ^o	2	—	4d ⁹ 5d	2	0.02	02CAL
480.20	208.247	1	4d ⁹ 5d	3G	5	—	4d ⁹ 5f	4	0.02	02CAL
480.313	208.198	59	4d ⁹ 5d	3D	2	—	4d ⁹ 5f	3	0.008	02CHU _b
482.068	207.440	160	4d ⁹ 5d	3G	4	—	4d ⁹ 5f	5	0.008	02CHU _b
482.695	207.170	108	4d ⁹ 5d	1P	1	—	4d ⁹ 5f	2	0.008	02CHU _b

Table B.5 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10 ³ cm ⁻¹)	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
483.367	206.882	148	4d ⁹ 5d	3G	3	—	4d ⁹ 5f	3H ^o	0.008	02CHU _b
483.556	206.801	73	4d ⁹ 5p	1p ^o	1	—	4d ⁹ 5d	3F	0.008	02CHU _b
484.139	206.552	71	4d ⁹ 5d	1D	2	—	4d ⁹ 5f	3G ^o	0.008	02CHU _b
484.258	206.501	118	4d ⁹ 5d	3D	3	—	4d ⁹ 5f	3F ^o	0.008	02CHU _b
484.365	206.456	142	4d ⁹ 5d	3D	1	—	4d ⁹ 5f	3F ^o	0.008	02CHU _b
485.38	206.024	2	4d ⁹ 5d	1F	3	—	4d ⁹ 5f	1F ^o	0.02	02CAL
485.56	205.948	5	4d ⁹ 5p	1p ^o	1	—	4d ⁹ 5d	1D	0.02	02CAL
486.070	205.732	57	4d ⁹ 5d	3D	3	—	4d ⁹ 5f	3F ^o	0.008	02CHU _b
486.30	205.634	4	4d ⁹ 5d	3p	0	—	4d ⁹ 5f	3D ^o	0.02	02CAL
486.959	205.356	229	4d ⁹ 5p	3p ^o	2	—	4d ⁹ 5d	3S	0.008	02CHU _b
487.131	205.284	123	4d ⁹ 5d	3p	2	—	4d ⁹ 5f	1F ^o	0.008	02CHU _b
487.285	205.219	64	4d ⁹ 5d	3G	5	—	4d ⁹ 5f	3H ^o	0.008	02CHU _b
488.718	204.617	178*	4d ⁹ 5d	3G	5	—	4d ⁹ 5f	3H ^o	0.008	02CHU _b
488.718	204.617	178*	4d ⁹ 5d	1D	2	—	4d ⁹ 5f	3D ^o	0.008	02CHU _b
489.110	204.453	151	4d ⁹ 5d	1F	3	—	4d ⁹ 5f	1G ^o	0.008	02CHU _b
489.300	204.374	85	4d ⁹ 5p	3p ^o	1	—	4d ⁹ 5d	3P	0.008	02CHU _b
490.564	203.847	266b	4d ⁹ 5d	1G	4	—	4d ⁹ 5f	1H ^o	0.008	02CHU _b
490.763	203.764	73	4d ⁹ 5d	3F	2	—	4d ⁹ 5f	3D ^o	0.008	02CHU _b
491.719	203.368	232	4d ⁹ 5d	3F	4	—	4d ⁹ 5f	3G ^o	0.008	02CHU _b
491.804	203.333	144	4d ⁹ 5d	3F	3	—	4d ⁹ 5f	3G ^o	0.008	02CHU _b
492.817	202.915	71	4d ⁹ 5p	3F ^o	2	—	4d ⁹ 5d	3P	0.008	02CHU _b
493.343	202.699	154	4d ⁹ 5p	1D ^o	2	—	4d ⁹ 5d	3G	0.008	02CHU _b
494.614	202.178	169	4d ⁹ 5p	3F ^o	2	—	4d ⁹ 5d	1F	0.008	02CHU _b
495.231	201.926	70	4d ⁹ 5d	3F	4	—	4d ⁹ 5f	3F ^o	0.008	02CHU _b
495.68	201.743	3	4d ⁹ 5d	3F	3	—	4d ⁹ 5f	3D ^o	0.02	02CAL

Table B.5 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10 ³ cm ⁻¹)	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line	
496.162	201.547	69	4d ⁹ 5p	3p ^o	1	—	4d ⁹ 5d	3P	2	0.008	02CHU _b
499.478	200.209	100	4d ⁹ 5p	3F ^o	4	—	4d ⁹ 5d	3F	4	0.008	02CHU _b
500.532	199.787	79	4d ⁹ 5p	3p ^o	0	—	4d ⁹ 5d	3D	1	0.008	02CHU _b
501.679	199.331	30	4d ⁹ 5p	3F ^o	2	—	4d ⁹ 5d	3D	3	0.008	02CHU _b
502.566	198.979	46	4d ⁹ 5p	1p ^o	1	—	4d ⁹ 5d	3P	1	0.008	02CHU _b
503.84	198.476	3	4d ⁹ 5p	3F ^o	4	—	4d ⁹ 5d	1F	3	0.02	02CAL
505.821	197.698	51	4d ⁹ 5p	3F ^o	2	—	4d ⁹ 5d	1P	1	0.008	02CHU _b
506.230	197.539	309	4d ⁹ 5p	1F ^o	3	—	4d ⁹ 5d	3F	3	0.008	02CHU _b
509.332	196.336	133	4d ⁹ 5p	3p ^o	1	—	4d ⁹ 5d	1P	1	0.008	02CHU _b
510.30	195.963	4	4d ⁹ 5p	3p ^o	0	—	4d ⁹ 5d	3P	1	0.02	02CAL
511.159	195.634	94	4d ⁹ 5p	3F ^o	4	—	4d ⁹ 5d	3D	3	0.008	02CHU _b
511.52	195.496	2	4d ⁹ 5p	3p ^o	1	—	4d ⁹ 5d	3D	2	0.02	02CAL
515.11	194.133	3	4d ⁹ 5d	3p	1	—	4d ⁹ 5f	1D ^o	2	0.02	02CAL
515.762	193.888	457	4d ⁹ 5p	3F ^o	4	—	4d ⁹ 5d	3G	5	0.008	02CHU _b
516.17	193.735	6	4d ⁹ 5d	3G	3	—	4d ⁹ 5f	3F ^o	4	0.02	02CAL
516.714	193.531	185	4d ⁹ 5p	1D ^o	2	—	4d ⁹ 5d	3P	2	0.008	02CHU _b
517.050	193.405	350m	4d ⁹ 5p	3D ^o	1	—	4d ⁹ 5d	3F	2	0.008	02CHU _b
517.714	193.157	354	4d ⁹ 5p	1F ^o	3	—	4d ⁹ 5d	1G	4	0.008	02CHU _b
518.23	192.965	4b	4d ⁹ 5d	3G	3	—	4d ⁹ 5f	3F ^o	3	0.02	02CAL
518.700	192.790	346	4d ⁹ 5p	1D ^o	2	—	4d ⁹ 5d	1F	3	0.008	02CHU _b
519.347	192.549	393	4d ⁹ 5p	3D ^o	2	—	4d ⁹ 5d	3F	3	0.008	02CHU _b
521.730	191.670	150	4d ⁹ 5p	3F ^o	4	—	4d ⁹ 5d	3G	4	0.008	02CHU _b
521.783	191.651	538	4d ⁹ 5p	3D ^o	3	—	4d ⁹ 5d	3F	4	0.008	02CHU _b
523.037	191.191	173	4d ⁹ 5p	1p ^o	1	—	4d ⁹ 5d	3P	2	0.008	02CHU _b
523.20	191.131	5	4d ⁹ 5d	1G	4	—	4d ⁹ 5f	3G ^o	5	0.02	02CAL

Table B.5 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10^3 cm^{-1})	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
526.523	189.925	205	4d ⁹ 5p	3D ^o	3	—	4d ⁹ 5d	1F	0.008	02CHU _b
527.206	189.679	183	4d ⁹ 5p	3D ^o	2	—	4d ⁹ 5d	1D	0.008	02CHU _b
527.929	189.419	110	4d ⁹ 5p	3D ^o	1	—	4d ⁹ 5d	3D	0.008	02CHU _b
528.876	189.080	119	4d ⁹ 5p	1F ^o	3	—	4d ⁹ 5d	3G	0.008	02CHU _b
531.040	188.310	162	4d ⁹ 5p	1D ^o	2	—	4d ⁹ 5d	1P	0.008	02CHU _b
534.528	187.081	195	4d ⁹ 5p	3D ^o	3	—	4d ⁹ 5d	3D	0.008	02CHU _b
537.701	185.977	160	4d ⁹ 5p	1P ^o	1	—	4d ⁹ 5d	1P	0.008	02CHU _b
538.820	185.591	114	4d ⁹ 5p	3D ^o	1	—	4d ⁹ 5d	3P	0.008	02CHU _b
541.665	184.616	100	4d ⁹ 5p	3D ^o	3	—	4d ⁹ 5d	3D	0.008	02CHU _b
546.118	183.111	234	4d ⁹ 5p	3D ^o	3	—	4d ⁹ 5d	3G	0.008	02CHU _b
547.309	182.712	239	4d ⁹ 5p	3D ^o	2	—	4d ⁹ 5d	3P	0.008	02CHU _b
550.21	181.749	1	4d ⁹ 5d	1P	1	—	4d ⁹ 6p	1P ^o	0.02	02CAL
561.013	178.249	97	4d ⁹ 5p	1D ^o	2	—	4d ⁹ 5d	3S	0.008	02CHU _b
596.379	167.679	61	4d ⁹ 5s	3D	3	—	4d ⁹ 5p	3D ^o	0.008	02CHU _b
609.050	164.190	132	4d ⁹ 5s	3D	2	—	4d ⁹ 5p	3D ^o	0.008	02CHU _b
614.670	162.689	80	4d ⁹ 5s	3D	3	—	4d ⁹ 5p	1F ^o	0.008	02CHU _b
619.909	161.314	99	4d ⁹ 5s	3D	2	—	4d ⁹ 5p	3D ^o	0.008	02CHU _b
628.144	159.199	100	4d ⁹ 5s	3D	2	—	4d ⁹ 5p	1F ^o	0.008	02CHU _b
658.146	151.942	470	4d ⁹ 5s	3D	3	—	4d ⁹ 5p	3D ^o	0.009	02CHU _b
661.812	151.100	260	4d ⁹ 5s	3D	1	—	4d ⁹ 5p	3D ^o	0.009	02CHU _b
670.810	149.0735	75	4d ⁹ 5s	3D	3	—	4d ⁹ 5p	1D ^o	0.009	02CHU _b
673.602	148.4556	239	4d ⁹ 5s	3D	2	—	4d ⁹ 5p	3D ^o	0.009	02CHU _b
674.673	148.2200	244	4d ⁹ 5s	3D	1	—	4d ⁹ 5p	3D ^o	0.009	02CHU _b
676.040	147.9202	200m	4d ⁹ 5s	3D	2	—	4d ⁹ 5p	1P ^o	0.009	02CHU _b
677.280	147.6494	300m	4d ⁹ 5s	1D	2	—	4d ⁹ 5p	3D ^o	0.009	02CHU _b

Table B.5 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10 ³ cm ⁻¹)	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
686.885	145.5848	256	4d ⁹ 5s	3D	2	—	4d ⁹ 5p	1D ^o	0.009	02CHU _b
690.731	144.7742	103	4d ⁹ 5s	1D	2	—	4d ⁹ 5p	3D ^o	0.009	02CHU _b
697.417	143.3862	494	4d ⁹ 5s	3D	3	—	4d ⁹ 5p	3F ^o	0.009	02CHU _b
700.962	142.6611	396	4d ⁹ 5s	1D	2	—	4d ⁹ 5p	1F ^o	0.009	02CHU _b
725.378	137.8592	107	4d ⁹ 5s	3D	1	—	4d ⁹ 5p	3P ^o	0.009	02CHU _b
726.923	137.5662	148	4d ⁹ 5s	3D	2	—	4d ⁹ 5p	3P ^o	0.009	02CHU _b
734.224	136.1982	80	4d ⁹ 5s	3D	2	—	4d ⁹ 5p	3F ^o	0.009	02CHU _b
741.683	134.8285	152	4d ⁹ 5s	3D	1	—	4d ⁹ 5p	1P ^o	0.009	02CHU _b
754.770	132.4907	121	4d ⁹ 5s	3D	1	—	4d ⁹ 5p	1D ^o	0.009	02CHU _b
758.066	131.9146	131	4d ⁹ 5s	1D	2	—	4d ⁹ 5p	3D ^o	0.009	02CHU _b
761.125	131.3845	731b	4d ⁹ 5s	1D	2	—	4d ⁹ 5p	1P ^o	0.009	02CHU _b
774.916	129.0462	134	4d ⁹ 5s	1D	2	—	4d ⁹ 5p	1D ^o	0.009	02CHU _b
796.712	125.5159	168	4d ⁹ 5s	3D	3	—	4d ⁹ 5p	3F ^o	0.009	02CHU _b
812.297	123.1077	253	4d ⁹ 5s	3D	1	—	4d ⁹ 5p	3F ^o	0.010	02CHU _b
819.470	122.0301	390	4d ⁹ 5s	3D	2	—	4d ⁹ 5p	3F ^o	0.010	02CHU _b
819.875	121.9698	404	4d ⁹ 5s	3D	3	—	4d ⁹ 5p	3P ^o	0.010	02CHU _b
826.270	121.0258	258	4d ⁹ 5s	1D	2	—	4d ⁹ 5p	3P ^o	0.010	02CHU _b
835.729	119.6560	224	4d ⁹ 5s	1D	2	—	4d ⁹ 5p	3F ^o	0.010	02CHU _b
844.006	118.4826	149	4d ⁹ 5s	3D	2	—	4d ⁹ 5p	3P ^o	0.010	02CHU _b

Table B.6 Energy levels of Xe x.

Energy level (cm ⁻¹)	Parity	Configuration	Term	J	Source of level
0.	0	4d ⁹	2D	5/2	02CHU
16725.	0	4d ⁹	2D	3/2	02CHU
629040.	1	4d ⁸ 5p	629040 ^o	7/2	02CHU
644130.	1	4d ⁸ 5p	644130 ^o	3/2	02CHU
646494.	1	4d ⁸ 5p	646494 ^o	5/2	02CHU
646880.	1	4d ⁸ 5p	646880 ^o	7/2	02CHU
654245.	1	4d ⁸ 5p	654245 ^o	3/2	02CHU
656520.	1	4d ⁸ 5p	656520 ^o	1/2	02CHU
657645.	1	4d ⁸ 5p	657645 ^o	5/2	02CHU
658993.	1	4d ⁸ 5p	658993 ^o	7/2	02CHU
662160.	1	4d ⁸ 5p	662160 ^o	3/2	02CHU
664256.	1	4d ⁸ 5p	664256 ^o	5/2	02CHU
668525.	1	4d ⁸ 5p	668525 ^o	5/2	02CHU
669531.	1	4d ⁸ 5p	669531 ^o	7/2	02CHU
671045.	1	4d ⁸ 5p	671045 ^o	5/2	02CHU
672762.?	1	4d ⁸ 5p	672762 ^o	7/2	02CHU
674159.	1	4d ⁸ 5p	674159 ^o	3/2	02CHU
675652.	1	4d ⁸ 5p	675652 ^o	5/2	02CHU
675878.	1	4d ⁸ 5p	675878 ^o	7/2	02CHU
677421.	1	4d ⁸ 5p	677421 ^o	3/2	02CHU
677704.	1	4d ⁸ 5p	677704 ^o	1/2	02CHU
681425.	1	4d ⁸ 5p	681425 ^o	1/2	02CHU
682838.	1	4d ⁸ 5p	682838 ^o	5/2	02CHU
682998.	1	4d ⁸ 5p	682998 ^o	3/2	02CHU
684240.	1	4d ⁸ 5p	684240 ^o	7/2	02CHU
688121.	1	4d ⁸ 5p	688121 ^o	3/2	02CHU

Table B.6 (Continued).

Energy level (cm ⁻¹)	Parity	Configuration	Term	<i>J</i>	Source of level
690757.	1	4d ⁸ 5p	690757 ^o	5/2	02CHU
691306.	1	4d ⁸ 5p	691306 ^o	3/2	02CHU
694056.	1	4d ⁸ 5p	694056 ^o	5/2	02CHU
695239.	1	4d ⁸ 5p	695239 ^o	1/2	02CHU
696975.	1	4d ⁸ 5p	696975 ^o	3/2	02CHU
701735.	1	4d ⁸ 5p	701735 ^o	5/2	02CHU
703997.	1	4d ⁸ 5p	703997 ^o	7/2	02CHU
705669.	1	4d ⁸ 5p	705669 ^o	1/2	02CHU
723216.	1	4d ⁸ 5p	723216 ^o	1/2	02CHU
745212.	1	4d ⁸ 5p	745212 ^o	3/2	02CHU
629234.	1	4p ⁵ 4d ¹⁰	629234 ^o	3/2	02CHU
924721.	1	4p ⁵ 4d ¹⁰	924721 ^o	1/2	02CHU
676893.	1	4d ⁸ 4f	676893 ^o	7/2	02CHU
678351.	1	4d ⁸ 4f	678351 ^o	5/2	02CHU
682437.	1	4d ⁸ 4f	682437 ^o	3/2	02CHU
684807.	1	4d ⁸ 4f	684807 ^o	1/2	02CHU
686273.	1	4d ⁸ 4f	686273 ^o	5/2	02CHU
687770.	1	4d ⁸ 4f	687770 ^o	7/2	02CHU
689190.	1	4d ⁸ 4f	689190 ^o	3/2	02CHU
697440.	1	4d ⁸ 4f	697440 ^o	3/2	02CHU
698751.	1	4d ⁸ 4f	698751 ^o	5/2	02CHU
701155.	1	4d ⁸ 4f	701155 ^o	5/2	02CHU
702652.	1	4d ⁸ 4f	702652 ^o	1/2	02CHU
708748.	1	4d ⁸ 4f	708748 ^o	7/2	02CHU
711392.	1	4d ⁸ 4f	711392 ^o	5/2	02CHU

Table B.6 (Continued).

Energy level (cm ⁻¹)	Parity	Configuration	Term	<i>J</i>	Source of level
713643.	1	4d ⁸ 4f	713643 ^o	5/2	02CHU
721870.	1	4d ⁸ 4f	721870 ^o	5/2	02CHU
725785.	1	4d ⁸ 4f	725785 ^o	1/2	02CHU
737104.	1	4d ⁸ 4f	737104 ^o	1/2	02CHU
749681.	1	4d ⁸ 4f	749681 ^o	3/2	02CHU
753489.	1	4d ⁸ 4f	753489 ^o	1/2	02CHU
864592.	1	4d ⁸ 4f	864592 ^o	5/2	02CHU
870470.	1	4d ⁸ 4f	870470 ^o	7/2	02CHU
874794.	1	4d ⁸ 4f	874794 ^o	3/2	02CHU
881539.	1	4d ⁸ 4f	881539 ^o	3/2	02CHU
887203.	1	4d ⁸ 4f	887203 ^o	5/2	02CHU

Table B.7 Spectral lines of Xe x.

Observed vacuum wavelength (Å)	Observed wave number (10 ³ cm ⁻¹)	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
110.133	907.99	15	4d ⁹	2D	3/2	—	924721°	1/2	0.003	02CHU
112.714	887.20	3	4d ⁹	2D	5/2	—	887203°	5/2	0.003	02CHU
113.438	881.54	15	4d ⁹	2D	5/2	—	881539°	3/2	0.003	02CHU
114.312	874.80	30	4d ⁹	2D	5/2	—	874794°	3/2	0.003	02CHU
114.880	870.47	80*	4d ⁹	2D	3/2	—	887203°	5/2	0.003	02CHU
114.880	870.47	80*	4d ⁹	2D	5/2	—	870470°	7/2	0.003	02CHU
115.632	864.81	30	4d ⁹	2D	3/2	—	881539°	3/2	0.003	02CHU
115.661	864.60	60	4d ⁹	2D	5/2	—	864592°	5/2	0.003	02CHU
116.541	858.07	12	4d ⁹	2D	3/2	—	874794°	3/2	0.003	02CHU
133.390	749.681	7	4d ⁹	2D	5/2	—	749681°	3/2	0.003	02CHU
134.189	745.218	6	4d ⁹	2D	5/2	—	745212°	3/2	0.003	02CHU
135.729	736.762	10	4d ⁹	2D	3/2	—	753489°	1/2	0.003	02CHU
137.272	728.481	10	4d ⁹	2D	3/2	—	745212°	3/2	0.003	02CHU
138.529	721.871	3	4d ⁹	2D	5/2	—	721870°	5/2	0.003	02CHU
138.816	720.378	7	4d ⁹	2D	3/2	—	737104°	1/2	0.003	02CHU
140.126	713.643	4	4d ⁹	2D	5/2	—	713643°	5/2	0.003	02CHU
141.032	709.059	5	4d ⁹	2D	3/2	—	725785°	1/2	0.003	02CHU
141.094	708.747	9	4d ⁹	2D	5/2	—	708748°	7/2	0.003	02CHU
141.545	706.489	6	4d ⁹	2D	3/2	—	723216°	1/2	0.003	02CHU
142.046	703.997	25	4d ⁹	2D	5/2	—	703997°	7/2	0.003	02CHU
142.502	701.745	3	4d ⁹	2D	5/2	—	701735°	5/2	0.003	02CHU
143.381	697.442	8	4d ⁹	2D	5/2	—	697440°	3/2	0.003	02CHU
143.478	696.971	10m	4d ⁹	2D	5/2	—	696975°	3/2	0.003	02CHU
143.488	696.922	7m	4d ⁹	2D	3/2	—	713643°	5/2	0.003	02CHU
143.954	694.666	2	4d ⁹	2D	3/2	—	711392°	5/2	0.003	02CHU

Table B.7 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10^3 cm^{-1})	Intensity and comment	Classification configuration	Term	J	Configuration	Term	J	Uncertainty of observed wavelength (Å)	Source of line
144.079	694.064	2	$4d^9$	$2D$	$5/2$	$4d^8 5p$	694056^o	$5/2$	0.003	02CHU
144.655	691.300	20	$4d^9$	$2D$	$5/2$	$4d^8 5p$	691306^o	$3/2$	0.003	02CHU
144.771	690.746	7	$4d^9$	$2D$	$5/2$	$4d^8 5p$	690757^o	$5/2$	0.003	02CHU
145.096	689.199	5	$4d^9$	$2D$	$5/2$	$4d^8 4f$	689190^o	$3/2$	0.003	02CHU
145.150	688.942	35	$4d^9$	$2D$	$3/2$	$4d^8 5p$	705669^o	$1/2$	0.003	02CHU
145.325	688.113	25	$4d^9$	$2D$	$5/2$	$4d^8 5p$	688121^o	$3/2$	0.003	02CHU
145.397	687.772	4	$4d^9$	$2D$	$5/2$	$4d^8 4f$	687770^o	$7/2$	0.003	02CHU
145.715	686.271	4	$4d^9$	$2D$	$5/2$	$4d^8 4f$	686273^o	$5/2$	0.003	02CHU
145.798	685.928	3	$4d^9$	$2D$	$3/2$	$4d^8 4f$	702652^o	$1/2$	0.003	02CHU
145.983	685.011	55	$4d^9$	$2D$	$3/2$	$4d^8 5p$	701735^o	$5/2$	0.003	02CHU
146.107	684.430	17	$4d^9$	$2D$	$3/2$	$4d^8 4f$	701155^o	$5/2$	0.003	02CHU
146.148	684.238	8	$4d^9$	$2D$	$5/2$	$4d^8 5p$	684240^o	$7/2$	0.003	02CHU
146.413	682.999	15	$4d^9$	$2D$	$5/2$	$4d^8 5p$	682998^o	$3/2$	0.003	02CHU
146.448	682.836	5	$4d^9$	$2D$	$5/2$	$4d^8 5p$	682838^o	$5/2$	0.003	02CHU
146.532	682.445	4	$4d^9$	$2D$	$5/2$	$4d^8 4f$	682437^o	$3/2$	0.003	02CHU
146.622	682.026	5	$4d^9$	$2D$	$3/2$	$4d^8 4f$	698751^o	$5/2$	0.003	02CHU
147.005	680.249	2	$4d^9$	$2D$	$3/2$	$4d^8 5p$	696975^o	$3/2$	0.003	02CHU
147.381	678.514	8	$4d^9$	$2D$	$3/2$	$4d^8 5p$	695239^o	$1/2$	0.003	02CHU
147.418	678.343	6	$4d^9$	$2D$	$5/2$	$4d^8 4f$	678351^o	$5/2$	0.003	02CHU
147.618	677.424	72	$4d^9$	$2D$	$5/2$	$4d^8 5p$	677421^o	$3/2$	0.003	02CHU
147.640	677.323	34	$4d^9$	$2D$	$3/2$	$4d^8 5p$	694056^o	$5/2$	0.003	02CHU
147.734	676.892	6	$4d^9$	$2D$	$5/2$	$4d^8 4f$	676893^o	$7/2$	0.003	02CHU
147.956	675.877	100	$4d^9$	$2D$	$5/2$	$4d^8 5p$	675878^o	$7/2$	0.003	02CHU
148.238	674.591	10	$4d^9$	$2D$	$3/2$	$4d^8 5p$	691306^o	$3/2$	0.003	02CHU
148.333	674.159	30	$4d^9$	$2D$	$5/2$	$4d^8 5p$	674159^o	$3/2$	0.003	02CHU

Table B.7 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10 ³ cm ⁻¹)	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
148.359	674.041	52	4d ⁹	2D	3/2	—	4d ⁸ 5p	5/2	0.003	02CHU
148.641	672.762	6?	4d ⁹	2D	5/2	—	4d ⁸ 5p	7/2	0.003	02CHU
148.709	672.454	23	4d ⁹	2D	3/2	—	4d ⁸ 4f	3/2	0.003	02CHU
148.942	671.402	44	4d ⁹	2D	3/2	—	4d ⁸ 5p	3/2	0.003	02CHU
149.020	671.051	75	4d ⁹	2D	5/2	—	4d ⁸ 5p	5/2	0.003	02CHU
149.358	669.532	80	4d ⁹	2D	5/2	—	4d ⁸ 5p	7/2	0.003	02CHU
149.583	668.525	42	4d ⁹	2D	5/2	—	4d ⁸ 5p	5/2	0.003	02CHU
149.682	668.083	4	4d ⁹	2D	3/2	—	4d ⁸ 4f	1/2	0.003	02CHU
150.089	666.271	150b	4d ⁹	2D	3/2	—	4d ⁸ 5p	3/2	0.003	02CHU
150.124	666.116	95b	4d ⁹	2D	3/2	—	4d ⁸ 5p	5/2	0.003	02CHU
150.216	665.708	5	4d ⁹	2D	3/2	—	4d ⁸ 4f	3/2	0.003	02CHU
150.444	664.699	9	4d ⁹	2D	3/2	—	4d ⁸ 5p	1/2	0.003	02CHU
150.544	664.258	90	4d ⁹	2D	5/2	—	4d ⁸ 5p	5/2	0.003	02CHU
151.020	662.164	10	4d ⁹	2D	5/2	—	4d ⁸ 5p	3/2	0.003	02CHU
151.141	661.634	9	4d ⁹	2D	3/2	—	4d ⁸ 4f	5/2	0.003	02CHU
151.291	660.978	6	4d ⁹	2D	3/2	—	4d ⁸ 5p	1/2	0.003	02CHU
151.356	660.694	4	4d ⁹	2D	3/2	—	4d ⁸ 5p	3/2	0.003	02CHU
151.747	658.992	80	4d ⁹	2D	5/2	—	4d ⁸ 5p	7/2	0.003	02CHU
151.762	658.926	27	4d ⁹	2D	3/2	—	4d ⁸ 5p	5/2	0.003	02CHU
152.058	657.644	78	4d ⁹	2D	5/2	—	4d ⁸ 5p	5/2	0.003	02CHU
152.832	654.313	6	4d ⁹	2D	3/2	—	4d ⁸ 5p	5/2	0.003	02CHU
152.849	654.240	5	4d ⁹	2D	5/2	—	4d ⁸ 5p	3/2	0.003	02CHU
154.433	647.530	6	4d ⁹	2D	3/2	—	4d ⁸ 5p	5/2	0.003	02CHU
154.588	646.881	8	4d ⁹	2D	5/2	—	4d ⁸ 5p	7/2	0.003	02CHU
154.680	646.496	24	4d ⁹	2D	5/2	—	4d ⁸ 5p	5/2	0.003	02CHU

Table B.7 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10^3 cm^{-1})	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
154.935	645.432	15	4d ⁹	² D	3/2	—	662160°	3/2	0.003	02CHU
155.248	644.131	4	4d ⁹	² D	5/2	—	644130°	3/2	0.003	02CHU
156.300	639.795	3	4d ⁹	² D	3/2	—	656520°	1/2	0.003	02CHU
156.857	637.523	5	4d ⁹	² D	3/2	—	654245°	3/2	0.003	02CHU
158.924	629.232	7	4d ⁹	² D	5/2	—	629234°	3/2	0.003	02CHU
158.972	629.042	3	4d ⁹	² D	5/2	—	629040°	7/2	0.003	02CHU
159.388	627.400	10m	4d ⁹	² D	3/2	—	644130°	3/2	0.003	02CHU
163.262	612.512	3	4d ⁹	² D	3/2	—	629234°	3/2	0.003	02CHU

Table B.8 Energy levels of Xe XI.

Energy level (cm ⁻¹)	Parity	Configuration	Term	J	Source of level
0.	0	4p ⁶ 4d ⁸	3F	4	03CHU _b
13140.	0	4p ⁶ 4d ⁸	3F	2	03CHU _b
15205.	0	4p ⁶ 4d ⁸	3F	3	03CHU _b
26670.	0	4p ⁶ 4d ⁸	3P	2	03CHU _b
32210.	0	4p ⁶ 4d ⁸	3P	0	03CHU _b
34610.	0	4p ⁶ 4d ⁸	3P	1	03CHU _b
40835.	0	4p ⁶ 4d ⁸	1G	4	03CHU _b
42900.	0	4p ⁶ 4d ⁸	1D	2	03CHU _b
88130.	0	4p ⁶ 4d ⁸	1S	0	03CHU _b
679572 ?	1	4p ⁵ 4d ⁹	679572 ^o	3	03CHU _b
681023 ?	1	4p ⁵ 4d ⁹	681023 ^o	2	03CHU _b
687020 ?	1	4p ⁵ 4d ⁹	687020 ^o	4	03CHU _b
717330 ?	1	4p ⁵ 4d ⁹	717330 ^o	3	03CHU _b
944705	1	4p ⁵ 4d ⁹	944705 ^o	2	03CHU _b
951795	1	4p ⁵ 4d ⁹	951795 ^o	2	03CHU _b
957488	1	4p ⁵ 4d ⁹	957488 ^o	3	03CHU _b
695376 ?	1	4p ⁶ 4d ⁷ 5p	695376 ^o	4	03CHU _b
709285 ?	1	4p ⁶ 4d ⁷ 5p	709285 ^o	3	03CHU _b
712223	1	4p ⁶ 4d ⁷ 5p	712223 ^o	4	03CHU _b
714855	1	4p ⁶ 4d ⁷ 5p	714855 ^o	3	03CHU _b
715730	1	4p ⁶ 4d ⁷ 5p	715730 ^o	2	03CHU _b
721001 ?	1	4p ⁶ 4d ⁷ 5p	721001 ^o	2	03CHU _b
722439	1	4p ⁶ 4d ⁷ 5p	722439 ^o	5	03CHU _b
725053	1	4p ⁶ 4d ⁷ 5p	725053 ^o	4	03CHU _b
725825	1	4p ⁶ 4d ⁷ 5p	725825 ^o	3	03CHU _b
730345	1	4p ⁶ 4d ⁷ 5p	730345 ^o	5	03CHU _b

Table B.8 (Continued).

Energy level (cm^{-1})	Parity	Configuration	Term	J	Source of level
731458	1	$4p^6 4d^7 5p$	731458^o	4	03CHU _b
733755	1	$4p^6 4d^7 5p$	733755^o	3	03CHU _b
737388	1	$4p^6 4d^7 5p$	737388^o	4	03CHU _b
738248	1	$4p^6 4d^7 5p$	738248^o	5	03CHU _b
739322	1	$4p^6 4d^7 5p$	739322^o	3	03CHU _b
739542	1	$4p^6 4d^7 5p$	739542^o	4	03CHU _b
740348	1	$4p^6 4d^7 5p$	740348^o	5	03CHU _b
740757	1	$4p^6 4d^7 5p$	740757^o	2	03CHU _b
741800	1	$4p^6 4d^7 5p$	741800^o	3	03CHU _b
742594	1	$4p^6 4d^7 5p$	742594^o	1	03CHU _b
744537	1	$4p^6 4d^7 5p$	744537^o	4	03CHU _b
744955	1	$4p^6 4d^7 5p$	744955^o	3	03CHU _b
745470	1	$4p^6 4d^7 5p$	745470^o	1	03CHU _b
746445	1	$4p^6 4d^7 5p$	746445^o	3	03CHU _b
746552	1	$4p^6 4d^7 5p$	746552^o	2	03CHU _b
749351	1	$4p^6 4d^7 5p$	749351^o	3	03CHU _b
750512	1	$4p^6 4d^7 5p$	750512^o	2	03CHU _b
752054	1	$4p^6 4d^7 5p$	752054^o	3	03CHU _b
752155	1	$4p^6 4d^7 5p$	752155^o	1	03CHU _b
752285	1	$4p^6 4d^7 5p$	752285^o	4	03CHU _b
753352	1	$4p^6 4d^7 5p$	753352^o	5	03CHU _b
753795	1	$4p^6 4d^7 5p$	753795^o	2	03CHU _b
754745	1	$4p^6 4d^7 5p$	754745^o	1	03CHU _b
754860	1	$4p^6 4d^7 5p$	754860^o	3	03CHU _b
755831	1	$4p^6 4d^7 5p$	755831^o	4	03CHU _b
756016	1	$4p^6 4d^7 5p$	756016^o	4	03CHU _b
756170	1	$4p^6 4d^7 5p$	756170^o	2	03CHU _b

Table B.8 (Continued).

Energy level (cm ⁻¹)	Parity	Configuration	Term	<i>J</i>	Source of level
758337	1	4p ⁶ 4d ⁷ 5p	758337 ^o	1	03CHU _b
759110	1	4p ⁶ 4d ⁷ 5p	759110 ^o	3	03CHU _b
759260	1	4p ⁶ 4d ⁷ 5p	759260 ^o	5	03CHU _b
760950	1	4p ⁶ 4d ⁷ 5p	760950 ^o	1	03CHU _b
761266	1	4p ⁶ 4d ⁷ 5p	761266 ^o	3	03CHU _b
762105	1	4p ⁶ 4d ⁷ 5p	762105 ^o	2	03CHU _b
763070	1	4p ⁶ 4d ⁷ 5p	763070 ^o	4	03CHU _b
765052	1	4p ⁶ 4d ⁷ 5p	765052 ^o	2	03CHU _b
765770	1	4p ⁶ 4d ⁷ 5p	765770 ^o	1	03CHU _b
766625	1	4p ⁶ 4d ⁷ 5p	766625 ^o	2	03CHU _b
766860	1	4p ⁶ 4d ⁷ 5p	766860 ^o	3	03CHU _b
766947	1	4p ⁶ 4d ⁷ 5p	766947 ^o	5	03CHU _b
767369	1	4p ⁶ 4d ⁷ 5p	767369 ^o	1	03CHU _b
767700	1	4p ⁶ 4d ⁷ 5p	767700 ^o	5	03CHU _b
768773	1	4p ⁶ 4d ⁷ 5p	768773 ^o	3	03CHU _b
773315	1	4p ⁶ 4d ⁷ 5p	773315 ^o	2	03CHU _b
773715	1	4p ⁶ 4d ⁷ 5p	773715 ^o	3	03CHU _b
773968	1	4p ⁶ 4d ⁷ 5p	773968 ^o	4	03CHU _b
773968	1	4p ⁶ 4d ⁷ 5p	773968 ^o	5	03CHU _b
775030	1	4p ⁶ 4d ⁷ 5p	775030 ^o	1	03CHU _b
775570	1	4p ⁶ 4d ⁷ 5p	775570 ^o	3	03CHU _b
775775	1	4p ⁶ 4d ⁷ 5p	775775 ^o	4	03CHU _b
778350	1	4p ⁶ 4d ⁷ 5p	778350 ^o	1	03CHU _b
780503	1	4p ⁶ 4d ⁷ 5p	780503 ^o	3	03CHU _b
781822	1	4p ⁶ 4d ⁷ 5p	781822 ^o	2	03CHU _b
784035	1	4p ⁶ 4d ⁷ 5p	784035 ^o	1	03CHU _b
786580	1	4p ⁶ 4d ⁷ 5p	786580 ^o	2	03CHU _b

Table B.8 (Continued).

Energy level (cm^{-1})	Parity	Configuration	Term	J	Source of level
788145	1	$4p^6 4d^7 5p$	788145^o	2	03CHU _b
788396	1	$4p^6 4d^7 5p$	788396^o	1	03CHU _b
788465	1	$4p^6 4d^7 5p$	788465^o	3	03CHU _b
789029	1	$4p^6 4d^7 5p$	789029^o	5	03CHU _b
791805	1	$4p^6 4d^7 5p$	791805^o	1	03CHU _b
792311	1	$4p^6 4d^7 5p$	792311^o	0	03CHU _b
795135	1	$4p^6 4d^7 5p$	795135^o	3	03CHU _b
795995	1	$4p^6 4d^7 5p$	795995^o	2	03CHU _b
801225	1	$4p^6 4d^7 5p$	801225^o	3	03CHU _b
802905	1	$4p^6 4d^7 5p$	802905^o	2	03CHU _b
808130	1	$4p^6 4d^7 5p$	808130^o	1	03CHU _b
824474	1	$4p^6 4d^7 5p$	824474^o	3	03CHU _b
828875	1	$4p^6 4d^7 5p$	828875^o	2	03CHU _b
830260	1	$4p^6 4d^7 5p$	830260^o	1	03CHU _b
838289	1	$4p^6 4d^7 5p$	838289^o	3	03CHU _b
730235 ?	1	$4p^6 4d^7 4f$	730235^o	4	03CHU _b
735246	1	$4p^6 4d^7 4f$	735246^o	4	03CHU _b
736077 ?	1	$4p^6 4d^7 4f$	736077^o	5	03CHU _b
742430	1	$4p^6 4d^7 4f$	742430^o	5	03CHU _b
745762	1	$4p^6 4d^7 4f$	745762^o	3	03CHU _b
748644 ?	1	$4p^6 4d^7 4f$	748644^o	1	03CHU _b
769217	1	$4p^6 4d^7 4f$	769217^o	2	03CHU _b
772875	1	$4p^6 4d^7 4f$	772875^o	4	03CHU _b
773363	1	$4p^6 4d^7 4f$	773363^o	4	03CHU _b
773519	1	$4p^6 4d^7 4f$	773519^o	5	03CHU _b
776253	1	$4p^6 4d^7 4f$	776253^o	3	03CHU _b

Table B.8 (Continued).

Energy level (cm ⁻¹)	Parity	Configuration	Term	<i>J</i>	Source of level
776787	1	4p ⁶ 4d ⁷ 4f	776787 ^o	4	03CHU _b
780805	1	4p ⁶ 4d ⁷ 4f	780805 ^o	2	03CHU _b
784826	1	4p ⁶ 4d ⁷ 4f	784826 ^o	3	03CHU _b
787403	1	4p ⁶ 4d ⁷ 4f	787403 ^o	1	03CHU _b
791395	1	4p ⁶ 4d ⁷ 4f	791395 ^o	3	03CHU _b
794365	1	4p ⁶ 4d ⁷ 4f	794365 ^o	2	03CHU _b
892420	1	4p ⁶ 4d ⁷ 4f	892420 ^o	4	03CHU _b
894941	1	4p ⁶ 4d ⁷ 4f	894941 ^o	3	03CHU _b
897383	1	4p ⁶ 4d ⁷ 4f	897383 ^o	5	03CHU _b
902577	1	4p ⁶ 4d ⁷ 4f	902577 ^o	1	03CHU _b
907711	1	4p ⁶ 4d ⁷ 4f	907711 ^o	2	03CHU _b
911082	1	4p ⁶ 4d ⁷ 4f	911082 ^o	4	03CHU _b
911665	1	4p ⁶ 4d ⁷ 4f	911665 ^o	2	03CHU _b
912600	1	4p ⁶ 4d ⁷ 4f	912600 ^o	3	03CHU _b
913877	1	4p ⁶ 4d ⁷ 4f	913877 ^o	1	03CHU _b
922295	1	4p ⁶ 4d ⁷ 4f	922295 ^o	3	03CHU _b
924500	1	4p ⁶ 4d ⁷ 4f	924500 ^o	2	03CHU _b
925010	1	4p ⁶ 4d ⁷ 4f	925010 ^o	1	03CHU _b
925626	1	4p ⁶ 4d ⁷ 4f	925626 ^o	4	03CHU _b
931420	1	4p ⁶ 4d ⁷ 4f	931420 ^o	1	03CHU _b
933343	1	4p ⁶ 4d ⁷ 4f	933343 ^o	0	03CHU _b
935035	1	4p ⁶ 4d ⁷ 4f	935035 ^o	3	03CHU _b
938628	1	4p ⁶ 4d ⁷ 4f	938628 ^o	5	03CHU _b
947660	1	4p ⁶ 4d ⁷ 4f	947660 ^o	1	03CHU _b
989020	1	4p ⁶ 4d ⁷ 4f	989020 ^o	1	03CHU _b

Table B.9 Spectral lines of Xe XI.

Observed vacuum wavelength (Å)	Observed wave number (10^3 cm^{-1})	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
105.699	946.08	14	$4p^6 4d^8$	$1D$	2	$4p^6 4d^7 4f$	989020°	1	0.003	03CHU _b
106.125	942.29	52	$4p^6 4d^8$	$3F$	3	$4p^5 4d^9$	957488°	3	0.003	03CHU _b
109.027	917.20	276	$4p^6 4d^8$	$3P$	1	$4p^5 4d^9$	951795°	2	0.003	03CHU _b
109.093	916.65	314	$4p^6 4d^8$	$1G$	4	$4p^5 4d^9$	957488°	3	0.003	03CHU _b
109.339	914.59	217	$4p^6 4d^8$	$1D$	2	$4p^5 4d^9$	957488°	3	0.003	03CHU _b
109.878	910.10	286	$4p^6 4d^8$	$3P$	1	$4p^5 4d^9$	944705°	2	0.003	03CHU _b
110.026	908.88	121	$4p^6 4d^8$	$1D$	2	$4p^5 4d^9$	951795°	2	0.003	03CHU _b
110.531	904.72	263*	$4p^6 4d^8$	$1D$	2	$4p^6 4d^7 4f$	947660°	1	0.003	03CHU _b
110.531	904.72	263*	$4p^6 4d^8$	$3P$	2	$4p^6 4d^7 4f$	931420°	1	0.003	03CHU _b
110.889	901.80	107	$4p^6 4d^8$	$1D$	2	$4p^5 4d^9$	944705°	2	0.003	03CHU _b
110.998	900.92	140	$4p^6 4d^8$	$1S$	0	$4p^6 4d^7 4f$	989020°	1	0.003	03CHU _b
111.174	899.49	176	$4p^6 4d^8$	$3F$	2	$4p^6 4d^7 4f$	912600°	3	0.003	03CHU _b
111.268	898.73	148	$4p^6 4d^8$	$3P$	1	$4p^6 4d^7 4f$	933343°	0	0.003	03CHU _b
111.290	898.55	164	$4p^6 4d^8$	$3F$	2	$4p^6 4d^7 4f$	911665°	2	0.003	03CHU _b
111.384	897.80	635*	$4p^6 4d^8$	$3P$	2	$4p^6 4d^7 4f$	924500°	2	0.003	03CHU _b
111.384	897.80	635*	$4p^6 4d^8$	$1G$	4	$4p^6 4d^7 4f$	938628°	5	0.003	03CHU _b
111.435	897.38	559*	$4p^6 4d^8$	$3F$	3	$4p^6 4d^7 4f$	912600°	3	0.003	03CHU _b
111.435	897.38	559*	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 4f$	897383°	5	0.003	03CHU _b
111.504	896.83	148	$4p^6 4d^8$	$3P$	1	$4p^6 4d^7 4f$	931420°	1	0.003	03CHU _b
111.552	896.44	169	$4p^6 4d^8$	$3F$	3	$4p^6 4d^7 4f$	911665°	2	0.003	03CHU _b
111.622	895.88	577	$4p^6 4d^8$	$3F$	3	$4p^6 4d^7 4f$	911082°	4	0.003	03CHU _b
111.654	895.62	447	$4p^6 4d^8$	$3P$	2	$4p^6 4d^7 4f$	922295°	3	0.003	03CHU _b
111.706	895.21	534	$4p^6 4d^8$	$3F$	2	$4p^6 4d^7 4f$	908390°	3	0.003	03CHU _b
111.739	894.94	467	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 4f$	894941°	3	0.003	03CHU _b
111.785	894.57	387	$4p^6 4d^8$	$3F$	2	$4p^6 4d^7 4f$	907711°	2	0.003	03CHU _b

Table B.9 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10 ³ cm ⁻¹)	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
111.834	894.18	85	4p ⁶ 4d ⁸	¹ G	4	—	935035°	3	0.003	03CHU _b
111.954	893.22	161	4p ⁶ 4d ⁸	³ F	3	—	908390°	3	0.003	03CHU _b
112.006	892.81	192	4p ⁶ 4d ⁸	³ P	0	—	925010°	1	0.003	03CHU _b
112.045	892.50	200m	4p ⁶ 4d ⁸	³ F	3	—	907711°	2	0.003	03CHU _b
112.055	892.42	626	4p ⁶ 4d ⁸	³ F	4	—	892420°	4	0.003	03CHU _b
112.089	892.15	388	4p ⁶ 4d ⁸	¹ D	2	—	935035°	3	0.003	03CHU _b
112.373	889.89	56	4p ⁶ 4d ⁸	³ P	1	—	924500°	2	0.003	03CHU _b
112.431	889.43	139	4p ⁶ 4d ⁸	³ F	2	—	902577°	1	0.003	03CHU _b
112.713	887.21	143bl	4p ⁶ 4d ⁸	³ P	2	—	913877°	1	0.003	03CHU _b
112.877	885.92	52	4p ⁶ 4d ⁸	³ P	2	—	912600°	3	0.003	03CHU _b
113.021	884.79	420	4p ⁶ 4d ⁸	¹ G	4	—	925626°	4	0.003	03CHU _b
113.366	882.10	35	4p ⁶ 4d ⁸	¹ D	2	—	925010°	1	0.003	03CHU _b
113.731	879.27	74	4p ⁶ 4d ⁸	³ P	1	—	913877°	1	0.003	03CHU _b
114.020	877.04	131	4p ⁶ 4d ⁸	³ P	1	—	911665°	2	0.003	03CHU _b
114.713	871.74	37	4p ⁶ 4d ⁸	¹ G	4	—	912600°	3	0.003	03CHU _b
116.342	859.53	60	4p ⁶ 4d ⁸	¹ S	0	—	947660°	1	0.003	03CHU _b
119.291	838.29	20	4p ⁶ 4d ⁸	³ F	4	—	838289°	3	0.003	03CHU _b
122.902	813.656	41	4p ⁶ 4d ⁸	³ F	3	—	828875°	2	0.003	03CHU _b
126.360	791.390	11	4p ⁶ 4d ⁸	³ F	4	—	791395°	3	0.003	03CHU _b
127.006	787.364	6	4p ⁶ 4d ⁸	¹ D	2	—	830260°	1	0.003	03CHU _b
127.227	785.997	12	4p ⁶ 4d ⁸	¹ D	2	—	828875°	2	0.003	03CHU _b
127.610	783.638	26	4p ⁶ 4d ⁸	¹ G	4	—	824474°	3	0.003	03CHU _b
127.967	781.451	9	4p ⁶ 4d ⁸	³ P	2	—	808130°	1	0.003	03CHU _b
128.080	780.762	5	4p ⁶ 4d ⁸	³ F	3	—	795995°	2	0.003	03CHU _b
128.219	779.916	17	4p ⁶ 4d ⁸	³ F	3	—	795135°	3	0.003	03CHU _b

Table B.9 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10^3 cm^{-1})	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
128.344	779.156	9	$4p^6 4d^8$	$3F$	3	—	794365°	2	0.003	03CHU _b
128.834	776.193	17	$4p^6 4d^8$	$3F$	3	—	791395°	3	0.003	03CHU _b
129.640	771.367	8	$4p^6 4d^8$	$3F$	3	—	786580°	2	0.003	03CHU _b
129.934	769.622	18	$4p^6 4d^8$	$3F$	3	—	784826°	3	0.003	03CHU _b
129.987	769.308	30	$4p^6 4d^8$	$3P$	2	—	795995°	2	0.003	03CHU _b
130.079	768.764	27	$4p^6 4d^8$	$3F$	4	—	768773°	3	0.003	03CHU _b
130.163	768.267	27	$4p^6 4d^8$	$3P$	1	—	802905°	2	0.003	03CHU _b
130.262	767.684	15	$4p^6 4d^8$	$3F$	4	—	767700°	5	0.003	03CHU _b
130.442	766.624	15	$4p^6 4d^8$	$3F$	3	—	781822°	2	0.003	03CHU _b
130.679	765.234	23	$4p^6 4d^8$	$3F$	2	—	778350°	1	0.003	03CHU _b
131.055	763.038	27	$4p^6 4d^8$	$3F$	4	—	763070°	4	0.003	03CHU _b
131.160	762.428	12	$4p^6 4d^8$	$3F$	2	—	775570°	3	0.003	03CHU _b
131.281	761.725	12	$4p^6 4d^8$	$3P$	2	—	788396°	1	0.003	03CHU _b
131.321	761.493	11	$4p^6 4d^8$	$3P$	2	—	788145°	2	0.003	03CHU _b
131.398	761.047	14	$4p^6 4d^8$	$3F$	3	—	776253°	3	0.003	03CHU _b
131.481	760.566	8	$4p^6 4d^8$	$3F$	3	—	775775°	4	0.003	03CHU _b
131.515	760.370	156	$4p^6 4d^8$	$1G$	4	—	801225°	3	0.003	03CHU _b
131.573	760.034	14	$4p^6 4d^8$	$1D$	2	—	802905°	2	0.003	03CHU _b
131.620	759.763	17	$4p^6 4d^8$	$3P$	1	—	794365°	2	0.003	03CHU _b
131.648	759.601	12	$4p^6 4d^8$	$3P$	0	—	791805°	1	0.003	03CHU _b
131.711	759.238	57	$4p^6 4d^8$	$3F$	4	—	759260°	5	0.003	03CHU _b
131.733	759.111	102	$4p^6 4d^8$	$3F$	4	—	759110°	3	0.003	03CHU _b
131.865	758.351	27	$4p^6 4d^8$	$1D$	2	—	801225°	3	0.003	03CHU _b
131.905	758.121	12	$4p^6 4d^8$	$3F$	3	—	773315°	2	0.003	03CHU _b
131.978	757.702	20	$4p^6 4d^8$	$3P$	1	—	792311°	0	0.003	03CHU _b

Table B.9 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10 ³ cm ⁻¹)	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
132.067	757.191	5	4p ⁶ 4d ⁸	3P	1	—	791805°	1	0.003	03CHU _b
132.305	755.829	84m	4p ⁶ 4d ⁸	3F	4	—	755831°	4	0.003	03CHU _b
132.471	754.882	32	4p ⁶ 4d ⁸	3F	4	—	754860°	3	0.003	03CHU _b
132.573	754.301	170	4p ⁶ 4d ⁸	1G	4	—	795135°	3	0.003	03CHU _b
132.623	754.017	11	4p ⁶ 4d ⁸	3F	3	—	769217°	2	0.003	03CHU _b
132.658	753.818	55	4p ⁶ 4d ⁸	3P	2	—	780503°	3	0.003	03CHU _b
132.701	753.574	53	4p ⁶ 4d ⁸	3F	3	—	768773°	3	0.003	03CHU _b
132.740	753.352	24	4p ⁶ 4d ⁸	3F	4	—	753352°	5	0.003	03CHU _b
132.783	753.108	18	4p ⁶ 4d ⁸	1D	2	—	795995°	2	0.003	03CHU _b
132.839	752.791	14	4p ⁶ 4d ⁸	3P	1	—	787403°	1	0.003	03CHU _b
132.928	752.287	47	4p ⁶ 4d ⁸	3F	4	—	752285°	4	0.003	03CHU _b
132.983	751.976	114	4p ⁶ 4d ⁸	3P	1	—	786580°	2	0.003	03CHU _b
133.042	751.642	8*	4p ⁶ 4d ⁸	3P	2	—	778350°	1	0.003	03CHU _b
133.042	751.642	8*	4p ⁶ 4d ⁸	3F	3	—	766860°	3	0.003	03CHU _b
133.072	751.473	15	4p ⁶ 4d ⁸	1D	2	—	794365°	2	0.003	03CHU _b
133.082	751.416	16m	4p ⁶ 4d ⁸	3F	3	—	766625°	2	0.003	03CHU _b
133.361	749.844	63	4p ⁶ 4d ⁸	3F	3	—	765052°	2	0.003	03CHU _b
133.437	749.417	23	4p ⁶ 4d ⁸	3P	1	—	784035°	1	0.003	03CHU _b
133.513	748.991	23	4p ⁶ 4d ⁸	3F	2	—	762105°	2	0.003	03CHU _b
133.529	748.901	52	4p ⁶ 4d ⁸	1D	2	—	791805°	1	0.003	03CHU _b
133.655	748.195	323	4p ⁶ 4d ⁸	1G	4	—	789029°	5	0.003	03CHU _b
133.710	747.887	15	4p ⁶ 4d ⁸	3F	3	—	763070°	4	0.003	03CHU _b
133.760	747.608	8	4p ⁶ 4d ⁸	1G	4	—	788465°	3	0.003	03CHU _b
133.861	747.044	9	4p ⁶ 4d ⁸	3P	2	—	773715°	3	0.003	03CHU _b
133.891	746.876	14	4p ⁶ 4d ⁸	3F	3	—	762105°	2	0.003	03CHU _b

Table B.9 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10^3 cm^{-1})	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
133.934	746.636	50	$4p^6 4d^8$	$3P$	2	$4p^6 4d^7 5p$	773315°	2	0.003	03CHU _b
133.968	746.447	29	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 5p$	746445°	3	0.003	03CHU _b
134.037	746.063	309	$4p^6 4d^8$	$3F$	3	$4p^6 4d^7 5p$	761266°	3	0.003	03CHU _b
134.091	745.762	156	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 4f$	745762°	3	0.003	03CHU _b
134.124	745.579	84	$4p^6 4d^8$	$1D$	2	$4p^6 4d^7 5p$	788465°	3	0.003	03CHU _b
134.187	745.229	24bl	$4p^6 4d^8$	$1D$	2	$4p^6 4d^7 5p$	788145°	2	0.003	03CHU _b
134.238	744.946	138	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 5p$	744955°	3	0.003	03CHU _b
134.312	744.535	89	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 5p$	744537°	4	0.003	03CHU _b
134.426	743.904	29	$4p^6 4d^8$	$3F$	3	$4p^6 4d^7 5p$	759110°	3	0.003	03CHU _b
134.581	743.047	59	$4p^6 4d^8$	$3F$	2	$4p^6 4d^7 5p$	756170°	2	0.003	03CHU _b
134.626	742.799	8	$4p^6 4d^8$	$3P$	0	$4p^6 4d^7 5p$	775030°	1	0.003	03CHU _b
134.673	742.539	48	$4p^6 4d^8$	$3P$	2	$4p^6 4d^7 4f$	769217°	2	0.003	03CHU _b
134.689	742.451	20	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 4f$	742430°	5	0.003	03CHU _b
134.750	742.115	99	$4p^6 4d^8$	$1S$	0	$4p^6 4d^7 5p$	830260°	1	0.003	03CHU _b
134.844	741.598	89	$4p^6 4d^8$	$3F$	2	$4p^6 4d^7 5p$	754745°	1	0.003	03CHU _b
134.927	741.142	218	$4p^6 4d^8$	$1D$	2	$4p^6 4d^7 5p$	784035°	1	0.003	03CHU _b
134.962	740.949	222	$4p^6 4d^8$	$3F$	3	$4p^6 4d^7 5p$	756170°	2	0.003	03CHU _b
134.987	740.812	392	$4p^6 4d^8$	$3F$	3	$4p^6 4d^7 5p$	756016°	4	0.003	03CHU _b
135.072	740.346	518	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 5p$	740348°	5	0.003	03CHU _b
135.100	740.192	179	$4p^6 4d^8$	$3P$	2	$4p^6 4d^7 5p$	766860°	3	0.003	03CHU _b
135.145	739.946	63	$4p^6 4d^8$	$3P$	2	$4p^6 4d^7 5p$	766625°	2	0.003	03CHU _b
135.202	739.634	53	$4p^6 4d^8$	$3F$	3	$4p^6 4d^7 5p$	754860°	3	0.003	03CHU _b
135.219	739.541	135	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 5p$	739542°	4	0.003	03CHU _b
135.259	739.322	60	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 5p$	739322°	3	0.003	03CHU _b
135.298	739.109	123	$4p^6 4d^8$	$3P$	2	$4p^6 4d^7 5p$	765770°	1	0.003	03CHU _b

Table B.9 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10 ³ cm ⁻¹)	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
135.317	739.005	95	4p ⁶ 4d ⁸	3F	2	—	752155°	1	0.003	03CHU _b
135.334	738.913	165*	4p ⁶ 4d ⁸	1D	2	—	781822°	2	0.003	03CHU _b
135.334	738.913	165*	4p ⁶ 4d ⁸	3F	2	—	752054°	3	0.003	03CHU _b
135.393	738.591	66	4p ⁶ 4d ⁸	3F	3	—	753795°	2	0.003	03CHU _b
135.431	738.383	14	4p ⁶ 4d ⁸	3P	2	—	765052°	2	0.003	03CHU _b
135.456	738.247	11	4p ⁶ 4d ⁸	3F	4	—	738248°	5	0.003	03CHU _b
135.519	737.904	60m	4p ⁶ 4d ⁸	1D	2	—	780805°	2	0.003	03CHU _b
135.571	737.621	80	4p ⁶ 4d ⁸	1D	2	—	780503°	3	0.003	03CHU _b
135.614	737.387	339	4p ⁶ 4d ⁸	3F	4	—	737388°	4	0.003	03CHU _b
135.855	736.079	18?	4p ⁶ 4d ⁸	3F	4	—	736077°	5	0.003	03CHU _b
135.878	735.954	71	4p ⁶ 4d ⁸	1G	4	—	776787°	4	0.003	03CHU _b
135.961	735.505	48?	4p ⁶ 4d ⁸	3F	2	—	748644°	1	0.003	03CHU _b
135.997	735.310	38	4p ⁶ 4d ⁸	3F	3	—	750512°	2	0.003	03CHU _b
136.009	735.245	50	4p ⁶ 4d ⁸	3F	4	—	735246°	4	0.003	03CHU _b
136.025	735.159	33	4p ⁶ 4d ⁸	3P	0	—	767369°	1	0.003	03CHU _b
136.065	734.943	50	4p ⁶ 4d ⁸	1G	4	—	775775°	4	0.003	03CHU _b
136.188	734.279	54	4p ⁶ 4d ⁸	3P	2	—	760950°	1	0.003	03CHU _b
136.213	734.144	336	4p ⁶ 4d ⁸	3F	3	—	749351°	3	0.003	03CHU _b
136.290	733.730	63	4p ⁶ 4d ⁸	3F	4	—	733755°	3	0.003	03CHU _b
136.324	733.547	35	4p ⁶ 4d ⁸	3P	0	—	765770°	1	0.003	03CHU _b
136.348	733.417	122	4p ⁶ 4d ⁸	3F	2	—	746552°	2	0.003	03CHU _b
136.401	733.132	236*	4p ⁶ 4d ⁸	1G	4	—	773968°	4	0.003	03CHU _b
136.401	733.132	236*	4p ⁶ 4d ⁸	1G	4	—	773968°	5	0.003	03CHU _b
136.451	732.864	75	4p ⁶ 4d ⁸	1G	4	—	773715°	3	0.003	03CHU _b
136.484	732.687	23	4p ⁶ 4d ⁸	1G	4	—	773519°	5	0.003	03CHU _b

Table B.9 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10^3 cm^{-1})	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
136.514	732.526	143	$4p^6 4d^8$	$1G$	4	$4p^6 4d^7 4f$	77363°	4	0.003	03CHU _b
136.547	732.349	65	$4p^6 4d^8$	$3F$	2	$4p^6 4d^7 5p$	745470°	1	0.003	03CHU _b
136.584	732.150	48	$4p^6 4d^8$	$1D$	2	$4p^6 4d^7 5p$	775030°	1	0.003	03CHU _b
136.605	732.038	315*	$4p^6 4d^8$	$1G$	4	$4p^6 4d^7 4f$	772875°	4	0.003	03CHU _b
136.605	732.038	315*	$4p^6 4d^8$	$3P$	1	$4p^6 4d^7 5p$	766625°	2	0.003	03CHU _b
136.670	731.689	18	$4p^6 4d^8$	$3P$	2	$4p^6 4d^7 5p$	758337°	1	0.003	03CHU _b
136.713	731.459	127	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 5p$	731458°	4	0.003	03CHU _b
136.735	731.342	21	$4p^6 4d^8$	$3F$	3	$4p^6 4d^7 5p$	746552°	2	0.003	03CHU _b
136.829	730.839	21	$4p^6 4d^8$	$1D$	2	$4p^6 4d^7 5p$	773715°	3	0.003	03CHU _b
136.908	730.418	11	$4p^6 4d^8$	$1D$	2	$4p^6 4d^7 5p$	773315°	2	0.003	03CHU _b
136.922	730.343	29	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 5p$	730345°	5	0.003	03CHU _b
136.942	730.236	15?	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 4f$	730235°	4	0.003	03CHU _b
137.031	729.762	21	$4p^6 4d^8$	$3F$	3	$4p^6 4d^7 5p$	744955°	3	0.003	03CHU _b
137.238	728.661	98	$4p^6 4d^8$	$3F$	2	$4p^6 4d^7 5p$	741800°	3	0.003	03CHU _b
137.438	727.601	15	$4p^6 4d^8$	$3F$	2	$4p^6 4d^7 5p$	740757°	2	0.003	03CHU _b
137.524	727.146	8	$4p^6 4d^8$	$3P$	2	$4p^6 4d^7 5p$	753795°	2	0.003	03CHU _b
137.574	726.882	12	$4p^6 4d^8$	$1G$	4	$4p^6 4d^7 5p$	767700°	5	0.003	03CHU _b
137.677	726.338	65	$4p^6 4d^8$	$3P$	1	$4p^6 4d^7 5p$	760950°	1	0.003	03CHU _b
137.720	726.111	35	$4p^6 4d^8$	$1G$	4	$4p^6 4d^7 5p$	766947°	5	0.003	03CHU _b
137.778	725.805	60	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 5p$	725825°	3	0.003	03CHU _b
137.921	725.053	27	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 5p$	725053°	4	0.003	03CHU _b
138.152	723.840	30	$4p^6 4d^8$	$3P$	2	$4p^6 4d^7 5p$	750512°	2	0.003	03CHU _b
138.178	723.704	16	$4p^6 4d^8$	$3P$	1	$4p^6 4d^7 5p$	758337°	1	0.003	03CHU _b
138.420	722.439	20	$4p^6 4d^8$	$3F$	4	$4p^6 4d^7 5p$	722439°	5	0.003	03CHU _b
138.459	722.235	159	$4p^6 4d^8$	$1G$	4	$4p^6 4d^7 5p$	763070°	4	0.003	03CHU _b

Table B.9 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10 ³ cm ⁻¹)	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
138.765	720.643	29	4p ⁶ 4d ⁸	3F	2	—	4p ⁶ 4d ⁷ 5p	3	0.003	03CHU _b
138.889	719.999	21	4p ⁶ 4d ⁸	1S	0	—	4p ⁶ 4d ⁷ 5p	1	0.003	03CHU _b
138.896	719.963	23	4p ⁶ 4d ⁸	3P	0	—	4p ⁶ 4d ⁷ 5p	1	0.003	03CHU _b
139.050	719.166	59	4p ⁶ 4d ⁸	3P	1	—	4p ⁶ 4d ⁷ 5p	2	0.003	03CHU _b
139.166	718.566	33	4p ⁶ 4d ⁸	3F	3	—	4p ⁶ 4d ⁷ 5p	3	0.003	03CHU _b
139.190	718.442	102	4p ⁶ 4d ⁸	1G	4	—	4p ⁶ 4d ⁷ 5p	5	0.003	03CHU _b
139.689	715.876	21	4p ⁶ 4d ⁸	3P	1	—	4p ⁶ 4d ⁷ 5p	2	0.003	03CHU _b
139.825	715.180	39	4p ⁶ 4d ⁸	1G	4	—	4p ⁶ 4d ⁷ 5p	4	0.003	03CHU _b
139.836	715.123	30	4p ⁶ 4d ⁸	3P	2	—	4p ⁶ 4d ⁷ 5p	3	0.003	03CHU _b
139.893	714.832	15	4p ⁶ 4d ⁸	3F	4	—	4p ⁶ 4d ⁷ 5p	3	0.003	03CHU _b
140.036	714.102	21	4p ⁶ 4d ⁸	3P	2	—	4p ⁶ 4d ⁷ 5p	2	0.003	03CHU _b
140.207	713.231	16	4p ⁶ 4d ⁸	3P	0	—	4p ⁶ 4d ⁷ 5p	1	0.003	03CHU _b
140.314	712.687	10	4p ⁶ 4d ⁸	3F	2	—	4p ⁶ 4d ⁷ 5p	3	0.003	03CHU _b
140.347	712.520	16	4p ⁶ 4d ⁸	1G	4	—	4p ⁶ 4d ⁷ 5p	5	0.003	03CHU _b
140.405	712.225	29	4p ⁶ 4d ⁸	3F	4	—	4p ⁶ 4d ⁷ 5p	4	0.003	03CHU _b
140.478	711.855	5	4p ⁶ 4d ⁸	1D	2	—	4p ⁶ 4d ⁷ 5p	1	0.003	03CHU _b
140.723	710.616	9	4p ⁶ 4d ⁸	3F	3	—	4p ⁶ 4d ⁷ 5p	3	0.003	03CHU _b
140.987	709.285	6?	4p ⁶ 4d ⁸	3F	4	—	4p ⁶ 4d ⁷ 5p	3	0.003	03CHU _b
141.246	707.985	16	4p ⁶ 4d ⁸	3P	1	—	4p ⁶ 4d ⁷ 5p	1	0.003	03CHU _b
141.271	707.859	11?	4p ⁶ 4d ⁸	3F	2	—	4p ⁶ 4d ⁷ 5p	2	0.003	03CHU _b
141.428	707.074	15	4p ⁶ 4d ⁸	3P	2	—	4p ⁶ 4d ⁷ 5p	3	0.003	03CHU _b
142.112	703.670	6	4p ⁶ 4d ⁸	1S	0	—	4p ⁶ 4d ⁷ 5p	1	0.003	03CHU _b
142.328	702.602	5	4p ⁶ 4d ⁸	3F	2	—	4p ⁶ 4d ⁷ 5p	2	0.003	03CHU _b
142.539	701.562	6	4p ⁶ 4d ⁸	1G	4	—	4p ⁶ 4d ⁷ 4f	5	0.003	03CHU _b
142.753	700.511	8	4p ⁶ 4d ⁸	3F	3	—	4p ⁶ 4d ⁷ 5p	2	0.003	03CHU _b

Table B.9 (Continued).

Observed vacuum wavelength (Å)	Observed wave number (10^3 cm^{-1})	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line
142.925	699.668	14	$4p^6 4d^8$	^3F	3	$4p^6 4d^7 5p$	714855°	3	0.003	03CHU _b
143.026	699.174	15	$4p^6 4d^8$	^3P	2	$4p^6 4d^7 5p$	725825°	3	0.003	03CHU _b
143.807	695.376	21?	$4p^6 4d^8$	^3F	4	$4p^6 4d^7 5p$	695376°	4	0.003	03CHU _b
145.556	687.021	8?	$4p^6 4d^8$	^3F	4	$4p^5 4d^9$	687020°	4	0.003	03CHU _b
147.149	679.583	11?	$4p^6 4d^8$	^3F	4	$4p^5 4d^9$	679572°	3	0.003	03CHU _b
147.821	676.494	8?	$4p^6 4d^8$	^1G	4	$4p^5 4d^9$	717330°	3	0.003	03CHU _b
149.727	667.882	18?	$4p^6 4d^8$	^3F	2	$4p^5 4d^9$	681023°	2	0.003	03CHU _b
156.562	638.725	8?	$4p^6 4d^8$	^1G	4	$4p^5 4d^9$	679572°	3	0.003	03CHU _b

Table B.10 Energy levels of Xe XIX.

Energy level (cm ⁻¹)	Parity	Configuration	Term	<i>J</i>	Source of level
0.	0	4p ⁶	1S	0	91SUG
759088	1	4p ⁵ 4d	3D ^o	1	91SUG
922237	1	4p ⁵ 4d	1p ^o	1	91SUG

Table B.11 Spectral lines of Xe XIX.

Observed vacuum wavelength (Å)	Observed wave number (10 ³ cm ⁻¹)	Intensity and comment	Classification configuration	Term	<i>J</i>	Configuration	Term	<i>J</i>	Uncertainty of observed wavelength (Å)	Source of line	
108.409	922.43	10p	4p ⁶	1 S	0	-	4p ⁵ 4d	1 p ^o	1	0.005	91SUG
131.740	759.07	1	4p ⁶	1 S	0	-	4p ⁵ 4d	3 D ^o	1	0.005	91SUG



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Chapter 4

Atomic Tin Data

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4.1 Introduction

A spectrum of Sn in the region around 135 Å arises from transitions in Sn ions with the 4d electrons in the ground configuration. Because of the very complex structure of these transitions, the spectrum is largely unknown. Only four lines were identified in Sn XIV, where the ground configuration is $4p^64d$. We made calculations of the energy levels and transition probabilities in the Sn VI–XV spectra using the Flexible Atomic Code (FAC). Some results of similar calculations made with the aid of the Cowan code also can be found in Chapter 5. The spectrum of Sn excited in a low-inductance vacuum spark was recorded on a high-resolution grazing-incidence spectrograph in the region 100–200 Å and compared with the results of

the calculations. Due to the large uncertainty of the calculations, the straightforward identification of the experimental spectrum is impossible; but some general features can be traced.

4.2 Theoretical Approach

The FAC authored by Ming Feng Gu has been chosen for the calculations of energy levels and transition probabilities of Sn ions. The FAC is a publicly available¹ complete software package for the computation of various atomic data. The choice was caused by the following advantages of the FAC:

- It combines the strengths of existing atomic codes [CIV3, SUPERSTRUCTURE, multiconfiguration Hartree-Fock (MCHF) and multiconfiguration Dirac-Fock (MCDF) codes, and the HULLAC package] with modifications to numerical procedures made to extend the capability and improve the efficiency and robustness.
- It has a uniform, flexible, and easy-to-use user interface for accessing all computational tasks and performing bulk-scale calculations.
- A fully relativistic approach based on the Dirac equation is used throughout the entire package, which allows its application to ions with large nuclear charge.

The bound states of the atomic system are calculated in the configuration-mixing approximation with convenient specification of mixing schemes; the radial orbitals for the construction of the basis states are derived from a modified self-consistent Dirac-Fock-Slater iteration on a fictitious mean configuration with fractional occupation numbers, representing the average electron cloud of the configurations included in the calculation.

The mean configuration in the construction of the potential is used in order to take into account the screening of more than one configuration involved in the physical processes to be calculated. This mean configuration is usually obtained by distributing the active electrons in the initial and final states. Therefore, the potential obtained is not optimized to a single configuration; rather, it is a compromise to accommodate different configurations. To reduce the error of level energies due to the use of this less than optimized potential, a special correction procedure is applied. Before the potential for the mean configuration is calculated, an optimized potential for each configuration is obtained, and the average energy of the configuration using this potential is calculated. The average energy of each configuration is then recalculated using the potential optimized for the mean configuration. The difference of the two average energies is then applied as a correction to the states within that configuration after the Hamiltonian is diagonalized.

The radiative transition rates are calculated in the single-multipole approximation. This means that the interference between different multipoles is not taken into account, although rates corresponding to arbitrary multipoles can be calculated.

4.3 Results of the Calculations

Sn ions, mostly emitting in the region around 135 Å, have a ground-state configuration $4p^6 4d^M$ with $M = 0, \dots, 9$ respectively for Sn XV, ..., Sn VI. The most important excited configurations decaying to the levels of the ground configuration are $4p^6 4d^{M-1} 4f$, $4p^6 4d^{M-1} 5p$, $4p^5 4d^{M+1}$, and $4p^5 4d^M 5s$. Calculations of the odd-level systems were made in a configuration-interaction approach in which several highly excited configurations responsible for large correlation effects were added: $4p^6 4d^{M-1} nf$ ($n = 5, 6$), $4p^3 4d^{M+3}$, $4p^5 4d^{M-1} 5p^2$, and $4p^5 4d^{M-1} 5f^2$.

Tables with the results of the calculations are presented in the appendix. These tables contain the ionization potentials in electron volts, the designations, energies, and $2J$ values of the lower and upper levels of transitions, and the wavelengths (λ , Å) and probabilities (A , s^{-1}) of transitions. Only the transitions with A values higher than $A_{\max}/10$ are given for the complex configurations, because the full tables take too much space in these cases. The transitions in the tables are sorted according to the energy of the upper level in each ion. Figure 4.1 shows these data in convenient visual form. It should be noted that each ion starting from Sn VII has a clearly seen array of intense lines, whose maximum shifts to shorter wavelengths with increasing ionization stage.

4.4 Registration of Sn Plasma Spectra

Spectra of Sn ions in the extreme vacuum UV region were taken with high resolution on a 3-m grazing-incidence spectrograph. This spectrograph is equipped with a holographic grating of 3600 lines/mm; the angle of incidence of radiation on the grating is 85 deg. The plate factor of the spectrograph varies from 0.26 to 0.46 Å/mm over the 100- to 350-Å region, respectively. The apparatus linewidth is about 0.04 mm around 135 Å, which corresponds to a resolving power about 10^4 in this region. This resolution is comparable to the physical resolution in the spectra in this region, limited by line broadening in the plasma sources. Spectra were taken on thin glass photographic plates (Kodak SWR or Ilford Q).

A three-electrode triggered vacuum spark in low-inductance coaxial configuration is used for the excitation of the spectra. The main discharge circuit has a capacitance $C = 150$ to $12 \mu\text{F}$ charged to a voltage of 1 to 10 kV, respectively. The minimal inductance is about $L = 80 \text{ nH}$. Auxiliary inductance up to several microhenries is introduced (together with a change in the voltage) to lower the temperature of the plasma so as to study the behavior of line intensities in response to a change in temperature, thus giving an idea of which stage of ionization can belong to a particular line. Tin is placed in an aluminum cylindrical anode 4 mm in diameter. The distance between anode and cathode is $\approx 3\text{--}4 \text{ mm}$. Triggering is performed by a high-voltage (about 15 kV) low-power discharge between cathode and triggering electrode in a sliding spark configuration.

For the measurements of photographic plates containing thousands of spectral lines, two instruments are used: an automatic comparator developed at the Institute

of Spectroscopy (Troitsk), and a commercially available UMAX PowerLook 3000 scanner. For wavelength calibration the lines Al V, Al VI, O V, and O VI, present in the spectra as impurities in some excitation conditions, are used. The standard

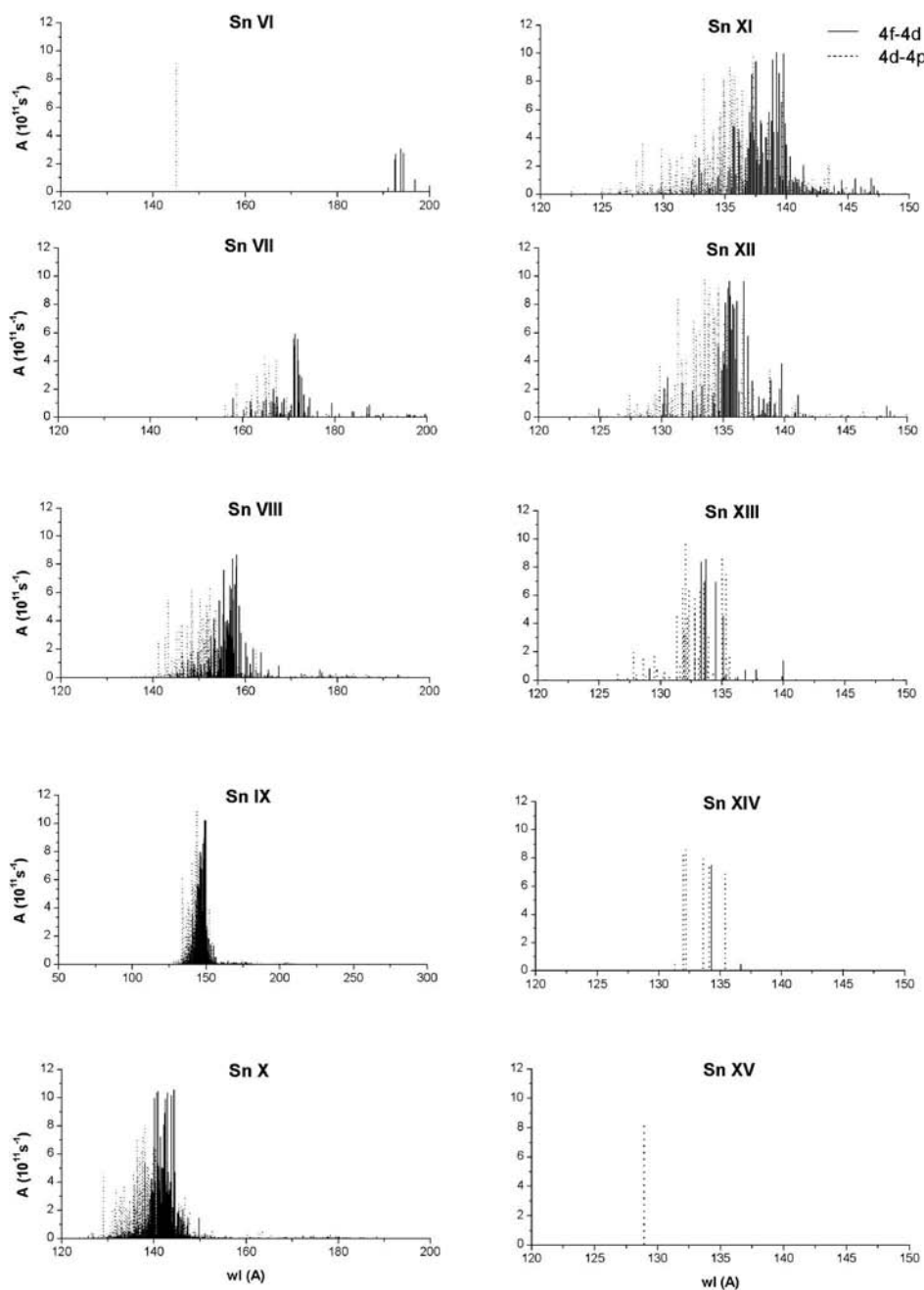


Figure 4.1 Theoretical plots of transition probabilities for Sn VI–XV, calculated with the FAC.¹

error of the derived wavelengths is estimated as $0.005 \text{ \AA}$. Relative intensities of the lines are evaluated without taking account of the spectral response of the spectrograph and photoplates. It should be noted that the spectral efficiency does not change substantially in the $130\text{--}140\text{-\AA}$ region. The intensity 1000 was assigned to the strongest line in the spectrum.

4.5 Primary Classification on Charge States

The Sn spectrum in the region $120\text{--}175 \text{ \AA}$ excited in a high-current mode of vacuum spark operation is presented in Fig. 4.2. This spectrum was excited using a $12\text{-}\mu\text{F}$ capacitance bank charged to a 4-kV voltage. The full inductance of the discharge circuit was $0.2 \text{ }\mu\text{H}$, which corresponds to a peak discharge current of about 30 kA . For comparison, Fig. 4.3 gives the calculated spectrum in the same wavelength region. The calculated spectrum is obtained by a superposition of the wavelengths and the corresponding A values. The vacuum spark spectrum of Sn consists of about 500 lines in the region $110\text{--}175 \text{ \AA}$, belonging to the transitions mainly in the Sn VII–XIV spectra. General features of the experimental spectrum can be easily identified by this comparison. Lines in the region $\approx 161\text{--}173 \text{ \AA}$ represent mainly the transition arrays of the Sn VII spectrum; $\approx 150\text{--}160 \text{ \AA}$, the Sn VIII; and $\approx 144\text{--}148 \text{ \AA}$, the Sn IX. The most intense lines around $142 \text{ \AA}$ belong to the Sn X spectrum, and around $138 \text{ \AA}$ to the Sn XI spectrum.

About 50 lines lying on the quasi-continuum background consisting of a large amount of partly or fully overlapped weaker lines are located in the region $135 \text{ \AA} \pm 1\%$. They are listed in Table 4.1. Table 4.1 also contains three known lines² of Sn XIV lying outside of the $135\text{-}\text{\AA} \pm 1\%$ region, showing that our wavelengths are in agreement with previous measurements.

The Sn spectrum on an expanded scale for the region $130\text{--}140 \text{ \AA}$ in the comparison with calculated spectra of Sn ions is shown in Fig. 4.4. The most intense lines

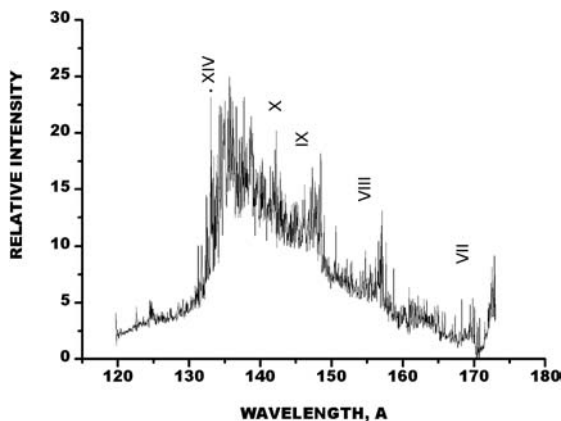


Figure 4.2 Sn spectrum excited in a vacuum spark. Marked are known lines² of Sn XIV and the transition arrays of Sn VII–X, which can be traced from a comparison with the calculated spectrum of Fig. 4.3.

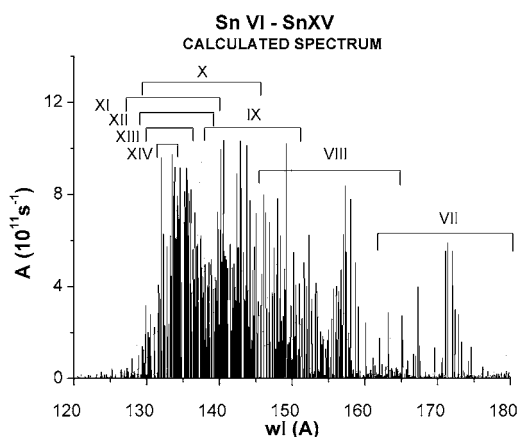


Figure 4.3 Calculated spectrum (transition probability distribution) of Sn VI–XV in the region 120–175 Å.

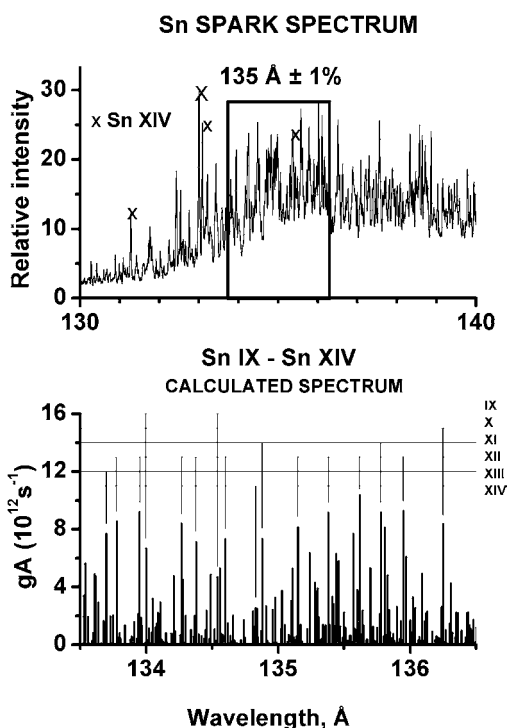


Figure 4.4 Comparison of calculated and spark spectra of Sn in the region 130–140 Å.

in this region belong to the overlapping spectra of Sn XI–XIV. Less intense lines of Sn X and Sn IX contribute to a background. The calculations show that the background can also have lines of transitions from more highly excited configurations, depending on the plasma conditions.

Table 4.1 Measured spectrum of Sn vacuum spark in the region of 135 Å.

I	λ (Å)	ν (cm^{-1})	Previous measurements ²
385	131.357	761285	131.361 Sn XIV
999	133.014	751800	133.020 Sn XIV
793	133.099	751321	133.105 Sn XIV
278	133.671	748101	
218	133.754	747639	
443	133.793	747418	
316	133.828	747222	
573	133.926	746678	
179	133.975	746403	
196	133.990	746321	
130	134.014	746187	
356	134.151	745424	
552	134.209	745102	
617	134.230	744989	
266	134.301	744595	
215	134.360	744266	
350	134.392	744088	
664	134.451	743760	
480	134.491	743541	
128	134.547	743230	
338	134.644	742698	
502	134.673	742538	
503	134.717	742292	
468	134.743	742149	
553	134.787	741911	
503	134.855	741536	
494	134.896	741308	
582	134.939	741070	
348	135.012	740669	
190	135.082	740289	
154	135.139	739974	
302	135.178	739764	
397	135.257	739330	
568	135.315	739015	135.315 Sn XIV
440	135.331	738924	
371	135.382	738646	
230	135.410	738494	
315	135.437	738349	
674	135.517	737910	
469	135.556	737697	
335	135.665	737107	
577	135.720	736810	
377	135.756	736615	
205	135.787	736443	
386	135.838	736168	
343	135.912	735767	
683	135.955	735532	
614	136.042	735062	
403	136.104	734727	
245	136.157	734442	
328	136.205	734184	
188	136.248	733953	
85	136.298	733682	

Table 4.2 Comparison of calculated and experimental wavelengths of Sn XIV.

Transition	$\lambda_{\text{Obs.}} (\text{\AA})^2$	$\lambda_{\text{Calc.}} (\text{\AA})$	Obs.–Calc. ($\text{\AA}$)
$4p^6 4d^2 D_{5/2} - 4p^6 4d^2 ({}^3F)^2 D_{5/2}$	133.105	133.6	–0.5
$4p^6 4d^2 D_{3/2} - 4p^6 4d^2 ({}^3F)^2 D_{3/2}$	131.361	131.7	–0.3
$4p^6 4d^2 D_{3/2} - 4p^6 4d^2 ({}^1G)^2 D_{5/2}$	135.315	134.3	1.0
$4p^6 4d^2 D_{5/2} - 4p^6 4d^2 ({}^1G)^2 D_{7/2}$	133.020	132.0	1.0

The accuracy of the wavelength calculations for transitions around 135 Å can be checked only by using the Sn XIV spectrum, where four lines were experimentally identified in a Tokamak plasma² (see Table 4.2). Even for this relatively simple ion with the ground configuration $4p^6 4d$, the difference between experiment and calculations is up to $\pm 0.7\%$. Moreover, the accuracy of the calculations is expected to be much worse for the more complex configurations. This shows the necessity of experimental spectrum identification and corresponding correction of theoretical calculations on that basis for the reliable modeling of plasma emissivity in the region $135 \text{ \AA} \pm 1\%$. Particularly, an extrapolation of energy parameters of the configurations is needed. It can be made using the spectroscopic data in the isoelectronic and isonuclear sequences.

4.6 Conclusion

Calculations of the energy levels, wavelengths, and transition probabilities for the Sn VI–XV spectra have been made with the FAC. First, spectra of Sn excited in a vacuum spark were recorded on a high-resolution grazing-incidence spectrograph in the region 100–175 Å. A comparison of the experimental spectra with the distributions of theoretical transition probabilities permits primary classification of charge states in the experimental spectrum. The structure of the Sn spectrum in the region $135 \text{ \AA} \pm 1\%$ is very complex, being a mixture of the Sn XI–XIV lines. The accuracy of the theoretical predictions in this region, checked on known lines of Sn XIV, is not enough for reliable line identifications. Empirical correction of the *ab initio* calculations is needed. Further experiments will be necessary, taking spectra with other spark conditions, to distinguish lines belonging to different stages of ionization. The identification of less overlapping Sn VII–X spectra should be made, which will give valuable information on the scaling of the theoretical calculations for the Sn XI–XIV spectra for improving their predictions.

Acknowledgments

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Appendix: Results of Theoretical Calculations of Sn Ion Spectra

Sn vi

Table A.1 Ionization potential 92.585 eV.

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d9	0	5	4d8 5p	308296	5	324.400	5.77E+09
4d9	0	5	4d8 5p	314107	5	318.400	9.03E+09
4d9	0	5	4d8 5p	316625	7	315.870	9.33E+09
4d9	0	5	4d8 5p	319254	3	313.270	7.61E+09
4d9	9200	3	4d8 5p	320996	3	320.760	8.06E+09
4d9	0	5	4d8 5p	322994	3	309.640	6.26E+09
4d9	0	5	4d8 5p	327659	3	305.230	1.12E+10
4d9	9200	3	4d8 5p	327659	3	314.050	1.32E+10
4d9	9200	3	4d8 5p	331536	5	310.270	1.02E+10
4d9	9200	3	4d8 5p	336515	1	305.550	2.31E+10
4d9	0	5	4d8 4f	470037	3	212.770	1.16E+10
4d9	0	5	4d8 4f	475983	3	210.120	1.73E+10
4d9	0	5	4d8 4f	482029	3	207.480	3.80E+10
4d9	9200	3	4d8 4f	490137	1	207.950	1.54E+11
4d9	0	5	4d8 4f	508278	7	196.770	8.76E+10
4d9	9200	3	4d8 4f	509283	5	199.990	4.62E+10
4d9	0	5	4d8 4f	516202	5	193.750	3.06E+11
4d9	0	5	4d8 4f	519662	7	192.460	2.32E+11
4d9	0	5	4d8 4f	523529	3	191.030	3.07E+10
4d9	9200	3	4d8 4f	523529	3	194.450	2.78E+11
4d9	9200	3	4d8 4f	528398	5	192.630	2.71E+11
4d9	9200	3	4p5 4d10	698949	1	145.000	9.11E+11
4d9	0	5	4p5 4d9 5s	767740	7	130.270	4.19E+10
4d9	0	5	4p5 4d9 5s	777088	3	128.700	1.02E+10
4d9	9200	3	4p5 4d9 5s	777088	3	130.240	1.25E+10
4d9	0	5	4p5 4d9 5s	777101	5	128.700	1.82E+10
4d9	0	5	4p5 4d9 5s	787292	7	127.030	2.09E+10
4d9	9200	3	4p5 4d9 5s	788947	5	128.260	2.96E+10
4d9	9200	3	4p5 4d9 5s	807160	5	125.330	2.01E+10
4d9	0	5	4p5 4d9 5s	812538	3	123.090	1.97E+10
4d9	9200	3	4p5 4d9 5s	812538	3	124.500	1.78E+10
4d9	9200	3	4p5 4d9 5s	817619	1	123.710	4.90E+10
4d9	0	5	4p5 4d9 5s	827791	5	120.820	4.31E+10
4d9	0	5	4p5 4d9 5s	836240	3	119.600	1.45E+10
4d9	9200	3	4p5 4d9 5s	843534	3	119.870	2.83E+10
4d9	9200	3	4p5 4d9 5s	845407	5	119.600	2.24E+10
4d9	0	5	4p5 4d9 5s	864822	5	115.640	1.41E+10
4d9	0	5	4p5 4d9 5s	869976	3	114.960	2.97E+10
4d9	0	5	4p5 4d9 5s	904504	7	110.570	2.31E+10
4d9	9200	3	4p5 4d9 5s	905603	5	111.570	1.22E+10
4d9	9200	3	4p5 4d9 5s	907557	1	111.330	2.46E+10
4d9	9200	3	4p5 4d9 5s	908761	3	111.180	1.05E+10

Sn VII

Table A.2 Ionization potential 113.075 eV.

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d8	8127	6	4d7 4f	542757	6	187.070	7.39E+10
4d8	29469	4	4d7 4f	562682	2	187.560	8.76E+10
4d8	0	8	4d7 4f	584634	10	171.070	5.55E+11
4d8	0	8	4d7 4f	591845	8	168.980	1.32E+11
4d8	8127	6	4d7 4f	591845	8	171.340	4.35E+11
4d8	10261	4	4d7 4f	594302	6	171.240	5.06E+11
4d8	0	8	4p5 4d9	597970	8	167.250	4.00E+11
4d8	8127	6	4p5 4d9	597970	8	169.560	1.38E+11
4d8	0	8	4d7 4f	600479	6	166.550	1.07E+11
4d8	19499	4	4d7 4f	600479	6	172.140	4.04E+11
4d8	10261	4	4d7 4f	603560	2	168.570	1.06E+11
4d8	19499	4	4d7 4f	603560	2	171.240	1.52E+11
4d8	26544	0	4d7 4f	603560	2	173.330	1.61E+11
4d8	29469	4	4d7 4f	603560	2	174.210	7.68E+10
4d8	8127	6	4d7 4f	605291	4	167.480	1.45E+11
4d8	19499	4	4d7 4f	605291	4	170.730	8.97E+10
4d8	26760	2	4d7 4f	605291	4	172.870	2.80E+11
4d8	10261	4	4d7 4f	606851	2	167.640	7.88E+10
4d8	26544	0	4d7 4f	606851	2	172.340	1.07E+11
4d8	26760	2	4d7 4f	606851	2	172.410	3.01E+11
4d8	0	8	4d7 4f	607928	6	164.510	1.16E+11
4d8	8127	6	4d7 4f	607928	6	166.740	2.01E+11
4d8	29469	4	4d7 4f	607928	6	172.890	1.22E+11
4d8	31575	8	4d7 4f	612947	8	172.030	5.54E+11
4d8	10261	4	4p5 4d9	613401	4	165.820	3.62E+11
4d8	26760	2	4p5 4d9	613401	4	170.480	7.22E+10
4d8	8127	6	4d7 4f	613916	6	165.090	1.24E+11
4d8	29469	4	4d7 4f	613916	6	171.120	3.92E+11
4d8	31575	8	4d7 4f	614957	10	171.430	5.91E+11
4d8	8127	6	4p5 4d	625327	4	162.040	1.78E+11
4d8	19499	4	4p5 4d	625327	4	165.080	2.75E+11
4d8	10261	4	4d7 4f	628413	2	161.790	1.14E+11
4d8	26544	0	4d7 4f	628413	2	166.170	1.16E+11
4d8	29469	4	4d7 4f	628413	2	166.980	9.97E+10
4d8	70900	0	4d7 4f	628413	2	179.390	1.03E+11
4d8	0	8	4p5 4d9	630380	6	158.650	2.32E+11
4d8	8127	6	4p5 4d9	630380	6	160.730	7.36E+10
4d8	19499	4	4p5 4d9	630380	6	163.720	1.02E+11
4d8	19499	4	4p5 4d9	632138	2	163.250	1.07E+11
4d8	26760	2	4p5 4d9	632138	2	165.210	1.68E+11
4d8	29469	4	4p5 4d9	632138	2	165.950	7.68E+10
4d8	26760	2	4p5 4d9	633486	0	164.840	4.26E+11
4d8	29469	4	4p5 4d9	642464	4	163.150	2.87E+11
4d8	10261	4	4d7 4f	643804	2	157.860	1.34E+11
4d8	70900	0	4d7 4f	643804	2	174.570	1.38E+11
4d8	8127	6	4p5 4d9	648390	4	156.200	8.10E+10
4d8	26760	2	4p5 4d9	648390	4	160.890	1.10E+11

Sn VIII

Table A.3 Ionization potential 134.624 eV.

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d7	0	9	4d6 4f	635911	11	157.270	8.39E+11
4d7	0	9	4d6 4f	643079	9	155.520	1.79E+11
4d7	7138	7	4d6 4f	643079	9	157.270	6.64E+11
4d7	7138	7	4d6 4f	647685	7	156.140	1.55E+11
4d7	10754	5	4d6 4f	647685	7	157.020	6.26E+11
4d7	10754	5	4d6 4f	651141	5	156.170	1.68E+11
4d7	12829	3	4d6 4f	651141	5	156.680	6.48E+11
4d7	0	9	4d6 4f	652353	7	153.310	4.17E+11
4d7	23631	5	4d6 4f	652353	7	159.070	3.13E+11
4d7	0	9	4p5 4d8	656585	9	152.320	6.26E+11
4d7	7138	7	4p5 4d8	656585	9	154.000	1.49E+11
4d7	24408	9	4d6 4f	657423	11	157.990	7.81E+11
4d7	7138	7	4d6 4f	658495	5	153.540	2.69E+11
4d7	21735	3	4d6 4f	658495	5	157.060	2.84E+11
4d7	23631	5	4d6 4f	658495	5	157.530	1.71E+11
4d7	10754	5	4d6 4f	660465	3	153.930	2.05E+11
4d7	12829	3	4d6 4f	660465	3	154.430	1.07E+11
4d7	21735	3	4d6 4f	660465	3	156.580	3.01E+11
4d7	23631	5	4d6 4f	660465	3	157.050	1.11E+11
4d7	21735	3	4d6 4f	662999	5	155.960	3.61E+11
4d7	23631	5	4d6 4f	662999	5	156.420	3.79E+11
4d7	31059	7	4d6 4f	664968	9	157.770	6.59E+11
4d7	0	9	4p5 4d8	665176	7	150.350	1.82E+11
4d7	7138	7	4p5 4d8	665176	7	151.990	4.01E+11
4d7	10754	5	4p5 4d8	665176	7	152.830	1.51E+11
4d7	21735	3	4d6 4f	665338	1	155.390	7.59E+11
4d7	32718	11	4d6 4f	665428	13	158.070	8.66E+11
4d7	12829	3	4d6 4f	668442	1	152.550	2.95E+11
4d7	27557	1	4d6 4f	668442	1	156.050	3.99E+11
4d7	23631	5	4d6 4f	669829	3	154.770	2.23E+11
4d7	27557	1	4d6 4f	669829	3	155.720	3.92E+11
4d7	7138	7	4p5 4d8	670169	5	150.840	1.58E+11
4d7	10754	5	4p5 4d8	670169	5	151.670	4.36E+11
4d7	12829	3	4p5 4d8	670169	5	152.150	1.36E+11
4d7	34353	3	4p5 4d8	670169	5	157.300	1.11E+11
4d7	32718	11	4d6 4f	670645	11	156.780	4.74E+11
4d7	40298	9	4d6 4f	670645	11	158.660	3.15E+11
4d7	24408	9	4d6 4f	671937	9	154.450	5.41E+11
4d7	32718	11	4d6 4f	671937	9	156.460	9.53E+10
4d7	24408	9	4d6 4f	672372	7	154.350	1.70E+11
4d7	31059	7	4d6 4f	672372	7	155.950	1.99E+11
4d7	36890	5	4d6 4f	672372	7	157.380	3.28E+11
4d7	51731	5	4d6 4f	672372	7	161.140	9.14E+10
4d7	10754	5	4p5 4d8	672596	3	151.110	2.35E+11
4d7	12829	3	4p5 4d8	672596	3	151.590	5.05E+11
4d7	7138	7	4d6 4f	675042	5	149.740	1.76E+11
4d7	23631	5	4d6 4f	675042	5	153.530	1.30E+11
4d7	34353	3	4d6 4f	675042	5	156.100	4.03E+11

Table A.3 (Continued).

Lower level			Upper level			λ (Å)	A (s^{-1})
Config.	E (cm^{-1})	$2J$	Config.	E (cm^{-1})	$2J$		
4d7	31059	7	4d6 4f	675276	7	155.250	1.71E+11
4d7	36890	5	4d6 4f	675276	7	156.660	3.65E+11
4d7	51731	5	4d6 4f	675276	7	160.390	1.46E+11
4d7	32718	11	4d6 4f	675855	11	155.510	2.60E+11
4d7	40298	9	4d6 4f	675855	11	157.360	5.52E+11
4d7	34353	3	4d6 4f	679702	3	154.970	2.13E+11
4d7	40030	1	4d6 4f	679702	3	156.350	3.34E+11
4d7	12829	3	4p5 4d8	680411	1	149.810	3.18E+11
4d7	27557	1	4p5 4d8	680411	1	153.190	3.72E+11
4d7	34353	3	4p5 4d8	680411	1	154.800	1.21E+11
4d7	7138	7	4p5 4d8	681054	5	148.400	1.80E+11
4d7	10754	5	4p5 4d8	681054	5	149.210	1.35E+11
4d7	21735	3	4p5 4d8	681054	5	151.690	1.02E+11
4d7	23631	5	4p5 4d8	681054	5	152.130	1.11E+11
4d7	34353	3	4p5 4d8	681054	5	154.650	9.11E+10
4d7	36890	5	4p5 4d8	681054	5	155.260	1.21E+11
4d7	0	9	4p5 4d8	682817	7	146.470	1.49E+11
4d7	23631	5	4p5 4d8	682817	7	151.720	2.32E+11
4d7	24408	9	4p5 4d8	682817	7	151.900	1.07E+11
4d7	31059	7	4p5 4d8	682817	7	153.450	1.97E+11
4d7	10754	5	4p5 4d8	683008	3	148.770	1.83E+11
4d7	23631	5	4p5 4d8	683008	3	151.680	1.40E+11
4d7	27557	1	4p5 4d8	683008	3	152.590	9.52E+10
4d7	34353	3	4p5 4d8	683008	3	154.180	1.85E+11
4d7	36890	5	4p5 4d8	683008	3	154.790	9.74E+10
4d7	40298	9	4d6 4f	685782	9	154.940	1.68E+11
4d7	55709	7	4d6 4f	685782	9	158.730	5.05E+11
4d7	31059	7	4d6 4f	685981	5	152.710	1.38E+11
4d7	48508	3	4d6 4f	685981	5	156.890	2.33E+11
4d7	51731	5	4d6 4f	685981	5	157.690	1.99E+11
4d7	23631	5	4d6 4f	688736	7	150.370	8.82E+10
4d7	31059	7	4d6 4f	688736	7	152.070	1.36E+11
4d7	51731	5	4d6 4f	688736	7	157.000	3.53E+11
4d7	10754	5	4p5 4d8	688895	3	147.480	9.87E+10
4d7	21735	3	4p5 4d8	688895	3	149.910	2.51E+11
4d7	36890	5	4p5 4d8	688895	3	153.390	2.25E+11
4d7	34353	3	4p5 4d8	691963	1	152.080	2.16E+11
4d7	40030	1	4p5 4d8	691963	1	153.410	3.80E+11
4d7	31059	7	4d6 4f	692565	5	151.190	9.48E+10
4d7	48508	3	4d6 4f	692565	5	155.280	4.45E+11
4d7	51731	5	4d6 4f	692565	5	156.070	1.91E+11
4d7	12829	3	4p5 4d8	694886	1	146.630	1.11E+11
4d7	34353	3	4p5 4d8	694886	1	151.410	3.77E+11
4d7	40030	1	4p5 4d8	694886	1	152.720	3.47E+11
4d7	24408	9	4d6 4f	695702	7	148.980	8.84E+10
4d7	55709	7	4d6 4f	695702	7	156.270	3.06E+11
4d7	84059	5	4d6 4f	695702	7	163.510	1.76E+11
4d7	21735	3	4p5 4d8	696550	3	148.210	1.60E+11
4d7	23631	5	4p5 4d8	696550	3	148.620	9.56E+10
4d7	36890	5	4p5 4d8	696550	3	151.610	2.69E+11
4d7	40030	1	4p5 4d8	696550	3	152.340	1.00E+11
4d7	36890	5	4d6 4f	698501	3	151.160	9.31E+10
4d7	48508	3	4d6 4f	698501	3	153.870	1.26E+11

Table A.3 (Continued).

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d7	51731	5	4d6 4f	698501	3	154.630	1.30E+11
4d7	80358	3	4d6 4f	698501	3	161.790	2.06E+11
4d7	40298	9	4p5 4d8	698964	9	151.840	4.52E+11
4d7	55709	7	4p5 4d8	698964	9	155.480	1.25E+11
4d7	34353	3	4p5 4d8	700292	5	150.180	1.35E+11
4d7	36890	5	4p5 4d8	700292	5	150.760	2.79E+11
4d7	84059	5	4p5 4d8	700292	5	162.300	1.87E+11
4d7	23631	5	4p5 4d8	707715	3	146.200	1.43E+11
4d7	27557	1	4p5 4d8	707715	3	147.040	9.74E+10
4d7	34353	3	4p5 4d8	707715	3	148.530	2.49E+11
4d7	40030	1	4p5 4d8	707715	3	149.790	1.32E+11
4d7	31059	7	4d6 4f	708591	5	147.610	1.27E+11
4d7	55709	7	4d6 4f	708591	5	153.190	2.00E+11
4d7	84059	5	4d6 4f	708591	5	160.140	2.42E+11
4d7	24408	9	4p5 4d8	710652	7	145.740	3.18E+11
4d7	36890	5	4p5 4d8	710652	7	148.440	1.04E+11
4d7	55709	7	4p5 4d8	710652	7	152.700	2.36E+11
4d7	48508	3	4p5 4d8	714404	1	150.190	5.52E+11
4d7	31059	7	4p5 4d8	719797	5	145.210	9.17E+10
4d7	36890	5	4p5 4d8	719797	5	146.450	1.87E+11
4d7	51731	5	4p5 4d8	719797	5	149.700	1.80E+11
4d7	80358	3	4p5 4d8	719797	5	156.410	2.22E+11
4d7	40298	9	4p5 4d8	723657	7	146.350	3.65E+11
4d7	51731	5	4p5 4d8	723657	7	148.840	9.42E+10
4d7	55709	7	4p5 4d8	723657	7	149.730	9.08E+10
4d7	84059	5	4p5 4d8	723657	7	156.370	1.78E+11
4d7	48508	3	4p5 4d8	727199	3	147.360	3.59E+11
4d7	51731	5	4p5 4d8	727199	3	148.060	2.52E+11
4d7	32718	11	4p5 4d8	730887	9	143.250	5.50E+11
4d7	55709	7	4p5 4d8	730887	9	148.130	1.58E+11
4d7	31059	7	4p5 4d8	731710	5	142.740	2.80E+11
4d7	80358	3	4p5 4d8	731710	5	153.550	4.71E+11
4d7	48508	3	4p5 4d8	742523	3	144.110	1.37E+11
4d7	51731	5	4p5 4d8	742523	3	144.780	1.24E+11
4d7	80358	3	4p5 4d8	742523	3	151.040	4.13E+11
4d7	55709	7	4p5 4d8	745151	5	145.060	3.15E+11
4d7	84059	5	4p5 4d8	745151	5	151.280	2.62E+11
4d7	40298	9	4p5 4d8	748512	7	141.220	2.37E+11
4d7	84059	5	4p5 4d8	748512	7	150.520	4.07E+11
4d7	80358	3	4p5 4d8	754148	1	148.430	6.21E+11
4d7	84059	5	4p5 4d8	757180	3	148.580	5.15E+11

Sn IX

Table A.4 Ionization potential 155.522 eV.

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d6	0	8	4d5 4f	674628	10	148.250	1.52E+11
4d6	0	8	4d5 4f	675735	10	148.000	7.83E+11
4d6	0	8	4d5 4f	680953	8	146.870	3.66E+11
4d6	5127	6	4d5 4f	680953	8	147.980	6.17E+11
4d6	0	8	4p5 4d7	683731	6	146.270	3.74E+11
4d6	5127	6	4p5 4d7	683731	6	147.380	1.51E+11
4d6	6967	4	4p5 4d7	683731	6	147.780	4.50E+11
4d6	0	8	4p5 4d7	685839	6	145.820	4.53E+11
4d6	5127	6	4p5 4d7	685839	6	146.920	4.27E+11
4d6	6967	4	4d5 4f	686593	4	147.160	5.09E+11
4d6	8896	2	4d5 4f	686593	4	147.580	3.73E+11
4d6	6967	4	4d5 4f	688350	2	146.780	1.29E+11
4d6	8896	2	4d5 4f	688350	2	147.190	4.64E+11
4d6	9622	0	4d5 4f	688350	2	147.350	3.72E+11
4d6	5127	6	4d5 4f	695095	4	144.950	5.73E+11
4d6	6967	4	4d5 4f	695095	4	145.340	2.47E+11
4d6	29332	12	4d5 4f	698278	12	149.510	1.56E+11
4d6	29882	10	4d5 4f	698278	12	149.630	7.52E+11
4d6	26984	8	4d5 4f	698320	10	148.970	9.01E+11
4d6	29332	12	4d5 4f	699487	14	149.240	1.02E+12
4d6	6967	4	4d5 4f	699642	2	144.390	5.73E+11
4d6	8896	2	4d5 4f	699642	2	144.790	3.05E+11
4d6	0	8	4p5 4d7	701437	6	142.580	1.39E+11
4d6	5127	6	4p5 4d7	701437	6	143.630	3.73E+11
4d6	6967	4	4p5 4d7	701437	6	144.010	3.86E+11
4d6	30122	4	4p5 4d7	701437	6	148.980	1.36E+11
4d6	0	8	4p5 4d7	702029	8	142.460	5.69E+11
4d6	5127	6	4p5 4d7	702029	8	143.510	2.72E+11
4d6	26984	8	4p5 4d7	702029	8	148.160	1.22E+11
4d6	5127	6	4p5 4d7	703555	4	143.200	3.37E+11
4d6	6967	4	4p5 4d7	703555	4	143.570	1.52E+11
4d6	8896	2	4p5 4d7	703555	4	143.970	5.06E+11
4d6	6967	4	4d5 4f	704281	2	143.420	2.93E+11
4d6	8896	2	4d5 4f	704281	2	143.820	1.59E+11
4d6	9622	0	4d5 4f	704281	2	143.970	5.49E+11
4d6	8896	2	4p5 4d7	704890	0	143.700	1.08E+12
4d6	29332	12	4d5 4f	705366	12	147.940	4.98E+11
4d6	29882	10	4d5 4f	705366	12	148.060	2.51E+11
4d6	40602	10	4d5 4f	705366	12	150.450	2.44E+11
4d6	29882	10	4d5 4f	706177	8	147.880	1.12E+11
4d6	34717	6	4d5 4f	706177	8	148.950	4.77E+11
4d6	29882	10	4d5 4f	707316	10	147.630	3.64E+11
4d6	36402	8	4d5 4f	707316	10	149.070	3.85E+11
4d6	26984	8	4d5 4f	709045	6	146.630	3.51E+11
4d6	30122	4	4d5 4f	709045	6	147.310	1.55E+11
4d6	47160	4	4d5 4f	709045	6	151.100	1.31E+11
4d6	30122	4	4d5 4f	710923	4	146.900	6.79E+11

Table A.4 (Continued).

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d6	26984	8	4d5 4f	711047	8	146.200	1.38E+11
4d6	29882	10	4d5 4f	711047	8	146.830	2.53E+11
4d6	34717	6	4d5 4f	711047	8	147.870	1.21E+11
4d6	36402	8	4d5 4f	711047	8	148.240	1.26E+11
4d6	48796	6	4d5 4f	711047	8	151.020	1.97E+11
4d6	36395	4	4d5 4f	711632	6	148.110	8.60E+11
4d6	36402	8	4d5 4f	713261	10	147.760	3.72E+11
4d6	43005	8	4d5 4f	713261	10	149.210	5.07E+11
4d6	47910	12	4d5 4f	714974	14	149.930	1.02E+12
4d6	30122	4	4d5 4f	714996	4	146.030	2.05E+11
4d6	34717	6	4d5 4f	714996	4	147.020	1.58E+11
4d6	36395	4	4d5 4f	714996	4	147.380	2.83E+11
4d6	30122	4	4d5 4f	715784	2	145.860	6.86E+11
4d6	42869	2	4d5 4f	715784	2	148.630	1.80E+11
4d6	26984	8	4d5 4f	715804	8	145.190	1.99E+11
4d6	34717	6	4d5 4f	715804	8	146.840	1.97E+11
4d6	43005	8	4d5 4f	715804	8	148.650	1.66E+11
4d6	44896	6	4d5 4f	715804	8	149.070	2.92E+11
4d6	29332	12	4d5 4f	716295	10	145.590	1.86E+11
4d6	29882	10	4d5 4f	716295	10	145.700	2.01E+11
4d6	36402	8	4d5 4f	716295	10	147.100	1.57E+11
4d6	40602	10	4d5 4f	716295	10	148.010	2.68E+11
4d6	29332	12	4p5 4d7	716322	12	145.580	2.82E+11
4d6	40602	10	4p5 4d7	716322	12	148.010	5.95E+11
4d6	47910	12	4p5 4d7	716322	12	149.630	1.35E+11
4d6	30122	4	4d5 4f	717964	6	145.400	5.15E+11
4d6	47160	4	4d5 4f	717964	6	149.090	1.26E+11
4d6	26984	8	4p5 4d7	719423	8	144.430	2.87E+11
4d6	44896	6	4p5 4d7	719423	8	148.270	3.50E+11
4d6	48796	6	4p5 4d7	719423	8	149.130	1.34E+11
4d6	36395	4	4d5 4f	722000	4	145.870	3.14E+11
4d6	34717	6	4d5 4f	722374	6	145.440	5.40E+11
4d6	47160	4	4d5 4f	722374	6	148.120	1.28E+11
4d6	63717	6	4d5 4f	722374	6	151.840	1.84E+11
4d6	30122	4	4d5 4f	723837	2	144.170	1.10E+11
4d6	36395	4	4d5 4f	723837	2	145.480	2.74E+11
4d6	47160	4	4d5 4f	723837	2	147.800	2.60E+11
4d6	49581	2	4d5 4f	723837	2	148.330	1.12E+11
4d6	41989	0	4d5 4f	724899	2	146.450	7.21E+11
4d6	26984	8	4p5 4d7	725634	6	143.150	2.01E+11
4d6	43005	8	4p5 4d7	725634	6	146.510	1.22E+11
4d6	48796	6	4p5 4d7	725634	6	147.760	1.70E+11
4d6	29882	10	4p5 4d7	726184	10	143.630	2.38E+11
4d6	40602	10	4p5 4d7	726184	10	145.880	2.32E+11
4d6	43005	8	4p5 4d7	726184	10	146.390	2.35E+11
4d6	42869	2	4d5 4f	726304	0	146.340	7.72E+11
4d6	73892	2	4d5 4f	726304	0	153.300	1.42E+11
4d6	43005	8	4d5 4f	726519	8	146.320	2.85E+11
4d6	44896	6	4d5 4f	726519	8	146.730	1.49E+11
4d6	63717	6	4d5 4f	726519	8	150.890	1.28E+11
4d6	54525	8	4d5 4f	727505	10	148.610	7.48E+11
4d6	36402	8	4d5 4f	727739	6	144.660	1.20E+11
4d6	44896	6	4d5 4f	727739	6	146.460	1.08E+11

Table A.4 (Continued).

Lower level			Upper level			λ (Å)	A (s^{-1})
Config.	E (cm^{-1})	$2J$	Config.	E (cm^{-1})	$2J$		
4d6	48796	6	4d5 4f	727739	6	147.310	2.33E+11
4d6	61559	4	4d5 4f	727739	6	150.130	1.71E+11
4d6	34717	6	4d5 4f	727752	4	144.310	1.31E+11
4d6	42869	2	4d5 4f	727752	4	146.030	1.38E+11
4d6	47160	4	4d5 4f	727752	4	146.950	2.61E+11
4d6	48796	6	4d5 4f	727752	4	147.300	1.22E+11
4d6	42869	2	4p5 4d7	729794	2	145.590	1.81E+11
4d6	47160	4	4p5 4d7	729794	2	146.510	3.05E+11
4d6	60909	0	4p5 4d7	729794	2	149.520	1.33E+11
4d6	36402	8	4d5 4f	730171	8	144.160	5.01E+11
4d6	76881	8	4d5 4f	730171	8	153.090	1.41E+11
4d6	36402	8	4p5 4d7	732789	6	143.620	2.65E+11
4d6	44896	6	4p5 4d7	732789	6	145.390	2.30E+11
4d6	42869	2	4d5 4f	733142	4	144.890	3.28E+11
4d6	49581	2	4d5 4f	733142	4	146.310	3.55E+11
4d6	61559	4	4d5 4f	733142	4	148.920	1.15E+11
4d6	49581	2	4d5 4f	734366	0	146.050	7.98E+11
4d6	48796	6	4d5 4f	735622	4	145.610	1.87E+11
4d6	61559	4	4d5 4f	735622	4	148.370	2.87E+11
4d6	34717	6	4d5 4f	735809	6	142.650	2.38E+11
4d6	48796	6	4d5 4f	735809	6	145.580	1.23E+11
4d6	61559	4	4d5 4f	735809	6	148.330	1.61E+11
4d6	63717	6	4d5 4f	735809	6	148.810	2.72E+11
4d6	42869	2	4d5 4f	737367	2	144.010	2.42E+11
4d6	49581	2	4d5 4f	737367	2	145.410	4.40E+11
4d6	40602	10	4p5 4d7	738525	12	143.300	1.15E+11
4d6	47910	12	4p5 4d7	738525	12	144.820	7.85E+11
4d6	34717	6	4p5 4d7	739766	4	141.850	1.84E+11
4d6	48796	6	4p5 4d7	739766	4	144.740	1.91E+11
4d6	61559	4	4p5 4d7	739766	4	147.470	1.33E+11
4d6	73892	2	4p5 4d7	739766	4	150.200	1.51E+11
4d6	43005	8	4p5 4d7	739889	6	143.510	1.42E+11
4d6	47160	4	4p5 4d7	739889	6	144.370	3.21E+11
4d6	61559	4	4p5 4d7	739889	6	147.440	1.77E+11
4d6	40602	10	4d5 4f	740896	8	142.810	1.84E+11
4d6	48796	6	4d5 4f	740896	8	144.510	1.38E+11
4d6	54525	8	4d5 4f	740896	8	145.710	1.69E+11
4d6	63717	6	4d5 4f	740896	8	147.690	1.25E+11
4d6	76881	8	4d5 4f	740896	8	150.620	2.77E+11
4d6	63717	6	4p5 4d7	741850	8	147.480	5.69E+11
4d6	36395	4	4p5 4d7	744594	2	141.220	1.53E+11
4d6	42869	2	4p5 4d7	744594	2	142.520	1.34E+11
4d6	73892	2	4p5 4d7	744594	2	149.120	3.46E+11
4d6	47910	12	4p5 4d7	744784	10	143.520	3.40E+11
4d6	88218	8	4p5 4d7	744784	10	152.330	3.86E+11
4d6	36402	8	4p5 4d7	746031	6	140.940	1.82E+11
4d6	44896	6	4p5 4d7	746031	6	142.640	2.79E+11
4d6	54525	8	4p5 4d7	746031	6	144.630	1.70E+11
4d6	47160	4	4p5 4d7	747639	2	142.780	2.22E+11
4d6	60909	0	4p5 4d7	747639	2	145.640	5.54E+11
4d6	29882	10	4p5 4d7	748040	8	139.260	1.20E+11
4d6	43005	8	4p5 4d7	748040	8	141.850	2.21E+11
4d6	54525	8	4p5 4d7	748040	8	144.210	3.12E+11

Table A.4 (Continued).

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d6	81573	6	4p5 4d7	748040	8	150.060	1.50E+11
4d6	44896	6	4p5 4d7	749651	4	141.910	2.82E+11
4d6	49581	2	4p5 4d7	749651	4	142.860	2.35E+11
4d6	77419	4	4p5 4d7	749651	4	148.780	1.22E+11
4d6	29332	12	4p5 4d7	751159	10	138.550	2.63E+11
4d6	29882	10	4p5 4d7	751159	10	138.660	1.12E+11
4d6	40602	10	4p5 4d7	751159	10	140.750	2.36E+11
4d6	76881	8	4p5 4d7	751159	10	148.320	2.23E+11
4d6	47160	4	4p5 4d7	752238	4	141.850	2.73E+11
4d6	61559	4	4p5 4d7	752238	4	144.800	1.27E+11
4d6	83172	4	4p5 4d7	752238	4	149.480	1.10E+11
4d6	29882	10	4p5 4d7	753368	8	138.240	2.17E+11
4d6	40602	10	4p5 4d7	753368	8	140.320	1.22E+11
4d6	48796	6	4p5 4d7	753368	8	141.950	3.06E+11
4d6	54525	8	4p5 4d7	753368	8	143.110	2.40E+11
4d6	54525	8	4p5 4d7	757149	6	142.340	2.53E+11
4d6	77419	4	4p5 4d7	757149	6	147.130	3.60E+11
4d6	81573	6	4p5 4d7	757149	6	148.040	1.28E+11
4d6	77419	4	4d5 4f	758717	6	146.800	1.41E+11
4d6	81573	6	4d5 4f	758717	6	147.700	1.28E+11
4d6	83172	4	4d5 4f	758717	6	148.050	2.57E+11
4d6	48796	6	4p5 4d7	759376	4	140.750	1.65E+11
4d6	73892	2	4p5 4d7	759376	4	145.900	3.01E+11
4d6	83172	4	4p5 4d7	759376	4	147.900	2.42E+11
4d6	73004	0	4p5 4d7	762202	2	145.110	1.99E+11
4d6	73892	2	4p5 4d7	762202	2	145.300	1.99E+11
4d6	42869	2	4p5 4d7	763299	0	138.820	1.95E+11
4d6	49581	2	4p5 4d7	763299	0	140.130	1.48E+11
4d6	73892	2	4p5 4d7	763299	0	145.070	7.18E+11
4d6	61559	4	4p5 4d7	763334	6	142.510	1.67E+11
4d6	81573	6	4p5 4d7	763334	6	146.700	1.11E+11
4d6	114196	4	4p5 4d7	763334	6	154.070	1.50E+11
4d6	36402	8	4p5 4d7	765512	6	137.170	1.59E+11
4d6	77419	4	4p5 4d7	765512	6	145.350	3.35E+11
4d6	83172	4	4p5 4d7	765512	6	146.570	1.25E+11
4d6	36395	4	4p5 4d7	765776	2	137.120	1.48E+11
4d6	49581	2	4p5 4d7	765776	2	139.640	2.03E+11
4d6	61559	4	4p5 4d7	765776	2	142.020	1.48E+11
4d6	73004	0	4p5 4d7	765776	2	144.370	1.73E+11
4d6	73892	2	4p5 4d7	765776	2	144.550	1.41E+11
4d6	81573	6	4p5 4d7	765945	8	146.140	4.99E+11
4d6	88218	8	4p5 4d7	765945	8	147.570	2.39E+11
4d6	48796	6	4p5 4d7	769399	4	138.790	1.09E+11
4d6	63717	6	4p5 4d7	769399	4	141.720	1.96E+11
4d6	77419	4	4p5 4d7	769399	4	144.530	1.67E+11
4d6	83172	4	4p5 4d7	769399	4	145.740	1.19E+11
4d6	61559	4	4d5 4f	771337	2	140.910	3.62E+11
4d6	73004	0	4d5 4f	771337	2	143.220	4.57E+11
4d6	40602	10	4p5 4d7	772611	8	136.630	3.40E+11
4d6	54525	8	4p5 4d7	772611	8	139.280	1.19E+11
4d6	76881	8	4p5 4d7	772611	8	143.750	3.53E+11
4d6	29332	12	4p5 4d7	772705	10	134.540	4.27E+11
4d6	76881	8	4p5 4d7	772705	10	143.730	5.74E+11

Table A.4 (Continued).

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d6	44896	6	4p5 4d7	774159	4	137.140	1.34E+11
4d6	47160	4	4p5 4d7	774159	4	137.570	1.13E+11
4d6	63717	6	4p5 4d7	774159	4	140.770	1.19E+11
4d6	83172	4	4p5 4d7	774159	4	144.740	2.73E+11
4d6	43005	8	4p5 4d7	776049	6	136.430	3.13E+11
4d6	81573	6	4p5 4d7	776049	6	144.010	1.56E+11
4d6	88218	8	4p5 4d7	776049	6	145.400	1.31E+11
4d6	44896	6	4p5 4d7	781374	4	135.800	1.19E+11
4d6	63717	6	4p5 4d7	781374	4	139.360	3.92E+11
4d6	73892	2	4p5 4d7	781374	4	141.360	1.78E+11
4d6	77419	4	4p5 4d7	781374	4	142.070	2.14E+11
4d6	61559	4	4p5 4d7	784361	2	138.370	1.27E+11
4d6	77419	4	4p5 4d7	784361	2	141.470	5.85E+11
4d6	114196	4	4p5 4d7	784361	2	149.240	1.19E+11
4d6	54525	8	4p5 4d7	787551	6	136.440	1.96E+11
4d6	61559	4	4p5 4d7	787551	6	137.760	1.46E+11
4d6	76881	8	4p5 4d7	787551	6	140.730	3.57E+11
4d6	81573	6	4p5 4d7	789180	8	141.340	2.53E+11
4d6	88218	8	4p5 4d7	789180	8	142.680	5.69E+11
4d6	77419	4	4d5 4f	792133	2	139.930	1.34E+11
4d6	83172	4	4d5 4f	792133	2	141.070	2.17E+11
4d6	114196	4	4d5 4f	792133	2	147.520	3.07E+11
4d6	147005	0	4d5 4f	792133	2	155.030	1.35E+11
4d6	81573	6	4p5 4d7	793592	4	140.460	7.16E+11
4d6	83172	4	4p5 4d7	793832	2	140.730	5.52E+11
4d6	47910	12	4p5 4d7	794263	10	134.000	6.08E+11
4d6	88218	8	4p5 4d7	794263	10	141.650	4.80E+11
4d6	76881	8	4p5 4d7	798900	6	138.520	4.07E+11
4d6	81573	6	4p5 4d7	798900	6	139.420	1.37E+11
4d6	83172	4	4p5 4d7	798900	6	139.730	3.08E+11
4d6	114196	4	4p5 4d7	813603	4	143.000	8.26E+11
4d6	88218	8	4p5 4d7	814271	6	137.750	4.39E+11
4d6	114196	4	4p5 4d7	814271	6	142.860	5.13E+11
4d6	114196	4	4p5 4d7	840377	2	137.720	1.94E+11
4d6	147005	0	4p5 4d7	840377	2	144.240	7.77E+11

Sn x

Table A.5 Ionization potential 183.779 eV.

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d5	0	5	4d4 4f	709675	3	140.930	1.05E+12
4d5	0	5	4d4 4f	711253	5	140.610	1.04E+12
4d5	0	5	4d4 4f	713243	7	140.220	9.95E+11
4d5	38121	5	4d4 4f	740210	7	142.450	8.92E+11
4d5	41340	11	4d4 4f	740962	13	142.950	1.04E+12
4d5	38121	5	4d4 4f	742204	3	142.050	3.98E+11
4d5	42919	5	4d4 4f	742204	3	143.020	3.61E+11
4d5	47166	1	4d4 4f	742204	3	143.890	1.10E+11
4d5	40776	7	4d4 4f	742381	9	142.550	6.85E+11
4d5	50677	7	4d4 4f	742381	9	144.590	1.45E+11
4d5	41965	9	4d4 4f	743306	11	142.600	9.91E+11
4d5	38121	5	4d4 4f	743369	5	141.810	1.68E+11
4d5	40776	7	4d4 4f	743369	5	142.350	1.49E+11
4d5	44301	3	4d4 4f	743369	5	143.060	4.73E+11
4d5	40776	7	4d4 4f	743970	7	142.230	3.54E+11
4d5	41965	9	4d4 4f	743970	7	142.470	1.16E+11
4d5	42919	5	4d4 4f	743970	7	142.660	3.80E+11
4d5	44301	3	4d4 4f	744033	1	142.930	7.00E+11
4d5	47166	1	4d4 4f	744033	1	143.520	1.98E+11
4d5	40776	7	4d4 4f	744380	9	142.140	2.74E+11
4d5	41340	11	4d4 4f	744380	9	142.260	1.13E+11
4d5	41965	9	4d4 4f	744380	9	142.380	4.69E+11
4d5	50677	7	4d4 4f	744380	9	144.170	1.32E+11
4d5	41340	11	4d4 4f	744864	11	142.160	8.06E+11
4d5	66411	9	4d4 4f	744864	11	147.410	1.49E+11
4d5	38121	5	4d4 4f	747329	5	141.020	5.17E+11
4d5	44301	3	4d4 4f	747329	5	142.260	2.33E+11
4d5	44301	3	4d4 4f	749623	3	141.800	2.22E+11
4d5	47166	1	4d4 4f	749623	3	142.370	5.26E+11
4d5	42919	5	4d4 4f	749745	5	141.490	4.27E+11
4d5	50677	7	4d4 4f	749745	5	143.060	2.94E+11
4d5	40776	7	4d4 4f	750873	7	140.840	3.65E+11
4d5	42919	5	4d4 4f	750873	7	141.270	2.54E+11
4d5	65922	7	4d4 4f	750873	7	146.010	1.40E+11
4d5	58200	11	4d4 4f	753814	13	143.780	1.01E+12
4d5	61198	13	4d4 4f	753928	15	144.370	1.06E+12
4d5	38121	5	4d4 4f	754453	3	139.620	3.01E+11
4d5	42919	5	4d4 4f	754453	3	140.560	2.64E+11
4d5	54669	1	4d4 4f	754453	3	142.920	1.21E+11
4d5	44301	3	4d4 4f	754840	1	140.760	1.30E+11
4d5	47166	1	4d4 4f	754840	1	141.320	3.42E+11
4d5	54669	1	4d4 4f	754840	1	142.840	3.31E+11
4d5	56267	3	4d4 4f	754840	1	143.170	1.06E+11
4d5	41965	9	4d4 4f	755319	9	140.200	2.78E+11
4d5	50677	7	4d4 4f	755319	9	141.930	2.44E+11
4d5	66411	9	4d4 4f	755319	9	145.170	1.74E+11
4d5	73229	9	4d4 4f	755319	9	146.630	1.24E+11
4d5	41965	9	4p5 4d6	755445	7	140.180	3.53E+11
4d5	42919	5	4p5 4d6	755445	7	140.360	2.66E+11

Table A.5 (Continued).

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d5	38121	5	4p5 4d6	757333	5	139.060	1.44E+11
4d5	40776	7	4p5 4d6	757333	5	139.570	4.89E+11
4d5	44301	3	4p5 4d6	757333	5	140.260	1.28E+11
4d5	50677	7	4d4 4f	757549	7	141.490	4.98E+11
4d5	54733	5	4d4 4f	757549	7	142.300	2.60E+11
4d5	42919	5	4p5 4d6	758427	3	139.780	1.60E+11
4d5	54669	1	4p5 4d6	758427	3	142.110	1.63E+11
4d5	54733	5	4p5 4d6	758427	3	142.120	2.87E+11
4d5	56267	3	4p5 4d6	758427	3	142.430	1.58E+11
4d5	41340	11	4d4 4f	760192	9	139.130	2.83E+11
4d5	50677	7	4d4 4f	760192	9	140.960	4.13E+11
4d5	66411	9	4d4 4f	760192	9	144.160	2.16E+11
4d5	54733	5	4d4 4f	760290	5	141.750	5.05E+11
4d5	56267	3	4d4 4f	760290	5	142.060	3.36E+11
4d5	44301	3	4d4 4f	760509	3	139.640	3.49E+11
4d5	56267	3	4d4 4f	760509	3	142.010	4.24E+11
4d5	54733	5	4d4 4f	763660	7	141.080	4.14E+11
4d5	64662	5	4d4 4f	763660	7	143.080	1.54E+11
4d5	65922	7	4d4 4f	763660	7	143.340	2.53E+11
4d5	42919	5	4p5 4d6	763699	5	138.760	3.18E+11
4d5	50677	7	4p5 4d6	763699	5	140.270	2.36E+11
4d5	54733	5	4p5 4d6	763699	5	141.070	1.47E+11
4d5	47166	1	4d4 4f	763893	1	139.540	4.27E+11
4d5	54669	1	4d4 4f	763893	1	141.020	1.60E+11
4d5	56267	3	4d4 4f	763893	1	141.330	1.59E+11
4d5	58200	11	4d4 4f	764955	11	141.510	4.40E+11
4d5	73229	9	4d4 4f	764955	11	144.580	4.72E+11
4d5	44301	3	4d4 4f	767320	3	138.330	1.40E+11
4d5	54669	1	4d4 4f	767320	3	140.340	4.01E+11
4d5	56267	3	4d4 4f	767320	3	140.650	2.02E+11
4d5	65922	7	4d4 4f	768020	9	142.450	5.78E+11
4d5	58200	11	4d4 4f	768469	11	140.810	3.37E+11
4d5	66411	9	4d4 4f	768469	11	142.460	4.88E+11
4d5	64662	5	4d4 4f	769311	7	141.930	3.08E+11
4d5	73229	9	4d4 4f	769311	7	143.680	1.18E+11
4d5	79875	5	4d4 4f	769311	7	145.060	1.87E+11
4d5	56267	3	4d4 4f	770605	5	140.010	1.08E+11
4d5	64662	5	4d4 4f	770605	5	141.670	1.54E+11
4d5	65471	3	4d4 4f	770605	5	141.830	5.04E+11
4d5	50677	7	4d4 4f	771212	5	138.800	1.60E+11
4d5	56267	3	4d4 4f	771212	5	139.890	3.30E+11
4d5	65471	3	4d4 4f	771212	5	141.710	2.53E+11
4d5	58200	11	4d4 4f	772528	9	140.010	2.35E+11
4d5	74378	7	4d4 4f	772528	9	143.250	3.13E+11
4d5	83781	7	4d4 4f	772528	9	145.210	1.75E+11
4d5	40776	7	4p5 4d6	774508	7	136.310	1.66E+11
4d5	41965	9	4p5 4d6	774508	7	136.530	1.47E+11
4d5	65922	7	4p5 4d6	774508	7	141.140	1.20E+11
4d5	83781	7	4p5 4d6	774508	7	144.790	1.10E+11
4d5	61198	13	4p5 4d6	775066	13	140.100	5.84E+11
4d5	80062	11	4p5 4d6	775066	13	143.900	3.83E+11
4d5	64662	5	4d4 4f	775674	5	140.660	2.68E+11
4d5	70679	5	4d4 4f	775674	5	141.860	3.09E+11

Table A.5 (Continued).

Lower level			Upper level			λ (Å)	A (s^{-1})
Config.	E (cm^{-1})	$2J$	Config.	E (cm^{-1})	$2J$		
4d5	79875	5	4d4 4f	775674	5	143.740	1.27E+11
4d5	54733	5	4d4 4f	775818	3	138.700	1.17E+11
4d5	65471	3	4d4 4f	775818	3	140.790	5.33E+11
4d5	65922	7	4d4 4f	776272	9	140.790	2.77E+11
4d5	66411	9	4d4 4f	776272	9	140.890	1.27E+11
4d5	77891	7	4d4 4f	776272	9	143.210	2.77E+11
4d5	61198	13	4d4 4f	777118	11	139.700	3.40E+11
4d5	66411	9	4d4 4f	777118	11	140.720	1.68E+11
4d5	82992	9	4d4 4f	777118	11	144.080	2.24E+11
4d5	109450	9	4d4 4f	777118	11	149.790	1.49E+11
4d5	70679	5	4d4 4f	777771	7	141.440	7.20E+11
4d5	64662	5	4d4 4f	778573	3	140.090	6.46E+11
4d5	75837	3	4d4 4f	778573	3	142.320	1.30E+11
4d5	64662	5	4d4 4f	778653	5	140.070	2.02E+11
4d5	70679	5	4d4 4f	778653	5	141.270	1.18E+11
4d5	75837	3	4d4 4f	778653	5	142.300	3.40E+11
4d5	58200	11	4d4 4f	779490	11	138.660	1.16E+11
4d5	73229	9	4d4 4f	779490	11	141.610	2.07E+11
4d5	80062	11	4d4 4f	779490	11	142.990	1.42E+11
4d5	82992	9	4d4 4f	779490	11	143.590	4.04E+11
4d5	64662	5	4p5 4d6	780423	7	139.730	3.16E+11
4d5	73229	9	4p5 4d6	780423	7	141.420	1.11E+11
4d5	74378	7	4p5 4d6	780423	7	141.650	2.05E+11
4d5	66411	9	4d4 4f	782416	9	139.680	1.18E+11
4d5	74378	7	4d4 4f	782416	9	141.250	1.80E+11
4d5	77891	7	4d4 4f	782416	9	141.960	5.00E+11
4d5	65471	3	4d4 4f	782961	1	139.390	3.20E+11
4d5	75837	3	4d4 4f	782961	1	141.430	1.24E+11
4d5	89599	1	4d4 4f	782961	1	144.240	1.38E+11
4d5	99410	3	4d4 4f	782961	1	146.310	2.10E+11
4d5	61198	13	4p5 4d6	783430	13	138.480	3.90E+11
4d5	80062	11	4p5 4d6	783430	13	142.190	6.76E+11
4d5	44301	3	4p5 4d6	784450	3	135.120	1.24E+11
4d5	47166	1	4p5 4d6	784450	3	135.650	2.51E+11
4d5	54733	5	4p5 4d6	784450	3	137.060	3.31E+11
4d5	65471	3	4p5 4d6	784450	3	139.100	2.27E+11
4d5	64662	5	4d4 4f	784938	5	138.850	1.75E+11
4d5	65471	3	4d4 4f	784938	5	139.010	1.40E+11
4d5	75837	3	4d4 4f	784938	5	141.040	2.30E+11
4d5	79875	5	4d4 4f	784938	5	141.850	1.09E+11
4d5	66411	9	4p5 4d6	786227	11	138.940	1.46E+11
4d5	73229	9	4p5 4d6	786227	11	140.270	2.57E+11
4d5	80062	11	4p5 4d6	786227	11	141.630	1.57E+11
4d5	109450	9	4p5 4d6	786227	11	147.780	1.80E+11
4d5	77891	7	4p5 4d6	786242	7	141.190	1.35E+11
4d5	79875	5	4p5 4d6	786242	7	141.590	1.12E+11
4d5	82992	9	4p5 4d6	786242	7	142.210	1.62E+11
4d5	102468	5	4p5 4d6	786242	7	146.260	1.35E+11
4d5	79875	5	4d4 4f	786910	3	141.450	2.73E+11
4d5	89599	1	4d4 4f	786910	3	143.430	3.45E+11
4d5	74378	7	4d4 4f	787126	5	140.320	1.23E+11
4d5	75837	3	4d4 4f	787126	5	140.610	2.65E+11
4d5	99410	3	4d4 4f	787126	5	145.430	2.02E+11

Table A.5 (Continued).

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d5	74378	7	4p5 4d6	787488	7	140.250	1.34E+11
4d5	77891	7	4p5 4d6	787488	7	140.940	2.88E+11
4d5	79875	5	4p5 4d6	787488	7	141.340	2.35E+11
4d5	74378	7	4d4 4f	788903	9	139.970	1.12E+11
4d5	82992	9	4d4 4f	788903	9	141.680	2.13E+11
4d5	83781	7	4d4 4f	788903	9	141.840	3.99E+11
4d5	54669	1	4p5 4d6	789932	1	136.020	3.42E+11
4d5	56267	3	4p5 4d6	789932	1	136.320	3.99E+11
4d5	89599	1	4p5 4d6	789932	1	142.810	1.55E+11
4d5	56267	3	4p5 4d6	790517	1	136.210	2.04E+11
4d5	65471	3	4p5 4d6	790517	1	137.940	1.35E+11
4d5	75837	3	4p5 4d6	790517	1	139.940	1.67E+11
4d5	89599	1	4p5 4d6	790517	1	142.690	4.10E+11
4d5	64662	5	4p5 4d6	791053	3	137.680	1.18E+11
4d5	75837	3	4p5 4d6	791053	3	139.830	6.50E+11
4d5	70679	5	4p5 4d6	791896	5	138.670	1.20E+11
4d5	79875	5	4p5 4d6	791896	5	140.460	3.17E+11
4d5	83781	7	4p5 4d6	791896	5	141.240	1.53E+11
4d5	86510	5	4p5 4d6	791896	5	141.780	1.63E+11
4d5	50677	7	4p5 4d6	792505	7	134.820	1.53E+11
4d5	66411	9	4p5 4d6	792505	7	137.740	1.08E+11
4d5	70679	5	4p5 4d6	792505	7	138.550	1.15E+11
4d5	74378	7	4p5 4d6	792505	7	139.270	2.03E+11
4d5	77891	7	4p5 4d6	792505	7	139.950	1.57E+11
4d5	41340	11	4p5 4d6	793539	9	132.960	1.84E+11
4d5	66411	9	4p5 4d6	793539	9	137.540	1.26E+11
4d5	80062	11	4p5 4d6	793539	9	140.180	1.62E+11
4d5	79875	5	4p5 4d6	796443	3	139.570	2.19E+11
4d5	89599	1	4p5 4d6	796443	3	141.490	1.59E+11
4d5	99410	3	4p5 4d6	796443	3	143.480	2.33E+11
4d5	73229	9	4d4 4f	797221	9	138.140	5.33E+11
4d5	82992	9	4d4 4f	797221	9	140.030	1.33E+11
4d5	110709	7	4d4 4f	797221	9	145.680	1.50E+11
4d5	65922	7	4p5 4d6	798550	5	136.510	1.60E+11
4d5	77891	7	4p5 4d6	798550	5	138.780	1.24E+11
4d5	86510	5	4p5 4d6	798550	5	140.460	2.13E+11
4d5	65922	7	4p5 4d6	798820	5	136.460	1.19E+11
4d5	75837	3	4p5 4d6	798820	5	138.330	1.21E+11
4d5	79875	5	4p5 4d6	798820	5	139.110	1.81E+11
4d5	86510	5	4p5 4d6	798820	5	140.410	1.20E+11
4d5	86510	5	4p5 4d6	799006	7	140.370	6.28E+11
4d5	65922	7	4p5 4d6	801460	5	135.970	4.00E+11
4d5	86510	5	4p5 4d6	801460	5	139.890	2.73E+11
4d5	66411	9	4p5 4d6	802193	7	135.930	2.06E+11
4d5	83781	7	4p5 4d6	802193	7	139.210	3.91E+11
4d5	56267	3	4p5 4d6	803297	1	133.880	1.69E+11
4d5	65471	3	4p5 4d6	803297	1	135.550	3.22E+11
4d5	75837	3	4p5 4d6	803297	1	137.480	5.38E+11
4d5	70679	5	4p5 4d6	803682	3	136.440	5.62E+11
4d5	79875	5	4p5 4d6	803682	3	138.180	1.67E+11
4d5	41340	11	4p5 4d6	804680	9	131.020	1.93E+11
4d5	66411	9	4p5 4d6	804680	9	135.470	1.26E+11
4d5	74378	7	4p5 4d6	804680	9	136.950	1.92E+11

Table A.5 (Continued).

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d5	80062	11	4p5 4d6	804680	9	138.020	1.66E+11
4d5	82992	9	4p5 4d6	804680	9	138.580	2.40E+11
4d5	66411	9	4p5 4d6	808121	7	134.840	2.64E+11
4d5	74378	7	4p5 4d6	808121	7	136.300	1.07E+11
4d5	82992	9	4p5 4d6	808121	7	137.920	2.04E+11
4d5	83781	7	4p5 4d6	808121	7	138.070	1.64E+11
4d5	73229	9	4p5 4d6	810770	7	135.600	4.73E+11
4d5	77891	7	4p5 4d6	810770	7	136.460	1.34E+11
4d5	79875	5	4p5 4d6	810770	7	136.840	1.63E+11
4d5	102468	5	4p5 4d6	810770	7	141.200	1.85E+11
4d5	86510	5	4p5 4d6	811497	3	137.950	3.74E+11
4d5	99410	3	4p5 4d6	811497	3	140.450	1.30E+11
4d5	130330	3	4p5 4d6	811497	3	146.820	2.88E+11
4d5	74378	7	4p5 4d6	812069	5	135.570	2.80E+11
4d5	83781	7	4p5 4d6	812069	5	137.320	3.25E+11
4d5	86510	5	4p5 4d6	813313	3	137.610	3.52E+11
4d5	99410	3	4p5 4d6	813313	3	140.090	2.83E+11
4d5	80062	11	4p5 4d6	814100	11	136.250	6.97E+11
4d5	82992	9	4p5 4d6	814100	11	136.800	3.11E+11
4d5	58200	11	4p5 4d6	818538	9	131.540	2.06E+11
4d5	80062	11	4p5 4d6	818538	9	135.430	1.29E+11
4d5	83781	7	4p5 4d6	818538	9	136.120	2.17E+11
4d5	109450	9	4p5 4d6	818538	9	141.040	1.56E+11
4d5	110709	7	4p5 4d6	818538	9	141.290	2.82E+11
4d5	74378	7	4p5 4d6	819168	5	134.280	1.42E+11
4d5	102468	5	4p5 4d6	819168	5	139.550	4.13E+11
4d5	110709	7	4p5 4d6	819168	5	141.170	1.35E+11
4d5	89599	1	4p5 4d6	822403	3	136.480	4.30E+11
4d5	99410	3	4p5 4d6	822403	3	138.330	1.14E+11
4d5	102468	5	4p5 4d6	822403	3	138.920	3.78E+11
4d5	86510	5	4p5 4d6	823123	7	135.770	1.78E+11
4d5	102468	5	4p5 4d6	823123	7	138.780	2.09E+11
4d5	109450	9	4p5 4d6	823123	7	140.140	3.37E+11
4d5	144068	5	4p5 4d6	823123	7	147.280	1.54E+11
4d5	80062	11	4p5 4d6	824749	9	134.300	2.00E+11
4d5	82992	9	4p5 4d6	824749	9	134.830	2.56E+11
4d5	109450	9	4p5 4d6	824749	9	139.820	4.23E+11
4d5	99410	3	4p5 4d6	826486	5	137.550	2.15E+11
4d5	110709	7	4p5 4d6	826486	5	139.730	3.16E+11
4d5	89599	1	4p5 4d6	827459	1	135.540	3.03E+11
4d5	99410	3	4p5 4d6	827459	1	137.370	6.08E+11
4d5	77891	7	4p5 4d6	829369	5	133.090	2.52E+11
4d5	99410	3	4p5 4d6	829369	5	137.010	3.42E+11
4d5	102468	5	4p5 4d6	829369	5	137.590	2.92E+11
4d5	86510	5	4p5 4d6	829627	3	134.580	1.71E+11
4d5	102468	5	4p5 4d6	829627	3	137.540	1.51E+11
4d5	130330	3	4p5 4d6	829627	3	143.020	1.91E+11
4d5	133097	1	4p5 4d6	829627	3	143.590	1.60E+11
4d5	144068	5	4p5 4d6	829627	3	145.880	2.23E+11
4d5	82992	9	4p5 4d6	831376	7	133.640	3.65E+11
4d5	102468	5	4p5 4d6	831376	7	137.210	1.95E+11
4d5	109450	9	4p5 4d6	831376	7	138.540	1.31E+11
4d5	110709	7	4p5 4d6	831376	7	138.780	2.09E+11

Table A.5 (Continued).

Lower level			Upper level			λ (Å)	A (s^{-1})
Config.	E (cm^{-1})	$2J$	Config.	E (cm^{-1})	$2J$		
4d5	58200	11	4p5 4d6	833277	9	129.030	1.92E+11
4d5	80062	11	4p5 4d6	833277	9	132.780	2.93E+11
4d5	109450	9	4p5 4d6	833277	9	138.170	2.18E+11
4d5	110709	7	4p5 4d6	833277	9	138.410	3.95E+11
4d5	133097	1	4p5 4d6	833826	1	142.730	5.40E+11
4d5	145980	3	4p5 4d6	833826	1	145.400	2.43E+11
4d5	77891	7	4p5 4d6	835156	7	132.070	1.19E+11
4d5	82992	9	4p5 4d6	835156	7	132.970	1.27E+11
4d5	102468	5	4p5 4d6	835156	7	136.500	1.45E+11
4d5	110709	7	4p5 4d6	835156	7	138.050	5.96E+11
4d5	61198	13	4p5 4d6	835737	11	129.120	4.60E+11
4d5	109450	9	4p5 4d6	835737	11	137.700	7.41E+11
4d5	83781	7	4p5 4d6	843163	5	131.700	1.79E+11
4d5	130330	3	4p5 4d6	843163	5	140.300	5.08E+11
4d5	144068	5	4p5 4d6	843163	5	143.060	1.19E+11
4d5	130330	3	4p5 4d6	844344	1	140.070	6.23E+11
4d5	133097	1	4p5 4d6	844344	1	140.620	1.14E+11
4d5	145980	3	4p5 4d6	844344	1	143.210	1.42E+11
4d5	99410	3	4p5 4d6	846399	3	133.890	1.42E+11
4d5	130330	3	4p5 4d6	846399	3	139.670	1.77E+11
4d5	133097	1	4p5 4d6	846399	3	140.210	4.70E+11
4d5	130330	3	4p5 4d6	854575	5	138.090	2.49E+11
4d5	144068	5	4p5 4d6	854575	5	140.760	2.28E+11
4d5	145980	3	4p5 4d6	854575	5	141.140	4.80E+11
4d5	110709	7	4p5 4d6	865558	5	132.490	2.30E+11
4d5	144068	5	4p5 4d6	865558	5	138.620	5.05E+11
4d5	145980	3	4p5 4d6	865558	5	138.990	3.03E+11
4d5	133097	1	4p5 4d6	866045	3	136.450	2.38E+11
4d5	144068	5	4p5 4d6	866045	3	138.530	3.29E+11
4d5	145980	3	4p5 4d6	866045	3	138.890	4.49E+11
4d5	130330	3	4p5 4d6	866644	1	135.830	3.64E+11
4d5	133097	1	4p5 4d6	866644	1	136.340	2.44E+11
4d5	145980	3	4p5 4d6	866644	1	138.780	4.97E+11
4d5	109450	9	4p5 4d6	868096	7	131.830	3.48E+11
4d5	144068	5	4p5 4d6	868096	7	138.130	8.04E+11
4d5	130330	3	4p5 4d6	876493	3	134.040	2.10E+11
4d5	144068	5	4p5 4d6	876493	3	136.550	3.04E+11
4d5	145980	3	4p5 4d6	876493	3	136.910	5.76E+11

Sn xi

Table A.6 Ionization potential 207.109 eV.

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d4	2852	2	4d3 4f	720254	0	139.410	8.56E+11
4d4	0	0	4d3 4f	720731	2	138.760	4.64E+11
4d4	6373	4	4d3 4f	720731	2	140.000	3.33E+11
4d4	2852	2	4d3 5p1	724186	4	138.650	1.78E+11
4d4	9928	6	4d3 5p1	724186	4	140.020	1.66E+11
4d4	2852	2	4d3 5p1	724718	4	138.550	2.16E+11
4d4	9928	6	4d3 5p1	724718	4	139.920	1.57E+11
4d4	0	0	4d3 4f	728109	2	137.360	3.32E+11
4d4	2852	2	4d3 4f	728109	2	137.900	5.23E+11
4d4	6373	4	4d3 4f	728109	2	138.570	1.75E+11
4d4	6373	4	4d3 4f	728304	6	138.530	2.36E+11
4d4	9928	6	4d3 4f	728304	6	139.220	4.06E+11
4d4	13328	8	4d3 4f	728304	6	139.880	2.28E+11
4d4	2852	2	4d3 4f	731644	4	137.230	4.73E+11
4d4	6373	4	4d3 4f	731644	4	137.900	4.88E+11
4d4	9928	6	4d3 4f	731877	8	138.530	1.16E+11
4d4	13328	8	4d3 4f	731877	8	139.190	7.51E+11
4d4	6373	4	4p5 4d5	734929	6	137.270	2.69E+11
4d4	9928	6	4p5 4d5	734929	6	137.950	1.19E+11
4d4	6373	4	4d3 4f	735688	6	137.130	4.39E+11
4d4	9928	6	4d3 4f	735688	6	137.800	2.09E+11
4d4	0	0	4p5 4d5	735806	2	135.920	1.31E+11
4d4	2852	2	4p5 4d5	735806	2	136.450	4.53E+11
4d4	6373	4	4p5 4d5	735806	2	137.110	4.20E+11
4d4	9928	6	4d3 4f	738723	8	137.230	8.51E+11
4d4	13328	8	4d3 4f	738723	8	137.870	1.57E+11
4d4	13328	8	4d3 4f	740852	10	137.470	9.41E+11
4d4	29341	0	4d3 4f	749161	2	138.940	1.60E+11
4d4	39629	4	4d3 4f	749161	2	140.960	1.05E+11
4d4	31484	8	4d3 4f	751473	10	138.910	9.55E+11
4d4	31484	8	4d3 4f	752279	8	138.750	5.20E+11
4d4	37874	6	4d3 4f	752279	8	139.990	3.51E+11
4d4	6373	4	4p5 4d5	752933	4	133.960	3.74E+11
4d4	9928	6	4p5 4d5	752933	4	134.600	5.81E+11
4d4	31484	8	4d3 4f	754122	6	138.400	3.29E+11
4d4	37874	6	4d3 4f	754122	6	139.630	2.06E+11
4d4	39629	4	4d3 4f	754122	6	139.980	1.85E+11
4d4	29341	0	4d3 4f	754309	2	137.950	4.62E+11
4d4	38099	2	4d3 4f	754309	2	139.640	1.08E+11
4d4	39748	12	4d3 4f	754906	14	139.850	9.99E+11
4d4	36827	10	4d3 4f	755183	12	139.220	1.01E+12
4d4	37874	6	4d3 4f	758013	4	138.880	3.43E+11
4d4	38099	2	4d3 4f	758013	4	138.920	3.26E+11
4d4	47218	4	4d3 4f	758013	4	140.700	1.21E+11
4d4	29341	0	4d3 4f	759835	2	136.910	3.28E+11
4d4	39629	4	4d3 4f	759835	2	138.870	3.73E+11
4d4	31484	8	4d3 4f	760376	8	137.210	2.55E+11
4d4	37874	6	4d3 4f	760376	8	138.420	3.63E+11
4d4	42941	8	4d3 4f	760376	8	139.400	2.58E+11

Table A.6 (Continued).

Lower level			Upper level			λ (Å)	A (s^{-1})
Config.	E (cm^{-1})	$2J$	Config.	E (cm^{-1})	$2J$		
4d4	36827	10	4d3 4f	760843	10	138.140	2.96E+11
4d4	42941	8	4d3 4f	760843	10	139.310	4.41E+11
4d4	37874	6	4p5 4d5	761196	4	138.270	1.55E+11
4d4	38099	2	4p5 4d5	761196	4	138.310	3.40E+11
4d4	39629	4	4p5 4d5	761196	4	138.600	3.84E+11
4d4	37874	6	4d3 4f	761281	6	138.250	3.43E+11
4d4	39629	4	4d3 4f	761281	6	138.590	5.82E+11
4d4	47218	4	4d3 4f	761931	6	139.930	3.24E+11
4d4	36827	10	4d3 4f	764584	8	137.430	3.86E+11
4d4	47303	8	4d3 4f	764584	8	139.430	1.11E+11
4d4	53999	6	4d3 4f	764584	8	140.750	1.06E+11
4d4	13328	8	4d3 4f	765857	6	132.900	2.59E+11
4d4	47303	8	4d3 4f	765857	6	139.190	1.83E+11
4d4	38099	2	4p5 4d5	766755	0	137.260	9.77E+11
4d4	39748	12	4d3 4f	766861	10	137.550	2.38E+11
4d4	47303	8	4d3 4f	766861	10	138.990	4.40E+11
4d4	85910	8	4d3 4f	766861	10	146.870	1.15E+11
4d4	39748	12	4d3 4f	766950	12	137.530	4.37E+11
4d4	51907	10	4d3 4f	766950	12	139.870	5.01E+11
4d4	9928	6	4p5 4d5	767733	6	131.980	1.07E+11
4d4	13328	8	4p5 4d5	767733	6	132.570	4.14E+11
4d4	53999	6	4p5 4d5	767733	6	140.130	1.97E+11
4d4	38099	2	4d3 4f	768058	2	137.010	5.82E+11
4d4	56337	4	4d3 4f	768058	2	140.520	1.03E+11
4d4	31484	8	4p5 4d5	769593	8	135.500	1.26E+11
4d4	37874	6	4p5 4d5	769593	8	136.680	2.05E+11
4d4	42941	8	4p5 4d5	769593	8	137.630	4.80E+11
4d4	39629	4	4d3 4f	770410	4	136.860	1.39E+11
4d4	47218	4	4d3 4f	770410	4	138.290	3.31E+11
4d4	83704	4	4d3 4f	770410	4	145.640	1.10E+11
4d4	38099	2	4d3 4f	771386	4	136.390	1.04E+11
4d4	48459	6	4d3 4f	771386	4	138.340	4.07E+11
4d4	58464	2	4d3 4f	771386	4	140.280	2.67E+11
4d4	56185	12	4d3 4f	771665	14	139.780	9.89E+11
4d4	39748	12	4p5 4d5	773249	10	136.350	2.03E+11
4d4	42941	8	4p5 4d5	773249	10	136.950	1.51E+11
4d4	47303	8	4p5 4d5	773249	10	137.770	1.42E+11
4d4	51907	10	4p5 4d5	773249	10	138.650	3.35E+11
4d4	36827	10	4d3 4f	773827	10	135.700	4.82E+11
4d4	47303	8	4d3 4f	773827	10	137.660	3.37E+11
4d4	47303	8	4d3 4f	774165	8	137.590	2.08E+11
4d4	48459	6	4d3 4f	774165	8	137.810	1.98E+11
4d4	51907	10	4d3 4f	774165	8	138.470	1.26E+11
4d4	53999	6	4d3 4f	774165	8	138.870	2.45E+11
4d4	47218	4	4d3 4f	775852	2	137.260	5.14E+11
4d4	58464	2	4d3 4f	775852	2	139.410	1.34E+11
4d4	42941	8	4p5 4d5	775960	6	136.440	1.80E+11
4d4	48459	6	4p5 4d5	775960	6	137.470	3.29E+11
4d4	38099	2	4p5 4d5	775977	4	135.540	1.01E+11
4d4	39629	4	4p5 4d5	775977	4	135.820	1.24E+11
4d4	53999	6	4p5 4d5	775977	4	138.530	5.05E+11
4d4	47303	8	4p5 4d5	776132	8	137.220	2.43E+11
4d4	48459	6	4p5 4d5	776132	8	137.440	6.23E+11

Table A.6 (Continued).

Lower level			Upper level			λ (Å)	A (s^{-1})
Config.	E (cm^{-1})	$2J$	Config.	E (cm^{-1})	$2J$		
4d4	47218	4	4d3 4f	778911	6	136.690	2.59E+11
4d4	56337	4	4d3 4f	778911	6	138.410	4.06E+11
4d4	37874	6	4d3 4f	781907	4	134.420	1.20E+11
4d4	47218	4	4d3 4f	781907	4	136.130	4.60E+11
4d4	56337	4	4d3 4f	781907	4	137.840	1.08E+11
4d4	39748	12	4p5 4d5	782804	12	134.600	5.35E+11
4d4	51907	10	4p5 4d5	782804	12	136.830	3.33E+11
4d4	56185	12	4p5 4d5	782804	12	137.640	2.04E+11
4d4	31484	8	4d3 4f	783127	6	133.060	1.45E+11
4d4	47218	4	4d3 4f	783127	6	135.900	1.39E+11
4d4	48459	6	4d3 4f	783127	6	136.130	2.80E+11
4d4	39629	4	4d3 4f	783349	2	134.480	1.34E+11
4d4	47218	4	4d3 4f	783349	2	135.860	1.04E+11
4d4	58464	2	4d3 4f	783349	2	137.970	4.98E+11
4d4	67703	0	4d3 4f	783349	2	139.750	2.04E+11
4d4	47218	4	4p5 4d5	784358	2	135.680	1.16E+11
4d4	56337	4	4p5 4d5	784358	2	137.380	3.46E+11
4d4	67703	0	4p5 4d5	784358	2	139.550	1.62E+11
4d4	36827	10	4p5 4d5	784587	8	133.750	2.26E+11
4d4	47303	8	4p5 4d5	784587	8	135.650	1.49E+11
4d4	53999	6	4p5 4d5	784587	8	136.890	1.96E+11
4d4	63979	8	4p5 4d5	784587	8	138.790	1.17E+11
4d4	42941	8	4p5 4d5	785628	10	134.660	1.84E+11
4d4	51907	10	4p5 4d5	785628	10	136.310	3.87E+11
4d4	56185	12	4p5 4d5	785628	10	137.110	1.87E+11
4d4	58464	2	4p5 4d5	788409	0	137.010	6.24E+11
4d4	91473	2	4p5 4d5	788409	0	143.500	1.99E+11
4d4	47303	8	4p5 4d5	789184	6	134.810	3.30E+11
4d4	56337	4	4p5 4d5	789184	6	136.470	1.35E+11
4d4	70036	4	4p5 4d5	789184	6	139.070	2.06E+11
4d4	51907	10	4d3 4f	791030	8	135.310	1.66E+11
4d4	74795	6	4d3 4f	791030	8	139.640	6.58E+11
4d4	56337	4	4p5 4d5	791478	4	136.040	5.10E+11
4d4	58464	2	4p5 4d5	791478	4	136.440	1.88E+11
4d4	74795	6	4p5 4d5	791478	4	139.550	1.35E+11
4d4	31484	8	4p5 4d5	795039	6	130.980	1.35E+11
4d4	53999	6	4p5 4d5	795039	6	134.960	3.45E+11
4d4	63979	8	4p5 4d5	795039	6	136.800	1.38E+11
4d4	37874	6	4p5 4d5	795225	4	132.060	1.85E+11
4d4	39629	4	4p5 4d5	795225	4	132.360	2.66E+11
4d4	56337	4	4p5 4d5	795225	4	135.350	1.38E+11
4d4	58464	2	4p5 4d5	795225	4	135.750	2.32E+11
4d4	74795	6	4p5 4d5	795225	4	138.820	1.14E+11
4d4	39748	12	4p5 4d5	795358	10	132.360	1.11E+11
4d4	56185	12	4p5 4d5	795358	10	135.300	3.54E+11
4d4	98034	8	4p5 4d5	795358	10	143.420	2.05E+11
4d4	56337	4	4p5 4d5	795497	2	135.310	1.92E+11
4d4	58464	2	4p5 4d5	795497	2	135.700	1.33E+11
4d4	67703	0	4p5 4d5	795497	2	137.420	1.03E+11
4d4	70036	4	4p5 4d5	795497	2	137.860	3.05E+11
4d4	37874	6	4p5 4d5	797859	6	131.600	1.45E+11
4d4	42941	8	4p5 4d5	797859	6	132.480	1.27E+11
4d4	56337	4	4p5 4d5	797859	6	134.870	1.33E+11

Table A.6 (Continued).

Lower level			Upper level			λ (Å)	A (s^{-1})
Config.	E (cm^{-1})	$2J$	Config.	E (cm^{-1})	$2J$		
4d4	70036	4	4p5 4d5	797859	6	137.410	1.83E+11
4d4	48459	6	4p5 4d5	798318	4	133.370	1.73E+11
4d4	70036	4	4p5 4d5	798318	4	137.330	3.04E+11
4d4	74795	6	4p5 4d5	798318	4	138.230	1.55E+11
4d4	91473	2	4p5 4d5	798318	4	141.490	1.12E+11
4d4	47303	8	4p5 4d5	799506	8	132.960	1.16E+11
4d4	63979	8	4p5 4d5	799506	8	135.970	6.75E+11
4d4	63979	8	4p5 4d5	800556	10	135.780	8.34E+11
4d4	42941	8	4p5 4d5	802047	6	131.750	1.40E+11
4d4	63979	8	4p5 4d5	802047	6	135.510	1.70E+11
4d4	70036	4	4p5 4d5	802047	6	136.630	1.93E+11
4d4	88023	4	4d3 4f	802752	2	139.930	3.25E+11
4d4	95490	0	4d3 4f	802752	2	141.410	2.07E+11
4d4	51907	10	4p5 4d5	803797	8	133.010	2.37E+11
4d4	53999	6	4p5 4d5	803797	8	133.390	1.80E+11
4d4	74795	6	4p5 4d5	803797	8	137.190	1.20E+11
4d4	89460	6	4p5 4d5	803797	8	140.010	2.94E+11
4d4	51907	10	4p5 4d5	806209	12	132.590	2.31E+11
4d4	56185	12	4p5 4d5	806209	12	133.350	8.40E+11
4d4	70036	4	4d3 4f	806298	4	135.840	4.80E+11
4d4	89460	6	4d3 4f	806298	4	139.520	1.29E+11
4d4	91473	2	4d3 4f	806298	4	139.910	1.79E+11
4d4	70036	4	4d3 4f	808879	6	135.360	1.91E+11
4d4	74795	6	4d3 4f	808879	6	136.240	3.73E+11
4d4	88023	4	4d3 4f	808879	6	138.740	2.43E+11
4d4	58464	2	4p5 4d5	810170	4	133.050	1.52E+11
4d4	74795	6	4p5 4d5	810170	4	136.000	3.38E+11
4d4	63979	8	4p5 4d5	812792	6	133.560	2.75E+11
4d4	83704	4	4p5 4d5	812792	6	137.170	2.33E+11
4d4	85910	8	4p5 4d5	812792	6	137.590	1.48E+11
4d4	67703	0	4p5 4d5	816269	2	133.600	2.72E+11
4d4	70036	4	4p5 4d5	816269	2	134.020	3.75E+11
4d4	83704	4	4p5 4d5	817008	2	136.390	3.24E+11
4d4	91473	2	4p5 4d5	817008	2	137.850	2.65E+11
4d4	51907	10	4p5 4d5	818165	8	130.520	2.68E+11
4d4	74795	6	4p5 4d5	818165	8	134.540	1.27E+11
4d4	89460	6	4p5 4d5	818165	8	137.250	4.44E+11
4d4	98034	8	4p5 4d5	818165	8	138.880	1.04E+11
4d4	63979	8	4p5 4d5	818954	6	132.470	2.02E+11
4d4	74795	6	4p5 4d5	818954	6	134.400	1.04E+11
4d4	88023	4	4p5 4d5	818954	6	136.830	3.82E+11
4d4	89460	6	4p5 4d5	818954	6	137.100	1.17E+11
4d4	83704	4	4p5 4d5	822121	4	135.440	5.89E+11
4d4	88023	4	4p5 4d5	822121	4	136.240	2.74E+11
4d4	39748	12	4p5 4d5	822323	10	127.800	2.28E+11
4d4	85910	8	4p5 4d5	822323	10	135.810	7.39E+11
4d4	83704	4	4p5 4d5	825403	6	134.840	2.69E+11
4d4	85910	8	4p5 4d5	825403	6	135.240	1.38E+11
4d4	89460	6	4p5 4d5	825403	6	135.900	1.67E+11
4d4	98034	8	4p5 4d5	825403	6	137.500	2.34E+11
4d4	56337	4	4p5 4d5	825941	2	129.950	1.58E+11
4d4	83704	4	4p5 4d5	825941	2	134.740	2.63E+11
4d4	91473	2	4p5 4d5	825941	2	136.170	3.01E+11

Table A.6 (Continued).

Lower level			Upper level			λ (Å)	A (s^{-1})
Config.	E (cm^{-1})	$2J$	Config.	E (cm^{-1})	$2J$		
4d4	95490	0	4p5 4d5	825941	2	136.920	1.12E+11
4d4	85910	8	4p5 4d5	827378	8	134.880	8.15E+11
4d4	83704	4	4p5 4d5	828976	4	134.200	1.45E+11
4d4	88023	4	4p5 4d5	828976	4	134.980	6.54E+11
4d4	58464	2	4p5 4d5	829016	0	129.790	3.17E+11
4d4	91473	2	4p5 4d5	829016	0	135.600	8.36E+11
4d4	74795	6	4p5 4d5	830207	6	132.390	1.52E+11
4d4	83704	4	4p5 4d5	830207	6	133.970	1.85E+11
4d4	85910	8	4p5 4d5	830207	6	134.370	2.85E+11
4d4	89460	6	4p5 4d5	830207	6	135.020	1.52E+11
4d4	89460	6	4p5 4d5	835298	4	134.090	4.39E+11
4d4	91473	2	4p5 4d5	835298	4	134.460	4.73E+11
4d4	125578	4	4p5 4d5	835298	4	140.920	1.01E+11
4d4	74795	6	4p5 4d5	835531	6	131.470	2.84E+11
4d4	89460	6	4p5 4d5	835531	6	134.050	4.55E+11
4d4	98034	8	4p5 4d5	835531	6	135.610	2.13E+11
4d4	56185	12	4p5 4d5	835729	10	128.300	3.55E+11
4d4	98034	8	4p5 4d5	835729	10	135.570	6.99E+11
4d4	88023	4	4p5 4d5	837765	2	133.400	3.71E+11
4d4	91473	2	4p5 4d5	837765	2	134.010	1.02E+11
4d4	95490	0	4p5 4d5	837765	2	134.740	5.71E+11
4d4	89460	6	4p5 4d5	839544	8	133.330	1.84E+11
4d4	98034	8	4p5 4d5	839544	8	134.880	8.01E+11
4d4	91473	2	4p5 4d5	841656	4	133.320	1.13E+11
4d4	125578	4	4p5 4d5	841656	4	139.670	7.23E+11
4d4	125578	4	4p5 4d5	859030	2	136.360	7.33E+11
4d4	160342	0	4p5 4d5	859030	2	143.140	1.04E+11
4d4	98034	8	4p5 4d5	863985	6	130.570	2.19E+11
4d4	125578	4	4p5 4d5	863985	6	135.440	9.00E+11
4d4	125578	4	4p5 4d5	888549	2	131.080	2.55E+11
4d4	160342	0	4p5 4d5	888549	2	137.340	8.74E+11

Sn xii**Table A.7** Ionization potential 231.815 eV.

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d3	45091	11	4d2 5p	714578	9	149.390	1.50E+11
4d3	48104	9	4d2 5p	727005	7	147.310	9.89E+10
4d3	0	3	4p5 4d4	731107	3	136.800	1.34E+11
4d3	0	3	4d2 4f	731595	3	136.700	6.14E+11
4d3	0	3	4d2 4f	738323	5	135.460	9.68E+11
4d3	5629	5	4d2 4f	740516	5	136.090	8.23E+11
4d3	24757	3	4d2 5p	741654	3	139.510	1.17E+11
4d3	0	3	4d2 4f	743004	1	134.600	4.99E+11
4d3	26697	1	4d2 4f	743004	1	139.620	2.01E+11
4d3	5629	5	4d2 4f	744572	3	135.340	3.46E+11
4d3	24757	3	4d2 4f	744572	3	138.940	2.65E+11
4d3	5629	5	4d2 4f	745155	7	135.240	7.97E+11
4d3	11397	7	4d2 4f	745155	7	136.300	1.84E+11
4d3	11397	7	4d2 4f	749916	5	135.420	4.69E+11
4d3	24757	3	4d2 4f	749916	5	137.920	1.46E+11
4d3	34724	5	4d2 4f	749916	5	139.840	1.59E+11
4d3	26697	1	4d2 4f	750078	3	138.260	1.33E+11
4d3	34724	5	4d2 4f	750078	3	139.810	3.83E+11
4d3	11397	7	4d2 4f	751395	9	135.150	8.15E+11
4d3	16610	9	4d2 4f	751395	9	136.110	1.62E+11
4d3	5629	5	4p5 4d4	751613	7	134.070	1.46E+11
4d3	11397	7	4p5 4d4	751613	7	135.110	6.59E+11
4d3	16610	9	4d2 4f	754065	11	135.620	8.64E+11
4d3	33281	9	4d2 4f	754065	11	138.750	1.12E+11
4d3	16610	9	4p5 4d4	755224	7	135.410	4.17E+11
4d3	34724	5	4p5 4d4	755224	7	138.810	2.75E+11
4d3	96730	3	4d2 5p	760460	1	150.680	1.03E+11
4d3	11397	7	4p5 4d4	760838	9	133.450	1.31E+11
4d3	16610	9	4p5 4d4	760838	9	134.380	7.11E+11
4d3	11397	7	4p5 4d4	764047	5	132.880	1.77E+11
4d3	24757	3	4p5 4d4	764047	5	135.280	7.16E+11
4d3	5629	5	4d2 4f	765134	3	131.680	2.43E+11
4d3	24757	3	4d2 4f	765134	3	135.080	1.68E+11
4d3	26697	1	4d2 4f	765134	3	135.440	4.23E+11
4d3	0	3	4d2 4f	766577	1	130.470	2.81E+11
4d3	26697	1	4d2 4f	766577	1	135.170	6.99E+11
4d3	33281	9	4d2 4f	768932	11	135.950	7.73E+11
4d3	26697	1	4d2 4f	769903	3	134.570	1.85E+11
4d3	40007	3	4d2 4f	769903	3	137.020	5.77E+11
4d3	32221	7	4d2 4f	770948	9	135.380	9.16E+11
4d3	0	3	4p5 4d4	771992	1	129.550	1.27E+11
4d3	24757	3	4p5 4d4	771992	1	133.840	6.69E+11
4d3	42399	1	4p5 4d4	771992	1	137.080	2.00E+11
4d3	32221	7	4d2 4f	772892	7	135.030	4.67E+11
4d3	33281	9	4d2 4f	772892	7	135.220	1.35E+11
4d3	64020	5	4d2 4f	772892	7	141.090	1.57E+11
4d3	32221	7	4d2 4f	773568	7	134.910	3.33E+11
4d3	33281	9	4d2 4f	773568	7	135.100	3.79E+11
4d3	32221	7	4p5 4d4	773941	5	134.840	4.19E+11

Table A.7 (Continued).

Lower level			Upper level			λ (Å)	A (s^{-1})
Config.	E (cm^{-1})	$2J$	Config.	E (cm^{-1})	$2J$		
4d3	40007	3	4p5 4d4	773941	5	136.270	1.70E+11
4d3	64020	5	4p5 4d4	773941	5	140.880	1.05E+11
4d3	45091	11	4d2 4f	776868	13	136.670	9.66E+11
4d3	32221	7	4d2 4f	777366	5	134.220	1.54E+11
4d3	40007	3	4d2 4f	777366	5	135.640	3.97E+11
4d3	49668	5	4d2 4f	777366	5	137.440	2.58E+11
4d3	24757	3	4d2 4f	779322	1	132.540	1.89E+11
4d3	42399	1	4d2 4f	779322	1	135.720	6.22E+11
4d3	33281	9	4p5 4d4	779925	9	133.950	9.21E+11
4d3	42399	1	4p5 4d4	780470	3	135.500	5.57E+11
4d3	64020	5	4p5 4d4	780470	3	139.590	1.13E+11
4d3	34724	5	4p5 4d4	782225	3	133.800	2.02E+11
4d3	40007	3	4p5 4d4	782225	3	134.750	1.14E+11
4d3	49668	5	4p5 4d4	782225	3	136.520	2.72E+11
4d3	64020	5	4p5 4d4	782225	3	139.250	1.04E+11
4d3	45091	11	4p5 4d4	784326	9	135.290	3.69E+11
4d3	63493	7	4p5 4d4	784326	9	138.750	3.30E+11
4d3	11397	7	4p5 4d4	784454	5	129.370	1.42E+11
4d3	32221	7	4p5 4d4	784454	5	132.950	9.75E+10
4d3	34724	5	4p5 4d4	784454	5	133.400	3.00E+11
4d3	40007	3	4p5 4d4	784454	5	134.340	1.72E+11
4d3	63493	7	4p5 4d4	784454	5	138.720	1.06E+11
4d3	16610	9	4d2 4f	784935	7	130.170	2.02E+11
4d3	34724	5	4d2 4f	784935	7	133.310	2.22E+11
4d3	49668	5	4d2 4f	784935	7	136.020	4.12E+11
4d3	63493	7	4d2 4f	784935	7	138.630	9.90E+10
4d3	16610	9	4p5 4d4	788792	7	129.520	1.57E+11
4d3	34724	5	4p5 4d4	788792	7	132.630	2.88E+11
4d3	48104	9	4p5 4d4	788792	7	135.030	1.80E+11
4d3	49668	5	4p5 4d4	788792	7	135.310	2.36E+11
4d3	24757	3	4p5 4d4	791228	3	130.480	1.10E+11
4d3	26697	1	4p5 4d4	791228	3	130.810	1.34E+11
4d3	34724	5	4p5 4d4	791228	3	132.200	1.66E+11
4d3	49668	5	4p5 4d4	791228	3	134.870	1.64E+11
4d3	64020	5	4p5 4d4	791228	3	137.530	1.97E+11
4d3	34724	5	4p5 4d4	792610	5	131.960	4.33E+11
4d3	49668	5	4p5 4d4	792610	5	134.620	2.47E+11
4d3	40007	3	4p5 4d4	792815	1	132.850	5.71E+11
4d3	55334	3	4p5 4d4	792815	1	135.610	3.19E+11
4d3	45091	11	4p5 4d4	792950	11	133.730	1.64E+11
4d3	48104	9	4p5 4d4	792950	11	134.270	7.01E+11
4d3	48104	9	4p5 4d4	795711	9	133.780	8.55E+11
4d3	34724	5	4p5 4d4	798901	7	130.880	1.20E+11
4d3	48104	9	4p5 4d4	798901	7	133.210	4.06E+11
4d3	40007	3	4p5 4d4	799202	1	131.730	3.72E+11
4d3	55334	3	4p5 4d4	799202	1	134.450	5.09E+11
4d3	55334	3	4p5 4d4	800499	5	134.210	7.93E+11
4d3	55334	3	4p5 4d4	804237	3	133.540	7.58E+11
4d3	45091	11	4p5 4d4	807088	11	131.250	8.35E+11
4d3	48104	9	4p5 4d4	807088	11	131.770	2.32E+11
4d3	40007	3	4p5 4d4	808295	5	130.180	1.22E+11
4d3	63493	7	4p5 4d4	808295	5	134.280	2.15E+11
4d3	64020	5	4p5 4d4	808295	5	134.380	3.07E+11

Table A.7 (Continued).

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d3	42399	1	4p5 4d4	809768	3	130.330	1.89E+11
4d3	49668	5	4p5 4d4	809768	3	131.580	4.09E+11
4d3	55334	3	4p5 4d4	809768	3	132.570	1.09E+11
4d3	64020	5	4p5 4d4	809768	3	134.110	2.01E+11
4d3	49668	5	4p5 4d4	812431	7	131.120	2.25E+11
4d3	63493	7	4p5 4d4	812431	7	133.540	7.05E+11
4d3	45091	11	4p5 4d4	815155	9	129.870	3.59E+11
4d3	63493	7	4p5 4d4	815155	9	133.050	6.12E+11
4d3	49668	5	4p5 4d4	816879	5	130.360	1.80E+11
4d3	63493	7	4p5 4d4	816879	5	132.750	2.61E+11
4d3	64020	5	4p5 4d4	816879	5	132.840	4.40E+11
4d3	33281	9	4p5 4d4	818530	7	127.360	1.53E+11
4d3	48104	9	4p5 4d4	818530	7	129.810	1.92E+11
4d3	64020	5	4p5 4d4	818530	7	132.550	6.75E+11
4d3	96730	3	4p5 4d4	828695	1	136.640	7.21E+11
4d3	96190	5	4p5 4d4	832094	3	135.900	6.57E+11
4d3	96730	3	4d2 4f	833018	5	135.830	8.02E+11
4d3	96190	5	4p5 4d4	839228	7	134.600	9.17E+11
4d3	63493	7	4p5 4d4	839436	5	128.890	1.03E+11
4d3	96190	5	4p5 4d4	839436	5	134.560	8.82E+11
4d3	96730	3	4p5 4d4	845861	3	133.500	9.75E+11

Sn XIII**Table A.8** Ionization potential 257.578 eV.

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d2	0	4	4d1 5p	732639	2	136.510	2.11E+11
4d2	0	4	4d1 4f	740541	2	135.050	4.55E+11
4d2	26333	0	4d1 4f	740541	2	140.030	1.36E+11
4d2	9648	6	4d1 5p	742344	4	136.500	1.59E+11
4d2	0	4	4d1 4f	743619	6	134.490	6.93E+11
4d2	0	4	4d1 5p	745906	6	134.080	2.08E+11
4d2	0	4	4d1 5p	748170	4	133.680	3.33E+11
4d2	9648	6	4d1 5p	748170	4	135.420	1.20E+11
4d2	0	4	4d1 5p	749698	4	133.400	4.45E+11
4d2	9648	6	4d1 5p	749698	4	135.140	1.17E+11
4d2	18647	8	4d1 5p	755281	6	135.770	3.01E+11
4d2	9648	6	4d1 5p	756503	4	133.910	3.15E+11
4d2	9648	6	4d1 4f	757708	8	133.700	8.56E+11
4d2	26333	0	4d1 5p	758159	2	136.660	1.37E+11
4d2	27681	4	4d1 5p	758159	2	136.910	2.13E+11
4d2	31362	2	4d1 5p	758159	2	137.610	2.23E+11
4d2	9648	6	4d1 4f	758181	6	133.610	6.99E+11

Table A.8 (Continued).

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d2	31362	2	4d1 5p	759970	0	137.260	6.20E+11
4d2	18647	8	4p5 4d3	765342	6	133.940	3.01E+11
4d2	27681	4	4p5 4d3	765342	6	135.580	1.58E+11
4d2	31362	2	4d1 5p	765409	2	136.250	1.94E+11
4d2	18647	8	4d1 5p	766656	8	133.700	2.68E+11
4d2	27681	4	4p5 4d3	766848	4	135.300	7.46E+11
4d2	31362	2	4d1 5p	767997	0	135.770	2.24E+11
4d2	18647	8	4d1 4f	768673	10	133.340	8.36E+11
4d2	42191	4	4d1 5p	769073	4	137.590	1.37E+11
4d2	42621	8	4d1 5p	771657	6	137.180	3.40E+11
4d2	18647	8	4p5 4d3	777702	8	131.760	6.48E+11
4d2	26333	0	4d1 5p	780328	2	132.640	1.44E+11
4d2	27681	4	4d1 5p	780328	2	132.880	1.82E+11
4d2	18647	8	4p5 4d3	780527	6	131.270	1.97E+11
4d2	27681	4	4p5 4d3	780527	6	132.850	4.58E+11
4d2	0	4	4p5 4d3	782764	2	127.770	1.93E+11
4d2	26333	0	4p5 4d3	782764	2	132.220	4.36E+11
4d2	31362	2	4p5 4d3	782764	2	133.100	1.48E+11
4d2	9648	6	4p5 4d3	787121	4	128.640	1.45E+11
4d2	31362	2	4p5 4d3	787121	4	132.330	6.29E+11
4d2	27681	4	4p5 4d3	789627	2	131.260	4.47E+11
4d2	31362	2	4p5 4d3	789627	2	131.900	3.46E+11
4d2	42191	4	4p5 4d3	789627	2	133.810	1.31E+11
4d2	42191	4	4p5 4d3	791153	4	133.530	6.81E+11
4d2	42191	4	4p5 4d3	793042	2	133.200	6.23E+11
4d2	42621	8	4d1 4f	793153	10	133.250	8.27E+11
4d2	42191	4	4p5 4d3	795438	6	132.770	5.75E+11
4d2	42621	8	4p5 4d3	795438	6	132.850	1.26E+11
4d2	42191	4	4p5 4d3	800154	6	131.950	3.44E+11
4d2	42621	8	4p5 4d3	800154	6	132.020	3.11E+11
4d2	42621	8	4p5 4d3	800237	8	132.010	9.60E+11
4d2	88721	0	4p5 4d3	829362	2	135.030	8.55E+11

Sn xiv

Table A.9 Ionization potential 282.328 eV.

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4d	0	3	4p5 4d2	557675	5	179.340	4.20E+09
4d	0	3	4p5 4d2	575548	5	173.770	3.17E+09
4d	0	3	4p5 4d2	590211	3	169.450	9.97E+09
4d	13210	5	4p5 4d2	596028	5	171.600	4.94E+09
4d	13210	5	4p5 4d2	607489	5	168.290	4.90E+09
4d	0	3	4p5 4d2	613546	1	163.010	1.88E+10
4d	13210	5	4p5 4d2	625298	3	163.390	2.17E+10
4d	0	3	4p5 4d2	636044	5	157.240	2.73E+09
4d	13210	5	4p5 4d2	636044	5	160.580	7.31E+09
4d	13210	5	4p5 4d2	649938	7	157.070	9.66E+09
4d	0	3	4p5 4d2	689599	1	145.030	8.73E+09
4d	0	3	4p5 4d2	738708	1	135.390	6.87E+11
4d	0	3	4f	744790	5	134.280	7.51E+11
4d	13210	5	4f	744790	5	136.710	4.45E+10
4d	0	3	4p5 4d2	756741	3	132.160	8.59E+11
4d	13210	5	4p5 4d2	758974	3	134.110	7.32E+11
4d	0	3	4p5 4d2	761690	5	131.300	4.35E+10
4d	13210	5	4p5 4d2	761690	5	133.620	7.93E+11
4d	13210	5	4p5 4d2	771128	7	131.960	8.19E+11
4d	0	3	5p	786280	1	127.200	7.43E+10
4d	13210	5	5p	811760	3	125.240	4.43E+10
4d	0	3	4p5 4d 5s	1185448	1	84.366	9.80E+09
4d	0	3	4p5 4d 5s	1194210	3	83.747	7.60E+09
4d	13210	5	4p5 4d 5s	1194210	3	84.684	5.75E+09
4d	0	3	4p5 4d 5s	1203945	1	83.070	1.41E+11
4d	13210	5	4p5 4d 5s	1211070	5	83.492	6.80E+09
4d	13210	5	4p5 4d 5s	1213763	7	83.305	5.87E+09
4d	0	3	4p5 4d 5s	1218530	5	82.076	7.72E+10
4d	13210	5	4p5 4d 5s	1218530	5	82.976	5.04E+09
4d	0	3	4p5 4d 5s	1221125	3	81.902	7.04E+10
4d	13210	5	4p5 4d 5s	1221125	3	82.797	4.91E+10
4d	13210	5	4p5 4d 5s	1226599	7	82.424	1.04E+11
4d	0	3	4p5 4d 5s	1229831	3	81.322	1.65E+10
4d	13210	5	4p5 4d 5s	1229831	3	82.205	4.99E+10
4d	0	3	4p5 4d 5s	1231958	5	81.181	6.52E+10
4d	13210	5	4p5 4d 5s	1231958	5	82.061	1.56E+10
4d	13210	5	4p5 4d 5s	1247866	7	81.004	2.47E+10
4d	13210	5	4p5 4d 5s	1254860	5	80.548	8.57E+10
4d	0	3	4p5 4d 5s	1278338	3	78.236	3.25E+10
4d	13210	5	4p5 4d 5s	1278338	3	79.053	1.54E+10
4d	0	3	4p5 4d 5s	1290489	3	77.499	6.99E+10
4d	13210	5	4p5 4d 5s	1290489	3	78.301	6.29E+09
4d	0	3	4p5 4d 5s	1295074	5	77.225	9.05E+10
4d	13210	5	4p5 4d 5s	1307132	5	77.294	4.73E+10
4d	13210	5	4p5 4d 5s	1312421	3	76.979	4.72E+10
4d	13210	5	4p5 4d 5s	1316067	7	76.764	6.79E+10
4d	13210	5	4p5 4d 5s	1320629	5	76.496	5.54E+10
4d	0	3	4p5 4d 5s	1435796	1	69.656	5.10E+10
4d	0	3	4p5 4d 5s	1435919	3	69.650	1.10E+10
4d	13210	5	4p5 4d 5s	1435919	3	70.297	3.32E+10

Sn xv

Table A.10 Ionization potential 383.804 eV.

Lower level			Upper level			λ (Å)	A (s ⁻¹)
Config.	E (cm ⁻¹)	$2J$	Config.	E (cm ⁻¹)	$2J$		
4p6	0	0	4p5 4d	537619	2	186.030	9.96E+07
4p6	0	0	4p5 4d	618618	2	161.670	1.91E+10
4p6	0	0	4p5 4d	775716	2	128.930	8.10E+11
4p6	0	0	4p5 5s	1287633	2	77.672	1.49E+11
4p6	0	0	4p5 5s	1363425	2	73.354	8.42E+10

References

1. The FAC software can be obtained at <http://kipac-tree.stanford.edu/fac/>.
2. J. Sugar, V. Kaufman, and W. L. Rowan, “Rb-like spectra: Pd X to Nd XXIV,” *J. Opt. Soc. Am. B* **9**(11), 1959 (1992).



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Chapter 5

Atomic Physics of Highly Charged Ions and the Case for Sn as a Source Material

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5.1 Introduction and Background

Projection lithography schemes based on 13.5-nm multilayer mirrors (MLMs) have been under intense scrutiny since the mid-1990s.¹ Stearns and coworkers² first demonstrated a reflectivity of 61% at this wavelength using Mo/Si multilayer optics, a figure that has been improved in the intervening period to a present value close to 72%. Ceglio and Hawryluk³ proposed that a suitable scheme would require a 1% conversion efficiency (CE) of incident laser pulse energy to soft x rays in a 0.3-nm band centered at this peak. Kauffman et al.⁴ attained this figure using 7.5-ns, 300-mJ frequency-doubled Nd:YAG pulses focused to a power density of $2 \times 10^{11} \text{ W cm}^{-2}$ onto a tin target. This figure has now been revised upwards because of the increased costs of producing a suitable exposure tool, to better than

3% CE into 2% bandwidth, because this is necessary for the successful commercialization of such a source.

Because of the debris problems associated with the use of tin, other target materials were sought with strong emission in the 13–14-nm region. Jin and Richardson⁵ used mass-limited water ice targets that emitted O VI lines near 13 nm to limit the debris. Shevelko et al.⁶ subsequently undertook an extensive study of the spectra of a large number of elements from LPPs with a KrF excimer laser focused to a power density of $10^{12} \text{ W cm}^{-2}$ onto planar targets, including tin, and found that the maximum intensity was in fact obtained for Ge and Re targets under these conditions. However, all of their work was with solid targets that produced significant debris in the form of both ions and particulates of various sizes. The need to reduce particulate emission led to the choice of xenon, which as an inert gas should provide a debris-free source. There is a line group in the spectrum of xenon that has been shown by a number of researchers to arise from $4d^8\text{--}4d^75p$ transitions in Xe XI.^{7,8} These lines have recently been measured to an accuracy of 0.01 nm by Churilov et al.,⁹ who have identified all of the lines in this range by comparison with atomic structure calculations using the suite of codes developed by Cowan.¹⁰ The population of this ion stage needs to be optimized to attain maximum intensity. Note that, depending on the type of source and hence ion density, optimization is not always necessarily the same as maximizing a given ion population because of opacity effects.

Considerable work has been expended on exploring the feasibility of using LPPs of xenon clusters, produced by supersonic jets or gas puffs from nozzles,¹¹ or from solid xenon targets. The highest CE (1.2% into 2% bandwidth) has been achieved using solid xenon,¹² because plasma formation causes damage to nozzles, which in turn produces more debris. To surmount this problem, liquid jet targets were developed so that plasma formation could take place far away from the nozzle, and CEs of the order of 0.75% have been reported with this setup.¹³ In addition, a wide variety of pulsed discharge sources using xenon or xenon-helium mixtures are being actively investigated by a variety of companies and laboratories. For example, Cymer has developed a dense plasma focus (DPF) device that can give a CE of 0.42% at 12.4 J of input energy at repetition rates of a few hundred hertz.¹⁴ JMAR, Philips, and AIXUV have all built compact pinch discharge sources, again with CEs of the same order, and a capillary discharge source has been developed at Sandia National Laboratory capable of operation at repetition rates up to 1.7 kHz.¹⁵

However, the duty cycles of all of these sources are ultimately limited by heat dissipation. All of the CEs reported to date for these devices are close to 0.5%. The optimum in-band efficiency obtainable from LPPs appears to be of the order of 1%; therefore, xenon is not the optimum choice if 3% conversion is required.

5.2 The Case for Xenon

5.2.1 Atomic structure considerations

Using the Cowan¹⁰ suite of codes, it is possible to calculate the spectra of a range of ion stages in xenon. The theoretical results are shown in Fig. 5.1 for ion stages Xe IX (ground configuration $4d^{10}$) through XVIII (ground configuration $4d^1$), i.e., those stages containing 4d electrons in their valence, or outermost, subshell; those for Xe XI are presented in Fig. 5.2. In each of these spectra the bulk of the resonance emission lies in the 10–12-nm region, so that in a plasma containing a mixture of these ions, lines from adjacent stages overlap in energy. The transitions responsible arise from $4p^6 4d^n - 4p^5 4d^{n+1} + 4d^{n-1} 4f$ lines, which merge to form an unresolved transition array (UTA).¹⁶ Note that no excited-state population distribution has been assumed for any ion stage. An UTA generally has too many lines to unambiguously identify individual transitions, and in many cases the line separation is less than the linewidth; however, both the energy levels and spectral distributions can be parameterized statistically in terms of the moments of the array.¹⁷

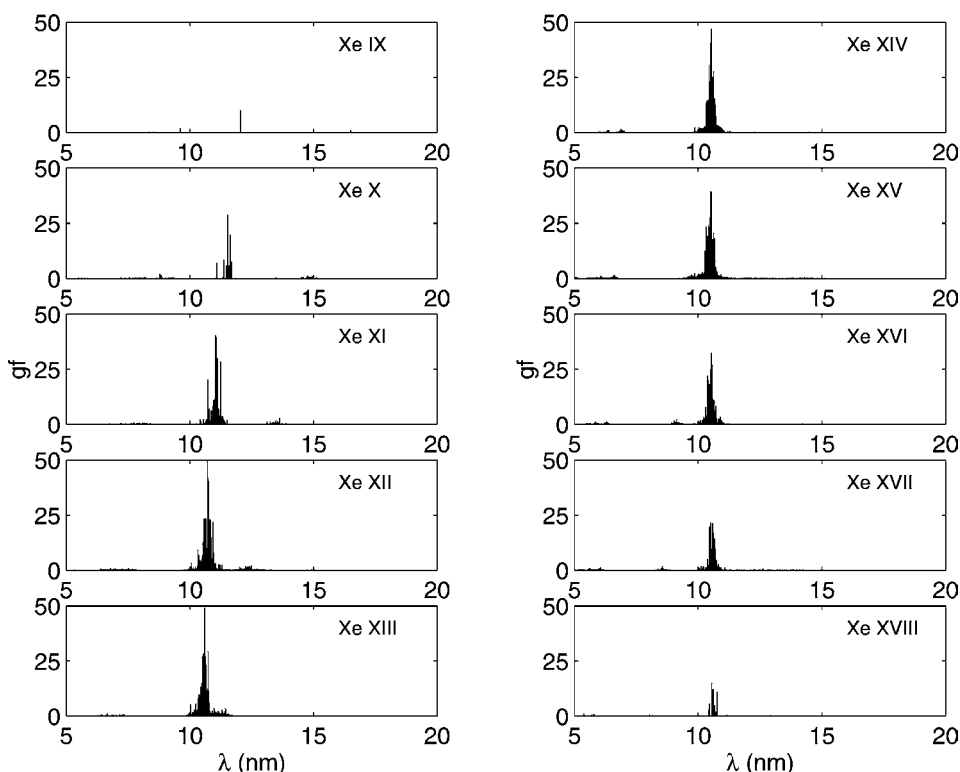


Figure 5.1 Theoretical plots of oscillator strength (gf value) versus λ for xenon in ion stages 8^+ through 17^+ , calculated with the Cowan¹⁰ code.

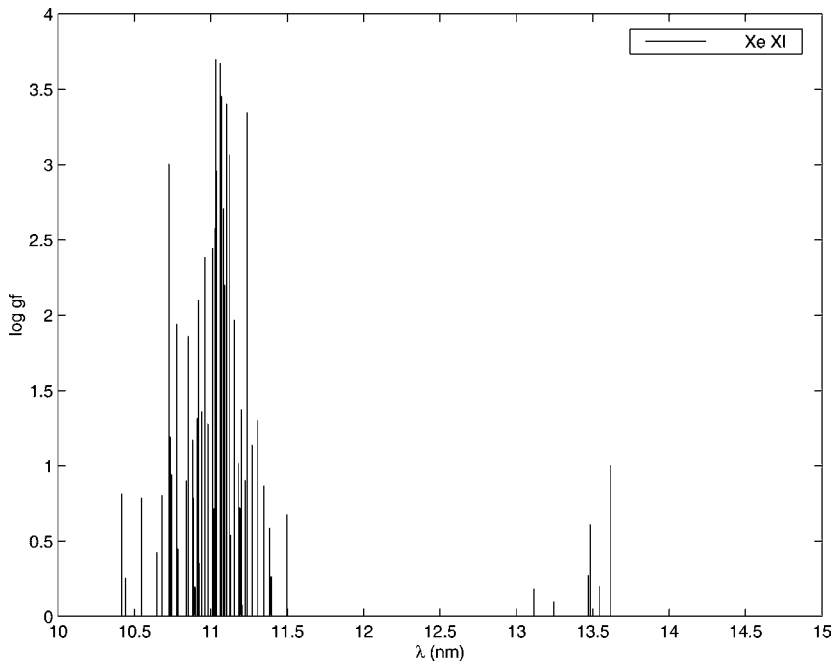


Figure 5.2 Theoretical spectrum of Xe^{10+} , calculated with the Cowan¹⁰ code.

In the case of energy levels, the n th-order centered moment is defined as (Fig. 5.3)

$$\mu_n^c = \frac{[\sum_k \langle k | \mathbf{H} | k \rangle - E_{av}]^n}{g_k}, \quad (5.1)$$

where g_k is the statistical weight of each level and $\mathbf{H}$ is the Hamiltonian operator.

The width of an array is then $2[2\ln(\mu_2^c)]^{1/2}$. The skewness, $\alpha_3 = \mu_3^c / \mu_2^{c3/2}$, measures the asymmetry of an array, while the kurtosis, $\alpha_4 = \mu_4^c / \mu_2^{c2}$, describes its shape and equals 3 for a Gaussian distribution.

In the case of spectral distributions, the line energies are weighted according to their line strength factors S_{km} , and the moments are defined as

$$\mu_n = \frac{[\sum_{k,m} \langle k | \mathbf{H} | k \rangle - \langle m | \mathbf{H} | m \rangle]^n S_{km}}{\sum_{k,m} S_{km}}. \quad (5.2)$$

Final-state configuration interaction between the $4p^5 4d^{n+1}$ and $4d^{n-1} 4f$ configurations causes these transitions to overlap in energy.¹⁹ Were they due to $4d$ - $4f$ excitation alone, for $4p^6 4d^n - 4d^{n-1} 4f$ the UTA model predicts that the position of the array peak should be at $E = E_{av}(a) - E_{av}(b) + \delta E$, where a and b refer to the two configurations involved and E_{av} corresponds to the average energy of a

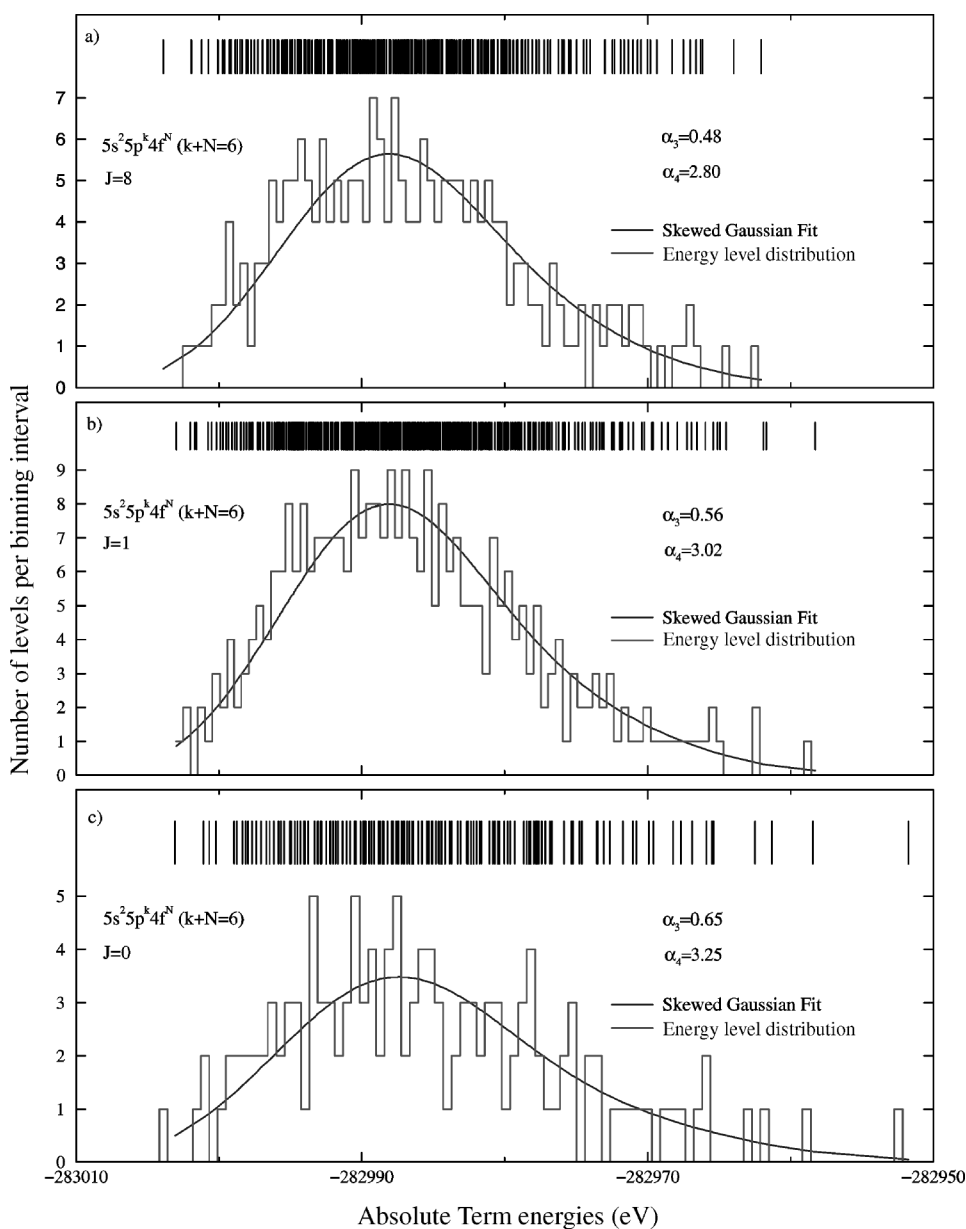


Figure 5.3 Level distributions for the lowest configurations in a study of Xe-like samarium. (Reprinted from Ref. 18 with permission from the Institute of Physics Publishing Ltd.)

configuration and

$$\delta E \sim \frac{2(n-1)G^1(4d, 4f)}{9}. \quad (5.3)$$

Here $G^1(4d, 4f)$ is the Slater-Condon parameter that represents the exchange interaction between the 4f electron and the 4d hole. Configuration interaction (CI)

effects between $4p^6 4d^{n-1} 4f$ and $4p^5 4d^{n+1}$ also cause spectral narrowing, so the UTAs have widths of ~ 5 nm. In an optically thin plasma, these lines should completely dominate the EUV emission, and indeed this is seen to be the case for sources such as electron beam ion traps (EBITs).²⁰ At the ion densities encountered in LPPs and also in DPPs, opacity effects become important and have the effect of reducing the intensity of the 11-nm UTA in comparison with that of the 4d–5p transition groups lying at longer wavelengths. For example, one such group in Xe X at 15 nm, first identified by Churilov and Joshi²¹ and Kaufman and Sugar,²² was recently shown by Böwering et al.²³ to be particularly intense under a particular set of experimental conditions relative to the UTA.

In Fig. 5.2, it is easy to compare the oscillator strength available to 4d–5p transitions with those of the $4p^6 4d^8 - 4p^5 4d^9 + 4d^7 4f$. It is seen that the summed oscillator strength available in 4d–5p transitions is significantly less than 10% of that attainable in the UTA.

5.2.2 Plasma considerations

Typical Q -switched lasers used for EUVL generation emit pulses with energies in the range from 200 mJ to 1 J on time scales from hundreds of picoseconds to tens of nanoseconds. The Nd:YAG lasers used in our work emit 1.1 J and 500 mJ of 1.064- μm radiation in 15 ns and 170 ps, respectively. When these lasers were focused onto a solid target to a focal spot size of diameter 40 μm , the maximum average power densities attained were 1.46×10^{12} and $5.85 \times 10^{13} \text{ W cm}^{-2}$, though they were typically used at $\sim 1 \times 10^{11}$ and $\sim 1 \times 10^{12} \text{ W cm}^{-2}$. According to the collisional radiative (CR) equilibrium model,²⁴ the corresponding electron temperatures T_e , which depend on laser flux density according to $T_e \propto \Phi^{3/5}$, are 49 and 194 eV. Calculations based on the CR model give

$$\frac{N_{z+1}}{N_z} = \frac{S(z, T_e)}{\alpha_r(z+1, T_e) + n_e \alpha_{3b}(z+1, T_e)} \quad (5.4)$$

for the ratio of the population of ions of charge $z+1$ to that of charge z , where $S(z, T_e)$ is the total collisional ionization rate coefficient, $\alpha_r(z+1, T_e)$ is the total radiative recombination rate coefficient, and $n_e \alpha_{3b}(z+1, T_e)$ is the total three-body recombination rate coefficient. Note that dielectronic recombination is not explicitly included in this model. In our case, the dominant ion stages are anticipated to be 15 and 20 times ionized. Theoretically, the maximum electron density depends on the cutoff density, which scales as λ^{-2} and for Nd:YAG radiation has a value of approximately 10^{21} cm^{-3} and decreases rapidly away from the interaction region, which is approximately 100 μm in extent. The ion expansion velocity is of the order of 10^6 – 10^7 cm s^{-1} . As the plasma expands, it cools, so absorption at the cooler margins is possible. Moreover, Filevich et al.²⁵ have recently shown that the EUV emission itself causes a cooler plasma to be generated in a region surrounding the expanding plasma plume, so radiation tangential to the surface can be absorbed in a cold plasma layer. Unfortunately, in xenon the neutral absorption

is well known to be dominated by a $4d \rightarrow \epsilon f$ shape resonance in the photoionization continuum,²⁶ which peaks near 15 nm but still has a cross section of 20 Mb at 13.5 nm.²⁷ In gas-jet plasmas evidence for neutral absorption is also evident.²⁸ In the first two ionization stages this feature persists, yielding cross sections of 25 and 22 Mb, respectively.^{29,30} By Xe^{4+} this feature has been replaced by discrete $4d \rightarrow 4f$ transitions, which yield a strong autoionizing line again near 13.5 nm,³¹ so absorption by neutrals and low ionization stages, if present on the periphery of the source, will greatly reduce the available intensity. Recently a calculation of the emission from xenon, with allowance made for opacity effects, was performed using the HULLAC code.³² This calculation showed a reduction at 13.5 nm and also an even more spectacular effect on the 11-nm band, whose intensity was reduced so that it almost matched that at 13.5 nm.

In addition, from the results of a calculation for the variation of ion population with electron temperature (Fig. 5.4) it is evident that the maximum concentration of Xe^{10+} attainable is only of the order of 40%. Therefore, any advantages of using xenon based on its gaseous nature and inherent cleanliness must be weighed against the disadvantages of the low density of emitting ions, the fact that the transition involved is at least a factor of 10 weaker than those occurring in the 11-nm band, and the fact that the wavelength of choice almost coincides with that of maximum absorption in the neutral and low ion stages.

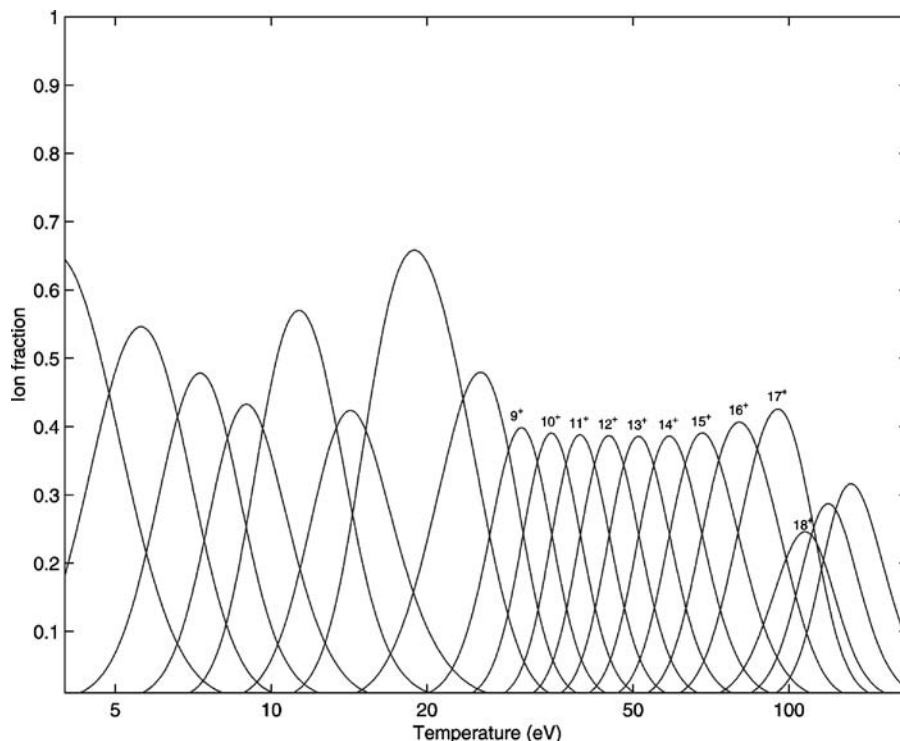


Figure 5.4 Xenon ion fraction distribution versus electron temperature.

5.3 Alternatives to Xenon; the Case for Tin

5.3.1 Atomic structure considerations and UTA

The same UTA as that in xenon at 11 nm is also observed in adjacent elements.³³ Since in every case it arises from $4p^6 4d^n - 4p^5 4d^{n+1} + 4d^{n-1} 4f$ transitions, the peak position is sensitive to atomic number and moves to shorter wavelengths as Z increases (Fig. 5.5).

From work ongoing at University College Dublin (UCD) since the late 1970s, tin was identified as potentially the strongest emitter at 13.5 nm, since the UTA is centered near that wavelength. It was further shown that if the tin concentration was reduced to approximately 10%, the peak brightness actually increased.¹⁶ Furthermore, if the remaining 90% of the constituents were low- Z materials, the radiation emitted was concentrated in a band 1–2 nm wide centered near 13.4 nm and the ordinary recombination continuum from the plasma was suppressed in comparison with that from a pure tin target. In fact, if pure targets are used, the recombination continuum contains most of the emitted radiation. It extends throughout the EUV, and if absorbed by the multilayer optics, could cause heating, distortion, and loss of focus. These results have been verified in a controlled study with tin-doped glass targets and are summarized in Fig. 5.6. In this figure the in-band intensity was

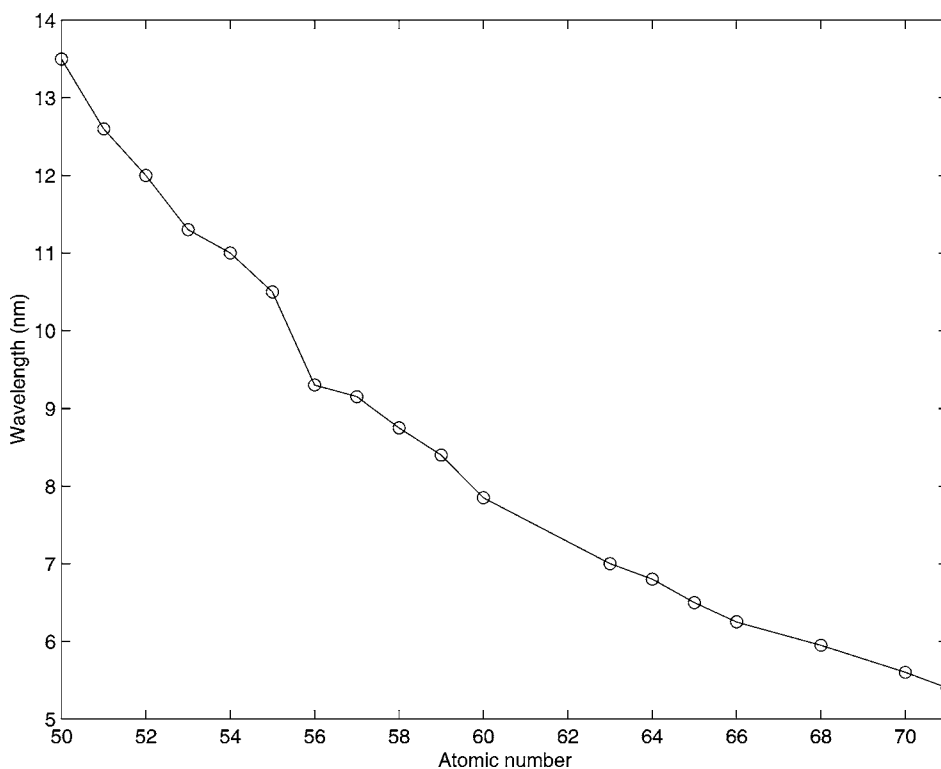
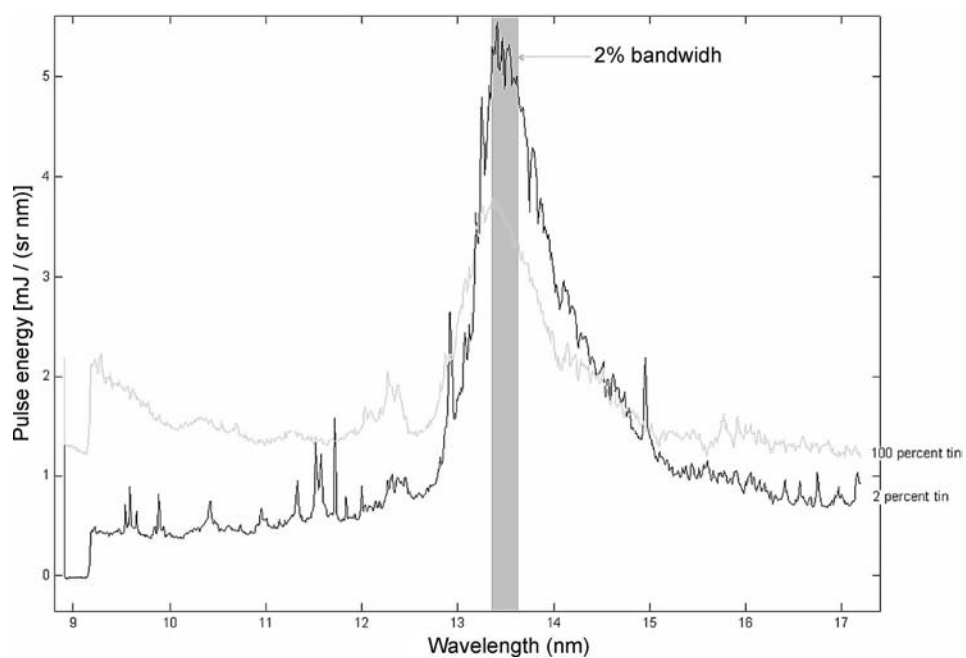
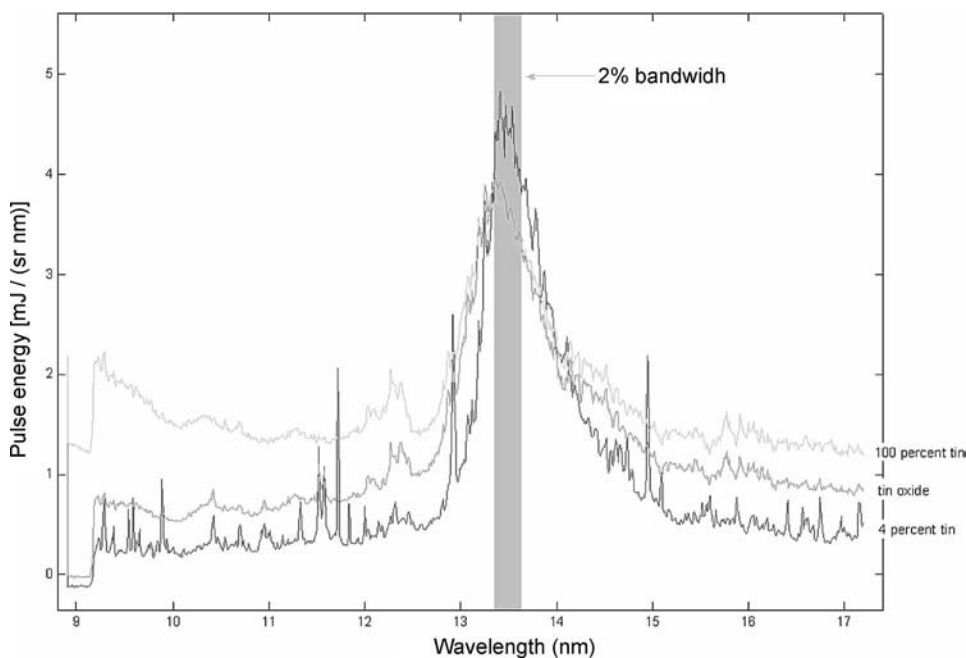


Figure 5.5 Variation of UTA peak position with wavelength: Sn ($Z = 50$) to Lu ($Z = 71$).



(a)



(b)

Figure 5.6 Variation of spectral emissions from LPPs differing in tin concentrations: (a) 100% pure tin and 2% tin; (b) 100% pure tin, tin oxide (33%), and a tin-doped glass target (4%).

determined using a calibrated CCD detector housed in a 0.25-m flat-field grazing-incidence vacuum spectrometer supplied by Jenoptik Microtechnik. It is evident that the brightness attainable with slab targets at 2% concentration is some 45% greater than with a pure tin target, but the optimum concentration needs to be clarified and will be sensitive to the laser pulse profile and focusing conditions, as these determine the ion-stage distribution that controls both emission and absorption. For 2% concentration the efficiency is estimated to be approximately 1.7%, based on the detector calibration and source geometry.

Both intensity and profile are very sensitive to concentration. In pure targets the UTA essentially appears as a modulation of the recombination continuum and there is considerable self-absorption, while from targets containing only a few percent of the element of interest the plasma becomes optically thin.³⁴ The observed increase in the intensity of the UTA with the decrease in the concentration agrees with the data of Choi et al.,³⁵ who, in a space-resolved study of emission from tin metal and tin oxide targets, found that the emission from a SnO₂ film target was everywhere greater than that from a tin slab target. For mass-limited targets, the peak intensity is essentially unaltered, but the profile width decreases as the tin concentration is reduced.³⁶ Presumably this reflects the fact that the emission at the UTA center is from the dominant ions for which the plasma is optically thick, while that from the wings emanates from both higher (shorter wavelength) and lower (longer wavelength) ion stages for which the plasma is closer to being optically thin. With decreasing concentration the populations essentially decrease uniformly, so that the emission at the wings decays more rapidly than from the center, because the plasma never becomes optically thin at the peak wavelength. Theoretically, the profile width is determined to a large extent by final-state $4p^5 4d^{n+1} + 4d^{n-1} 4f$ configuration interaction, which also causes the features to overlap in successive ion stages. The result of Hartree-Fock calculations with the Cowan code are presented in Fig. 5.7.

As in xenon, in performing these calculations, scaling factors for the Slater-Condon factors were chosen to best fit the observed UTA. The energy overlap in successive stages, like the intensity, is strongly related to the localization of the 4f radial wave function and its overlap with the 4d wave function.

5.3.2 Origin of UTA intensity

In neutral tin the radial potential experienced by an $l = 3$ electron contains both an attractive Coulomb term defined by its interaction with the nucleus and a repulsive centrifugal term, which effectively excludes the nf wave functions (top of Fig. 5.8) from the core region and resulting in a bimodal potential with two pronounced minima (bottom of Fig. 5.8). The first minimum, with its center near a_0 (the Bohr radius), is close to the 4d wave function peak but lacks sufficient depth to support a bound level, and, as in xenon, the $4d \rightarrow f$ channel is dominated by a $4d \rightarrow \epsilon f$ shape resonance that forms when the outgoing f electron has sufficient energy to overcome the centrifugal barrier. The outer shallow well, centered near $16a_0$,

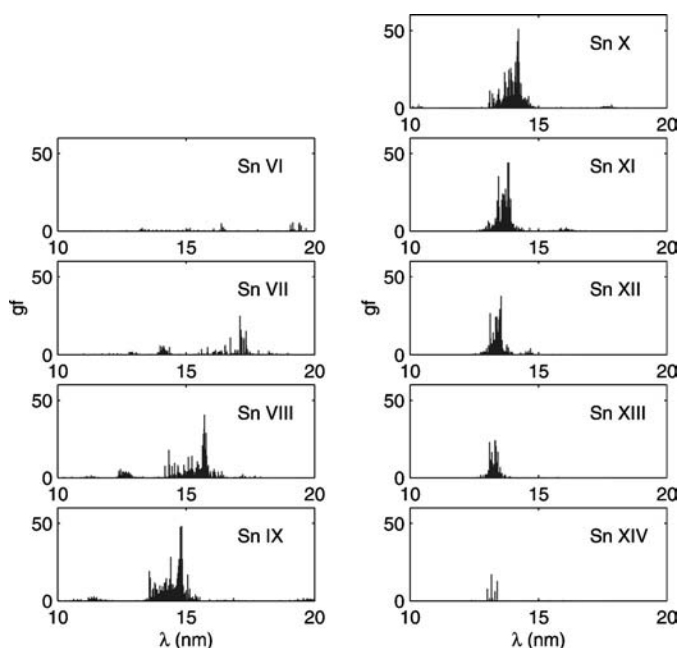


Figure 5.7 Theoretical EUV emission from tin in ion stages Sn^{5+} through Sn^{13+} , calculated with the Cowan suite of codes.¹⁰

is essentially hydrogenic in character and contains the $4f$ level. Because there is essentially no overlap with the $4d$ wave function in this region, transitions of the type $4d \rightarrow nf$ are absent, and the discrete spectrum will be dominated by $4d \rightarrow np$ lines.

With increasing ionization the centrifugal barrier disappears and $4f$ wave function contraction into the inner well region results in a transfer of oscillator strength from the continuum to the discrete spectrum.^{37–41} The labeling of the discrete states is very sensitive to the choice of basis used in any calculations, since the lowest $4d^n nf$ states are strongly *LS*-coupled and their wave functions are highly term-dependent.^{42,43} In fact, if the average energy of configuration (E_{av}) is used as the basis, then there is considerable hybridization amongst the different nf functions, and transitions to these states have appreciable oscillator strength by virtue of their sizable $4f_{\text{av}}$ component. As a result, the different $4d^n \rightarrow 4d^{n-1}nf$ transitions have appreciable oscillator strength and are generally stronger than the $4d \rightarrow np$ lines. With increasing ionization, the inner potential well becomes deeper and narrower, and the $4f$ wave function gradually contracts into the core region and has a large spatial overlap with the $4d$ wave function. As the inner well deepens, the nf level separation increases, the $4f$ and $4f_{\text{av}}$ functions become essentially the same and the oscillator strength becomes concentrated in the $4d^n \rightarrow 4d^{n-1}4f$ transitions. This behavior has been studied for a number of isonuclear sequences. In Fig. 5.9 the transfer of oscillator strength from a broad continuum resonance to discrete $4d \rightarrow 4f$ lines along the cesium isonuclear sequence is shown. Since these

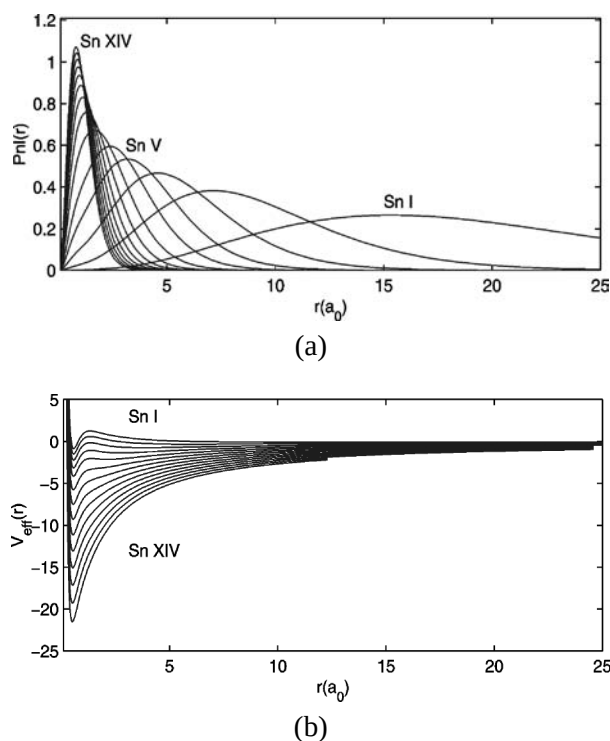


Figure 5.8 (a) 4f wave function contraction in tin with increasing ionization. (b) The $l = 3$ radial potential in tin for different ion stages.

resonances, which evolve into $\Delta n = 0$ transitions, are the strongest features observed in neutral photoabsorption spectra, the corresponding arrays in the spectra of highly ionized atoms must correspond to the strongest emission features attainable.

The EUV spectra of Sn through Sn^{4+} should be dominated by a $4d \rightarrow \varepsilon f$ continuum resonance. Since such phenomena are essentially many-body in nature, the appropriate theoretical description should reflect this. Two such theoretical prescriptions are many-body perturbation theory⁴⁴ and the random-phase approximation with exchange.⁴⁵ Another theoretical approach is the time-dependent local density approximation (TDLDA).⁴⁶ This approach has been shown to be very useful for studying changes in the 4d cross section with increasing ionization in iodine and cesium.^{47,48} In this work the relativistic TDLDA code DAVID^{49,50} was used to calculate the continuum cross section of each species above the 4d threshold. In all of these species it predicts a peak cross section of 24 Mb near 17 nm (73 eV). The calculated cross sections are included for comparison in Fig. 5.10.

It should be noted that the absorption cross section of these ions at 13.5 nm is close to 15 Mb, so that their presence in any source will lead to significant radiation transport problems.

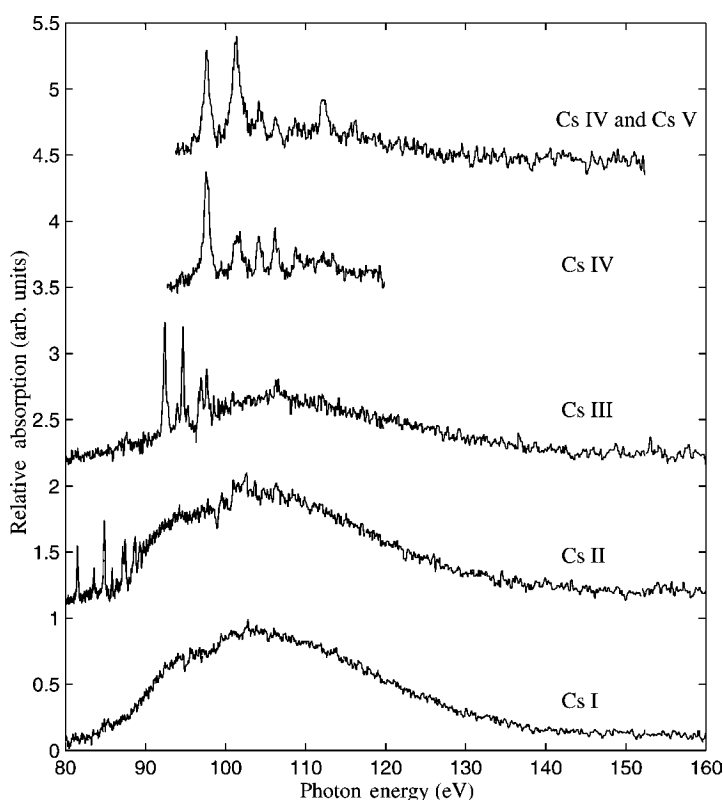


Figure 5.9 Variation in absorption cross section from Cs I–IV. Note the transfer of oscillator strength from $4d \rightarrow \epsilon f$ to $4d \rightarrow 4f$ with increasing ionization.

As already pointed out, the UTA emission is not due to $4d$ – $4f$ transitions alone, but arises from $4p^6 4d^n - 4p^5 4d^{n+1} + 4d^{n-1} 4f$ transitions, which merge to form a UTA consisting of tens of thousands of lines. Single-configuration calculations show that for $4d^n - 4d^{n-1} 4f$ transitions the strongest lines are displaced to the high-energy side of the interval between the centers of gravity of both configurations and that this displacement is essentially determined by the magnitude of the $\langle 4d | 4f \rangle$ radial overlap integral and the number of electrons in the $4d$ subshell. However, inclusion of CI effects effectively removes the dependence on $4d$ occupation and causes the oscillator-strength envelope of the transition array to narrow and overlap at the same energy position in successive ion stages. The strength of this interaction again depends on the magnitude of $\langle 4d | 4f \rangle$.

Thus, to optimize the brightness of an array, three criteria must be satisfied:

- The ion stages produced should contain an open $4d$ subshell.
- The $4f$ radial wave function should be completely localized in the ionic core in each ion stage. Consequently both $|\langle 4d | r | 4f \rangle|$ and CI effects, which cause overlapping and narrowing of the UTA, are maximized.
- The plasma should be optically thin to these UTA.

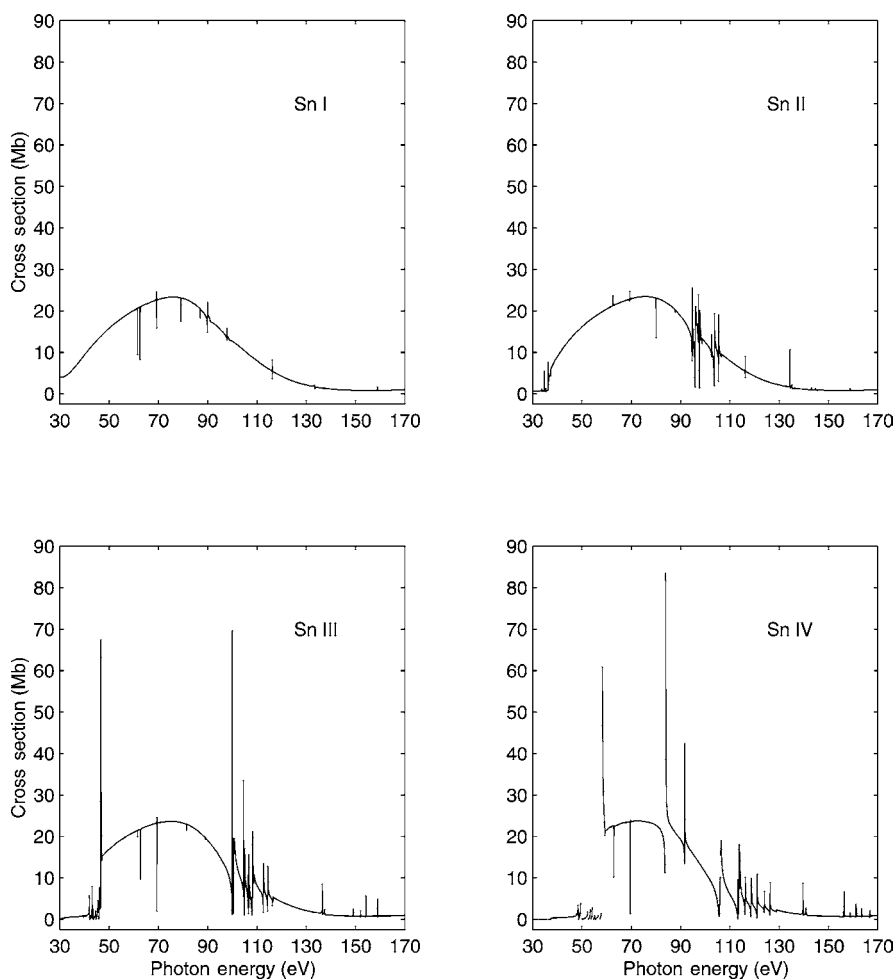


Figure 5.10 Theoretical absorption spectra of Sn I–IV, calculated with the TDLDA code DAVID.^{49,50} In Sn I–III the EUV spectra is dominated by a $4d \rightarrow \varepsilon f$ resonance.

For tin, the $\langle 4d | 4f \rangle$ overlap increases with increasing ionization and only stabilizes past Sn^{9+} (see Fig. 5.8). As a result, tin is not the brightest potential EUV source and has a relatively large bandwidth, though it is less sensitive to opacity effects, since the overlap of discrete $\Delta n = 0$ transitions in the UTA in adjacent ion stages is less complete, especially in stages below Sn^{9+} . Our calculations have also shown that production of more highly ionized ions with $4p^n$ ground configurations is, in general, undesirable, since $4p$ - $4d$ transitions move to longer wavelengths with increasing n and therefore would, if present, broaden the UTA.

For the rare-earth elements the $4f$ orbital is localized in the core region, and consequently the rate of change of $\langle 4d | 4f \rangle$ with increasing ionization is very small. Thus, the emission band is brightest and narrowest in the lanthanides. Under our experimental conditions it is in fact optimum in cerium, where a CE of $(4.2 \pm$

1.5)% at 8.8 nm using cerium-doped glass targets has been measured.⁵¹ However, at present no suitable MLMs have been developed for use at these wavelengths.

5.3.3 Optimum ion-stage distributions and plasma conditions

From Fig. 5.7 it is clear that the stages that contribute most at 13.5 nm are Sn^{8+} through Sn^{12+} . Calculations within the CR framework were first performed to obtain the ion distributions as a function of electron temperature near the critical electron density (Fig. 5.11). It can be seen from this figure that the condition for the production of the optimum ion-stage distribution for an optically thin plasma corresponds to electron temperatures in the 30–50-eV range.

To fine-tune the plasma requirements it is useful to define a figure of merit F , which is taken as the product of the summed gf values for transitions within each ion stage, weighted according to their distribution as a function of electron temperature with the MLM reflectivity

$$F = \sum_{\lambda} R(\lambda)^n \cdot \sum_z [f_z \cdot gf_{\lambda,z}], \quad (5.5)$$

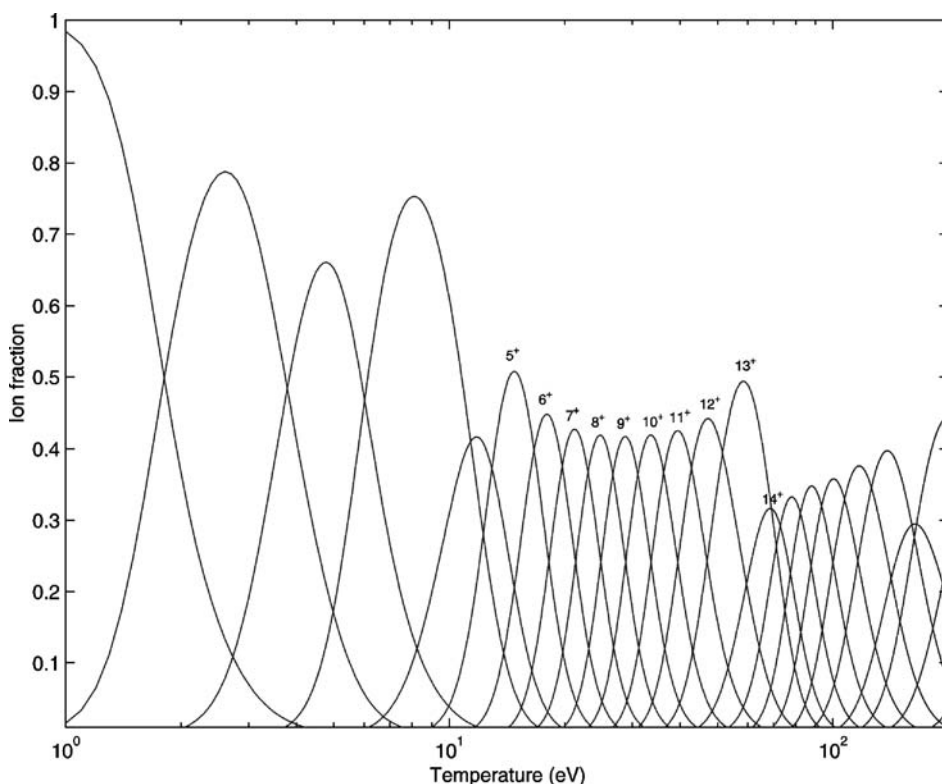


Figure 5.11 Tin ion fraction distribution versus electron temperature.

where $R(\lambda)$ is the reflectivity of the Mo/Si MLM, n is the number of mirrors, $\sum gf$ corresponds to the summed ionic oscillator strengths for an ion of charge z , and f_z is the fractional weighting of that ion stage.

The variation of F with T_e is shown in Fig. 5.12 for different values of n , from which it is evident that the optimum electron temperature is close to 40 eV. Note that this figure is based on the assumption that the theoretical spectra and therefore the scaling factors used are the most appropriate. To determine the precise scaling factors requires a high-resolution study and identification of a number of the lines, which for some stages may be impossible, as the line separation may be less than the individual linewidths. Moreover, the figure completely ignores opacity effects, which certainly distort the shape of the UTA, especially on the longer-wavelength side. Even allowing for these limitations, one would expect the predicted temperature to be close to the optimum one (within 20%).

Support for this can also be obtained from experimental results. In Fig. 5.13 the results of a measurement of CE as a function of laser power density on a solid tin target is shown. It is immediately evident that the peak brightness is obtained for $\Phi = 1 \times 10^{11} \text{ W cm}^{-2}$. A similar result was obtained for mass-limited targets containing tin.³⁶ From the CR model, the value of T_e corresponding to this flux density is 49 eV.

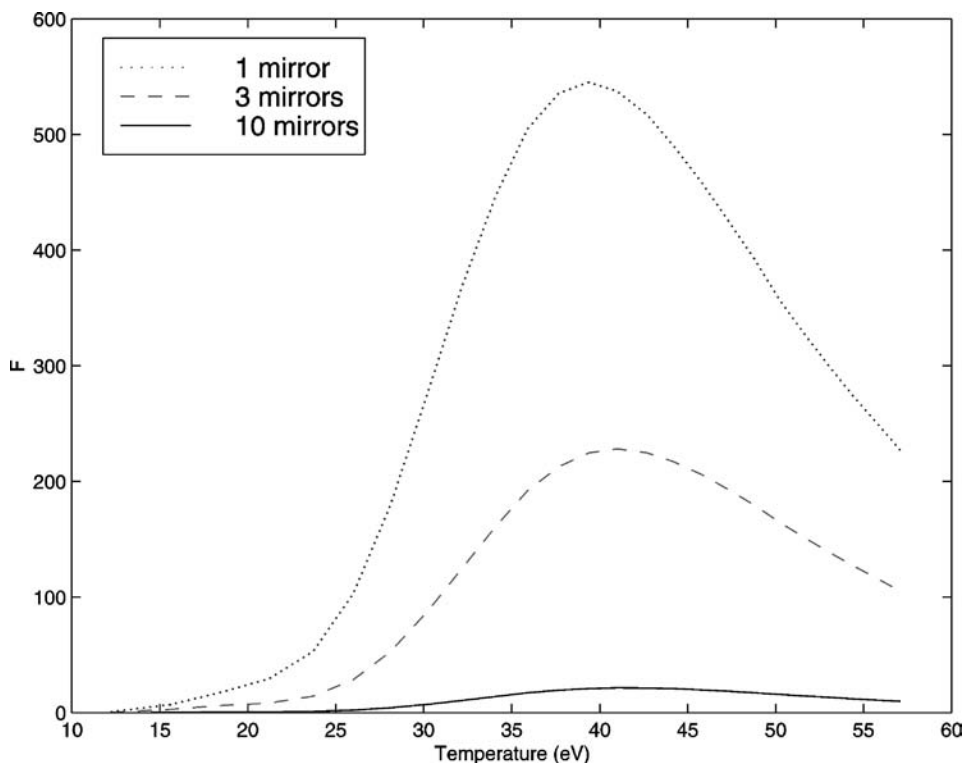


Figure 5.12 Variation of figure of merit with plasma electron temperature, assuming CR equilibrium for different numbers of mirrors.

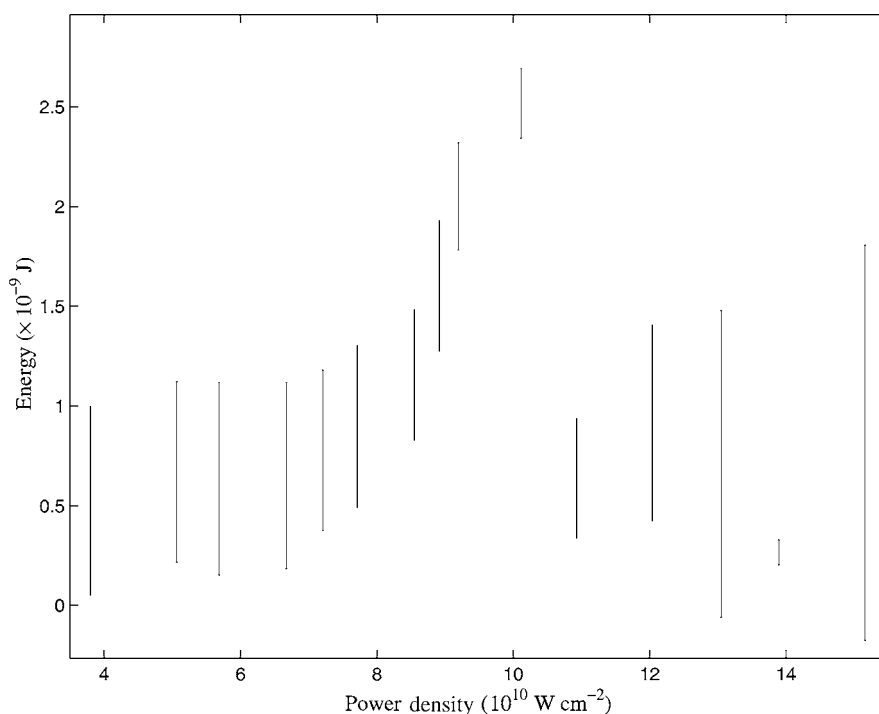


Figure 5.13 Variation in EUV output at 13.5 nm into 2% bandwidth with average laser pulse power density from a target containing pure tin.

5.3.4 Effect of prepulses

It is known that the use of a prepulse can greatly increase the EUV emission from a LPP. For example, a tenfold increase was recently observed for laser-irradiated ice droplets.⁵² In that experiment laser pulse durations ranging from 200 fs to 120 ps for pulse energies ranging from 20 to 100 mJ were employed. The best CE without a prepulse was found for the longest pulses, with a CE of 0.2% in 2.5% bandwidth into 4π sr at 13.0 nm on the 2p-4d lines of Li-like O VI. Addition of a prepulse increased the CE, and a maximum of 2% into 2.5% bandwidth was attained for 2-ps pulses at a 3-ns delay.

In our case, in a series of experiments, the emission from a plasma produced on a tin oxide in a glass target at a tin concentration of $\sim 1\%$ as a function of prepulse-pulse time delay was studied by synchronizing outputs from the 1.1-J, 15-ns Nd:YAG with that from the 500-mJ, 170-ps system. When the latter illuminated the plasma formed by the nanosecond system, an intensity enhancement of 75% was attained after a delay of 9 ns. If one assumes this enhancement is attained at all target compositions, then for the 2% tin in glass the efficiency using this arrangement could be increased to 2%–3% into 2π sr. With more careful illumination control and optimum target compositions, the figure 3% should be attainable.

Using the 170-ps system by itself, the beam was divided by inserting a 99% mirror at 45 deg and intercepting a controllable fraction. In this way any fraction desired could be removed to serve as a prepulse. The main pulse was then passed around an optical delay line and the output intensity at 13.5 nm monitored as a function of interpulse delay and prepulse-pulse ratio. The results are presented in Fig. 5.14, from which it is evident that the optimum conversion is attained with a time delay of 5 ns and a prepulse-pulse ratio of 1:9. This can be understood as follows: The prepulse generates a small compact plasma that only expands to a few tens of microns before the prepulse ends, and the emitting volume is very small. The plasma expands outward from the target, and the main pulse interacts with this larger plasma volume. After 5 ns, the plasma volume and density are optimum to ensure good coupling with the laser pulse. At longer delays the density drops below that needed for optimum heating and the EUV output decreases. A prepulse used in this way only produces a small amount of material, which is then further ionized by the main pulse. Experimentally, the debris quantity is proportional to the energy directly incident on the target. Thus, the volume of debris produced is greatly reduced in comparison with that from a single pulse of the same total energy.

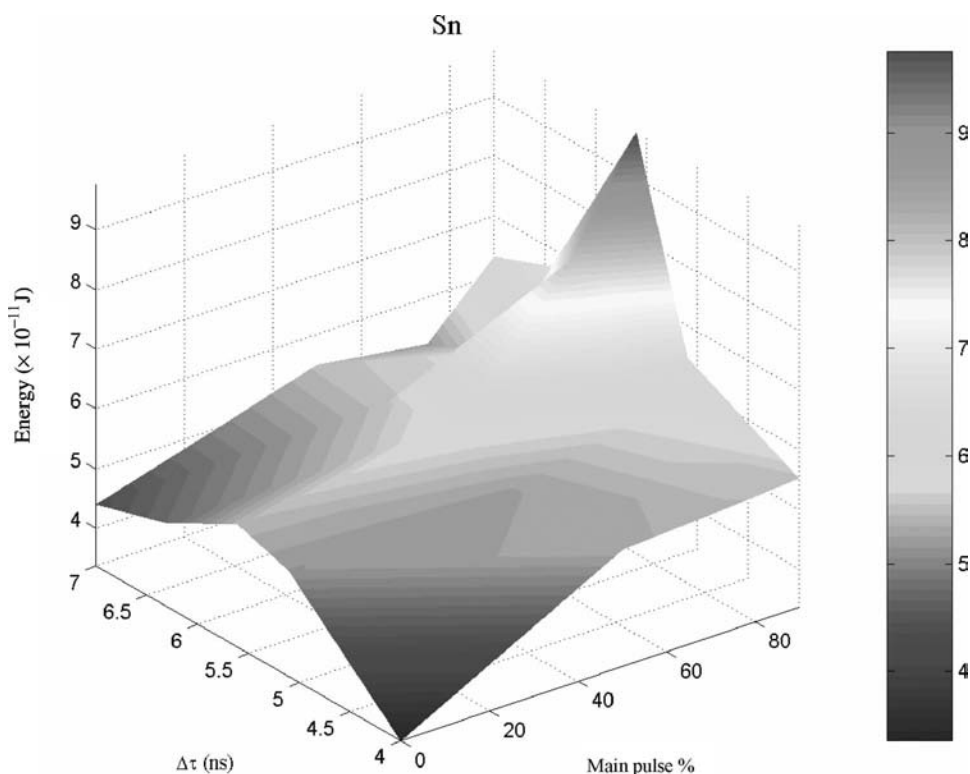


Figure 5.14 Variation in EUV output from a tin target as a function of prepulse-pulse fraction and interpulse delay. Note maximum emission for a 10:90 prepulse-pulse ratio at a time delay of 5 ns.

5.3.5 Debris

Debris generation from solid targets produced by laser blowoff has been the subject of much investigation, for deposition on nearby condenser optics poses a major constraint on any commercial exploitation of LPP soft-x-ray sources. The use of a low-pressure (0.2-torr) He background gas has been successful in reducing the emission of small particles ($<0.3\text{ }\mu\text{m}$) but has had minimal effect on larger particulates. Using 500 mJ of $1.064\text{-}\mu\text{m}$ radiation delivered in a 18-ns pulse, it was found that most debris is emitted 2–3 μs after the pulse and that 98% of the particulates travel slower than 640 m s^{-1} .⁵³ The mass deposition rate at 5 cm from the target was $1\text{ }\mu\text{g/cm}^2$ per shot.⁵⁴ Subsequently, the mass-limited cryogenic target was proposed, and the feasibility of using ice droplets demonstrated.⁵ More recently this target has been modified to include a small percentage of tin.⁵⁵ Other proposals have been to illuminate a thin film of tin, which evaporates upon irradiation by a laser pulse; to view the EUV emission from behind, i.e., in a direction opposite to the plasma expansion;⁵⁶ or to confine the tin plasma in a channel and again view the emission in a direction away from the expanding plume.^{57,58} For slab targets, the debris is minimized if tin-doped glasses or ceramics are used. The use of repeller fields has also been suggested,⁵⁴ and if all the debris were ionized, by using mass-limited, cavity-confined or prepulse-pulse-generated plasmas from slab targets, then fields could be quite efficient in deflecting the debris away from the multilayer optics.

5.4 Conclusions

We have shown that from both atomic-structure and plasma considerations the brightness attainable from a plasma containing a small percentage of tin is considerably greater than from xenon-based sources. Preliminary measurements indicate that CEs of 3% should be readily attainable if opacity effects are minimized (by controlling the concentration of tin in the target and the target geometry) and if the laser pulse shape and power density are carefully matched to the target conditions. Moreover, the use of dilute targets reduces the amount of out-of-band EUV emission, which is another problem that must be addressed.⁵⁵

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Chapter 6

Radiative Collapse in Z Pinches

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6.1 Introduction

Emission of radiation at short wavelengths demands hot plasmas, which are readily produced by the *pinch effect*. This term describes the self-constriction accompanied by heating of discharges by the magnetic field B of the current I in a discharge plasma. Pinching starts when the magnetic field pressure $B^2/2\mu_0$ exceeds the plasma particle pressure p , and it stops when the two are equal; this condition describes a magnetically confined plasma column. There are two complementary geometries: the linear, or Z, pinch and the Θ pinch (Fig. 6.1).

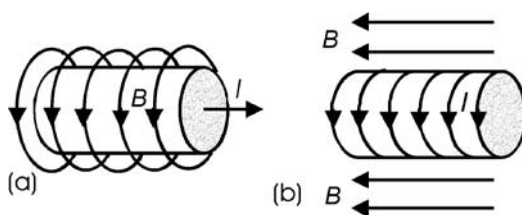


Figure 6.1 (a) Linear, or Z, pinch. (b) Θ pinch.

Both are axially symmetric. In the Z pinch the current flows along the axis (Z direction) and the plasma is confined by the azimuthal magnetic field of the current. In the second arrangement an azimuthal current (in the Θ direction) is induced in the plasma column by a rapidly varying current in a single-turn coil around the discharge vessel, and the confining magnetic field is parallel to the axis. Both discharges are operated in a pulsed mode, since the high currents required can conveniently be supplied only by discharging properly designed capacitor banks. Operation in pulsed mode is useful also for other reasons: the lifetime of hot plasma columns is limited by plasma losses at the ends of the column on the one hand, and on the other hand these plasmas are prone to hydromagnetic instabilities, which are extremely serious in the case of the Z pinch.¹

However, the transformation of electrical energy into plasma is rather inefficient in Θ -pinch devices of short length; thus nearly all discharge-based EUV sources employ the linear geometry. A typical Z-pinch discharge proceeds as follows: high voltage is applied to the electrodes of the discharge tube, and after breakdown the current starts to flow in a thin cylindrical low-temperature plasma shell adjacent to the insulating wall. This current produces a corresponding magnetic field outside the shell, which accelerates the plasma like a piston or a slug toward the axis till it stagnates on the axis. For rough estimates, modeling of the compression employing a simple “snowplow” model suffices, although a detailed description of the plasma state requires solving MHD equations combined with kinetic codes for ionization and population of the atomic species, taking into account also radiative transport. A cylindrical shock wave running ahead of the piston is characteristic of fast discharges. Several calculations are presented in this book; see, for example, Chapter 11. In this chapter we focus on the development of a magnetically confined plasma cylinder consisting of strongly radiating ions *after* it has been formed on the axis. In this state, energy is transferred to the plasma mainly by Joule heating.

6.2 Formation of Pinch Columns

There are several configurations in use that lead to the formation of a linear pinch column. They are discussed in several chapters of this book. The most straightforward setup is a gas-filled tube with the two electrodes at the ends, connected to a capacitor bank. It has been studied already for many decades, the main issues being

stability and possible application in nuclear fusion,²⁻⁴ although high-power emission in the x-ray region and its possible applications have been of concern, too. Another possible configuration is a so-called gas-puff pinch, where the filling gas is injected through an annular orifice into the interelectrode space, forming an initially hollow gas cylinder. This allows particularly efficient initial acceleration and plasma formation. Narrow-bore tubes characterize capillary discharges. One needs to distinguish ceramic tubes filled with gas and ablative capillaries, where the filling of the plasma channel is by ablation of wall material by a sliding spark at the beginning of the discharge. Usually capillary discharges experience a strong influx of wall material, which remains between the pinched plasma and wall and thus stabilizes the plasma column. Good compression is possible nevertheless, as is evident from end-on pinhole pictures; for example, see Ref. 5. A hollow cathode improves the initial plasma formation and is currently used in several designs; see, for example, Chapter 13. Similarly to the hollow-anode principle, a pseudospark geometry is established, which operates by self-ignition on the left side of the Paschen curve. For the last few decades, the plasma focus discharge has been recognized as a very promising option for a radiation source down to the x-ray region. It is also considered as a source for x-ray microscopy⁶ and lithography.⁷ Although the geometry, ignition, and rundown phase do not point to a Z pinch, after collapse a linear plasma column is formed in front of the anode.

Low-inductance vacuum spark discharges⁸ and the X pinch⁹ represent yet two other possibilities for x-ray sources.⁸ While a current of a few hundred kiloamperes is flowing through the plasma it becomes very hot, and by this means emission in the x-ray region is achieved. For high- Z elements temperatures of several keV are easily obtained. In the vacuum spark discharge, plasma is injected by a trigger spark into the interelectrode gap between a tipped anode and a flat cathode. Accelerated electrons from the trigger plasma evaporate anode material, and after breakdown a pinch forms and a micropinch may develop in the plasma made up of this anode material. Another option is the formation of the initial discharge plasma column using ablation of the cathode and/or anode material by a laser radiation pulse.¹⁰ The axial symmetry needed for successful pinching can be provided in that case by the axial symmetry of the laser plume. In the X pinch the capacitors are discharged through two or more fine wires, which cross and contact each other in the gap between the electrodes. A micropinch develops at the crossing point. Since the wires are destroyed every time after the discharge, it is unlikely that this system can be developed into a source for 13.5 nm.

In the following sections we are going to give descriptions of the physical processes leading to the appearance of an EUV-radiating plasma in a discharge with parameters typical for industrial EUV sources under consideration (stored energy from 2 to 20 J, maximal current from 10 to 30 kA, and duration of the first current half cycle from about 100 ns up to half a millisecond). The principal characteristics of an EUV radiator, such as source size, duration of EUV radiation, and reproducibility of EUV yield, will be discussed in the frame of the radiative collapse model presented below. Theoretical modeling is applied to the formulation of

the main design principles of an industrial EUV source. Where possible, theoretical predictions will be compared with experiment. In the next section we briefly describe the design of the experimental installation—the concept source PROTO I, which has been used for experimental tests of theoretical modeling and validation of some technical solutions.

6.3 Discharge Source for EUVL: High-Power, High-CE Alternative Concept Source

A number of EUV discharge source configurations—such as Z pinch, plasma focus, and capillary discharge—have been or are under investigation as possible solutions for industrial applications in EUVL. The history of these efforts and the results achieved are well presented in this book.

In the beginning Xe was explored mostly as the working material. The initial discharge symmetry and reproducible gas distribution needed for successful development of the discharge column was easily provided by the axial symmetry of the electrodes. With the initial conditions and a distance between electrodes not exceeding a few millimeters, the size of the EUV-radiating source was below 5×10^{-2} cm, which was in good agreement with the technical specifications of an EUVL apparatus. Strong concern, though, existed in regard to the power scalability of the EUV source based on Xe. Commercial lithography apparatus, in order to become commercially viable, must employ EUV sources, which, depending on the collector configuration, produce about 0.5–1 kW of EUV radiation in a 2% spectral band in 2π solid angle. Experiments have shown that it is hardly possible to expect a conversion efficiency (CE) for Xe higher than 0.5%–1%. That would result in the necessity to dissipate about 100–200 kW of electrical power in a rather small volume, less than 1 cm³. Such high power would unavoidably destroy the electrodes. Definitive characterizations of the difficulties one meets in using a Xe-based discharge as an industrial EUV source are given in other chapters of this book.

There are two directions in which the solution for this problem might be sought. The first one is the use of a material (element) that is expected to have stronger radiation near 13.5 nm than Xe. The second is the so-called *multiplication of sources*, an approach where the heat load is supposed to be distributed between a number of elementary discharge sources.¹¹

For the first approach the candidate was evident: Sn, an element with atomic number 50. (The physical reasons for the benefits of using Sn are given, e.g., in Chapters 4 and 8 of this book.) Experiments with LPP types of EUV sources have proven the possibility of increasing the CE by using Sn plasmas rather than Xe (see Chapter 24 and references there). Nevertheless, tin was not considered for a rather long time as a possible working material for discharges. The reason was the difficulty of creating tin vapors with sufficient density and axial symmetry. In 2002 we reported successful use of laser ablation of a tin cathode for the initiation of a vacuum spark.^{12(a)} The first experiments were carried out using a standard

vacuum spark geometry. The cathode was a hollow metal cylinder filled with tin. The anode was placed at a changeable distance of 3 to 5 mm from the cathode. Low inductance (≈ 10 nH) allowed delivery of currents up to 30 kA at a stored energy of 5 J. It was demonstrated that the CE could be 3–4 times higher than in the case of Xe; in our experiments the CE exceeded 2%.¹² Nevertheless the expected average heat load was still too high—50 kW for a small discharge geometry. Successful results of using tin as a working material in EUVL sources are reported as well in Chapters 16 and 18 of this volume.

The second direction of pursuit—source multiplication—did not result in successful solutions for gas systems. One might envision that the easiest solution would be a rotating configuration, where a new elementary discharge source replaces the previous one at the focus of the optical imaging system.^{11,12(b),13} As we pointed out earlier, the axial symmetry necessary in the gas discharges was provided by the axial symmetry of the electrode system. That assumes that every elementary discharge source must have full axial symmetry and its diameter must be at least a few millimeters, or even a few centimeters, depending on the type of the discharge and the stored electrical energy. To build a discharge system consisting of tens or hundreds of elementary discharge sources would first of all be excessively expensive; secondly, at an expected repetition rate of the source of the order of 10 kHz these elementary discharge sources must move with a very high velocity, approaching 100 m/s. Both conditions made this approach rather unrealistic.

A simple solution for the source multiplication approach is found as soon as we turn to ablated tin vapor. It is well known that ablation by a laser pulse or by an electron beam results in reasonably good axial symmetry of vapors relative to the normal to the target surface. It was found experimentally that with the proper initial material (vapor) configuration the vacuum discharge conserves the internal axial symmetry even at significant deviation of the electrode system from such symmetry. Finally, we found that normal Z-pinch-like discharge development is maintained even for a flat configuration of both electrodes. Application of flat electrodes did not significantly change the dynamics of pinching. The CE was conserved also on the same level, approximately 2%. This result immediately made the whole concept of source multiplication fully feasible. The first rotating system was accomplished in a form of two rotating disks (cathode disk and anode disk) as shown in Fig. 6.2, where a laser beam was focused on the edge of the cathode disk.^{12(b)} A discharge took place between the focus of the laser and the corresponding sector of the anode. Radiation was collected in the radial direction, where less debris is expected to be produced by the discharge. The main experiments presented below were performed using this concept prototype installation PROTO I, working at repetition rates up to 1000 Hz.

6.4 Neck Instabilities in Pinch Plasmas: Radiative Collapse

In the preceding sections we have discussed different ways for the formation of the plasma column in axially symmetrical discharges (ASDs). The characteristics

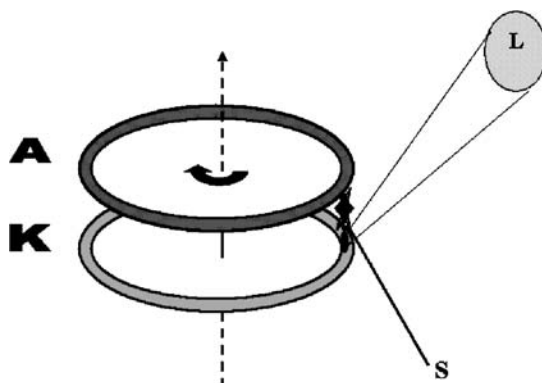


Figure 6.2 Schematic diagram of rotating EUV source: A, anode; K, cathode (replaceable); L, laser beam for Sn electrode ablation; S, spark.

of the prephase (e.g., the duration, resistance, and inductance of the plasma) may essentially depend on the geometry of the electrodes, the methods of supplying of the working material into the interelectrode gap, and the engineering characteristics of the discharge circuit. Nevertheless, after a plasma column has been formed on the discharge axis, further plasma development has many common features in almost all types of axially symmetric discharges. First of all, the plasma columns are unstable, and often *neck* instabilities are the first to develop. For plasmas containing strongly radiating heavy atoms the necks may develop in the regime of strong radiative losses mainly due to line radiation.¹⁴ This regime is known as *radiative collapse* (RC). We are going to show below that for plasmas of heavy ions (e.g., Xe, Sn) all types of ASD under discussion with a total stored electrical energy in the range 2–20 J emit EUV during the RC phase. For plasmas of light elements (e.g., Li), EUV radiation (such as the Ly- α line of H-like Li²⁺) could be radiated in the plasma-column necking mode as well, while that process is no longer a radiative collapse.

6.5 Plasma-Column Energy Balance; Pease-Braginskii Current; Critical Current for Heavy-Ion Plasmas

The homogeneous pinch plasma column in the steady state is often described in terms of a force balance in the radial direction between magnetic field pressure and plasma thermal pressure. This leads to a simple relation between the total number of ions in the column cross section, $N_i = \pi r^2 n_i$ (the ion line density), the electron temperature T_e , and the total current I . It is called the Bennett relation and may be written as

$$\frac{\mu_0 I^2}{4\pi} = (Z_{\text{eff}} + 1) N_i k T_e, \quad (6.1)$$

where Z_{eff} is the mean charge of the ions. In numerical form,

$$(Z_{\text{eff}} + 1)N_i T = 3.12 \times 10^{21} I^2, \quad (6.2)$$

where T is the plasma temperature in electron volts, N_i is the line density of the ions in cm^{-1} , and I is the pinch current in megamperes. The Bennett relation is fully applicable only when there are no other relevant forces and the radial velocity of the plasma is small compared to the sound velocity.

As we can see, the Bennett equilibrium does not contain such an important parameter as the plasma radius. The radial position of the plasma edge essentially depends on another type of equilibrium in the plasma—the energy balance. For most practical cases two quantities must be compared: Joule heating (Q_{Joule}) and radiation losses (Q_{rad}). Both quantities are usually given in power per unit length of the pinch column. For Q_{Joule} exceeding Q_{rad} generally the plasma is expanding, while higher radiative losses correspond to shrinking of the plasma column. For an optically thin hydrogen plasma column in Bennett equilibrium, the energy loss by bremsstrahlung balances Joule heating and the radiative losses are calculated by employing the Spitzer conductivity. The procedure may be extended to high-Z plasmas by using the relation for Joule heating per unit length of a Bennett discharge column,

$$Q_{\text{Joule}} \approx 3.3 \times 10^9 \frac{Z_{\text{eff}} \ln \Lambda}{T^{3/2}} \frac{I^2}{r^2}, \quad (6.3)$$

and the radiative power density for bremsstrahlung (free-free transitions),

$$Q_{\text{rad}} \approx Q_{\text{ff}} \approx 4.3 \times 10^{10} \frac{Z_{\text{eff}}^2}{(1 + Z_{\text{eff}}) T^{3/2}} \frac{I^4}{r^2}. \quad (6.4)$$

This leads to the well-known estimate of the Pease-Braginskii current^{15,16} for which the two power terms are equal:

$$I_{\text{P-Br}} \approx 0.27 \times (\ln \Lambda)^{1/2} \times \left(1 + \frac{1}{Z}\right). \quad (6.5)$$

Both Q_{Joule} and Q_{ff} are in watts per centimeter, and I is in megamperes.

Apart from the weak dependence on plasma parameters (through the Coulomb logarithm), the Pease-Braginskii current does not depend on the temperature T , because Joule heating and bremsstrahlung both increase with temperature as $T^{1/2}$ (provided Bennett equilibrium is satisfied). The relation above gives a value of approximately 1.6 MA for a hydrogen plasma, and $I_{\text{P-Br}}$ approaches 0.8 MA for a plasma of heavy, fully ionized atoms. However, heavier ions in a plasma are fully stripped only at exceedingly high temperatures $T > 3Z^2$ Ry. Usually in pinch plasmas heavy atoms are only partially ionized and the power in-line radiation far exceeds the power in bremsstrahlung. Under such conditions the critical current may

be orders of magnitude lower than the Pease-Braginskii current. For further analyses we build a simple analytical model very similar to the one presented in Refs. 8 and 14, but modify it slightly for the purposes of this review. While the principal features of pinch physics we are going to discuss are valid for a wider range of plasma parameters, we will make an attempt to adjust analytical expressions used for the lower temperature range (20–50 eV) and heavier elements ($Z_N \approx 50$).

Only a few experimental and theoretical data are available on the radiation power of heavy ions in this temperature range. Calculations show that for coronal plasmas at low temperatures the radiation power increases with increasing plasma temperature, reaches a maximum at some temperature T_{MAX} , and then gradually decreases, displaying local maxima corresponding to transitions from one open electron shell to another.^{17,18} The value of T_{MAX} varies rather slowly with the atomic number of the element, changing from approximately 25 eV for Ar to 100–120 eV for Sn and Xe. It can be roughly scaled as $T_{\text{MAX}} \approx 0.2Z_N^{1.6}$. The maximum power density (at $T = T_{\text{MAX}}$) grows with atomic number from $q \approx 10^{-25}n_en_i$ W/cm³ for Ar ($Z_N = 18$), reaching approximately $(0.6\text{--}0.8) \times 10^{-24}n_en_i$ W/cm³ for tin and xenon. No theoretical data for the radiation power at temperatures lower than T_{MAX} were found in the literature. Experimental data are even poorer. The radiation power of Xe plasmas was measured only at temperatures $T \approx 10$ eV and was found to be about $10^{-26}n_en_i$ W/cm³.¹⁹ Nevertheless, comparisons with calculations for other ions suggest that between 25 and 80 eV the radiation power of Sn plasmas (the corresponding interval for Xe is 30–100 eV) does not change significantly. In this temperature range losses are due to resonance transitions in ions with open d shell: $4p^64d^n - 4p^54d^{n+1} + 4d^{n-1}4f$ (see, e.g., Chapter 8 of this book). Practically all of these transitions in a large number of ionization stages are grouped around 90 eV for tin and 110 eV for xenon. The efficiency of excitation of the resonance transitions naturally increases with temperature [$\propto \exp(-h\nu/kT)$], but this increase is expected to be at least partly compensated by the decreasing number of equivalent electrons in the open d shell.

If the radiation power is presented in the form $q = \alpha \times 10^{-24}n_en_i$ W/cm³, one obtains for the line-radiation power $Q_{\text{rad}} = q \times \pi r^2$ of a Bennett plasma

$$Q_{\text{rad}} \approx 3 \times 10^{18} \frac{\alpha}{T^2 Z_{\text{eff}}} \frac{I^4}{r^2} \text{ W/cm}, \quad (6.6)$$

where α varies between 0.06 and 0.6 for the coronal plasma and the temperature lies between 25 and 100 eV.

Using the expression for Joule heating, we arrive at an estimate for the critical current:

$$I_{\text{CR}} \approx (1-2) \frac{10^{-4}}{\sqrt{\alpha}} T^{1/4} Z_{\text{eff}} [MA]. \quad (6.7)$$

This critical current, estimated analytically, may differ by about 50% from more accurate calculations, but nevertheless allows illustration of the basic physics be-

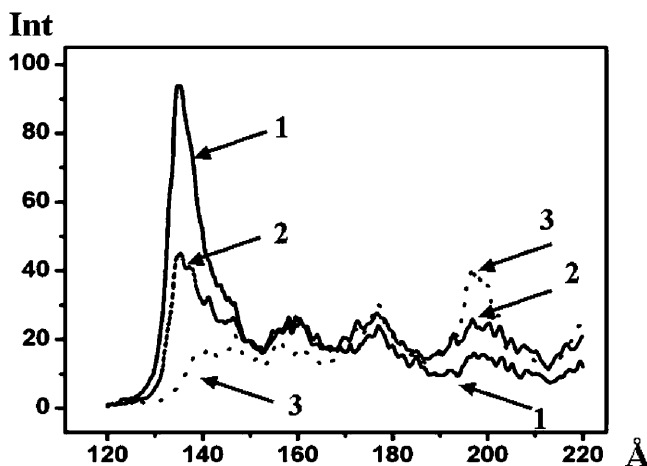


Figure 6.3 Sn spectra excited in a vacuum spark with laser triggering. Curve 1: $I \approx 18\text{--}20$ kA; curve 2: $I \approx 12\text{--}13$ kA; curve 3: $I \approx 8\text{--}9$ kA.

hind the different pinch phenomena. First of all, it shows that compression of xenon ($Z_N = 54$) or tin ($Z_N = 50$) plasmas with temperature $T \approx 25\text{--}50$ eV may start at a rather low current of about 10 kA or even lower. This estimate does not contradict known observations. If we assume that half of the stored electrical energy is accumulated in the inductance of the discharge circuit and that most discharges under discussion have $L \approx 10^{-8}$ H, the minimum stored energy for observation of EUV emission must be between 0.5 and 1 J.

The existence of a threshold value of the discharge current is illustrated in Fig. 6.3, where three spectra excited in pinch plasmas at different values of the discharge current are presented. The parameters of the discharge circuit were $L = 10^{-8}$ H, $C = 0.4$ μ F, with voltages up to $U = 5$ kV. The spectra demonstrate almost steplike changes of the plasma parameters for a comparatively small change of the discharge current. All other discharge characteristics were kept identical: geometry, discharge parameters, and properties of the ablating laser pulse. The upper curve shows the spectrum excited in the discharge with a current of about 18–20 kA. The strongest spectral maximum is around 13.5 nm, associated with transitions in ions $\text{Sn}^{+8}\text{--}\text{Sn}^{+13}$. At smaller currents $I \approx 12\text{--}13$ kA the recorded spectra have generally lower intensity, and a relative increase of the radiation from lower charged Sn ions is seen. As soon as the maximum discharge current is lower than 8–10 kA, the spectrum of the pinch changes drastically. The peak at 13.5 nm disappears almost completely; the strongest peaks are associated with lower ionization stages (22.5 nm for Sn^{+4} ; 20 nm for Sn^{+5} ; 18 nm for Sn^{+6}).

6.6 Neck Development Scenario

An estimate of the critical current was made using radiative losses for optically thin plasmas, which vary with radius as $1/r^2$. In the opposite extreme of blackbody radiation, the radiation depends only on the emitting area, and thus the radiation

per unit length increases linearly with radius. Figure 6.4 schematically illustrates the radiative energy loss as a function of radius for a Bennett plasma at a certain temperature and current. Note that for the small plasmas under consideration the surface radiation loss may be orders of magnitude lower than the blackbody limit schematically shown in the left upper corner. Unlike optically thin radiation, the equilibrium between optically thick radiation and Joule heating does give an equilibrium radius for the pinch, R_{EQ} in Fig. 6.4. Section 6.9 presents some estimates of this equilibrium radius. Evidently it depends on radiative properties of the plasma material, on the plasma temperature, and on the pinch current. The dependence of the radiation power on the plasma radius in optically thick cases cannot be easily calculated. Correct calculations must include a complex treatment of radiation transfer effects, and also the density shift of the ionization equilibrium, line-broadening effects, etc. This is indicated by the gray area in Fig. 6.4 and the uncertainty of the R_{EQ} value. Nevertheless, higher temperature corresponds to shorter-wavelength radiation, and thus at the same current deeper compression is needed for deviation from the optically thin case to take place. On the other hand, a larger current generally means a stronger role of the radiation ($\propto I^4$) than with Joule heating ($\propto I^2$) and thus generally a larger value of R_{EQ} at a given plasma temperature.

A hydromagnetically stable pinch with a constant current must stagnate on reaching the equilibrium radius, thus producing radiative shrinking of a hypothetical infinitely long cylinder. In reality, a typical pinch is hydromagnetically unstable to axial perturbations. The so-called sausage mode creates the conditions for radiative collapse (RC). A simplified scenario of the RC mode of the development of neck instability may be formulated as follows:

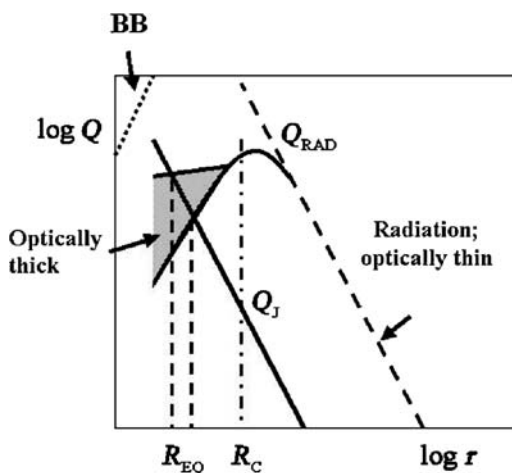


Figure 6.4 Radiative losses (Q_{RAD}) and Joule heating power (Q_J) per unit length of a cylindrical pinch versus the pinch radius r . The transition from the optically thin case (dashed line) to the optically thick case (solid line) is schematically shown. For the critical radius R_C and equilibrium radius R_{EQ} , see explanations in text.

1. After the plasma column reaches its energy balance at the equilibrium radius R_{EQ} , a *primary* hydromagnetic instability forms a plasma column of smaller size (diameter and length) characterized by a locally higher magnetic field pressure—a so-called *neck*.
2. The outflow of plasma from the high-pressure neck causes a disbalance of the Bennett pressure equilibrium, which in turn is restored by the magnetic pressure forces that increase the plasma temperature.
3. Higher plasma temperature corresponds to a shift in the ionization equilibrium to higher ionization stages and consequently of the radiation to shorter wavelengths.
4. The shorter-wavelength radiation has a longer photon mean free path, and the plasma is optically thin again. New energy equilibrium is reached by compression to a new (smaller) R_{EQ} corresponding to a higher plasma temperature.

The subdivision into separate stages 1–4 is evidently artificial. The process is repeated till the moment when the value of the critical current starts to exceed the current flowing in the pinch. Usually that termination is connected with outflow of plasma from the neck. When the total number of charged particles in the pinch cross section is too low, the appearance of anomalous resistance may greatly increase Joule heating, leading to plasma explosion and fast expansion.

6.7 Experimental Observation of Neck Instabilities; Plasma Outflow

Neck instabilities are known to be a common feature of almost all axial discharges. They have been observed in discharges over a wide current range—on vacuum sparks and Z pinches with currents between 50 and 200 kA, and in Z pinches and plasma foci with currents of a few megamperes.^{2,8} The presence of necks in low-current (10–30 kA) discharges was also expected but is not yet demonstrated. On the other hand, it is a well-known fact that even in gas-filled Z pinches the EUV-radiating plasma has a smaller axial dimension than the cathode-anode gap. This observation would be difficult to understand without the assumption that a high-temperature zone is created inside the main discharge column. Time-integrated pinhole images show that the radial size of the EUV source is also smaller than the initial discharge radius. Nevertheless, direct observations of discharge-column necking are of interest and are shown in Fig. 6.5.

Figure 6.5 presents a series of pinhole images of a vacuum spark discharge recorded on the concept tool PROTO I with a current of about 20 kA in tin vapors. Time frames were of about 20-ns duration. The time shift between the frames (numbered) is 10 ns. Thus exposure times of different frames are partly overlapped. The images have been recorded with the help of a time-gated open-microchannel plate camera sensitive to radiation below 150 nm (www.schulz-si.com). No filters are used for the upper images. They are formed, therefore, by integrated radiation between 1 and 150 nm. The bottom images are filtered by a Zr/Si filter and are

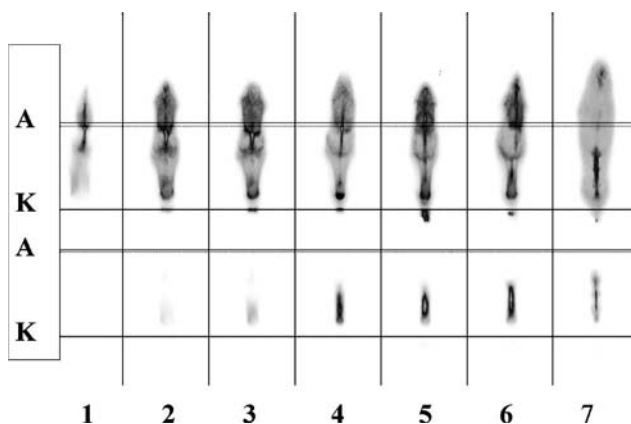


Figure 6.5 Time-framed pinhole images of Sn plasma in a vacuum spark discharge: A, anode; K, cathode; anode-cathode distance, 3 mm; duration of the microchannel camera frame, 20 ns; interval between frames, 10 ns. Upper images, not filtered; lower images, obtained with Zr/Si filter.

thus formed by EUV radiation between 8 and 16 nm. Simultaneous registration of time-gated and space-resolved spectra show that radiation around 13.5 nm is mostly responsible for the formation of the bottom images. Horizontal lines indicate the positions of cathode and anode, with a distance of 3.5 mm between them.

EUV radiation from the pinch starts only when the plasma column locally (at a distance of approximately half a millimeter from the cathode) shrinks to a diameter $\approx 0.3\text{--}0.4$ mm (frame 4). At maximum radiation the plasma has a diameter of about 0.2 mm and a length in the axial direction close to 1 mm. More than one neck may appear, and the position of maximum narrowing of the plasma column—the neck—gradually moves from the cathode to the anode. It often happens that during further development (compression) the neck is split into two or more subnecks (frame 7), keeping the aspect ratio of the sausage ($\gamma = \text{length}/\text{radius}$) approximately constant ($\gamma \approx 2\text{--}5$). The observed duration of EUV radiation corresponds well with an estimate of the sausage lifetime due to plasma outflow: $\tau \approx \gamma r / V_S$, where V_S is the ionic sound velocity in the plasma. At a velocity of 10^6 cm/s and a radius of 0.01–0.015 cm, expected lifetimes are 20–50 ns, which corresponds fairly well to the experimental observation.

6.8 Dissipation of Electrical Energy in the Discharge

The pinch dynamics shown in the previous figure correlate well with electrical and EUV signals recorded by an oscilloscope. An example is shown in Fig. 6.6. The discharge current starts to deviate from the ideal LC contour current immediately after breakdown. The initial energy dissipation is most probably connected with low conductivity of the rear plasma near the anode. The ablating laser pulse must be optimized to mitigate unnecessary energy loss. The EUV signal and a strong dissipation of electrical energy start after approximately 50 ns and correlate with

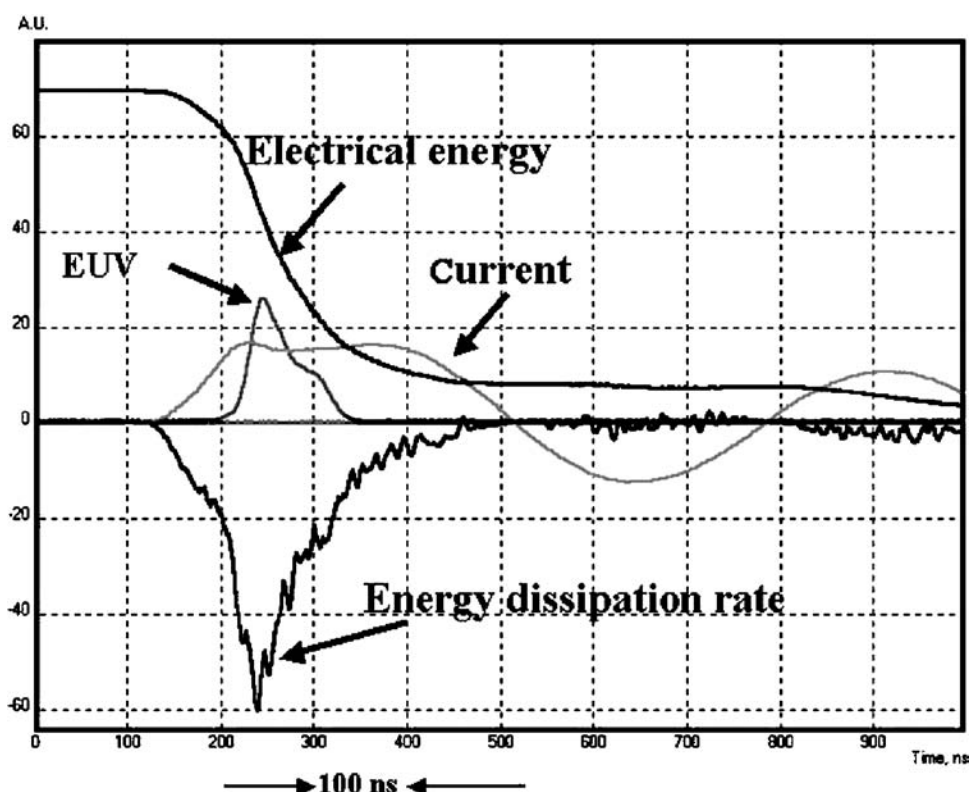


Figure 6.6 Oscilloscope traces of vacuum spark discharge. The discharge current, the EUV signal, and the calculated full electrical energy in the circuit and energy dissipation rate are given in arbitrary units.

the appearance of neck in the plasma column. Evidently that dissipated energy is spent on plasma heating, ionization, and emission of radiation. The EUV signal for these specific discharge conditions consists of two unresolved peaks. Such an EUV signal structure is usually associated with the occurrence of two or more subsequent micropinches—a so-called *zippering* effect (see below). The duration of every subpeak is about 30–40 ns. Expansion of the necks causes a slight increase of the current. Nevertheless, at this moment most of the stored electrical energy is dissipated in the discharge. Less than 15% of the initial electrical energy is still present in the capacitor bank and in the circuit inductance. Thus more than 70% of the stored energy was dissipated during the useful phase of the pinch.

6.9 Equilibrium Radius; EUV Source Size

The calculation of the equilibrium radius is connected with the problem of photon transport in plasmas containing ions with complex atomic structure that radiate simultaneously arrays of hundreds and thousands of almost unresolved lines. Some approaches to this very complex problem are discussed in Chapter 8. We may also

refer to the THERMOS code—an average-atom (AA) model that allows for a non-local thermodynamic equilibrium (NLTE) radiation field.²⁰

In this semiquantitative analysis, we explore an approach similar to the one used for the analytical description of neck-instability development at higher currents (a few kiloamperes) and higher plasma temperatures. Details of the analytical description are given in Ref. 8; here we present the final results adapted for the 10–30-kA current case.

The decrease in the radiation rate due to opacity is estimated as follows. When the plasma size is larger than the photon free path ($r \gg l_\nu$), emitted photons are absorbed by another atom (ion) in the plasma. With probability $p = 1/(1 + W_c/W_r)$ the photon will be reemitted in an arbitrary direction, where W_r is the radiative decay rate and W_c is the rate of collisional deexcitation ($n_e \langle \nu \sigma \rangle$). The energy of the reemitted photon is random with a probability distribution given by the line shape. If we assume that the photon experiences M scatterings before leaving the plasma, then the total probability for the photon to escape from the plasma may be expressed as p^M , and the radiation power of the optically thick plasma column becomes $Q \approx Q_{\text{RAD}} p^{1+M}$, where Q_{RAD} is the radiation power for the coronal, optically thin case. The deviation of the radiation power from the optically thin case is shown schematically in Fig. 6.4. We introduce the critical radius r_c where plasma radiation becomes surfacelike. This transition should occur approximately when a sizable fraction of the photons is reabsorbed—say, when $p^{1+M} \approx 1/e \approx 0.37$. Using an analytical expression from Ref. 8, one arrives at

$$R_c \approx 10^5 \frac{I^{4/3} Z_N^{1/6}}{Z_{\text{EFF}}^{1/6} T^{7/3}}. \quad (6.8)$$

Assuming that for $r < R_c$ the plasma column is optically thick and radiates surfacelike [$Q_{\text{RAD}}^{(S)} = Br$], we obtain an expression for the surfacelike radiation:

$$Q_{\text{RAD}}^{(S)} \approx 3 \times 10^3 \alpha \frac{T^5 Z^{1/2}}{Z_N^{1/2}} \times r \text{ W/cm}. \quad (6.9)$$

Comparison of $Q_{\text{RAD}}^{(S)}$ with Q_J gives an estimate of the *equilibrium radius* R_{eq} :

$$R_{\text{eq}} \approx (1-2) \times 10^2 \frac{Z_N^{1/6} \times Z^{1/6} \times I^{2/3}}{T^{13/6} \times \alpha^{1/3}} \text{ cm}. \quad (6.10)$$

At a current $I = 0.02$ MA, an effective charge $Z \approx 10$, and an electron temperature $T \approx 40$ eV, the equilibrium radius for the micropinch in a Sn plasma is expected to have a value $R_{\text{eq}} \approx 100 \mu\text{m}$, which is in good agreement with the experimental observations from time-resolved diagnostics. Our estimate is also in agreement with the experimental observation that for currents above the critical current threshold, higher current corresponds to larger plasma radius.

Using this relation for the plasma radius, one can try to establish an expected dependence of the CE on the current. Assuming that the plasma is optically thick and radiates surfacelike, the total radiated energy at a given electron temperature is proportional to surface $\times$ time. The surface of the radiating cylinder is $S = 2\pi r \times \gamma r \propto r^2$, and the duration of the emission is $\tau \approx \gamma r / V_S$; thus the radiated energy $E_{\text{Rad}} \propto r^3 \propto I^2$. Taking into account that the stored electrical energy can be scaled as $E_{\text{EL}} \sim LI^2$, we come to the conclusion that the $\text{CE} = E_{\text{Rad}}/E_{\text{EL}}$ does not depend (at least, not strongly) on the current. This result explains very well the fact that in spite of a large spread of the electrical parameters of the various discharge sources, all display rather close values of CE: for Xe, around 0.5%–0.7%, and for tin plasmas, around 2%. Comparatively small differences (which, nevertheless, may be rather important in a practical sense) may be attributed to the peculiarities of the initial prephase of discharge with (e.g.) different geometries. Our experiments also show quite a weak dependence of CE on the stored electrical energy, provided the current in the discharge exceeds the critical current. (For a discussion of additional conditions for the RC regime of the discharges, see below.)

6.10 Equilibrium Radius versus Linear Density Trajectory

Some important features of the neck development can be illustrated using a *trajectory* on a plane whose coordinates are the compression radius r and the total number of charged particles in the neck cross section, $N = n_i(1 + Z) \times \pi r^2 \approx n_e \times \pi r^2$ (Fig. 6.7). In a simplified approximation the total number of charged particles, N , is straightforwardly connected to the plasma temperature through the Bennett relation ($T \propto I^2/N$). We assume also a constant current in the pinch. The starting point of the trajectory (A) indicates that the initial plasma column was created with a radius r_A , the total number of particles was N_A , and the corresponding initial plasma temperature was T_A . The neck development can be seen as the result of

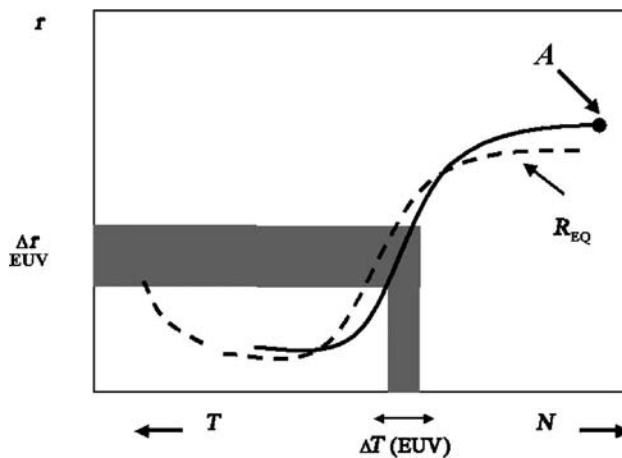


Figure 6.7 N – r trajectory of the neck development.

plasma outflow from the neck with a subsequent increase of the plasma temperature and plasma compression. Rather soon the plasma reaches the equilibrium radius (dashed curve), and further neck development follows the path $r = R_{\text{EQ}}[T(N)]$ (solid line), which may slightly deviate from the equilibrium radius trajectory. We emphasize that sliding along the $r(N)$ path is due to plasma outflow from the neck and this outflow determines the time characteristics of the process. During the evolution the plasma in the neck passes through the temperature interval corresponding to the appearance of ions radiating in the EUV—indicated as ΔT_{EUV} . The range in radial size of the EUV-radiating source is shown as ΔR_{EUV} .

6.11 Stability of Radiative-Collapse Trajectory, EUV Yield, and Shot-to-Shot Reproducibility

When studying the physics of neck instabilities in vacuum sparks with current 100–200 kA, it was found that, depending on the initial conditions, micropinches could be subdivided into two types.²¹ The first, a “good” type, was characterized by deep compression, high brightness, and rather good reproducibility of such plasma parameters as size and radiation yield. The second type was characterized by a low level of compression, with low and very unstable x-ray and VUV yield. Numerical modeling and experimental studies resulted in the conclusion that a region of stable initial parameters (radius and N) exists where the neck reaches a stable $R_{\text{EQ}}[T(N)]$ trajectory rather soon after breakdown. There exists also a zone of initial parameters, characterized by either too high an initial radius or too low an initial linear density in the pinch. For such pinches energy losses due to plasma outflow from the neck exceed radiative losses, and the neck does not reach the regime of radiative collapse. Both cases are illustrated in Fig. 6.8. The existence of a stability zone

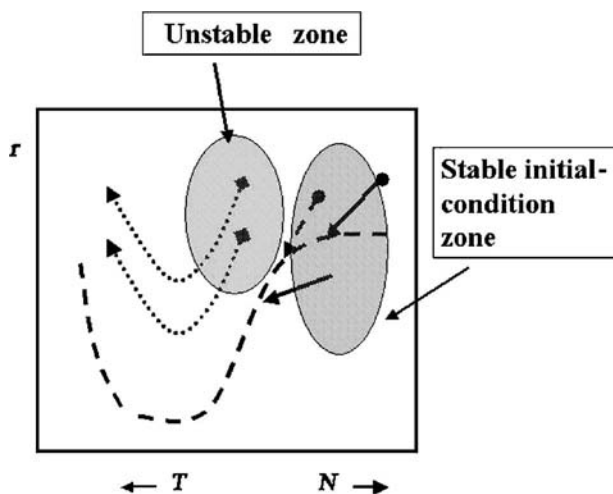


Figure 6.8 N – r trajectories for stable and unstable scenarios of neck development. $R_{\text{EQ}}(N)$ is shown as a dashed line. Dotted lines are unstable trajectories.

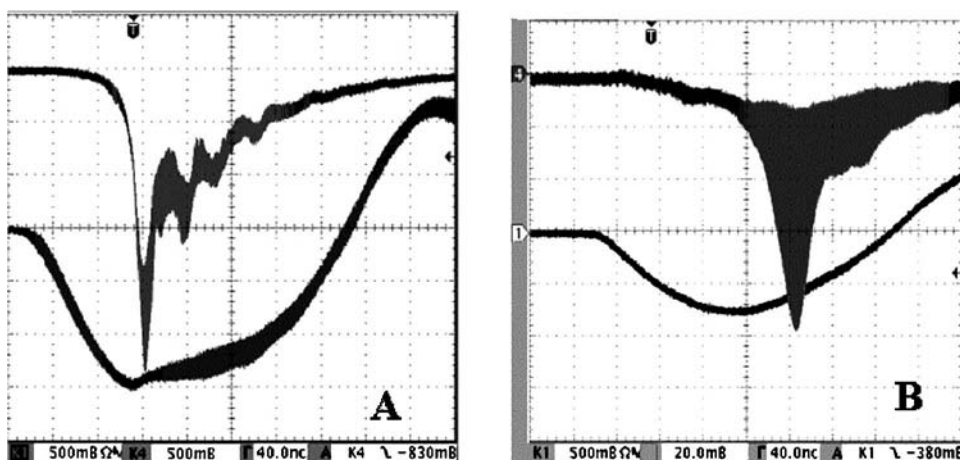


Figure 6.9 Oscilloscope trace for 256 shots (overlapped). Lower curve: current; upper curve: EUV signal. A: maximum current about 20 kA; B: current about 10 kA.

explains well the stability of radiation yield even at badly reproducible initial conditions when material is fed into the discharge by third-electrode triggering or by ablation from one or both electrodes by a laser pulse.^{10,21}

Figure 6.9(A) demonstrates reasonably high stability of the EUV signal at properly chosen parameters of ablating laser and discharge design parameters. It shows oscilloscope traces for current and EUV signal for 256 shots. We want to point out that visible smearing of both curves in Fig. 6.9(A) is mainly due to time jittering of the oscilloscope start-up recording time. Figure 6.9(B) illustrates an unstable discharge at a low current. If the current in the discharge only slightly exceeds the critical one, the radiative collapse may be interrupted at early stages of its development. For some good shots the CE may be as high as for the stable regime, but the EUV signal has a very unstable character.

Our modeling and experiments indicate that there exists a mechanism of self-stabilization of the trajectory of the micropinch development. Nevertheless, triggering of this stabilization mechanism depends on the initial parameters of the plasma column and on the discharge design characteristics.

6.12 Axial Size of the EUV Source; Zippering Effect

The axial dimension of the neck micropinch cannot be calculated in the zero-dimensional analytical model we have used to introduce some important features of the pinching of plasmas of heavy atoms. More advanced 2D modeling predicts $\gamma \approx 2\text{--}5$ for a single neck, and thus the axial size of our source is expected to be between 0.5 and 1 mm. Nevertheless, time-integrated images often reveal larger sizes—up to 1.5–2 mm. In parallel with increase of the pinch length we detect some increase of the EUV yield. For observation (collecting of radiation) in the direction perpendicular to the discharge axis, which was proposed in our concept

source, such an increase in length is of no use—restrictions imposed by the imaging optics do not allow utilization of radiation from a source with dimension larger than 1 mm. Time-gated pinhole images of the radiating plasma permit understanding of this phenomenon. Figure 6.10 demonstrates experimental evidence of the subsequent appearance of EUV-radiating micropinches in different positions on the discharge axis. Evidently the initial plasma column created by ablation of one of the electrodes is axially strongly inhomogeneous. As a result appropriate conditions for the development of necks in the radiative collapse regime may appear at slightly different moments of time for different axial positions.

Figure 6.10 shows time-framed and space-resolved spectra of a tin plasma in the VUV spectral region. Usually the appearance of subsequent micropinches correlates with a multipeak (in this case, double-peak—see Fig. 6.6) structure of the EUV time-resolved signal. For the scheme where useful radiation is collected perpendicular to the discharge axis, such an increase of the EUV source size could be unfavorable and must be avoided. Experiments show that proper choice of time profile and focusing of the laser (electron) ablating beam are able to mitigate zip-

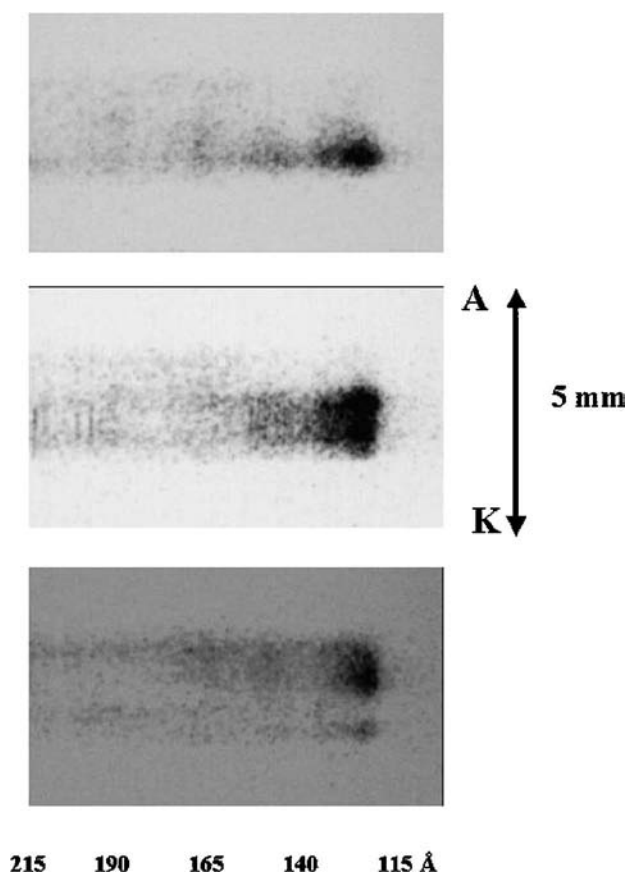


Figure 6.10 Time-gated and space-resolved spectra of Sn vacuum spark. Time delay between gates ≈ 20 ns.

pering and maintain the axial size of the EUV source inside the specification limits of the imaging optics.

6.13 Conclusions

In the previous sections we described the process of neck radiative collapse with a simplified analytical model. While this model allows the prediction of a number of essential features of pinch characteristics, many aspects of the pinch dynamics are outside the scope of such an approach. There exists a number of 1D and 2D numerical models created for modeling of pinch dynamics. One of them, relevant to EUVL source design, the reader can find in Chapter 11; another—code Z^* —was presented at the first EUVL symposium in Dallas in 2002.²²

In our group we are using a 2D code, described elsewhere.²³ This MHD code is based on an Eulerian grid. It uses partially implicit first-order approximations of the main equations, thus accelerating the calculation. The use of first-order approximation decreases the precision of the computations, though this is compensated by the high stability of the code, which yields physically reasonable results even on a rather crude grid. The main problem for all numerical models working with heavy-ion dense plasmas is radiation transport. Together with the THERMOS group, we are trying to incorporate atomic-physics calculations and radiation transport into the full treatment code.

The zippering effect (Fig. 6.10) was an example of importance of 2D modeling for understanding the pinch physics relevant to EUV production. As another example we refer to our results of 2D modeling of the Z -pinch discharge in Li plasmas, where due to the simple atomic structure of Li ions a full treatment of the radiation transport problem is feasible.¹² It was found that with a proper choice of electrode geometry and current profile, an auto-oscillating regime of pinching can be realized.

One chapter in a book does not allow adequate coverage of even a small part of the physics of discharges with axial symmetry— Z pinches. Many important aspects have been omitted or not even mentioned. Nevertheless, where possible, we have tried to show that understanding of the physical processes taking place in discharge plasmas is essential for EUVL source design.

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No other author biographies were available for this chapter.

Chapter 7

Fundamentals and Limits of Plasma-based EUV Sources

Rainer Lebert, Thomas Krücken, and H.-J. Kunze

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7.1 Introduction

EUVL exposure tools for more than 100-wafer/h throughput require highly efficient sources of EUV radiation. It is commonly accepted that the development of suitable EUV sources is one main risk factor in bringing this promising technology to a cost-effective implementation in high-volume semiconductor manufacturing fabs.^{1,2} While investing enormous efforts in developing such sources, it has become obvious that the requirement can be met only if these sources operate close to the physical limits and the limits of thermal engineering.

Several types of LPPs and DPPs are under investigation by several groups as EUV sources for the first EUV exposure tools.^{3–18} Within the last three years such sources have demonstrated improvements of several orders of magnitude with respect to relevant parameters such as power and component lifetime. On looking

at the present performance of EUV sources with up to 2% radiator efficiency into 2π sr, repetition rates of up to 10 kHz, input powers beyond 20 kW, and component lifetimes on the order of more than 10^{10} pulses, the development of EUV sources that can meet the performance specifications seems feasible, if only this pace of progress can be sustained.

In principle, there are many different concepts to generate LPPs and DPPs. Common to all approaches and all concepts is that an optimized conversion efficiency (CE), η , is of major importance because this minimizes the driving power, P_{in} , for a demanded EUV power, P_{EUV} :

$$\begin{aligned} P_{\text{EUV}} &= P_{\text{in}}\eta = P_{\text{electr}}\eta_{\text{radiator}}\eta_{\text{collector}} & (\text{DPP}), \\ P_{\text{EUV}} &= P_{\text{laser}}\eta_{\text{radiator}}\eta_{\text{collector}} & (\text{LPP}). \end{aligned} \quad (7.1)$$

Usually the radiator efficiency is given for a specified solid angle, i.e., 1 sr or 2π sr. The collector efficiency is governed by the solid angle Ω of the collector and the relative amount of flux that is usable with the etendue of the projection optics. Suppliers have plans for up to π -sr collectors for DPP and up to 5-sr collectors for LPP. Often the collector efficiency is given as a percentage of the collectable solid angle or as a percentage of 2π sr.

For the two basic concepts of DPP and LPP, the definition of CE is slightly different: While for DPPs we calculate efficiencies with respect to the electrical input power P_{electr} , LPP conversion is stated in relation to the average laser power P_{laser} , not taking into account the conversion from electrical energy into laser energy.

The input power to the EUV sources directly influences the cost of ownership (CoO) of the source with respect to both investment costs and operational costs. In addition, because the lifetime of source components degrades with increasing power input, a source with the highest CE and hence the lowest driving power has the best chances for technical realization and for achieving lowest CoO. This is of special importance for discharge sources, where the ultimate limiting factor is expected to be the cooling of the electrodes and their lifetime. With LPPs, the CoO is expected to be determined mainly by the high-power laser, which will be in the 5- to 30-kW class.

For LPPs, the efficiency is maximized by finding an optimized set of parameters for the laser driver matched to the target of choice. For DPPs, the efficiency depends critically on the concept to generate a suitable plasma and on the parameters to operate such a device, which govern how much power can be effectively coupled to the radiating plasma. The chances of succeeding in developing a viable source rise with decreasing demands on the electrical power to be handled in the discharge volume.

In this chapter we discuss efficiencies of pulsed plasma systems, starting from basic principles, in order to define combinations of suitable plasma parameters for the generation of the EUV-generating plasma sources.

7.2 Required Parameters of EUV Sources

7.2.1 General requirements

For high-throughput EUVL exposure tools, there is consensus among the major potential suppliers of EUV exposure tools about the specifications of EUV sources (see Chapter 2). The main specifications are related to EUV emission in a 2% bandwidth around 13.5 nm, 115 W of collected source power at the intermediate focus (IF), an etendue limit of 3 mm² sr, and a repetition rate of 10 kHz or higher.

The key figure of merit for sources, *collected power at the IF*, is determined by a series of factors:

- Inband EUV yield, governed by the radiator efficiency and input power.
- Collection efficiency (depending on the fraction of collected radiation, condenser reflectance, and etendue match).
- Transmission of the beamline, i.e., the vacuum between source and collector optics. In beamline transmission the necessity to mitigate debris—preventing any particulates, vapor, dust, or plasma from reaching the collector—is a determining factor.
- Transmission of additional spectral purity filters, which might become necessary to suppress out-of-EUV-band emission from the source. While most of the factors are determined by finding optimized technical solutions in engineering, the inband EUV yield is mainly governed by the physical properties of the sources and is treated in this chapter.

For estimating the power requirement at the location of the plasma, the losses of the collector must be taken into account. The reflectivity of the collector optics, the absorption by the debris mitigation system, and the solid-angle collection efficiency of the collector determine these losses. It is generally accepted that a typical best total collection efficiency can be assumed to be about 20% of the total inband emission into a half sphere (2π sr). This means that a source emitting at least 100 W/sr of inband EUV is required. For plasmas pulsed at 10 kHz this translates to 10 mJ/(pulse sr). Under the assumption of 100-ns pulses and 1 mm² of source surface (adapted to etendue), the intensity of the source would have to be about 6×10^5 W/mm² into 2π of inband EUV radiation only. This number will be used as the target for the basic discussions in the following sections.

7.2.2 Source efficiency

A first estimate of required CEs is obtained by assuming a value of 30 kW for the input power to the source, which translates to a requirement of CEs of at least 2% into 2π sr. This value is taken because a limit of 30 kW of electrical input power is estimated¹ for discharge plasmas, and because 30 kW is also assumed as the upper limit for acceptable CoO for laser systems. The total efficiency of the EUV source is governed by many factors:

- **Driver efficiency** (η_{driver})

The efficiency of driving the EUV source with external (electrical or laser) power. This can be separated into two significant factors:

1. The efficiency of the generator to supply the power ($\eta_{\text{generator}}$).
2. The efficiency of coupling the drive power into the radiating matter (plasma) (η_{coupling}).

The driver efficiency is given in percentage of power generated in the driver.

- **Radiator efficiency** (η_{rad})

After the driver energy is deposited into the radiating matter, there is an intrinsic efficiency for the radiation in the desired spectral band of use. Radiator efficiency is usually given in the same units as the total efficiency, with respect to 1 sr or 2π sr. The radiator efficiency is governed by two main factors:

1. **Plasma efficiency** (η_{plasma}), which is the fraction of the power deposited in the plasma that is radiated per steradian by the plasma in a specified direction.
2. **Spectral efficiency** (η_{spectral}), which is the fraction of the totally emitted radiation (into the defined solid angle) that can be used within the 2% bandwidth around the central wavelength.

- **Collection efficiency** ($\eta_{\text{collection}}$)

This is the product of source size and collection angle (etendue). It represents the capacity of the optical systems to transport radiative power. If the product of source size and solid angle collected is larger than the etendue of the projection optics, only a limited collection angle can be used. Typical etendue values are in the range of $3 \text{ mm}^2 \text{ sr}$. The total CE can hence be factored as

$$\eta_{\text{total}} = \eta_{\text{generator}} \cdot \eta_{\text{coupling}} \cdot \eta_{\text{plasma}} \cdot \eta_{\text{spectral}} \cdot \eta_{\text{collection}}, \quad (7.2)$$

where the efficiency of generation of suitable driver pulses ($\eta_{\text{generator}}$), the efficiency of coupling the driver pulse to the plasma (η_{coupling}), the efficiency of conversion by the plasma (η_{plasma}), the spectral efficiency η_{spectral} , and the efficiency of collection ($\eta_{\text{collection}}$) can be discussed and optimized separately. It becomes obvious that reaching 2% CE requires pushing each factor to its limit.

7.2.3 Single-pulse conversion and scalability with repetition rate

In principle the recipe to develop the best-suited source can be separated into the following tasks:

- **Optimization of the single-pulse radiator.** This depends on finding conditions for a radiator that emits single pulses of EUV inband emission most efficiently. This means reaching an intrinsic conversion efficiency much larger

than 2% in 2π sr for the given input power from a volume small enough to allow collection of radiation into the specified solid angle. This task is mainly connected with basic plasma physics, as will be seen later.

- **Finding a source concept suited for being scaled up.** The concept must allow for generating and for heating of a suitable radiator, and it must allow for scaling the repetition rates into the multikilohertz range while conserving the single-pulse features.
- **Optimization of the driver.** This depends on finding a driver that generates the best starting conditions and feeds sufficient power into the radiator with the highest possible efficiency in a way that is matched to reach the highest CEs.
- **Solving engineering problems for tool architecture and lifetime.** These include thermal management to sustain this operation mode for a long enough time, and avoiding erosion.

Unfortunately, these problems cannot be solved independently. Features of the driver influence the plasma and vice versa. Best CEs may not be suited for long lifetime, or best conversion may lead to a radiator that is not scalable, for example due to crosstalk from one pulse to the next.

In this chapter, we concentrate on the first task, i.e., single-pulse conversion.

7.3 Fundamental Limits

For a first orientation on achievable single-pulse conversion, one can use the Planck radiator as a guideline. Its spectral radiance $L_\lambda(T)$, given by Planck's law of radiation, can be written as¹⁰

$$L_\lambda(T) = \frac{2 \cdot (h \cdot c)^2}{\lambda^5} \cdot \frac{1}{\exp \left[(h \cdot c) / (\lambda \cdot kT) \right] - 1}, \quad (7.3)$$

where $L_\lambda d\lambda$ is the energy emitted per unit time, surface area, and solid angle in the spectral interval $(\lambda, \lambda + d\lambda)$.

Figure 7.1 shows Planck's law schematically with logarithmic y axis over the broad spectral range from IR to x rays for a temperature of 20 eV. For a blackbody radiator to be most efficient for a selected spectral band, the emission of use must be tuned to be as large as possible compared to the rest of the emission, which is usually referred to as *out-of-band* (OOB) emission. The Stefan-Boltzmann law gives the emission integrated over the full spectral range. By definition, the radiator efficiency equals the radiator efficiency for an ideal Planck radiator. Hence, its efficiency is governed by the spectral efficiency, which is shown in Fig. 7.2 as “in-band radiation” relative to the total radiation as a function of radiator temperature for the central wavelength at 13.5 nm. A maximum radiator efficiency of nearly 0.75%/ 2π sr is reached when the radiator temperature is around 23 eV, i.e., around 270,000 K. Obviously, such an emitter must be in the plasma state.

This optimized Planckian radiator would emit about 10^7 W/mm² sr of EUV inband radiation (dotted line in Fig. 7.2; the broken line gives the total radiance). In order to keep it emitting, at least the total power emitted must be replenished,

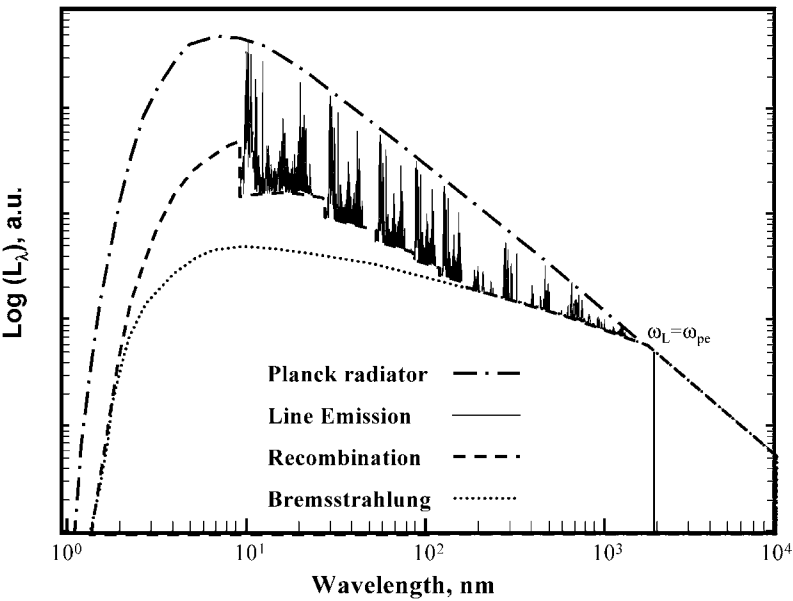


Figure 7.1 Schematic of Planck's law, with typical real plasma emission.

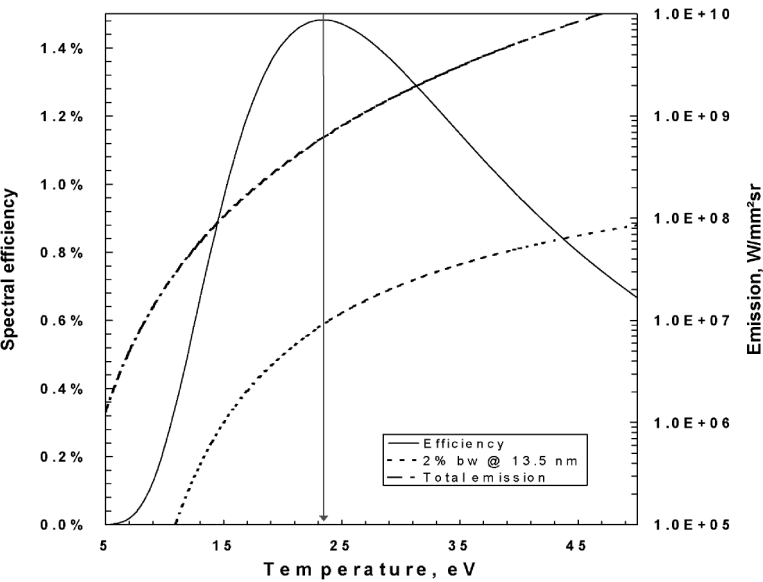


Figure 7.2 Spectral efficiency of a Planck radiator, (i.e., inband radiation relative to total radiation) reaches nearly 1.5% for 23 eV.

which corresponds to driving powers of at least 10^9 W. It is thus obvious that highly efficient EUV sources must be operated in the pulsed mode. Within pulsed power technologies, drive powers beyond 10^9 W are routinely generated in compact devices, but these power levels can be sustained only for some 100 ns.

If one tries to meet the demands for an EUV source with the optimized Planck emitter, it has to be taken into account that the etendue limits the product of the used solid angle and the effective source surface to $3 \text{ mm}^2 \text{ sr}$. To get some estimates, we assume the most effective case of using the full solid angle, i.e., making the effective source smaller than 0.3 mm^2 . Larger Planckian sources emit more light, but only smaller collection angles can be used. Hence, source development requires us to balance the collecting angle Ω with the source surface.

Taking a possible 10 kHz as the guideline, pulses of about 6 ns are needed to achieve 240 W of collectable flux, assuming all input power is coupled into the plasma. For this hypothetical Planck source, a driving power in the range of 30–40 kW would be sufficient. Figure 7.3 shows this minimum driving power and the pulse duration needed for 240-W collectible power (the factor-of-2 higher requirement at the source than at the IF allows for an assumed 50% collection efficiency) if the Planck source is operated at 10 kHz at different temperatures.

In summary, the approach of discussing an ideal Planckian emitter gives helpful guidelines for developing high-power EUV sources:

- Efficient EUV sources are plasmas of around 20–30-eV temperature.
- These plasmas are generated pulsed, employing driving powers in the range of 10^8 W.

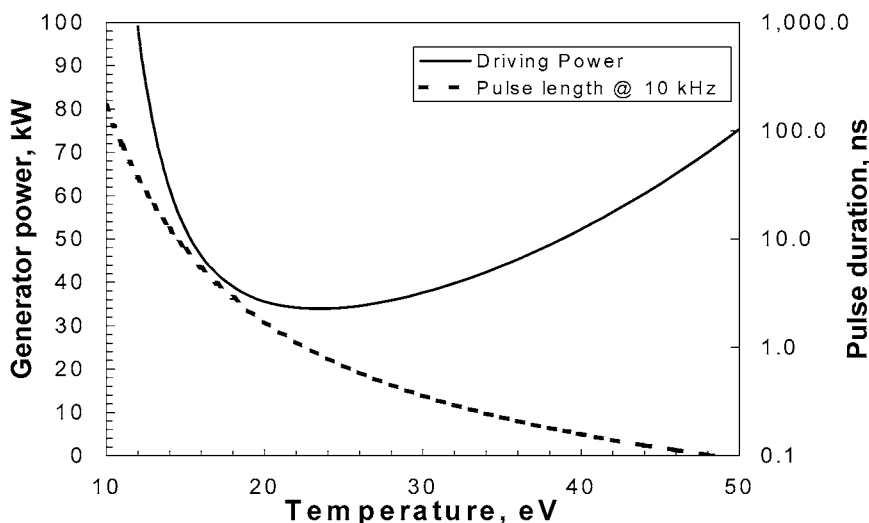


Figure 7.3 Estimated required input power for an ideal 3-mm^2 sr-etendue Planckian emitter for 240-W collectable power in 4π sr. Minimum input power required is around 30 kW. For 10 kHz, the pulse durations required are in the range of a few nanoseconds.

- The plasmas should emit radiation pulses in the range of 1–100 ns for 10-kHz repeated operation.
- The plasma sources should be as small as possible in order to keep losses low.
- 1.5% (in 2π sr) radiator CE seems to be feasible.
- Input powers of greater than ~ 30 kW coupled into the emitters are necessary.

The drawbacks of this approach of an ideal Planckian emitter are obvious:

- The basic idea of Planck's theory is a steady-state source in total thermodynamic equilibrium. In fact, however, we ended up with generating radiation pulses in the nanosecond range.
- A Planckian emitter by definition is optically thick at all wavelengths, which requires sufficient spatial extension for reabsorption of emitted photons. We arrived at demanding a source as small as possible, with extensions of less than 1 mm.
- The spectral efficiency is rather low. Although for a given temperature this source emits the highest flux, 98.5% of the emission is OOB. The consequence is obvious: an effective emitter must be tuned to higher spectral efficiency by reducing the OOB emission while keeping the inband emission as close as possible to the Planckian limit.

For a short-pulsed transient emitter, overheating may be an effective strategy if the excess energy is gained in the cooling phase.

The assumption of an emitter optically thick only for the inband emission was used in describing the dependence of the conversion efficiency of a lithium laser-produced plasma on the laser intensity.^{19,20} Figure 7.4 shows the experimentally obtained number of photons at 13.5 nm as a function of the laser intensity in comparison with theoretical calculations, which were based on only two assumptions: the electron temperature of the plasma scales like $kT_e \propto I^{4/9}$ with the laser intensity I , and the temperature is $kT = 20$ eV at a laser power of 10^{11} W/cm². The lithium ions emit in an opacity-broadened line at the Planckian limit. The agreement is very good. Figure 7.5 shows the total CE, obtained by dividing the emitted energy in the Lyman- α line by the laser pulse energy: η displays a maximum corresponding to a plasma temperature of 47 eV.

This result proves that the consideration of an ideal blackbody emitter is helpful in understanding the dependence of CE on plasma temperature. In the presented result, the dependence of the CE on laser intensity was described by using this argument alone. However, in comparison with the absolute values as calibrated in the past, the CE should be assumed higher by a factor of about 5 with updated knowledge. In order to gain some additional insight, we will discuss some details of radiation emission in plasmas in the next section.

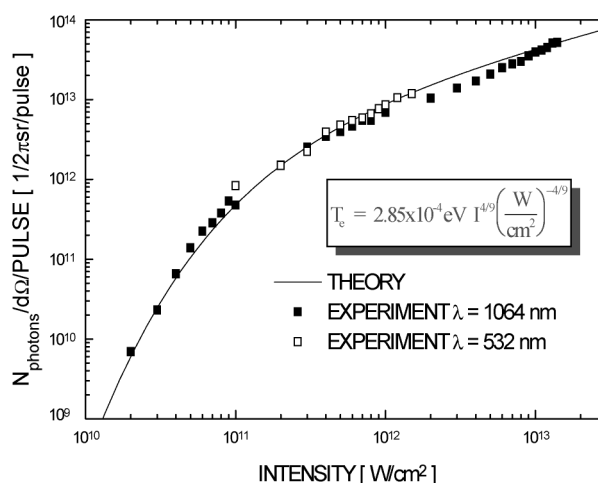


Figure 7.4 Experimental yield in Lyman- α line of laser-produced lithium plasma as function of laser intensity tuned by changing pulse energy. (Reprinted from Ref. 19 with permission from the Optical Society of America.)

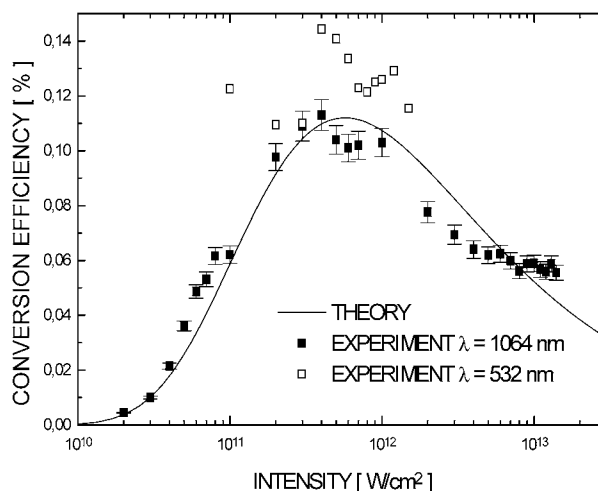


Figure 7.5 Experimental CE (per steradian) follows the theoretical values derived from the assumption of a Doppler-broadened optically thick line. (Reprinted from Ref. 19 with permission from the Optical Society of America.)

7.4 Fundamental Processes

In order to generate a small volume of plasma as an effective pulsed emitter of EUV radiation, matter must be heated and ionized to the ground state of an ion that has radiative transitions of suitable wavelengths, and finally these transitions must be excited by electrons of sufficient energy and density.

In a first approximation the ionization potentials of ions of interest all are about $4/3$ of the energy of the photons to be generated. For EUV around 13.5 nm this

leads to ionization potentials of 120–130 eV. This estimation is based on the knowledge that the first resonance lines (as, e.g., the Lyman- α lines in hydrogenlike ions) are of highest intensity. In plasmas, as a rule of thumb, a given ion is best emitting, i.e., is of high abundance, if the electron temperature is in the range of $1/5$ to $1/4$ of the ionization potential. This gives the range of desirable electron temperatures as $1/4$ to $1/3$ of the desired photon energy, which results in an estimate of 23 to 31 eV; this is nearly the same value as the blackbody approach demands.

Ionization and excitation must be accomplished within the lifetime of the plasma. Typical rate coefficients S for ionization are in the range of 10^{-7} cm³/s for neutral atoms (i.e., removing the first electron), and in the range of some 10^{-8} cm³/s for all the other outer-shell electrons. For low- Z elements two to five stages of ionization must be undergone, and for high- Z elements 10 or even more stages. As the time constant of ionization is the rate coefficient times the electron density, single ionization in 10 ns requires a minimum electron density of at least 10^{16} cm⁻³. The ionization is governed by the confinement parameter $\Phi = t_{\text{plasma}} n_e S$ for the corresponding ionization stage. If $\Phi < 1$, then ionization does not occur effectively. If $\Phi > 1$, then ionization can be completed. A good tuning of the EUV plasma is to generate electron densities such that $\Phi \approx 1$ for the radiating ion of interest. Then ionization into the ground state is achieved, while over-ionization is avoided. Hence, 10^{16} – 10^{18} cm⁻³ can be seen as the minimum and in some respects the optimum electron density for effective EUV emitters.

7.4.1 Quantum efficiency

We consider now specifically the energy that must be invested to generate one photon, and we call the inverse ratio of the yield to the input the *quantum efficiency*. In principle this is nothing but the radiator efficiency $\eta_{\text{plasma}} \eta_{\text{spectral}}$ defined earlier. The basic investment is always what is needed to heat the plasma to a temperature (thermal energy in electrons and ions) sufficiently high to yield a high abundance of ground-state ions of interest (potential energy), and then to excite the ions to the upper level for photon emission. With a probability depending on the branching ratio of the involved radiative transitions, one gains a usable photon. If the ground state is conserved, the ion can be re-excited after the emission to emit a total of N photons. This process terminates when the population of the ground state disappears. We consider the case that this loss of ground state is by ionization of the ion to the next—not usable—ionization stage. Figure 7.6 shows the rate coefficients for both ionization and excitation for a representative ideal ion of 122-eV ionization energy and a resonance transition at 92 eV (13.5 nm). These assumptions resemble very much the case of lithium and are also a model for the sum of transitions from collisionally mixed xenon states. It is obvious that the plasma temperature must exceed 18 eV before sufficient ionization and excitation can occur. The rate coefficient for ionization is only slightly lower than that for excitation. The diagram

in Fig. 7.7 reveals that about one photon can be emitted for lines of low oscillator strength ($f_{ij} = 0.1$), and about three for single resonance lines ($f_{ij} = 0.4$) such as those in low- Z ions.

These assumptions allow for estimating the quantum efficiency of the generation of EUV photons (92 eV) in a plasma of around 25-eV plasma temperature under the assumption of equilibrium of electron and ion temperatures. For the emis-

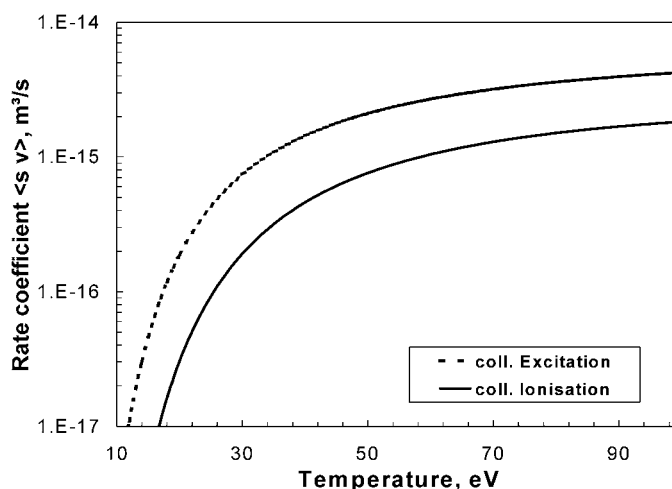


Figure 7.6 Rate coefficients for excitation and ionization²¹ as functions of electron temperature. Excitation rates are of the same order of magnitude as ionization rates except at threshold.

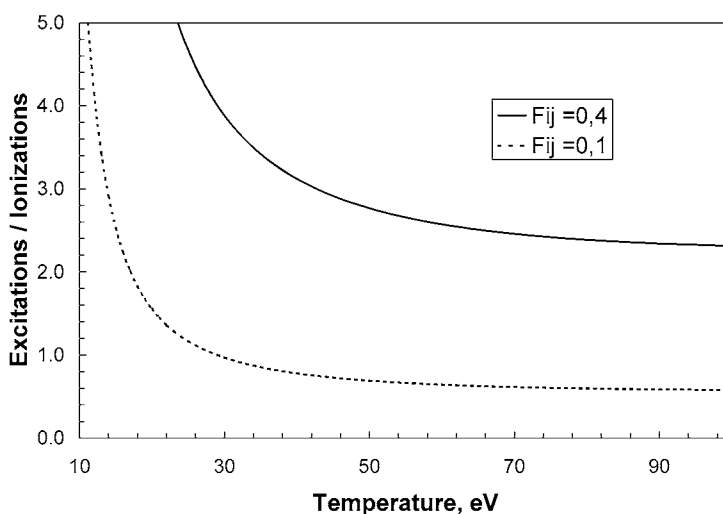


Figure 7.7 Ratio between excitation rates and ionization rates, interpreted as number of excitations before ionization occurs. Only strong resonance lines ($f_{ij} = 0.4$) can emit more than one photon before being ionized.

sion of 2 photons per atom, one obtains

$$\begin{aligned}\eta &\approx \frac{2h\nu}{\varepsilon_{\text{ion}} + 2\varepsilon_{\text{excitation}} + \varepsilon_{\text{plasma}}} \cong \frac{2h\nu}{\sum_{i=1}^{\langle Z \rangle} \varepsilon_{\text{ion}}^i + 2h\nu + \frac{3}{2}(\langle Z \rangle + 1)kT} \\ &\approx \frac{1}{1 + \frac{3}{16}(\langle Z \rangle + 1) + (1 \text{ to } 2)},\end{aligned}\quad (7.4)$$

with a typical value for the sum over the ionization stages of around 2 times the photon energy for low- Z and 4 times for high- Z elements, and with $kT > h/4$. One obtains 20% for lithium down to around 10% for xenon for 2π -sr emission. For lower temperatures, the efficiency could be higher, in principle; but inefficient radiative transport might eliminate this advantage.

7.5 Factors Influencing the Radiative Yield

Another approach to calculating radiator CEs is to study the emission of an effective theoretical plasma emitter in more detail, where we assume a cylindrical plasma (a column of length l and radius r_p). With no reabsorption of the radiation within the plasma (optically thin case), the inband radiant energy is the integral over the time-dependent basic emission processes, which are described by the spectral emission coefficient ε_λ (W/sr nm m³)

$$\begin{aligned}Y &= \int_0^{\Delta t} \int_0^\Omega \int_{\lambda_0 - \Delta\lambda/2}^{\lambda_0 + \Delta\lambda/2} \int_0^{r_p} \int_0^l \varepsilon_\lambda[x'(t), \lambda, \Omega', t'] 2\pi r' \cdot dr' \cdot d\lambda \cdot d\Omega' \cdot dt' \cdot dx' \\ &\approx L_\lambda(\lambda, \Omega, t) \cdot \Delta\lambda \cdot \Omega \cdot A_S \cdot \Delta t,\end{aligned}\quad (7.5)$$

where $\Delta\lambda$ is the bandwidth used, which is typically 2%, i.e., 270 pm for sources for EUVL. The product of Ω , the collected solid angle, and A_S , the source area (approximated as πr_p^2 , where r_p is the plasma radius) is limited by the etendue of the optical system to about 3 mm² sr. Hence, only the spectral radiance L_λ and the duration of the emission, Δt , are real tunable factors. The duration of the emission seems to be the most promising factor to increase the radiator conversion if one has generated a plasma with tailored spectral emission. However, for pulsed excitation, emission is terminated when the plasma cools down. Cooling processes involved are the emission of radiation, the heat conduction to cooler surfaces, plasma expansion, and particle losses from the source region. A typical time for the existence of a pinched plasma (compression, thermalization, and expansion) is the time Δt it takes an ion to traverse the plasma column,

$$\Delta t \approx \frac{d_{\text{plasma}}}{v_{\text{ion}}}, \quad (7.6)$$

where v_{ion} is the ion velocity

$$v_{\text{ion}} \cong 1.4 \times 10^4 \sqrt{\frac{kT_i}{eV}} \cdot \sqrt{\frac{u}{M}} \quad \text{m/s.}$$

Here, $2r_p = d_{\text{plasma}}$ is the shortest extension of the plasma, T_i is the ion temperature, and M is the atomic mass of the element. With $d_{\text{plasma}} = 500 \mu\text{m}$, $kT_i = 20 \text{ eV}$, and $M = 131 \text{ u}$ for xenon, the typical lifetime of the plasma is estimated to 90 ns.

With respect to lifetime, pinch plasmas behave differently from LPPs. The lifetime of LPPs might be significantly shorter due to smaller source sizes, and the fact that mass-limited targets are confined only inertially.

However, in order to emit efficiently, the plasma must stay hot enough during this time. A typical estimate of the radiative cooling time is the time until 50% of the energy is radiated: $\Delta t_{\text{cool}} = E_{\text{plasma}}/2P_{\text{emission}}$.

There are two approaches to estimate radiation losses. The first one is to consider simply the emission by a single line after collisional excitation. Taking self-absorption into account leads to the upper time limit

$$\begin{aligned} \Delta t_{\text{cool}} &\approx \frac{E_{\text{plasma}}/2}{P_{\text{emission}}} \approx \frac{E_{\text{ion}} \cdot n_i/2}{h\nu \cdot \langle \sigma v \rangle \cdot n_e \cdot n_i \cdot G(\tau_0)} \approx \frac{7/2}{\langle \sigma v \rangle \cdot n_e \cdot G(\tau_0)} \\ &\cong \frac{10^9 \text{ cm}^{-3}}{n_e \cdot G(\tau_0)} \text{ s}, \end{aligned} \quad (7.7)$$

where $\langle \sigma v \rangle$ is the rate coefficient for collisional excitation, and $G(\tau_0)$ is the escape factor of the photons [at optimal conditions for line emission $G(\tau_0) \leq 10^{-2}$; see below]. This implies cooling times in the nanosecond range for LPPs and in the hundred-nanosecond range for pinch plasmas with densities of 10^{18} cm^{-3} .

The second approach considers the radiative losses of an optically thick plasma. The Stefan-Boltzmann law gives a rough estimate of the power demand as $10^5 \text{ W/cm}^2 \times (kT/1 \text{ eV})^4$, which suggests a minimum intensity of $1.6 \times 10^8 \text{ W/mm}^2$ needed to sustain a 20-eV plasma. This leads to a lower time limit of about 50 ps for DPP and to times in the nanosecond range again for LPP. This indicates that optically thick emission overestimates losses with DPP, but seems to be an appropriate measure for LPP losses. If one compensates all losses by sufficient plasma heating, the emission time is determined by the duration of the heating pulses—e.g., the laser pulse duration in the case of LPPs.

In order to calculate the spectral radiance L_λ and hence the emission of an inhomogeneous plasma with reabsorption (not an optically thin plasma), the equation of radiative transfer must be solved. The solution can be given in analytic form for a *homogeneous* source:

$$L_\lambda = S_\lambda [1 - e^{-\tau(\lambda)}] = \frac{\varepsilon_\lambda}{\kappa(\lambda)} [1 - e^{-\tau(\lambda)}], \quad (7.8)$$

where $S_\lambda = \varepsilon_\lambda / \kappa(\lambda)$ is the source function, ε_λ and $\kappa(\lambda)$ are local emission and absorption coefficients, respectively, and $\tau(\lambda) = \int \kappa(\lambda) dx$ is the optical depth along the line of sight. The spectral radiance usually varies with time and location for each point on the surface of the source. At very high optical depths τ (optically thick plasma), the spectral radiance of the emission approaches the source function S_λ , which corresponds to the Planck function of a blackbody of the same temperature if the level distribution is thermal: it thus reaches maximum brilliance for the given temperature. At low optical depth $\tau \ll 1$ (optically thin plasma), the spectral radiance of line emission becomes again $L_\lambda = S_\lambda \tau = \varepsilon_\lambda d$, which is much lower than the emission of the corresponding Planck radiator.

Line emission is the preferred emission process with thermal plasmas because lines can emit with high spectral radiance and become optically thick first. The spectral radiance of continuous radiation is usually some orders of magnitude smaller in laboratory plasmas. With respect to the efficiency of line emission, the first resonance lines of ions are best suited, for two reasons. First, most electron-ion collisions leading to excitation are followed by the emission of a photon, and after the emission the ion is ready to accept another excitation. Second, the energy deposited into the level is not split up into photons of different energies (branching), as can be the case with excitation to higher levels. For a Doppler-broadened line with the center wavelength λ_0 , the optical depth for the homogeneous plasma is given by²²

$$\tau(\lambda) = \pi r_e \lambda^2 f_{pq} n_i(q) d \left(\frac{Mc^2}{2\pi k T \lambda_0^2} \right)^{1/2} \exp \left[-\frac{Mc^2}{2kT} \left(\frac{\lambda - \lambda_0}{\lambda_0} \right)^2 \right], \quad (7.9)$$

where r_e is the classical electron radius, f_{qp} is the absorption oscillator strength from a lower level q to an upper level p , $n_i(q)$ is the population density of the lower level q , M is the mass of the ion, and d is the length of the plasma along the line of sight.

The broadening of the optically thick line depends only weakly on the optical depth τ_0 at the line center, so that $\Delta\lambda \sim 2\Delta\lambda_{\text{Doppler}}$ is a good approximation for a single, initially Doppler-broadened line, and τ is in the range from 5 to 50.^{22,23} Hence, the Planck radiance of a single line at 13.5 nm (92 eV) is

$$L(13.5 \text{ nm}, kT) = 5.54 \times 10^7 \sqrt{\frac{kT}{\text{eV}}} \times \sqrt{\frac{\text{u}}{M}} \times \frac{1}{\exp[(92 \text{ eV})/(kT)] - 1} \left(\frac{\text{W}}{\text{cm}^2 \times \text{sr}} \right). \quad (7.10)$$

Figure 7.8 illustrates this radiance for some lines from neon plasmas ($M = 20.2 \text{ u}$) and from xenon plasmas ($M = 131.3 \text{ u}$).

It is evident that at low temperatures this line radiance is a very strong function of the temperature. Above about 60 eV it increases approximately as $(kT)^2$ till it reaches the Rayleigh–Jeans regime and scales with $(kT)^{3/2}$ above 300 eV.

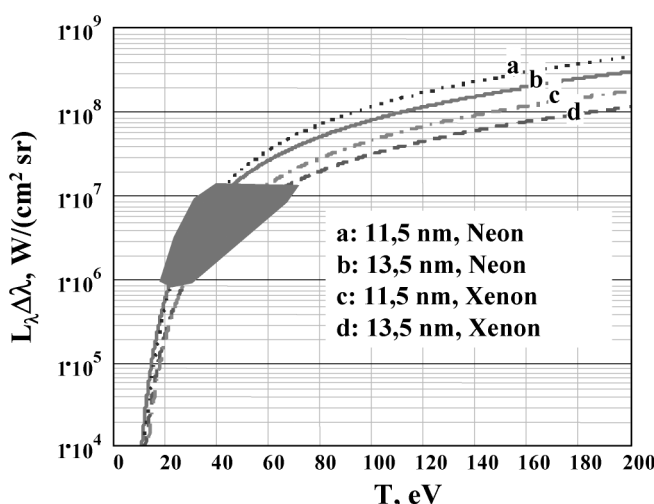


Figure 7.8 Radiance of optically thick lines at 11.5 and 13.5 nm from xenon and neon. (Reprinted from Ref. 22 with permission from IOS Press.)

The shaded region indicates the parameter range of the targeted plasmas. The radiance is in the range 10^6 – 10^7 W/cm² sr, which, employing the etendue of 3 mm² sr, translates to a collectible flux of 30 to 300 kW. Operation with 10 kHz and a pulse duration of 100 ns leads to an average collectible power of 30 to 300 W.

It is obvious in which direction improvements are possible: The emitter with a single line within the bandwidth of transmission must be replaced by emitters with many lines in this spectral band—unresolved transition arrays (UTAs) being one example.

With increasing plasma density, Stark broadening by plasma particles will begin to exceed Doppler broadening, but here no single convenient expression for the respective half-widths of the line profiles, which are Lorentzian, is available. On the other hand, for typical discharge plasmas Stark broadening should not dominate for xenon and tin lines at 13.5 nm, which can still be considered to be isolated. It is different for the Lyman- α line of Li III at 13.5 nm, which experiences the larger *linear* Stark effect. However, only at densities above 10^{18} cm⁻³ does Stark broadening tend to exceed Doppler broadening, corresponding to $kT = 25$ eV.²⁴

Unfortunately, large optical thickness—which is a prerequisite for reaching Planck's limit—means self-absorption of photons that were emitted after one successful excitation process. The influence on the radiator efficiency depends strongly on the geometry and density of the plasma under investigation. If the plasma is pencil-like, i.e., longer than thick, is observed along the axis, and is optically thick only in that direction, any subsequent emission in a radial direction will be lost and the energy wasted. If, however, the plasma is also optically thick in radial directions, the losses are balanced with gains, so that the CE is sustained.

An equivalent prerequisite for reaching Planckian emission is that the excited levels be in local thermodynamic equilibrium (LTE), i.e., that the population den-

sities of the levels follow a Boltzmann distribution. The relevant criterion is collisional coupling of the upper (u) and the lower level (l) of the transition of interest. This is guaranteed if the rate of collisional de-excitation, $\Gamma_{\text{col}}^{\downarrow}$, exceeds the rate of spontaneous decay, A_{ul} , at least by a factor of 10. This implies a lower limit of the electron density^{25,26} of

$$n_e \geq 9 \times 10^{17} \cdot \left(\frac{h\nu}{\text{Ry}} \right)^3 \cdot \left(\frac{kT}{\text{Ry}} \right)^{1/2} \text{ cm}^{-3}, \quad (7.11)$$

where 1 Ry = 13.6 eV is the Rydberg. For typical values for an EUV source, $h\nu = 92$ eV and $kT = 20$ eV, this limit exceeds 10^{20} cm^{-3} , which is reached with laser-produced plasmas but is difficult to obtain with discharge plasmas.

However, this criterion has to be modified when optical thickness becomes relevant. Self-absorption can be treated as reduced spontaneous emission and is taken into account by the escape factor $G(\tau_0)$, which is a function of the optical thickness in the line center τ_0 for the effective plasma dimension d , e.g., the diameter of the plasma.²⁷ LTE is now reached if the rate of collisional deexcitation significantly exceeds the *reduced* spontaneous emission $A_{\text{ul}}G(\tau_0)$:

$$\Gamma_{\text{col}}^{\downarrow} \approx 10A_{\text{ul}}G(\tau_0). \quad (7.12)$$

The criterion for minimum electron density thus is modified to

$$n_e \geq 9 \times 10^{17} \cdot \left(\frac{h\nu}{\text{Ry}} \right)^3 \cdot \left(\frac{kT_e}{\text{Ry}} \right)^{1/2} \cdot G(\tau_0) \text{ cm}^{-3}. \quad (7.13)$$

For optical depths $\tau > 3$ along the plasma diameter, the escape factor can be approximated by $G(\tau_0) \approx 1/\tau_0(\pi \ln \tau_0)^{1/2}$ (Ref. 26), and with $(\ln \tau_0)^{1/2} \approx 2$, the criterion may be written as

$$n_e \geq 4 \times 10^{17} \cdot \left(\frac{h\nu}{\text{Ry}} \right)^3 \cdot \left(\frac{kT_e}{\text{Ry}} \right)^{1/2} \cdot \frac{1}{\tau_0} \text{ cm}^{-3}. \quad (7.14)$$

Here²⁷ $n_i(g) \approx n_i/3$ is a reasonable approximation for the optimized ion distribution, and we obtain

$$n_e \geq 9 \times 10^{12} \left(\frac{h\nu}{\text{eV}} \right)^2 \cdot \left(\frac{kT_e}{\text{eV}} \right)^{1/2} \cdot \frac{(\langle Z \rangle)^{1/2}}{(M/u)^{1/4}} \cdot \left(\frac{\text{cm}}{d \cdot f_{\text{gu}}} \right)^{1/2} \text{ cm}^{-3}. \quad (7.15)$$

Here d is the shortest dimension of the plasma (for a cylindrical plasma, its diameter). For typical pinch plasma dimensions of 0.5 mm, temperatures of 25 eV, oscillator strengths f_{gu} in the range of 0.1, and $h\nu = 92$ eV, the lower limit is at electron densities of about $n_e = 5 \times 10^{18} \text{ cm}^{-3}$ for xenon plasmas ($\langle Z \rangle \approx 10$), corresponding to $\tau_0 \sim 28$, and this is achievable with pinch plasmas.

Based on these arguments, the radiator CE can be estimated as the inband energy emitted per steradian divided by the input energy. The input energy is the energy invested to generate the plasma, i.e., to heat the substance to the emitting ground state (amounting to ε_{ion} per ion) and, during its existence, to cover the radiative (and other) losses.

The obtained yield is assumed to be optically thick Planck emission in the inband spectral bandwidth (L_{opt}) over the observed surface. The emitting surface can be approximated by the surface of a sphere ($4\pi r^2$), allowing for a more cylindrical shape by multiplying by the aspect ratio (length/diameter, a), which corresponds to the quite realistic shape of a cylinder with spherical ends. This model leads to a volume of the plasma equal to $\frac{3}{4}a$ times the volume of the sphere. This plasma is assumed to emit for a duration Δt , which is defined by its lifetime, which is taken according to the estimate of Eq. (7.6):

$$\eta_{\text{opt}} = \frac{E_{\text{emitted}}}{E_{\text{plasma}} + E_{\text{heat}}} = \frac{L_{\text{opt}} \cdot 4\pi r_p^2 a \Delta t}{4\pi(\varepsilon_{\text{ion}} \cdot \pi r_p^3 a n_i + P_{\text{Heat}} \Delta t)}, \quad (7.16)$$

where η_{opt} and E_{emitted} are expressed per unit solid angle. Heating of the plasma can be estimated with the assumption, that—under ideal conditions—the plasma heating must cover all the losses. If the radiative losses are dominating, they can be estimated as the optimized emissivity divided by the spectral efficiency of the spectral distribution (η_{spectral}). The spectral efficiency can be determined as the ratio of the inband emission to the total emission and is determined by the spectral distribution of the ion species used. For a real Planck emitter, i.e., one that is optically thick over the whole spectral range from the x-ray to the IR spectral region, the spectral efficiency is as discussed in Fig. 7.2, i.e., about 1.5% at maximum:

$$\begin{aligned} \eta_{\text{opt}} &\leq \frac{L_{\text{opt}} \cdot 4\pi r_p^2 a \Delta t}{4\pi \left[\varepsilon_{\text{ion}} \cdot \pi r_p^3 a n_i + (L_{\text{opt}}/\eta_{\text{spectral}}) \cdot 4\pi r_p^2 a \Delta t \right]} \\ &= \frac{L_{\text{opt}} \Delta t}{\pi \left[\varepsilon_{\text{ion}} r_p n_i + (L_{\text{opt}}/\eta_{\text{spectral}}) \cdot 4 \Delta t \right]}. \end{aligned} \quad (7.17)$$

If the plasma is heated for a very long time, so that much more energy is invested for heating than for generating the plasma, then the plasma efficiency approaches 1, so that the radiator efficiencies can approach the spectral efficiency. On the other hand, the overall efficacy is also determined by the percentage of driver energy that is actually coupled into the pinch plasma. Other loss channels are often difficult to identify or quantify. For example, there will always be electrode losses, losses via heat conduction to the walls, and losses due to ohmic heating of the device. Also, parasitic currents, which bypass the pinch plasma and dissipate energy elsewhere, cannot be avoided in a practical source.³⁹ Spectral efficiencies have been determined experimentally for the EUV range only. They reach 6.6%

for xenon and up to 18.9% for tin.³¹ Recall that the spectral efficiency is the fraction of inband EUV radiation in the total EUV emission. The total efficiency is the product of the fraction of the used energy that is deposited in the plasma and the fraction of this that is emitted as EUV. With the experimental result of around 3% CE in 2π sr, the product of those two additional factors can be estimated to be around 17%, which is quite a good number for light sources in general. Assuming a factor of 2 for the inevitable OOB emission in the UV, visible, and IR seems to allow for a CE up to 5% in 2π sr for a cw plasma, which, however, turns out to be difficult to generate.

An evaluation of Eq. (7.16) shows estimated radiator efficiencies as a function of plasma temperature for a xenon plasma 200 μ m in diameter and 2 mm in length.³² The shape of the curve resembles experimental data on CEs as a function of laser intensity observed from LPPs (e.g., Ref. 19) and has been described in Ref. 20. The experimentally observed efficiencies are well below the predicted values.^{28–30}

However, for the comparison of such theoretical considerations with real experimental realizations, two additional factors are of relevance:

1. The efficiency of coupling the driver power into the plasma. With LPP, coupling efficiencies of up to 80% can be reached. In the early experiments with gas discharges, 50% coupling was considered an acceptable value.
2. The transmission through gases surrounding the emitting plasma. 20% losses in gas transmission can be assumed for discharge sources. Ideal LPPs with solid jet targets can reach higher values.

With these factors, an intrinsic plasma conversion of $(0.15 \pm 0.05)\%/sr$ [i.e., $(1 \pm 0.3)\%$ in 2π sr] is found from all experimental data, which is already close to the estimated optimum for a purely transient plasma.

To summarize, our discussion shows that higher temperatures are favorable as long as sufficient ground-state ions are present. A large plasma diameter is favorable. Heavier ions are better suited than light ions with respect to the plasma lifetime, but are less favorable with respect to the energy needed to generate the required ground state. Naturally, lines with high oscillator strengths (first resonance lines) are best. With respect to the last point, the comparison of single-line emitters such as lithium with multiline emitters such as xenon is complicated. It can be assumed that although the lithium Lyman- α line has $f = 0.4$ and xenon lines have $f < 0.1$, the sum of the oscillator strengths of all xenon lines of levels with similar excitation energy can be used, because these levels are strongly coupled by collisions.

Further insight requires more detailed studies of the real behavior, and especially of the interaction of the various processes involved. The next section will describe the theoretical models required for simulating the EUV emission pinch plasmas: atomic physics and radiation models are needed to compute the important spectral intensities. Furthermore, they supply material data such as radiative

power losses or ionization and recombination rates for MHD models to calculate the highly transient plasma properties, for example, those of a pinch discharge. Because the system is extremely complicated and many basic material data are not available, such models can only be useful in close collaboration with experiments. Some rather important properties of a pinch discharge, however, can be simulated with astonishingly good accuracy by rather simple models, which give useful hints to optimize the source efficiency.

7.6 Plasma Simulation: Tool for Source Optimization

Simple stationary estimations are not sufficient to optimize all aspects of practical plasma-based sources. This is of special importance for discharge-based systems, because they usually have more relevant processes involved and more complex geometries than LPPs. As discussed already, the method to generate the plasma, the efficiency of coupling power from the generator into the plasma, plasma dynamics, and radiative transport may be significant in maximizing the single-pulse efficiency. This all must be accomplished under additional boundary conditions in that electrode cooling, gas flow, and material aspects play significant roles when developing an effective EUV source. Plasma modeling and simulation can support and accelerate cutting-edge experimental and engineering development of sources for EUVL in many aspects. Prerequisites are that all relevant processes be taken into account and that both input and output allow direct coupling to real experiments, which means that the whole experimental chain from the properties of the generator up to the electrode geometries must be modeled and that the output must be compiled for direct comparison with experimental source diagnostics. In the following sections, we describe—as an example—the modeling of a DPP. The intention is to develop a feeling for possible optimization potentials based on modeling of the EUV emission of a pinch plasma in a real system and to compare this with the current status of development.

In general, in a discharge plasma a gas is heated and compressed by a pulsed current to temperatures in the range of several tens of electron volts, which leads to thermal emission due to transitions in the EUV. The pulsed current is produced by fast discharge of a storage capacitor. Typical discharge parameters are peak currents around 10–20 kA and durations ranging from 100 to 500 ns. Stored electrical energies are in the range of few joules to a few tens of joules.

The most promising emitters currently discussed are xenon and tin, as intense broadband emitters, and lithium, with its freestanding Lyman- α line at 13.5 nm.

The following section will describe the theoretical models required for simulating the EUV emission pinch plasmas: Atomic physics and radiation models are needed to compute the important spectral intensities. Furthermore, they supply material data such as radiative power losses and ionization and recombination rates for MHD models to calculate the highly transient plasma properties, for example, of a pinch discharge. Because the system is extremely complicated and many basic

material data are not available, such models can be useful only in close association with experiments.

7.7 Atomic Physics, Radiation, and Ionization Modeling

Since only the EUV radiation in a narrow inband wavelength region of $13.5 \text{ nm} \pm 1\%$ can be used in the reflecting optics of the illuminator, it is of essential importance to generate a spectrum that is strongly peaked in this region. On the other hand, the OOB radiation in other wavelength regions, which would lead only to unwanted energy losses and heating of the electrode system, must be minimized. These requirements led to the choice of 13.5 nm : the resonant first Lyman line, $2p-1s$, of hydrogenlike Li^{2+} is exactly at this wavelength. In the following we will show, however, that besides the technological problems, also the spectral properties of lithium are not optimal.

The evaluation of the spectral emissivity is based on the atomic structure—energy levels, oscillator strengths, and electron impact excitation rates—of the ions of interest. Compared to neutral atoms, the Coulomb interaction with the nucleus has a larger effect on the energy levels. Fortunately this allows for rather accurate calculations of the atomic structure in the Hartree-Fock approximation with relativistic extensions, as for example with the widely applied Cowan code.³³ For ions with open d shells, the high angular momentum of the outer electrons and configuration mixing cause a splitting into thousands of energy levels and consequently almost continuous, grasslike spectra. Besides energy levels, transition probabilities (Einstein A coefficients) and electron impact excitation rates are also calculated. These data allow in the next step the evaluation of excited-state populations of each ion by balancing its electron impact excitation and de-excitation and photonic transitions as a function of the surrounding plasma's parameters.

Assuming a Maxwellian electron energy distribution, the plasma is described by its electron density and temperature. In the low-electron-density limit where electron impact deexcitation is negligible compared to photonic decays, this leads to a corona equilibrium. In this case the excited-state populations—and hence the radiated power per ion—are proportional to the electron density. In the other limit of a very dense plasma, the photonic decays are much slower than collisional processes, and the excited-state populations—and consequently the emitted radiation—are independent of the electron density. The intermediate situation is called collisional radiative (CR) equilibrium.³⁴ These regimes appear in Fig. 7.9, showing the populations of three excited Xe^{10+} states of the configuration $4d^75p$ near 13.5 eV as a function of electron density for an electron temperature of 51 eV , which was found to be a typical value for optimized emission at our device. In the highly transient pinch discharges described here, the plasma conditions change rapidly during the compression. All three situations are such that a complete CR description is required to compute the total radiation and the spectra of individual ions as functions of electron temperature and density.

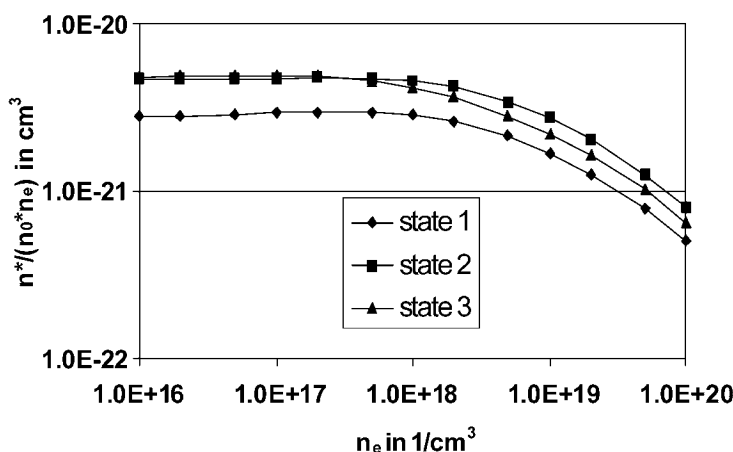


Figure 7.9 Some Xe^{10+} excited-state populations of the configuration $4d^7 5p$ at $kT_e = 51$ eV.

This or similar methods have been applied by various authors to compute (optically thin) spectra of interesting xenon and tin ions.^{36–39} Actually such spectral calculations⁴⁰ led the community to move from xenon to tin as radiator: whereas only one xenon ion, Xe^{10+} , radiates near 13.5 nm, several tin ions, viz., Sn^{8+} – Sn^{12+} , have strong transitions in this spectral range. And even Xe^{10+} has a large fraction of useless OOB radiation near 11 nm. Therefore, one expects and observes up to 5 times higher spectral efficiency [(inband radiation)/(OOB radiation)] with tin plasmas than with xenon plasmas. Consequently the heat load associated with a given inband radiation can be reduced by a factor of up to 5, for generating the same amount of inband radiation.

A more exact prediction of the inband efficiency of EUV sources is rather complicated; especially during the high-density phase of the transient discharge, when most of the EUV radiation is generated, photoabsorption strongly affects the emission. For example, the radiation of Xe^{10+} near 11 nm is considerably reduced, but also other lines from various xenon or tin ions are absorbed. A thorough simulation of these effects requires the solution of the radiation transport equations (RTEs) at each time step of the transient plasma simulation.^{41,42} Besides the immense computational effort, this also requires data about shapes and broadening mechanisms for thousands of spectral lines. Moreover, radiation absorption contributes considerably to the power balance and must therefore be coupled to the MHD model to compute temperature and density profiles. The method of escape factors,⁴³ however, can be applied to estimate which part of the spectrum will be affected by opacity and to predict trends.³⁹

Up to now we have discussed only the radiation properties of various ions in the EUV spectral range. The computation of the abundances of the various ion stages in the transient plasma requires ionization and recombination rate coefficients. For ions with many inner-shell electrons in high-density plasmas this is a very complicated matter, for dielectronic processes and intermediate metastable states become very important. The calculation of effective rates considering these processes is a

subject of current research; see for example Ref. 35. The situation becomes even more complicated if one takes into account that photoabsorption affects the population of excited states. Consequently also the effective ionization and recombination rates will depend on the radiation fields.

Knowing these effective rates, it is in principle possible to compute the equilibrium ionization, i.e., the abundances of the various ions, as a function of electron temperature and density. The plasma parameters in the highly transient discharges, however, change so fast that ionization equilibrium will not be achieved; a proper simulation should therefore include the full transient ionization dynamics.

7.8 MHD Description of the Pinch Phase of the Discharge

In the previous sections we investigated, using basic atomic physics, which ions are good radiators in the required wavelength region. Now we investigate the plasmas that produce these ions. Actually, there are two approaches: Laser-induced plasmas and discharge plasmas. In the following we will discuss only the properties of discharge plasmas. In all currently investigated discharges—capillary discharges, (hollow-cathode triggered) Z pinches, and plasma focus—the required high plasma densities are achieved by (supersonic) magnetic compression. A complete simulation of the pinch phase, during which the EUV radiation is emitted, requires the solution of the MHD equations in at least 2D axisymmetric geometry. Moreover, the electron energy equation and the ionization dynamics must be coupled to the RTEs to model the energy transfer by photons and the effects of photoionization in a highly transient, inhomogeneous plasma. Finally the plasma simulations must be coupled to a (rather simple) simulation of the external electrical circuit. Such very difficult and computer-intensive simulations have been applied in Refs. 41 and 42 to simulate EUV-generating discharge plasmas. A rather simple and fast approach, including a snowplow-shock description of the magnetic compression,⁴⁴ is discussed in Ref. 39. Such 0-dimensional models obviously cannot model as many effects as the full MHD simulations. But many important features, such as the coupling of electrical circuit and compression time scales or dynamic ionization, are surprisingly well described, and the short computation times (only a few minutes per run) allow for quick adaptation to experimental results. It is, for example, rather important to design the electrical circuit so that the current maximum is achieved at the time of maximum compression when ohmic heating becomes very effective. High abundance of ions that radiate in the wanted spectral range in that case leads to high inband EUV efficiencies.

Since the radiation will be used in an optical system, the size and (axial) location of the EUV-emitting region are other important issues. These depend strongly on electrode geometry and (initial) axial density profiles and can be modeled only by at least 2D MHD codes.

Also, pre-ionization and plasma electrode interaction, which cannot be modeled with MHD codes, may have a strong influence on electrical current profiles

and hence on the magnetic compression and size and location of the EUV emission.

7.9 Other Important Issues

In the preceding sections we discussed the means to improve the inband radiation efficiency of a pinch discharge. The total inband EUV power obtainable is, of course, then also limited by the total power the electrode system can handle. Hence, reducing electrode erosion and sputtering is another way to increase the EUV power by increasing the input power. This is usually done by increasing the frequency.⁴⁵ This repetition rate, however, is also limited by the time the plasma needs to recombine into an electrically isolating gas. After this time has elapsed, the capacitors can be charged again. These issues are not covered in this chapter.

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H.-J. Kunze. See Chapter 6.

Chapter 8

Z* Code for DPP and LPP Source Modeling

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8.1 Introduction

An EUV source is a critical component for the industrial extension of EUVL to feature sizes of 45 nm and beyond. In the ITRS road map,¹ the current specification requires an EUV source capable of producing inband radiation at 13.5 nm in excess of 115 W collectable over a 2% bandwidth at the intermediate focus (IF). This calls for extreme plasma parameters of unprecedented radiation efficiency.

DPPs, such as the hollow-cathode-triggered (HCT) Z-pinch, capillary discharge, and dense plasma focus (DPF), and also LPPs, are considered as possible candidates for the creation of a compact EUV radiation source. In plasma discharges, low- Z materials such as Li ($Z = 3$) or various high- Z materials such as Sn ($Z = 50$), In ($Z = 49$), or the gases Kr ($Z = 36$) and Xe ($Z = 54$), for instance, are considered for the generation of EUV radiation. The 5p-4f transitions in xenon ions Xe XI and 4d-4f resonances of a set of tin ions Xe V–XIV emit intensely in the 13.5-nm 2%-bandwidth spectral band.² Knowledge of the behavior of discharge plasmas with low- and high- Z elements is critical for the study of DPP or LPP and is of vital importance in the design of EUV sources.

A suitable source of radiation in the case of a high- Z radiator is the radiating multicharged ion plasma heated up to tens of electron volts. In such sources the complicated atomic and plasma physics, the nonstationary, nonequilibrium ionization process, and the radiation transport and plasma dynamics with self-consistent electromagnetic field (for discharge plasmas) interact strongly with each other. In a DPP plasma, heating is effected through several physical mechanisms: Joule dissipation; viscous kinetic energy dissipation, driven by the magnetic $\mathbf{j} \times \mathbf{B}$ force, in compression waves; and $P dV$ work of the preheated plasma. The energy deposition in the discharge often exceeds 10 keV per ion to create the highly charged ion plasma. The ionization degree may reach 10 or higher. A significant part of the deposited energy is radiated. Radiation may be partially trapped, especially in the most intense lines. Optical properties and the plasma equation of state (EOS) are, as a rule, in conditions far from local thermodynamic equilibrium (LTE), i.e., in a *non-LTE* state.

To find optimal conditions for the emission under complicated plasma behavior with an extensive set of parameters, it is important to use computer simulations. In view of requirements for size and stability, the emitting plasma source should be close to spherical or cylindrical symmetry. A complete plasma simulation tool with at least 2D effects should be used to model the transient plasma and to evaluate the radiation production. Modeling of complete plasma dynamics together with ionization phenomena and radiation transfer demands a rigorous approach such as that developed in high-energy-density physics (HEDP).

Z* is a computational code,³ designed at EPPRA in collaboration with the RRC Kurchatov Institute, the Troitsk Institute of Innovation and Fusion Research (TRINITI), and the Keldysh Institute of Applied Mathematics, Moscow, Russia, to focus specifically on the modeling of a multicharged ion plasma in experimental and industrial facilities, using a radiative magnetohydrodynamics (RMHD) approach. In this chapter, we will briefly describe the physical fundamentals of a

strongly radiating, high-energy-density plasma, before expanding on the numerical methods adopted in Z* to accurately and effectively simulate such a plasma. We will cover in Sec. 8.2 the underlying formalism necessary to describe the plasma dynamics, the atomic physics to model the plasma composition, and the radiation transport to treat the emission from such an evolving plasma structure, self-consistently in both space and time. Gaussian units are used throughout this chapter. In Sec. 8.3, we will describe the numerics developed in Z* to allow treatment of this physics in real-world plasmas with realistic boundary conditions. In Sec. 8.4, a number of case studies utilizing Z* for both DPP and LPP will then be presented, allowing us to highlight some of the unique features of both Z* and the specific plasma configurations of interests. The strengths and weaknesses of Z* in its current implementation can be seen for these examples.

8.2 Fundamentals of the Physics of EUV-Emitting Plasmas

One of the main characteristics of a plasma emitting intensely in a narrow EUV band is the presence of high-intensity nonequilibrium radiation in a wide spectral range. The plasma cannot be in LTE, for EUV emission occupies only a small part of the blackbody spectrum. The plasma dynamics must therefore be considered self-consistently with a nonequilibrium radiation field. Such self-consistent modeling of plasma dynamics together with plasma radiation is considered in the RMHD approach. In the following, we will discuss the elements that must be considered in such a modeling approach.

8.2.1 Radiative and ionization properties of multicharged ion plasmas

To accurately investigate the physical processes in a complex plasma, information about the properties of matter over a wide range of plasma parameters, including rate coefficients for radiative and collisional ionization and for recombination (including dielectronic capture) for multicharged ions, is required. These values may be obtained by using a proper atomic model. Furthermore, in practical plasmas, a complete level-kinetics consideration should be applied to describe the ionization processes and emission spectra.

Calculation of the emission spectra from the small-size plasma of high-current pulsed systems and LPPs requires the consideration of reabsorption of the radiation by the plasma in the presence of high-intensity nonequilibrium radiation. In a sufficiently simple case the problem may be considered by using the Biberman–Holstein approximation, which is valid when spectral lines do not overlap. This is not applicable, however, for a multicharged-ion plasma, where there are a lot of overlapping spectral lines. On the other hand, the full system of the level-population kinetic equations, including the processes induced by the nonequilibrium radiation field, is complicated for direct calculations. In addition, in a detailed

approach, it is difficult to describe correctly all important states and transitions with all necessary processes in multicharged plasmas such as plasmas of xenon or tin in the tenth degree of ionization. However, these factors alone do not limit the wide application of the full level kinetics.

For practical applications, the numerical procedure should be simple enough and its cost, in terms of computation time, must be low enough to be used in 2D RMHD simulations.

One suitable solution is to use an average-atom model⁴ where all possible states and transitions are taken into account. In this approximation an average ion with mean occupation numbers N_ν in state $\nu = nlj$ (where n is the principal quantum number, l is the orbital angular quantum number, and j is the quantum number of total angular momentum of the electron) is placed together with free electrons in a neutral spherical cell.⁵ The nonstationary kinetic balance for average occupation numbers N_ν is given by the equations⁶

$$\frac{dN_\nu}{dt} = \left(1 - \frac{N_\nu}{g_\nu}\right) S_\nu - N_\nu L_\nu, \quad (8.1)$$

where g_ν is a statistical weight of electrons in state ν ; S_ν is the total rate of the processes leading to an increase in the number of electrons in state ν , given by

$$S_\nu = \sum_{\mu < \nu} N_\mu (\alpha_{\mu\nu}^{\text{abs}} + \alpha_{\mu\nu}^{\text{ex}}) + \sum_{\mu > \nu} N_\mu (\alpha_{\mu\nu}^{\text{em}} + \alpha_{\mu\nu}^{\text{dex}}) + Z_0 (\alpha_\nu^{\text{ir}} + \alpha_\nu^{\text{phr}} + \alpha_\nu^{\text{dc}}); \quad (8.2)$$

$\mu = n'l'j'$; L_ν is the total rate of processes leading to a decrease of the number of electrons in this state, given by

$$L_\nu = \sum_{\mu < \nu} \left(1 - \frac{N_\mu}{g_\mu}\right) (\alpha_{\nu\mu}^{\text{em}} + \alpha_{\nu\mu}^{\text{dex}}) + \sum_{\mu > \nu} \left(1 - \frac{N_\mu}{g_\mu}\right) (\alpha_{\nu\mu}^{\text{abs}} + \alpha_{\nu\mu}^{\text{ex}}) + \alpha_\nu^{\text{ii}} + \alpha_\nu^{\text{phi}} + \alpha_\nu^{\text{ai}}; \quad (8.3)$$

$\alpha_{\mu\nu}^{\text{ex}}$, $\alpha_{\nu\mu}^{\text{dex}}$ are the rates of collisional excitation and deexcitation of level ν ; α_ν^{ii} , α_ν^{ir} are the rates of ionization and three-body recombination; $\alpha_{\mu\nu}^{\text{abs}}$, $\alpha_{\nu\mu}^{\text{em}}$ are the rates of absorption and emission in spectral lines; α_ν^{phi} , α_ν^{phr} are the rates of photoionization and radiative recombination; and α_ν^{ai} , α_ν^{dc} are the rates of the Auger effect (autoionization) and dielectronic capture. The average ion charge Z_0 determines the number of free electrons per atom, i.e., an average ionization degree is $Z_0 = Z - \sum N_\nu$, where Z is a nuclear charge of ions.

In level-kinetics calculations the rates obtained for the free ions are widely used. This is correct for low-density plasmas. With increasing density the applicability of such rates is no longer valid. As was shown in Ref. 7, due to density effects

the ionization and recombination rates for Xe plasma may significantly differ from those obtained for free ions.

The collisional rates can be calculated in the distorted-wave approximation (DWA)⁸ or with other well-known formulas.^{4,9} Oscillator strengths, energy levels, and other values are calculated on the basis of the relativistic Hartree-Fock-Slater model,⁵ depending on the occupancies N_v . Examples of collisional rates calculated in the DWA for ionization of Xe x to Xe xI ions and excitation rates of the 4d-5p transition of Xe xI are presented in Fig. 8.1.⁷

The photoprocess rates are calculated in terms of the corresponding cross sections, taking into account the radiation field.¹⁰ The relevant formulas may be found in Ref. 6. Since the rates and mean charge depend on the occupancies N_v [Eqs. (8.1)–(8.3)], even in the average-ion model they are nonlinear and depend on the radiation field.

When gas-dynamic processes proceed much more slowly than collisional and radiative ones, the quasi-stationary approximation can be applied. This type of quasi-stationarity is defined by rate processes, for example, as in the coronal equilibrium model¹¹ and the collisional-radiative equilibrium (CRE) model,^{4,12,13} which are widely used.

The dependence of radiating characteristics (absorption coefficients and emissivities) on the degree of absorbed radiation is the easiest to analyze in the quasi-stationary approximation.

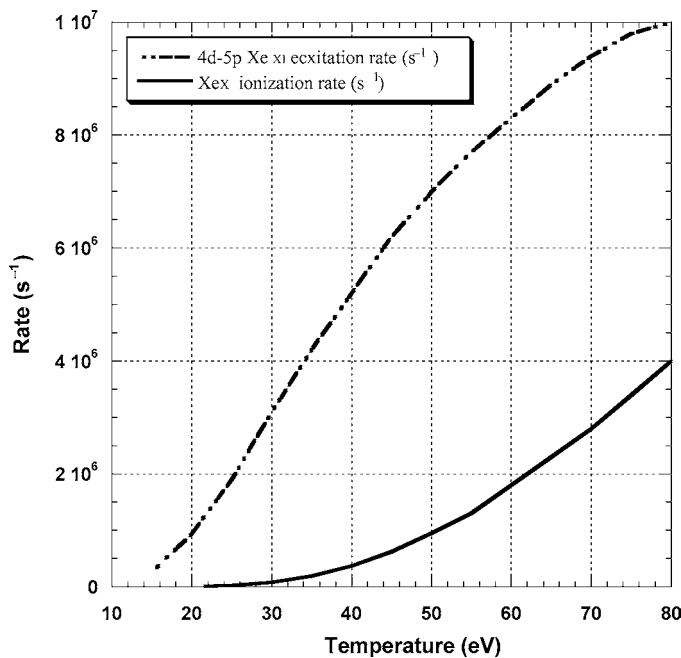


Figure 8.1 Ionization rate of Xe x ion (solid line) and excitation rate of 4d-5p transition of Xe xI ion (dashed line) versus temperature for plasma ion density $4.6 \times 10^{15} \text{ cm}^{-3}$.

To clarify the basic dependences on the nonequilibrium radiation, instead of solving the specific problem, we shall consider at first the quasi-stationary solutions of the system (8.1)–(8.3) with the inclusion of all collisional and radiative processes listed above, assuming an unspecified spectral intensity of radiation I_ω . In quasi-stationary approximation, i.e., $dN/dt = 0$, the Eqs. (8.1) may be rewritten in the form

$$N_\nu = \frac{g_\nu}{1 + g_\nu L_\nu / S_\nu}. \quad (8.4)$$

These equations are still nonlinear, because the rates S_ν and L_ν depend on the average occupation numbers N_ν , which for high- Z elements may be solved only numerically. Solving these equations, we obtain under given radiation field I_ω the elementary states of a quasi-stationary plasma: the average occupation numbers, energy levels, and wave functions of electrons. From these elements, we calculate the ionization degree, EOS, spectral absorption and emission coefficients, and necessary kinetic coefficients (thermal and electric conductivities, elastic collision rate, etc.) in the plasma.

In fast discharges the plasma is at low density. As we can see from the calculated ionization and excitation rates in Fig. 8.1, the stationary condition will not be reached during the discharge time. In this case the steady-state solutions (8.4) can only be used for estimations. Alternatively, special tables can be constructed and interpolated for nonstationary processes. These procedures are discussed in Sec. 8.3.1.

8.2.2 EUV emission and radiation transport

The influence of nonequilibrium radiation on the properties of a plasma is demonstrated on the xenon emission spectra in Fig. 8.2, where the emissivity of xenon is calculated at a temperature $T_e = 30$ eV and density $\rho = 10^{-6}$ g/cm³. The calculations were carried out both without reabsorption and with taking into account the radiation field, assuming that up to 0.4% of radiation is reabsorbed. It is apparent from the figures that back influence of radiation on the spectral characteristics of plasma and ionization degree is important. Partial radiation trapping can induce a significant deviation from the optically thin coronal equilibrium or CRE approximations for non-LTE plasma description as well as from those for LTE. Also, at such high temperatures the radiation field is formed in a plasma-dynamic process, affecting the microstates of the plasma ions and the radiative properties of the plasma. Likewise the microstates of the ions determine the emissivity and spectral absorption coefficients of the plasma. Reabsorption in the spectral lines can change the ionization stage and internal energy of the plasma at the same electron temperature, for these are strongly coupled to the electrons via level kinetics. The ionization kinetics and radiation transport therefore require a self-consistent description.

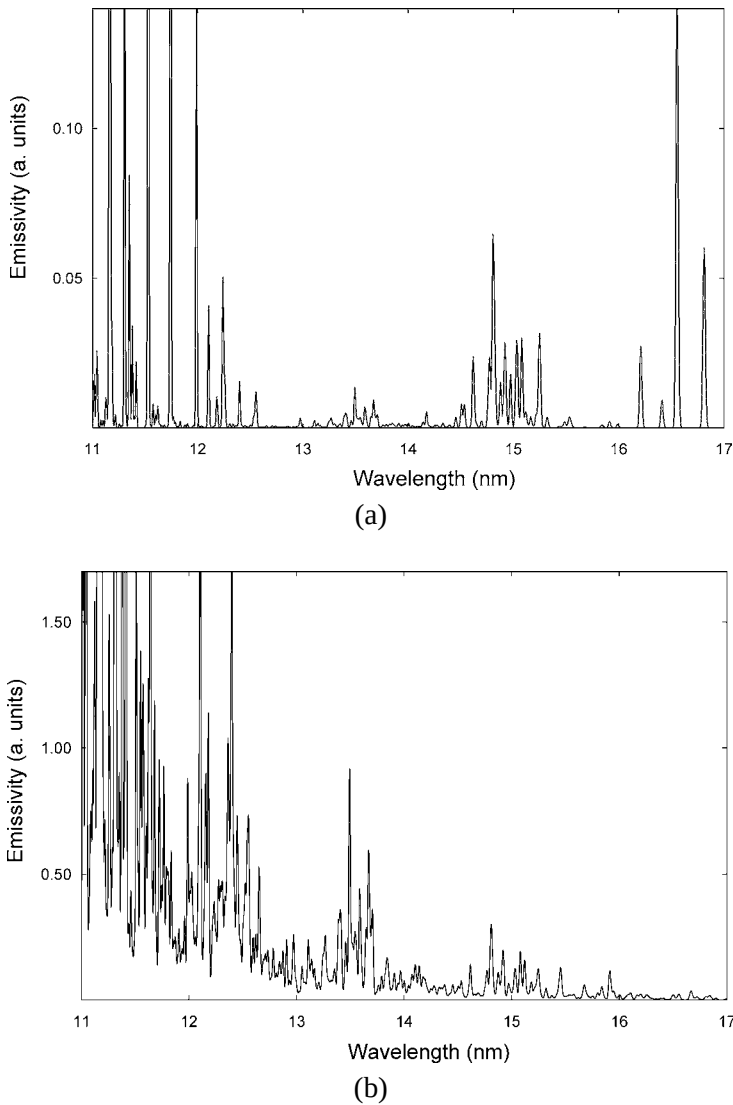


Figure 8.2 Emission spectra of xenon plasma versus wavelength λ at temperature 30 eV (a) without reabsorption ($Z_0 = 8.31$), and (b) with $\approx 0.4\%$ of radiation reabsorbed (right) ($Z_0 = 10.74$). Additional broadening is 0.05 eV.

The radiation transfer equation for spectral intensity I_ω with photon energy $\hbar\omega$, without free-electron scattering processes, has the form

$$\frac{1}{c} \frac{\partial I_\omega}{\partial t} + (\mathbf{\Omega} \cdot \nabla) I_\omega = j_\omega - k_\omega I_\omega, \quad (8.5)$$

where c is the speed of light, and $\mathbf{\Omega}$ is the unit vector in the direction of the radiation ray. The spectral absorption coefficient k_ω and emissivity j_ω are written

in a form taking into account induced emission. They depend on the local properties of a plasma, e.g., the density, temperature, and ion distribution, which, in turn, are dependent on the radiation field. The spectral absorption coefficients should be calculated in non-LTE, i.e., in dependence on the spectral radiation field $U_\omega = c^{-1} \int I_\omega d\Omega$, through the level occupancy balance considered in the last section. From the radiation transport Eq. (8.5) the radiation energy density $U = \int U_\omega d\omega$ and flux $\mathbf{F}_r = \int \mathbf{F}_\omega d\omega = \int \Omega I_\omega d\omega d\Omega$ are calculated and used in the energy balance of the RMHD system of equations.

As a rule the characteristic size of the DPP or LPP plasma of interest is much smaller than the distance traversed by the radiation during the evolution time, and a quasi-stationary approximation may be applied, i.e., the time derivative in Eq. (8.5) may be neglected. Between the spectral radiation flux density and the energy density, an important correlation follows from Eq. (8.5), viz., in the quasi-stationary case,

$$\nabla \mathbf{F}_\omega = 4\pi j_\omega - k_\omega c U_\omega. \quad (8.6)$$

A distribution of the spectral radiation energy density U_ω is necessary to calculate the radiation flux for energy balance in the RMHD and to calculate ion state kinetics to obtain the EUV emission in particular. Because a full redistribution over all photon energies can be assumed to take place in the processes of absorption and emission, knowledge of the radiation field alone is enough to calculate the radiation transport and the EUV emission.

To find the radiation field in the quasi-stationary case, by integrating the radiation transport Eq. (8.5) along the trajectories under cylindrical symmetry conditions, we obtain this expression for the intensity⁶:

$$I_\omega(r, z, \varphi, \theta) = \int_0^\tau \frac{j_\omega}{\kappa_\omega} e^{\tau' - \tau} d\tau', \quad (8.7)$$

where r, z are the radial and axial coordinates; ϕ, θ are the spherical angle coordinates of the trajectory (ϕ between the trajectory projection onto a plane perpendicular to the Z axis and the radial direction, and θ between the trajectory and the Z axis); $\tau = \tau(x) = \int_0^x (\kappa_\omega(r, z)/\sin \theta) dx$ is the optical depth; and $\tau' = \tau(x')$. The coordinate $x = x(r, \varphi)$ is taken along the projection of the ray onto a plane perpendicular to the Z axis. It is related to the radius r and angle ϕ of the direction of this projection by $x = \sqrt{r_{\text{out}}^2 - r^2 \sin^2 \varphi} + r \cos \varphi$, where r_{out} is some external radius, and where the boundary conditions on radiation may be described as stating that only outgoing radiation exists at $r = r_{\text{out}}$, i.e., $I_\omega|_{r=r_{\text{out}}} = 0$ at $\pi/2 < \phi < 3\pi/2$. The coordinate z of a trajectory is defined by the formula $z = z_{\text{out}} + x \cot \theta$, where z_{out} is the coordinate of the intersection of the trajectory and the surface $r = r_{\text{out}}$. The Eq. (8.7) for the intensity is solved self-consistently with the level-kinetics Eqs. (8.1), inasmuch as the spectral coefficients depend on the level occupancy numbers.

8.2.3 Plasma-dynamics description

The traditional ideal MHD model must be extended to take into account additional physics relevant to a EUV plasma source with realistic boundaries. It is necessary to take account of the displacement current in the Maxwell equation to allow for the situation when the conductivity tensor turns to zero, for instance, in an un-ionized neutral gas or insulator.

A suitable physical model of the plasma includes a quasi-neutral plasma MHD description in a self-consistent electromagnetic field with ionization and radiation. In the MHD model one assumes a zero-mass electron motion (generalized Ohm's law) with effective conductivity, taking into account as well the energy exchange between the electron plasma component and the heavy (i.e., ions and neutrals) component, thermal conduction, and radiation. The system of equations for the plasma mass density ρ , average plasma velocity $\mathbf{v}$, and two temperatures $T_{e,i}$ in the self-consistent electromagnetic field $\mathbf{E}$, $\mathbf{B}$ in the RMHD approximation is

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \quad \rho \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right] = -\nabla p + \frac{1}{c} \mathbf{j} \times \mathbf{B} - \nabla \hat{\pi}_{ii}, \\ p &= p_e + p_i, \\ \nabla \times \mathbf{E} &= -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}, \quad \nabla \times \mathbf{H} = \frac{4\pi}{c} \mathbf{j} + \frac{1}{c} \frac{\partial \varepsilon \mathbf{E}}{\partial t}, \quad \nabla \cdot \mathbf{B} = 0, \quad \mathbf{B} = \mu \mathbf{H}, \\ \mathbf{j} - \hat{\sigma} \cdot \frac{\mathbf{u} \times \mathbf{B}}{c} &= \hat{\sigma} \cdot \left(\mathbf{E}^* + \frac{\nabla p_e}{en_e} \right), \quad \mathbf{E}^* = \mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B}, \quad \mathbf{u} = -\frac{\mathbf{j}}{en_e}, \quad (8.8) \\ \rho \left\{ \frac{\partial \varepsilon_e}{\partial t} + [(\mathbf{v} + \mathbf{u}) \cdot \nabla] \varepsilon_e \right\} &= -p_e \nabla \cdot (\mathbf{v} + \mathbf{u}) - \nabla \cdot \mathbf{W}_e + \mathbf{j} \cdot \hat{\sigma}^{-1} \cdot \mathbf{j} \\ &\quad + Q_{ei} - \nabla \cdot \mathbf{F}_r + \mathbf{G}, \\ \rho \left[\frac{\partial \varepsilon_i}{\partial t} + (\mathbf{v} \cdot \nabla) \varepsilon_i \right] &= -p_i \nabla \cdot \mathbf{v} - \nabla \cdot \mathbf{W}_i - Q_{ei} - \hat{\pi}_{ii} \nabla \cdot \mathbf{v}, \\ W_{e,i} &= -\hat{\mathbf{k}}_{e,i} \cdot \nabla T_{e,i}. \end{aligned}$$

The radiation flux density $\mathbf{F}_r$ in the electron energy equation is calculated by means of the radiation transport equation considered above. The term $\mathbf{G}$ is introduced to take into account possible external heating, by laser light for example. The laser-light interaction with a substance needs to be separately considered and is discussed below in Sec. 8.4.3.

The quasi-neutrality of the plasma means $n_e \approx \bar{Z}n_i = \bar{Z}\rho/m_i$, because $\bar{Z}m_e/m_i \ll 1$. The Poisson equation is not introduced separately, so as to avoid introducing a new quantity such as the charge density. It is fulfilled automatically from the second Maxwell equation, because $\nabla \cdot (\nabla \times \mathbf{H}) = 0$, if the initial conditions for the electric field satisfy the Poisson equation too. In view of the special practical application of the physical equations, we assume that at the initial time, $\nabla \cdot \varepsilon \mathbf{E}|_{t=0} = 0$ everywhere in the space except, perhaps, at conductor boundaries.

The dielectric constant ε and magnetic permeability μ are introduced to describe homogeneously the plasma dynamics together with the electromagnetic field behavior in insulators and metallic objects (if necessary). For the plasma and gas $\varepsilon = \mu = 1$ are imposed.

Different plasmas and solid materials may be considered as differing from each other only by their properties, especially if solid materials can be sublimed and transformed to plasma. These properties of the plasma and other substances are described by the EOS, viz., the thermal pressure $p_{e,i}(\rho, T_{e,i}, \bar{Z})$, specific internal energy $\varepsilon_{e,i}(\rho, T_{e,i}, \bar{Z})$, and ionization degree $\bar{Z}(\rho, T_{e,i}, U, t)$; the kinetic coefficients and tensors, viz., the electron-ion energy exchange $Q_{ei}(\rho, T_{e,i}, \bar{Z})$, electrical conductivity $\hat{\sigma}(\rho, T_e, \bar{Z}, \mathbf{B}, \mathbf{u})$, thermal conductivities $\hat{\kappa}_{e,i}(\rho, T_e, \bar{Z}, \mathbf{B}, \mathbf{u})$, and ion viscosity $\hat{\tau}_{ii}(\rho, T_e, \bar{Z}, \mathbf{B}, \mathbf{v})$; and the radiation properties mentioned above. Here it is necessary to mention that, due to nonstationary effects, the ionization degree $\bar{Z}$ depends not only on the plasma density and temperature, but also on the time, through the ionization kinetics described by the level-kinetic Eqs. (8.1). The dependence of the conductivities on the electron drift velocity $\mathbf{u}$ is described through the concept of the anomalous resistivity in the low-density plasma regions due to plasma turbulence; the lower hybrid drift and ion sound waves are assumed to have low thresholds. The EOS and the kinetic coefficients are obtained by means of the cross sections of collisional processes between the electrons, ions, and atoms; and the interaction with radiation is calculated in the frame of the general quantum-statistical model and ionization kinetics or of the more simplified approaches described above. Their dependence on the magnetic field is described in Ref. 14.

In Sec. 8.3, the system of RMHD Eqs. (8.8) together with the radiation transport Eq. (8.5) and ionization kinetics (8.1) are applied to design an RMHD numerical model. Results on the modeling of DPP and LPP EUV sources are presented in Sec. 8.4.

8.2.4 Preionization processes

Weakly ionized plasma may be described by equations analogous to the MHD Eqs. (8.8) only if the quasi-neutrality condition is satisfied and the electron inertia is negligible, i.e., at sufficient degree of ionization. Those conditions are not fulfilled at the beginning of the ionization process, especially in the so-called preionization stage or triggering of a discharge. As is well known, this stage is unstable due to ionization instability that results in filamentation in the discharge. Nevertheless, in many cases, where electron inertia is not important, this stage may be

considered as a part of the main discharge process with just a specially calculated conductivity, taking into account the ionization kinetics of weakly ionized plasma.¹⁵ In general, the Boltzmann kinetic equation for electrons with ionization kinetics should be used. This general approach is not used in the code currently developed and will not be discussed in more detail here.

Instead, we will consider the specific case of the hollow-cathode system, which is widely used in EUV plasma sources. The hollow-cathode effect¹⁶ is considered in the electron-hydrodynamic approach. That effect is used in low-density discharges working on the left-hand side of the Paschen curve to produce a tight (of the order of 100 μm) preionized channel for effective energy transfer from the power supply to the discharge. Following Ref. 17, the electrons in a weakly ionized plasma are described by hydrodynamic equations, i.e.,

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\frac{e}{m_e} \left(\mathbf{E} + \frac{1}{c} \mathbf{u} \times \mathbf{B} \right) - R_{\text{eff}} n_a \mathbf{u} - R_{\text{ei}} n_i \mathbf{u}, \quad (8.9)$$

where $n_a = N - n_i$ is the neutral-atom density, and N is the total density of heavy particles (neutrals and ions), with self-consistent electromagnetic field

$$\begin{aligned} \nabla \times \mathbf{E} &= -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}, \quad \nabla \times \mathbf{B} = -\frac{4\pi}{c} e n_e \mathbf{u} + \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t}, \\ \nabla \cdot \mathbf{E} &= 4\pi e (n_i - n_e), \quad \nabla \cdot \mathbf{B} = 0, \end{aligned} \quad (8.10)$$

and ionization processes

$$\begin{aligned} \frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{u}) &= n_a n_e S - n_i n_e (L_{\text{ph}} + n_e L_3), \\ \frac{\partial n_i}{\partial t} &= n_a n_e S - n_i n_e (L_{\text{ph}} + n_e L_3). \end{aligned} \quad (8.11)$$

The ions, once ionized, are supposed to be motionless. The specific friction rates in the equation of motion (8.9) are determined by the inelastic and elastic collisions of electrons with atoms [$R_{\text{eff}} = u(\Sigma_{\text{in}} + \Sigma_{\text{el}})$] and ions ($R_{\text{ei}} = u\Sigma_{\text{ei}}$), where $\Sigma_{\text{in,el,ei}}$ are the respective cross sections. Important features of the cross sections for the considered phenomenon are the presence of a maximum in the ionization cross section (for heavy elements such as Xe, it is at 100 eV), and rapid decrease of all cross sections, at least as u^{-2} , at higher energy. The specific rates S , L_{ph} , and L_3 in Eq. (8.11) are determined by the respective cross sections for impact ionization, photoionization, and three-body recombination.

In the 1D case, the hollow-cathode effect described by Eqs. (8.9)–(8.11) was considered in Ref. 17. Section 8.4.1.2 will present the results of a 2D modeling of the preionization process in a capillary discharge using those equations.

8.2.5 Plasma– and radiation–solid-material interactions

There are various mechanisms of interaction between plasmas and solid surfaces (electrodes, insulators, device chamber walls), depending on the plasma temperature, emission, electric current, etc. As expected in a plasma EUV source, we do not have extreme temperatures and energetic particle fluxes like those in fusion facilities, nor do we have very high current density ($>10^9$ A/cm²) like that in microdischarges, nor megagauss magnetic fields and mega-electron-volt particle beams as in high-energy pulsed power. Therefore we can limit the choices by the following main effects:

1. heating of the electrodes by Joule dissipation;
2. surface heating and plasma cooling by means of plasma thermal conduction;
3. surface heating and damage by plasma radiation; and
4. damage to precision surfaces (optical elements) by fast ions emitted from the plasma.

In Z^* , the first three effects have all been included implicitly in the system of RMHD Eqs. (8.8) by taking account of the electrode and insulator materials in the main calculation loop. The procedure is further described in Sec. 8.3.2. The fourth effect, due to the presence of fast ions, requires separate particle modeling, and the physics is not included in the current version of Z^* . In the following, some of the physics issues behind these effects will be briefly explored.

1. The Joule dissipation in the electrodes is conditioned by the finite conductivity of metals. From the Bloch–Gruneisen law it is known that a metal's conductivity decreases with increasing temperature approximately as

$$\sigma(T) \sim \sigma_0 \frac{\theta}{T}, \quad (8.12)$$

where σ_0 is a constant and θ is the Debye temperature characteristic of the type of metal. Therefore, the Joule dissipation j^2/σ increases with heating if the current density j remains the same. As is well known, this situation leads to instability. From the energy balance equation we have

$$c_v \frac{\partial T}{\partial t} = \frac{j^2}{\sigma_0 \theta} T. \quad (8.13)$$

The specific thermal capacity c_v given by the Dulong–Petit law does not depend on temperature for $T > \theta$ (for instance, for tungsten $\theta = 383$ K). From Eq. (8.13) we see that the temperature increases as

$$T = T_0 e^{\int \gamma dt}, \quad \gamma = \frac{j^2}{\sigma_0 \theta c_v}, \quad (8.14)$$

leading to the conclusion that any initial perturbation in the temperature or the material properties will grow exponentially. However, in the electrodes of pulsed discharges, the current flows within a skin depth $\Delta \sim (c^2 t / 2\pi\sigma)^{1/2}$, and thus the current density decreases with increasing temperature, because the cross-sectional area through which the current flows increases due to decreasing σ [Eq. (8.12)]. The skin effect therefore stabilizes the thermal instability in the part of an electrode where the current flows along the surface.

The other situation occurs in the region of the electrode, where current passes from the electrode to the plasma and vice versa. In that zone the area where the current passes is defined by the plasma size rather than skin depth and does not depend so much on the electrode temperature. This leads to thermal instability, local overheating, the appearance of hot spots on electrodes, and, if the current is large enough (the temperature rise being limited by the thermal conduction of the electrode material), to local melting and sublimation of the metal. In high-power discharges such an instability affects the electrode erosion. To describe this effect, the MHD equations with self-consistent electromagnetic field must be solved together with magnetic field diffusion into the electrode, energy balance for electrode material with real EOS, electrical conductivity, and thermal conduction to evaluate correctly the distribution of the current and temperature in the electrode.

In vacuum discharges, cathode hot spots may be caused also by the electron emission instability,⁴⁶ as the electron emission increases with the temperature of a metal. This process should be described in a kinetic approach. This effect plays an significant role in vacuum discharges, but is less important in dense-plasma discharges.

2. A discharge plasma heated by the current also heats the electrodes by means of thermal conduction. At the same time the plasma is cooled and the near-wall plasma has a much lower temperature than that in the volume. Some plasma can then condense onto the surface and change its properties, which is important at high operating frequency for lifetime considerations. The plasma thermal conductivity increases with the plasma temperature, and the plasma energy content increases also. Even though the plasma has a much lower density than the solid material, the fast thermal conduction flux from plasma can evaporate a thin layer of the confining insulator with low thermal conductivity.

3. In a high-Z plasma such as one of xenon or tin, more than half of the energy deposited is emitted as radiation. The useful inband energy is just a few percent of the total radiation energy. It is easy to estimate how much energy will be emitted from a EUV tool generating 1 kW of inband energy into 4π sr. This amount of energy is absorbed by the solid surface and sublimates it layer by layer, introducing impurities into the plasma and decreasing the lifetime of the equipment. To calculate the amount of energy absorbed by the surfaces of the facility, it is necessary to calculate the radiation transport Eq. (8.5) in a plasma and its absorption in the solid material by using the full radiation spectrum rather than only the inband radiation.

4. Estimation of the emission of fast particles from plasma and their interaction with the surrounding surfaces demands some other approaches not described by RMHD. Fast particles should be considered in the frame of the Boltzmann kinetic equation, taking into account plasma ion transport from the plasma boundary through the ambient gas, the effect of charge exchange, and the formation of a flux of neutrals. This problem can be solved in postprocessing, for it does not affect the plasma dynamics. Postprocessing means that during RMHD simulation the plasma and the field parameters are obtained, and then these data are recalculated with some additional physical processes, such as fast ion flux from the tail of ion distribution function (Maxwell's function) transported from the plasma due to charge exchange. This flux can be calculated, for example, by means of the particle-in-cell method for solution of the Boltzmann kinetic equation. This approach is currently being implemented in the code Z^* .

8.3 Computational RMHD Code Z^*

The code Z^* is a numerical modeling tool developed for complete simulations of the behavior of a multicharged ion plasma in experimental and industrial facilities, using an RMHD formalism. It is derived from the well-proven code ZETA,¹⁸ developed for the purposes of plasma modeling in HEDP by the same team that put together Z^* . Using ZETA, various plasma systems on different large pulsed-power generators such as ANGARA-5 in TRINITI (Russia),¹⁹ the Z accelerator at SNL (USA),²⁰ and others have been simulated. ZETA was also successfully applied to simulate EUV radiation sources on the basis of capillary discharges on nanosecond²¹ and microsecond²² time scales.

Z^* is a special development designed specifically for complete simulations of industrial plasmas. It has been developed to perform calculations in complex geometries of electrodes and insulators with improved cold-start ionization processes and radiation transfer in nonequilibrium regimes, and to provide a high robustness at the same time.

The code Z^* is designed on the basis of the MHD equations of multicharged ion plasma in a 2D axially symmetric geometry with full radiation transport. Plasma radiation properties, ionization, and the EOS, as well as excitation and ionization rates and plasma kinetic coefficients, are calculated by means of interpolations from a set of tables prepared in preprocessing. Another set of tables prepared by the preprocessor is used for the postprocessing treatment of data obtained by the RMHD processor, to calculate detailed spectra of the plasma emission with high resolution in specific spectral bands—EUV or other regions as desired. Interpolations of preliminary prepared databases allow the code to avoid online calculations of a variety of processes such as plasma dynamics, atomic physics, and ion kinetics. As a result, the robustness of the code and accuracy of calculations of the main processes can be considerably increased.

The code Z* also includes an interactive interface for graphical adaptive computation-grid construction. For exploration of calculated data and presentation of results, a standard graphical package is applied.

8.3.1 Databases of radiation and ionization plasma properties

Most experimental plasmas under conditions of interest in practical applications exist in the non-LTE regime. The plasma properties are functions of the temperature, the mass density, and the local spectral radiation energy density and time. The databases on the EOSs for any materials and mixtures and on the spectral and plasma transport coefficients are calculated in Z* in preprocessing by the code THERMOS^{5,23} in both the optically thick LTE and the transparent non-LTE limit. The actual non-LTE condition is modeled by analytical interpolation, described in the following, between those two limits.

The Hartree-Fock-Slater quantum-statistical model of a self-consistent field for the matter is used in the code with the Dirac equation for atomic shells. For opacity calculations the ion state probabilities are obtained from a renormalized Gibbs-type distribution. The line shapes are Voigts with Lorenz widths given by electron pressure broadening, natural broadening, and the Stark effect. The Gaussian widths are given by Doppler broadening, taking into account an additional width calculated in the intermediate coupling scheme.³² Photoionization processes are considered in the average-atom approximation with corrections for configurations. Inverse bremsstrahlung is computed using the self-consistent potential and taking into account degeneracy effects. The equation of state is derived from the grand thermodynamic potential. Thermodynamic functions of electrons and nuclei are taken as the additive ones.

The databases are calculated in steady-state approximations, and to be able to take into account nonstationary effects on the plasma state, the rates of atomic processes are also calculated. For comparison, the calculated ionization degree of a tin plasma at the two limits of LTE and CRE, as functions of temperature and mass density, are represented in Fig. 8.3.

The detailed atomic structure and databases of spectral lines and ionization edges for Xe and Sn plasmas including I-XX ions are calculated by the code TERM.⁴³ By using this database the calculation of spectral opacities and emissivities is made with the code THERMOS. The nonlinear steady-state Eqs. (8.4) for level occupancies are solved by iteration cycles. Values of energies and oscillator strengths are found by solving the system of Hartree-Fock-Slater equations with obtained occupation numbers N_v . At a given temperature and density, the level of excitations depends on the radiation intensity and is calculated using interpolation between the two considered limits. The results for the calculated spectral emissivity of a tin plasma at the two limits of LTE and CRE are represented in Fig. 8.4.

For comparison of the EUV emission from Sn and Xe plasmas, relative emissivity properties are presented in Fig. 8.5 as the ratio of the emissivity within a

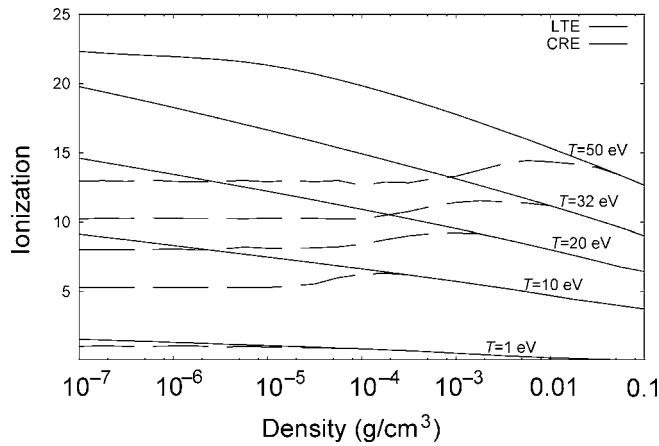


Figure 8.3 Ionization stage of tin plasma versus density at different temperatures, calculated in LTE and CRE.

2% band around 13.5 nm to the spectrum-integrated total emissivity. This relative value is important for definition of the necessary plasma parameters to optimize an EUV source. The emission of the tin plasma has a first maximum at $Z_0 = 10$ and increases again until $Z_0 = 15$. Xenon emission has a maximum at $Z_0 = 10$ too. Under the same ionization degree $Z_0 = 10$, the share of EUV emission from xenon is 6 times less than that from a tin plasma.

The behavior of the emission for the discharge depends on both radiation transport and plasma dynamics. The detailed tables obtained are used for calculations of the nonstationary ionization process together with radiation transport, through an interpolation procedure. To calculate the nonstationary effects of ionization, excitation, etc., in a multicharged plasma, instead of the kinetic Eq. (8.1), the simplified equations

$$\frac{df}{dt} = S \cdot [\Phi(f) - \Phi(f_{\text{eq}})] \quad (8.15)$$

are applied for the mean charge, radiation coefficients, and other atomic parameters, f being used in the RMHD equations. The effective rate $S(T_e, \rho, \bar{Z})$ (see, for instance, Fig. 8.1) and the corresponding steady-state value f_{eq} are recalculated and interpolated by means of a corresponding interpolating function $\Phi(f)$ [normalized to unity by the maximum value $\Phi_{\text{max}}(f) = 1$] from tables prepared in preprocessing.

To take into account the dependence of the plasma properties in non-LTE conditions on the local spectral radiation energy density U_ω and to avoid online calculations of complicated level kinetics, an analytical interpolation non-LTE model was developed,¹³ using, as a main parameter, the ratio of the absorbed local radiation intensity to its equilibrium value. The tables of plasma parameters are calculated beforehand by the code THERMOS over a wide range of temperature T_e

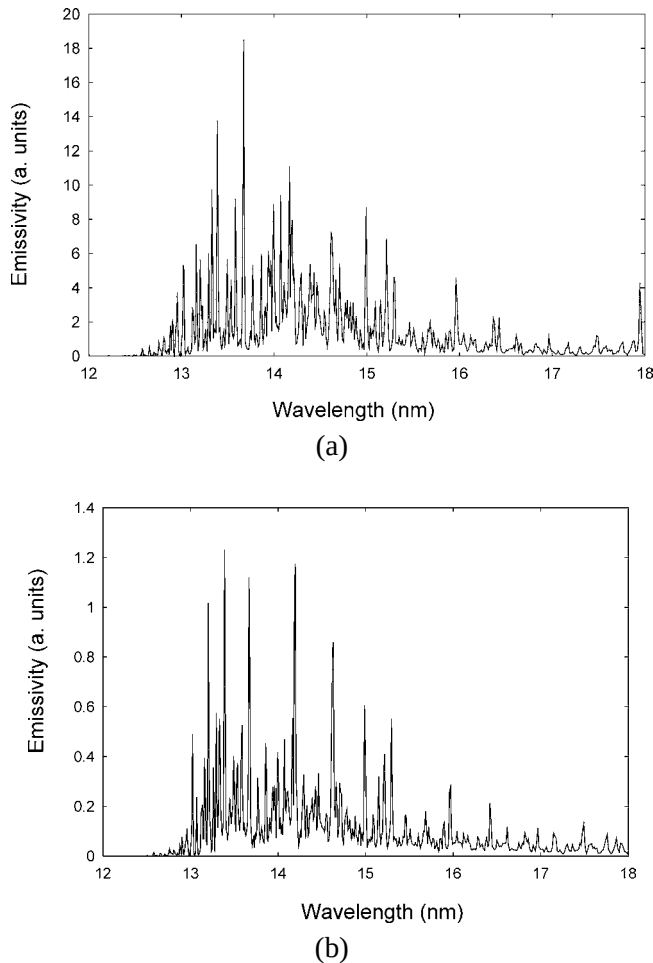


Figure 8.4 Emissivity spectrum of tin plasma at mass density 10^{-6} g/cm³ with (a) Saha equilibrium at $T_e = 16$ eV, and (b) with CRE at $T_e = 40$ eV (right), resulting in the same ionization state $Z_0 = 12$.

and mass density ρ in the transparent CRE and LTE limits. Non-LTE plasma characteristics, viz., the average ion charge $\bar{Z}(T_e, \rho, U)$, spectral opacity $\kappa_\omega(T_e, \rho, U)$, and emissivity $j_\omega(T_e, \rho, U)$, are then obtained by means of interpolation of the respective values for a transparent plasma defined at $U = 0$ calculated in CRE and for a plasma in LTE defined for Planckian radiation $U = U_p$ using a non-equilibrium parameter $\xi = U/U_p$.^{13,20} The parameter ξ is calculated by solving the self-consistent nonlinear radiation transfer equation together with the plasma dynamics. Other values from the tables for the EOS and the plasma kinetic coefficients, prepared by THERMOS over a wide range, are interpolated as functions of the temperature, density, and mean charge using this parameter ξ . Using this formalism, it is possible to approximate non-LTE values and to reduce consider-

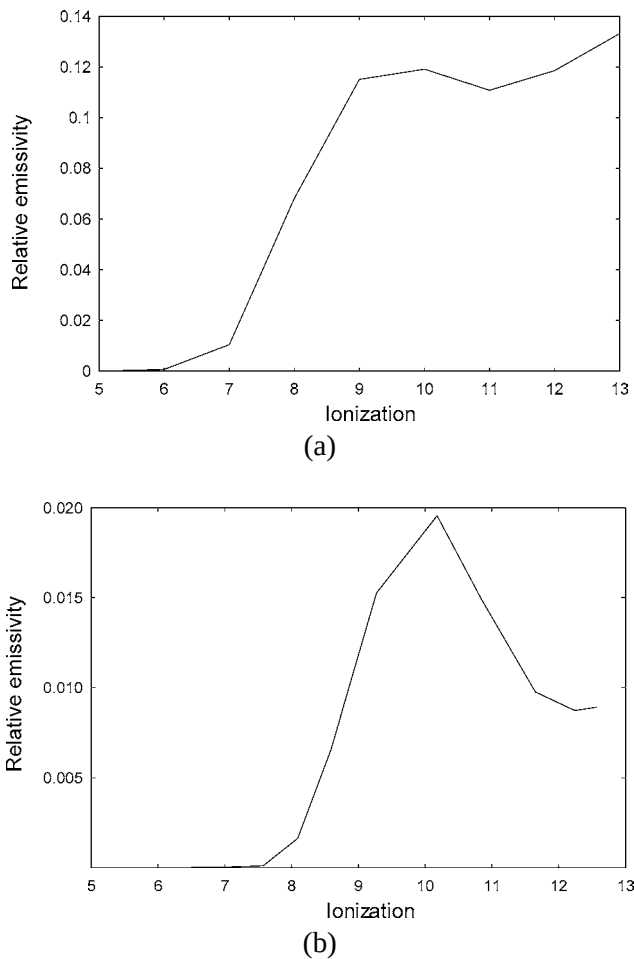


Figure 8.5 Relative emissivity (within 2% EUV band relative to spectrum integrated) versus ionization stage at mass density 10^{-5} g/cm^3 for (a) tin, and (b) xenon plasma.

ably the computing time of radiation transfer calculations in the RMHD computations.

Beyond the calculated region of the tables, extrapolations by Saha or Thomas–Fermi models are applied. For a solid, volumetric compression coefficients are introduced from published tables. The phase transition from solid to gas (plasma) is represented by the corresponding sublimation temperature and sublimation enthalpy. The liquid phase is ignored, but the transition energies are taken into account.

The influence of the magnetic field on multicharged-ion plasma kinetic coefficients is taken into account in the general case by conversion of field coefficients using Braginskii’s formulas, or using formulas taken directly from Ref. 14 for the case of an ideal plasma.

8.3.2 Effective conservative schemes for plasma RMHD modeling

The physical model established in Z^* includes the quasi-neutral plasma RMHD equations with self-consistent electromagnetic fields [Eq. (8.8)] and the radiation transport Eqs. (8.5) described above in Secs. 8.2.2 and 8.2.3. The mathematical model is based on a completely conservative, implicit difference scheme in Euler-Lagrange variables. The Euler-Lagrange variables²⁴ retain the advantages of the Lagrange and the Euler variables but reduce their disadvantages. Specifically, the Lagrange variables have no numerical diffusion and allow more precise solution of the MHD equations using implicit schemes, but there are problems of grid crossing that are computationally expensive to solve. While the Euler variables have no problem associated with grid crossing, they do have large numerical diffusion due to plasma convection, and thus demand very detailed grids. The Euler-Lagrange variables mean that plasma moves through the mesh with a relative velocity $\mathbf{w} = \mathbf{v} - D\mathbf{r}/Dt$, where $\mathbf{v}$ is the plasma velocity in the laboratory frame of reference [from the MHD equation of motion (8.8)], and $D\mathbf{r}/Dt$ is the speed of motion of the mesh. In particular, if $D\mathbf{r}/Dt = \mathbf{0}$ we have Euler variables, and if $D\mathbf{r}/Dt = \mathbf{v}$ we have Lagrange variables.

To design a completely conservative scheme²⁵ it is necessary to rewrite the MHD equations in a divergent form and to integrate afterward over the volume V enclosed by the surface s of a cell to get the equations of mass, momentum, and energy balance. For example, the mass and momentum balance equations are

$$\frac{D}{Dt} \int_V \rho dV + \oint_s \rho \mathbf{w} \cdot d\mathbf{s} = 0, \quad (8.16)$$

$$\begin{aligned} \frac{D}{Dt} \int_V \rho \mathbf{v} dV + \oint_s \mathbf{v} \rho \mathbf{w} \cdot d\mathbf{s} \\ = - \oint_s (p + \hat{\pi}_{ii}) d\mathbf{s} + \frac{1}{c} \int_V \mathbf{j} \times \mathbf{B} dV, \end{aligned} \quad (8.17)$$

and the electron internal energy balance is

$$\begin{aligned} \frac{D}{Dt} \int_V \rho \varepsilon_e dV + \oint_s \rho \varepsilon_e \mathbf{w} \cdot d\mathbf{s} \\ = - \oint_s [p_e(\mathbf{v} + \mathbf{u}) + \mathbf{W}_e - \rho \varepsilon_e \mathbf{u}] \cdot d\mathbf{s} \\ - \int_V \int (4\pi j_\omega - \kappa_\omega c U_\omega) d\omega dV \\ + \int_V [Q_{ei} + \mathbf{j} \cdot \hat{\sigma}^{-1} \cdot \mathbf{j} + G - (\mathbf{v} + \mathbf{u}) \nabla p_e] dV, \end{aligned} \quad (8.18)$$

where Eq. (8.6) was used for the radiation term. The same balance equations are written down for the kinetic energy $\int_V (\rho v^2/2) dV$, for the internal ion energy

$\int_V \rho \varepsilon_i dV$, for the electromagnetic energy $\int_V [(E^2/8\pi) + (B^2/8\pi)] dV$, and hence for the total energy. The “frozen” magnetic flux balance is also considered through the cell or any of its sides with surface s bounded by the contour l :

$$\begin{aligned} & \frac{D}{Dt} \int_s \mathbf{B} \cdot d\mathbf{s} - \oint_l \mathbf{w} \times \mathbf{B} \cdot d\mathbf{l} - \int_s \left[(\mathbf{B} \cdot \nabla) \frac{D\mathbf{r}}{Dt} - \mathbf{B} \left(\nabla \cdot \frac{D\mathbf{r}}{Dt} \right) \right] \cdot d\mathbf{s} \\ & = -c \oint_l \mathbf{E}^* \cdot d\mathbf{l}, \end{aligned} \quad (8.19)$$

where $\mathbf{E}^* = \mathbf{E} + (1/c)\mathbf{v} \times \mathbf{B}$ is the electric field in the plasma. The full set of all balance equations can be found in many papers, for example in Ref. 26. It must be remarked here that a completely conservative scheme is essential for the simulation of a physical system, in that it ensures that the solutions obtained are physical, since all integrals of the system exist at all times.

To realize the completely conservative scheme from the equations of balance, we define values of the density, specific energy, temperature, and pressure in each cell, and of velocity, electric field, and thermal and radiation flux at each node. The corresponding control volumes V are grid cell volumes (for mass and energy equations), or volumes constructed around each node (for the momentum equation), which together form the consistent system. Functions on the right-hand side of the balance equations are taken as linear combinations of their values at the previous time step and the new one, with weight η to satisfy the condition of complete conservation of the scheme, i.e., $F_\sigma = \eta F(t + \Delta t) + (1 - \eta)F(t)$. With that substitution the difference approximations of Eqs. (8.16)–(8.19) and their analogs are nonlinear.

To solve the obtained system of RMHD difference equations, an implicit scheme is used with Newton’s method. The right-hand sides of the equations are linearized. To reduce the number of functional derivatives that must be written down analytically, a method of splitting by processes is applied. In this method the most-correlated processes are grouped together and solved. In one group the equations corresponding to force balance (i.e., the motion and electromagnetic field equations) are included and solved in the first iteration cycle until the respective functions converge. Then a second group of equations, corresponding to energy balance (i.e., electron energy, radiation, and ion energy equations), are solved in another iteration cycle until convergence. But all processes of force and energy balance are related to each other, and therefore the two iteration cycles together are included in a common iteration cycle until the total energy balance converges. This splitting method allows considerable reduction of the dimensions of the matrices that are inverted during the iterative processes, under the condition of absolute scheme stability.²⁷

A numerical solution of the system of discrete RMHD equations is carried out in a three-stage algorithm considered in Refs. 24 and 28. The first one is a Lagrange stage, at which $\mathbf{w} = 0$ and from Lagrange-type equations functions at the

next time step $t + \Delta t$ are found. Equations (8.16)–(8.17) do not contain convective terms and have the simplest form for solution. The time step Δt is chosen automatically to allow the balance equations to converge. At the second stage, a new grid is defined by shifting nodes in accordance with the necessary algorithm (in particular, it may be simply returning the nodes to their original positions before the Lagrange step, corresponding to an Euler grid). At the third stage, all values are recalculated instantaneously, i.e., with a time step $Dt \rightarrow 0$. All balances are then verified again, and if convergence is not met, the procedure is repeated with reduction in the time step Δt until convergence is obtained. The third stage corresponds to the mutual convective movement of grid and substance, and inevitably leads to some numerical diffusion. To minimize numerical diffusion it is necessary to correct the Lagrange grid locally where necessary. Such an algorithm for grid reconstruction allows the reduction of numerical diffusion with respect to the recalculation onto the Euler grid. Finally, to calculate plasma motion with discontinuities and shock waves homogeneously, the usual method of an artificial viscosity added to the physical one is applied. Due to the artificial viscosity, the discontinuities are spread over a few neighboring cells. This allows the prediction of possible grid crossing and the proper treatment to be taken up as described above.

Solid objects such as electrodes, insulators, and rigid walls are treated with the same set of equations except the equation of motion (they are either motionless or moving with given speed), but with different conductive, nonconductive, radiative, and heat-capacity properties, until they are heated up to sublimation temperature and evaporated. This approach allows the code to simulate sophisticated experimental geometries without change of algorithm, and also the introduction of additional boundary conditions. Interaction of the plasma with the external power supply is realized through boundary conditions on the electric ($\mathbf{E}|_{\Gamma}$) and magnetic ($\mathbf{B}|_{\Gamma}$) fields, self-consistent with the electric circuit equations. For instance, an *LCR* circuit with a voltage generator can be represented by

$$\frac{dLI}{dt} + RI + \frac{\int Idt}{C} - \int_{\Gamma} \mathbf{E} \cdot d\mathbf{l} = U, \quad B_{\varphi}|_{\Gamma} = \frac{0.2I}{r|_{\Gamma}}, \quad (8.20)$$

where I (A) is the current through the discharge; the integral of the electric field is taken along the boundary Γ of the considered volume; U (V) is imposed by some voltage generator or neighboring electrical circuit loop, or a transmission line described by the telegraph equations; B_{φ} (G) is the azimuthal component of the magnetic field (for other components of the magnetic field, other special boundary conditions must be introduced); and r (cm) is the radius.

To summarize this subsection, the detailed, fully conservative approach described here in the numerical modeling of a plasma RMHD and the bounding surfaces allows Z^* to carry out robust and reliable simulation of complicated objects, such as multicharged ion plasmas with realistic boundary conditions.

8.3.3 Multigroup radiation transport model

Specific attention in Z^* is paid to radiation-transport simulation. The classical solution developed to tackle radiation transport in dense plasmas involves a multigroup approach to limit the radiation energy band. An averaged absorption and emission coefficient for the radiation is derived for each group, and a table containing detailed properties in connection with the equation of state is used.

In the multigroup approach, the full spectral range is divided into M spectral bands ($0 \rightarrow \omega_1, \dots, \omega_{m-1} \rightarrow \omega_m, \dots, \omega_{M-1} \rightarrow \infty$), including the most important intervals for the energy balance. To find the radiation energy, the quasi-stationary transport Eq. (8.7) must be integrated along trajectories under cylindrical symmetry conditions. In Z^* a semianalytical approximation is used to obtain an expression for the intensity. The emission and absorption coefficients j_ω, κ_ω in Eq. (8.7) depend on the coordinates r and z . In the approximation, the integral in Eq. (8.7) is integrated analytically inside each cell, where the coefficients j_ω, κ_ω do not depend on the coordinates, since numerical integration in the case of high reabsorption ($\Delta\tau \sim \kappa_\omega \Delta x / \sin \theta \gg 1$) can lead to large error.

To continue the classical solution, the multigroup approach is extended to the angular coordinate, i.e., the volume is also divided into groups $0 \rightarrow \varphi_1, \dots, \varphi_{k-1} \rightarrow \varphi_k, \dots, \varphi_{K-1} \rightarrow 2\pi$ for the azimuthal angle ϕ , and $0 \rightarrow \theta_1, \dots, \theta_{l-1} \rightarrow \theta_l, \dots, \theta_{L-1} \rightarrow \pi$ for the angle θ . Then, to find the spectral radiation energy U_ω in a cylindrical geometry, the integral over the volume of the cell and over the angular group is evaluated analytically; after that it is used in the energy balance Eq. (8.18).

This approach is much more complicated than the diffusion or quasi-diffusion model widely used to model the radiation transport. However, diffusion methods cannot be applied for semitransparent or transparent plasmas, for there is no physical basis for such applications. In a plasma where only strong lines may be reabsorbed, the main part of the photons have mean free paths comparable to or even larger than the plasma size. The radiation in the plasma is necessarily anisotropic and must be subjected to the transport Eq. (8.1).

In the method used in Z^* , the self-consistency of the nonlinear radiation transport and the non-LTE dependence of the plasma state on radiation energy are taken into account by means of an approximation of the radiative coefficients,^{13,20} as described earlier in Sec. 8.3.1. The result is realized through internal iterations, which are stable.

To examine radiation within the EUV spectral band of interest, special radiation groups are prepared for the range near 13.5 nm and the adjacent bands. The calculated EUV spectrum and details of the part of the spectrum within the band 13–14 nm are presented in Fig. 8.6. By summing over a given bandwidth it is possible to generate a time profile of the emission power and to find a conversion efficiency (CE) for the plasma EUV source, particularly for comparison with experimental measurements. By choosing specially oriented angle groups, the radiation flux to any diagnostic EUV detector may be also simulated.

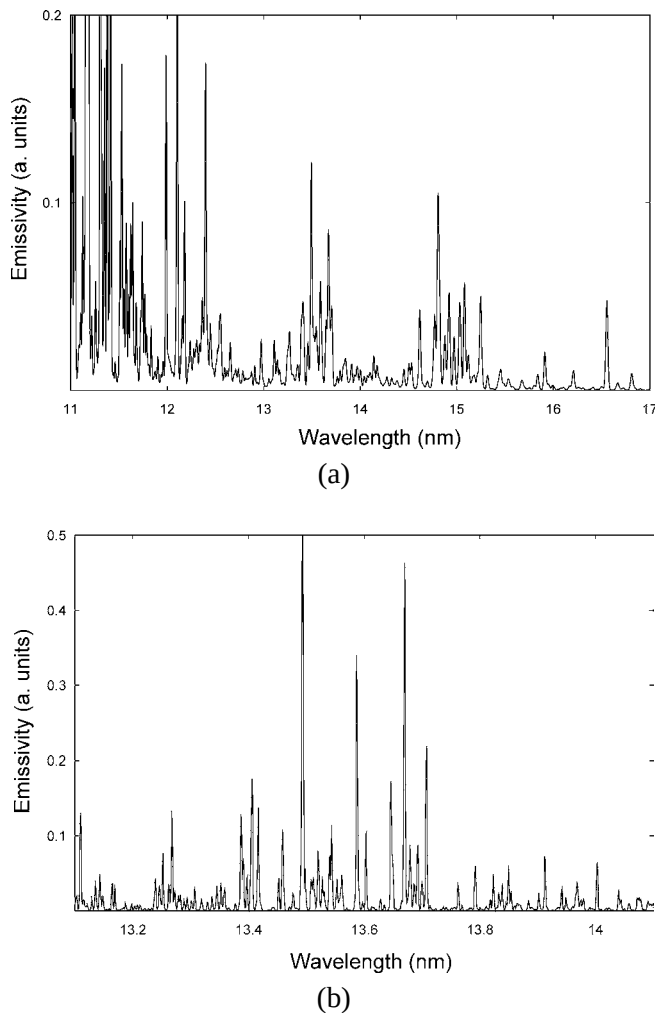


Figure 8.6 Calculated EUV Xe spectrum at $T_e = 40$ eV, $\rho = 10^{-6}$ g/cm³, in a CRE model: (a) over a broad band, and (b) detailed within the band 13–14 nm.

8.3.4 Spectral ray-tracing postprocessing

The number of radiation spectral energy intervals and angular sectors in a multi-group RMHD simulation cannot be high enough to obtain detailed radiation spectra from a high- Z plasma. The integral approach characteristic of the multigroup method also does not permit the monitoring of particular points in the plasma for diagnostics.

To process a detailed emission spectrum in a given direction of observation, the spectral postprocessor RAY has been developed for the 2D RMHD code Z*. RAY is designed on the basis of the codes ERAY^{18,19} and BILINE²⁹ and allows the effect of complex level kinetics to be included. In the postprocessor the distributions of plasma parameters such as the density, temperatures, ionization stage,

radiation field, and velocities obtained during the RMHD simulation are used as instant background data for recalculation of necessary functions, together with some additional physical processes. This allows one to establish an arbitrary straight observation path in 3D, in a cylindrically symmetrical geometry, and to calculate the ionization stage and ion configuration probabilities along this path, within the framework of the average-ion collisional-radiative model described, using the level-kinetic Eq. (8.1). The radiation transfer Eq. (8.5) is solved self-consistently along the observation path, both in continuum and in spectral lines, with simulation of the Doppler effect in a moving plasma. The equations of population kinetics are solved in steady-state approximation or chosen to fit the ionization stages calculated during the RMHD simulation by means of the simplified nonstationary ionization model (8.15). Ionization and excitation rates, distributions of energy levels, oscillator strengths and widths of spectral lines, and detailed (up to 5000 points) spectral absorption and emission coefficients are calculated by using the code THERMOS, with corrections from known experimental data. Such details are necessary to provide simulation output for benchmarking with experimental observations and to allow the modeling tool to be used for plasma optimization and diagnostic purposes.

8.4 EUV Radiation Source Simulations

DPP and LPP radiation sources have demonstrated promising features to satisfy the conditions necessary for a source in EUVL. The exact plasma characteristics most suitable for optimum EUV radiation are not clear and have not been reported in any detail. This hampers the scaling of each of the different types of discharges for EUV to higher radiation yield and has made objective comparison of DPP and LPP difficult.

DPP EUV radiation sources belong to a class of discharge plasmas where a driving current flows along a mainly axial direction—the Z pinch. In the Z pinch, a high-density plasma (HDP) is created by the driving current through electromagnetic forces, and heated to a high temperature by the same current. Properly designed, such a high-energy-density, tight plasma structure can transform electrical energy efficiently into radiation. At the same time, it is known from the experience of Z -pinch plasma study that such a plasma is unstable to $m = 0$ MHD neck instability and $m = 1$ 3D kink-mode instabilities.

From instability considerations, Z pinches may be classified as follows: fast Z pinches with current pulse time shorter than the inertial time t_c of Z -pinch compression,³⁰ and slow ones with pulse time much greater than the MHD time. In a fast Z pinch, the influence of MHD instability is less significant and the pinch is controlled, but the compression may not be very high, due to shock formation and preheating of plasma ahead of the compression. To obtain a high enough temperature in a fast Z pinch, it is necessary to have a high rate of current rise ($> 10^{12}$ A/s)¹⁵ and high current density ($> 10^5$ A/cm²). In slow Z pinches, plasma compression is ahead of current rise and the motion is oscillatory, i.e., compression

is followed by expansion and the cycle repeats. After a few oscillations the Z pinch is destroyed by MHD instability.

The neck or sausage instability creates a localized region of high density and high temperature. The density and temperature are limited by plasma outflow and consequent destruction of the MHD Z-pinch structure.³¹ On the other hand, in a high-Z plasma, such as that encountered in the DPP EUV sources, the radiation rate is high and it is possible to utilize this neck structure to create an intense radiation point. This point of extremely high energy density can be achieved when the radiation rate is higher than the heating rate in a plasma column undergoing compression by its own magnetic pressure, a phenomenon sometimes referred to as “radiative collapse” or, more appropriately, radiation-assisted magnetic compression. The key issue for EUV source application is whether this phenomenon can be controlled and whether the electrical energy in the system can be transferred to this pointlike structure, in time and in space, and can be efficiently converted to EUV radiation.⁴⁴ The neck formation may be induced by means of, for example, the initial density distribution, or by a special electrode form, or by organization of the special dynamics of the current sheath.

Yet another classification can be considered from the point of view of the current-sheath formation. The plasma conductivity limits a rising current to flow within a certain thickness on the surface of the plasma, defined by the skin depth. In a large-volume discharge the current flows initially in a layer much thinner than the chamber size and forms a current sheath. The sheath is accelerated by the magnetic field pressure and compresses the plasma ahead of it. In cylindrical systems, it compresses down onto the axis, i.e., the column of plasma pinches down. Because the compression rate is higher than the local sound speed, a shock wave is produced ahead of the compressing sheath structure. It ionizes and collects the gas during its motion, but some part of the gas is not captured into the motion and rests behind the sheath. This gas can trigger an additional current path, or current leakage, when the local voltage increases as a result of inductive and resistive effects during plasma pinching.

In a small-volume discharge, as is typical in a capillary discharge, another situation takes place. Due to the physical size of the capillary, the plasma dimension is less than the skin depth. There is no current sheath in this case, and the discharge plasma is compressed volumetrically by the magnetic field.²¹

In the simulations represented below we shall consider the influences of some of these described effects on the radiation emission. A series of simulations using Z* on plasma configurations such as the capillary discharge, dense plasma focus, and LPP has been performed, with a view to evaluating the functionality and suitability of such plasma systems for the purpose of plasma EUV radiation sources. To find optimal parameters for the emission under complicated conditions within different plasma devices, detailed numerical simulations were carried out. The plasma characteristics and radiation performance of these devices in the EUV spectral band are presented.

8.4.1 Capillary-discharge EUV source

Fast capillary discharges are simple and efficient means of producing high-energy-density radiation systems. In such a system, a high current is made to pass rapidly through a small-diameter insulating tube of millimeter dimension scale. The operation of a gas-filled capillary discharge with small dimension requires the proper preparation of the initial current conduction path in order to avoid a wall-initiated sliding spark discharge. This preionization condition can be produced in a number of ways, including the injection of a tight e-beam to create an ionization channel. By mating a suitable hollow-cathode structure to a capillary discharge, a self-generated on-axis electron beam is produced as a result of the transient hollow-cathode effect¹⁶ and leads to the formation of a preionized conducting channel on axis, where the main current begins to develop. This highly effective preionization process is inherent in the operation of the HCT Z pinch pioneered by Philips Extreme⁴⁵ and the micropulsed plasma (MPP) radiation source developed at EPPRA.³⁶

8.4.1.1 3D plasma compression

In most EUV capillary radiation sources so far developed,^{33–36} the operating gas is fed from one electrode and exhausted through the opposite electrode. The exhaust electrode connects the discharge system to the vacuum pumping system. Due to the almost Knudsen flow in the pressure regime of the operating discharge, a pressure gradient is established within the capillary between the two electrodes. The higher-pressure region is normally arranged to be at the cathode in order to utilize the self-generated e-beam for axial preionization.³⁴ It will be shown later that this axial preionization is important for optimum radiation performance. Furthermore, this gradient provides low EUV-radiation reabsorption by the cold gas at the anode side.

The pressure gradient creates a linear mass gradient of the gas along the capillary length. The compression time of the discharge plasma decreases as the linear mass decreases ($t_c \propto m^{1/2} c R_0 / I$), and the plasma near the anode therefore compresses faster than that near the cathode. Such a difference in the compression dynamics effectively causes faster increase of the magnetic field pressure near the anode and produces an axial compression wave along the capillary axis from the anode to the cathode. This effect is demonstrated in the analytical solution for the axially inhomogeneous capillary discharge in Appendix A, under the condition that the length of the capillary is much larger than its radius ($l \gg R_0$). It is shown that an axial velocity of the plasma is established as

$$v_z(r, z, t) = \frac{2r^2}{R^2} \int_0^t \frac{I^2}{mc^2} \frac{\partial R / \partial z}{R} dt', \quad (8.21)$$

where the linear mass density of the plasma, $m(z)$, is defined in terms of the initial axial density distribution $\rho_0(z)$ as $m(z) = \pi R_0^2 \rho_0(z)$. As a result, the radius of

the plasma during compression, R , depends on the time and the axial coordinate z (see also Appendix A). This solution shows that the plasma flows along the Z axis from the lower-density region to the higher-density region and thus the plasma is compressed three-dimensionally, unlike the 2D compression in the homogeneous cylindrical case. The formula (8.21) allows the density distribution $\rho_0(z)$ and capillary profile $R_0(z)$ to be optimized for more efficient radiation production.

A set of simulations was performed for fast capillary discharges in a geometry close to that of the experimental MPP discharge device established at EPPRA. The MPP radiation source is unique among the DPP sources in operating at a stored electrical energy $\ll 1$ J. It relies on a very low inductance discharge geometry to allow current of several kiloamperes to be delivered to a preionized discharge channel in several nanoseconds, despite the small energy used. The structure is shown schematically in Fig. 8.7(a). Various capillary diameters, from 0.8 to 3.2 mm, and lengths $l = 6$ –12 mm, with various gas compositions—including pure Ar, Kr, and Xe or their admixtures with He—at a range of pressures from 1 mTorr to 1 Torr, were examined.

These simulations were carried out with different driving parameters, including cell capacities and cell voltages, and different types of generator circuits. Many of these simulation results have been reported in various EUVL meetings.^{35–38}

In the following, we present details of some results on simulations obtained by Z* using the geometry presented in Fig. 8.7(b). An alumina capillary with internal diameter 1.6 mm and length 12 mm is placed between the electrodes. The capillary is filled with xenon with an initial pressure gradient from anode to cathode (2.6 to 107 mTorr) with imposed random initial perturbations within the range of

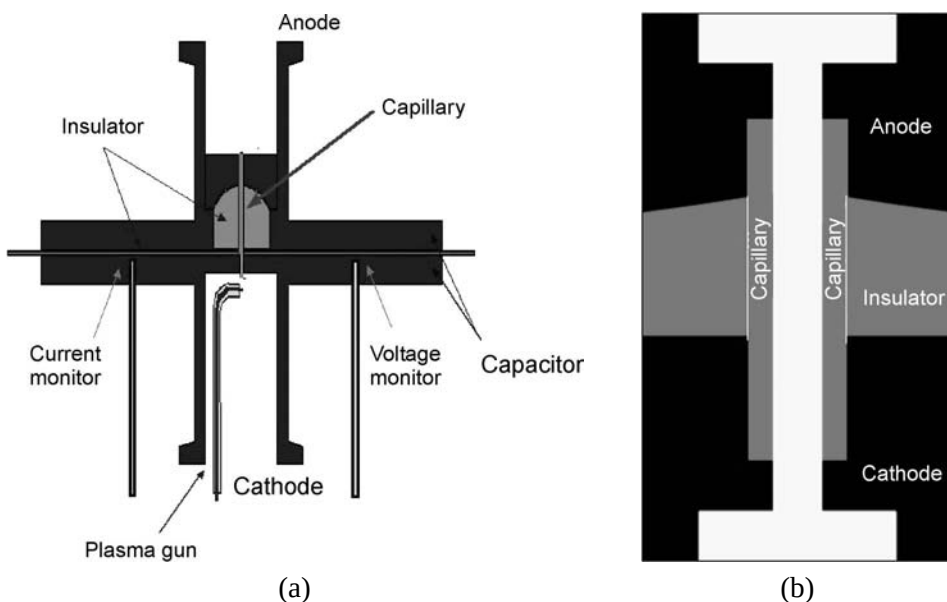


Figure 8.7 (a) Geometry of the EPPRA MPP capillary discharge; (b) zoomed view of the capillary region adopted for simulation.

$\pm 5\%$ to model the influence of the MHD instabilities (such as the Rayleigh-Taylor instability or thermal instability).

The local energy store is a 0.8-nF capacitor initially charged to 13 kV. The operating gas is assumed to be preionized, due to the hollow-cathode effect, in a tight 100- μm -diameter axial channel. The calculated discharge current and the EUV emission are presented in Fig. 8.8. A peak current of 5 kA is obtained with an oscillation period of 11 ns. The EUV radiation in the 13–14-nm band is seen to reach a maximum just after the first current peak. The discharge dynamics is presented in Fig. 8.9, showing the mass density distribution at different times. Due

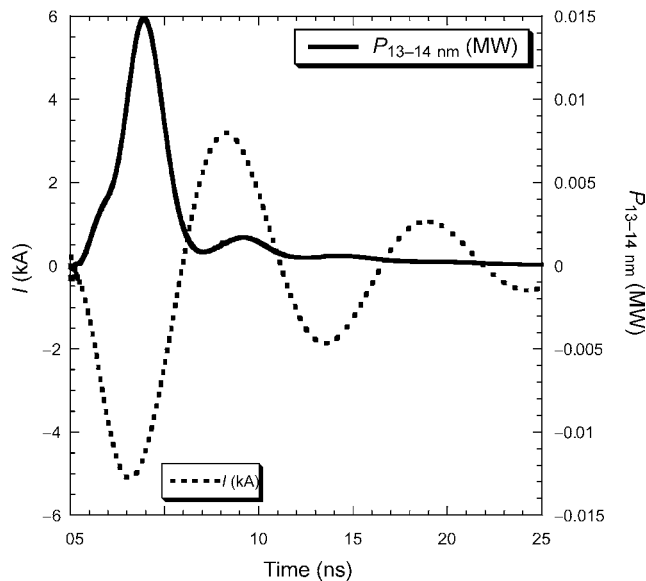


Figure 8.8 Current and EUV emission power of the MPP discharge versus time.

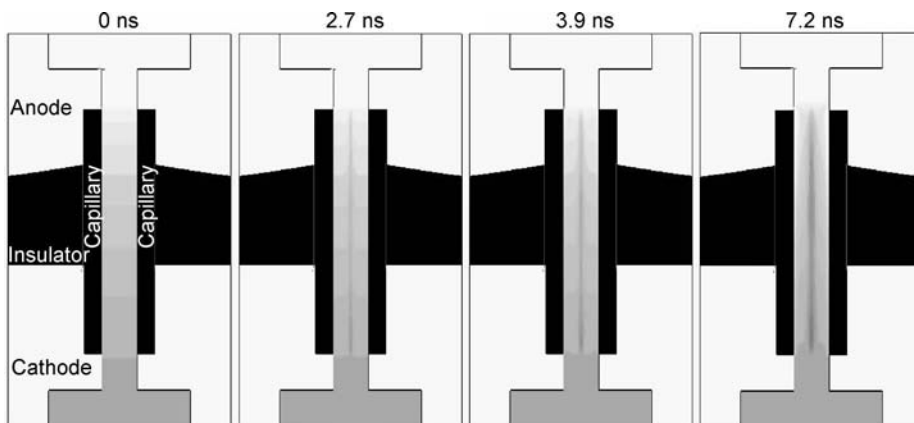


Figure 8.9 Discharge dynamics in the Xe MPP with a pressure-gradient filled capillary; density contours are shown at different times.

to the high radiation cooling rate of the heavy-ion plasma, the plasma temperature is relatively low, so that the thermal pressure is less than the magnetic one and the plasma conductivity is low enough to permit penetration of the magnetic field into plasma column. The capillary discharge plasma compresses volumetrically.

If the initial gas density gradient along the capillary is made high enough, the lower-density plasma is compressed faster and the cumulation in the low-density region generates a compression wave. The EUV radiation peaks at 3.9 ns, and the distribution of the inband EUV radiation power density at this time is shown in Fig. 8.10. It is produced mainly by a relatively dense plasma formed in the initially low density region near the anode. The plasma density reaches $7.7 \times 10^{-7} \text{ g/cm}^3$ at an electron temperature of 22 eV. The EUV emission source measured at half of the maximum value has a diameter of 0.17 mm and length of 5 mm.

At the time of peak emission, the xenon plasma compresses away from the capillary wall in the region of lowest plasma density near the anode. The current passes through zero at 5.8 ns and changes its sign. The plasma emission drops and reaches its minimum at 7 ns. The compression wave continues to move to higher density. At the second current maximum (about 2.5 kA), the plasma density is too high to be heated to the right condition and the EUV emission is much lower than at the first maximum.

The total emission of the xenon discharge through the open anode side in the spectral band 13–14 nm is about 50 $\mu\text{J}/\text{shot}$, which corresponds, by the spectral estimation in Fig. 8.6, to 35 $\mu\text{J}/\text{shot}$ in a 2% bandwidth around 13.5 nm. Since the plasma temperature does not reach the optimal value under the discharge conditions simulated, the percentage of EUV radiation may be increased if the current

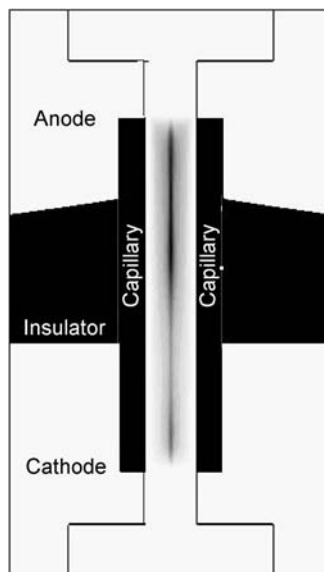


Figure 8.10 Instant image of the EUV source at a moment of the radiation pulse maximum (3.9 ns).

is increased. Such an optimization simulation was performed at a higher charging voltage of 20 kV, with other parameters in closely similar conditions. The inband EUV emission was found to increase by 4 times instead of the increase of less than 3 times predicted by simple I^2 scaling. This observation is confirmed by experimental measurements.

8.4.1.2 Influence of preionization

In simulations of the MPP capillary discharge at EPPRA, the best fit to experiment is obtained if the initial preionization is localized in a tight channel of 100- μm diameter along the capillary axis. To understand the preionization dynamics and the hollow-cathode effect, a special version of the code Z^* was developed, where MHD was replaced by electron hydrodynamics as described in Sec. 8.2.4 and ionization kinetics was implemented. The plasma is assumed to be motionless. The geometry of the MPP capillary shown in Fig. 8.7(b) was simulated. The ionization dynamics obtained is shown in Fig. 8.11.

During almost 2 ns an electron beam of several keV energy, initiated near the cathode, passes mainly along the axis of the capillary. The beam is tight, about 70 μm in diameter, due to a combination of electric field refracted onto the axis, as a result of the high dielectric constant of the capillary material (about 8.5 at such frequencies), and the self magnetic field. The beam and (mainly secondary) electrons produce ionization in time. At the same time electrons are exposed to the electrostatic turbulence, and the dynamics is rather complicated. Near the cathode, the electrons have lower energy and ionize more effectively. Near the anode, where all electrons come together, the ionization also rises more quickly. Due to the increased plasma conductivity, the electric field becomes localized between these clouds of plasma, and two ionization waves are observed to move respectively from

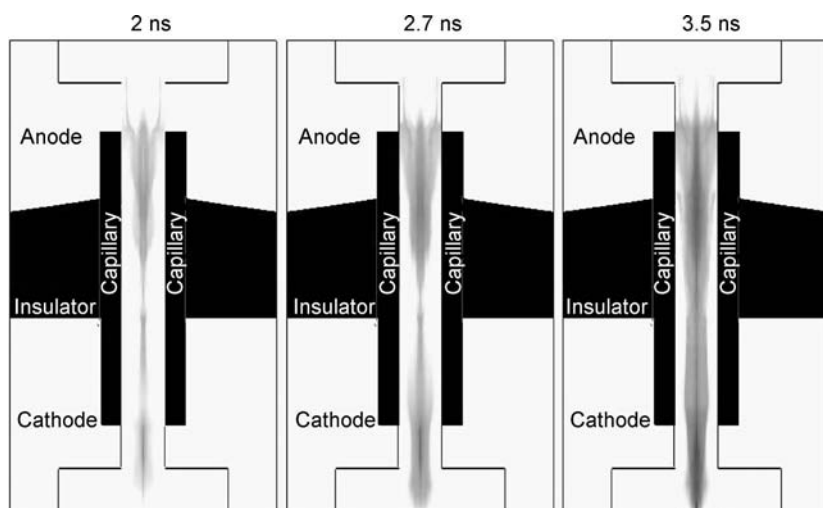


Figure 8.11 Preionization dynamics of a capillary discharge with contours of ion density n_1 shown at different times.

the anode and from the cathode toward the middle, and meet each other after 3 ns. At 4 ns the conductive channel occupies half the diameter of the capillary, but the high-density region is localized on axis. This preionized channel is similar to the initial condition chosen for simulation of the main discharge development.

To study the influence of the preionized channel size on the EUV emission yield from the MPP discharge, simulations with different preionization conditions were carried out for a Kr:He gas mixture with Z*. The results are shown in Fig. 8.12(a), which shows the radiation pulse behind a Zr filter as calculated in two cases: tight on-axis preionization and broad volume preionization. A large first radiation peak is observed for the tight preionization case. In Fig. 8.12(b), a series of experimental measurements taken with a fast diode behind Zr filter is shown, primarily looking at the radiation in the 8–16-nm band. The measurements were made in discharges with a fixed He pressure of 20 mTorr, measured at the anode side, but with different percentages of Kr admixture. Experimentally, it has been shown that a high percentage of Kr will lead to a large preionization channel. Qualitative agreement with the simulation results can be seen in the emission.

8.4.2 Dense-plasma-focus dynamics

The DPF configuration attracts attention because the radiation source is outside the interelectrode space and allows radiation to be collected from a large solid angle, almost 2π sr. In addition, in a DPF it is possible to realize nearly all the mechanisms of plasma heating in the discharge through kinetic energy, Joule heating, and $P dV$ work on the plasma, while in other pinch configurations the input of kinetic energy into plasma heating is comparably small. In Ref. 39, it was reported that in the 13.5-nm EUV spectrum (2% bandwidth), ≈ 55 mJ per pulse in 2π sr was obtained from a DPF, with an EUV efficiency of 0.45%.

The parameters of the DPF published in Ref. 39 were used as the basis for Z* modeling. Simulations were performed in the geometry as presented in Fig. 8.13. Steel is used as the material for the anode and cathode. Alumina is used as the material for the insulator between them. The vessel is filled by a gas mixture of 10% Xe and 90% He, with total pressure in the range 0.1–2 Torr, the initial gas distribution being homogeneous, with a density $\rho = (0.1\text{--}2.0) \times 10^{-6}$ g/cm³. An initial temperature of 1 eV is imposed in the plasma along the insulator, bridging the electrodes, to simulate preionization of the gas. The ambient gas is at room temperature. The electric power is supplied to the DPF by means of an LC circuit, with the capacitor ($C = 1.33$ μ F) charged initially up to $U_0 = 6.7$ kV. The switching is performed by an inductive switch LS, changing in inductance from $L_1 = 75$ nH to $L_2 = 1.8$ nH in 50 ns. Together with the impedance of the DPF, the circuit provides a peak current of 70–80 kA, about 140–150 ns from the start of the discharge.

8.4.2.1 Noncylindrical plasma-sheath dynamics and the current crowbar effect

The classical behavior of the DPF can be seen from the simulation results in Fig. 8.13. Initially, a current sheath is formed and begins to lift off the insulator

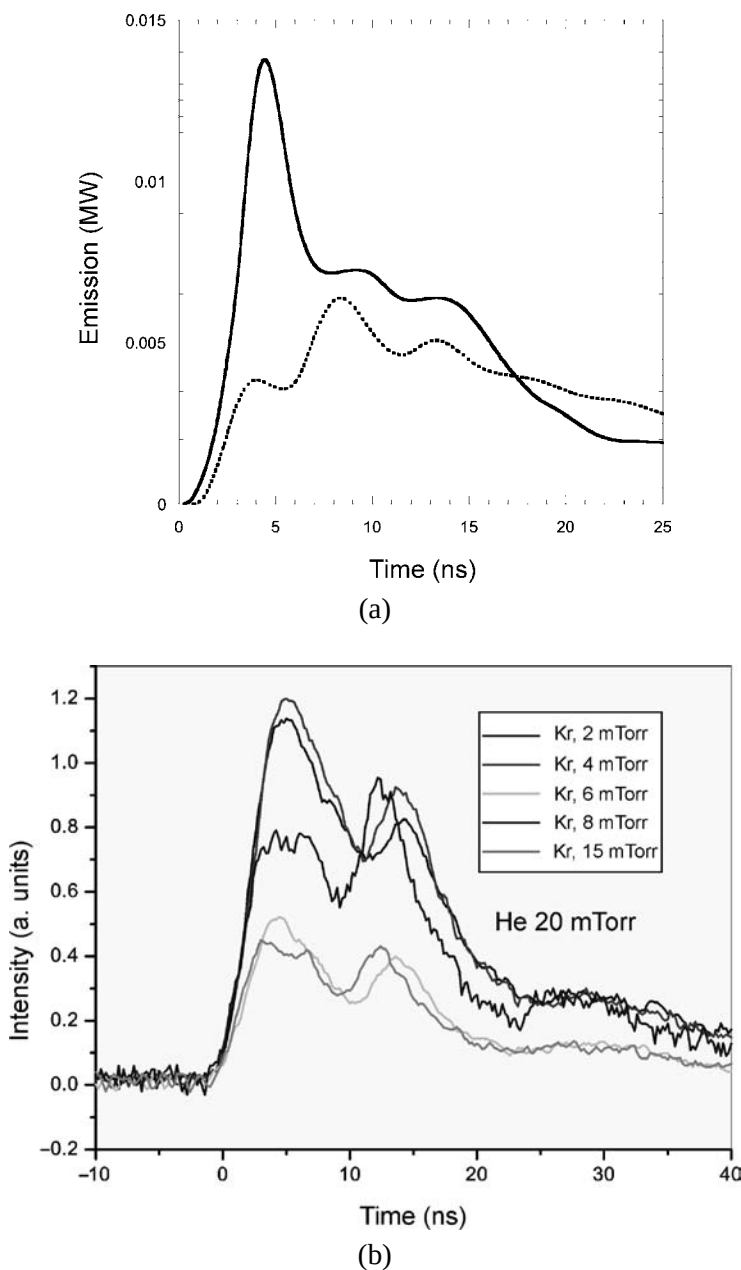


Figure 8.12 (a) Influence of the preionized channel on emission in the MPP capillary discharge with Kr:He admixture for axial (solid line) and broad (dashed line) preionization obtained in simulation. (b) Experimental measurements with different contents of Kr. The radiation is measured behind a Zr filter to confine the measurement to the 8–16-nm band.

as the current increases. It can be seen from the figure that a well-defined plasma sheath is formed, moving both radially outward and axially forward, toward the open end of the anode. This sheath motion continues, and a radially inward motion

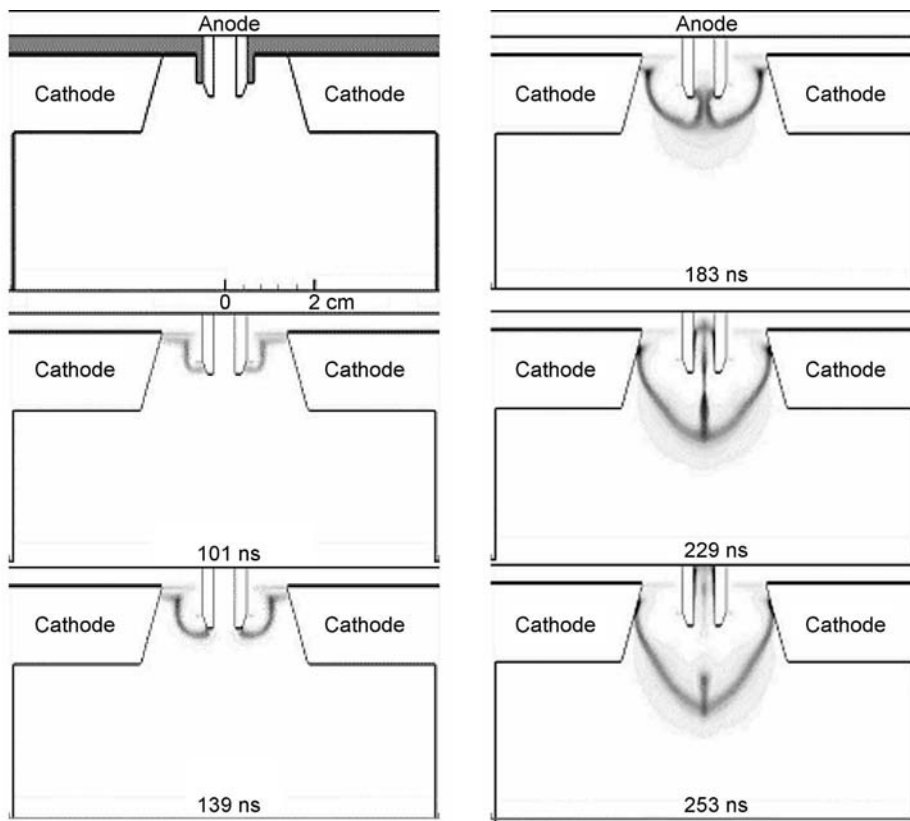


Figure 8.13 The plasma dynamics in a DPF observed from simulation, with contours of electron density n_e shown at different times.

develops when the sheath moves past the front of the anode. An axial pinch column can be seen, and later, a tight pinch on axis is formed just in front of the anode. This corresponds to the time of peak emission from the simulation. The sheath continues to move forward, as well as backward into the hollow anode structure. The tight pinch configuration has gone and the front of the plasma sheath has moved further forward.

As mentioned above, the behavior of the current sheath plays an important role in the DPF dynamics. To understand better the results of the simulations, we shall compare them with some simple models of plasma sheath dynamics. Estimations for the motion dynamics of a sheath in the ionized gas may be done by means of the snowplow model developed by M. Rosenbluth. An analysis is presented in Appendix B. Under the action of the magnetic field pressure, the maximum sheath velocity V must be such that $V_{sp} < V < U_M$, where U_M is the magnetic sound speed and V_{sp} is the snowplow velocity.

For the simulated parameters $I = 78$ kA, $R = 0.5$ cm, and $\rho = 10^{-6}$ g/cm³, the estimated snowplow velocity is $V_{sp} = 5.1 \times 10^6$ cm/s and the magnetic sound speed is $U_M = 8.7 \times 10^6$ cm/s. This is to be compared with similar results obtained

from the simulation, where the plasma velocity reaches $V = 8 \times 10^6$ cm/s at the moment of current maximum, 145 ns. The sheath is stretched due to its curvature.

During implosion, the current sheath has a thickness $\delta \sim c^2/4\pi\sigma V$, much less than the skin depth for an accelerated plasma shell.⁴⁰ As a result, some plasma remains behind the sheath and may contribute to additional current channels, especially when the local electric field increases substantially as a result of the local pinching process. In this case, a part of the current is diverted from the pinch to this plasma (crowbar effect) and no longer contributes to the heating of the pinch. This can be observed in the simulation throughout the pictures from 139 to 253 ns.

8.4.2.2 Radiation characterization

A series of simulations using Z^* were carried out on the DPF, with a view to optimizing the density of the xenon-helium mixture to obtain maximum inband (13–14 nm) EUV yield under a given stored electrical energy. To model the radiating plasma, the ionization properties, radiation transport, and plasma kinetic coefficients of a gas mixture of 10% xenon and 90% helium, in a wide range of temperatures and densities, were prepared by the THERMOS code in special tables. Results of such an optimization are presented in Fig. 8.14, where the inband and total (spectrum-integrated) radiation energies are calculated for different initial gas mixture pressures. The maximum values of these two quantities are found to occur at different densities. The total emission of the DPF has a very different behavior from the inband emission. This can be understood as follows.

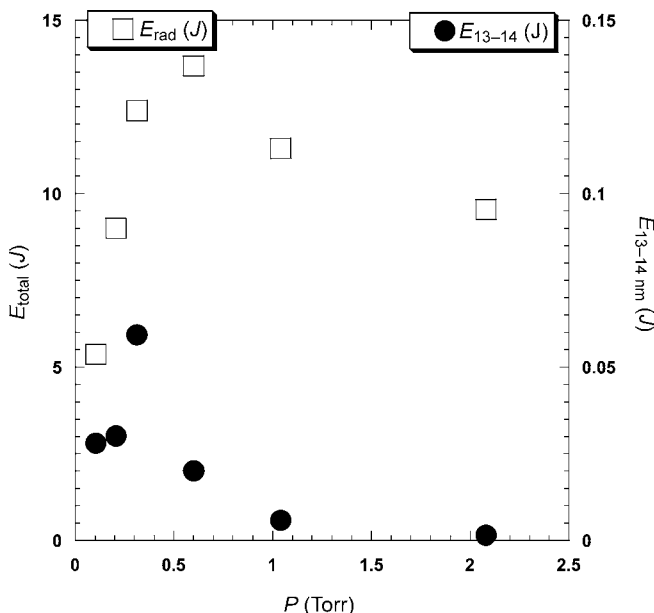


Figure 8.14 Inband EUV and total emission energy in a DPF with 10% Xe admixture to He, versus initial gas pressure.

The inband emission is produced mainly by Xe XI ions, most abundant at the temperatures of 30–80 eV, depending on the plasma density. But the total radiation, for the same pressure, is produced by a set of ions and has a higher value at lower temperatures and higher densities. For the given geometry and electrical energy, the maximum EUV emission output occurs at $P = 0.3$ Torr. At lower pressures the discharge is not stable and the EUV emission drops, while at higher pressures the temperature is not enough to produce sufficient ions of Xe XI, necessary for emission near 13.5 nm. The total emission has a maximum at a higher pressure, about 0.6 Torr.

As the optimal range of plasma parameters is not wide, a good understanding of the plasma dynamics becomes very important. Below we shall return to Fig. 8.13 and examine some more details of the dynamics of the DPF for this optimal initial pressure.

Since the inductive switch has a turn-on time of 50 ns, the initial discharge current in the DPF increases slowly, to about 6 kA at 44 ns. There is no significant movement of the preionized channel. When the inductance of the inductive switch decreases to several nanohenries, the current grows rapidly and the plasma in the channel begins to be heated by the Joule effect. The current in the DPF is presented in Fig. 8.15 together with the inband emission obtained.

Around 60 ns from the start of the discharge, the magnetic pressure from the current overcomes the thermal pressure of the heated channel, and a compression

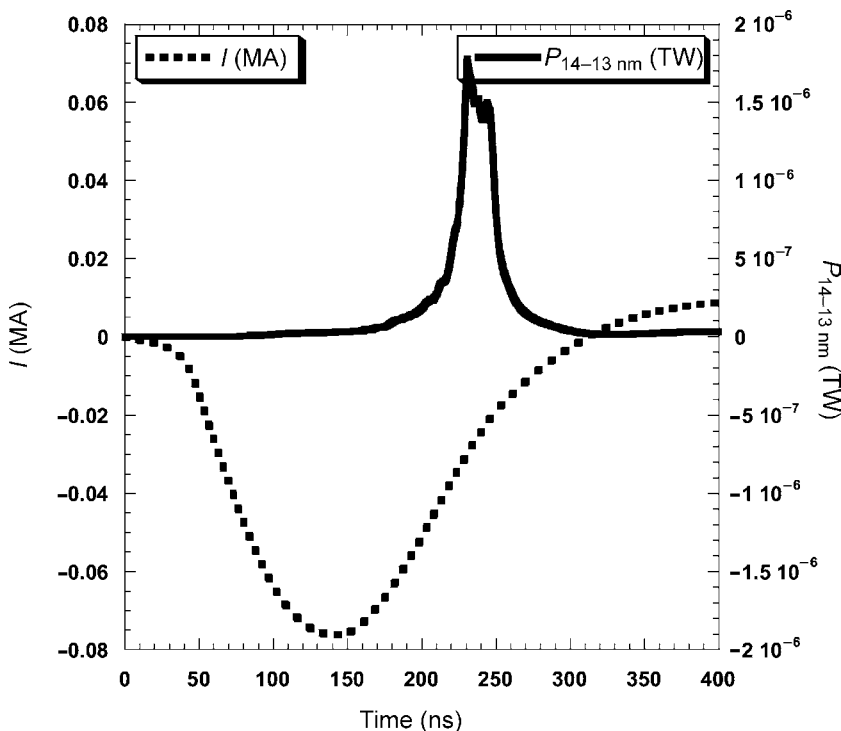


Figure 8.15 Current pulse and EUV emission power pulse in the DPF versus time.

wave starts in the plasma, forming a plasma sheath. With further current growth, the compression wave transforms to a shock wave. The plasma is then heated by viscous ion heating in the shock wave, as well as by the Joule heating. The electron temperature increases and, due to the strong dependence of plasma emission on the electron temperature, the radiation power from the plasma increases also.

The magnetic field pressure has an inverse square dependence on the radius ($B^2/8\pi \propto 1/R^2$), and thus the highest velocity of the sheath is near the anode. This gives the moving plasma sheath a characteristic curved profile. This curved moving sheath can clearly be seen from the calculated density contour plots in Fig. 8.13. At 139 ns, the sheath has come to the end of the anode. The current continues to flow mainly through the sheath.

After this time, the sheath begins to turn around the anode end, and a portion of the sheath starts to compress radially inward. As a result, the time derivative of the inductance increases rapidly due to the current-carrying plasma sheath, and a catastrophic change in the electric field behind the plasma sheath is observed. This leads to an effective second breakdown of the plasma left behind by the moving sheath and a shunting of part of the current flow. This crowbar effect causes a substantial part of the magnetic field to remain trapped. Some part of the current continues to drive the sheath forward in both radial and axial directions, but at a slower rate. Simulations show a great influence of the crowbar effect on the plasma-sheath dynamics in that it reduces the efficiency of the plasma acceleration and heating near the moment of pinching, when the condition for inband radiation is attained.

The current reaches the maximum value of 78 kA at 145 ns. At this moment the sheath is accelerated to a velocity of 8×10^6 cm/s. The ion state Xe VIII (ionization energy near 110 eV) begins to be reached and gives a small contribution to the 13–14-nm band, due to double electron excitation. However, the probability of double electron excitation is exponentially small.

The fraction of EUV emission in the adjacent (10–13 nm) band becomes significant at this time, reaching some 25% of the total radiation. This is due to the large number of ion stages in the 4f-4d transition contributing to radiation in this band. This is shown in Fig. 8.16.

At 180 ns, pinching of the plasma onto the axis begins. Both the electron temperature and the inband emission increase. During the pinching process, the plasma ions are heated up to $T_i \approx 1.8$ keV and the electrons preheated to $T_e \approx 30$ eV. Further heating of the plasma in the pinch continues by Joule heating and the $P dV$ work of the magnetic force. The total radiation and the adjacent (10–13 nm) emission both reach their maxima at 210 ns, at which point some 35% of the total radiation falls in the adjacent band. The current at this point has fallen to half the maximum value; however, due to plasma compression and consequent increase in current density, the Joule heating reaches a maximum. But the temperature is still not high enough for significant numbers of Xe XI ions to be present, and thus the inband radiation remains low.

After 220 ns the plasma has collapsed onto the axis and its stagnation begins. The plasma kinetic energy is suddenly converted to thermal energy, and the plasma

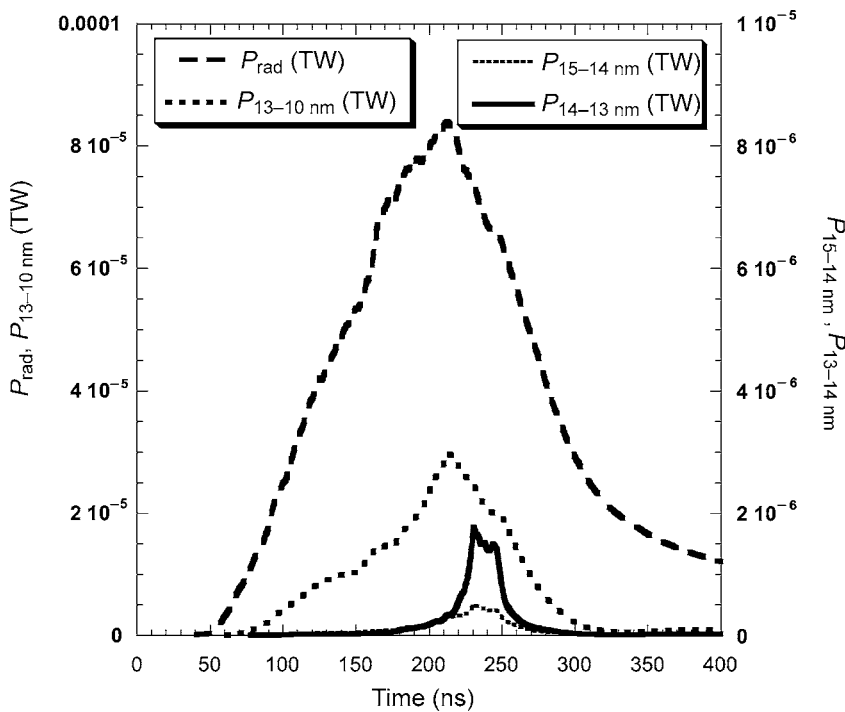


Figure 8.16 Total, inband, and adjacent-band EUV emission power in the DPF versus time.

is heated rapidly. As the temperature increases, the inband emission rises exponentially, as shown in Figs. 8.15 and 8.16, and reaches a maximum value of 1.8 MW at 229 ns. A spectrum of the EUV radiation between 11 and 17 nm at this moment, restored in postprocessing, is presented in Fig. 8.17. The inband EUV burst duration is 25 ns FWHM. The emitted energy is 60 mJ.

In Fig. 8.18, an instant image of the inband EUV source at the radiation maximum at 229 ns is shown. This is obtained from the simulation by identification of the main transition stages contributing to the inband radiation.

At the brightest point, the electron temperature $T_e = 60$ eV, the electron density $n_e = 4.9 \times 10^{16} \text{ cm}^{-3}$, and the corresponding mass density $\rho = 4.8 \times 10^{-7} \text{ g/cm}^3$. The dimensions of this radiation source are 0.66-mm diameter and 3.5-mm length (measured at the position of half the maximum value). The mean ion charge of xenon calculated from these data ($Z_{Xe} = 10.6$) is less than that calculated from kinetic equilibrium. This indicates that the xenon ions are ionized in a nonstationary condition.

The relatively low-density plasma found in the pinch is heated and ionized continuously. Due to the low plasma density, the rate of ionization is small, and the ionization stage never reaches the equilibrium value deduced from the free-electron temperature. A detailed analysis shows that, in a xenon plasma, the photoprocesses produce additional ionization due to the high opacity at the centers of the most intense lines.

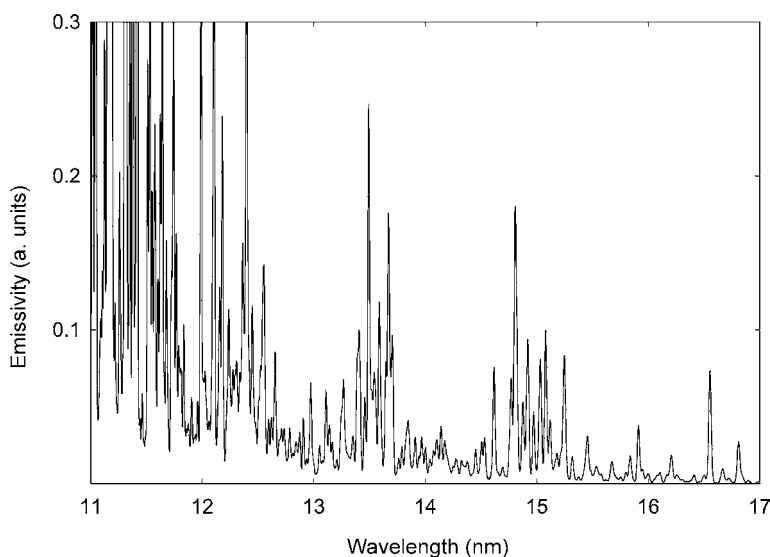


Figure 8.17 EUV spectrum emitted by Xe in the DPF at maximum inband EUV emission at 229 ns.

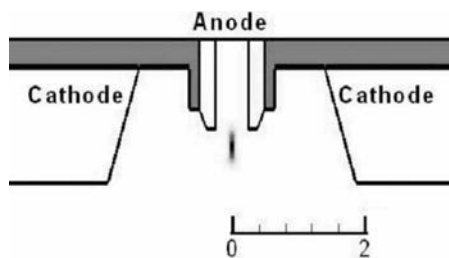


Figure 8.18 Instant image of the EUV source at the moment of the peak inband radiation at 229 ns in the DPF.

After several oscillations around the axis (compression and expansion), after 250 ns, the plasma cools down due to radiation and expansion of the plasma along the Z axis. During this time, the plasma moves along the axis with a high velocity, $\approx 4 \times 10^6$ cm/s. The Joule heating alone is not enough to support the plasma temperature because the current at that time has fallen significantly (to below 20 kA); and due to the crowbar effect, the main part of it flows through the surrounding plasma and not through the main pinch. The inband emission drops much faster than the total radiation, as seen in Fig. 8.16, because it depends exponentially on the temperature. At 253 ns, the electron temperature has decreased to 40 eV and the inband emission drops by a factor of 3.

After 300 ns the EUV emission disappears almost completely, as the electron temperature drops below 12 eV. However, the sheath continues to move along the axis with a speed of up to 2×10^7 cm/s, and the total radiation remains at about

30% of the peak level. This could pose a problem for any optical elements placed in front of the DPF to collect the radiation.

The total radiation is produced by a much larger volume of plasma at lower temperatures. The main emission is within the 10–30-eV band. It reaches the maximum of 85 MW with a pulse of ≈ 150 -ns FWHM, longer than the current pulse. The radiation is partially reabsorbed by the ambient xenon. A part of this radiation energy (12.5 J) falls on the anode, which is close to the pinch, with an energy flux density reaching 12 J/cm² per shot. This is greater than the sublimation energy on the surface of the electrode material. Even a small amount of ablated electrode material is enough to contaminate the discharge plasma, due to the low density of the latter compared with the density of a solid substance.

From this brief description of the simulation result from a typical DPF and the physical processes revealed that are relevant to EUV radiation, it is clear that there remains scope to increase the inband radiation output of the plasma, particularly through the tailoring of the driving current pulse, as well as through optimization of the discharge geometry. It also highlights the potential problem of component lifetime due to plasma radiation and heating.

8.4.3 LPP emission efficiency

Optimization of the LPP EUV source is a complex problem, despite the absence of the considerable influence of the electromagnetic fields found in the DPP. Achieving EUV emission efficiency from the LPP depends on several requirements: efficiency of laser energy absorption by the plasma, attainment of the optimum plasma temperature and density for efficient inband radiation, and minimization of radiation reabsorption by the expanding plasma. All these factors may be considered in their complexity through modeling.

To simulate the LPP EUV sources with the code Z*, the laser energy transfer process is implemented in a special version with zero electromagnetic field. Details of the model adopted for the laser interaction with materials are presented in Appendix C.

8.4.3.1 Xe and Sn slab targets and Xe gas puff

Calculations were done with a simple slab solid-target geometry, and simulations were performed for short-wavelength 248-nm KrF laser light, since xenon has a high absorption (more than tin) in this case. The laser-beam profile was set at 10-ns FWHM with a focal spot of 25- μ m diameter. The laser energy was varied between 0.01 and 1 J. A solid xenon target under cryogenic initial temperature and a metallic tin target were modeled.

The dynamics of the plasma evolution for the Xe and Sn targets are presented in Fig. 8.19³⁸ for a laser energy of 0.12 J, corresponding to an intensity of 2.3 TW/cm².

In general, the plasma dynamics is similar in the two targets. The laser light is absorbed at first in regions with high enough density; a plasma is created and

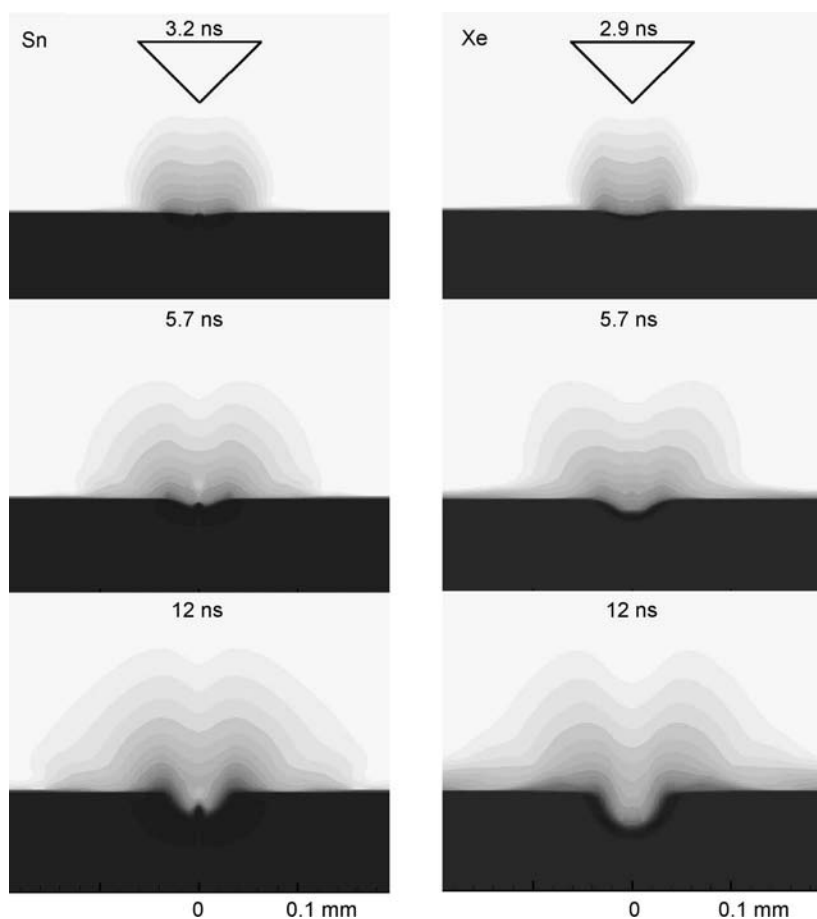


Figure 8.19 LPP dynamics for Sn (left) and Xe (right) slab target with density contours shown at different times. Black represents high density, white represents low density.

expands; the laser light penetrates deeper into regions with density $0.1\text{--}0.2\text{ g/cm}^3$ and heats up the plasma volume, creating an intense shock wave, which propagates into the solid material.

In detail, some differences in the dynamics can be seen. Tin absorbs a little less laser energy (0.05 J) than xenon (0.07 J), but due to its lower atomic weight expands faster. Due to the different EOS, a higher density is created behind the shock wave in tin. The tin plasma splashes, with the formation of a cumulative dense jet on the axis (this jet sometimes produces intense short emission spikes). Approximately half of the absorbed laser energy is reemitted.

In neither case does the plasma expand isotropically. It is more rarified along the laser beam axis due to plasma heating in this region through bound-bound laser-light absorption. Lower plasma density means exponentially lower EUV re-absorption in that direction. This is particularly important in the case of Xe, where the absorption coefficient at the inband wavelength is large.

The maximum in EUV emission is reached at 5.7 ns in both cases. At the brightest region in EUV emission, the electron temperature is $T_e \approx 50\text{--}60$ eV, and the mass density is $\rho \approx 0.1\text{--}0.2$ g/cm³, which is lower than the critical density for 248-nm wavelength. The inband (13–14 nm) radiation efficiency was presented in Ref. 38. The result has been recalculated for a 2% bandwidth, and Fig. 8.20 shows the EUV radiation efficiency for the Xe and Sn slab targets as a function of laser energy input.

In this calculation, reabsorption of EUV by the expanding plasma was taken into account in the multigroup radiation transport. The average attenuation in the hot plasma is about 0.5 at the moment of maximum emission. As we can see, the EUV efficiency for the Sn target has a maximum CE $\approx 2.6\%$ around a laser energy of 0.1 J for 248-nm laser wavelength. The optimum condition for the Xe target is at a higher laser energy, ≈ 0.6 J, with a CE $\approx 1.5\%$. From Fig. 8.19 we can see also that at the end of the laser pulse, craters of about 80 μm in diameter appear in the targets. The material from them contributes to debris.

In the same Fig. 8.20, the efficiency of a xenon gas-puff target is presented. It is significantly lower due to lower laser absorption by the relatively low-density plasma. The gas-puff plasma modeling was performed for the experiment at FOM.⁴¹ It is illustrated in Fig. 8.21, showing the shock-wave excitation by a double laser pulse to increase the plasma density.

8.4.3.2 Spherical Xe and Sn targets

Some of the experiments on LPP EUV sources were performed with IR glass lasers at 1064-nm wavelength using spherical droplet targets. Z* was used to model such

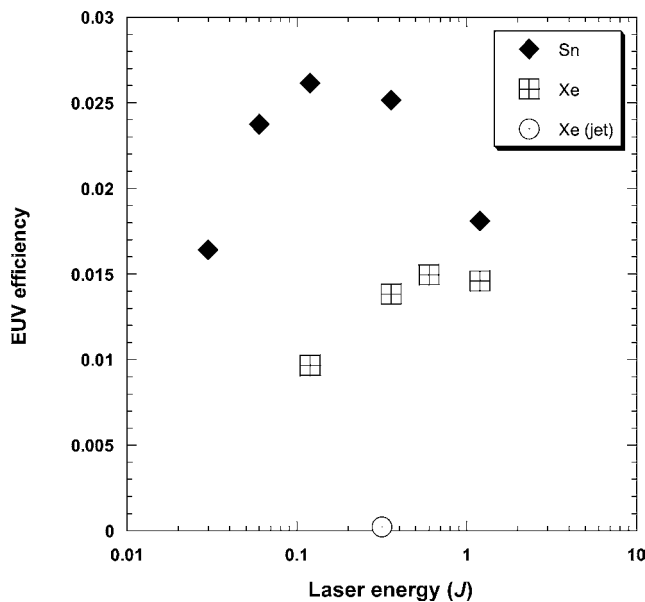


Figure 8.20 Inband EUV emission efficiencies in a 2% bandwidth for Xe and Sn slab targets versus laser energy.

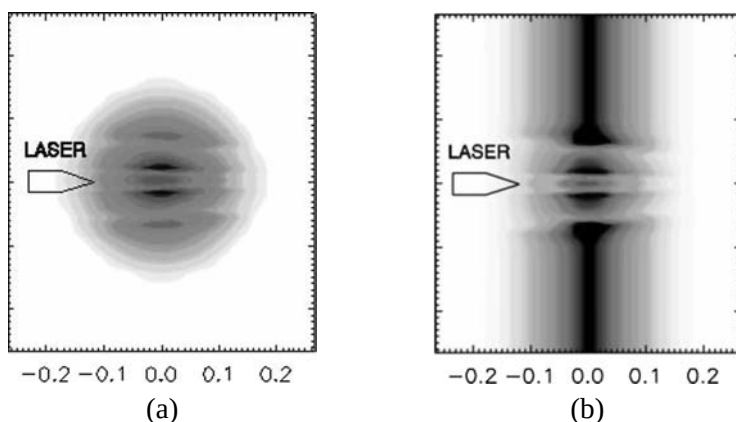


Figure 8.21 Cross section of the xenon jet at initial conditions and showing the density in shock waves produced in 20 ns after a picosecond prepulse through (a) cylindrical geometry, i.e., in the jet cross plane, and (b) slab geometry, i.e., in the jet axial plane.

LPP sources. A flat laser pulse of 15-ns duration and 30–300-mJ energy, focused to a 40- μm -diameter spot, was considered in the simulations. The target was either a solid tin or a cryogenic xenon droplet, with a 30- μm diameter. We shall compare Xe and Sn target emission efficiencies in the EUV band at an incident laser energy of 50 mJ. The dynamics of Xe and Sn LPPs are represented in Fig. 8.22. In Fig. 8.23, graphs of the laser-power absorption by Xe and Sn targets are presented together with the EUV emission pulses.

The xenon target has absorbed 34 mJ, and the Sn target absorbed 48 mJ, due to a higher bound-bound absorption. The inband EUV yield recalculated to a 2% bandwidth from the Sn target reaches 2.46 mJ, or 1.48 mJ in $2\pi\text{sr}$, recalculated to a solid angle around the laser beam. The CE is about 3%. This is higher than that obtained for the xenon droplet, at 0.32 mJ in $2\pi\text{sr}$ and $\text{CE} \approx 0.65\%$.

It should be noted that the effective total emission solid angle is less than 4π , as there is a shadow behind the dense plasma due to the target. The emitting plasma has the shape of a conical shell. Laser absorption and EUV emission are localized mainly at the critical density. The interaction of the laser light with plasma at critical density is unstable, and the emitting shell consists of hot spots. The brightest points in EUV have a high temperature of 67 eV and a mass density of 0.018 g/cm^3 . The source position of the EUV-emitting region moves in time, moving more than 5 μm up due to plasma expansion in the first half of the pulse, and then 25 μm down due to target ablation and acceleration of the remaining dense part under the ablation pressure (rocket motion).

8.5 Summary

To model adequately the multicharged ion plasma in EUV radiation sources, a sufficiently complex physical model must be developed to take into account the plasma dynamics under the influence of an electromagnetic field, as well as the

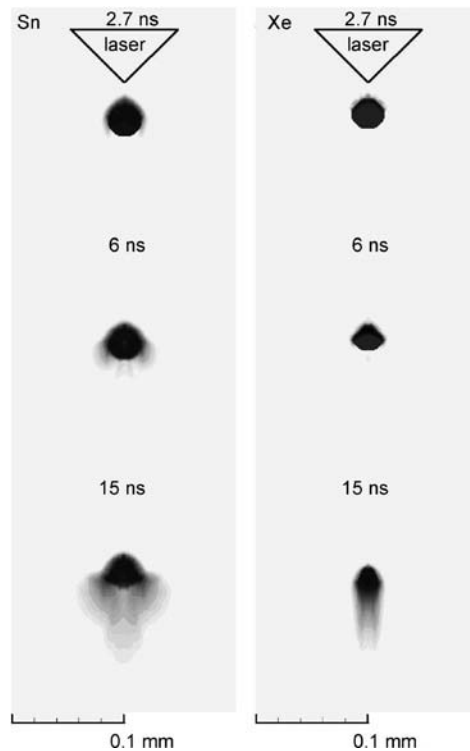
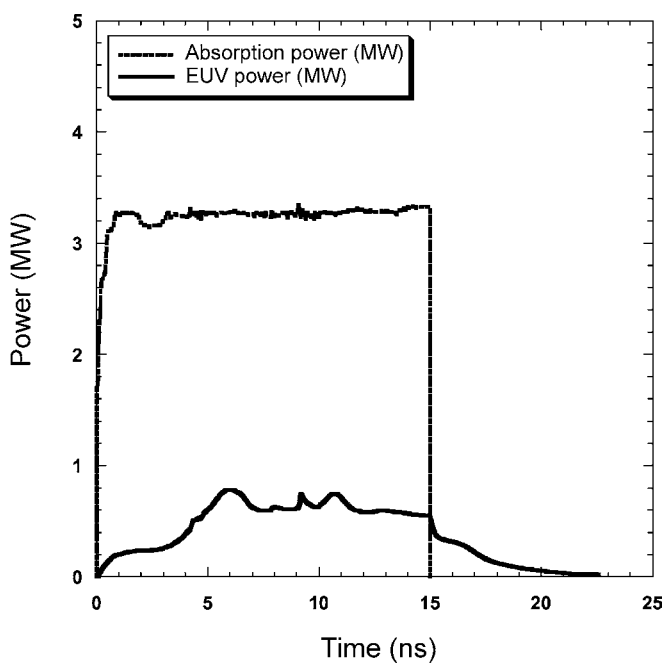


Figure 8.22 LPP dynamics of Sn and Xe droplet targets with density contours shown at different times.

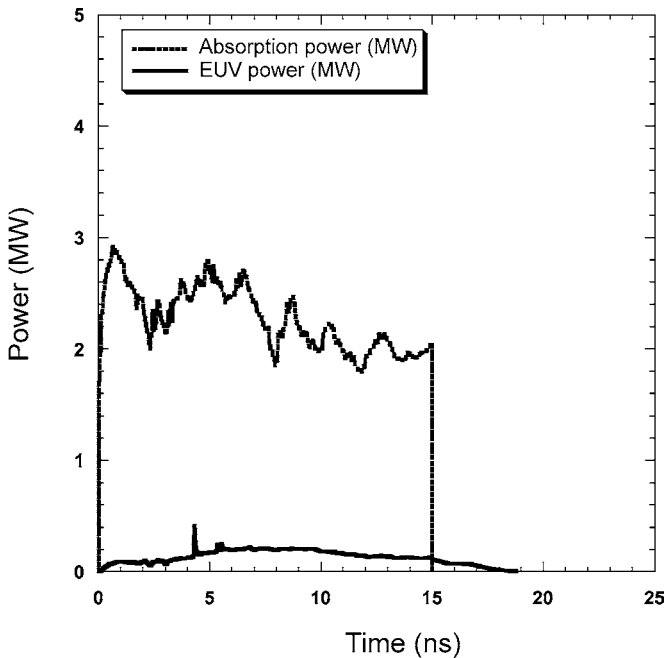
self-consistent ionization and radiation phenomena. The calculations of radiation transport and ionization kinetics should be able to treat nonequilibrium, nonstationary plasmas under conditions of partial radiation reabsorption. These requirements and the underlying physics description have been briefly discussed in this chapter. The solution implemented, in the 2D radiation MHD code Z*, satisfies a majority of these requirements. It calculates atomic and ionization properties, equation of state, kinetic and transport coefficients, rates of ionization and excitation, and detailed spectral properties of complex ion compound plasmas (such as those of Xe, Sn, or their admixtures) in the nonequilibrium regime. It models plasma dynamics in sophisticated geometries, self-consistently with the radiation transfer in an electromagnetic field.

The RMHD code Z* allows one

- to carry out complete simulations of plasma radiation sources in geometry and conditions close to the actual experimental setup,
- to evaluate the functionality and suitability of different plasma systems for the purposes of plasma radiation sources, and
- to define optimal plasma, as well as device, parameters for high radiation emission.



(a)



(b)

Figure 8.23 Laser-power absorption and EUV emission history of (a) Sn, and (b) Xe droplet targets versus time.

In the practical examples given, we have shown how Z^* can be applied to

- obtain the time evolution and dimensions of an EUV-radiation emitter,
- study preionization and 3D plasma compression in a gradient capillary discharge,
- evaluate the parameter dependence of DPF radiation,
- evaluate the efficiency of Sn and Xe EUV radiators in LPP sources, and
- generally optimize geometries and plasma conditions for better EUV radiation yield.

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Appendix A: Analytical Solution for the Axially Inhomogeneous Capillary Discharge

The dynamics of a solid-filled, current-carrying cylindrical plasma channel, being set in motion by the self azimuthal magnetic field B , under the condition of negligible thermal pressure with respect to the magnetic pressure [$p/(B^2/8\pi) \ll 1$], is described by simplified MHD equations following from Eq. (8.8), neglecting thermal pressure, displacement current, and electron drift velocity:

$$\rho \left(\frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + v_z \frac{\partial v_r}{\partial z} \right) = -\frac{1}{c} j_z B, \quad (\text{A8.1})$$

$$\rho \left(\frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + v_z \frac{\partial v_z}{\partial z} \right) = \frac{1}{c} j_r B, \quad (\text{A8.2})$$

$$\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \rho v_r) + \rho \frac{\partial v_z}{\partial z} + v_z \frac{\partial \rho}{\partial z} = 0, \quad (\text{A8.3})$$

$$\frac{\partial B}{\partial t} + \frac{\partial}{\partial r} (v_r B) + \frac{\partial}{\partial z} (v_z B) = \frac{\partial}{\partial r} \left(\frac{D}{r} \frac{\partial}{\partial r} (r B) \right) + \frac{\partial}{\partial z} D \frac{\partial B}{\partial z}, \quad (\text{A8.4})$$

$$\frac{4\pi}{c} j_r = -\frac{\partial B}{\partial z}, \quad \frac{4\pi}{c} j_z = \frac{1}{r} \frac{\partial}{\partial r} (r B), \quad (\text{A8.5})$$

where $D = c^2/4\pi\sigma_\perp$, with $\sigma_\perp$ the plasma conductivity transverse to the magnetic field.

Let us consider first only weak variations along the channel length, i.e., $\partial/\partial z \ll \partial/\partial r$. In a zeroth approximation, when the variables are independent of the Z coordinate (i.e., $\partial/\partial z = 0$), we have $j_r = 0$ and $v_z = 0$.

At sufficiently fast diffusion ($t \gg R^2/D$, where R is the plasma column radius), the density of the longitudinal current is constant inside the plasma, i.e., at $r < R$,

$$j_z = \frac{I}{\pi R^2}, \quad B = \frac{2I}{c} \frac{r}{R^2}, \quad (\text{A8.6})$$

where $I(t)$ is the current. The column radius $R(t)$ decreases in time due to plasma compression under the Ampere force. From Eqs. (A8.4) and (A8.3), it follows that

$$\nu_r = r \frac{\dot{R}}{R}, \quad \rho = \rho_0 \frac{R_0^2}{R^2}, \quad (\text{A8.7})$$

where we denote the time derivative $\partial/\partial t$ by a dot, and R_0 is the initial plasma radius. As follows from Eq. (A8.1) with Eqs. (A8.6) and (A8.7), the plasma radius is described by the equation

$$\ddot{R} = -\frac{2}{mc^2} \frac{I^2}{R}, \quad (\text{A8.8})$$

where the plasma mass per unit length is $m = \pi R_0^2 \rho_0 = \pi \rho R^2$. This type of equation is often encountered in the theory of magnetically driven liners and Z pinches. We introduce dimensionless variables $\xi = R_0/R$ and $\tau = t/t_0$, where $t_0 = \sqrt{m}(cR_0/I_0)$ and I_0 is the current amplitude. For a constant current $I(t) = I_0$ the solution is

$$\tau(\xi) = \frac{\sqrt{\pi}}{2} \text{Erf}(\sqrt{\ln \xi}), \quad (\text{A8.9})$$

where $\text{Erf}(x)$ is the error function. The formal compression time, when $R \rightarrow 0$ (i.e., $\xi \rightarrow \infty$) and $\tau(\infty) = \sqrt{\pi}/2 \approx 0.89$, is $t_c \approx t_0$.

If the plasma density or the radius of the plasma channel depends on the coordinate z , i.e., $\rho_0(z)$ or $R_0(z)$, then in the first-order approximation for nonhomogeneity the radial component of current density is not zero:

$$j_r = \frac{Ir}{\pi R^3} \frac{\partial R}{\partial z}. \quad (\text{A8.10})$$

Important to note here is that $R(z, t)$, $\dot{R}$, and $\partial R/\partial z$ are functions of time t [Eq. (A8.8)] and the coordinate z [depending only on $\rho_0(z)$, since $m = \pi R_0^2 \rho_0$]. Substituting Eqs. (A8.6) and (A8.10) in Eq. (A8.2), in the first-order approximation the axial motion is described by the following equation:

$$\dot{u} = \frac{2I^2}{mc^2} \frac{\partial R/\partial z}{R}, \quad (\text{A8.11})$$

where $v_z = u(z, t)(r^2/R^2)$. A solution satisfying the initial condition $u(t = 0) = 0$ is

$$v_z(r, z, t) = \frac{2r^2}{R^2} \int_0^t \frac{I^2}{mc^2} \frac{\partial R/\partial z}{R} dt'. \quad (\text{A8.12})$$

In particular, for the case when a current $I(t) = I_0$ and the initial plasma column radius R_0 are constant, the integral in Eq. (A8.12) may be evaluated with the help of the relation (A8.8) and the solution (A8.9). For the axial velocity we obtain a solution

$$v_z(r, z, t) = \frac{r^2}{2t_0 \sqrt{\ln(R_0/R)}} \frac{R_0}{R} \left[\ln\left(\frac{R_0}{R}\right) \left(1 + \frac{t}{t_0}\right) - \frac{t}{2t_0} \right] \frac{\partial \ln \rho_0}{\partial z}. \quad (\text{A8.13})$$

This solution demonstrates that Eqs. (A8.8), (A8.11), and (A8.12) describe the plasma flow along the axis and the plasma column compression. The plasma flows along the Z axis from lower density to higher density and is compressed radially. So the plasma is compressed three-dimensionally, unlike the 2D compression in the homogeneous cylindrical case.

Appendix B: Estimations for the Motion Dynamics of a Sheath in the Ionized Gas via the Snowplow Model

In the snowplow model (Fig. B8.1), the sheath in motion with velocity V , driven by the magnetic field pressure, rakes up the ambient ionized gas with density ρ , i.e., the mass per unit area, m , of the sheath increases; the acceleration of the sheath under magnetic field pressure is described by the momentum equation:

$$\frac{dm}{dt} = V\rho, \quad \frac{d}{dt}(mV) = \frac{B^2}{8\pi}. \quad (\text{B8.1})$$

For a given current $I(t)$ the magnetic field at radius R is $B = 0.2I/R$, where the magnetic field is measured in gauss, the current in amperes, and the radius in cen-

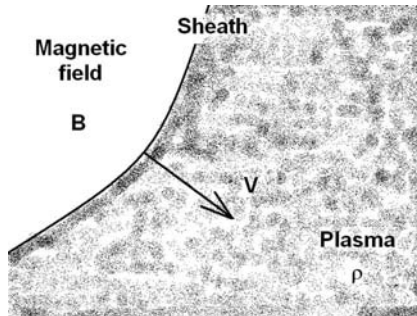


Figure B8.1 Snowplow model.

timeters. For the case when motion of a sheath is along the Z axis, these equations may be solved analytically for a set of dependences of the current on time. In particular, for a linearly rising current within the time interval $0 < t < t_m$, i.e., $I(t) = I_m(t/t_m)$, it follows that

$$V = V_{sp} = \frac{B}{\sqrt{12\pi\rho}} = V_m \frac{t}{t_m}, \quad m = \rho \int V_{sp} dt = \rho V_m \frac{t^2}{2t_m},$$

$$V_m = \frac{0.2I_m}{R\sqrt{12\pi\rho}}, \quad (\text{B8.2})$$

where the velocity is measured in centimeters per second, and the density in grams per cubic centimeter. The solution (B8.2) shows that with linearly rising current, the sheath is uniformly accelerated and reaches maximal velocity $V_{sp} = V_m$ at time $t = t_m$.

Stretching of the sheath in the tangential direction due to the dependence of the magnetic pressure on radius ($B^2/8\pi \propto 1/R^2$) may modify the ideal snowplow motion. Equations describing snowplow motion with a curved sheath may be found in Ref. 15. But they are too complicated to obtain analytical solutions even in such a simple model. To estimate the influence of sheath stretching, let us suppose, contrary to the snowplow model, that the density of the ambient plasma does not attach to the sheath, but instantly flows down along the sheath, because a sheath in a radiating plasma has a finite thickness. In this case the upper limit for the sheath velocity is the magnetic sound speed in the plasma. In the limit of intensely radiating plasma, the magnetic pressure is much greater than the thermal one ($B^2/8\pi \gg P$), and the magnetic sound speed is

$$U_M \approx \frac{B}{\sqrt{4\pi\rho}}. \quad (\text{B8.3})$$

Comparing Eqs. (B8.2) and (B8.3), we see that the ratio of the maximum possible velocity U_M to the snowplow velocity V_{sp} is $\sqrt{3}$.

The current-sheath thickness is described by the magnetic field diffusion equation and the continuity equation of the magnetically accelerated plasma.^{20,40} In the case when the motionless plasma in front of the sheath is negligible, the solutions⁴⁰ show that the magnetic field in the sheath has a characteristic thickness equal to the skin depth $\Delta \sim (c^2 t / 2\pi\sigma)^{1/2}$, and the main sheath density distribution is over a layer half as thick. Another picture takes place if the gas density in front of the sheath is high enough and preionized. The magnetic field diffusion equation written for the azimuthal component B is

$$\frac{\partial B}{\partial t} = -\frac{\partial}{\partial r} v_r B + \frac{\partial}{\partial r} \frac{c^2}{4\pi\sigma} \frac{\partial r B}{r \partial r}. \quad (\text{B8.4})$$

In the case of quasi-stationary sheath motion, comparing terms on the left-hand side of Eq. (B8.4), we can estimate the characteristic current sheath thickness as $\delta \sim c^2/(4\pi\sigma V)$.

Appendix C: Calculation of the Laser Energy Transport Process

The laser-light transport is calculated by means of a simplified two-direction transfer model taking into account the absorption and reflection of the laser light along an arbitrary given trajectory $\mathbf{s}(r, z)$, i.e.,

$$\frac{\partial \psi_+}{\partial \mathbf{s}} = -(\kappa_l + r_l)\psi_+, \quad -\frac{\partial \psi_-}{\partial \mathbf{s}} = -\kappa_l\psi_- + r_l\psi_+, \quad (\text{C8.1})$$

where ψ_+ , ψ_- are the flux densities of direct and reflected laser light, respectively. The reflection coefficient r_l from the critical-density zone ($\omega_{pe}^2 > \omega_l^2$) is $r_l = (\omega_{pe}^2 - \omega_l^2)^{1/2}/c$. The laser-light absorption coefficient, $\kappa_l = \kappa_{st} + \kappa_r + \kappa_{bi} + \gamma\kappa'_{bb}$, includes the interaction of radiation with the electrons, ions, and neutral atoms: κ_{st} for collisional (inverse bremsstrahlung) absorption with plasma dispersion properties (critical-density effect),⁴² κ_r for resonant absorption (due to Langmuir plasma-oscillation resonant excitation),⁴² κ'_{bb} for the effective bond-bond excitation calculated from spectral tables at laser quantum energy $\hbar\omega_l$ taking into account the induced deexcitation, and κ_{bi} for one-quantum or multiquantum (if the laser quantum energy is lower than the ground-state ionization energy) ionization, calculated from spectral tables also; the parameter γ is introduced to take into account the probability of dissipation of absorbed laser energy in bound-bound electron excitation to thermal energy. The conversion of laser energy absorbed due to level excitation to plasma is realized through nonradiating deexcitation described by the probability w_{3b} . The stepwise ionization described by probability w_n is also possible if several quanta are absorbed successively, i.e., the first quantum excites the ground state, the second one excites the resulting state, etc., and just the last one ionizes the atom. The parameter γ is determined by these probabilities and the spontaneous-emission probability w_{se} , viz., $\gamma \approx (w_{3b} + w_n)/(w_{3b} + w_n + w_{se})$, calculated from spectral tables. Under these approximations, the heating of electrons by the laser light flux $\mathbf{L}_e$ in the energy Eq. (8.8) is

$$G = \nabla \cdot \mathbf{L}_e = \kappa_l(\psi_+ + \psi_-). \quad (\text{C8.2})$$

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Chapter 9

HEIGHTS-EUV Package for DPP Source Modeling

A. Hassanein, V. Morozov, V. Sizyuk, V. Tolkach, and B. Rice

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9.1 Introduction

This chapter presents an integrated model that is being developed to describe the hydrodynamic and optical processes that occur in DPP devices for EUVL applications. The developed model will eventually address the following subjects: plasma evolution and magnetohydrodynamic (MHD) processes, atomic data and plasma properties, detailed photon radiation transport, and interaction between plasma/radiation and material. Regions with differing propagation speeds of perturbation require accurate numerical solutions of the MHD equations. The total variation diminishing (TVD) scheme in the Lax-Friedrich formulation for the description of magnetic compression and diffusion in a cylindrical multidimensional geometry is the most suitable and is used in our model. Depending on the complexity of the problem and the availability of computer time, a combination of various atomic and plasma models is being developed for populations of atomic levels, ion concentrations, plasma properties, and opacities. These include a collisional radiation equilibrium plasma model, a Hartree-Fock (HF) self-consistent-field atomic model, and a Hartree-Fock-Slater (HFS) method with splitting of atomic levels. Because of its influence on the whole dynamics of the discharge, radiation transport

for both continuum and lines with detailed spectral profiles is modeled by various discrete-ordinate and Monte Carlo methods. The developed models have been integrated into the HEIGHTS-EUV computer simulation package. The features of the package allow one to study the hydrodynamics and radiation of two-gas mixtures in dense plasma focus (DPF) devices in the presence of impurities and erosion products that can affect radiation output.

The goal of this chapter is to provide an overview of methods and techniques we use to simulate MHD and optical processes that occur in DPP devices of various electrode constructions. The general types of DPP devices that can be simulated within the HEIGHTS-EUV package are schematically shown in Fig. 9.1: (a) the DPF device, (b) the Z-pinch device, and (c) the hollow-cathode triggered pinch plasma source.^{1–3} The electrodes are drawn solid and shown in gray. The device is filled with xenon gas under an initial pressure in the range of several tens of millitorr at room temperature, corresponding to an initial density of the gas in the range of 10^{14} – 10^{15} cm⁻³. It is also assumed that a preionization step heats the gas to a temperature of near 1 eV and initiates the discharge.

Typical representatives of the DPP devices are the conduction-type devices. The plasma is an element of the electric circuit, which gets its discharge current from the feeding capacitor C_0 . The simulation of the discharge by using the external (experimentally recorded) current may lead to the violation of the self-consistency principle, because the energy balance is not conserved and the plasma dynamics can be distorted. The physical processes that take place in these DPP devices are identical and can be described within the same mathematical model. The distinguishing features of each particular design can also be affected by the initial and boundary conditions, such as the design and geometry of solid walls, the initial plasma parameters, the parameters of the electric circuit, and the methods of

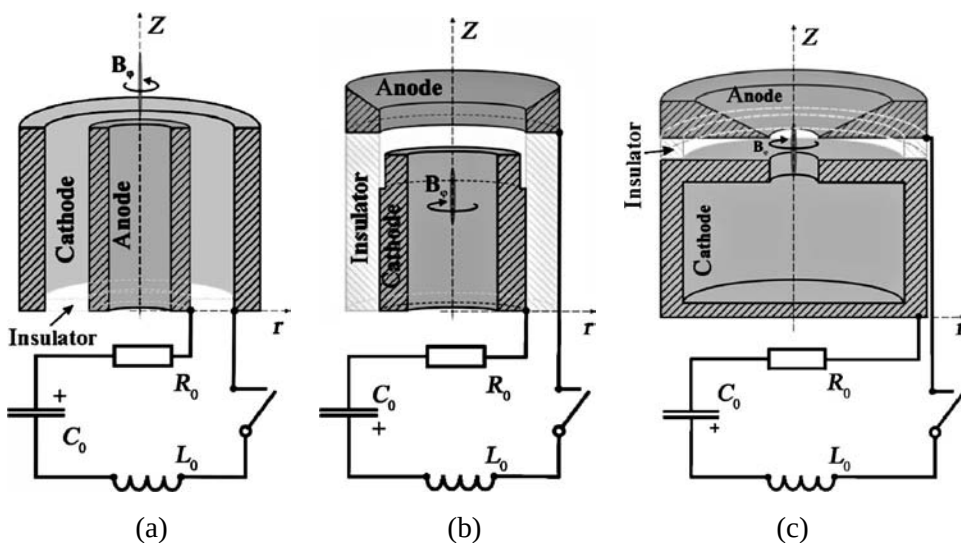


Figure 9.1 Schematics of DPP devices.

turning the device on and off. The MHD processes, radiation transport, and thermal conduction are implemented as a part of the HEIGHTS-EUV package, while design-specific features are implemented as additional blocks.

9.2 Magnetohydrodynamics

The behavior of a conductive flow in the magnetic field due to the current displacement triggered by the discharge is described by the general set of 3D resistive conservative MHD equations. In modeling such functioning DPP devices as Z-pinch, plasma focus, and Θ -pinch devices, the organization of the correct energy exchange is a key to successful simulation. The energy exchange is determined by the set of different energy transport processes, including magnetic diffusion, thermal conduction, and radiation energy loss.

The plasma is represented by the conservative variables of mass density ρ , momentum density $\rho\mathbf{v}$, total energy density e , and magnetic field $\mathbf{B}$:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (9.1)$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left(\rho \mathbf{v} \mathbf{v} + p_{\text{tot}} - \frac{1}{4\pi} \mathbf{B} \mathbf{B} \right) = 0, \quad (9.2)$$

$$\begin{aligned} \frac{\partial e_{\text{tot}}}{\partial t} + \nabla \cdot \left[\mathbf{v}(e_{\text{tot}} + p_{\text{tot}}) - \frac{1}{4\pi} (\mathbf{v} \cdot \mathbf{B}) \mathbf{B} + \frac{c^2 \eta}{16\pi^2} (\nabla \times \mathbf{B}) \times \mathbf{B} \right] \\ = Q_{\text{th}} + Q_{\text{rad}}, \end{aligned} \quad (9.3)$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{v} \mathbf{B} - \mathbf{B} \mathbf{v}) + \frac{c^2}{4\pi} \nabla \times (\eta \nabla \times \mathbf{B}) = 0. \quad (9.4)$$

Equations (9.1)–(9.4) represent the conservation of mass, momentum, energy, and magnetic flux, respectively. If not mentioned otherwise, all values are given in Gaussian units. In the rest of the chapter, the magnetic permeability μ is assumed to be 1. The total energy density is determined as a sum of internal, kinetic, and magnetic energy densities, whereas the pressure term is separated into hydrodynamic and magnetic parts:

$$\begin{aligned} e_{\text{tot}} &= e_{\text{h}} + \frac{\mathbf{B}^2}{8\pi} = e_{\text{int}} + \frac{\rho \mathbf{v}^2}{2} + \frac{\mathbf{B}^2}{8\pi}, \\ p_{\text{tot}} &= p_{\text{h}} + \frac{\mathbf{B}^2}{8\pi}. \end{aligned} \quad (9.5)$$

To complete this full system of MHD equations, functional forms for the thermodynamic pressure $p_{\text{h}} = p_{\text{h}}(e_{\text{int}}, \rho)$ and resistivity $\eta = \eta(e_{\text{int}}, \rho)$ are calculated from the equation of state, discussed below. Details of implementing and solving the set of the MHD equations by the TVD method in the Lax-Friedrich formulation for cylindrical geometries can be found elsewhere.^{4–6} The thermal conduction

must be calculated for the gas-plasma environment, the properties of which can significantly vary from point to point. Direct integration of the heat-flux divergence $\nabla \lambda \cdot \nabla T$ within the hydrodynamic scheme can often lead to nonconvergence and disruption of the solution. An alternative approach is to present the divergence term as a heat source Q_{th} and organize, in cylindrical coordinates, a separate thermal conduction scheme:

$$\frac{\partial e_{\text{tot}}}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} r \lambda \frac{\partial T}{\partial r} - \frac{\partial}{\partial z} \lambda \frac{\partial T}{\partial z} = 0, \quad (9.6)$$

$$Q_{\text{th}} = \frac{\partial e_{\text{tot}}}{\partial t} = \nabla \lambda \cdot \nabla T, \quad (9.7)$$

where Q_{th} is the energy correction to the energy Eq. (9.3), and $\lambda = \lambda(e_{\text{int}}, \rho)$ is the thermal conductivity.

In the evolution of the plasma pinch, the temperatures of the plasma can vary within the broad range from fractions of an electron volt to hundreds of electron volts. At such different temperatures, several mechanisms can contribute to the thermal conductivity. At low temperatures with low charge state, the classical elastic scattering by neutral atoms gives the main contribution to the total thermal conductivity. Correction is needed to allow for the dependence of the atom diameter on the energy of impact. At higher ionization states, an ambipolar diffusion—the diffusion of the neutral atoms in the plasma—contributes to the total value. When a neutral atom appears in the hot area, it is ionized, losing energy equal to the ionization energy. At still higher ionization states, the electronic thermal conduction is a main contributor, which is given by the classic Spitzer formula with the correction for nonideality of the plasma. Similarly, we can also calculate the ionic thermal conduction, but it is substantially weaker than the electronic conduction. The process of energy transfer by the photons emitted from the hotter areas and absorbed by the colder ones is included directly in the form of radiation transport, as described below.

In view of the cylindrical symmetry of a DPP device, we wrote the general set of MHD Eqs. (9.1)–(9.4) in cylindrical coordinates (r, φ, z) ; we neglected the plasma motion in the φ direction and assumed that the magnetic field had only one component B_φ . These simplifications allowed us to reformulate the problem in coordinate form, which provided efficient numerical implementation and various easily implemented enhancements.

The design features and the conditions of a particular EUV source are described in the form of boundary conditions.^{5,7} In simplified form, one may subdivide these conditions into three major parts:

- *Hydrodynamic* conditions are set on the boundaries of the hydrodynamic domain and include the condition of free pass, the conditions on the inflow and outflow, and the condition of the symmetry of the device.

- *Magnetic* conditions are set on the magnetic field and include the condition of the driven current in the electric circuit in the area of the feeding voltage, the condition at the conductive walls, and the condition at the axis of symmetry to provide the cylindrical symmetry of the magnetic field.
- *Thermal conduction* conditions are set at the boundaries of the domain and include the given temperature of the wall, the condition of the insulating wall, and the conditions of incoming and outgoing heat flux.

9.3 External Electric Circuit

The most important factors in initiating and governing the plasma discharge in a DPP device are the design and parameters of the external electric circuit. As shown in Fig. 9.2, the electric circuit is normally represented by a set of three elements: the direct conductance C_0 , the resistance R_0 of the wires, and the parasitic inductance L_0 . The circuit is incorporated into the MHD, where the DPP device is given by its resistance R_{DPP} and inductance L_{DPP} . Since the plasma parameters depend upon the whole dynamics of the discharge, they provide feedback from the MHD to the electric circuit, changing the behavior of the current as a function of time.

The voltage drop in the DPP device is caused by the induced and the ohmic voltages. The inductance of the DPP device can be expressed by the Faraday law, which describes an induced voltage caused by the change of the magnetic flux. The resistance losses of the device are calculated from the Joule heating. Finally, the distribution of the continuous current in the electric circuit is regulated by the Kirchhoff law, which can be written for the voltage on a capacitor as a function of time. Being incorporated into the general set, the electric-circuit equation is solved self-consistently with the MHD in the form

$$U(t) = \frac{\partial}{\partial t} L_0 I(t) + R_0 I(t) + \frac{\partial}{\partial t} L_{\text{DPP}} I(t) + R_{\text{DPP}} I(t),$$

$$\frac{\partial U(t)}{\partial t} = -\frac{I(t)}{C_0}.$$
(9.8)

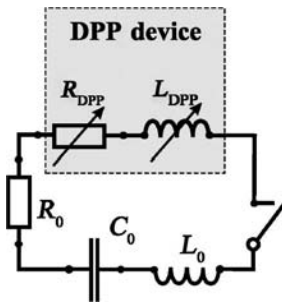


Figure 9.2 Schematic of electric circuit for a typical DPP device.

Figure 9.3 shows results of HEIGHTS simulation of the current for various DPP devices. In general, the dynamics of the process is described similarly for most devices, despite the differences in design and initial conditions of simulated devices and experimental facilities.

9.4 Detailed Radiation Transport

If the density of the excited particles in the plasma is high enough, one of the substantial mechanisms of heat exchange is radiation transport. The transfer of radiant energy takes place only when the mean free path of a photon corresponding

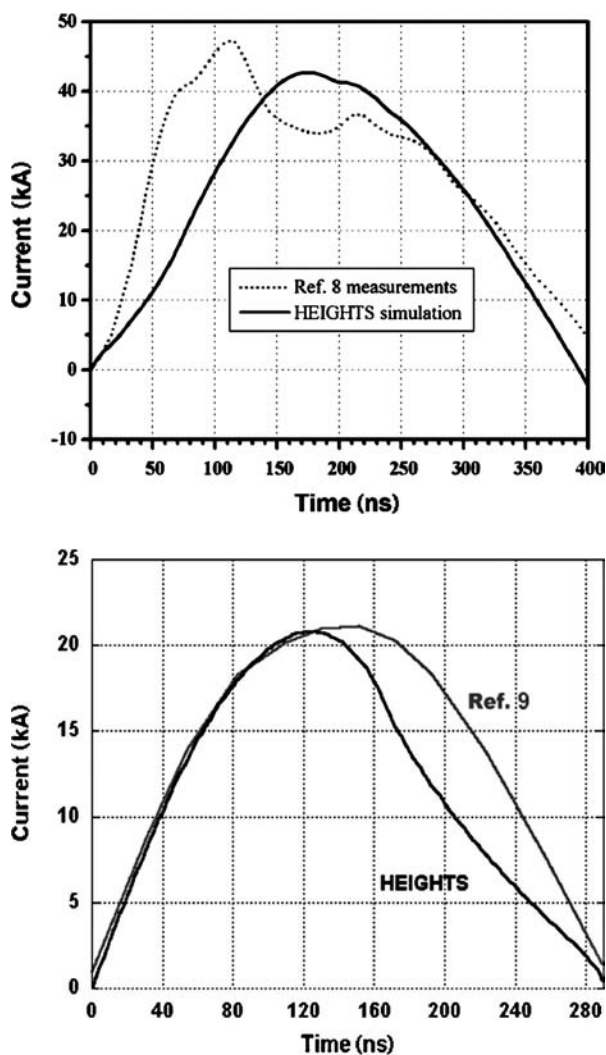


Figure 9.3 Experimental (from Ref. 8) and calculated (from Ref. 9, HEIGHTS) current profiles.

to the center of the emitting line is much less than the size of the hydrodynamic domain. In such a condition the radiation transfer is carried out by those photons, the frequency of which corresponds to the wings of the emitting lines and results in the absorption in colder areas of those photons emitted from the hotter plasma parts.

In studying the transfer of the radiant energy, one needs to distinguish two aspects of the modeling of a DPP device. First, solving the hydrodynamic part of the problem requires correction (redistribution) of the plasma internal energy and, accordingly, correction of the evolution of the whole pinch dynamics. The key is the accurate and detailed calculation of the radiant energy redistribution in the whole plasma domain over the very broad spectral range of participating photons. The second aspect is the detailed calculation of the effective radiation of the EUV source within the operating energy range of $13.5 \text{ nm} \pm 2\%$. In this case, the calculation of the radiation transport must be restricted to take account of only those photons whose energies are in the mentioned range.

In numerical simulation of the radiation transport processes, the radiant energy flux is calculated by integrating the radiation transport equation (RTE),^{10,11} which represents the conservation of emitted and absorbed energy along the direction of the transfer. Deterministic transport methods divide the computational domain in space, energy, and angles.¹² The radiation intensity along each direction is determined by integrating the RTE, and the directions are given by the angles of the chosen numerical quadrature. In contrast to the direct resolution of the integro-differential RTE, where one calculates a continuous function of the radiation intensity, the probabilistic model of the energy redistribution operates in discrete ranges of the radiative energies.¹¹ Given the importance of the correctness and the accuracy of the radiation transport, we are using both methods to ensure and benchmark the validity of our simulation.

At each point of the MHD zone, the local temperature T , the Planck function I_P , and the optical coefficients κ_{emi} and κ_{abs} of emission and absorption of the photon with energy E determine the specific intensity of radiation. To solve for the radiation transport in axisymmetric cylindrical coordinates (r, z) by the discrete-ordinate method (DRT), the RTE for intensity I_E can be written along the direction s as

$$\frac{dI_E}{ds} = \sin \theta \left(\mu \frac{\partial I_E}{\partial r} + \frac{1 - \mu^2}{r} \frac{\partial I_E}{\partial \mu} \right) + \cos \theta \frac{\partial I_E}{\partial z} = \kappa_{\text{emi}} I_P - \kappa_{\text{abs}} I_E. \quad (9.9)$$

Here, θ is the angle between the direction of the ray (s) and the z axis, φ is the angle between the projection of the direction s on the plane perpendicular to z and the normal to the cylindrical surface, and $\mu = \cos \varphi$. The intensity in the direction s is calculated by integration over all the photon frequencies. The net flux S_{rad} is obtained by integrating over all the angles:

$$S_{\text{rad}} = \int \left[\int_0^{2\pi} \delta \varphi \int_0^\pi I_E(\theta, \varphi) \cos \theta \sin \theta d\theta \right] dE. \quad (9.10)$$

Finally, the radiation energy loss in each cell is found from $Q_{\text{rad}} = \nabla \cdot S_{\text{rad}}$. Essentially, this method is the result of finite-differencing of the directional dependence of the RTE. Integrals over solid angles are approximated by numerical quadrature, the choice of which defines the directions of the DRT. The solution is carried out simultaneously with the energy-balance solution to provide the distribution of the local energy source, temperature, and density profiles. The method is time-consuming and resource-intensive. This makes it difficult to conduct a parametric study of a DPP device in practice.

Alternatively, the Monte Carlo-based radiation transport (MCRT) method handles and analyzes the discrete portions of the radiant energy separately. Studying the trajectory and the behavior, as well as the number, of emitted and absorbed photons in the test energy groups at each point of the plasma domain (or at the points that present the major interest), one may evaluate the redistribution of the energy due to photon transport. The energy and the trajectory of photon movement are determined by the Monte Carlo technique. It is supposed that each portion is a monochromatic set of photons. The total energy of a portion is a sum of the energies of the component photons, and the portion is called a *macrophoton* or *photon bundle*. The number of test photon bundles is determined by the hydrodynamic parameters of a cell and analyzed by the MCRT method. The energies of the bundles are distributed according to the emission coefficient of the cell. Later on, the history, the behavior, and the paths of the photons are statistically accumulated in the form and energy redistribution within the domain.

To calculate the number N of photons emitted within the spectral range $[E_{\text{min}}, E_{\text{max}}]$ by a domain of volume V per unit time, the emission coefficient $\kappa_{\text{emi}}(T, \rho, \varepsilon)$ needs to be integrated with the Planck function over total spectrum of energies ε :¹³

$$N = V \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{\kappa_{\text{emi}}(T, \rho, \varepsilon) \varepsilon^2}{h^3 \pi^2 c^2} \left(e^{\varepsilon/T} - 1 \right)^{-1} d\varepsilon. \quad (9.11)$$

Here, as elsewhere below, we use traditional notation for the Planck constant $\hbar$ and speed of light c . The energy of the photon is calculated accordingly to the probability density, which in turn is expressed through the emission of the cell. After moving through the domain, the photon can be absorbed as described by the absorption probability density, which grows exponentially with the photon mean free path. Finally, the correction Q_{rad} in the energy Eq. (9.3) due to radiation transport is found, knowing the number and the energy of emitted and absorbed photons in each cell of the hydrodynamic domain:

$$Q_{\text{rad}} = \sum_i^{N_{\text{abs}}} \varepsilon_i - \sum_j^{N_{\text{emi}}} \varepsilon_j. \quad (9.12)$$

To improve the efficiency of the method, we utilize weight factors of the statistically collected events. Based on the emission of the cells, the first factor is used

to rebalance the number of emitted photons from the less-emitting cells in favor of the most-emitting cells. The accuracy of the computation is regulated by the maximal number $N_{\max}$ of photons emitted from a cell. Another weight factor is used to avoid tracking those photons that are emitted and immediately absorbed within the same cell.

The comparative results on the accuracy of DRT and MCRT methods are shown in Fig. 9.4 for typical temperature and density distributions, obtained from the simulation of a Cymer-like device. Both the quantitative and the qualitative behavior of the radiation flux are the same, despite the Monte Carlo method being significantly

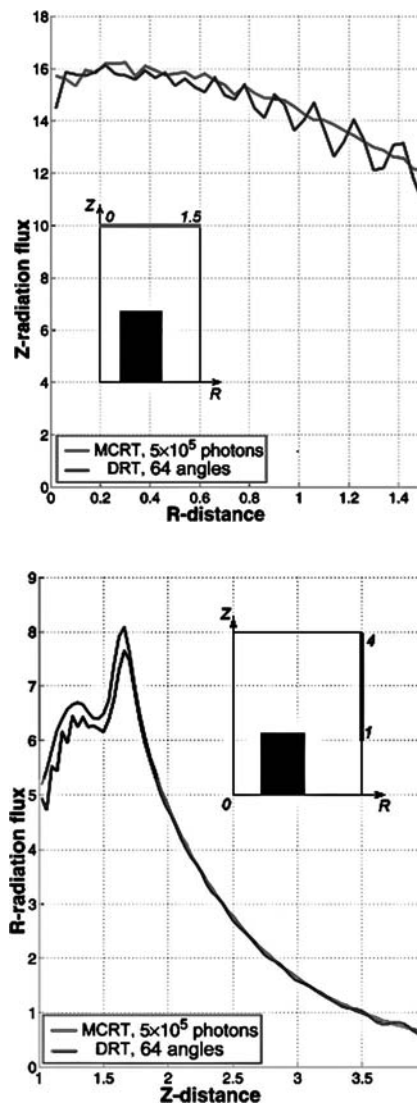


Figure 9.4 Accuracy of HEIGHTS calculations for radiation transport (arb. units).

faster by approximately a factor of 300. This also confirms the high accuracy and reliability of the implementation of the methods.

9.5 Atomic Physics and Opacities

Several studies^{14,15} report that radiative emission and transport play a key role in the dynamics and energy balance of laboratory plasmas. In recent years, other studies^{16,17} have shown that the high-temperature, moderate-density plasma is not in local thermodynamic equilibrium (LTE), and the radiative properties of plasmas that are optically thick to line radiation are not well described by either coronal or Saha–Boltzmann models.

Normally, in the case of intermediate temperatures and densities, when collisional processes are still significant but, at the same time, radiative effects become apparent and are not negligible, it is necessary to solve the system of kinetic equations self-consistently with the radiation field. The model in its self-consistent formulation takes account of nonlocal processes of photoexcitation and photoionization, and that significantly complicates the computations. The problem becomes particularly difficult for high- Z plasmas because of their very large number of ionization and excitation levels.

The simulation of the dynamics of the pinch evolution is a typical problem with a wide range of working temperature and density values and so with a very complicated ionic structure. Detailed resolution of each possible level for each possible ion, and consequently each electronic transition in the ion, over the wide ranges of temperatures, densities, and energies is enormously laborious, especially when taking account of the complicated fine structure of each split level. Thus, consistent solving of the MHD and radiation transport equations requires the plasma properties and equation of state be obtained on the basis of simplified methods of calculation for the structures of the atomic levels and transition probabilities. One such method is the HFS approximation,¹⁸ which determines the energies and other atomic characteristics for each nl configuration of each ion that might appear in the plasma.

In the condition of central symmetry, a wave function of an N -electron atom can be represented in the form of the product of radial and angular constituents. The radial wave function of an atom can be represented as the product of radial wave functions of the electrons. It is assumed that equivalent electrons have the same radial wave function. Numerical resolution of the HFS equation for each nl configuration is performed by the iterative process described in Ref. 19. The set of calculated binding energies forms the structure of the energy levels, and each value represents the energy required to remove a given electron from the atom.

The wave function found from solution of the HFS equations can be used to calculate energetic and probabilistic ion properties. The wavelengths and spin-orbit splitting constants are the main energetic properties. The probabilistic properties, such as oscillator strengths and photoionization cross sections, are expressed

through the matrix elements of two or more radial wave functions of participating initial and final states.

This study utilizes the description of populations of atomic levels by a collisional-radiation equilibrium (CRE) formulation, which is equally applicable to the limited cases of temperature ranges and intermediate-temperature intervals, because it includes both collisional and radiative effects. The fact that the CRE model considers the transitions between all atomic levels is of particular importance. Non-local effects are allowed for by an escape factor,²⁰ which neglects photoexcitation in the continuum and reduces the strength of spontaneous transitions. Such an approximation is a fair description of the plasma behavior under conditions when an external source of hard radiation is absent.

The plasma ionization state and population levels n for a prescribed set of temperatures and densities are calculated by solving the system of kinetic equations in stationary form:

$$\frac{dn_i}{dt} = -n_i \sum_{j \neq i} K_{ij} + \sum_{i \neq j} n_j K_{ji} = 0. \quad (9.13)$$

Collisional electron excitation and deexcitation, collisional electron ionization, three-body recombination, spontaneous transition, and photo- and di-electronic recombination are included in the calculation of the total rates of electron transition, K_{ij} , from level i to level j . The ion and electron concentrations N_i and N_e are found from the known population levels for a given temperature and substituted into a set of equations of state. Generally, a two-temperature approximation for the pressure p contains corresponding terms for the kinetic energies of ions and electrons. The equation for the internal energy e_{int} contains the terms for ionization and excitation of electrons:

$$p = kT_i \sum_i N_i + kT_e N_e, \quad (9.14)$$

$$e_{\text{int}} = \frac{3kT_e N_e}{2\rho} + \frac{3kT_i \sum_i N_i}{2\rho} + \frac{1}{\rho} \sum_i N_i (R_i + Q_i),$$

where R_i is the sum of ionization potentials from the neutral atom to the $(i - 1)$ th ion, and Q_i is the mean excitation energy of the i th ion. In our approximation, the electron and ion temperatures are set equal: $T_e = T_i = T$.

The reciprocal of the resistivity η —the electrical conductivity σ —is the sum of conductivities σ_c and σ_n corresponding to electron scattering on charged and neutral particles^{21,22}:

$$\eta = \frac{1}{\sigma} = \frac{1}{\sigma_c} + \frac{1}{\sigma_n}, \quad \sigma_c = \frac{4\sqrt{2}}{\pi\sqrt{\pi}} \frac{(kT_e)^{3/2}\beta}{e^2 Z \Lambda}, \quad \sigma_n = \frac{3N_e e^2}{\sqrt{2\pi m_e k T_e} N_0 s_0}. \quad (9.15)$$

Here, we use standard notation for the Coulomb logarithm Λ , concentration of neutral atoms N_0 , electron charge e , and mean ion charge Z . The parameter β is an electron-electron scattering correction.²² Empirical values of the transport cross sections s_0 are taken from Ref. 23.

The computational accuracy and completeness of calculated opacities depend upon the accuracy and completeness of the atomic data (such as electronic wave functions, energy levels, transition probabilities, oscillator strengths, and other derived values) and populations of atomic levels. As earlier shown in Refs. 5, 6, 24, and 25, taking account of the electrostatic and spin-orbit splitting of atomic shells and spectral lines may influence the quantitative and qualitative characteristics of radiation transport effects and the dynamics of the energy balance in the plasma. Self-consistent-field methods such as the Dirac-Fock (DF) or HF are believed to be the most accurate and practical atomic methods.^{26,19} However, the very large number of energy levels limits their applicability for plasma calculations.

A method for calculating the optical coefficients for high- Z plasmas within the CRE model was developed and implemented in Ref. 24. The distinguishing feature of the method is the joint use of HFS atomic data and Racah techniques for angular moments. The splitting of a configuration is interpreted as a switch to the energy level being dependent on the quantum numbers L , S , and J , as well as on the quantum numbers that uniquely specify the energy of a term. With the first-order approximation of perturbation theory, one can obtain the energetic corrections that give the energy of electron interaction²⁷:

$$E = \sum_k F_k(nl, nl) f_k + \sum_k F_k(nl, n'l') a_k + \sum_k G_k(nl, n'l') b_k. \quad (9.16)$$

The three terms on the right side express respectively the interaction between equivalent electrons inside the shell and the direct and exchange electron interactions for the nl and $n'l'$ shells. The expressions for the Slater integrals F_k and G_k and the angular factors f_k , a_k , and b_k are rather complex and can be found in the literature on the theory of atomic structure.^{27,28}

Spin-orbit splitting results in either one-particle interaction of the electron's spin with its own orbital angular momentum, or the interaction of the total spin of a shell with the total orbital angular momentum of that shell. More complicated effects are neglected. The splitting of unfilled shells with equivalent electrons is given by cumbersome formulas and depends on the type of coupling. We use the LS -coupling approximation, and the spin-orbit splitting is determined by the Landé interval rule^{29,30}:

$$\Delta E_J = 0.5 \cdot A \cdot [J(J+1) - L(L+1) - S(S+1)], \quad (9.17)$$

where A is the fine-structure splitting constant.

Numerical implementation of energy-level splitting is done by several procedures, including calculation of optical coefficients of absorption and emission, the

photoabsorption threshold, and the kinetic matrix for generating populations of levels. The procedure of splitting is realized similarly for all mentioned calculations, and its algorithm depends on the type of splitting level. The relative probabilities for split components are calculated from the corresponding oscillator strength of the transition with the help of the Racah technique, as described in Refs. 31 and 24. The assumption that the Boltzmann equilibrium is reached between split components of the same configuration significantly simplifies the calculation of relative populations in that configuration. Then, the ionization state and relative populations of levels can be derived by means of the traditional CRE model for the nl shell.

The electronic transitions and their accompanying absorption and emission of photons are subdivided into three types: bremsstrahlung; photoionization from ground, excited, and inner levels; and discrete transitions. The latter are approximated in the form of dipole transitions and include transitions between ground and excited states, transitions between excited states, and, partly, the transitions from inner shells. Because of their importance, the profiles of spectral lines are processed very carefully by means of the major broadening mechanisms such as radiation, Stark, Doppler, and resonance broadening.³²

The total absorption coefficient κ_{abs} is calculated as a sum of absorption coefficients for free-free (κ_{ff}), bound-free (κ_{bf}), and bound-bound (κ_{bb}) radiation transitions, weighted with the population levels N_{ij} , where index i refers to the ionization state, and index j to the excitation level. The coefficients are explained as

$$\begin{aligned}\kappa_{\text{ff}}(T, \rho, \hbar\omega) &= \sum_i \sigma_i(T, \hbar\omega) N_i(T, \rho) N_e(T, \rho) \left[1 - \exp\left(-\frac{\hbar\omega}{kT}\right) \right], \\ \kappa_{\text{bf}}(T, \rho, \hbar\omega) &= \sum_i \sum_j \sigma_{ij}(\hbar\omega) N_{ij}(T, \rho), \\ \kappa_{\text{bb}}(T, \rho, \hbar\omega) &= \sum_i \sum_{j,k} \frac{\pi e^2}{m_e c} f_{jk} \Phi(T, \rho, \omega) N_{ij}(T, \rho).\end{aligned}\tag{9.18}$$

Knowing the cross sections of inverse processes, we can calculate the total emission coefficient κ_{emi} by similar formulas. The values of the oscillator strengths f_{jk} , photoionization cross sections σ_{ij} , line profile Φ , and Gaunt factors G_i are given elsewhere.^{24,31,33}

The results from computation of the absorption coefficient of the xenon plasma for our simulation density ($1 \times 10^{15} \text{ cm}^{-3}$) and temperature (50 eV) are shown in Fig. 9.5. Additionally, detailed resolution is given for several important energy ranges. The computations are from the CRE model with several modifications: continuum absorption, continuum with HFS-line absorption, and continuum with split-line absorption. The width of the frequency interval was comparable to the Doppler width of the strongest spectral lines, which provides satisfactory resolution of line profiles. Major differences are observed in the energy interval from 10 to

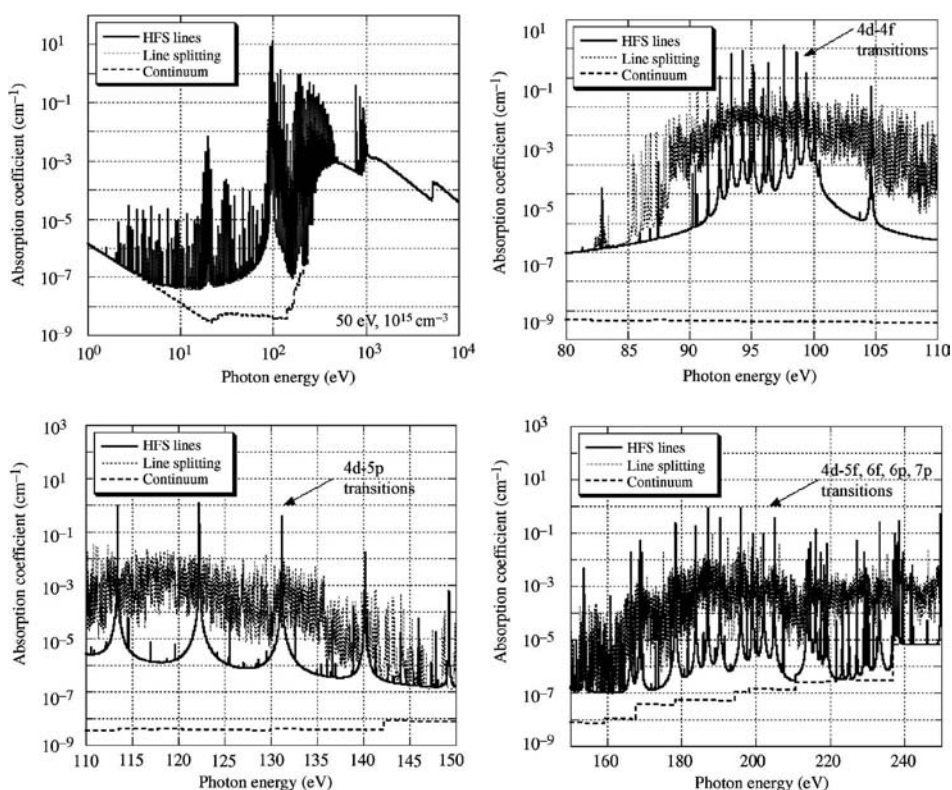


Figure 9.5 Absorption coefficients of Xe plasma at 50 eV and $1 \times 10^{15} \text{ cm}^{-3}$.

3000 eV. At around 100 eV, the lines are split, corresponding to transitions $4d^q - 4d^{q-1}4f$, $4d^q - 4d^{q-1}5p$, and $4p^6 4d^q - 4p^5 4d^{q+1}$.

The amplitudes of the split lines are not very high; however, the number of lines is very large, and practically all lines are optically thin in the energy range in question. By our technique, the detailed emission and absorption spectra are initially calculated on a very fine spectral-frequency mesh (up to 100,000 points) for the expected range of MHD values. Because of the large size of the generated opacity tables, the use of such detailed data is impractical, and the emission and absorption coefficients are averaged over spectral groups.

There is no rigorous theory for averaging the opacities over a group of frequencies. Such an averaging procedure may be considered correct only when the absorption coefficient is essentially constant within the group, or the optical thickness of each line is very small, and the absorption becomes a nearly linear function of the frequency. Such a situation is possible only for the continuum, and even in that case, every photoionization threshold must become a boundary of a group. The situation becomes even more complicated for the line spectrum, where the absorption coefficient often exhibits a very deep drop of several orders of magnitude within a very limited frequency interval, say, from the center of a very strong line to the wings of the same line, and the center of the line is optically very thick. More-

over, the temperature and density values may vary; this condition leads to spectral lines from the other ions, and the width of the existing lines also changes.

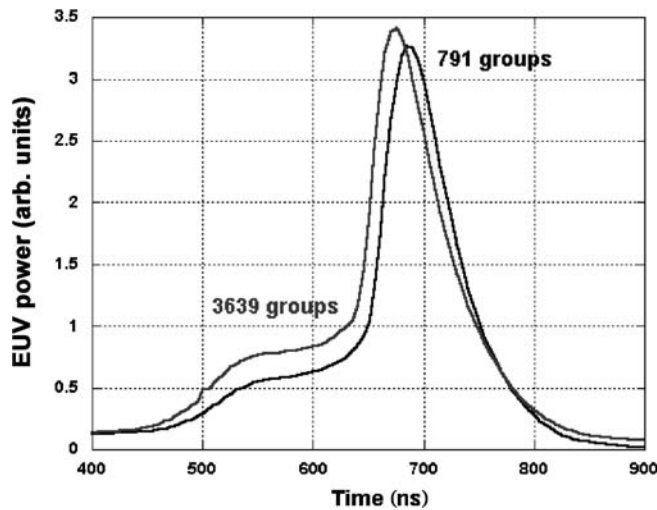
From a practical viewpoint, an organized selection of several of the strongest lines is a reasonable way to describe optical coefficients in detail within the most important hydrodynamic ranges for typical temperature and density values. The other lines are averaged within broad enough groups. Unfortunately, one does not know the typical values a priori, because the primary goal of the numerical simulation is the determination of the typical hydrodynamic parameters within the important areas of the plasma domain.

For a uniform isothermal plasma, the optical thickness of a spectral line is determined by the multiplication of the absorption coefficient of the line by the linear dimension of the plasma: $\tau(\varepsilon) = \kappa_{\text{abs}}(\varepsilon) \cdot l$. In the case of a nonuniform, non-isothermal plasma, this definition is generalized to $\tau(\varepsilon) = \int \kappa_{\text{abs}}(T, \rho, \varepsilon) dl$ over the interval Δl , where the ion exits emitting at the frequency ε . The borders of the groups are calculated from the following considerations. First, the width of a group, $\Delta\varepsilon$, should never exceed αT , where T is the plasma temperature and α is some parameter chosen for averaging. This condition provides the smooth averaging of opacities in the continuum region, where the averaging is normally performed within the broad groups, and the optical thickness is significantly less than unity. The second consideration is the requirement of invariability of the optical coefficient at some chosen value β within the group. This condition provides a well-specified resolution of the spectral lines with the optical thickness nearly at unity, and of the wings of the lines with the optical thickness greater than unity. The final consideration is that all those frequencies that belong in the detailed spectrum to a line with $\tau(\varepsilon) \geq 1$ are also included within the borders of the groups. This arrangement provides a very thorough resolution of strong lines in the averaging spectrum. By variation of the parameters α and β , several group mean opacities are generated with different levels of completeness.

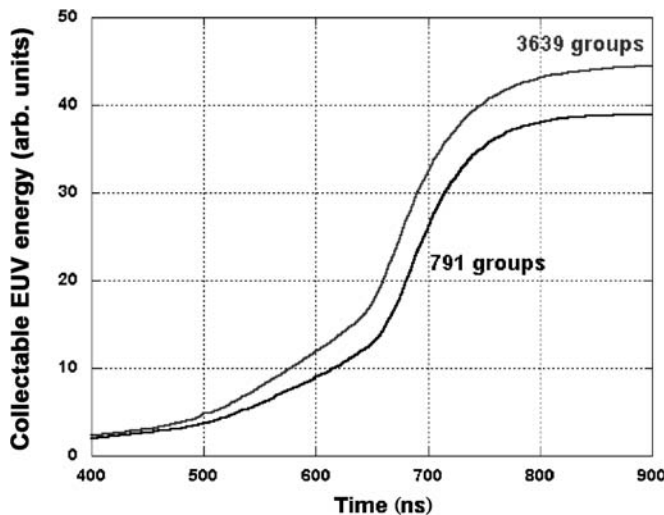
Based upon several recent studies,^{2,34} it was initially supposed that the maximum radiation transport corresponds to the moment of pinch formation. Typical pinch parameters are the following: the temperature is close to 25 eV, the density is 10^{17} cm^{-3} , the spectral range in radiation energies varies from 5 to 250 eV, and the average optical plasma thickness is 1 cm. We generated two sets of opacities, averaged over 240 and 791 spectral groups. The comparison of the radiation fluxes showed good agreement and allowed us to choose values for the hydrodynamic parameters from the most-emitting areas. After that, we selected 10 typical temperature and density values and generated the optimal scale of spectral groups, after which, combining all scales, the summary energy scale had 3639 energy groups. The result of the self-consistent hydrodynamic and radiation transport calculations with these opacities can also be used for further improvement of the quality of the coefficients. We have calculated and compared the dynamics of the typical DPP device with the opacities averaged over both 791 and 3639 groups. The dynamics of the plasma is left unchanged, signifying that 791 groups is a quite reasonable initial choice. Nevertheless, during the time of formation and evolution of the pinch,

the detailed opacities show a 5% difference between the 791 and the 3639 groups. Such a difference is quite insignificant from the hydrodynamic point of view, but as seen from Fig. 9.6, is important from the point of view of collectible EUV.

In the first mode of modeling, the radiation transport is calculated self-consistently with respect to the magnetic hydrodynamics, as described above. The goal is to obtain the temperature and density distributions for the second mode of modeling: the calculation of the EUV of the source. The second mode utilizes the same radiation transport method, but another set of opacities.



(a)



(b)

Figure 9.6 Typical (a) pinch EUV power, and (b) collectible energy, for 791 versus 3639 optical groups.

In using the HFS model for the calculation of energy levels, the typical accuracy of the result is within 10%; this is unacceptable for the EUV range of $13.5 \text{ nm} \pm 2\%$. In contrast with HFS, the more accurate HF model treats the upper and lower states as split into components, and each component is a set of levels with different quantum numbers L , S , and J . The values of the splitting can exceed the required 2% of the transition energy. It thus becomes important to know what fraction of the whole transition is situated within the range of interest.

Several well-known HF methods, each of which calculates the energy levels (and transitions) slightly differently, can be implemented for such a narrow range.³⁰ In the calculation of the lower state, the average term is often approximated, in that all states with different L , S , and J quantum numbers are supposed to have the same radial wave function and eigenvalue. As shown above, the splitting by L , S , and J is defined by Slater integrals and various angular factors, which represent electrostatic, spin-orbit, and exchange interactions. Relativistic corrections are found within the limits of perturbation theory. To calculate the atomic structures of the EUV-emitting ions, we use the mathematically stricter *LSD* HF method.³⁰ The total energy of a term is found by solving a separate set of HF equations for each $^S L$ term. Precisely, the method should be called *LS ν D* HF, because the total energy for d shells also depends on the seniority number ν . The splitting of a configuration is found later as the difference of the total energies. In contrast to the average-term HF, all *LSD* HF wave functions, eigenfunctions, and Slater integrals depend on the L and S quantum numbers for inner and outer shells. This condition requires longer, but more accurate, computations, and is very important for calculation of the total energies of the atomic levels.

The angular wave functions are normally calculated separately from the radial wave functions by the summation of the electron momenta. As a rule, the two limiting cases are rarely realized in practice, namely, when electrostatic interaction is considered predominant (*LS* coupling) or the spin-orbit interaction exceeds the electrostatic interaction (*jj* coupling). In intermediate cases, the Hamiltonian matrix cannot be written diagonally in any coupling scheme. Therefore, the complete matrix is written by transforming the Coulomb matrix from *LS* representation to *jj* representation. The eigenvalues of the Hamiltonian matrix are found later by numerical diagonalization, and the eigenvector defines the composition (and purity) of the level corresponding to these eigenvalues and eigenvectors. The level is normally called by the name of the largest contribution of the basis terms from the purity vector. Note that the energy levels found within the intermediate coupling never have 100%-pure *LS* or *jj* coupling, and a difference always exists between the level assigned within the intermediate coupling and the level calculated within the pure coupling scheme and accordingly assigned as required by the scheme.

The calculation was performed for $4d^n-4d^{n-1}4f$, $4d^n-4d^{n-1}5p$, and $4p^6d^n-4p^54d^{n+1}$ transitions of Xe IX–XVIII ions. As found, the components of $4d^n-4d^{n-1}4f$ do not fall within the $13.5\text{-nm} \pm 2\%$ energy range. The components of

the $4d^n-4d^{n-1}5p$ transition for the Xe XI ion can partly cover the range, and the $4p^6d^n-4p^54d^{n+1}$ transition of Xe IX–XVIII has a very broad splitting interval, much broader than the required 2% range.

9.6 Results and Discussion

The results of a DPF discharge depend on the detailed physics of the discharge, the geometrical design features of the device, the electric circuit design, the initial conditions in the chamber, and the current profile. As simulated by the HEIGHTS-EUV package, we present the comparative results of detailed simulation of the discharge near the moment of plasma pinch for the typical designs of EUV sources.

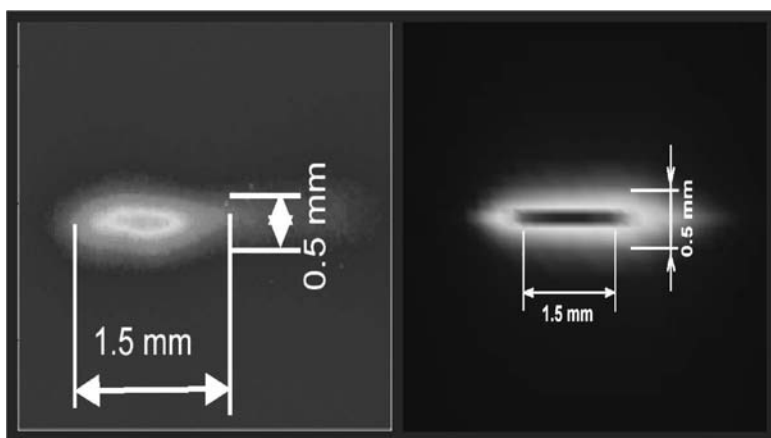


Figure 9.7 Details of the plasma pinch: (left) Ref. 8 experimental study, and (right) the HEIGHTS-EUV simulation.

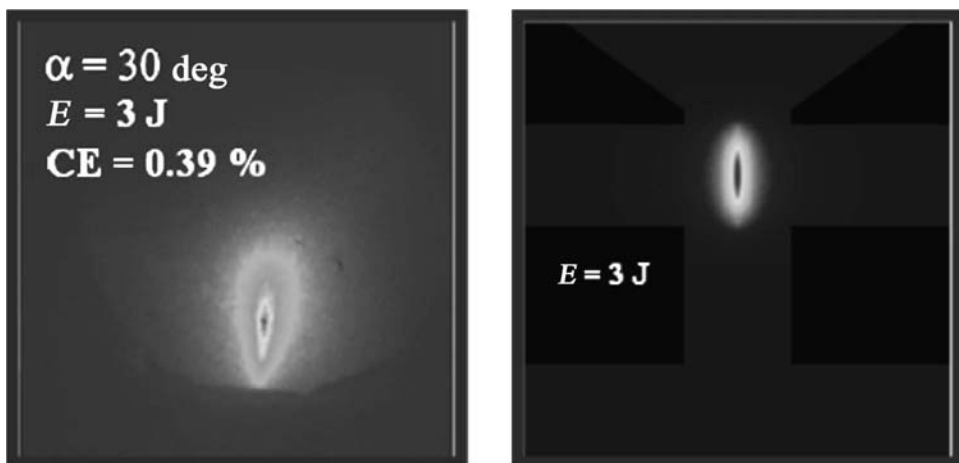


Figure 9.8 Details of the pinch: Ref. 9 experimental study (left) and the HEIGHTS-EUV simulation (right).

The measurements of the pinch, provided in Ref. 8, are in very good agreement with the HEIGHTS simulation, as seen from Fig. 9.7. Similar measurements of the plasma pinch, presented in Ref. 9, agree with our HEIGHTS simulation, as shown in Fig. 9.8.

In optimizing the design of a DPP device, the clear advantage of computer simulation is its flexibility in changing the critical parameters of the discharge. As well known and noted in various studies,^{5,8,9} the energy load and the electric circuit parameters are vital to the whole dynamics of the pinch: pinching time, reaching the desired thermodynamic state, and collecting the usable EUV radiation. As shown

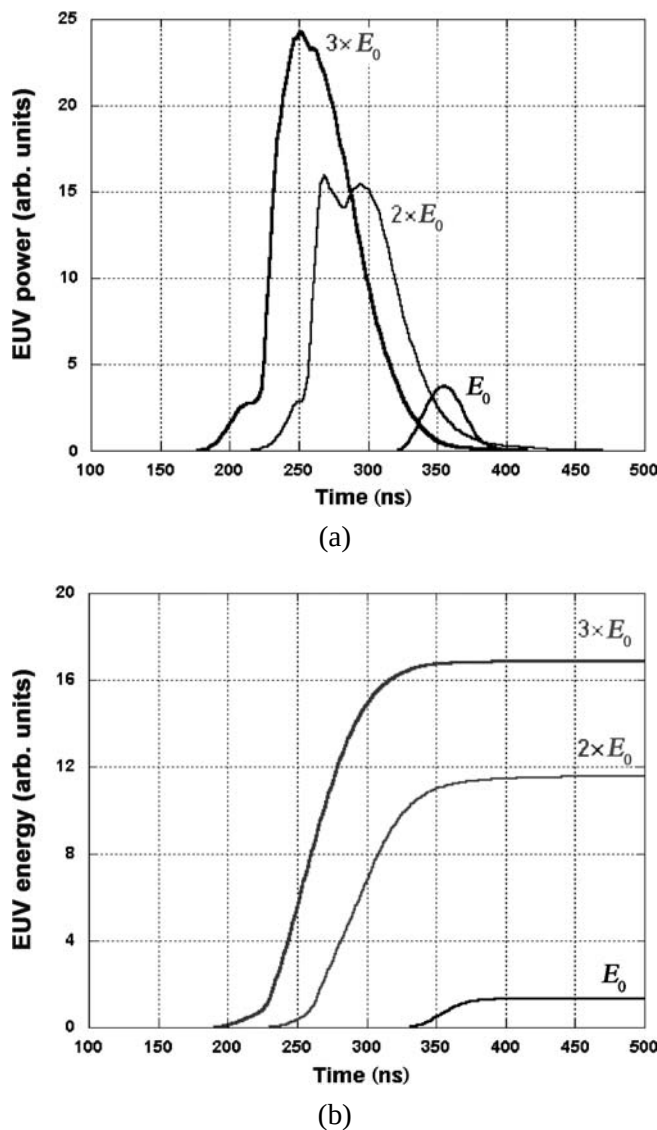


Figure 9.9 Optimization of the discharge, showing load increase for fixed initial pressure P_0 .

in Fig. 9.9, when the energy load is increased, a typical discharge produces higher EUV radiation power and allows collection of more EUV energy. Obviously this is not always true, because when the load is too high, the incoming energy will heat the plasma to higher temperatures so that the concentration of required Xe^{10+} ions becomes low; consequently, less EUV is produced. These calculations give us a hint on how to change the initial plasma parameters: for example, to reduce the pressure to maintain the high EUV collectable energy while reducing the energy input and, as a consequence, reducing the load on the electrodes and stabilizing the EUV source.

9.7 Conclusion

This study presents an integrated model that is being developed to describe the hydrodynamics and optical processes that occur in DPP devices. The model addresses three main subjects: plasma evolution and MHD processes, detailed photon radiation transport, and interaction between plasma/radiation and material. The developed models and numerical methods are being implemented and integrated in the computer simulation package HEIGHTS-EUV—a tool that can be used to study, optimize, and enhance our understanding of the hydrodynamics and radiation processes in DPP devices and the issues related to component erosion and lifetime estimates.

Acknowledgments

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No author biographies were available for this chapter.

Chapter 10

Modeling LPP Sources

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Michel Poirier, and Thomas Blenski

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10.1 Introduction

Although plasmas produced by lasers have been the subject of intense study over the past 40 years, those that are being considered as sources for EUVL offer new challenges in both design and understanding. The requirements of these sources are unique relative to other interests and applications of laser plasmas. EUVL demands a source that emits strong radiation only in one radiation band. The plasma must be small and be stable in position and light emission. It must be a high-repetition-rate source to satisfy dose stability. Moreover, strong consideration must be given to constraining the particulate and ion emission from the source: protecting the EUV illumination optics from degradation or erosion for long exposure times is one of the principal challenges. This combination of requirements forces consideration of features of laser plasmas outside the focus of most studies. They pose new challenges in the understanding, characterization, and design of laser plasmas.

This chapter addresses one of these challenges. The EUV roadmap requires a bright source in a narrow spectral band in the vicinity of a 13-nm wavelength. This wavelength and the width of the spectral band (≈ 0.26 nm) are set by the characteristics of the collection and imaging optics employed. The brightness required, which can be expressed in several ways [115 W of inband radiation at ≈ 13.5 nm, 2% bandwidth, at the intermediate focus (IF), or perhaps, more fundamentally, ≈ 400 W of inband radiation within 2π sr at the source], challenges the limits of laser and laser-plasma technology. Laser plasmas emit radiation that is both characteristic of the plasma conditions and characteristic of the excited ion states created in the plasma. In satisfying the needs for a source, our challenge from a theoretical viewpoint is to understand and model this emission, at least under conditions that are likely to satisfy the intense brightness requirement in a practical system.

It is for these reasons that in this chapter we concentrate on laser plasmas that have characteristics conducive to the creation of high-brightness, high-repetition-rate point EUV sources. We focus on the theory of laser-light interaction, plasma expansion, and radiant emission, seeking plasmas that are most likely to meet these needs. Thus we consider here spherical, 1D models of laser plasmas dominated by inverse bremsstrahlung absorption (IBA), thermal excitation, and classical energy transport. We focus on plasmas formed from ions that have strong emission lines in the 13-nm region. There are several candidates, including Li, O, Xe, Sn, and others. Low- Z materials such as Li and O have been examined in previous studies, and are now thought to be incapable of providing sufficient emission, or to be too impractical as a source. Here we examine mostly emission from so-called *unresolved transition arrays* (UTAs), tightly packed emission lines from multitudes of excited-state transitions in multiple ions in materials such as Xe and Sn. Theoretically this is a very challenging problem. Not only does it require a thorough understanding of the plasma state, but more important, and much more difficult to model, is the understanding of the detailed radiation transfer from all these transitions. To our knowledge this has not yet been accomplished completely. Thus, this chapter is a report on progress toward this end. First we summarize those basic

processes in laser plasmas that are relevant to the plasma regime involved in EUV sources. Then we describe the application of conventional plasma fluid models to the laser light's interaction with the plasma and its subsequent expansion. Finally, we go on to describe in some detail the various aspects of modeling the radiation from high- Z plasmas, particularly the emission spectra as derived from detailed atomic physics codes.

10.2 EUVL Source Requirements

There is considerable hope for laser plasmas being able to meet the requirements for an EUVL source. This stems from several features. The plasma and the source that is energizing it are separate. The plasma source can be located in free space, far from any secondary sources of debris. With most target designs this allows large angular access to the source, in principle larger than 2π sr. The separation of laser and EUV source allows for high repetition rates without fear of thermal loading. Nonetheless, the current EUV source requirements are very severe, and significant progress needs to be made to achieve the required performance within acceptable cost scenarios.

The principal performance requirements of an EUVL laser-plasma source are well known and have been summarized in Chapter 2. At source brightness levels of ≈ 400 W in 2π sr and 2% spectral bandwidth at 13.5 nm, the pulse-to-pulse stability must be $\sim 1\%$, assuming source repetition rates > 10 kHz. The source must be small (< 1 mm in size), be stable in position, and be capable of continuous operation for $> 10^{11}$ shots, with $< 3\%$ downtime for scheduled maintenance. Two other challenging requirements must also be met. The fraction of *out-of-band* radiation (the radiation that is not reflected by the XUV optics and is therefore largely absorbed by the first collector mirror) must be below its thermal loading limits. Moreover, the particulate and ion emission from the source, usually transmitted by line of sight, must be very strongly inhibited from impinging on the first mirror, in order to preserve its life over many months of operation.

These considerations have led to several laser-plasma source scenarios with different source media. Early studies^{1,2} showed that several source materials can produce emission at the required wavelength (such as Li, O₂, Xe, and Sn), but that experiments with massive solid planar targets produced copious levels of particulate debris. This led very quickly to the selection of Xe, and to a lesser extent O₂, as the source materials of preference.^{3,4} Both are gaseous, and therefore less threatening with respect to debris. Li-like oxygen emits a strong narrow line from the 4d-3p transition at 13.1 nm. A Xe plasma at a temperature of ≈ 30 eV will consist predominantly of Xe⁺¹⁰ (Fig. 10.1), which has a band of emission in the region of 13.5 nm (Fig. 10.2).

Laser plasmas of Xe have been investigated with various target formats. Initially, Xe gas sprays were used.⁵ Then, in efforts to increase the fractional emission within the 13.5-nm (2% bandwidth) band, clusters,⁶ microscopic jets,⁷ and high-speed droplet streams⁸ were used.

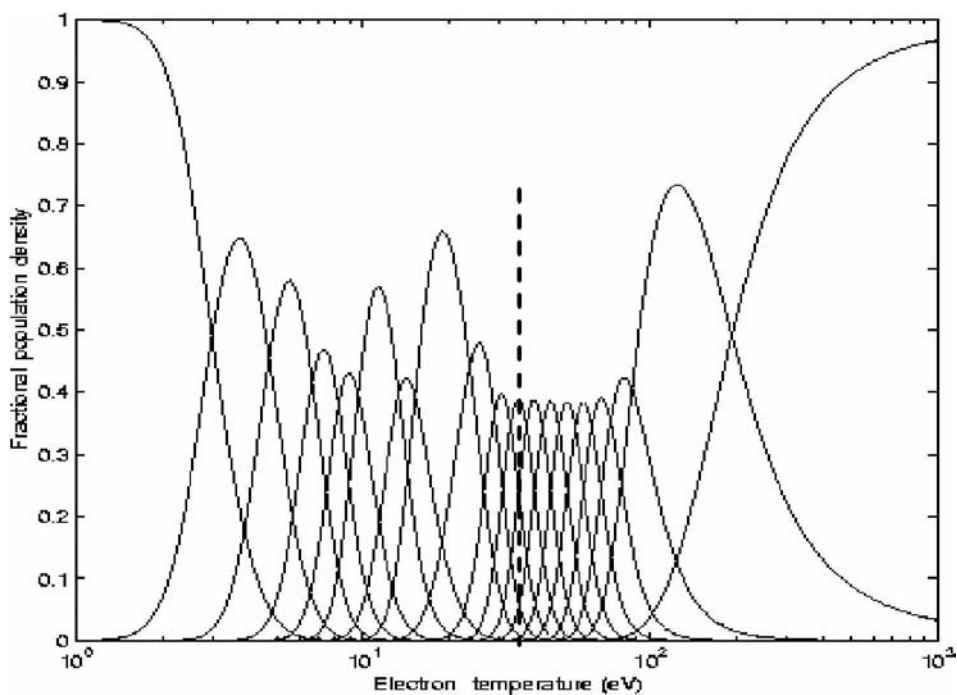


Figure 10.1 Fractional population of Xe ions at $n_e = 10^{21} \text{ cm}^{-3}$ as a function of electron temperature.

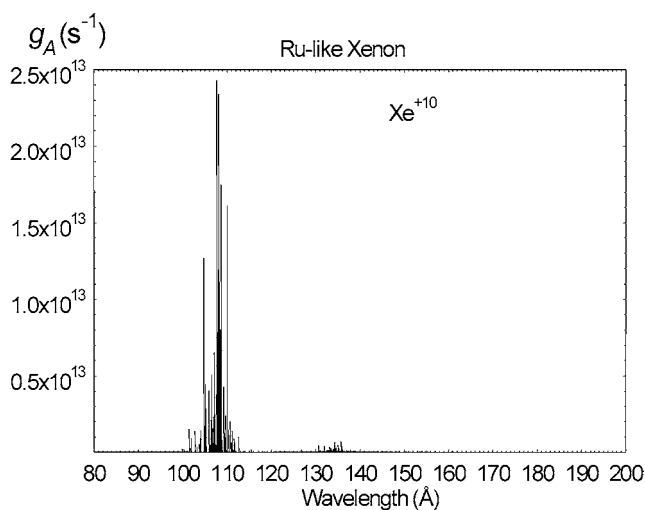


Figure 10.2 Cowan-code calculation of emission of Xe^{+10} at a temperature of $\approx 30 \text{ eV}$.

More recently a new format for delivering microscopic droplet targets of Sn has been devised.⁹ As a target material, Sn's advantage is that the main UTA transitions from many Sn ions (Sn^{+7} – Sn^{+12}) can contribute to the EUV emission (as with Xe, at a certain plasma temperature—for Sn, $T_e \approx 28 \text{ eV}$ —primarily three ionization states are created). Thus, many more emission lines can contribute to

the emission (Fig. 10.3). In principle, tin-doped droplet laser plasma targets should be more efficient in generating 13-nm emission than Xe. Some evidence for this is already available.¹⁰ However, the challenge to make this source sufficiently clean of particulate matter is certainly more difficult.

This chapter focuses mainly on the modeling of Xe and Sn laser plasma sources, since these are the most likely candidates. From a modeling standpoint they are also the most challenging.

10.3 Physical Processes in Laser Plasmas

Here we describe the primary interaction processes that occur in the formation and development of plasmas created by nanosecond lasers. We largely summarize more detailed treatises on this topic.^{11–13} Laser pulse intensities above 10^{10} W/cm² are sufficient to ionize atoms, transforming any matter to plasma. The spectral nature of the emission from the produced plasma is characteristic of its temperature and the species of ions created. EUV radiation is best produced by plasmas having an electronic temperature T_e of several tens of electron volts and electron densities $n_e = 10^{19}$ to 10^{21} cm⁻³. To achieve this temperature in plasmas of Xe or Sn, the laser intensity should exceed 10^{11} W/cm².

10.3.1 Laser coupling and interaction processes

As laser light propagates in the plasma, several mechanisms can account for the transfer of energy from the laser electromagnetic (EM) wave to the plasma, according to the interaction regime. Initial ionization of laser-plasma target material takes place by photoionization processes. If the intensity of the laser radiation is high enough, an atom is ionized by absorbing several photons, this process being called multiphoton ionization.¹⁴ For higher intensities tunnel ionization becomes dominant; in this process the strong electric field of the laser is able to tilt the

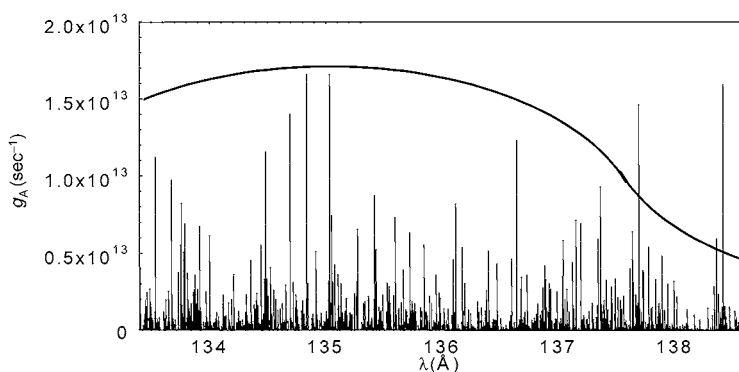


Figure 10.3 Cowan-code prediction for the probabilities gA of the Sn radiative transitions. The smooth curve is the 2% spectral bandwidth response of the multilayer mirror system centered at 13.5 nm.

atomic potential energy of the electron, enabling it to tunnel out of the atom. Since the ions have much larger mass than the electrons, the interaction of the EM field with the ions can be neglected in comparison with that with the electrons. The electrons freed by photoionization gain kinetic energy by oscillating in the $\mathbf{E}$ field of the laser. Inelastic collisions between these electrons and atoms or ions result in a further cascade of ionization. Elastic collisions with ions yield conversion of the electron's kinetic energy into thermal energy of the plasma. This process of plasma heating by laser radiation is known as IBA. Although elastic and inelastic collisions generally take place at the same time, the cascade ionization is especially important in the starting phase of the plasma.

IBA plays a central role in heating the plasma. The electrons, while oscillating under the action of the laser electric field, collide with the ions, giving rise to transfer of EM energy to the plasma. The absorption coefficient for IBA can be written as¹⁵

$$\alpha_{\text{IB}} = \frac{1.08 \times 10^{-5}}{\lambda^2} Z^* \left(\frac{n_e}{n_c} \right)^2 \frac{\ln \Lambda}{\sqrt{1 - (n_e/n_c)}} \frac{1}{T_e^{3/2}}. \quad (10.1)$$

This equation is written in the international SI system of units with the absorption coefficient expressed in m^{-1} , where λ is the wavelength of the incident laser beam in m, Z^* is the average ion charge, $\hat{T}_e$ is the electron temperature in eV, n_e is the electron density, and n_c is the critical density at which the electron plasma frequency

$$\omega_{\text{pe}} = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}},$$

which is equal to the laser light frequency ω , which is given by

$$n_c = \frac{m_e \epsilon_0 \omega^2}{e^2}, \quad (10.2)$$

$$n_c \text{ (m}^{-3}\text{)} = \frac{1.12 \times 10^{21}}{\lambda^2 \text{ (m)}},$$

and $\ln \Lambda$ is the Coulomb logarithm

$$\ln \Lambda = \ln \left(\frac{3k_B T_e 4\pi \epsilon_0}{Z e^2} \sqrt{\frac{k_B T_e \epsilon_0}{e^2 n_e}} \right), \quad (10.3)$$

$$\ln \Lambda = \ln \left(1.55 \times 10^{13} \frac{\hat{T}_e^{3/2}}{Z n_e^{1/2}} \right),$$

where $\hat{T}_e$ is the electron temperature in electron volts, and $\hat{T}_e = k_B T_e / e$ with k_B is Boltzmann's constant, and T_e is in Kelvin. For laser light with wavelength 200–1000 nm, $n_c \approx 3 \times 10^{28}$ to 10^{27} m^{-3} . Therefore, n_e will be well below the critical

density n_c in the case of droplet laser plasmas. For plasmas produced by long laser pulses (several nanoseconds), the electron density scale is sufficiently long that most of the IBA absorption occurs at n_e well below the critical density n_c . The absorption coefficient for IBA is then proportional to the electron density squared (neglecting the n_e dependence of the Coulomb logarithm). If sufficient laser radiation penetrates to electron densities that approach the critical density, then the absorption increases very strongly. In the limit of $n_e \rightarrow n_c$, or $\omega \rightarrow \omega_{pe}$, resonant energy transfer to plasma motion takes place. This process, referred to as resonant absorption, is also described as the excitation of plasma waves. For n_e above the critical density, laser radiation is completely reflected. It is clear from Eq. (10.1) that IBA absorption decreases as the electron temperature increases. And it is higher for higher electron densities and for higher- Z plasmas.

10.3.2 Analytical description of plasma expansion

As the plasma is produced, it develops and expands in the surrounding vacuum. The expansion speed is determined by the temperature of the electrons and the mass of the ions. It determines how fast energy must be supplied to the plasma if it is to reach a high temperature. The electron-ion thermal expansion velocity is roughly equal to the ion acoustic velocity^{15–17}

$$v_{\text{exp}} \approx c_s = \sqrt{\frac{Z^* \gamma k_B T_e}{M_i}}, \quad (10.4)$$

where T_i and Z^* are the ion temperature and the average ion charge, respectively, M_i is the ion mass, and $\gamma = 1 + 2/N$ is the thermodynamic ratio of specific heats for a system with N degrees of freedom. The expansion velocity is in large part dominated by the electron thermal pressure. It is driven by the electron temperature $k_B T_e$ but limited by the inertia of the ions through their mass M_i , as can be seen in Eq. (10.4). In practical units the expansion velocity can be expressed as

$$v_{\text{exp}} = 1.26 \times 10^8 \left(\frac{Z^* k_B T_e}{M_i} \right)^{1/2} \frac{\text{cm}}{\text{s}}, \quad (10.5)$$

where $k_B T_e$ is in electron volts, the ion mass M_i is expressed in units of the proton mass, and γ is taken as 5/3.

As the plasma expands, thermal energy is then converted into direct kinetic energy. The xenon plasma rate estimated from this acoustic velocity (using $M_i = 131.29$, $Z^* = 10$, and $T_e \sim 10$ eV) is about 1.1×10^6 cm/s. And the expansion velocity of a tin plasma (with $M_i = 118.7$, $Z^* = 10$, and $T_e \approx 30$ eV) is about 2×10^6 cm/s. The expansion of LPPs leads to a rapid decrease of electron (and ion) density. This results in less absorption by the IBA process, as shown by Eq. (10.1). As soon as the generated plasma has sufficiently expanded, the absorption of the incident laser power will become weak. Hence, to obtain high CE, the laser pulses should not be too long.

10.3.3 Local thermodynamic equilibrium and non-LTE plasmas

Laboratory plasmas do not satisfy the conditions for thermal equilibrium (TE), i.e., that all electrons, ions, and radiation are strongly coupled and share the same temperature. However, many laser plasmas can be described as being in local thermodynamic equilibrium (LTE), where the populations of available energy levels is determined by electron-ion collisions, and it is assumed that the effects of radiation processes on these populations are negligible. LTE conditions are more likely to be satisfied in laser plasmas of low- Z materials, where collisional processes are dominant over radiative processes, and in plasmas that are optically thin, so that radiation can escape from the plasma. For a Maxwellian electron distribution, the plasma will be optically thin if the electron density n_e fulfills

$$n_e \text{ (cm}^{-3}\text{)} \geq 1.7 \times 10^{14} T_e^{1/2} \Delta E_{u,1}^3, \quad (10.6)$$

where T_e is the electron temperature and $\Delta E_{u,1}$ is the transition energy, both expressed in electron volts. If the plasma is optically thick, that is, radiation generated within the plasma is coupled to the ions and electrons, then lower values of n_e can be used.

Plasmas produced by nanosecond lasers pulses from high- Z materials cannot generally be considered to be in LTE. Considerable energy is converted into radiation—both line radiation and blackbody Planckian emission—and this radiation plays an important part in determining the population of the available energy states. This is the so-called non-LTE (NLTE) regime. A much more complicated energy transfer situation exists, with the opportunity for many more physical processes to occur. In addition to electron collisions, radiative deexcitation and photoelectric and recombination processes will come into play. Modeling these processes in an exact way is more challenging.

10.4 Modeling Laser-Target Interactions and Plasma Expansion

10.4.1 Laser plasmas with hydrodynamic codes

The most common approach to modeling the expansion of laser plasmas produced by nanosecond laser pulses, particularly those interactions dominated by IBA energy coupling, is through the use of two-fluid plasma hydrodynamic codes. The code used at the Laser Plasma Laboratory (LPL) at the University of Central Florida (UCF) is the well-known hydro code, MED 103,¹⁸ developed from an original code by Christiansen et al.¹⁹ This code has been widely used in many laboratories for simulating the hydrodynamic expansion of laser plasmas for many different plasma conditions. This one-dimensional, 90-cell Lagrangian code contains models for most laser-plasma coupling physics and for electron and radiation transport. Energy-balance transport from one cell to the next is calculated self-consistently in a series of time steps. In each cell the electron and ion densities and temperatures,

the average ion state, and many other plasma parameters (the plasma's viscosity, velocity, pressure, etc.) are determined. The code is fairly easy to run for a variety of input laser pulse shapes, wavelengths, and intensity parameter values. The code can also simulate spherical and cylindrical, as well as planar, expansion geometry for targets consisting of many layers of different materials. The ions in the code are always considered to have a perfect-gas equation of state, usually with electron density obtained from the Fermi-Dirac distribution.

Assuming charge neutrality, the electron and ion fluids share the same velocity, so that the equation of motion can be expressed as

$$\rho \frac{du}{dt} = -\frac{dp}{dx}, \quad (10.7)$$

where ρ is the mass density, u is the fluid velocity, and $p = p_e + p_i$ is the hydrodynamic pressure. The two fluids, electrons and ions, are governed by an energy equation, which partitions the absorbed laser energy into thermodynamic and kinetic states. This general energy equation is

$$C_v \frac{dT}{dt} + B_T \frac{d\rho}{dt} + p \frac{dV}{dt} = S, \quad (10.8)$$

where S is the rate of energy input per unit mass, $C_v = (\partial U / \partial T)_\rho$ is the specific heat per unit volume, $B_T = (\partial U / \partial \rho)_T$ describes the variation of internal energy due to the interaction between particles within the same subsystem, and $U = pV / (\gamma - 1)$ is the internal energy per unit mass.¹⁶ Energy is exchanged between electrons and ions by collisions. The ion energy source term, S_i , is composed of thermal conduction, electron-ion energy exchange, and shock heating terms. Electron-ion energy exchange, bremsstrahlung, laser absorption, and thermal conduction terms are the principal constituents of the electron source term S_e .

Electron energy transport in most LPPs is by diffusive conduction of cold electrons.²⁰ Application of classical diffusion theory yields a heat flow expressed as

$$q_e = -\frac{1}{3} \lambda_e v_e n_e k \nabla T_e = -K \nabla T_e, \quad (10.9)$$

where λ_e is the mean free path for 90-deg deflection of electrons in multiple Coulomb collisions with ions and is expressed (in m units) as

$$\lambda_e = 1.12 \times 10^7 \frac{T_e^2}{Z n_e \ln \Lambda}, \quad (10.10)$$

and K is the classical Spitzer-Harm conductivity²¹ (in mho/m units) given by

$$K = 2 \times 10^{-4} \frac{T_e^{5/2}}{Z \ln \Lambda}, \quad (10.11)$$

where $\ln \Lambda$ is the Coulomb logarithm as given by Eq. (10.3). The Spitzer-Harm conductivity is valid only if the plasma electron temperature gradient is not too large. Quantitatively, this can be stated as $\lambda_e/L < 10^{-2}$, where $L = T/(dT/dx)$ is the temperature scale length.²² In terms of heat flow this can be stated as $q/q_f < 2.4 \times 10^{-2}$, where $q_f = n_e k T_e (k T_e / m_e)^{1/2}$ is the freestreaming limit of the heat flow and is associated with all electrons streaming in the same direction.²²

LPPs are generally characterized by steep temperature and density gradients under conditions where the energy conduction is not well described by the Spitzer-Harm conductivity. Numerical solutions of the Fokker-Planck equation reveal that the Spitzer-Harm theory overestimates the actual heat flow.²³ To circumvent this problem, the heat flux is restricted to the harmonic mean

$$\frac{1}{q'_e} = \frac{1}{q_e} + \frac{1}{q'_f}, \quad (10.12)$$

where q'_f is the product of an adjustable parameter f —a so-called *flux limiter*—and the freestreaming limit q_f . In the case of very large q_e the heat flux reduces to $q'_e = q'_f = f q_f$. The value of f is usually adjusted to match experimental results and is typically around $f = 0.1$.²¹ Allowing for this flux limit, the modified conductivity becomes²⁰

$$K'_e = K_e \left(1 + f \frac{\lambda_e}{T_e} \frac{dT_e}{dx} \right)^{-1}. \quad (10.13)$$

The effect of reducing the heat flow is to limit the energy conducted to the target and therefore to reduce the ablation rate. The laser energy, now more confined to the lower-density plasma, causes an increase in temperature and more rapid low-density expansion, whereas the higher-density plasma will be cooler and not expand as rapidly. The end result for the plasma is that the density profile becomes steeper.²⁴ Simulations with varying values of f reveal that the effects of the inhibited heat flow become more prevalent at intensities of $\sim 10^{13}$ W/cm² and higher, where heat fluxes are larger.²⁵

10.4.2 Simple spherical target

The LPL group has used the MED 103 code extensively to model liquid droplet laser plasmas in spherical geometry, and is in the process of comparing these simulations with experiments. An example of a comparison between code and experiment is illustrated in Figs. 10.4 to 10.6. Figure 10.4 shows calculations at -4 , 0 , and $+4$ ns relative to the pulse peak for a laser pulse of intensity $I = 4.5 \times 10^{11}$ W/cm², wavelength $\lambda = 1.064$ μ m, pulse duration τ (FWHM) = 10 ns, and spot size $\omega = 80$ μ m in the focal plane, for a spherical droplet target of oxygen (water) having a radius $r = 18$ μ m. The flux limiter f was set to 0.1.

The code predicts a maximum electron temperature of about 56 eV at an electron density of 5.6×10^{20} cm⁻³ at the peak of the laser pulse, or $t = 0$ ns. The

temperatures in the high-electron-density regions of the plasma are as follows: at 10^{22} cm^{-3} , $T_e = 2 \text{ eV}$; at 10^{21} cm^{-3} , $T_e = 45 \text{ eV}$; at 10^{20} cm^{-3} , $T_e = 40 \text{ eV}$; at 10^{19} cm^{-3} , $T_e = 22 \text{ eV}$. Most of the short-wavelength emission from such a plasma would originate from the region of 10^{20} – 10^{21} cm^{-3} .

Subnanosecond optical interferometry has been developed by the LPL group to measure the electron density distribution of the plasma created by this laser pulse on water droplet. As is shown in the companion chapter by Richardson et al. (Chapter 26), this model reproduces quite well the pseudospherical expansion of the plasma from the spherical target, even with one-directional laser irradiation. An example of this is shown in Fig. 10.5.

Modeling the line emission from water droplets (oxygen) was accomplished with the Spectra code.²⁶ This code assumes LTE and calculates the ionization distribution, excited-state populations, and allowed transitions. The atomic physics data required for this code were acquired from the Opacity Project database.²⁷ The Opacity Project was implemented to calculate and compile the atomic data necessary for estimates of stellar envelope opacities. The database consists of atomic data for the astrophysically abundant elements, $Z = 1$ –26. Coupled with these data, the Spectra code produces synthetic spectra from 1 to 1000 nm.

With the assumption of LTE, the Saha equation is used in conjunction with the atomic data to calculate the ionization distribution when given a particular plasma temperature and ion density. The code then calculates the populations of various excited levels within each ion and then the relative intensities of the various line

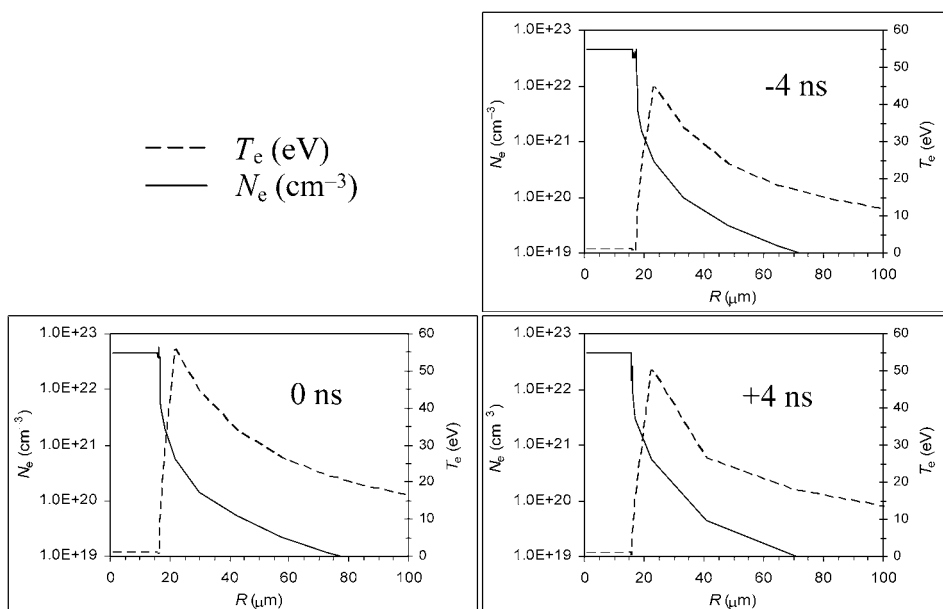


Figure 10.4 MED 103 simulations of the spherical expansion, as a function of radius R , of N_e and T_e from a 38- μm -diameter droplet. Oxygen ions are irradiated by a Gaussian 10-ns 1064-nm laser pulse at an intensity of $\sim 2 \times 10^{11} \text{ W/cm}^2$.

emissions. The calculated line shapes are assumed to be Lorentzian, and the line widths are based on the modified semiempirical method (MSEM).²⁸ Using the impact approximation, the width of an isolated line is given by

$$w = N \left[v \left(\sum_{i'} \sigma_{i'i} + \sum_{f'} \sigma_{f'f} \right) \right]_{\text{av}} + w_{\text{el}}, \quad (10.14)$$

where N is the electron density, $\sigma_{i'i}$ is the inelastic cross section for collisional transitions to state j' from level j of the optical transition, and w_{el} is the linewidth induced by elastic collisions. The average is over the electron velocity v .

A typical spectrum of the O plasma emission for a droplet laser plasma source is shown in Fig. 10.6, compared with the Spectra prediction of the relative amplitude

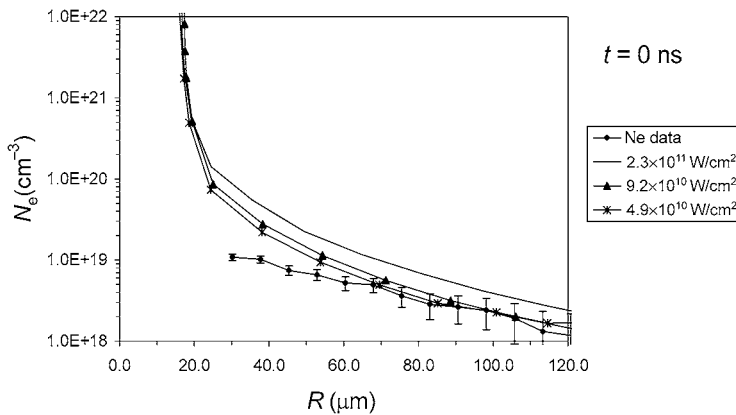


Figure 10.5 Electron density profile of plasma at the peak of the laser pulse, measured by interferometry, compared with MED 103 predictions at several intensities.

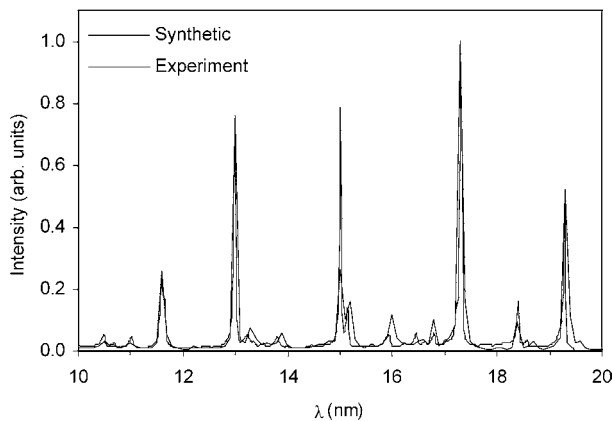


Figure 10.6 Comparison of measured emission spectrum from water droplet target with model predictions of Spectra, based on input from the MED 103 hydrocode.

and widths of the individual line emission in the 10–18-nm range. The agreement between the code predictions and the measured data is remarkably close.

10.4.3 Xe and Sn emissions

Here we describe some details of the model calculations we are making for Xe laser plasmas. Although the emphasis is on the methods we use, some loose comparisons are made with Xe data obtained from the EXULITE experiment with Xe spray targets at CEA-Saclay.^{29–31} The Xe calculation have been performed with the hydrodynamic Lagrangian code CHIVAS³² applied to model single droplets. The atomic physics modules (used as a postprocessor) in these calculations were simplified: the radiative losses have been neglected except the line emission in the vicinity of the 13.5-nm band. In the simulation performed by Ceccotti,³³ the droplet is replaced by a Xe slab at the liquid density with the laser light impinging on one side. Introducing the experimental conditions into the code, the electron temperature T_e in the droplet is found to be of the order of 30–35 eV at the laser intensity peak, and the electron density n_e is found to be slightly lower than $3.7 \times 10^{20} \text{ cm}^{-3}$. Using a simple collisional-radiative model based on the original work by Colombant and Tonon,³⁴ one gets that the dominant ion stage is Xe^{10+} . The plasma electron density obtained in this way is quite close to the value established as a necessary (but not sufficient) condition for the LTE regime. The emitted flux has been calculated for each value of n_e and T as a minimum between the value obtained from the corona model and the value obtained from the LTE model. Both models have been formulated in the hydrogenic approximation. The correction with respect to the opacity (calculated in the same approximation) has been included. These results, obtained by considering the droplets in the slab approximation, have been checked against possible 2D effects by Auguste,³⁵ who used the Castor code.³⁶ The results stemming from the 2D calculations are not different from the results in the slab approximation assumed in the CHIVAS modeling.

An interesting question that relates to this droplet target is whether the laser-target interaction can be modeled in the approximation of a single droplet. For instance, one may ask whether during the laser action the droplets have enough time to expand and form a macroplasma interacting with the laser in a rather complicated manner. The expansion velocity obtained from the modeling of single droplet with the CHIVAS code performed by the EXULITE group³⁷ indicates that the formation of such a macroplasma could be possible. Taking into account the specific gravity of liquid xenon as 3.6 g/cm^3 , the average diameter of droplets as $12 \text{ }\mu\text{m}$, and the average density in the interaction zone as 10^{20} at./cm^3 leads to the conclusion that the droplet radius expansion up to approximately $30 \text{ }\mu\text{m}$ would lead to a homogeneous plasma. The calculation with the CHIVAS code leads to expansion velocities varying between $8 \times 10^6 \text{ cm/s}$ in the coronal regime to $2 \times 10^6 \text{ cm/s}$ for the denser region of the expanding target. Such expansion leads to a macroplasma within a time equal to a fraction of the laser pulse duration. Let us note that these values obtained for the droplet expansion velocity are not far from the sound velocity of an LTE Xe plasma at 30 eV, which is roughly $1.7 \times 10^6 \text{ cm/s}$.

In order to understand in detail the interaction between the laser and the Xe droplet spray, Auguste from CEA-Saclay has developed³⁸ a code in which this interaction is modeled in a real 3D geometry. In this model one takes into account individual droplets in the spherical approximation, as in the method used previously by Garloff et al.³⁹ to calculate the interaction of a water droplet with laser light. Moreover, in Auguste's model each realistic configuration of many droplets in the interaction zone is taken into account by 3D laser ray tracing, including calculated absorption and reflection. At the end the results are averaged over all possible droplet configurations. In the paper by Garloff et al.,³⁸ the plasma density in the droplet is taken for simplicity as being homogeneous inside the sphere. In Auguste's code the assumed fixed form of each droplet density is a Gaussian function.³⁹ The results obtained from this modeling indicates that important droplet expansion occurs at the beginning of the laser pulse, which results in a rather inefficient overall coupling between the laser and the spray.

10.5 Atomic Physics Modeling of Laser Plasmas

10.5.1 Atomic models

Detailed analyses of the radiative properties of xenon over a wide range of charge states are rather scarce up to now,^{40,41} and of tin even more so.^{42,43} As demonstrated below, especially in the description of $\Delta n = 0$ transitions such as are important in Sn, configuration interaction (CI) must be taken into account. Therefore, models based on the single-configuration approximation—such as the average atom (AA) or the monoconfiguration Hartree-Fock (HF) or Dirac-Fock (DF) formalism—though sufficient to provide some insight into the relevant ions and electronic transitions, are certainly too crude to deal properly with EUV emission in such cases.

10.5.1.1 Average-atom model

The AA model has been proposed as a theoretical approach to the hot dense plasma for various astrophysical and thermonuclear fusion application. Its origins are connected with the use of the Thomas-Fermi (TF) model⁴⁴ in dense plasmas.^{45–47} All these models have been proposed for LTE plasmas. The introduction of the density-functional theory⁴⁸ was an occasion to consider the variational character of the ion-cell TF model at finite temperature.⁴⁹ A comprehensive inclusion of the quantum-mechanical shell effects for bound electrons in a self-consistent AA model has been proposed by Rozsnyai.⁵⁰ In Rozsnyai's model the bound-electron density is calculated from a set of fictitious bound shells using the fractional occupation numbers given by the Fermi-Dirac function. The continuum-electron density is calculated in the TF approximation. The bound shells stem from a spherically symmetric self-consistent potential, which is the sum of two parts: the Coulomb term and exchange-correlation correction; the first term comes from the electron density and

the nuclear charge Ze , and the second can be calculated in the local density approximation (at present one of the best formulas for that potential can be found in Ref. 51). The ion cell is neutral, which allows one to find the electronic chemical potential of the plasma.

Let us note that the direct applications of the AA models are in the field of plasma thermodynamics and not of plasma optical properties. Indeed, the AA models provide reasonable equations of state and mean ionization charges. Their direct use for the calculation of the optical properties is in principle not allowed. That is because the AA quantum orbitals should be considered as auxiliary quantities to construct the electron density. Despite that, various heuristic extensions of the AA model to NLTE situations have been proposed (see, for instance, Ref. 52), especially for rapid calculation of the NLTE opacities needed in hydrodynamic codes. In the NLTE codes the populations of the bound AA levels are determined from collisional-radiative rate equations (see Sec. 10.5.1.7 below). The methods using screened hydrogenic models⁵³ could be especially rapid. One of the recent screened hydrogenic models has been elaborated by Perrot,⁵⁴ who proposed to include l splitting.

10.5.1.2 Detailed configuration accounting method

In principle the formulas describing the interaction of multielectron LTE plasma ions with photons require the calculation of all excited eigenstates of ions of different charges. Even for low- Z elements the number of such eigenstates may be very large. For this reason, at the early stage of the development of the plasma photoabsorption codes, the usual procedure was to avoid the diagonalization of the atomic Hamiltonian. All levels were supposed to have a degenerate energy that could be found without diagonalization.⁵⁵ A configuration can be constructed starting from one-electron subshells (defined by the n, l or n, l, j quantum numbers found in the AA approximation) and choosing integer occupation numbers of these subshells that do not exceed the subshell degeneracies. This set of quantum numbers, together with their integer occupation numbers, defines a detailed configuration. The corresponding self-consistent potential can be calculated for each configuration. One may do that using the density-functional approach or using the restricted HF approximation, which takes the exchange into account explicitly.⁵⁶ Again, as in the case of the AA, the one-electron states obtained from the configuration self-consistent potential cannot be directly used in the formula for the photoabsorption cross sections. However, some early opacity codes were based on ad hoc approximate formulas using the averaged configuration energies. The use of such early direct configuration accounting (DCA) approaches has been criticized in the literature as leading to errors in the bound-bound absorption and emission structures, especially in the case of the $\Delta n = 0$ transitions;^{56,57} a discussion of this issue can be found in Ref. 58.

An important advance that gave the DCA approach a firm theoretical basis is associated with the rigorous statistical methods proposed by Bauche, Bauche-Arnoult, and Klapisch.^{59–62} These methods are based on the notion of the UTA

and its relativistic version, the spin-orbit split array (SOSA). The statistical methods proposed in Refs. 59–62 deal with optical transitions between all states belonging to two different configurations. These transitions form UTAs that can be represented by Gaussian functions of the photon frequency. The three moments characterizing such a UTA can be calculated exactly from closed formulas that can be found in the mentioned literature.^{59–62} The one-electron states of each configuration are usually obtained in a common self-consistent potential calculated for that specific configuration. In the original literature the absorption or emission structures obtained from these moments are usually referred to as UTAs only in the nonrelativistic approach.^{59,60} If the one-electron states are calculated in the relativistic formalism (full Hartree-Fock-Dirac approach or approach based on the Pauli correction⁵⁵), they are referred to in this literature as SOSA absorption or emission structures.⁶¹ The SOSA and UTA approaches have been widely used to interpret opacity measurements in various laboratory plasmas.

10.5.1.3 Configuration interaction

In some cases the optical transitions in dense plasmas cannot be described by a transition array associated with a one-electron transition between well-defined initial and final configurations. In the atomic physics theory this means that in the diagonalization procedure the multielectron levels must be expanded in a basis belonging to two or more configurations. Although in such a situation the terminology based on a one-electron basis cannot be rigorously applied, we will keep using it to refer to the dominating configuration in the multiconfiguration expansion.⁶³ This CI may result in a strong redistribution of the transition probability between the various configurations. A striking illustration of this fact will be given below (Sec. 10.5.3).

Another possible effect is the presence in the spectrum of apparently forbidden electronic transitions due to mixing. For instance, in the Mo^{15+} spectrum, the configuration $3s^23p^63d^84s$ could not deexcite toward $3s^23p^53d^{10}$ via a single-electron dipolar electric transition; but a mixing through CI of the former configuration with other configurations such as $3s3p^63d^{10}$ or $3s^23p^63d^9$ makes the transition possible. Formalisms such as the UTA method or the supraconfiguration approximation cannot include such effects, but detailed methods are usually able to take them into account.

10.5.1.4 Detailed term accounting

There are many situations where a detailed calculation of all relevant lines is necessary. The DCA methods using the UTA and SOSA approximation are of a statistical nature and can be applied when the number of lines is sufficiently large that they form unresolved structures. This is the case for some transitions arrays in medium- and high- Z elements. The detailed lines may be useful for spectroscopy and even to obtain better agreement between the observed and calculated spectra when the statistical methods are not sufficient. The UTA methods may also fail to account for the radiation transfer when the absorption coefficient cannot be approximated

by a smooth function of the photon energy. Moreover, though there exist Monte Carlo methods,⁶⁴ one may be interested in a detailed spectrum involving all the lines when some lines are well isolated or when the CI is important (as was said before, the present statistical methods cannot take account of the CI). Methods for when numerous (tens of thousands, millions, or even more) lines are individually computed are called detailed term accounting (DTA) methods.

The DTA methods require in principle the diagonalization of the Hamiltonian in a multiconfiguration basis. To do this, the codes usually take advantage of the techniques of Racah algebra,⁵⁵ which allows one to derive algebraic expressions for angular momentum matrix elements between basis functions of relevant configurations. These wave functions are described at the fine-structure level in the pure-coupling representation, so that the Hamiltonian matrix is diagonal in the quantum numbers J , M (the total angular momentum of electrons and its projection along a given axis). The Hamiltonian is then diagonalized in each square matrix block of given quantum number J , and the resulting eigenvectors and energies are used to calculate the cross sections for all relevant radiative transitions. This procedure is almost common to all codes. There have been some attempts to use a direct diagonalization of angular momentum operators instead of the Racah algebra,^{58,64} but these methods are not efficient in the case of large numbers of lines.

Among the codes using the Racah algebra, the most popular are Cowan's multiconfiguration Hartree-Fock (MCHF) code,⁵⁶ the multiconfiguration Dirac-Fock (MCDF) codes written by Grant^{65,66} and Bruneau,^{67,68} and the parametric potential code HULLAC written by Bar-Shalom, Klapisch, and Oreg.⁶⁹

10.5.1.5 Superconfiguration approximation

The UTA and SOSA formalisms are also used as an essential part of the superconfiguration approximation.⁷⁰ This approximation is especially useful in medium- and high- Z -element plasmas in conditions in which the number of configurations can be too large for the DCA approach. In the superconfiguration approximation, first proposed in the supertransition array (STA) code,^{70,71} the configurations are grouped into superconfigurations that are close in energy. The self-consistent potential (used to obtain the one-electron basis) is now calculated for each superconfiguration, which means that it is averaged over all configurations belonging to that superconfiguration. The method treats one-electron transitions between all states belonging to two different superconfigurations, starting from the assumption that these transitions can be represented by a Gaussian function of frequency. The three moments characterizing a STA can be calculated via rapid and efficient recurrent formulas^{70,72} at the price of the following approximation: the energy of the configuration C that is used in the Boltzmann probability factor $P_C = A \exp(-E_C/T)$ (A is the normalization factor) has been expressed as

$$E_C \approx \sum_i q_i^{(C)} \varepsilon_i + \left\langle E_1^{(C)} \right\rangle_S.$$

This approximation means that only the term linear in the subshell populations $q_i^{(C)}$ (i runs over all subshells) is taken into account explicitly, while the term quadratic in the population numbers is averaged over the superconfiguration. In practice the assumption seems to be justified when the energy differences between configurations belonging to the same superconfiguration are of the order of the temperature.

It is important to stress that both the UTA and the SOSA approach in the DCA as well as the STA-type methods are based on the assumption that the CI can be neglected. This approximation is usually justified in hot dense plasmas.

As will be seen later, detailed atomic codes such as MCHF and MCDF, and parametric potential codes such as the HULLAC code, bear the common drawback that they require some prior knowledge of the relevant atomic parameters for the emission process. The superconfiguration approximation does not require any a priori knowledge of the relevant ions and transitions involved. For instance, in the case of the SCO code⁷² based on that approach, one has just to define a series of supershells that regroup ordinary nl or nlj orbitals. For a given temperature and density, the SCO code then computes a series of relevant superconfigurations, which are defined by a set of integer population numbers for each supershell, such as $[(1s2s2p)^{10}(3s)^2(3p3d)^6(4s4p4d)^1]$. It consistently includes the thermodynamics (under the LTE hypothesis; but there exist superconfiguration codes SCROLL⁷³ and AVERROES⁷⁴ that take account of the collisional radiative rate equations).

10.5.1.6 Principal available atomic structure codes

We will not be exhaustive here, but instead focus our attention on the codes used in the published articles that attempt to model the emission of a laser-produced xenon or tin plasma source. In these studies, it is necessary to use a code that takes account of the CIs, which are known to be very strong for the $\Delta n = 0$ transitions of interest in the xenon and tin plasma sources (see Sec. 10.5.3). There are many approaches to calculating the radial wave functions of the one-electron basis necessary to construct the coupled many-electron wave functions used to diagonalize the Hamiltonian.

In the HULLAC code,⁶⁹ the Dirac equation is solved in the parametric central potential approximation in order to get the relativistic energies and the one-electron wave functions. The parametric potential is optimized by minimizing the total energy of groups of relativistic configurations. This is a very efficient method, for various reasons: the parametric potential method always gives a solution for each configuration (sometimes at the price of lower accuracy); it provides radial equations even for configurations with several open shells; the exact exchange contribution is included; and finally it produces orthogonal basis functions. Its weak point lies in the relevance of the parametric potential approximation for complex configurations (with several excited electrons), and in the way it groups the configurations for the minimization process. This code was used to model the EXULITE laser-produced xenon plasma source.³⁰

In the Cowan code⁵⁵ or similar MCHF codes, the radial wave functions are calculated by solving the Schrödinger equation for each specified electron configuration using the Hartree-Fock approximation with relativistic extensions (HFR). These codes are widely used in the community, since they are relatively easy to run and can produce results with good accuracy. Such a code is used by Böwering et al.⁷⁵ to model a xenon plasma focus discharge, and also by Churilov et al.⁷⁶ for the interpretation of a xenon vacuum spark plasma. An alternative method, used in the MCDF codes,^{65–68} consists in solving the nonlocal DF equations for each electron configuration of interest. This allows one to take account of the exact exchange contribution to the one-electron basis. This code can produce data of very high accuracy, but the resolution of the self-consistent nonhomogeneous Dirac-Hartree-Fock equations sometimes does not converge in the case of excited configurations, especially when several open shells are involved. A characterization of a laser-produced tin plasma source using calculations with the MCDF code is presented by Cerjan.⁷⁷

10.5.1.7 Collisional-radiative codes

In the situations where the plasma is not in LTE (see Sec. 10.3.3), the densities of the various ionic states cannot be found from the general principles of statistical physics. In the general case, the population kinetics of each excited species is given by a rate equation that represents the population balance due to the microscopic processes in the plasma. The principal radiative and collisional processes involved in the plasma are described in Sec. 10.3.3. The rate equation for the ionic states i reads

$$\frac{dN_i}{dt} = -N_i \sum_{j \neq i} R_{i \rightarrow j} + \sum_{j \neq i} N_j R_{j \rightarrow i}, \quad (10.15)$$

where N_i is the population density (in m^{-3}) of species i , and $R_{j \rightarrow i}$ and $R_{i \rightarrow j}$ (in s^{-1}) are the rates of population and depopulation of species i due to the various processes in the plasma. The set of coupled rate equations, one for each ionic state, must be solved simultaneously in order to obtain the population kinetics. Therefore, an essential characteristic of a collisional-radiative code is the representation of the ionic states of the plasma, which will determine the size of the rate equations to be solved, and thus the numerical cost of the method.

In the HULLAC code⁶⁹ or other DTA codes,^{65–67} ionic states are described at the fine-structure level, including the configuration interactions. This is clearly the pertinent approach to model emission structures that are known to be sensitive to the CI effects. However, this method can require a very large number of levels in order to obtain a correct calculation of population kinetics and of the emission features in the spectrum. This is particularly true for the laser-produced xenon or tin plasma sources of interest, in which ions may have one or several open shells. In practice, for these applications, only a limited number of parent configurations

(which are split into detailed multielectron levels by the code) can be taken into account.

In order to limit the number of ionic states while keeping a realistic description of the plasma, it is possible to use collisional-radiative codes based on the superconfiguration approach,^{70,72} described in Sec. 10.5.1.5. In the SCROLL code,⁷³ an iterative process is used to define the supershells, starting from a single supershell gathering all orbitals, and refining the supershells till the spectrum converges. The AVERROES⁷⁴ code defines the supershells as Layzer complexes, i.e., by grouping orbitals of the same principal quantum number n . In practice, this allows one to reduce the number of relevant superconfigurations to a few hundred. The populations of the superconfigurations obey a set of rate equations similar to Eq. (10.6), except that the global transition rates are computed as average values of the configuration-configuration rates belonging to the superconfigurations. Though these codes cannot allow for the configuration interactions, they can easily take into account all relevant ions and their configurations. They can be useful for estimating the non-LTE ionic distribution, and for providing information on the relative strength of different bound-bound transitions, as well as the bound-free spectrum.³⁰

In the SCAALP code⁷⁸ and the similar non-LTE AA model^{79,80} introduced in Sec. 10.5.1.1, a single fictitious electron configuration populated with a noninteger number of electrons is used to represent the average excited species of the plasma. The description of the electron structure with this single-configuration approximation is too coarse to produce a representative emission spectrum of the plasma, but it can be used to initialize a (noninteracting) detailed-configuration accounting approach (see Sec. 10.5.1.2) resulting in a more detailed spectrum.⁵² A similar approach has been proposed in Ref. 80, in which the AA wave functions are used in order to construct detailed configurations and calculate their optical and collisional transition rates. To ensure the convergence of the code to the LTE limit, detailed balance is applied between the collisional rates and their inverse processes. But the *ab initio* formulation of the transition rates and the approximations used to calculate them are not always unique. Empirical formulas, fitted to experimental data, may exist also. In the third non-LTE kinetics workshop,⁸¹ held in 2003 at Gaithersburg, a significant dispersion between results of non-LTE codes a priori similar has been observed in several cases. Actually, realistic non-LTE calculation is still an open problem.

10.5.2 Radiation transfer models

10.5.2.1 Elementary radiative transfer and Kirchhoff's law

Studies of radiation transfer are very important in LPPs. Radiation is a critical energy transport (and loss) mechanism and is also a key part of the ionization-recombination balance. Much of the early work on radiation transfer was done in the context of astrophysics, and there is an extensive astrophysical literature on the subject (see, for instance, Ref. 82).

The most common macroscopic description of the interaction of matter with radiation uses the equation of radiative transfer, which describes the balance between emission, absorption, and transport of photons:

$$\frac{dI_\nu}{ds} = \left(\frac{1}{c} \frac{\partial}{\partial t} + \boldsymbol{\Omega} \cdot \nabla \right) I_\nu(s) = \eta_\nu(s) - \alpha_\nu(s) I_\nu(s), \quad (10.16)$$

where s is measured along the beam in the propagation direction, and I_ν is the specific intensity (in $\text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1}$). The quantities α_ν and η_ν are the macroscopic absorption (in m^{-1}) and emission (in $\text{W m}^{-3} \text{Hz}^{-1} \text{sr}^{-1}$) coefficients, respectively, which ultimately derive from the microscopic processes. The specific intensity I_ν is proportional to the photon distribution function, and Eq. (10.7) can be recognized as a Boltzmann equation with the absorption and emission terms arising from collisions between photons and matter.

The formal solution of Eq. (10.16) (i.e., for specified emission and absorption) can be written analytically as

$$I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu} + \int_0^{\tau_\nu} S_\nu(\tau'_\nu) e^{-(\tau_\nu - \tau'_\nu)} d\tau'_\nu, \quad (10.17)$$

where $S_\nu = \eta_\nu/\alpha_\nu$ is called the source function, and τ_ν (dimensionless) is the optical depth of the plasma, defined by the formula

$$\tau_\nu(s) = \int_0^s \alpha_\nu(s') ds'. \quad (10.18)$$

The first term on the right-hand side of Eq. (10.17) represents the attenuation along the ray of the external radiative field of intensity $I_\nu(0)$, whereas the second term is the self-emission of the plasma in that direction. This expression illustrates several important points. For optically thick material (i.e., $\tau_\nu \gg 1$), the intensity approaches the source function: $I_\nu \rightarrow S_\nu$. For optically thin material, I_ν need not have any relationship to the local value of S_ν , but is directly determined by values of S_ν within about one optical depth. Finally, the emission spectrum measured along a line of sight corresponds to photons that escape the plasma within about one optical depth of the surface. This point is particularly important for the interpretation of spectra from a nonuniform plasma, as the observed intensity at different frequencies reflects conditions at different depths into the plasma.

For a system in thermal equilibrium, emission and absorption must balance, resulting in Kirchhoff's law:

$$\eta_\nu = B_\nu \alpha_\nu, \quad (10.19)$$

where $B_\nu(T)$ is the Planck function:

$$B_\nu(T) = \frac{2\pi h \nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}. \quad (10.20)$$

This property is a consequence of the principle of detailed balance in a system with a Maxwellian electron distribution. Although this relationship does not hold in general, it often provides a handy benchmark for quick estimates.

A simple way to estimate the emission spectra is to assume that the plasma is nearly homogeneous and can be characterized by a single electron temperature and ion density. This allows one to simplify the expression of the self-emission and get

$$I_{\nu}(\tau_{\nu}) = S_{\nu}(1 - e^{-\tau_{\nu}}). \quad (10.21)$$

For example, let us consider a plane target irradiated with a laser pulse at normal incidence. Equation (10.21) represents a reasonable approach to model the emission spectrum measured in the transverse direction, because the lateral expansion of the plasma is almost self-similar with limited gradients of temperature and density. On the other hand, Eq. (10.21) is not well suited to simulate the emission intensity of the plasma measured longitudinally along the beam axis, since in that direction larger gradients can be expected. However, even in the latter case, fitting the emission spectrum with Eq. (10.21) allows one to estimate roughly the mean properties of the plasma (average temperature and density, optical depth). The effect of reabsorption on the emission spectrum of a laser-produced xenon source was qualitatively studied in Ref. 30 using Eq. (10.21) under the assumption of LTE, i.e., for

$$S_{\nu} = B_{\nu}(T). \quad (10.22)$$

A similar approach was used in Ref. 75 to model DPPs, with the source function evaluated in coronal equilibrium. In the previously cited thesis,³¹ it is shown that reabsorption can substantially modify the ratio between the main emission band at 10 nm, due to the 4d-4f and 4p-4d transition arrays mixed by configuration interaction and originating from Xe^{10+} to Xe^{13+} , and the emission structures at 13.5 nm, due to 4d-5p transitions of Xe^{10+} .

The radiative transfer equation written in the form Eq. (10.17) is deceptively simple in that it hides the fact that the absorption and emission coefficients depend on the local properties of the material (temperature, density, population distributions), which themselves depend on the radiation field. The radiation introduces a nonlinear coupling between different physical processes (e.g., in hydrodynamic and cross-section calculations) by altering the energy balance, ionization balance, and excited-state distributions. It also introduces a nonlocal coupling through photon transport, which can extend well beyond the simple estimate of one optical depth. Specialized computational techniques are used to self-consistently solve for the radiation field along with the material properties. Codes such as CHIVAS,³² mentioned in Sec. 10.4.3, treat these problems in a consistent manner, using greatly simplifying approximations (screened-hydrogenic AA model for atomic physics, multigroup diffusion approach to radiation transfer, etc.) in order to keep computation times reasonable. Codes such as CRETIN⁸³ attempt to self-consistently

combine more detailed atomic-physics treatments with general radiative-transfer algorithms, particularly for situations where important lines are optically thick.

10.5.2.2 Radiation diffusion; Planck and Rosseland mean absorption coefficients

From the solution (10.21) of the radiation transfer equation, we can anticipate different behaviors in two separate regimes with respect to the optical depth: the optically thick limit ($\tau_\nu \gg 1$) and optically thin limit ($\tau_\nu \ll 1$). This is true for computational methods as well. Both these regimes play an important role in LPPs.

In plasmas that are optically very thick, the radiation at large optical depths will be nearly isotropic. In this case, the radiative-transfer equation can be well approximated by a diffusion equation:

$$\frac{1}{c} \frac{\partial J_\nu}{\partial t} - \nabla \cdot \frac{1}{3\alpha_\nu} \nabla J_\nu = \eta_\nu - \alpha_\nu J_\nu, \quad (10.23)$$

where

$$J_\nu = \frac{1}{4\pi} \int d\Omega I_\nu. \quad (10.24)$$

This set of equations is significantly smaller and simpler than Eq. (10.16), inasmuch as the description of the radiation is no longer angle-dependent and the diffusion equation is easier to solve than the Boltzmann equation. The implicit non-linear dependence between the radiation and the material properties remains the same.

If we also assume that the spectrum is nearly Planckian, then the correct frequency-integrated flux can be obtained with the Rosseland mean absorption coefficient α_R ⁸²:

$$\frac{1}{\alpha_R} = \frac{\int_0^\infty (1/\alpha_\nu) d/dT[B_\nu(T)] d\nu}{\int_0^\infty d/dT[B_\nu(T)] d\nu} = \frac{\pi}{4\sigma T^3} \int_0^\infty \frac{1}{\alpha_\nu} \frac{dB_\nu(T)}{dT} d\nu, \quad (10.25)$$

where σ is the Stefan–Boltzmann constant ($5.67 \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ K}^{-4}$). The inverse mean weights the most transparent frequencies highest, because this radiation can transport energy most easily. The importance of the most transparent frequencies is common to all applications of radiative transfer. The Rosseland mean must be used with care, in that it requires that all significant frequencies be optically thick.

If we instead wish to obtain the correct amount of emitted energy, then the appropriate mean absorption coefficient is the Planck mean α_P , defined by

$$\alpha_P = \frac{\int_0^\infty \alpha_\nu B_\nu(T) d\nu}{\int_0^\infty B_\nu(T) d\nu} = \frac{1}{\sigma T^4} \int_0^\infty \alpha_\nu B_\nu(T) d\nu. \quad (10.26)$$

This is most appropriate in the optically thin limit, i.e., when $\tau_\nu \ll 1$. In this case, no significant reabsorption occurs in the plasma, and the emerging intensity is given by the intensity integrated over the path length:

$$I_\nu(L) = \eta_\nu L. \quad (10.27)$$

This is a good approximation for the coronal region of the LPP, which is characterized by a very low density and a high temperature. The maximum of the emission intensity is obtained in the LTE limit, when the total net flux is roughly equal to $F \approx L \alpha_p \sigma T^4$. Again, this approximation must be used with care, for an optically thin plasma is frequently not close to LTE.

Although the applicability of the full Rosseland and Planck mean absorption coefficients is quite restricted, their frequency-dependent analogs are very useful in the multigroup diffusion approximation. Here, the radiation field is discretized in frequency, and the absorption and emission coefficients are averaged over a single frequency interval:

$$\frac{1}{c} \frac{\partial J_\nu}{\partial t} - \nabla \cdot \frac{1}{3\alpha_\nu^R} \nabla J_\nu = \eta_\nu - \alpha_\nu^P J_\nu. \quad (10.28)$$

This equation is used heavily for radiation-hydrodynamics calculations and does quite well in many applications, due to the use of the two absorption coefficients with their different properties. However, the restriction to (near) LTE situations remains.

For conditions far from LTE, it is usually the case that some significant portion of the spectrum is optically thin and the full radiative-transfer equation must be solved. The main complication arises from the fact that photons can be emitted and reabsorbed many times in optically thick spectral regions before being emitted, and escaping, in an optically thin spectral region. This behavior is reflected in slow convergence rates for the numerical solution unless special techniques are used. Developing general techniques that can be used with the variety of atomic models mentioned above remains an area of active research.

10.5.3 Influence of atomic physics on models

The atomic physics of multiply charged ions relevant for nanolithography, either xenon or tin, is mainly related to the 4d-4f and 4d-5p transition arrays' properties. They will be discussed first; then we will focus on their consequences for the tin emission spectrum as calculated by the HULLAC code, and finally we will examine to what extent the SCO code may describe the plasma emission.

10.5.3.1 Atomic-physics properties of the 4d-*n*f and 4d-*np* transitions

A first significant feature concerns the evolution of the repartition of the 4d- ϵ f oscillator strength as a function of the f electron energy ϵ . It is known that the

effective potential acting on the f electrons has a double well resulting from a competition between the electrostatic potential and the centrifugal barrier. For neutral xenon and its low-charge ions (charge ≤ 4), the $4d\text{-}\epsilon f$ oscillator strength belongs mostly to the bound-free spectrum, resulting in a *giant resonance* in the continuum.^{30,84} For large ion charge states, the $4f$ wave function collapses in the inner well and the main oscillator strengths shift to the $4d\text{-}4f$ transition, since the $4d$ and $4f$ wave functions significantly overlap.

The second effect present in Xe and Sn ions is the CI. For two decades, in particular owing to the work by Mandelbaum et al.⁸⁵ on highly charged lanthanide ions, it has been well known that CI is present in the excited states belonging to $4p^6 4d^{N-1} 4f$ and $4p^5 4d^{N+1}$ configurations. This CI may result in the quenching of many lines, and it may strongly shift and narrow transition arrays associated with the lines between the $4p^6 4d^N$ ground state and the above-mentioned excited states. A similar effect in the case of Cs has been described by Cummings and O'Sullivan.⁸⁶ Moreover, in praseodymium ($Z = 59$) it was demonstrated that the position of the resulting structure depends weakly on Z^* (i.e., on the net ion charge), and therefore the corresponding arrays for the various ions coalesce in a strong structure. The same observation has been made for similarly charged Xe ions at the tokamak of Fontenay-aux-Roses,⁴⁰ and confirmed by synchrotron-radiation photoionization experiments by Bizau et al.⁸⁴

As pointed out in a previous publication,³⁰ this effect strongly narrows the 100–110-Å emission band from the xenon plasmas typical for the XUV lithography experiments, while it hardly affects the 135-Å lines in the Xe^{10+} ion. This is due to the fact that the 100–110-Å band comes from $4\text{-}4$ transitions, while the 135-Å structure is mainly associated with the $4d\text{-}5p$ lines, weakly perturbed by CI effects.

10.5.3.2 Results from the HULLAC code; CI effects in Sn^{9+}

In Sn the CI effect manifests itself differently, since in this case the main emission band due to the $4\text{-}4$ transitions is in the wavelength region relevant for nanolithography, at 135 Å. This is shown in Figs. 10.7 and 10.8, where we display the emission spectra of the Sn^{9+} ion in the 90–200-Å range, computed with CI included (Fig. 10.7) or not (Fig. 10.8). The following configurations have been included: $4p^6 4d^5$ for the lower state, $4p^5 4d^6$, $4p^6 4d^4 5p$, $4p^6 4d^4 6p$, and $4p^6 4d^4 4\text{-}6f$ for the excited states, with a common closed core $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2$. It has been checked that on adding excited states like those considered by O'Sullivan⁴³ ($4p^6 4d^4 5s$, $4p^6 4d^4 5d$, $4p^6 4d^4 7\text{-}8p$), the emission spectrum is not drastically changed in the 90–200-Å region, the only noticeable difference being a small background signal appearing in the 90-Å region.

The effect of CI described above can be observed in Figs. 10.7 and 10.8. Without CI, the $4d\text{-}4f$ lines appear as a large structure ranging from 130 to 170 Å; they are mixed with the $4p\text{-}4d$ lines—which are widely distributed in the 120–180-Å region—and overlap slightly with the $4d\text{-}5p$ structure around 175 Å. The isolated structure in the 100–110-Å region is associated with the $4d\text{-}5f$ lines. When CI is

included, the mixing of configurations $4p^5 4d^6$ and $4p^6 4d^4 4f$ results in a strong narrowing of the broad structure, which is now precisely centered in the 130–140-Å region for the Sn^{9+} ion, which could be important for the nanolithography applications.

In the present computations, we did not take account of the free-bound emission, but it is not expected to play a major role, as indicated by the similar analysis of Xe ions.³⁰ Figure 10.9 corresponds to a low-density case (mass density 0.01 g/cm^3 , i.e., ionic density $5.1 \times 10^{19} \text{ cm}^{-3}$; medium length $L = 20 \text{ }\mu\text{m}$), where continuum lowering remains negligible. This plot will be further discussed in Sec. 10.5.4. The continuum emission could play a more important role at higher densities. Besides, a HULLAC computation of the Sn^{11+} ground-state position gives an ionization potential of 184.5 eV for the Sn^{9+} ion, in good agreement with the 184.3-eV value computed by Cerjan⁷⁷ with Grant's MCDF code. This implies

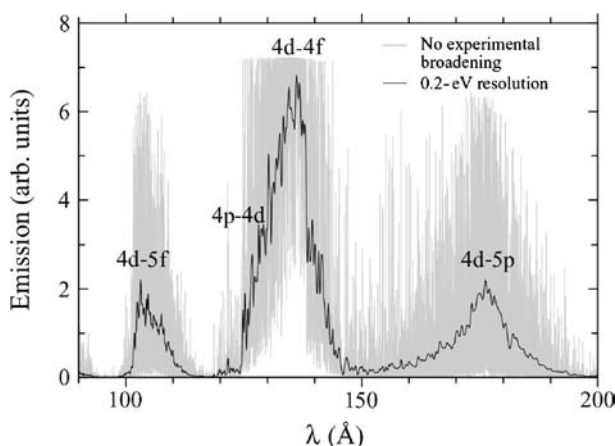


Figure 10.7 HULLAC computation of Sn^{9+} emission spectrum including CI.

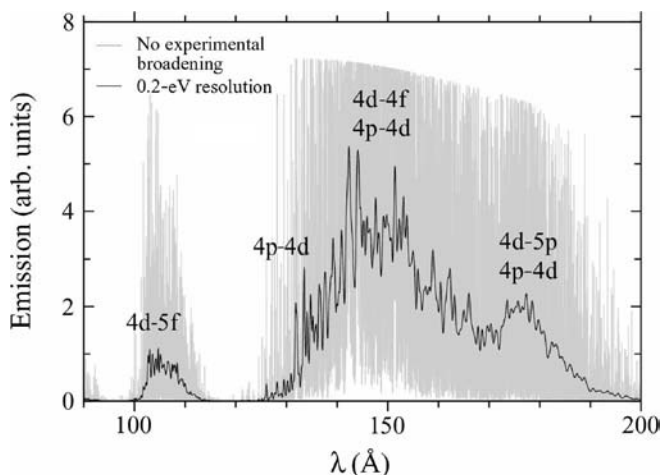


Figure 10.8 HULLAC computation of Sn^{9+} emission spectrum without CI.

that for the displayed wavelengths greater than the threshold at 67.2 Å (corresponding to 184.5-eV photon energy), singly excited states Sn^{9+} do not autoionize.

We see in Figs. 10.7 and 10.8 that the 100–110-Å structure, attributed to the 4d-5f transitions, keeps the same shape with or without CI, although the absolute emission is much higher with CI included. Similarly, the peak at 175 Å from the 4d-5p transitions remains unchanged when CI is included. Finally, when CI is included, some prominent 4p-4d lines appear on the short-wavelength side of the main 130–140-Å peak.

The present analysis corroborates previous results on xenon,³⁰ but bears a special meaning in that the narrowing of the array concerns the 135-Å region. Moreover, in the case of tin, a series of charge states must be included here, while in the case of xenon the 135-Å signal was due mostly to the unique Xe^{10+} charge state.

Another potentially important effect is the influence of doubly excited atomic states on the emission spectra. Although their Boltzmann factor is small, they are numerous and in principle should not be neglected. We have done some preliminary calculations on Sn^{9+} and obtained resulting spectra in which numerous lines appear in the 140–170-Å region, which tend to fill the gap between the 4d-4f and 4d-5p structures. However, this approach may be viewed as questionable, since we could not take the autoionization broadening correctly into account.

10.5.3.3 Tin emission calculated from the SCO code

Results obtained in Sn with the SCO code at 30 eV are presented in Fig. 10.9. This spectrum offers a striking overall analogy with the HULLAC computations without CI effects (Fig. 10.8), except for the 4d-5f structure around 100 Å, which is missing here. The similarity between Figs. 10.7 and 10.8 is not surprising, since

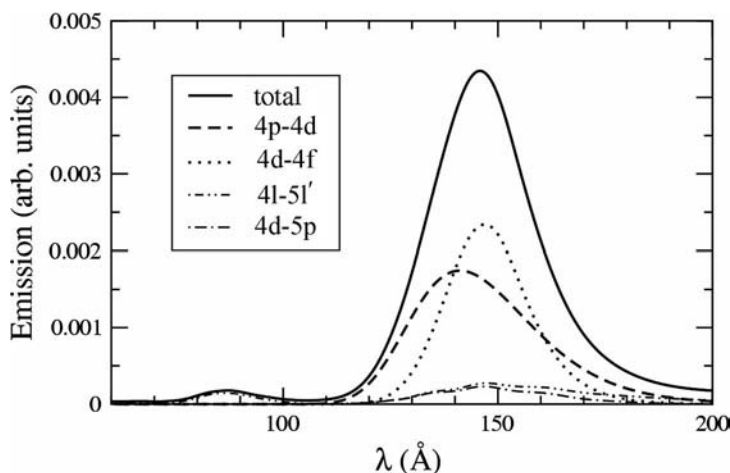


Figure 10.9 Emission spectrum of tin at 30 eV according to the superconfiguration code SCO, in arbitrary units. The mass density is 0.01 g/cm³, i.e., 5.1×10^{19} ions/cm³, and the areal density 2×10^{-5} g/cm². The SCO computation does not lead to any noticeable contribution from the 4d-5f transitions.

the SCO code obviously does not include CI. The average charge is 10.55, and the ion charge distribution is 1.76×10^{-2} , 0.131, 0.325, 0.355, 0.147, 2.20×10^{-2} for Sn^{8+} to Sn^{13+} ions, respectively.

The superconfiguration formalism allows us to detail the contribution of each mono-electronic transition. In this figure we have therefore singled out the 4p-4d, 4d-4f, and 4l-5l' transitions. The large structure around 145 Å mainly originates from 4p-4d and 4d-4f transitions. The $\Delta n \neq 0$ transitions 4l-5l' play a lesser role there, but contribute also to the main peak. The small peak close to 87 Å can be associated to the 4p-5s transitions. Within this formalism, no noticeable contribution from the 4d-5f transitions is observed, at variance with the HULLAC Sn^{9+} results detailed above. Finally, one must notice that the 30-eV temperature has been chosen in order to compare emission in tin and xenon (see next section), but in the tin case HULLAC computations have demonstrated that the best candidate for 135-Å emission is Sn^{9+} , and therefore optimal emission conditions would require a lower temperature.

It has been checked with the SCO code that, in the current domain of density and temperature, the contribution of bound-free and free-free transitions is moderate. A more detailed computation using the HULLAC code confirms the small importance of the continuum in the usual conditions for nanolithography. However, because of pressure ionization, an increase of the ion density favors these transitions³⁰: at $5 \times 10^{-2} \text{ g/cm}^3$ ($2.5 \times 10^{20} \text{ ions/cm}^3$), a SCO calculation demonstrates that about 5% of the main emission peak at 112 Å comes from the continuum contribution; at 0.3 g/cm^3 ($1.5 \times 10^{21} \text{ ions/cm}^3$), most of the emission is due to bound-free or free-free transitions.

10.5.4 Examples of emission spectra and comparison with experiment

Though a large amount of effort has been devoted to the spectroscopic analysis of multiply charged ions present in LPP, detailed comparisons of computed and experimental emission spectra are rather scarce. In this respect we must quote the pioneering work by Cerjan⁷⁷ on solid Sn targets irradiated by 1064-nm 7.5-ns pulses. He obtained only rough agreement between experimental spectra and MCDF computations. Oddly enough, this work does not emphasize the prominent effect of the Sn^{9+} ion on the emission spectra (though the special importance of 133-Å radiation, related to the availability of efficient Mo/Si mirrors, is mentioned), but large structures are observed close to 80–100 eV (125–155 Å) and 140–170 eV (70–90 Å, a range not covered in the present analysis). Moreover, one must mention more recent and accurate comparisons in Xe by Böwering et al.,⁷⁵ but this work refers to discharge plasmas, which fall a little outside the scope of this chapter devoted to LPPs. We describe below the theoretical analysis of the spectrum obtained by the EXULITE team from the xenon-droplet-spray target, described in Sec. 10.4.4.

Assuming a mass density of 0.01 g/cm^3 , i.e., a density of 4.6×10^{19} ions per cm^3 , and a 30-eV temperature, we have calculated and analyzed the SCO emission spectrum corresponding to that xenon plasma. Principal quantum numbers as high as 10 have been considered; we have used the following five supershells: (1s2s2p3s3p3d4s), (4p), (4d), (4f), (5s–10m). The emission spectrum is displayed in Fig. 10.10. The computed average charge is 10.66, and the ion populations are 1.99×10^{-2} , 0.114, 0.297, 0.357, 0.177, 3.16×10^{-2} for Xe^{8+} to Xe^{13+} ions respectively. These populations are quite similar to the Sn case. Most of the conclusions about the Sn emission spectrum apply here too.

Since the atomic number of xenon is greater than that of tin, the main broad emission structure for a 30-eV plasma is shifted toward lower wavelengths, with a maximum close to $112 \text{ \AA}$. Comparison of Fig. 10.10 with the tin spectrum (Fig. 10.9) even suggests that the element next to tin in the periodic table, antimony, might be a better candidate for the $135\text{-}\text{\AA}$ emission. The present analysis demonstrates that the dominant contribution comes from the 4d-4f lines. Smaller structures may be attributed to the 4p-4d lines (around $130 \text{ \AA}$) and the 4l-5l' lines, noticeably at $70 \text{ \AA}$ (4p-5s) and $125 \text{ \AA}$ (4d-5p). The main peak at $112 \text{ \AA}$ is sensitive to the coupling scheme: a *jj* coupling would give incorrect results, different from the present intermediate-coupling data; in contrast, the 4p-5s structure at $70 \text{ \AA}$ does not depend on the coupling type.

As in tin, in xenon the contribution from bound-free and free-free transitions analyzed with the SCO code proved to be negligible in this range of ionic density; however, when the density becomes $5 \times 10^{-2} \text{ g/cm}^3$ ($2.3 \times 10^{20} \text{ ions/cm}^3$), more than 5% of the main peak comes from the continuum contribution, while at 0.3 g/cm^3 most of the emission would arise from it.

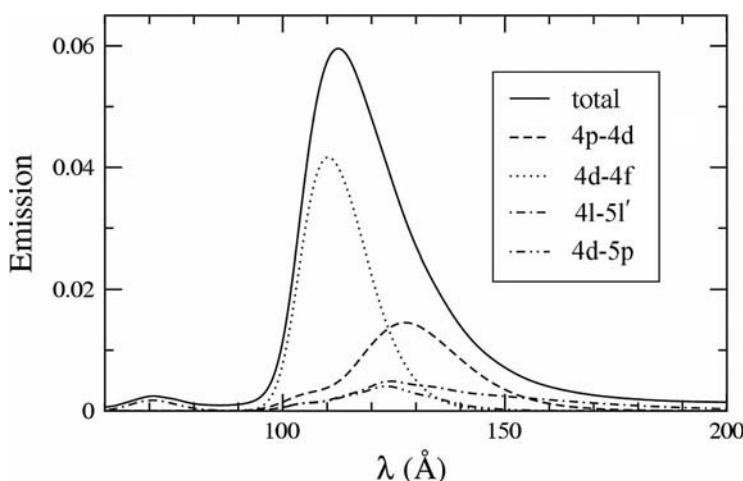


Figure 10.10 Emission spectrum of xenon at 30 eV according to the SCO code, in arbitrary units. The mass density is 0.01 g/cm^3 , i.e., $4.6 \times 10^{19} \text{ ions/cm}^3$, and the areal density $5 \times 10^{-4} \text{ g/cm}^2$. The contribution of the various main mono-electronic transitions is singled out.

In a previous work,³⁰ we were able to calculate theoretical spectra for a Xe EUV emission source starting from an assumption of LTE and using the solution [see Eqs. (10.21) and (10.22)]

$$E(\nu) = B(\nu)\{1 - \exp[-K(\nu)L]\} \quad (10.29)$$

of the radiative transfer equation. It has been demonstrated there that the emissive properties associated with the 4d-5p transitions in the 135-Å region may be satisfactorily modeled assuming a 26-eV ionic temperature, a 0.01-g/cm³ mass density (i.e., 4.6×10^{19} ions/cm³), and a 40-μm active medium length. This last value has been confirmed by an elementary analysis of the droplet expansion, starting with a sound velocity at the 30-eV temperature equal to 1.7×10^6 cm/s and a pulse duration of the order of 8 ns.

To account for the emission from the relevant ionic states in a formalism including configuration interaction, computations have been made on Xe⁸⁺ to Xe¹³⁺ spectra using HULLAC code. The ionic distribution has been derived from the Saha–Boltzmann ionization equation. A typical spectrum is presented in Fig. 10.11, along with a comparison with experimental data from laser-irradiated Xe droplets. The overall agreement is acceptable, especially in the 135-Å region. The large structure close to 110 Å is broader in the numerical simulation than in the experiment. It has been established that significantly better agreement may be ob-

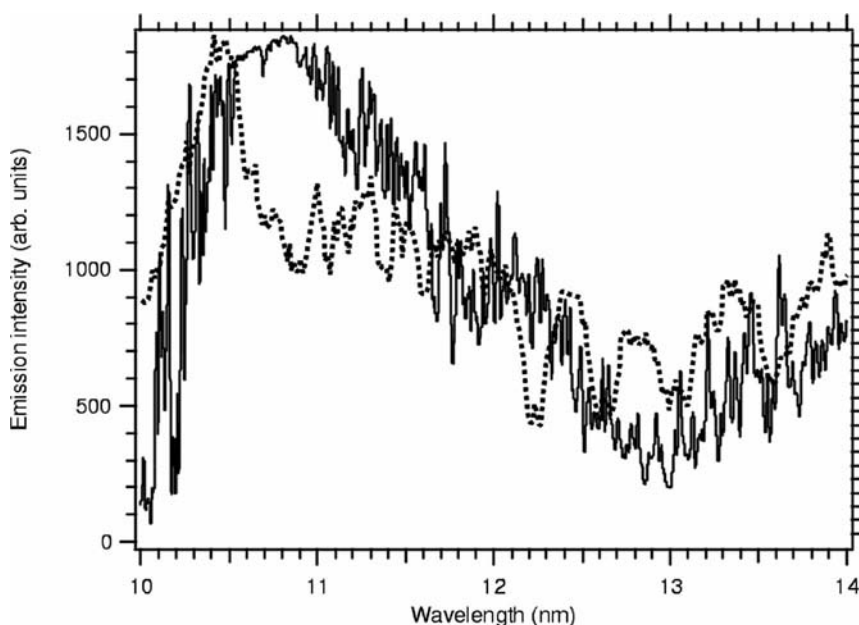


Figure 10.11 Emission intensity of a xenon droplet target irradiated by 8-ns 1-J YAG laser pulses (dotted line), compared with a HULLAC computation assuming a 26-eV temperature, 0.01-g/cm³ mass density, and 40-μm slab thickness (solid line).

tained in this region by assuming a lower temperature (about 22 eV). This suggests that temperature gradients are probably important in the active region.

10.6 Future Trends

This review outlines the detailed theory involved in laser plasmas and the complex radiation physics involved in the emission of EUV light from plasmas created from materials such as Xe and Sn, and summarizes the current computer models being used to make realistic predictions of this emission. We have shown how hydrodynamic plasma codes such as Med 103 and CHIVAS effectively model the plasma expansion and simulate the electron density and temperature distributions. We have described a number of collisional-radiative codes used to describe LTE and non-LTE AA-based models for estimating the relative ion abundance, excitation, and emission (SCROLL, AVERROES, SCAALP, and HULLAC) and made comparisons of experimental data with HULLAC. Towards acquiring a more comprehensive non-LTE model of the emission from these plasmas, we are implementing the non-LTE radiative-transfer CRETIN code. In CRETIN, each element in the plasma is modeled with numerous atomic states, corresponding to the distribution of electrons in various atomic levels. Transitions between levels are caused by interactions between electrons, ions, and photons. CRETIN itself contains no atomic data. The level structure and transition processes for each element included in a simulation are specified in an external data file, referred to as an atomic model. We

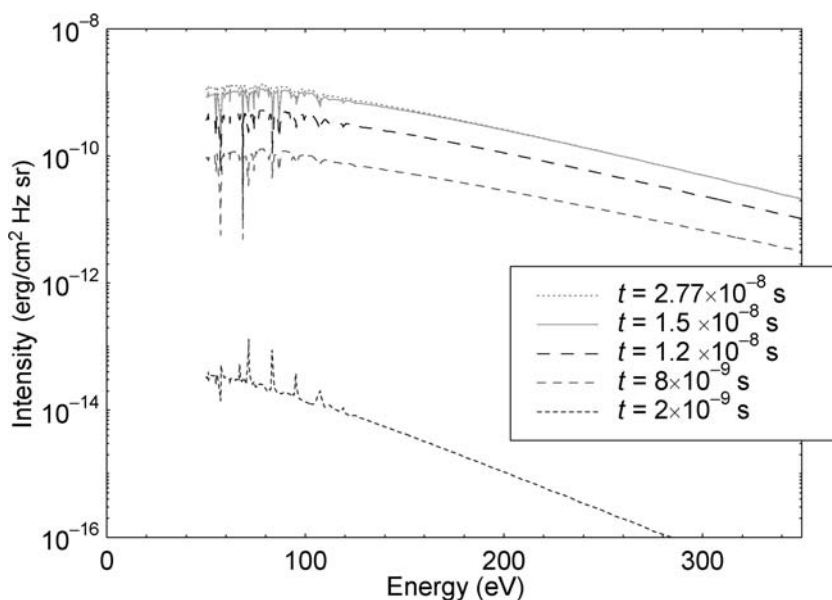


Figure 10.12 Simulated time-integrated detector spectra for several times after laser impinging on the target. The intensities are calculated for one position at the outer end of the plasma.

are currently using atomic codes such as COWAN and FAC to calculate these data. For reasons of convenience, fits to hydrodynamics parameters are currently used to drive the CRETIN simulations, rather than using the hydrodynamic results directly. The fit can easily be extended or modified to investigate different scenarios without redoing the hydrodynamic simulation. Simulated detector spectra are shown in Fig. 10.12 for one position, integrated over time. More detailed calculations are in progress.

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Chapter 11

Conversion Efficiency of LPP Sources

Katsunobu Nishihara, Akira Sasaki, Atsushi Sunahara, and
Takeshi Nishikawa

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11.1 Introduction

Some EUV light sources have been promoted that use LPPs, and some that use DPPs (see, for example, Ref. 1). Although each proposed source has significant advantages, the LPP offers an especially attractive prospective application range due to advances in laser technology and tunability of the source emission by target-material selection. The LPP EUV light source also has the advantages of small source size, due to the focusability of the laser, and less debris in that the target is isolated from the energy driver. Many of the sources under consideration use 13.5-nm radiation from multicharged xenon, tin, and other low- Z ions, because Mo/Si multilayer mirrors have high reflectivity at this wavelength.

One key requirement in the source development is a high conversion efficiency (CE) from the incident laser energy on the target to 13.5-nm EUV emission energy in a 2% bandwidth over 2π sr. Figure 11.1(a) summarizes recent experimental values of the CE for various types of targets, such as the xenon liquid jet,^{2–8}

xenon cluster jet,⁹ cryogenic xenon,¹⁰ frozen xenon,^{11,12} solid tin,^{13–16} and liquid tin jet.^{17,18} A CE of a few percent is achieved for tin, and a relatively small CE of $\leq 1\%$ is obtained for xenon. Most of the inband radiation is due to line emissions

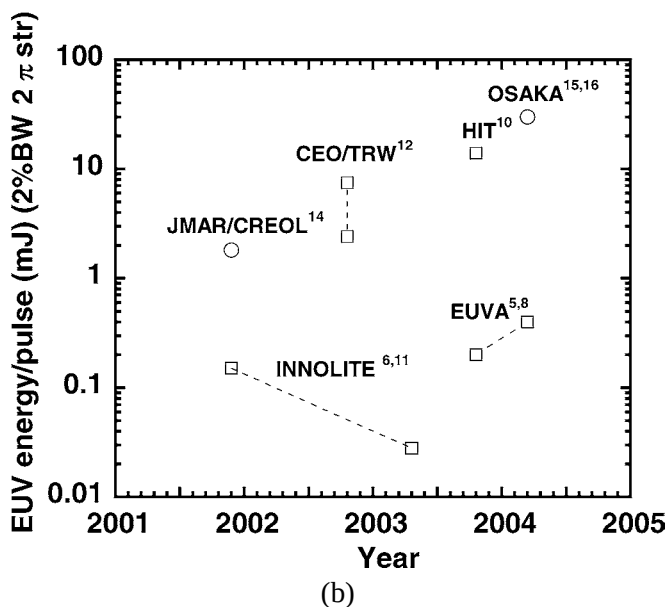
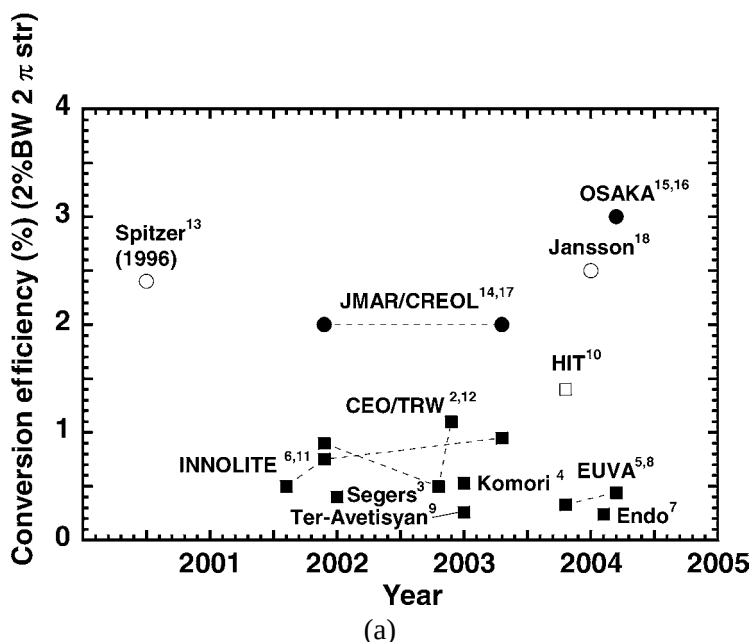


Figure 11.1 (a) Recent experimental values of the CE for xenon (squares) and tin (circles). Open symbols indicate estimated values and superscripts denote reference number. (b) 13.5-nm EUV energy with 2% bandwidth per shot.

corresponding to 4d-5p transitions of Xe^{10+} ions and 4d-4f and 4p-4d transitions of Sn^{8+-12+} ions. In addition to xenon and tin, the CE of other materials has also been measured, such as water jets¹⁹ and mixtures of low-Z materials.²⁰ However, their CEs are small compared to those of xenon and tin. Therefore, we consider only xenon and tin targets in this chapter. The 13.5-nm EUV radiation energy per pulse must exceed a certain value for practical use, as will be discussed in the next section. Figure 11.1(b) shows some experimental results on the radiation energy in a 2% bandwidth over 2π sr.

Since the electron temperature should be around 20–50 eV for xenon and tin to emit EUV inband photons, there exists an optimum laser intensity to heat plasma to that range. Since laser absorption occurs only near a target surface and a laser-produced hot plasma expands into vacuum, no stationary plasma exists. Therefore, spectral consideration is not enough to obtain the optimum laser intensity, and we must consider the dynamics of the LPP. We have developed a power balance model²¹ to investigate the CE and its laser intensity dependence, which shows fairly good agreement with experiments, at least for tin.

In Sec. 11.2, we discuss a possible design window²¹ for a source plasma for practical use. The power balance model is described in Sec. 11.3. We briefly present atomic models and radiation hydrodynamic code used for the evaluation of the CE in Sec. 11.4. Section 11.5 is devoted to comparison with experiments, and to discussion of the laser-wavelength dependence of the CE for tin and of the effects of satellite lines and opacity on the CE for xenon. A discussion and summary are given in Sec. 11.6.

11.2 Design Window for Practical Use

The requirements on the light source for lithography are the following²² (see Chapter 2 for details): the EUV power at wavelength 13.5 nm within a 2% bandwidth should be greater than 115 W after intermediate focus (IF), with a repetition rate of 7–10 kHz, an etendue of 1–3 mm² sr, and a CE greater than 1%. In this section we estimate a possible design window for a source plasma that may emit enough inband radiation to satisfy the requirements for the light source. We here assume the following parameters for a focusing system for EUV light from the source to the IF point: solid angle of the collection mirror, $\Omega = 5$ sr ($\varepsilon_{\Omega} = 5/2\pi = 0.8$); reflectivity of the collector optics, $\varepsilon_R = 0.55$; transmittance through the debris mitigation system, $\varepsilon_{tm} = 0.9$; and transmittance through the debris collector, $\varepsilon_{td} = 0.8$ (see Chapter 34 for details). In order to achieve an EUV power of 115 W after the IF, the EUV power at the source should then be 365 W [= (115 W)/ $\varepsilon_{\Omega}\varepsilon_R\varepsilon_{tm}\varepsilon_{td}$], and the EUV energy per shot is then $E_{\text{EUV}} = 37$ mJ for a repetition rate of 10 kHz and 52 mJ for one of 7 kHz. The achieved EUV energies shown in Fig. 11.1(b) are smaller than the required value except for those at Osaka.^{15,16} The radiation source area, $S = \pi r^2$, should correspond to a diameter $\phi = 2r = 500\text{--}870$ μm in order to achieve the etendue of 1–3 mm² sr (= $S\Omega$), if the light from the source within a solid angle of 5 sr is collected. It should be noted that the etendue of an LPP is

mainly determined by the plasma diameter, since the plasma thickness is smaller than the diameter, as will be discussed below.

Since the plasma expansion speed is determined by the ion sound speed c_s , the diameter of the source plasma can be larger than the plasma expansion distance, if $\phi > c_s \tau_L$, where τ_L is the laser pulse duration. The laser spot sizes in most of the present experiments are much smaller than 500 μm , and thus lateral heat conduction loss and multidimensional expansion loss cannot be neglected. However, for a diameter of 500 μm , a regime of 1D expansion can be achieved without significant lateral heat conduction loss. Spitzer et al.¹³ have shown by varying the laser spot size on a solid tin target that the saturation of the CE occurs at diameters above 400 μm for fixed laser intensity in a range of 10^{10} – 10^{11} W/cm^2 . We can thus assume that 1D flow can be achieved for a realistic use of the light source.

If we consider laser pulse durations of $\tau_L = 1$ – 10 ns, the EUV intensity should be in the range from $I_{\text{EUV}} = E_{\text{EUV}}/S\tau_L = 6.2 \times 10^8$ W/cm^2 (10 kHz, $\phi = 500$ μm , $\tau_L = 10$ ns) to 2.7×10^{10} W/cm^2 (7 kHz, $\phi = 870$ μm , $\tau_L = 1$ ns). Therefore a CE greater than $\eta_{\text{EUV}} = 1\%$ should be achieved with a laser intensity of $I_L = I_{\text{EUV}}/\eta_{\text{EUV}} = 6 \times 10^{10}$ to 3×10^{12} W/cm^2 .

The required plasma density can be estimated as follows: we consider a planar plasma in which the number density of ions emitting the EUV radiation at 13.5 nm with 2% bandwidth is given by n^* and of which the length is of the order of $l_{\text{OD}=1}$, defined as the distance corresponding to optical depth 1 for 13.5-nm photons. The number of photons emitted from a unit area per unit time is approximately given by $N_{\text{photon}} = 4l_{\text{OD}=1}n^*A_{\text{Ein}}$, where A_{Ein} is the Einstein coefficient for emission, $A_{\text{Ein}} = 3.7 \times 10^{11}(g_{n'}/g_n)f_{n'n}$. Here g_n is the statistical weight of the n th level, and $f_{n'n}$ is the oscillator strength. The photon number should satisfy the condition $N_{\text{photon}} = I_{\text{EUV}}/h\nu$, where h is Planck's constant. The EUV radiation at 13.5 nm with 2% bandwidth is mostly due to the 4f-4d, 4p-4d, and 5p-4d transitions for tin and xenon. If we assume that $l_{\text{OD}=1} = 10$ – 100 μm , the oscillator strength is $(g_{n'}/g_n)f_{n'n} = 1$, and the abundance of the ions emitting the EUV radiation is 0.1, then the ion density required can be in the range of 10^{18} – 10^{20} cm^{-3} . Those parameters for the possible design window are summarized in Table 11.1. We will show that these source parameters within the design window can be achieved with use of the power balance model²¹ and radiation hydrodynamic simulations.

Table 11.1 Possible design window of laser and plasma parameters for practical use of EUV sources.

Source diameter	500–870 μm
Ion density	10^{18} – 10^{20} cm^{-3}
13.5-nm radiation intensity with 2% bandwidth	6×10^8 – 3×10^{10} W/cm^2
Laser intensity	6×10^{10} – 3×10^{12} W/cm^2

11.3 Power Balance Model

We analytically estimate a scaling law for the CE of the laser intensity from a power balance consideration.²¹ We consider a target of which the initial density is higher than the laser critical density, where the electron plasma frequency equals the incident laser frequency. Since laser light propagates up to the critical density in plasma, laser absorption occurs only near the surface of the target, and hot plasma spurts out. Since a laser-produced hot plasma expands into vacuum, no stationary plasma exists. Therefore, spectral consideration is not enough to obtain the CE, and we must consider the dynamics of the LPP. Figure 11.2 shows typical profiles of ion density, electron temperature, and plasma flow velocity at the laser peak, when a 1.2-ns Gaussian laser pulse of 1.06- μm wavelength with an intensity of $5 \times 10^{10} \text{ W/cm}^2$ irradiates a planar solid tin target. These laser conditions are chosen to be the same as those in the experiments at Osaka,^{15,16} which will be discussed in Sec. 11.5.1. Nearly 100% of the laser energy is absorbed, mainly due to inverse bremsstrahlung absorption (IBA), i.e., electron-ion collisions, because of the highly charged state of the ions. A part of the absorbed energy is transferred into the high-density region, due to electron heat conduction and radiative transport from the hot low-density laser absorption region. Energy transferred to the high-density region causes laser ablation and accelerates the plasma outward. Thus the LPP consists of two regions: the hot low-density region and the relatively cold high-density region ahead of it. The former region is often called the *corona*. In laser ablation the energy transferred into the high-density region is much smaller than that in the corona: approximately 10% of the absorbed energy.²³

Because of the high electron conductivity in the corona, the corona plasma is approximately isothermal. We may assume that an isothermal expansion follows the laser-ablation surface. The expression for the isothermal expansion is obtained from the equation of continuity and the equation of motion,

$$\frac{\partial}{\partial t} n_i + \frac{\partial}{\partial x} n_i v = 0, \quad (11.1)$$

$$m n_i \left(\frac{\partial}{\partial t} + v \frac{\partial}{\partial x} \right) v = -T_e \frac{\partial}{\partial x} n_e, \quad (11.2)$$

where $n_i(x, t)$, $n_e(x, t)$, $v(x, t)$, and T_e are the ion density, electron density, flow velocity, and electron temperature in energy units, respectively, and x , t , and m are the space coordinate, time, and ion mass, respectively. By assuming a self-similar solution $n(\xi)$ and $v(\xi)$, where $\xi = x/t$, and charge neutrality ($n_e = Z^* n_i$), we obtain the density and velocity as

$$n_i(x, t) = n_0 e^{-x/c_s t}, \quad (11.3)$$

$$v(x, t) = \frac{x}{t} + c_s, \quad (11.4)$$

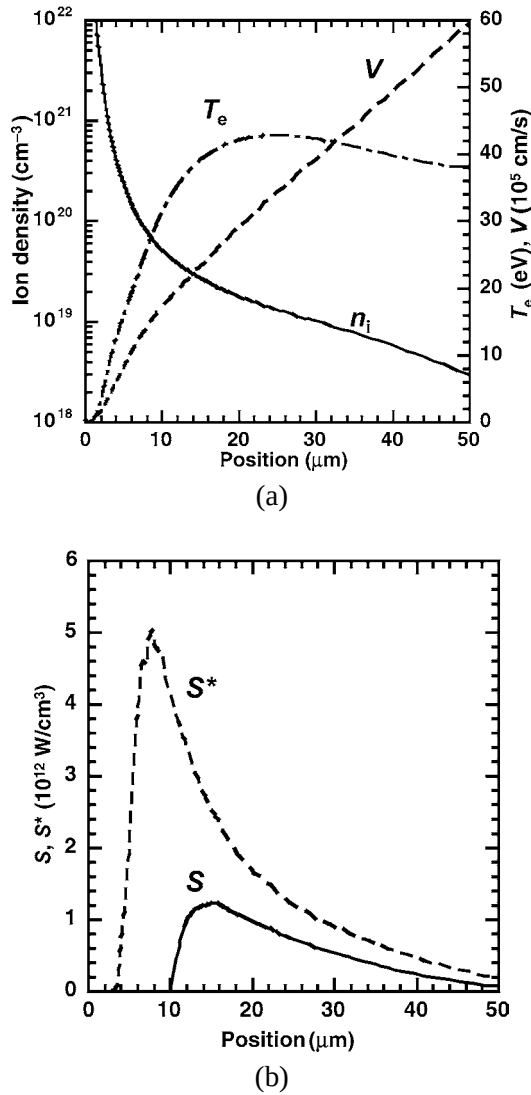


Figure 11.2 (a) Spatial profiles of ion density (solid line), flow velocity (dashed line), and electron temperature (dash-dotted line). (b) Spatial profiles of inband emissivity $S_{\text{EUV}}^* = (4\pi\eta^\gamma)_{\text{EUV}}$ (dashed line) and effective emissivity $S_{\text{EUV}} = (4\pi\eta^\gamma - c\chi^\gamma E^\gamma)_{\text{EUV}}$ (solid line).

where $c_s = (Z^*T_e/m_i)^{1/2}$ is the ion sound speed and Z^* is the average ionization state. Here we have assumed that the laser ablation accelerates the plasma outward and the velocity reaches the sound speed at $x = 0$. The isothermal solution shows that the density decreases exponentially and the expansion velocity increases linearly with distance at fixed time, which agrees well with the radiation hydrodynamic simulation shown in Fig. 11.2. The agreement indicates that the isothermal self-similar solution given by Eqs. (11.3)–(11.4) is a good approximation in the corona.

We now consider the energy fluxes required to sustain the isothermal expansion.²⁴ Since we have assumed that the fluid velocity of the ablation plasma reaches the ion sound speed at $x = 0$ with an ion density of n_0 , the kinetic energy loss per unit time can be calculated as

$$I_{\text{kin}} = \frac{d}{dt} \int_0^\infty \frac{1}{2} m v^2 n_i dx + \frac{1}{2} m c_s^2 n_0 c_s = 3 Z^*(n_0, T_e) n_0 T_e c_s, \quad (11.5)$$

using Eqs. (11.3)–(11.4). For a high- Z^* plasma, we must consider the energy flux required for ionization of target and radiation loss as well as the expansion loss. Since the ion number flux across $x = 0$ is $n_0 c_s$, the ionization loss per unit time and per unit area is estimated to be

$$I_{\text{ion}} = \left[E_{\text{ion}}(n_0, T_e) + \frac{3}{2} Z^*(n_0, T_e) T_e \right] n_0 c_s, \quad (11.6)$$

where $E_{\text{ion}}(n_0, T_e)$ is the ionization energy required for an atom to reach the ionization state $Z^*(n_0, T_e)$. Here the second term is the electron internal energy, and we have neglected the ion internal energy because $Z^* \gg 1$. The ionization energy $E_{\text{ion}}(n_0, T_e)$ and the ionization state $Z^*(n_0, T_e)$ depend on the density n_0 and the electron temperature T_e .

If we assume that the radiative emissivity is given by a power law in the density as n^α , the radiation loss flux in the corona is approximated as

$$I_{\text{rad}} = \int_0^\infty P_r(n_i, T_e) dx = P_r(n_0, T_e) \frac{c_s t}{\alpha}, \quad (11.7)$$

where $P_r(n_0, T_e)$ is the emissivity per unit time and per unit volume integrated over the radiation spectrum. In the density range considered here, α is estimated to be approximately 1.35 for tin, using an average-ion model that will be described in Sec. 11.4.1. A detailed atomic model with the use of the HULLAC code, which will be explained in Sec. 11.4.2, gives $\alpha = 1.22$.

Since Eq. (11.7) is time-dependent, it may be valid only for a certain range of the laser pulse duration. If $c_s t / \alpha$ exceeds an average value of the radiation mean free path, it should be limited to the mean free path or the radiation transport should be solved for. We use the laser pulse duration τ_L for t in Eq. (11.7) in the comparison with experiments below.

Since photons emitted in the corona propagate both outward and inward, half of the photons can be absorbed in the high-density region, mainly due to bound-free transitions. We assume a local thermodynamic equilibrium (LTE) and blackbody radiation in the high-density region. Thus radiation flux with almost the same magnitude as the absorbed flux can be reemitted.

Since the energy loss in the corona plasma is much greater than that in the high-density region,²⁴ the sum of the loss fluxes may be taken approximately equal to

the incident laser intensity, i.e.,

$$I_L \approx I_{\text{kin}} + I_{\text{ion}} + I_{\text{rad}}. \quad (11.8)$$

From this flux conservation and with the use of atomic data for the ionization energy $E_{\text{ion}}(n_0, T_e)$, the ionization state $Z^*(n_0, T_e)$, and the emissivity $P_r(n_0, T_e)$ obtained from the average-ion model, we can evaluate the electron temperature and the various loss fluxes as functions of the incident laser intensity, as shown in Fig. 11.3. Here we have used experimental parameters for the tin target, which will be discussed in Sec. 11.5.1; namely, the laser pulse duration of $\tau_L = 1.2$ ns and $n_0 = 3 \times 10^{19} \text{ cm}^{-3}$, from the result shown in Fig. 11.2. As shown in Fig. 11.3, the electron temperature in the corona varies from 20 to 140 eV, corresponding to laser intensities from 10^{10} to $2 \times 10^{12} \text{ W/cm}^2$. The radiation loss dominates the kinetic and ionization losses throughout the laser intensity range plotted for the density $n_0 = 3 \times 10^{19} \text{ cm}^{-3}$. For a weak laser intensity ($\leq 10^{11} \text{ W/cm}^2$), the ionization loss is approximately two times greater than the kinetic loss, whereas the kinetic loss becomes large at high intensity ($\geq 10^{12} \text{ W/cm}^2$). The increase of the expansion loss at the high intensity is due to the scaling of $I_{\text{kin}} \propto T_e^{3/2}$, which determines the temperature scaling $T_e \propto I_{\text{kin}}^{2/3}$ for low- Z targets. However, it is no longer valid for a high- Z material where the radiation and ionization losses dominate, as shown in Fig. 11.3. As is seen there, the scaling of the electron temperature with laser

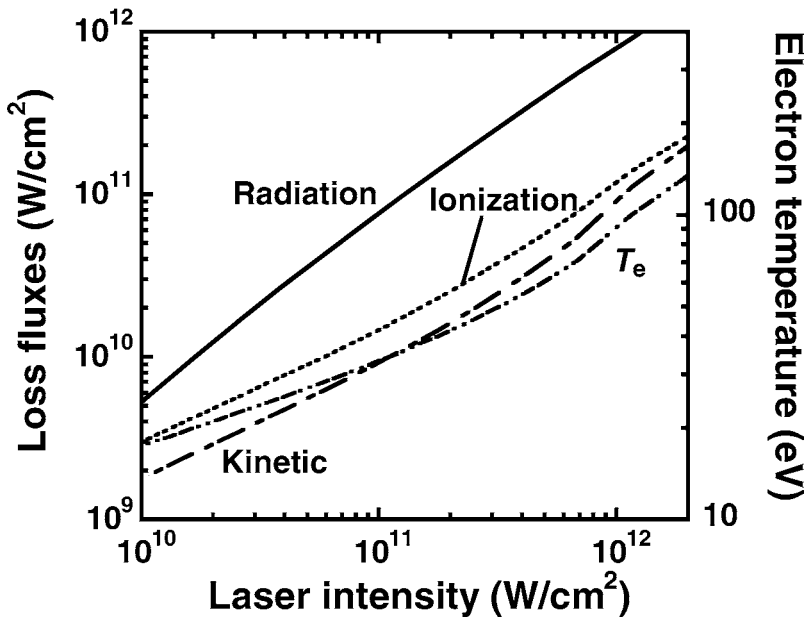


Figure 11.3 Various loss fluxes for tin obtained from the power balance model: radiation loss (solid line), ionization loss (dotted line), expansion loss (dash-dotted line), and electron temperature (double-dash double-dotted line) as functions of laser intensity, which is assumed to be equal to the total loss flux.

intensity is approximately given by $T_e \propto I_L^{0.45}$ near 10^{11} W/cm² and $T_e \propto I_L^{0.6}$ near 10^{12} W/cm² for tin. The radiation consists of a wide range of photon energy, and the emission spectrum changes drastically with the electron temperature, and thus with the laser intensity, as will be shown in Sec. 11.5.1.

We consider two regions of the EUV radiation source; one is the corona region, and the other is the high-density region. The 13.5-nm radiation with 2% bandwidth from the corona can be estimated in the same way as Eq. (11.7) with the knowledge of the inband emissivity $P_{\text{EUV}}(n_0, T_e)$. For the radiation from the high-density region, we assume that half of the emission from the corona is absorbed in the high-density region due to bound-free transitions and that LTE can be achieved. Those features of the high-density region are observed in the radiation-hydrodynamic simulations, as will be shown in Sec. 11.5.1. Then the 13.5-nm emission with 2% bandwidth from the high-density region can be calculated from the Planckian distribution function of the radiation with the radiation temperature determined from the total emission from the corona, namely $\sigma T_R^4 = I_{\text{rad}}/2$, where σ is the Stefan-Boltzmann constant. The radiation temperature thus estimated agrees well with the simulations. The CE from the incident laser to the EUV inband emission can then be estimated as

$$\eta_{\text{EUV}} = \frac{I_{\text{EUV,CR}} + I_{\text{EUV,HD}}}{I_{\text{rad}} + I_{\text{ion}} + I_{\text{kin}}}, \quad (11.9)$$

$$I_{\text{EUV,CR}} = P_{\text{EUV}}(n_0, T_e) \frac{c_s \tau_L}{2\alpha_{\text{EUV}}}, \quad I_{\text{EUV,HD}} = \Delta I_{\text{P,EUV}}(T_R), \quad \sigma T_R^4 = \frac{I_{\text{rad}}}{2},$$

where $P_{\text{EUV}}(n_0, T_e)$ is the emissivity of 13.5-nm radiation with 2% bandwidth in the corona, and $\Delta I_{\text{P,EUV}}(T_R)$ is the inband radiation flux determined from the Planckian distribution function with the radiation temperature T_R . The value of α_{EUV} is approximately 1.1 for tin in the density range considered. Both the average-ion model and the HULLAC code give the same α_{EUV} value. If $c_s t / \alpha_{\text{EUV}}$ in the inband EUV intensity $I_{\text{EUV,CR}}$ exceeds the mean free path of the corresponding line transitions, we must consider self-absorption of the emission in the corona or else solve the radiation transport problem. Details will be discussed in Sec. 11.5.2. It should also be noted that the density n_0 cannot be determined self-consistently in the model. However, since the kinetic energy loss and ionization loss are approximately linearly proportional to the density and the emissivity has a weak nonlinearity ($\alpha = 1.35$), the CE given by Eq. (11.9) does not change much with the density assumed, at least in the range of $n_0 = (1-4) \times 10^{19}$ cm⁻³. We will discuss the dependence of the CE on the ion density and thus the laser wavelength in Sec. 11.5.2. We can estimate the CE, Eq. (11.9), with the use of $Z^*(n_0, T_e)$, $E_{\text{ion}}(n_0, T_e)$, $P_r(n_0, T_e)$, and $P_{\text{EUV}}(n_0, T_e)$ evaluated from atomic codes.

11.4 Atomic Models and Radiation Hydrodynamic Code

In this section we briefly describe the atomic models and radiation hydrodynamic code used for the evaluation of the CE.

11.4.1 Average-ion model with (n, l) splitting and radiation hydrodynamic code

Although the average-ion model²⁵ assumes a fictitious ion with noninteger averaged charge state, it has great advantage because the thermodynamical self-consistency required for the equation of state used in radiation hydrodynamic simulations is achieved with less difficulty. An atomic model with (n, l) splitting is required for xenon and tin plasmas, where n and l are the principal quantum number and the quantum number specifying the total orbital angular momentum. With use of the average-ion model together with the screened hydrogenic model (SHM) of (n, l) splitting by Perrot,²⁶ we obtained successful results in understanding laser fusion plasmas.²⁷ However, we have found that the first ionization potential predicted by the Perrot's model has a negative value; in other words, the total energy of bound electrons of an ion decreases as the ionization proceeds. This defect is not so small in modeling low-charge plasmas such as EUV light sources. We have developed a new SHM²⁸ to solve this problem.

More's SHM²⁹ gives the total energy of bound electrons by a simple equation,

$$E_{\text{ion}} = - \sum_n P_n \frac{Q_n^2}{2n^2}. \quad (11.10)$$

In the new SHM, we introduce the relativistic effect on the energy level and an improvement in the self-screening, which also was defective in the pervious SHM. Using the new SHM, the screened charge Q_{nl} and the one-electron energy level E_{nl} are, respectively, given by

$$\begin{aligned} Q_{nl} &= Z - \sum_{m_{n'l'} < m_{nl}} P_{n'l'} \sigma_{nl,n'l'} + \max[P_{nl} - 1, 0] \sigma_{nl,nl}, \\ E_{nl} &= -\frac{Q_{nl}^2}{2n^2} \left\{ 1 + \frac{\beta^2 Q_{nl}^2}{n^2} \left(\frac{n}{k} - \frac{3}{4} \right) \right. \\ &\quad \times \left[1 - \max(P_{nl} - 1, 0) \left(\frac{4\sigma_{nl,nl}}{Q_{nl}} + \frac{6\sigma_{nl,nl}^2}{Q_{nl}^2} + \frac{4\sigma_{nl,nl}^3}{Q_{nl}^3} + \frac{\sigma_{nl,nl}^4}{Q_{nl}^4} \right) \right] \Big\} \\ &\quad + \sum_{m_{n'l'} > m_{nl}} \frac{P_{n'l'}}{2n'^2} \left[2Q_{nl} + \sigma_{n'l',nl} + \frac{\beta^2 Q_{nl}^3}{n^2} \left(\frac{n'}{k'} - \frac{3}{4} \right) \right] \end{aligned}$$

$$\times \left(4 + \frac{6\sigma_{n'l',nl}}{Q_{nl}} + \frac{4\sigma_{n'l',nl}^2}{Q_{nl}^2} + \frac{\sigma_{n'l',nl}^3}{Q_{nl}^3} \right) \sigma_{n'l',nl} + \frac{\max[P_{nl} - 1, 0]}{2n^2} (2Q_{nl} + \sigma_{nl,nl}) \sigma_{nl,nl}, \quad (11.11)$$

where Z is the atomic number, P_{nl} is the population of the (n, l) subshell, β is the fine-structure constant, $\sigma_{nl,n'l'}$ is the screening constant, and k is $l + 1$ in the relativistic correction. In the summation in Eq. (11.11),

$$m_{10}, m_{20}, m_{21}, m_{30}, m_{31}, m_{32}, m_{40}, m_{41}, m_{42}, m_{50}, m_{51}, m_{43}, \dots \\ = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, \dots \quad (11.12)$$

The screening relation is not hydrogenic, but in the filling order of electrons for real ions instead. The total energy of bound electrons is given by simple summation,

$$E_{\text{ion}} = - \sum_{nl} P_{nl} \frac{Q_{nl}^2}{2n^2} \left[1 + \frac{\beta^2 Q_{nl}^2}{n^2} \left(\frac{n}{k} - \frac{3}{4} \right) \right]. \quad (11.13)$$

A set of screening constants was determined from the results of HULLAC code for tin and xenon.³⁰ Table 11.2 shows the transition energy of tin ions with different charge states. From the table, we see that the new SHM with (n, l) splitting predicts fairly good values of the transition energy.

Using the average-ion model with the new SHM, we can solve rate equations in which collisional and radiative rate coefficients of hydrogenic ions are scaled by the dipole oscillator strength generated by the HULLAC code. Collisional radiative equilibrium (CRE) is assumed in calculating the emissivity and opacity used for the radiation transport in the radiation hydrodynamic code. The difficulty arises in the calculation of the spectral opacity and emissivity in the average-ion model, because of the fictitious ion with the averaged charge. The strength of the 4d-4f line in the average-ion model, for example, reflects all the contribution of the 4d-4f lines

Table 11.2 Transition energies of tin ion with different charge states given by the SHM and HULLAC code. Values (nm) are as displayed by SHM/HULLAC.

Charge state	4d-4f	4p-4d	4d-5p	4d-5f
13	12.8/13.1	12.7/12.8	12.3/12.4	7.4/7.8
12	12.8/13.0	13.1/12.8	13.1/13.3	7.8/8.3
11	12.9/13.0	13.4/13.0	14.1/14.6	8.3/9.0
10	13.1/13.2	13.7/13.2	15.3/16.0	8.9/9.6
9	13.6/13.5	13.9/13.5	16.8/16.0	9.7/10.4
8	14.3/14.1	14.0/14.1	18.7/17.5	10.6/11.3
7	15.3/15.0	14.0/14.7	21.2/17.6	11.9/12.4
6	16.7/16.8	14.0/14.1	24.6/25.6	13.5/13.7
5	18.8/19.1	13.9/14.6	29.5/30.1	15.7/15.6
4	22.0/22.8	—	37.0/37.0	19.0/18.6

from Rb-like to Pd-like ions. In the average-ion model developed, the probability of electron occupation in the sublevel (n, l) is assumed to be given by the ratio of the fractional population of P_{nl} to the statistical weight D_{nl} : $x_n = P_{nl}/D_{nl}$. The population of an ion that has a different number of bound electrons in the sublevel (n, l) can be given by a binomial distribution in the LTE. For example, the population of an ion, $F_{P_{4d}=5}$, which has five electrons in the sublevel $(4, 3)$, is given by

$$F_{P_{4d}=5} = x_{1s}^2 x_{2s}^2 x_{2p}^6 x_{3s}^2 x_{3p}^6 x_{3d}^{10} x_{4s}^2 x_{4p}^6 \frac{10!}{(10-5)!5!} x_{4d}^5 (1-x_{4d})^5 (1-x_{4f})^{14} \dots \quad (11.14)$$

Using the statistical method, we can calculate the opacity and emissivity, including the contribution from spectra of different charge states. In addition, term splitting of the Gaussian shape estimated from HULLAC code and line broadening due to Doppler and electron collisions are treated in the spectral calculations. Figure 11.4 shows the emissivity for tin with $T_e = 30$ eV and $n_i = 10^{19} \text{ cm}^{-3}$ thus obtained.

For a 1D Lagrangian radiation hydrodynamic code, we applied the one-fluid two-temperature model:

$$\begin{aligned} \rho \frac{dv}{dt} &= -\frac{\partial(p_i + p_e + q)}{\partial x}, \\ \rho c v_i \frac{dT_i}{dt} &= -p_{\text{THi}} \frac{\partial v}{\partial x} + \frac{\partial}{\partial x} \left(\kappa_i \frac{\partial T_i}{\partial x} \right) + \frac{T_e - T_i}{\tau_{ei}} + Q_i, \end{aligned} \quad (11.15)$$

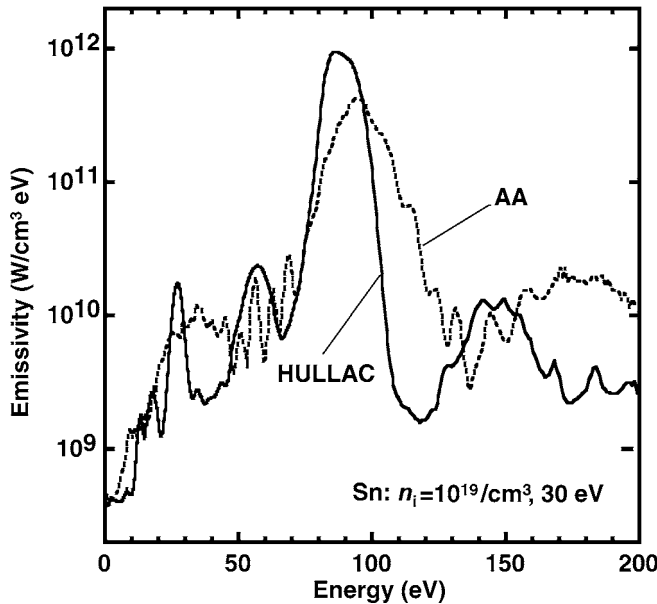


Figure 11.4 Emissivity of tin with $T_e = 30$ eV and $n_i = 10^{19} \text{ cm}^{-3}$, obtained from average-atom (AA) model (dotted line) and HULLAC (solid line).

$$\rho c_{Ve} \frac{dT_e}{dt} = -p_{THe} \frac{\partial v}{\partial x} + \frac{\partial}{\partial x} \left(\kappa_e \frac{\partial T_e}{\partial x} \right) - \frac{T_e - T_i}{\tau_{ei}} + Q_e.$$

Here ρ , p , q , and c_V are the mass density, pressure, artificial viscosity, and specific heat, respectively, and the subscripts i and e indicate ion and electron. p_{TH} is defined as $p_{TH} = T(\partial p / \partial T)_\rho$. The terms Q_e and Q_i indicate electron heating due to the laser and radiation absorption, and ion heating due to viscosity. For the thermal conduction, we applied the flux-limited Spitzer-Härm model,³¹ using the thermal conductivity^{32,33} κ and the electron-ion energy relaxation time τ_{ei} in the Spitzer model.³⁴ For the laser absorption process, we assumed inverse bremsstrahlung³⁵ with the Langdon effect.³⁶ In evaluating the radiation transport, we applied the multigroup diffusion approximation model³⁷ using the flux limiter, as given by

$$\rho \frac{d}{dt} \left(\frac{E^\gamma}{\rho} \right) - \frac{\partial}{\partial x} \left(D^\gamma \frac{\partial E^\gamma}{\partial x} \right) = 4\pi\eta^\gamma - c\chi^\gamma E^\gamma, \quad (11.16)$$

where E^γ is the energy density of photons with the energy $h\nu$. Here h and c are Planck's constant and the speed of light, respectively; η^γ and χ^γ are, respectively, the emissivity and absorption coefficient for photon energy $h\nu$; and D^γ is the diffusion coefficient defined by $D^\gamma = c/\chi^\gamma$, which is limited by the free-streaming flux $F_L^\gamma = cE^\gamma$. Photon energy in the range from 0 to 1.5 keV is divided into 1500 bins with 1-eV width. The variables p , c_V , p_{TH} , η^γ , and χ^γ are obtained as functions of density and temperature based on the (n, l) -splitting screened hydrogen model described above and a self-consistent equation of state.³⁸ For obtaining the equation of state for an ion, we adopt the Cowan model.³⁹

11.4.2 Detailed atomic model with use of HULLAC code

A detailed atomic model is required for predicting the spectral profile of the transition array, which depends on atomic number, ion charge, and plasma conditions, and estimating the fraction of emission power in the desired bandwidth. The plasma temperature for the lithographic EUV source is between 20 and 50 eV, where the ion charge is around 10. The near-10+-ionized Xe and Sn have a ground configuration of $4d^i$. These N-shell ions exhibit strong emission through 4d-4f resonance lines at the EUV wavelength.⁴⁰ Because of the half-filled N-shell configuration, the emission line consists of a large number of fine-structure transitions. Furthermore, the emission lines from several different charge states overlap each other, and the observed spectrum of 4d-4f transitions usually appears as a broad transition array with $\Delta\lambda/\lambda \approx 0.1$. In the case of Xe and Sn, the 4d-5p transition array also appears in the same wavelength region.

It is shown by O'Sullivan that the configuration interaction (CI) changes the EUV spectrum of Xe and Sn significantly.^{41,42} We investigate the effect of CI by comparing the calculations including different sets of configurations using HULLAC⁴³ and GRASP.⁴⁴ It is shown that the binding energy of the ground

configuration ($4d^n$) is shifted by amounts up to 10 eV by the CI effect with two-electron excited states such as $4d^{n-2}4f^2$. However, the wavelengths of 4d-4f and 4d-5p transitions are found to be rather sensitive to the CI between upper states, because in the presence of orbital collapse these configurations have similar excitation energies.

The calculated wavelengths of the resonance lines of Xe and Sn ions are summarized in Fig. 11.5. Here the HULLAC code was used in the calculation of the energy-level structure. In the case of Sn, the effect of the CI brings the wavelength of both 4p-4d and 4d-4f transitions of Sn^{8+} – $12+$ near 13 nm. In the case of Xe, it is shown that 4d-5p transitions of 10+ ions make the main contribution to the EUV emission in the 13.5-nm band.

We calculate the ion abundance and level population of Xe and Sn ions using the collisional radiative model⁴⁵ (CRM), taking into account the energy-level structure, which is similar to those shown in Fig. 11.6. Since the inclusion of a large number of multiply excited and inner-shell-excited configurations is necessary in order to calculate the spectrum, we apply a mixed model approach, in which the detailed term accounting (DTA) model is used for the resonance lines, whereas fine-structure transitions are averaged to form unresolved transition arrays⁴⁶ (UTAs) for satellite lines. The present model allows us to practically reproduce the experimental spectrum, which originates from overlapping millions of fine-structure transitions. Furthermore, for the accurate estimation of the CE of the EUV source, we calculate the wavelengths and the spectral distribution of the resonance lines using HULLAC, including the effect of the CI. On the other hand, the wavelengths and widths of satellite lines are obtained from calculations without the CI, because the CI is less critical for the wavelength of individual lines.

With the present atomic model, we calculate the emissivity and opacity of Xe and Sn plasmas in CRE. Furthermore, we calculate the EUV spectrum to study the experimental spectral structure, as will be discussed in Sec. 11.5.3.

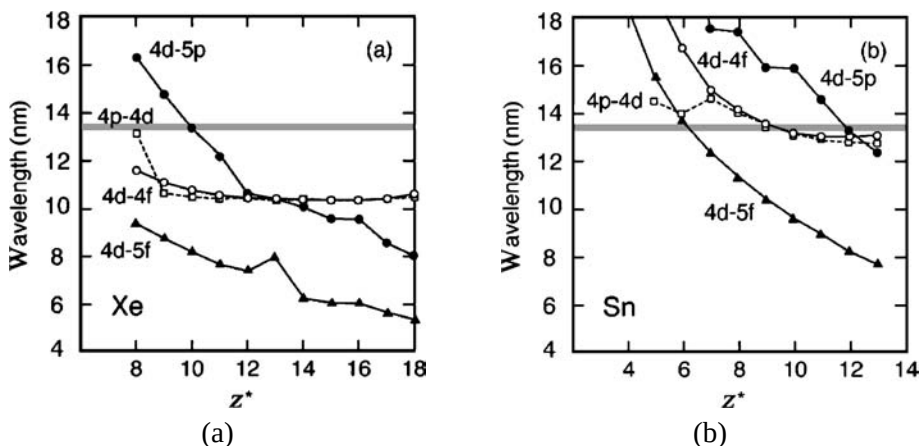


Figure 11.5 Wavelengths of resonance lines of (a) Xe, and (b) Sn.

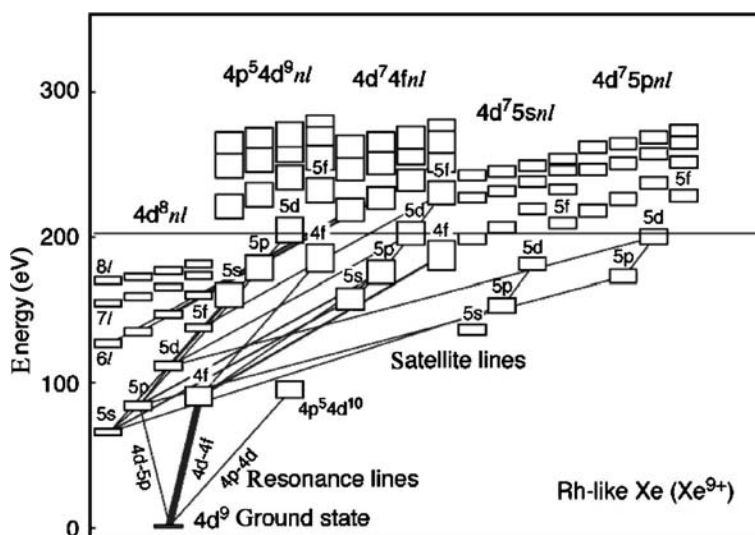


Figure 11.6 Energy-level diagram of Xe^{9+} .

11.5 Conversion Efficiency for Tin and Xenon

11.5.1 Tin: calculation and comparison with experiments

Here we evaluate the laser intensity dependence of the CE for a tin target and compare it with experiments. Pioneer work by Spitzer et al.¹³ showed almost the same dependence as the experiments^{15,16,21} carried out at Osaka. At Osaka, solid plastic spheres overcoated with 1- μm -thick tin are irradiated uniformly with 12 beams of the GEKKO XII laser system⁴⁷ in order to measure the dependence of the CE on the laser intensity without lateral-energy-transport loss and lateral-expansion loss. The wavelength and duration of the laser pulses are 1.06 μm and 1.2 ns, respectively. The target diameter is typically 700 μm . By adjusting the laser energy (0.5–15 J) and the target diameter, the laser irradiance is varied from 2×10^{10} to 2×10^{12} W/cm^2 .

EUV emission was observed with an absolutely calibrated energy meter called E-mon, manufactured by Jenoptik Inc.,⁴⁸ and a transmission grating spectrometer coupled with an absolutely calibrated back-illuminated CCD camera (TGS-CCD). The TGS-CCD with a pinhole disk covered a spectral range of 1–20 nm with spectral resolution 0.42 nm. Quite different radiation spectra have been observed at different laser intensities from the TGS-CCD. Figure 11.7 shows time-integrated spectra from the tin plasma created at three different laser intensities: 8.8×10^{10} , 3×10^{11} , and 9×10^{11} W/cm². The spectrum mainly consists of three spectral bands. The component at 1–2.5 nm is attributed to the transitions from $n = 4$ or 5 to $n = 3$ (so-called M-shell transitions), where n is the principal quantum number, for a tin plasma of higher than 100-eV electron temperature, and corresponding charge states of 22+ to 33+. The component at 4–8 nm is attributed to transitions

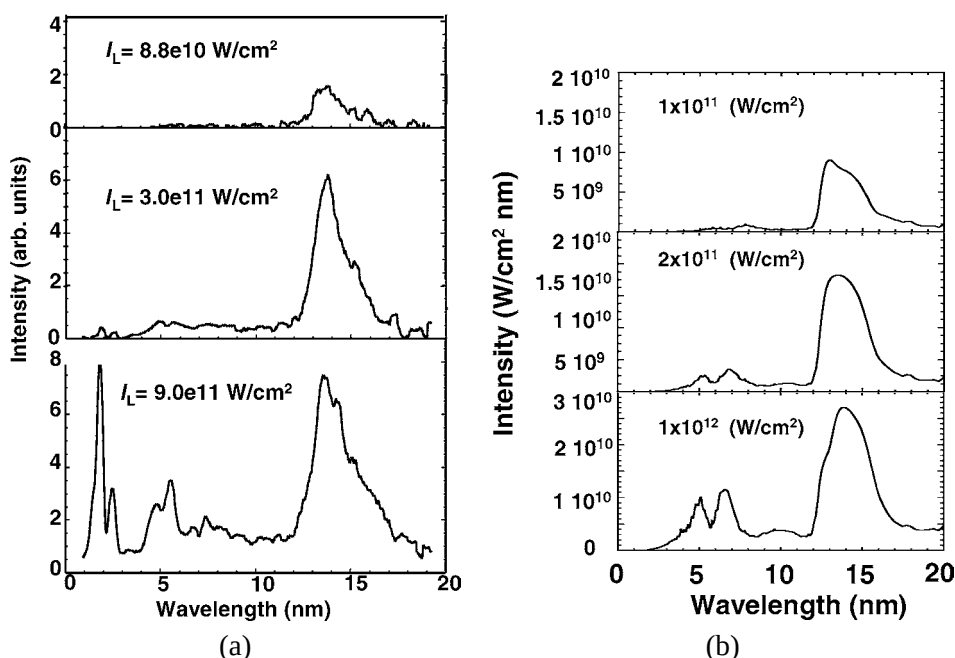


Figure 11.7 (a) Experimental emission spectra (time-integrated) of tin plasmas created at laser intensities of 9×10^{11} (bottom), 3×10^{11} (middle), and 8.8×10^{10} (top) W/cm^2 from 1.057- μm laser. (b) Simulation spectra in the EUV regime at laser peak with laser intensities of 10^{12} (bottom), 2×10^{11} (middle), and 10^{11} (top) W/cm^2 , respectively.

from $n = 5$ or 6 to $n = 4$ (N-shell transitions, with charge states $14+$ to $21+$) for electron temperatures of 30–200 eV. The component at 12–17 nm is due to $\Delta n = 0$ (mainly 4d–4f) transitions, $8+$ to $13+$, for electron temperatures of 20–50 eV. The identification of these components in terms of atomic transitions was made by comparison with a screened hydrogenic ion model,⁴⁹ where the evaluation of the dominant spectral component is given as a function of electron temperature estimated from the power balance model. With decrease of the laser intensity, the first two components decrease more than the one at 12–17 nm; the shortest-wavelength band (1–3 nm) decreases especially rapidly. The radiation consists of a wide range of energies, and the change of the emission spectra is due to the change of the electron temperature, which in turn depends on the laser intensity, as shown in Fig. 11.3. Figure 11.8 shows the laser intensity dependence of photon wavelength, which is obtained from the electron temperature estimated from the power balance model as shown in Fig. 11.3, according to the average-ion model. The laser intensity dependence of the spectra explains the observation shown in Fig. 11.7 at least qualitatively. This agreement between the theory and the experiments indicates the validity of the power balance model.

Radiation spectra in the UV regime for various laser intensities are also calculated with the use of the ray-tracing method, using the electron temperature and density profiles at the laser peak obtained from the radiation hydrodynamic simula-

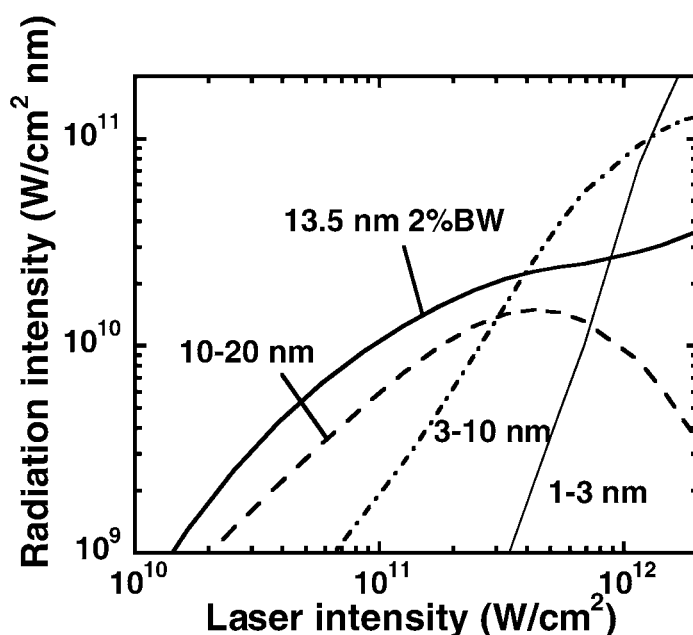


Figure 11.8 Various components of emission obtained from the power balance model: 13.5-nm emission with 2% bandwidth (thick solid line), emission with 1–3-nm wavelength (thin solid line), 3–10-nm wavelength (dash-dotted line), 10–20-nm wavelength (dashed line).

tions. The results are presented in Fig. 11.7(b), which shows quite good agreement between the experiments and simulations.

The dependence of the CE on the laser intensity was measured with the energy meter and the TGS-CCD. The overall detection bandwidth for the E-mon was 3.2%, so the energy meter signal was corrected to provide EUV energy in the 2% bandwidth, using the spectral profile obtained with the TGS-CCD. Figure 11.9 shows the 13.5-nm CE as a function of laser intensity on the targets, both experimental results (dots) and theoretical values (lines) obtained from the power balance model. The solid and dashed lines in Fig. 11.9 give the CE [η_{EUV} in Eq. (11.9)] estimated from the total 13.5-nm radiation from the corona ($I_{\text{EUV,CR}}$) and from the high-density region ($I_{\text{EUV,HD}}$), respectively, with the use of atomic data discussed in Sec. 11.4.1. The theoretical value of the CE agrees fairly well with the experimental results. The highest CE is attained at $(0.5\text{--}1) \times 10^{11} \text{ W/cm}^2$ for a tin target. It should be noted that here we have assumed the density $n_0 = 3 \times 10^{19} \text{ cm}^{-3}$; however, the maximum CE has very weak dependence on the density assumed, as will be discussed in detail in Sec. 11.5.2. The laser intensity that gives the maximum CE slightly increases with increase of the density n_0 assumed. As shown in Fig. 11.9, at the low laser intensity of $(0.5\text{--}1) \times 10^{11} \text{ W/cm}^2$ that gives the maximum CE, most of the 13.5-nm emission comes from the corona, while at high intensity, higher than 10^{12} W/cm^2 , most of the 13.5-nm emission comes from the high-density region, because the electron temperature is too high in the corona.

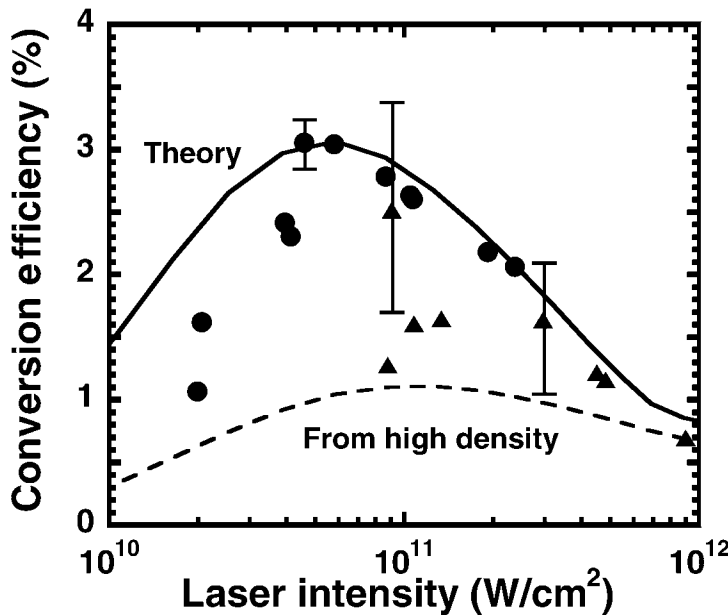


Figure 11.9 CE of tin: experimental results (dots by E-mon; triangles by TGS); theoretical results obtained from the power balance model (total inband EUV, solid line; inband EUV from the high-density region, dashed line).

As shown in Fig. 11.2, the LPP is not uniform in space. In order to understand from where most of the inband emission comes, we calculate the effective inband emissivity S_{EUV} from the right-hand side of Eq. (11.16), namely, $S_{\text{EUV}} = (4\pi\eta^\nu - c\chi^\nu E^\nu)_{\text{EUV}}$, where the notation $()_{\text{EUV}}$ represents the value integrated over the EUV 2% bandwidth. The simulation result is shown in Fig. 11.2(b) with the emissivity $S_{\text{EUV}}^* = (4\pi\eta^\nu)_{\text{EUV}}$. It should be noted that the self-absorption of the EUV is taken into account in the effective emissivity. The effective emissivity S_{EUV} has a peak near the ion density of $3 \times 10^{19} \text{ cm}^{-3}$ that is used in the previous discussion, and an electron temperature of about 30–40 eV. On the other hand, the local emissivity S_{EUV}^* has a peak at relatively high density and low temperature, where the emission and absorption of the inband EUV are almost balanced with each other and thus the Planckian intensity determined from the local temperature is achieved.

As discussed before, $I_{\text{EUV,CR}}$ in Eq. (11.9) increases with time, which suggests that a longer pulse may result in a higher CE. However, opacity of the inband EUV emission should be taken into account for a longer pulse. The effect of the opacity on CE may depend on the material, the laser wavelength, and the laser intensity and its pulse duration. Details will be discussed in Sec. 11.5.2.

11.5.2 Dependence of CE on laser wavelength

Here we discuss the dependence of the CE on laser wavelength from 10.6 to $0.26 \mu\text{m}$, where the limits correspond to a CO_2 laser and the fourth harmonic

of a Nd-glass laser, respectively. Most of the laser energy is absorbed due to the inverse bremsstrahlung emission near the critical electron density of a laser, $n_e = n_c = 1.1 \times 10^{21} (\lambda_{L\mu m})^{-2} \text{ cm}^{-3}$, where $\lambda_{L\mu m}$ is the laser wavelength in microns. In Secs. 11.3 and 11.5.1, we have assumed that the CE does not change much with the density n_0 . However, since the critical density varies more than two orders of magnitude according to the change of the wavelength, we have to consider its dependence of the CE.

We plot contours of constant CE obtained from the power balance model in the n_0 - T_e plane in Fig. 11.10, using Eqs. (11.5)–(11.9) with the average-ion model. Here a 10-ns laser pulse is assumed. One can see from the figure that the CE has a strong dependence on the electron temperature, while its density dependence is relatively weak. The electron temperature of about 30 eV results in high CE for 13.5-nm inband emission from tin. As described before, the total radiation emissivity is roughly proportional to n_0^α with $\alpha \approx 1.35$ [Eq. (11.7)], while the inband emissivity is $\alpha_{EUV} \approx 1.1$ [Eq. (11.9)]. Therefore, the portion of inband emission in the total radiation decreases with increasing density, which causes the decrease of the CE in the high-density region in Fig. 11.10. On the other hand, since the ionization and kinetic losses are linearly proportional to the density as given in Eqs. (11.5)–(11.6), those losses become large compared with the radiation loss at low density, so that the CE decreases in the low-density region, as shown in Fig. 11.10. As a result, ion densities of 10^{18} – 10^{20} cm^{-3} give rise to a high CE, and those coincide with the densities in the design window in Table 11.1. It should be noted, however, that the absolute value of the CE in Fig. 11.10 is overestimated, because the corona is not transparent anymore for a plasma with a pulse duration of 10 ns, as will be discussed below.

If we assume the average ionization state of $Z^* \approx 10$, laser absorption should occur near ion densities of $n_{ic} = 10^{18}$ and $1.6 \times 10^{21} \text{ cm}^{-3}$, corresponding to the critical electron densities for 10.6- and 0.26- μm lasers, respectively. If the inband

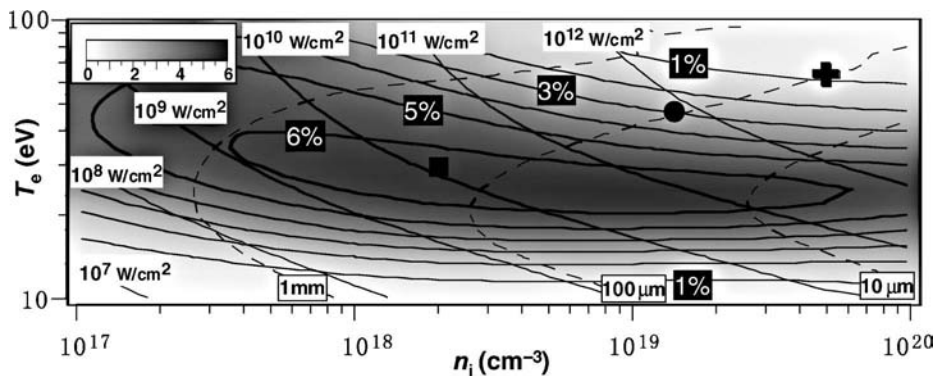


Figure 11.10 Contours of the CE obtained from the power balance model (solid lines for every 1% from 1–6%, with gray scale) in the plane of ion density (n_i) and electron temperature (T_e) with simulation points for laser wavelength of 10.6 μm (square), 1.06 μm (circle), and 0.26 μm (cross). Solid lines from left top to right bottom indicate laser intensity required, and dashed lines represent corona plasma length corresponding to optical depth 1.

emission occurs in these density regions, the use of a short-wavelength laser may fail to obtain the high CE. We have carried out many radiation hydrodynamic simulations to evaluate the CE for different laser wavelengths. Since the total loss depends on the density, the optimum laser intensity required for heating plasma up to the optimum temperature may change with the laser wavelength. A Gaussian laser pulse is used with the fixed pulse duration of 10 ns FWHM.

Figures 11.11 and 11.12 show spatial profiles of the ion density n_i , electron temperature T_e , and average ionization state Z^* at the laser peak for a $\lambda_L = 0.26\text{-}\mu\text{m}$ laser with intensity $I_L = 10^{12}\text{ W/cm}^2$ and a $10.6\text{-}\mu\text{m}$ laser with $I_L = 10^{10}\text{ W/cm}^2$, respectively. These laser intensities result in the highest CE for each wavelength, when we use atomic data based on the average ion model discussed in Sec. 11.4.1. In these figures, we have also plotted the effective emissivity S_{EUV} and the emissivity S_{EUV}^* introduced in Sec. 11.5.1. For the case of the $0.26\text{-}\mu\text{m}$ laser, we see large differences between S_{EUV} and S_{EUV}^* in their shapes and peak positions. The S_{EUV}^* without absorption has a peak near the critical density at a distance of $x = 20\text{ }\mu\text{m}$ from the initial target surface, where the ion density is $n_i = 3 \times 10^{20}\text{ cm}^{-3}$. On the other hand, the S_{EUV} with absorption has a peak around $x_S = 183\text{ }\mu\text{m}$, where $n_i = 5 \times 10^{19}\text{ cm}^{-3}$ and $T_e = 63\text{ eV}$. The large difference between S_{EUV} and S_{EUV}^* at $x = 20\text{ }\mu\text{m}$ is due to the fact that the LTE between electrons and the inband emission is achieved in this high-density region with $n_i = 3 \times 10^{20}\text{ cm}^{-3}$. It should be noted that the distance between the peak positions of S_{EUV} and S_{EUV}^* for the $0.26\text{-}\mu\text{m}$ laser with 10-ns pulse duration is much longer than that for the $1.06\text{-}\mu\text{m}$ laser with 1.2-ns pulse duration, as shown in Fig. 11.2(b).

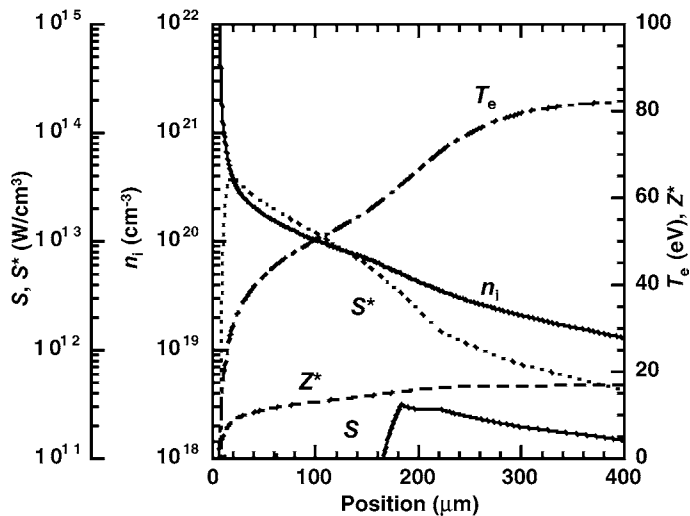


Figure 11.11 Spatial profiles of ion density (solid line), electron temperature (dash-dotted line), ionization state (dashed line), effective inband emissivity S_{EUV} (solid line), and emissivity S_{EUV}^* (dotted line) at laser peak for $0.26\text{-}\mu\text{m}$ laser with 10-ns pulse.

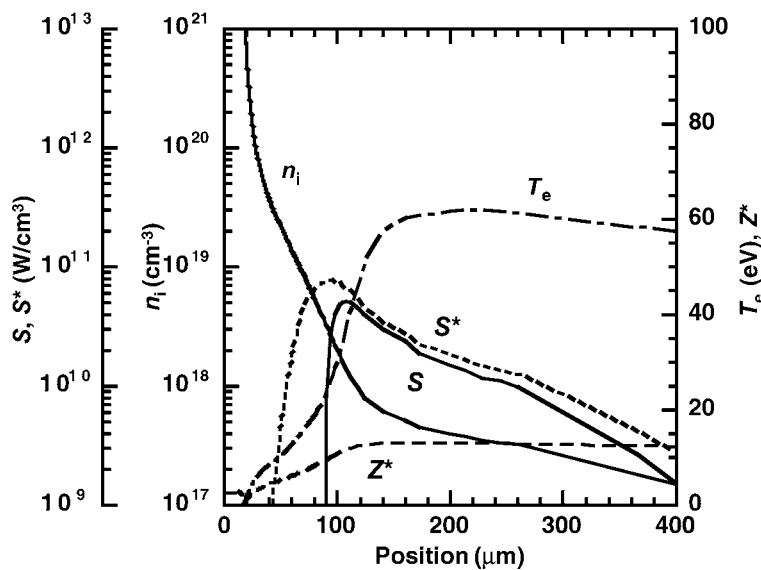


Figure 11.12 Spatial profiles of ion density (solid line), electron temperature (dash-dotted line), ionization state (dashed line), effective inband emissivity S_{EUV} (solid line), and emissivity S_{EUV}^* (dotted line) at laser peak for a 10.6- μm laser with 10-ns pulse.

On the contrary, for the case of the 10.6- μm laser, the profiles of S_{EUV} and S_{EUV}^* are almost the same, which indicates that almost of all the EUV radiation contributes to the EUV flux without absorption. The S_{EUV} has a peak near the critical density at a distance of around $x_S = 95 \mu\text{m}$ from the initial target surface, where the ion density is $n_i = 2 \times 10^{18} \text{ cm}^{-3}$ and the electron temperature $T_e = 31 \text{ eV}$. The high-density region with the LTE is not formed at such a low density.

Table 11.3 summarizes simulation results carried out for different wavelengths, in which the laser intensity corresponds to the intensity leading to the maximum CE for each laser wavelength. If we use more detailed atomic data based on HULLAC, the optimum laser intensity for a 0.26- μm laser decreases to $2 \times 10^{11} \text{ W/cm}^2$ due to large opacity but does not result in many differences for 10.6- μm and 1.06- μm lasers. It should be noted from Table 11.3 that the relation between the optimum

Table 11.3 Various plasma parameters at a peak of the effective emissivity S_{EUV} , for different laser wavelengths λ_L . Symbols: τ_L = laser pulse duration, I_L = optimum laser intensity giving the maximum CE for each laser wavelength, x_S = distance of the peak from the initial target surface, n_{iS} = ion density, T_{eS} = electron temperature, and L_S = density scale length at the peak.

λ_L (μm)	τ_L (ns)	I_L (W/cm^2)	x_S (μm)	n_{iS} (cm^{-3})	T_{eS} (eV)	L_S (μm)
10.6	10	1×10^{10}	101	2.0×10^{18}	31	50
1.06	10	1×10^{11}	180	1.3×10^{19}	46	160
0.26	10	1×10^{12}	183	5.0×10^{19}	63	245

laser intensity and the laser wavelength is approximately given as $I_L \lambda_L^{1.2}$, rather than $I_L \lambda_L^2$. This is due to the fact that the ion density n_i where the inband emission mostly occurs is much lower than the critical density n_{ic} for the short-wavelength lasers. The ion density and electron temperature at the peak position of S_{EUV} listed in Table 11.3 are also plotted in Fig. 11.10. As can be seen in the figure, the longer wavelength gives the higher CE. This is also confirmed in the simulations. The 10.6- μm laser gives approximately 1.9 times higher CE than the 1.06- μm laser, while the 0.26- μm laser gives 0.55 times lower CE.

Since for the 10.6- μm laser the optimum laser intensity is rather low, 10^{10} W/cm^2 , the inband EUV energy per shot may not satisfy the requirement for practical use as discussed in Sec. 11.2. However, the simulation results show that the CE does not decrease much with the increase of the laser intensity. This is due to the fact that the region higher than the critical density is heated by electron thermal conduction and the CE does not decrease much with increasing electron temperature at low density, as shown in Fig. 11.10. The increase of the pulse duration also results in an increase of the inband EUV energy per shot. For the 10.6- μm laser, the laser absorption efficiency also increases with the pulse duration. It was about 80% for a 10-ns pulse.

There may be an optimum pulse duration leading to higher CE for each laser wavelength. However, a longer pulse leads to a longer plasma scale, and the corona plasma may cease to be transparent, as discussed above. The density scale length $L_S = n_i / (\partial n_i / \partial x)$ in Table 11.3 is determined at the peak position of S_{EUV} for each case. Here, L_S approximately corresponds to the characteristic length of the EUV emission region. The increase of L_S at shorter wavelengths is due to the increase of the electron temperature at the peak position of S_{EUV} . The dashed lines in Fig. 11.10 show the length $l_{OD=1} = 1 / (\chi^\gamma)_{EUV}$ calculated from the density and temperature using the AA model. If L_S becomes much longer than $l_{OD=1}$, the inband emission does not proportionally increase with the increase of the characteristic plasma length. For the short-wavelength laser with the pulse duration of 10 ns, L_S becomes longer than $l_{OD=1}$, so that the further increase of the pulse duration may not result in an increase of the CE. However, the longer pulse may work well for the 10.6- μm laser. It should be mentioned, however, that an increase of the pulse duration may cause an increase of high-energy ions as shown Eq. (11.5). Further study is required for the optimization of the laser pulse duration.

11.5.3 Xenon: effects of satellite lines and opacity

We apply the power balance model for a xenon target. Figure 11.13 shows the laser-intensity dependence of the electron temperature and the various loss fluxes. The dependences are almost the same as those with tin, shown in Fig. 11.3. The power balance model gives a CE of approximately 2% at about 10^{11} W/cm^2 with 1.2-ns pulse duration, with the use of atomic data obtained from the average-ion model. However, atomic data obtained from the detailed atomic model introduced in Sec. 11.4.2 show that the inband emission is about 1.5% of total emission at an

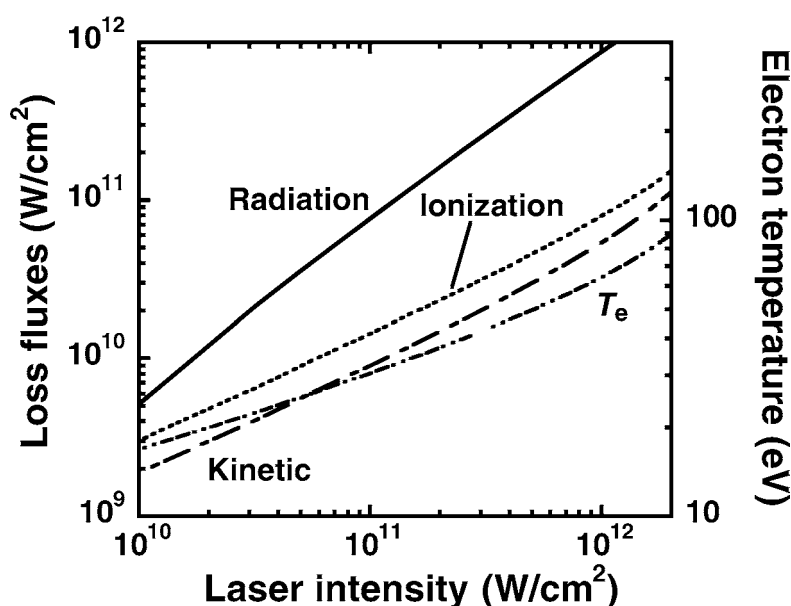


Figure 11.13 Various loss fluxes for xenon obtained from the power balance model: radiation loss (thick solid line), ionization loss (dotted line), expansion loss (dash-dotted line), and electron temperature (double-dot double-dash line) as functions of laser intensity, which is assumed to be equal to the total loss flux.

electron temperature of 25 eV, and it decreases with increasing electron temperature, as will be discussed below. Therefore, the CE of 2% could be an overestimate.

The theoretical value of the optimum laser intensity does not agree with experiments. Most of the experiments shown in Fig. 11.1 show that the maximum CE appears at higher intensity, around 10^{12} W/cm² or more. However, none of the experiments with xenon were carried out with a laser spot size (and target size) greater than 500 μ m, as may be required for the validity of the 1D expansion assumed here. A small target size causes large kinetic loss and thus requires higher laser intensity. We have recently found that experiments with larger target size show that the optimum laser intensity appears around 10^{11} W/cm², which agrees with the power balance model.

We now discuss the effect of detailed atomic processes on the CE of the Xe plasma in terms of satellite line emission and the opacity of the emission lines. We find from our collisional radiative model calculation that the multiply excited and inner-shell-excited configurations are significantly populated in high-density plasmas, resulting in considerable emission and absorption through 4d-4f and 4d-5p satellite lines. In particular, with the electron density of the emitting region above 10^{20} cm⁻³, we find that the population in the plasma approaches LTE, leading to an optical depth of the typical LPP greater than one; thus the opacity effect should be taken into account.⁵⁰ As shown in the previous analysis of the spectrum of the 3d-4f transition array from LPP,⁵¹ the satellite lines form a tail structure, called the *red wing*, on the longer-wavelength side of the resonance lines. As the optical

depth of the resonance lines increases, the intensity of the resonance lines saturates due to self-absorption. Consequently, the relative intensity of the satellite lines will increase, resulting in broad spectral width of the transition array.

We here compare analytical spectra with the emission from liquid Xe jet targets⁴ to clarify these effects, which are shown in Fig. 11.14. In Fig. 11.14(a), the experimental spectrum exhibits a dominant peak near 11 nm accompanied by weaker peaks at longer wavelengths. The peak at 11 nm is attributed to overlapping 4d-4f transitions from Xe^{8+} – $11+$, and the peaks in the longer-wavelength region are attributed to 4d-5p transitions from Xe^{10+} (13.5 nm),⁵² Xe^{9+} (14.8 nm),⁵³

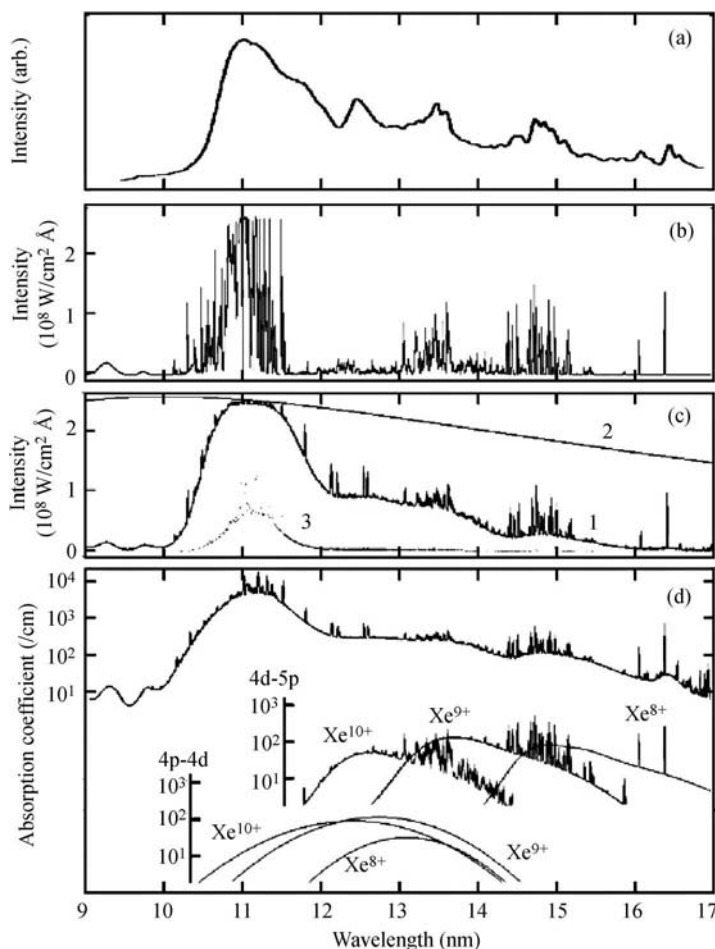


Figure 11.14 (a) Typical LPP EUV spectrum. (Reprinted from Ref. 4 with permission from the American Institute of Physics.) Calculated emission intensity of Xe: (b) without satellite lines, and (c) with satellite lines. Figure (c) shows radiation intensity from the surface of a uniform plasma with a radius of $10 \mu\text{m}$ (curve 1), Planckian intensity (curve 2), and relative emissivity (curve 3). (d) Absorption coefficient from the Xe plasma at $T_e = 25 \text{ eV}$ and $n_e = 10^{21}/\text{cm}^3$, assuming LTE population. Figure (d) also shows the contribution of 4d-5p and 4p-4d satellite lines for each charge state to the absorption coefficient.

and Xe^{8+} (16 nm).⁵⁴ In the experiment the emission is expected to occur near the critical density. It is found from our collisional radiative model that for the electron densities $> 10^{20} \text{ cm}^{-3}$ and a temperature of 25 eV, all atomic states can be assumed to be in LTE, where the ionization balance and level populations can be determined from the Saha-Boltzman relation. For a spherical plasma in LTE, the radiation intensity I_ν from its surface is also simply calculated using an analytical formula as⁵⁵

$$I_\nu = I_{\nu P} \left[1 - \frac{1}{2\ell^2} + \left(\frac{1}{\ell} + \frac{1}{2\ell^2} \right) \exp(-2\ell) \right], \quad (11.17)$$

as a function of the Planck radiation intensity $I_{\nu P}$ and radial optical depth ℓ .

The calculated spectrum without satellite lines, shown in Fig. 11.14(b), differs significantly from the experiment in its red-wing structure. In the present calculation, the resonance lines are calculated using a line-by-line (DTA) model including the effect of CI, whereas the satellite lines are calculated using a UTA approximation with averaged transition probability, energy, and linewidth. It is found that the emission on the longer-wavelength side of the 4d-4f transition array (11.5–13 nm) and the background level of the 4d-5p transition arrays (12–16 nm) can be explained only by considering the satellite lines, as shown in Fig. 11.14(c).

Figure 11.14(d) shows the contribution of each satellite channel to the absorption coefficient of the plasma. Absorption between 11 and 12 nm is mainly due to 4d-4f satellites, such as $4d^{i-2}4f_{nl} \rightarrow 4d^{i-1}nl$ transitions, where nl indicates the orbit of the spectator electron. It is also shown that 4d-5p resonance lines from each charge state have satellite lines, $4d^{i-2}5p_{nl} \rightarrow 4d^{i-1}nl$ transitions, on their longer-wavelength side. In addition, 4p-4d transitions and their satellite lines, $4p^54d^i_{nl} \rightarrow 4p^64d^i_{nl}$ transitions, contribute to the broad background level between 11 and 14 nm. Eventually, the absorption coefficient of Xe plasmas shows a broad structure between 11 and 16 nm. Note that emissivity of the 4d-4f resonance line is still much stronger than that of the satellite lines.

As shown in Fig. 11.14(c), the emission spectrum calculated including the effect of satellite lines and opacity reproduces the experiment fairly well. Thus, in order to perform a radiation hydrodynamics simulation to predict the CE, we calculated and tabulated the emissivity and opacity of Xe and Sn plasmas as functions of the electron temperature T_e and the ion density n_i , using the present atomic model, in which CRE and an optically thin plasma are assumed. Figure 11.15 shows the spectral emissivity of Xe plasma at the ion density $4 \times 10^{19} \text{ cm}^{-3}$ and electron temperature 30 eV. The comparison of the emissivities with and without the effects of CI and satellite lines shows that the broad structure originates mainly from the satellite lines. Furthermore, we have estimated the spectral efficiency, which is defined as the ratio of the inband to the total EUV emission intensity. We found that since the main part of the emission appears in the 11-nm band in Xe, the spectral efficiency is approximately 1/6 of that of Sn. We also found that the high efficiency is obtained within a limited temperature range, where the Xe^{10+} ion has a significant abundance. It is interesting that the optically thick calculation, shown

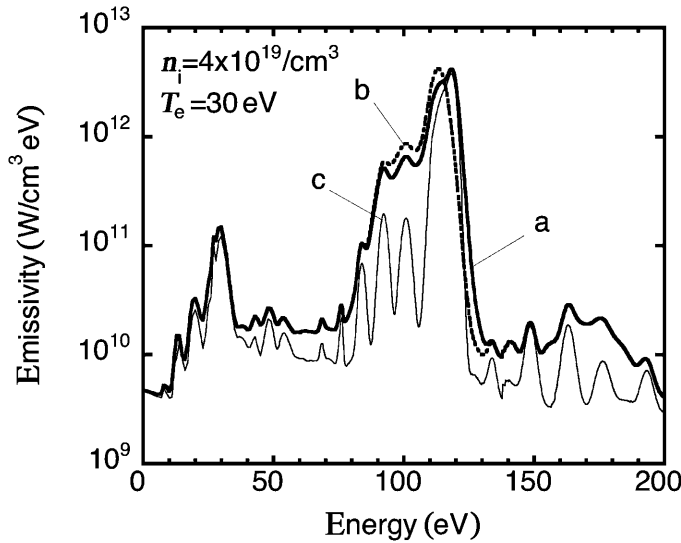


Figure 11.15 Calculated emissivity of Xe plasma for $n_i = 4 \times 10^{19}/\text{cm}^3$ and $T_e = 30 \text{ eV}$: (a) including the effect of Cl on the resonance lines and satellite lines, (b) without the effect of Cl, (c) only from 4d-4f resonance lines.

in Fig. 11.14, yields similar spectral efficiency. Detailed analysis of the spectral efficiency and its dependence on the atomic model will be published elsewhere.

Assuming the same conversion as for the Sn target from laser energy to the total radiation energy (around 50%), as discussed before, we expect a maximum CE of 1% for Xe targets. Further experimental investigation and comparison with theory are required, with a larger spot size, to identify the optimal pumping condition of the Xe source.

11.6 Discussion and Summary

We have presented a simple analytical model of a scaling law for the CE, which agrees fairly well with the experimental results, at least for a solid tin target. The model also explains features of the observed spectrum, such as its drastic changes with the laser intensity, observed in the experiments. It is shown that the CE into 13.5 nm with 2% bandwidth has its maximum of 3% at a laser intensity of $(0.5\text{--}1) \times 10^{11} \text{ W/cm}^2$ for a tin target. We have also introduced a possible design window for practical usefulness of an EUV source. The scaling law and the experimental results show that this design window, shown in Table 11.1, can be achieved. If we use the parameters of a focusing system introduced in Sec. 11.2, the EUV power at the IF can be estimated as

$$P_{\text{EUV}} = \eta_{\text{EUV}} S I_L \tau_L \varepsilon_{\Omega} \varepsilon_R \varepsilon_{\text{tm}} \varepsilon_{\text{td}} R_p = 280 \text{ W}, \quad (11.18)$$

where we have assumed the CE $\eta_{\text{EUV}} = 0.03$, the laser spot diameter $\phi = 870 \mu\text{m}$ corresponding to an etendue of $3 \text{ mm}^2 \text{ sr}$, the laser intensity is 10^{11} W/cm^2 , the

pulse duration is 5 ns, and the repetition rate $R_p = 10$ kHz. The estimated inband EUV power of 280 W at the IF is well above the source requirement of 115 W, which may allow some margin in design for use. The EUV power for xenon targets is still marginal, if the highest CE is 1% and one uses the same laser intensity and the same pulse duration as in the above estimation. However, it may also be possible to satisfy the requirement by using a higher intensity or longer pulse duration than those in the estimation.

We have also discussed the dependence of the CE on the laser wavelength from 10.6 to 0.26 μm . Since the CE depends very weakly on the density in the range from 10^{18} to 10^{20} cm^{-3} , the 10.6- μm laser also gives rise to high CE, probably higher than that with the 1.06- μm laser. The optimum laser intensity is estimated for each laser wavelength. Effects of satellites and opacity on the CE are discussed for xenon. Similar effects occur for tin. The optimum pulse duration for each wavelength still remains for future investigation. A power balance model taking the self-absorption of the EUV into account is being developed for both tin and xenon, and will be published elsewhere.

It should also be noted that a very high CE of 2.5% has been reported recently for lithium.⁵⁶

Acknowledgments

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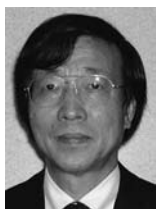
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Chapter 12

Dense Plasma Focus Source

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12.1 Introduction

With the emergence of EUVL as the chosen technology for next-generation lithography (NGL) systems, significant effort has been spent in developing light sources consistent with the challenging requirements of the scanner manufacturers¹ as well as meeting the aggressive demands of the end users for high-volume manufacturing (HVM).² A light source with extremely high power and brightness is required for integration into a scanner tool based on reflective optics with multilayer (ML) coatings, since it needs to be designed for highest throughput at a wavelength of 13.5 nm. Over the past six years at Cymer Inc., we have pursued the research and development of DPPs to meet the demands for commercial HVM tools. A dense

plasma focus (DPF) configuration was chosen because it provides an open geometry with large possible collection angle and can be operated over a wide parameter range. The main thrust of our research and development is devoted to achieving the challenging industry demands on light-source performance, requiring extremely high output power (>100 W), cleanliness, and component lifetime.

In this chapter we review the DPF development efforts at Cymer Inc. and discuss the various areas of investigation we have concentrated on during our efforts to optimize the performance of the light source. The main focus is on the characterization of the various EUV output parameters for different operating conditions. We also discuss thermal management, modeling efforts, debris mitigation, light collection, scalability, and risk areas. More extensive and detailed discussions of some particular aspects of the DPF source are described in our previous annual progress reports on source development.^{3–9}

The plasma-focus scheme was developed independently several decades ago by Mather¹⁰ and by Filippov et al.¹¹ In a typical Mather-type DPF configuration, an annular sliding plasma discharge is first produced between coaxial electrodes in a so-called *rundown* phase. Strong magnetic forces created by the high discharge current then lead to a pinch event after plasma compression, with a hot dense microplasma zone developing on the axis near the end of the inner electrode. This highly ionized plasma is confined for a short time and emits intense EUV and soft x-ray radiation. Apart from the main application of large-scale DPF devices for fusion research (typically operated with single pulses), low-energy instruments (with less than ~ 1 -kJ stored energy) with submicrosecond pulse duration and sometimes higher repetition frequencies have also been investigated as radiation sources by several groups.^{12–16} Our choice of the DPF configuration was born out of related work on coaxial plasma guns and plasma thrusters for space applications.^{17–20} At Cymer Inc., we have adopted the DPF source technology because small-scale configurations can be constructed with very low discharge-circuit inductance and only moderate electrical power consumption while showing at the same time excellent prospects for reliable multikilohertz operation and high EUV generation efficiency.

12.2 Overview of the Source

The main features of our present-generation DPF machines have been described in detail previously.^{6–9} Using a reliable, all-solid-state pulsed-power system that is scalable to high repetition rates (6–10 kHz), fast 4.2-kV pulses are delivered to the coaxial electrode set of the discharge with low inductance via a magnetic pulse-compression scheme. After preionization from separately energized electrodes, an annular moving current sheet is formed between anode and cathode in the discharge gas. The $\mathbf{J} \times \mathbf{B}$ forces then accelerate and compress the plasma to a small dense region on the axis. The pinch event occurs in time near the current maximum (about 40 kA) at a location in front of the electrodes. The highly ionized excited species formed by collisions in the pinch region give rise to intense emission of EUV radiation near 13.5 nm. For a Xe light source, the DPF operation at a given

pressure can be optimized by injecting helium gas in addition to xenon. The electron temperature, the ion distribution, and therefore also the spectral distribution of the EUV output are dependent on the energy input as well as the gas flow, the pressure, and the pumping speed.²¹ Although the majority of our development studies were carried out with xenon gas, we have also operated our sources with good success using metal fuels such as lithium^{3,4} and tin.⁹

In order to address several development areas in parallel, in our investigations seven DPF machines were assembled. They served to focus on different issues such as plasma optimization, thermal engineering, power scaling, metrology, and debris mitigation. In most of our past work we used the “conventional” DPF configuration with a positively biased central electrode (anode) and grounded outer electrode (cathode). However, strong EUV generation with similar conversion efficiencies (CEs) was also observed when a negative voltage was applied to the inner electrode. In this case the DPF can also be operated without preionization in a self-breakdown mode. In agreement with other DPF discharges,²² the optimum pressure is found to be lower for the negative-polarity DPF, leading to a reduction of absorption by xenon gas. Very recently, we described the effects of the electrode polarity on the source performance in a detailed study.²³

The source output can be scaled by increasing repetition rate, CE, and collection efficiency. This requires improvements and optimization in various areas: the pulsed-power system, thermal extraction, gas dynamics, and electrode materials, as well as geometry and preionization. Higher efficiencies may be attained by optimization of the plasma conditions and also by using better-matched source elements and collector designs with high acceptance angle and coatings for high reflectivity. As described below, significant improvements were obtained in most of these areas.

12.3 Pulsed-Power Development

To generate the required high-voltage, high-energy electrical pulse, the pulsed-power system utilizes solid-state switching and several stages of magnetic pulse compression, similar to that applied in our excimer lasers. The entire module is arranged in coaxial geometry. For the present fourth-generation system, eight IGBT switches are used in parallel (Fig. 12.1); the capacitor decks C_0 – C_2 each consist of parallel-serial arrangements of many polypropylene film capacitors. With the exception of LS_1 , advanced soft-magnetic alloy materials are used for the magnetic switches and transformer cores. Applying a charging voltage of 1300 V from a resonant charging power supply, an output pulse of about 4 kV is generated with a rise time of less than 50 ns. The pulse-charging system is optimized for high-power and high-repetition-rate operation and is scalable to 10 kHz. When running at the maximum C_2 voltage, up to 13.5 J of energy can be delivered to the electrodes. The energy of pulses reflected from the DPF load is recovered and transferred back to C_0 . The circuit schematics of the multistage compression scheme are shown in Fig. 12.1; a detailed description of the pulsed-power system is given in Ref. 24. To

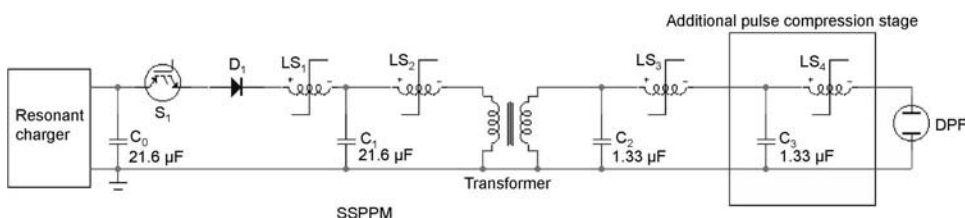


Figure 12.1 Schematics of the DPF pulsed-power circuit. The fourth-generation system is configured without the additional compression stage.

reduce the drive inductance even further, an additional compression stage after the transformer is presently under development, applying ceramic capacitors. Furthermore, appropriate cooling hardware is being developed for solid-state devices and magnetic cores to support high-average-power operation.

12.4 EUV Output Energy and Conversion Efficiency

The source output power is of prime concern for a production-worthy EUV system. Therefore, absolute inband EUV emission measurements and studies of CE for different operation conditions of the DPF were carried out using arrangements in differentially pumped diagnostic vessels similar to the FOM Flying Circus configuration.²⁵ As described previously,^{5,6} the radiation from the pinch is reflected from a curved Mo/Si multilayer mirror (MLM) through a thin zirconium foil onto an uncoated IRD AXUV-100 photodiode. Taking into account the geometry, foil transmission, mirror reflectivity, and detector quantum efficiency, the inband EUV output power (for 2% bandwidth into 2π sr) is obtained from the time-integrated signal. The output power and CE were determined as a function of the energy dissipated in the discharge as calculated from the maximum and minimum of the C_2 voltage waveform. By optimizing the gas recipe, electrode size, and geometry as well as other parameters, over the past years the measured pulse output energies have been made greater than 50 mJ/pulse and the CE has been increased to 0.5% (see also Ref. 7). Figures 12.2 and 12.3 show a comparison of the dependence of the inband energy at 13.5 nm and the CE for positive- and negative-polarity DPF systems for xenon. The slopes of the curves are approximately equal for the two polarities, with the CE reaching a plateau at high input energies. The pulse-to-pulse root mean square (rms) output energy stability is about 7% at low repetition rates. When using tin as target material, a CE of $\approx 1.7\%$ was obtained for operation of the DPF with a mixture of tin and argon.

12.5 Operation at High Repetition Rates

Stable performance of the source at high repetition rates is important for high exposure dose and accurate dose control. Burst-mode operation at increasingly

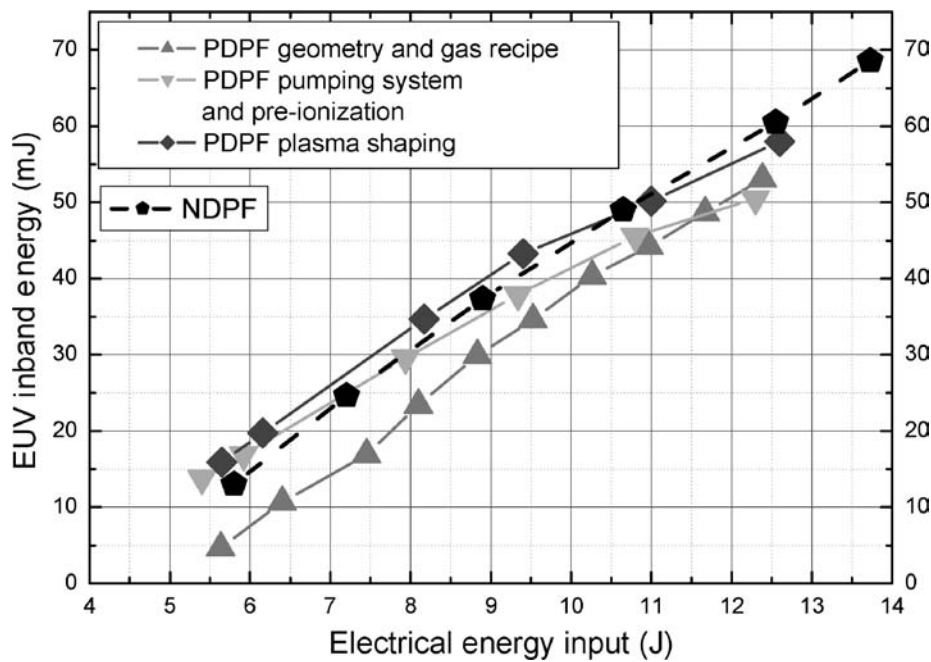


Figure 12.2 EUV inband energy versus input energy for positive (P) and negative (N) DPF operation.

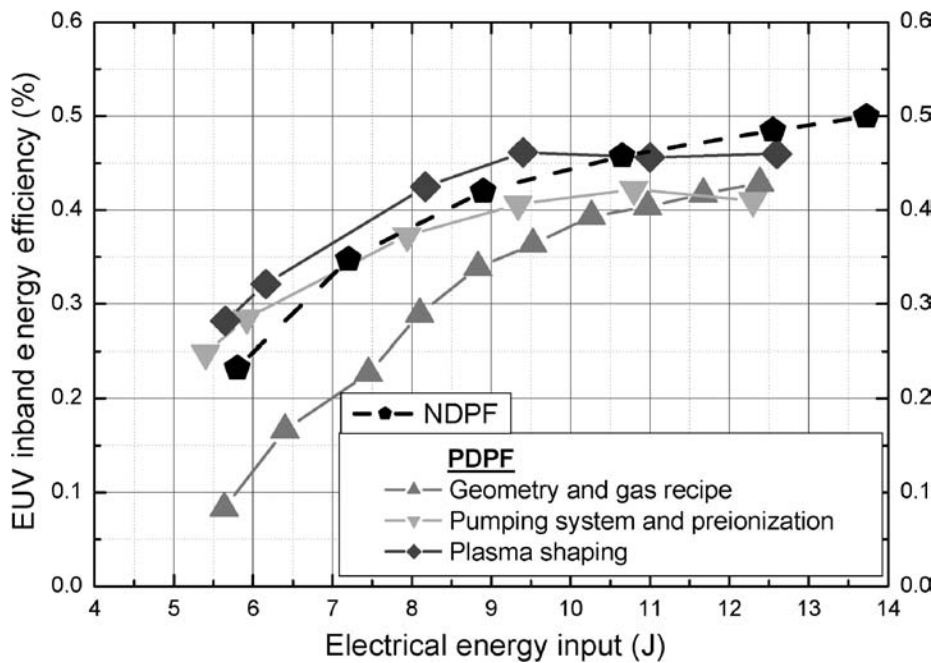


Figure 12.3 EUV inband efficiency versus input energy for positive (P) and negative (N) DPF operation.

higher repetition rates has been demonstrated on several of our DPF systems. Figure 12.4 shows the variation of the time-integrated inband output energy during a burst of more than 300 pulses for a positive-polarity DPF with uncooled electrodes at 5 kHz. The shape of the characteristic transient at the beginning of the pulse burst is highly dependent on operating conditions such as electrode geometry, gas recipe, and preionization system. The EUV output energy is strongly correlated with the degree of coupling of the stored pulse energy to the discharge. This indicates that the energy stability is strongly affected by details of the discharge formation process and energy coupling mechanisms. On excluding the initial transient in the burst, pulse energy stability variations were typically $\approx 7\%$ – 8% rms at high repetition rates.

The EUV output energy was also measured for continuous operation at a repetition rate of 2 kHz at negative polarity using second-generation direct water-cooled electrodes. Employing an EUV monitor with debris suppression tube, inband output energies of 38 mJ/pulse (into 2π sr, 2% bandwidth) were observed, corresponding to 76 W of continuous average output power. Furthermore, additional test runs with continuous operation at 50% duty cycle and 5-kHz repetition rate were carried out.

12.6 Thermal Management

Several factors contribute to the heating of the source during operation: Energy is transferred by radiation from the plasma to the electrodes, the chamber, and

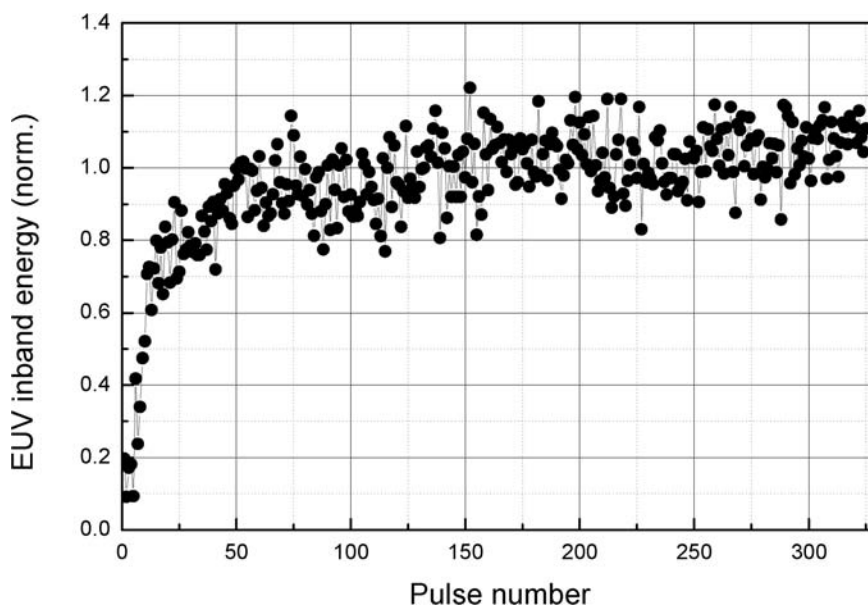


Figure 12.4 DPF operation at 5 kHz for 325 pulses. The rms energy stability disregarding the first 50 pulses is 8.6%.

the debris-shield–collector assembly. Heating by conduction from the plasma and ohmic heating of the electrodes also leads to sizable amounts of transferred energy. Surface temperature distributions in the range of 650 to 2000°C for different DPF configurations were examined by means of thermographic imaging. We found that in comparison with negative-polarity operation, a larger energy fraction is deposited at the inner electrode in the case of positive polarity.

Thermal engineering of the discharge region of our DPF light source has included the testing of different water-cooled designs for the inner electrode using open annular channels, porous-metal channels, and microchannels. Water cooling was also applied to the outer electrode and the vacuum vessel. In addition, manufacturing techniques to produce electrodes using refractory metals such as tungsten and molybdenum and discharge insulator development have progressed significantly. Thermal test runs at steady-state repetition rates of up to 2300 Hz have been carried out with a total energy of >28 kW removed from the electrodes and the vessel, including the coolant pumping power. Lifetimes of up to 35 million pulses have been demonstrated, the end of life being characterized by noncatastrophic coolant leakage. Figure 12.5 shows an example of calorimetric data, at different repetition rates, for the total extracted power as obtained from thermocouple sensors at different positions at the inner and outer electrodes and the chamber. Our results indicate that DPF operation at negative polarity leads to a smaller relative heat dissipation fraction at the inner electrode than does positive polarity.

Computer simulations have been updated using empirical data to more accurately model the detailed thermal loading on the inner electrode. The resulting tem-

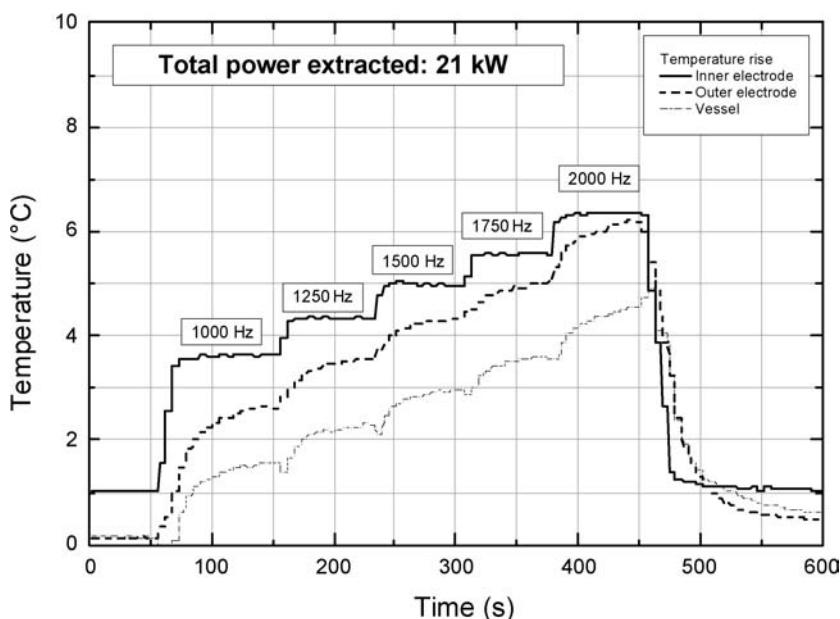


Figure 12.5 Temperature rise of coolant flow associated with the inner electrode, outer electrode, and vessel for the negative-polarity DPF versus time at increasing repetition rates.

perature distribution calculated for the electrode shows good correlation between areas of high temperature in the model and those of highest erosion observed in experiments. Thermal modeling predicts manageable inner-electrode temperatures for up to 3-kHz operation with our second-generation cooling design.

12.7 EUV Source Size and Spatial and Angular Distribution

The EUV source size must be small in order to achieve a very high brightness. Moreover, the etendue has a direct influence on the attainable collection efficiency.^{1,26} Therefore, we have measured the source size by means of EUV imaging techniques. Depending on the operating conditions, the averaged DPF source volume has an elongated shape with a full width at half maximum (FWHM) in the range of 0.3–0.4 mm and 2.5–4.5 mm perpendicular and parallel to the axis, respectively. Studies of the source size were carried out using a back-illuminated CCD camera and a thin metal foil for spectral filtering. At first, measurements were performed both on axis and off axis, using a pinhole-imaging technique, for both single-pulse and pulse-averaged spatial images.^{5,6} However, such data contain also some contributions from more energetic out-of-band radiation and typically lead to an underestimation of the true source size. In order to obtain more accurate inband data, we have therefore employed a pinhole-free at-wavelength imaging technique using spherical MLMs^{7,8} and have also included in the pinhole arrangement a reflection from a MLM at 45-deg incidence in front of the CCD camera.⁹ The latter arrangement is shown in Fig. 12.6. A comparison of inband measurements using the EUV monitor and the integrated CCD signal on a pulse-to-pulse basis has yielded almost perfect agreement, with a correlation coefficient > 0.97 . The corresponding source position stability was also determined from the fluctuations of the centroid in measurements of the source size and was found to be typically less than 0.05 mm rms.

The dose stability and the uniformity of the filling of the entrance pupil of the illumination optics are directly connected with the angular stability of the source. Therefore, the emission from the source was examined by correlation measurements at different angles, using pairs of our calibrated EUV monitors. High correlation (> 0.95) of the inband EUV emission was detected for DPF operation at both low and high (2 kHz) repetition rates. High angular emission correlation was also observed for other detector combinations. These results indicate that for individual pulses the pinch dynamics leads to similar emission characteristics irrespective of the different angular directions. Pulse averaging improves this correlation even further.

12.8 EUV Spectra

Spectral analysis of the emitted EUV radiation is important for the determination of the partitioning of inband and out-of-band emission, for estimation of the mean electron temperature, and for characterization of the spectral output stability at

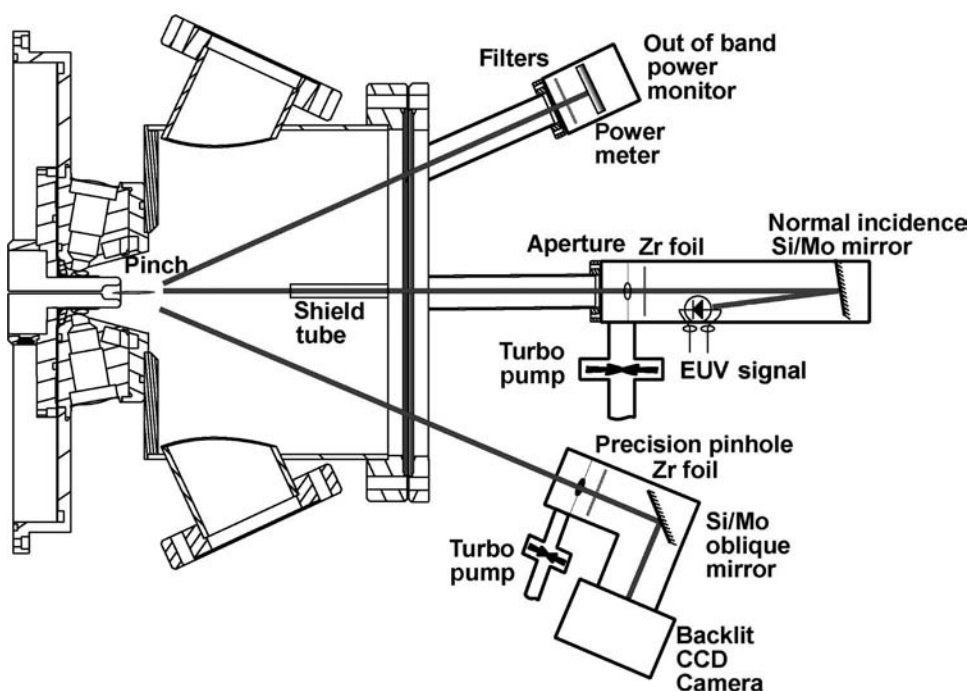


Figure 12.6 Schematics of the EUV metrology. The source imaging is performed with a CCD camera, a 45-deg multilayer-coated mirror, a filter foil, and a pinhole aperture. The EUV absolute energy is measured using a photodiode and MLM-based energy diagnostics.

different DPF operating conditions. Measurements of the EUV emission spectra from the DPF were carried out for a variety of source elements and with special emphasis for the case of xenon. In our early work we discussed the lithium spectra³ and the spectra of xenon and various other source gases⁵ using step-by-step recording with a grazing-incidence spectrometer at a resolution of 0.02 nm. Later on, we employed a transmission-grating arrangement with a CCD camera that allowed recording of single-pulse xenon spectra at lower resolution.^{7,8} The DPF spectrum for tin near 13.5 nm was also measured with this detection scheme.⁹ A high-resolution spectrum of xenon is displayed in Fig. 12.7 together with a typical theoretical reflectance curve for a Mo/Si MLM.

It was found that the emission of xenon depends strongly on the operating conditions, as previously seen in the xenon spectrum of a preionized Z pinch by McGoeck.²⁷ The spectral distribution changes when the deposited energy, the discharge current, the gas mixture, or the gas pressure is changed. Spectra at increasing input energies showed an increase of the emission of more highly ionized xenon, indicating a higher average electron temperature.^{5,21} On the other hand, for fixed DPF operating conditions subsequent single-pulse spectra exhibited only small intensity fluctuations that may be attributed to differences of the final compression and heating of the pinch plasma from one pulse to the next. Generally, larger changes were observed for the short-wavelength regions of the spectra, cor-

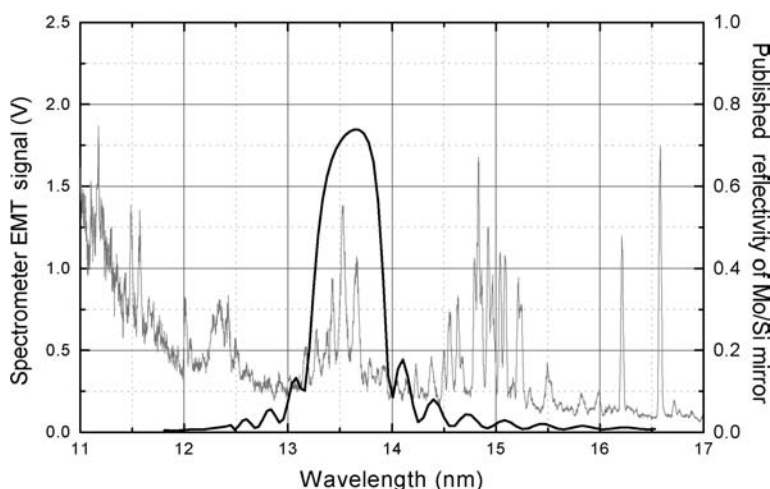


Figure 12.7 Measured EUV spectrum for xenon and MLM reflectance curve.

responding to emission from more highly ionized xenon in the hottest zone of the plasma. The main features of the xenon spectra can be analyzed by a comparison of our results with similar data for a capillary discharge obtained by Klosner and Silfvast.²⁸

12.9 Spectral and Plasma Modeling

Modeling of radiative interactions and of the plasma magnetohydrodynamics (MHD) leads to a better understanding of the critical parameters influencing energy coupling and plasma emission. More detailed analysis of the xenon spectra was obtained from a comparison with Hartree-Fock (HF) model calculations.²¹ They were carried out in order to obtain information on the various spectral contributions for different pinch conditions. A comparison of single-pulse spectra measured with the transmission grating at the same total gas pressure but for different Xe flow rates is shown in Fig. 12.8.⁸ An analysis of the relative intensity changes of the Xe IX to Xe XII line groups indicates that the average plasma temperature increases with decreasing xenon flow rate. The calculations reproduce the main features of the experimental spectrum, in particular for the wavelength region at around 13.5 nm that is assigned to many overlapping 4d-5p transitions of Xe¹⁰⁺ ions. The model calculations also revealed that the influence of the optical thickness on the spectral emission intensities is significant and larger for the 4d-4f transitions than for 4d-5p, due to their higher oscillator strengths. A more extensive discussion of the Xe spectra, the line group assignments, and the model calculations for different electron temperatures with inclusion of opacity effects is given elsewhere.²¹

For inclusion of a time-dependent fluid description of the plasma, we used the magnetohydroradiative-dynamic research (MHRDR) code described in Refs. 29

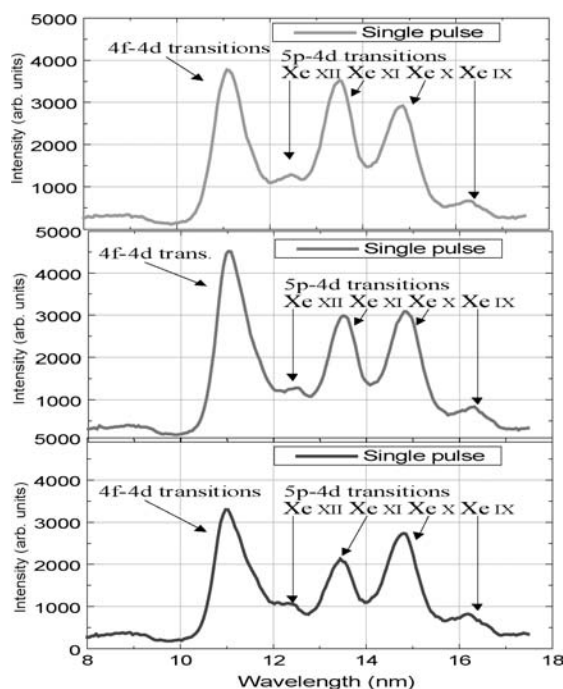
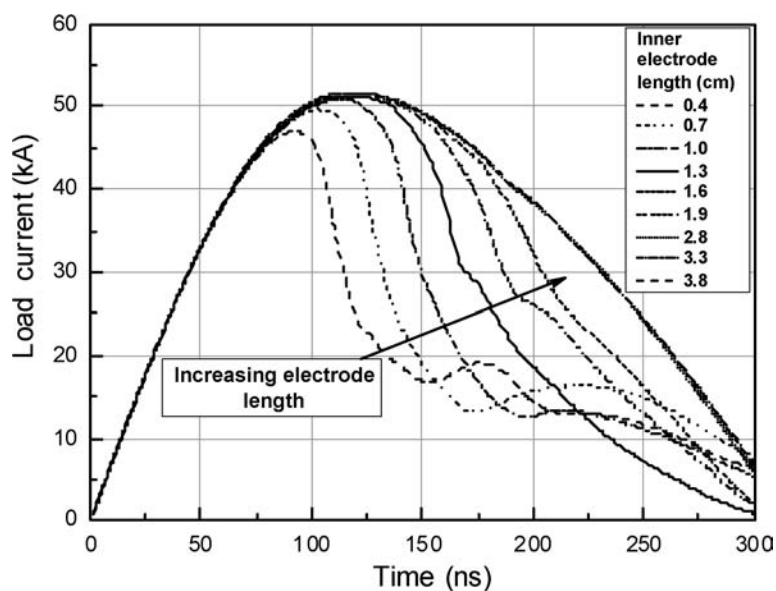


Figure 12.8 Single-pulse spectra at constant pressure versus Xe flow rate. The xenon flow rate increases and the plasma temperature decreases from top to bottom.

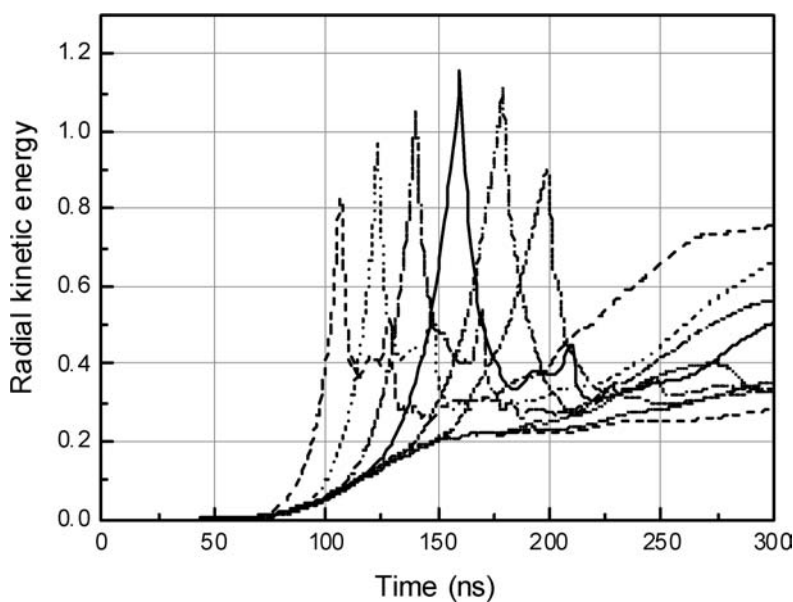
and 30. It includes thermal conduction, radiation, ionization, and material properties in an equation-of-state formulation. Figure 12.9 shows the calculated radial kinetic energy and discharge current as a function of time during the discharge for different lengths of the inner electrode. The magnitude of the radial kinetic energy peak at the instant of the plasma pinch is a measure of the coupling efficiency. The length for which the kinetic energy is maximized corresponds to the best transfer of magnetic energy to internal plasma energy. The timing of the pinch is optimized to the discharge circuit with the time constant fixed externally. The circuit and gross electrode geometry can thus be optimized for best plasma performance.

12.10 Metal Target Elements

Previously, we gave a detailed discussion of the prior-generation DPF performance with lithium vapor as target element.^{3,4} Lithium has the advantage of narrowband line emission at the peak of the reflectance curve of MLMs optimized for 13.5 nm and of comparatively small out-of-band emission contributions. We have now also carried out some experiments with a present-generation DPF machine on lithium micropowder and also on tin powder targets.²³ We have measured the EUV in-band energy, the CE, and the emission spectra. Figure 12.10 shows a comparison of spectra obtained with the transmission-grating spectrometer for operation with a mixture of tin and argon. The spectrum clearly shows the appearance of an emis-



(a)



(b)

Figure 12.9 Simulations using the MHRDR code: (a) load current waveforms for various lengths of the inner electrode; (b) associated radial kinetic energy. Note that there exists an optimum length for maximizing the radial kinetic energy.

sion line at 13.5 nm when tin is added to the DPF. The CE for these data was approximately 1.7%. The actual pulse energy was approximately 200 mJ per pulse at low repetition rates. The source emission spot with tin is seen to be more spheri-

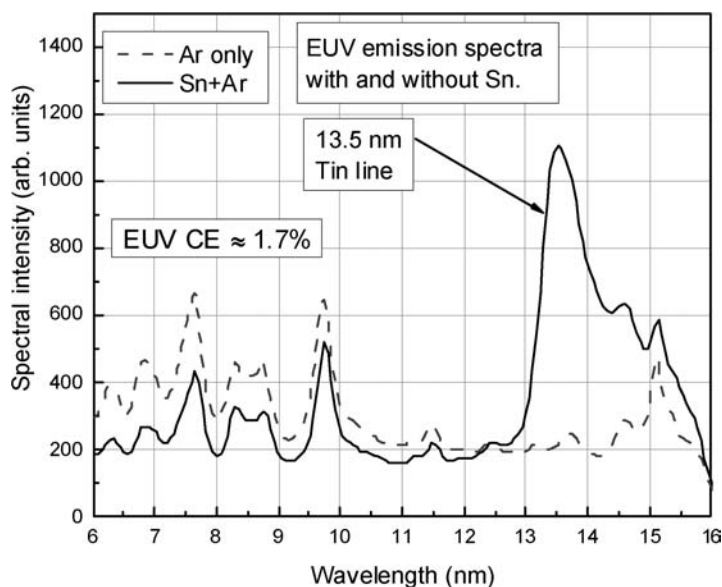


Figure 12.10 Emission spectrum of the DPF discharge operated with pure Ar and with Ar plus added Sn. The data were obtained using the transmission-grating spectrometer.

cal than that obtained with Xe gas. Work in this area is being continued in order to obtain further CE improvements.

12.11 Debris Mitigation and Contamination Studies

The lifetime of the first collection mirror is of major concern for all EUV light sources. The generated debris contains fast ions and neutrals. Even if the debris is effectively shielded, the optics lifetime can still be limited by degradation due to contamination leading to oxidation or EUV-catalyzed carbon growth on the mirror surface. Therefore, a significant portion of our EUV development program is addressing debris mitigation and environmental control in order to maintain a clean collector optic.

We have previously demonstrated that debris from the inner electrode can be efficiently suppressed by a debris shield with long channels, exhibiting typical reduction factors of $\sim 100/\text{cm}$.⁶ In order to verify the stopping power of channels with different diameters and to better understand the debris-suppression scaling, we have also used a multichannel test fixture consisting of an array of channels with different lengths and orientation angles relative to the pinch axis;⁷ see Fig. 12.11. Furthermore, we have continued to eliminate potential sources of hydrocarbon outgassing and improved our vacuum system by utilizing magnetically levitated turbomolecular pumps. Our previously reported results with multichannel arrays simulating debris shields^{6,7} showed that EUV-catalyzed carbon deposition significantly exceeded the rate of all other sources of debris generation. The analysis of subsequent experiments under improved vacuum conditions with 3 million pulses

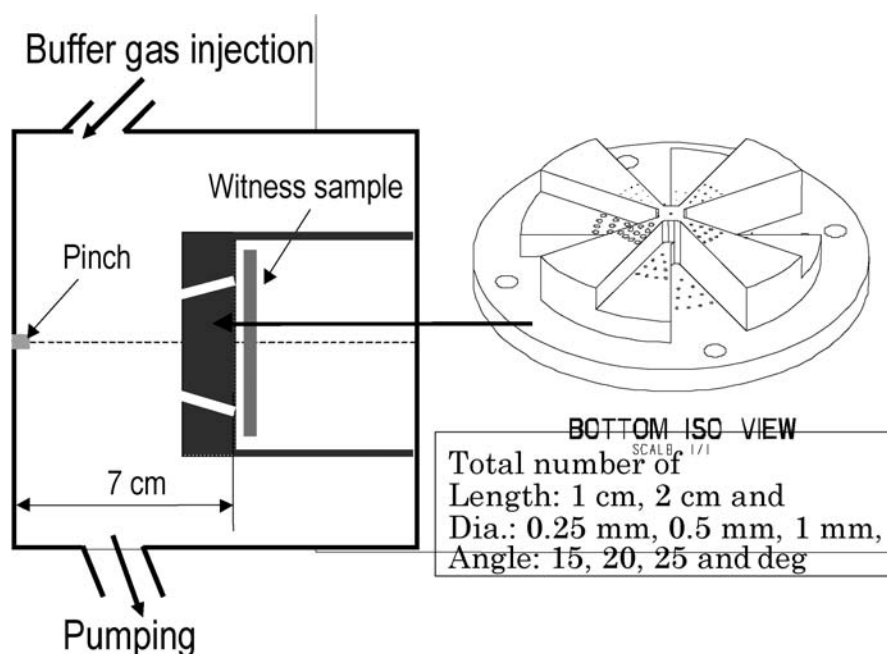


Figure 12.11 Arrangement for measuring the stopping power of different channels as a function of incident angle and channel length.

showed that the coating of witness samples generated by debris contained carbon, oxygen, aluminum, and xenon. No evidence of electrode material was seen, and the observed rate of carbon buildup⁹ was 100 times lower than in the previous experiments. Although we have made a considerable improvement in the system cleanliness, we have not yet identified all of the source terms for carbon in our system. Future experiments will require additional measures of cleanliness handling, using ultraclean electropolished vacuum vessels.

12.12 EUV Collector

For a discharge-based EUV light source, the plasma size and related etendue considerations point toward the use of a nested-shell collection optics employing grazing angles of incidence.^{1,26} The requirement of an intermediate focus (IF) aperture separating the source-collector module from the remaining illumination optics leads to an ellipsoidal shape of collector surface. In the past,^{4,5} we have therefore investigated grazing-incidence collector shells coated with palladium and ruthenium. A computation program was developed to assist in the optimization of the optical design by ray tracing and to model the angle-dependent reflectivity. The individual shells are fabricated by electroplating nickel onto a polished mandrel. The results of far- and near-field testing with visible light were described previously.⁵ Wavefront errors become more pronounced for the outer shells of the collector, due to deformation of the shells under their own weight. Although optical testing

has been carried out for several prototypes with thicker shells, limitations due to lifetime were encountered. The overall EUV collection efficiency is significantly influenced by the transmission of the debris shield and, to a lesser extent, by the shell support structure.

12.13 Lifetime Limitations and Power Scaling

The lifetimes of the inner electrode and the collector mirrors are the limiting parameters during use at high duty cycles. Fast exchange of the inner electrode and (less frequent) exchange of the collector assembly can be arranged. Erosion data derived from weighing of inner electrodes after exposure to millions of pulses at continuous operation at ≈ 50 Hz were consistent with the thermal results. The weight loss per pulse was measured for several different electrode materials, including various forms and alloys with tungsten. Tungsten has favorable impulsivity characteristics.⁷ The electrode lifetime decreases with increasing repetition rate. Operation with negative polarity at the inner electrode resulted in a 2 times reduction of the erosion rates of the electrode material of choice. Test runs indicate that the electrode life is extendable to beyond 100 million pulses. At present, the projected collector optics lifetime is above 300 million pulses. It is ultimately connected with the efficiency and acceptable reduction in EUV transmission of the debris shield. The economical use of an assembly of replicated collector shells can be envisioned.

The power scaling of the DPF source can be estimated based on the present results. Table 12.1 shows the various factors that govern the inband EUV power obtainable at the IF. With the present state of the DPF technology, using xenon as the source element, at 3.1-kW thermal extraction power and 140-W generated inband EUV power, about 14 W of EUV power will be obtained at the IF. The collection efficiency and the transmission factors are listed in Table 12.1. Future developments should enable the generation of 300-W EUV power (for Xe, at higher CE and thermal power extraction; see Table 12.1). In order to reach EUV power levels

Table 12.1 Output power scaling for the DPF source operated with Xe or Sn.

	Today	Future	Required	Required
Steady-state mode	Xe	Xe	Xe	Sn
Thermal extraction power (W)	31,000	50,000	100,000	35000
CE	0.45%	0.60%	0.70%	2.00%
EUV power (W), 2% bw, 2π sr	140	300	700	700
Collection efficiency	20%	30%	30%	30%
Collected EUV (W)	28	90	210	210
Collector transmission	70%	70%	70%	70%
Debris mitigation transm.	80%	80%	80%	80%
Spectral-purity filter transm.	100%	100%	100%	100%
Gas transmission	90%	90%	90%	90%
EUV at IF (W)	14.1	45.4	105.8	105.8

above 100 W at the IF, even under favorable conditions, a thermal extraction power of 100 kW or more will be required in the case of a Xe-based DPF source. However, as shown in the last column of Table 12.1, due to its higher CE number, tin as source element will meet these requirements for HVM already at 35-kW extraction power.

12.14 Summary and Conclusion

Significant progress has been made in all aspects of DPF source development over the past years. We have demonstrated continuous improvements of inband EUV output power, CE, and other source parameters. A summary of the source parameters achieved by the end of the year 2003 is given in Table 12.2 for both Xe and Sn. The highest inband output power obtained with xenon in continuous operation mode at 2-kHz repetition rate was 76 W (emitted into 2π sr). Using the burst mode, we have operated at up to 5 kHz with approximately 200 W of inband power. Charging the DPF with negative polarity allows operation in either a self-breakdown mode or a preionized mode, with slightly different source parameters. The thermal load distribution is more favorable in this case. The trend in CE seems to indicate a saturation at 0.5% with xenon for both positive and negative polarity.

We have successfully demonstrated tin and lithium as more efficient metal target elements. For tin, at equivalent operating conditions, approximately a fourfold increase in EUV output energy and CE was observed over operation with xenon gas. We have implemented several advanced source metrology systems employing EUV photodiodes for output power measurements, and CCD cameras for source size measurements. Both detection schemes show excellent correlation on a pulse-to-pulse basis. Likewise, high degrees of correlation were obtained for EUV emission into different angles from measurements of the angular distribution stability. Imaging arrangements for source size measurements were refined in several steps and yield now consistent and reliable data on the size of the emitting hot plasma zone.

We are continuing to make progress in the thermal engineering of the pulsed-power system and discharge electrodes. With the changes outlined in this chapter we expect to be able to operate the pulsed-power system in a continuous mode at

Table 12.2 Summary of the characteristic data obtained for Xe and Sn.

Data characteristic	Xe	Sn
EUV efficiency (2% BW, 2π sr)	$\approx 0.50\%$	$\approx 1.7\%$
EUV energy per pulse (2% BW, 2π sr)	≈ 70 mJ	≈ 200 mJ
Average source size (FWHM)	$\approx 0.33 \times 4.1$ mm	$\approx 0.73 \times 2.75$ mm
Source position stability (centroid)	< 0.05 mm, rms	
Continuous repetition rate	2500 Hz	20 Hz
Burst repetition rate	5000 Hz	
Energy stability	$\approx 7\%$, rms	
Average EUV output power (2% BW, 2π sr)	76 W	4 W
EUV output power, burst (2% BW, 2π sr)	200 W	

>5-kHz repetition rate. The high degree of coupling of stored energy to the discharge (>90%) enables us to operate with a lower total stored energy in the pulsed-power system. The tested electrode cooling designs have demonstrated the capability to extract >21 kW of total discharge power from the electrode with >11 kW from the smaller inner electrode. Results of the thermal modeling indicate that the present-generation water-cooled electrodes should be thermally manageable up to 3 kHz in continuous operation.

Comparison of our xenon spectra with HF model calculations yielded good agreement and gave valuable information on the transitions contributing to the EUV emission. The use of MHD plasma modeling codes such as MHRDR has allowed us to explore design regions that are not easily accessible experimentally. Reasonably good qualitative agreement has been observed between the variation of modeled and experimentally measured source parameters as a function of electrode length and gas pressure.

Measurements of debris reduction with single- and multiple-channel shields showed reduction factors of 100 per centimeter of channel length. Extrapolation of these results suggests that channel lengths of 4 cm are required. Results of debris mitigation and potential optics contamination studies indicate that low levels of hydrocarbon contamination in the vacuum system continue to be a problem. Significant improvements in the control of the vacuum environment will be required to eliminate EUV- and DUV-catalyzed carbon growth on mirror surfaces. A nested-shell collector arrangement working at grazing incidence angles is suited best for the discharge source. Data collected so far show promise that a rugged, low-cost method is available with a clear path towards higher collection efficiencies. The electrode wear is considerable, and inner-electrode exchange is required after extended operation at high repetition rates. The power levels required for HVM can be achieved in a DPF source with tin as the source element at thermal extraction powers on the order of 35 kW.

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Chapter 13

Hollow-Cathode-Triggered Plasma Pinch Discharge

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13.1 Introduction

The light source has been identified as being the most critical single component on the way to realizing EUVL. The requirements on the source are derived from a throughput model for the processing of up to 120 wafers per hour in a commercial EUV scanner. In the current status of design of the scanner, this means a requirement of 115-W collected inband EUV.¹ The 115 W refers to the power emitted in a 2% band around the center wavelength of 13.5 nm. For etendue limits imposed by the optical system, the radiation must be emitted out of a small volume of a few cubic millimeters in order to be collectable by the optical system. Typical collector openings are limited to a geometrical opening of 2–3 sr; collector efficiencies

are on the order of 50%–80%. The source power is defined to include all of these above effects.

Philips Extreme UV, as a joint venture of Philips and Fraunhofer ILT, is running an extensive program to realize high-power sources well suited for production. The source concept is the hollow-cathode-triggered (HCT) gas discharge. Many aspects of it have been published in a series of preceding papers.^{2–6} The program includes fundamental research on ignition and pinch formation, but mainly focuses on the many engineering problems, such as power scaling, electrode lifetime, collector protection, and closed-loop dose control. So far, Xe has been used as a radiator, which, however, is considered as having insufficient conversion efficiency (CE) to meet the long-term power requirements. To address this issue, a research program using Sn as a radiator has been started. Sn is well known for its favorable spectral distribution; however, it has the disadvantage of being more difficult to handle. Handling problems occur both in its delivery to and in its removal from the system. Nevertheless, it seems to be the only possibility for ever achieving the required high power levels.

The chapter addresses some of the problems associated with both Xe and Sn sources. In Sec. 13.2, the physics of ignition and pinching of an HCT source will be described. Section 13.3 summarizes the results achieved so far in developing commercial EUV sources. Emphasis is put on the physical principles rather than the engineering aspects.

13.2 Physics of EUV Sources based on Hollow-Cathode-Triggered Gas Discharges

13.2.1 General remarks

The principle of the present concept for generating pinch plasmas, which are emitters of thermal radiation in the EUV, is the pseudospark discharge. Since its discovery in 1978,⁷ this kind of low-pressure gas discharge has been extensively investigated both theoretically and experimentally. The main focus has been on its use as a high-current switch for pulsed-power applications and as a source of highly brilliant electron and ion beams.⁸ The main difference for its use as an EUV source is that a high, pulsed current for compression and heating of the working gas is used, which is usually a high-*Z* element. A general description of the pseudospark discharge is found, e.g., in Ref. 8. The basic concept for use as an EUV emitter is presented in Refs. 2 and 3. This concept is called the HCT pinch plasma discharge. There are numerous publications dealing with problems, especially for pseudospark switches, with regard to ignition, electrode lifetime, electrode erosion, and means of triggering the discharge, which are also of interest for the HCT concept. However, especially for the ignition and the high-current phase, there remains a variety of open questions. These have led to investigations of high-power light-source development, which are described in detail in the subsequent sections.

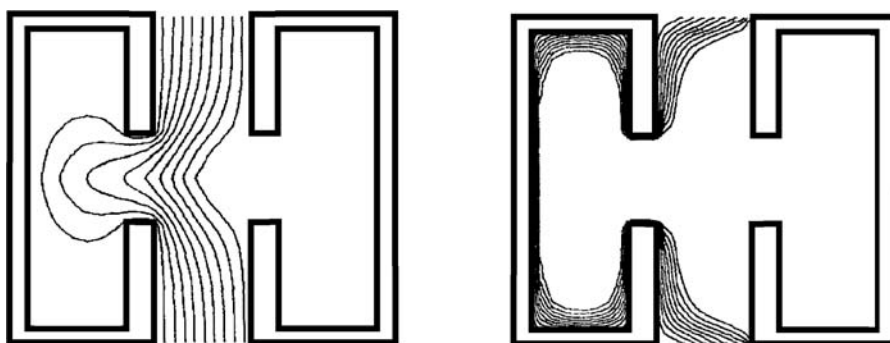


Figure 13.1 Evolution of the electric potential for a pseudospark discharge simulation,⁹ showing the buildup of the virtual anode (left) and the hollow-cathode plasma phase (right).

The design of the HCT lamp in its basic form is very simple: Two parallel plates with opposing central boreholes are connected to a capacitor bank. The connection must have a very low inductance to allow for fast current buildup during the pinch phase. On the anode side, the electrode system is open for outcoupling of the light. On the cathode side, a hollow recess is connected to the borehole to form the hollow cathode. The electrode system is in a low-pressure environment of usually 10–100 Pa of a heavy gas, leading to operation on the left branch of the Paschen curve. On applying a voltage, typically in the range of several kilovolts, to the electrode system, ionization processes take place along the long electrical field lines in the vicinity of the boreholes. Electrons are extracted by the anode, which leads to a positive cloud of remaining slow ions. This cloud extends into the hollow cathode, forming a virtual anode. This process is illustrated in Fig. 13.1, following the simulation in Ref. 9. This virtual anode leads to the pendulum effect for electrons in the hollow cathode. The effective path for such electrons increases, which leads to very effective ionization. A hollow-cathode plasma builds up, which shifts the anode potential close to the cathode walls as shown in Fig. 13.1. The electrical field increases to values sufficient for the ignition of cathode spots and evaporation of material. With the ignition of the cathode spots, the storage capacity can be discharged, leading to peak currents of typically 10 kA. Current attachment at the cathode is preferred to attachment in the gap and at the borehole wall. The pulsed current leads to a compression and heating of the plasma channel across the gap, leading to a pinch plasma several hundred microns in diameter and of length from 1 mm to several millimeters, depending on the particular geometry of the boreholes.

13.2.2 Ignition phase

For the present concept the understanding of the plasma ignition is of special interest compared to other concepts such as the plasma focus, the Z pinch, or the capillary discharge. Here the buildup of a low-resistivity plasma and the feeding of a pulsed current to the electrode system are more strongly coupled due to the

omission of a switch between the electrode system and the storage capacity. This requires some more basic understanding of the relevant processes and parameters, but the concept allows one to work without a sophisticated pulsed-power technology for the energy supply.

The influencing parameters are the gas density, the operating voltage, the charging-voltage rise time, the geometry of cathode and anode (including the opening and the hollow cathode), the electrode material, and also the initial conditions such as the plasma density remaining from the preceding shot. Theoretical guidance is expected concerning the breakdown condition, especially with respect to optimizing a third blocking electrode inside the hollow cathode and operating as a trigger. Furthermore, calculations should allow estimating the spatial distributions of the ion and electron densities at the beginning of the high-current phase as input parameters for the pinch plasma evolution. It is also important to model the plasma decay, which determines the maximum repetition rate. There are several theoretical works on modeling of the plasma ignition, which lead to a good qualitative description of the discharge phases.^{9–11} Their transfer to the present problem, however, is not fully possible, since aspects such as operation in xenon and the description of the third electrode are not considered. Furthermore, the models known in the literature make use of a hybrid description of a two-fluid model in combination with a Monte Carlo ansatz for ionizing processes and the evolution of beams.

We have chosen a model that fully describes the ignition in a Monte Carlo model, since the fluid description is not valid for proper description of the ignition phase. The electrons have large mean free paths and thus high average energies, which are not consistent with a fluid description.

The Monte Carlo method is used to solve the equation for the distribution functions f_i of electrons and different ion species:

$$\frac{\partial f_i}{\partial t} + \mathbf{v} \frac{\partial f_i}{\partial \mathbf{r}} + \frac{q_i}{m_i} \mathbf{E}_{\text{mean}} \frac{\partial f_i}{\partial \mathbf{v}} = \sum_k C_k f_k. \quad (13.1)$$

Here C_k is the collision operator, which takes the processes of electron impact ionization, elastic electron-ion collisions, and electron impact excitation into account. The particle motion is simply described by

$$\frac{d\mathbf{v}}{dt} = \frac{q_i}{m_i} \mathbf{E}(\mathbf{r}), \quad \frac{d\mathbf{r}}{dt} = \mathbf{v}, \quad (13.2)$$

where $\mathbf{E}$ is the self-consistent electrical field determined by the plasma and the voltage applied to the electrode system.

The electrical field is calculated self-consistently by solving the Poisson equation:

$$\Delta \Phi = -\frac{e}{\epsilon_0} (n_i - n_e) \quad \text{and} \quad \mathbf{E} = -\nabla \Phi. \quad (13.3)$$

The collisions are considered as random processes with R a pseudorandom number:

$$\int_0^t p_{\text{coll}}(t') dt' = R. \quad (13.4)$$

Figure 13.2 shows an example for an ignition in xenon. The neutral-gas pressure is 26 Pa. The cathode voltage is 1.5 kV. The distances shown in Fig. 13.2 are in millimeters. For the calculation a starting electron and ion density of 10^6 cm^{-3} has been chosen. The pictures in Fig. 13.2 show the distribution of charge carriers (electrons and ions) after 5, 20, and 21 μs . The left electrode is the cathode. Most of the initial ionization processes take place in the hollow anode in the vicinity of the borehole and along the axis within the gap, as shown in the 5- μs diagram. Most of the electrons are extracted, which leads to an excess of ions.

At this instant the maximum ion density is $8.4 \times 10^8 \text{ cm}^{-3}$, whereas the maximum electron density is $0.14 \times 10^8 \text{ cm}^{-3}$. The maximum electron and ion densities increase to $n_e^{\text{max}} = 3.7 \times 10^{10} \text{ cm}^{-3}$ and $n_i^{\text{max}} = 2.2 \times 10^{10} \text{ cm}^{-3}$ for the 20- μs case in the middle picture. The ionization processes shift more and more towards the hollow cathode. The right picture shows the forming of the virtual anode within the hollow cathode at 21.2 μs . There the maximum electron and ion densities are nearly identical, around $8 \times 10^{11} \text{ cm}^{-3}$.

For description of further development of the discharge, including the hollow-cathode plasma and the onset of the pinching phase, some numerical problems have to be solved. However, the current software package already allows for, e.g., modeling and improving of trigger shapes and potentials located in the hollow cathode for one- or multiborehole arrangements.

13.2.3 High-current phase and basic lifetime considerations

The generation and modeling of EUV radiation by the emission of highly charged ions in the pinch phase is extensively discussed in another chapter of this book.¹² This subsection will focus on the state of the art for the transition from the glow phase of the pseudospark discharge to the arc phase and give some general discussion of electrode erosion.

Generally, in any kind of low-pressure pinch plasma discharge the current density is of the order of 10 kA/cm^2 . The occurrence of cathode spots and thus the evaporation of electrode material, which are delivering the required current from the electrode surface, is unavoidable. The special feature of the pseudospark discharge is the possibility of a relatively homogeneous and simultaneous ignition of cathode spots over a large area. The transition from the glow plasma in the hollow-cathode phase to the high-current arc phase has been discussed qualitatively in several contributions.^{13,14} The hollow-cathode plasma leads to a sheath thickness of typically several tens of microns and a voltage drop on the 100-V scale. This leads to electrical fields in the range of 10^7 – 10^8 V/m , which is sufficient for the ignition of cathode spots. Typical current densities in the transition phase are in

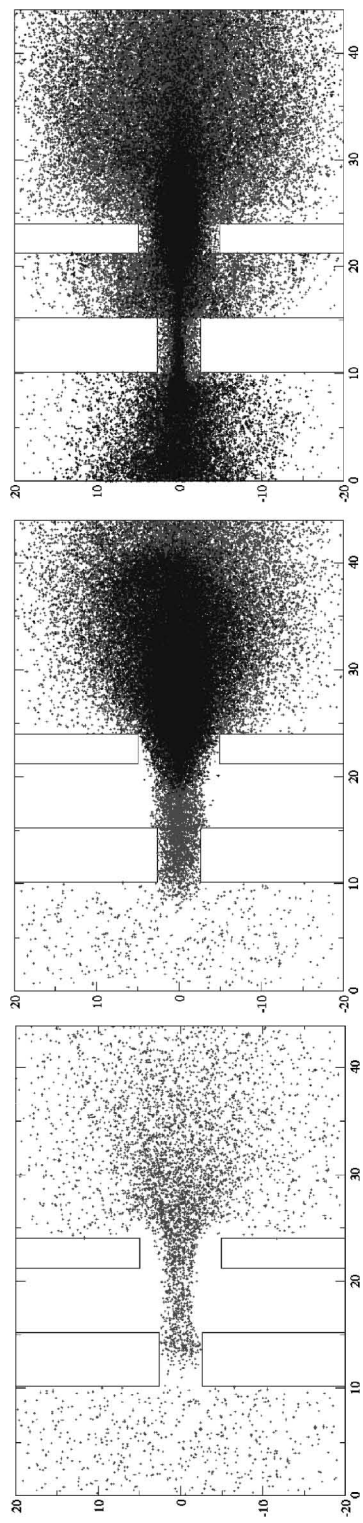


Figure 13.2 Spatial distribution of ion and electron densities according to a Monte Carlo simulation in the hollow cathode (left electrode) and hollow anode (right electrode) at instants 5, 20, and 21 μ s after the beginning of the simulation for an applied voltage of 1.5 kV. The simulation ends with the forming of the virtual anode inside the hollow cathode.

the range of 10–100 A/cm². The transition to high-current transport is on the 10-ns scale, which is typically one order of magnitude smaller than the pinch-current duration.

Although the glow-to-arc transition is understood qualitatively in the pseudospark discharge, there is still work to be done for further understanding of the spatial current distribution over the electrode surface for the EUV light source, so as, for example, to minimize electrode erosion by operating in a mode of lowest erosion rate. Most of the existing work refers to hydrogen or helium, which are preferred in switches. Relevant rates and time scales shift drastically when operating with xenon.

The cathode surfaces of HCT electrodes have been investigated by means of electron microscopy. Traces of type 1 and type 2 (following the nomenclature of Anders and Anders¹⁵) are found on the polished metal surfaces, as in other high-current applications of the pseudospark discharge. For low-pressure gas discharges the type 1 spots have the lowest erosion rate: 1–10 µg/C in a single spot. The net erosion is usually one order of magnitude lower, since most of the evaporated electrode material is redeposited onto the electrode surface after the discharge. Typical erosion rates are on the order of a few micrograms per coulomb, or a few times 10⁻⁴ mm³/C, for metal cathodes.

For an HCT EUV source, such an erosion rate would lead to a removal of around 1 cm³, or 10 g, after 10⁹ shots. The electrode geometry, however, determines the pinch geometry and also the CE. An erosion of 1 cm³ would be unacceptably high for a system with a single cathode borehole. Thus strategies must be applied in order to reduce the influence of the electrode geometry in general on the pinch plasma properties and keep the deformation as small as possible. One means is the use of multiborehole arrangements, which is described below. This strategy is also used in other concepts.¹⁶

13.3 The Philips HCT Source: Design and Results

13.3.1 Design of the HCT lamp

Typical geometrical dimensions are 5–10-mm plate distance and borehole diameter. The hollow cathode itself may have a diameter between 10 and 50 mm. The lamp head, including the electrode system and the storage capacitors, needs to be connected to a power supply and put in a vacuum system where a controlled gas pressure can be imposed. The pressure, voltage, and geometrical dimensions of the device determine the breakdown conditions. Upon increasing the voltage, the breakdown occurs spontaneously at a certain voltage. If the parameters of the electrical circuitry are chosen appropriately, current buildup leads to pinch formation and EUV radiation. Typical circuit parameters are an inductance below 10 nH, capacitance between 50 nF and 2 µF, and voltage between 2 and 20 kV. There is no single optimum parameter set; the lamp can be operated in a broad range of parameters, which allows optimization for other parameters such as the lifetime of the electrodes and the pinch size.

Compared to competing concepts such as the Z pinch or plasma focus, the key advantages of the HCT concept are the absence of insulating materials near the pinch region, and self-breakdown. The first property allows far more effective cooling and protection against sputter damage; the second property allows for simple design of the electrical circuitry in that no high-current switches are necessary.

In a further development stage, the simple HCT concept has been supplemented by a trigger electrode that is inserted into the hollow cathode (Fig. 13.3). This electrode is connected via a low-power switch to the cathode and is at a positive potential relative to the cathode during the charging cycle of the capacitors. Its basic function is to remove the initial electrons in the hollow cathode prior to breakdown, hence impeding the breakdown itself. This comes down to shifting the Paschen curve to an effective Paschen curve that is higher in breakdown voltage (Fig. 13.3). When the capacitor is charged to a voltage below the effective Paschen curve, but above the corresponding curve without a trigger voltage, switching the trigger off will immediately move the system into breakdown. It is important to note that the trigger circuit does not carry a high current. The effect of the trigger is a widening of the operation margins. In particular, it allows operation over a wide pressure range. Moreover, the timing of the pulses is now entirely determined by the timing of a low-power trigger pulse. A recent study of the effect of a blocking electrode on a xenon-operated discharge is found in Ref. 17.

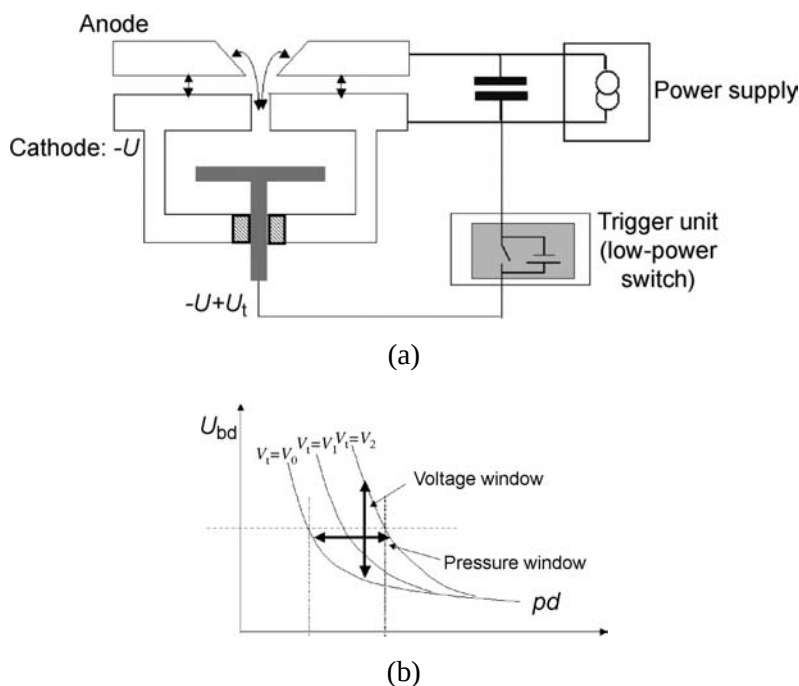


Figure 13.3 (a) Schematic design of a triggered hollow-cathode discharge device. Anode and cathode are connected to the high-power circuitry; the trigger electrode is connected to the cathode via low-power circuitry. (b) Paschen curve showing the breakdown condition as a function of pressure (p) times plate distance (d), and for different trigger potentials.

The development of a multiborehole cathode has remedied the heavy thermal and sputter load on the electrodes and, as already mentioned, suppressed the deformation of the cathode geometry by distributing the attaching current over a larger surface. The heat-load problem is addressed in more detail in Sec. 13.3.4. Generally, the most effective means of reducing the heat load is to increase the distance of the hot pinch plasma from the electrode surface.

A typical plasma-wall distance for a single-hole electrode system is 5 mm. An extension of the pseudospark concept—again known from switches—is a device with more than one borehole connecting the hollow cathode with the gap (Fig. 13.4). Here, the holes are connected to one single hollow cathode and provide each hole a fraction of the total current. The single hollow cathode controls the breakdown process and leads to simultaneous discharge in all channels. Upon choosing the right discharge conditions, it is possible to have currents in single holes sufficiently small not to form an individual pinch while the joint current of all holes is sufficiently large to form a pinch in the middle of the array of holes. If these holes are far apart, the pinch can be far away from any wall. In our experiments, we have realized wall distances as large as 15 mm. In Fig. 13.4, EUV pictures of an eight-hole cathode are shown on a linear scale and on a logarithmic scale to amplify the radiation from single holes. It appears that the radiation intensity at noncentral positions is only a minute fraction of the intensity at the central position.

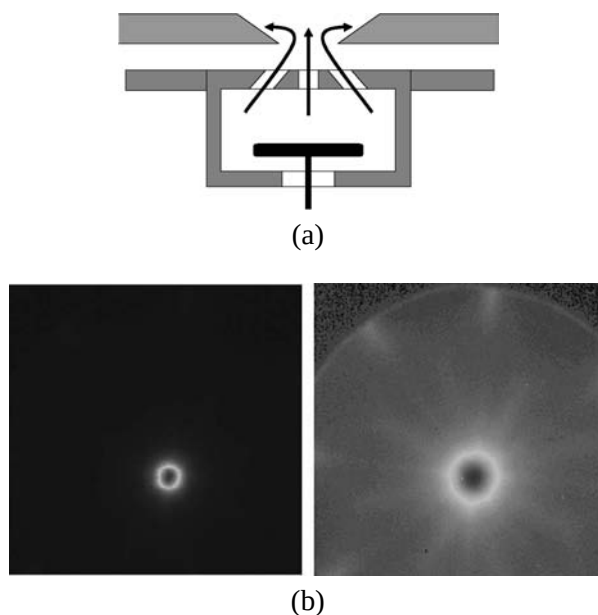


Figure 13.4 (a) Schematic of a multiborehole configuration of the HCT lamp. (b) End-on EUV pinhole pictures of an eight-hole configuration; the left side shows the picture on a linear intensity scale, and the right side shows it on a logarithmic intensity scale to highlight the minute intensity fraction originating from the individual holes.

13.3.2 Conversion efficiency

The CE is defined as the output energy divided by the energy initially stored on the capacitor bank. Here, the output energy is the radiation energy in a solid angle of 2π and in a bandwidth of $\pm 1\%$ around the center wavelength of 13.5 nm. The output energy is measured with a standard measuring tool that consists of a diode and two multilayer filters that filter out roughly a 4% bandwidth around 13.5 nm. The final output energy must be recalculated from the measured diode signal and the measured spectrum of the radiating species. Tools are calibrated at the Bessy synchrotron in Berlin. Spectra for Sn and Xe are shown in Fig. 13.5. The inband portion around 13.5 nm is shaded and calculated as a fraction of the total energy between 9 and 18 nm.

The CE is determined by many factors: how much energy remains in the circuitry, resistive losses in the electrode system and the cathode fall, current leakage in the plasma outside of the pinch plasma, out-of-band radiation from EUV all the way up to infrared, ionization, and acceleration of particles. To set up an accurate energy balance is still a matter for research, since a number of data are not easily accessible to experiments (e.g., cathode fall, ionization distribution). The impedance matching of the system is such that more than 90% of the energy stored on the capacitors is coupled into the plasma. The highest CE for Xe is 0.8% for a long pinch; for a small pinch, in practical cases, values around 0.5% are achieved. Another way of looking at this number is to say that roughly 15% of the total energy is converted into EUV radiation between 9 and 19 nm (1% in 4π sr divided by the fraction 0.066 of inband energy). With another 10% of the energy left in the circuitry, this means that the remaining 75% of the total energy is dissipated in other loss channels. The major part of this is attributed to fast ions, bypass currents, and VUV/DUV radiation.

From Fig. 13.5, it is apparent that Sn has a more favorable spectral distribution than Xe and would lead to a factor 3 improvement if everything else were equal. In fact, we have demonstrated CEs of up to 2.5% in a Sn pinch plasma discharge with 3-J pulse energy. In this experiment, we employed the same hollow-cathode configuration as in the Xe case, but added a mechanism to deliver Sn into the vapor phase. The value 2.5% is an extreme case achieved only after fine-tuning discharge parameters. In a more usual environment, CE values of 2% are achieved for a frequency range of 0–6 kHz and a pulse energy between 1.5 and 4 J.

The lamp has been operated up to very high frequencies. The highest frequency for the Xe lamp was 7 kHz (20-kW input power) and for the Sn lamp was 6 kHz (14-kW input power). In both cases, CEs did not depend strongly on input power and were almost the same as for low-power operation.

13.3.3 Collection efficiency

Next to CE, collection efficiency is the most important parameter in characterizing lamp properties. The overall collection efficiency is defined as the fraction of

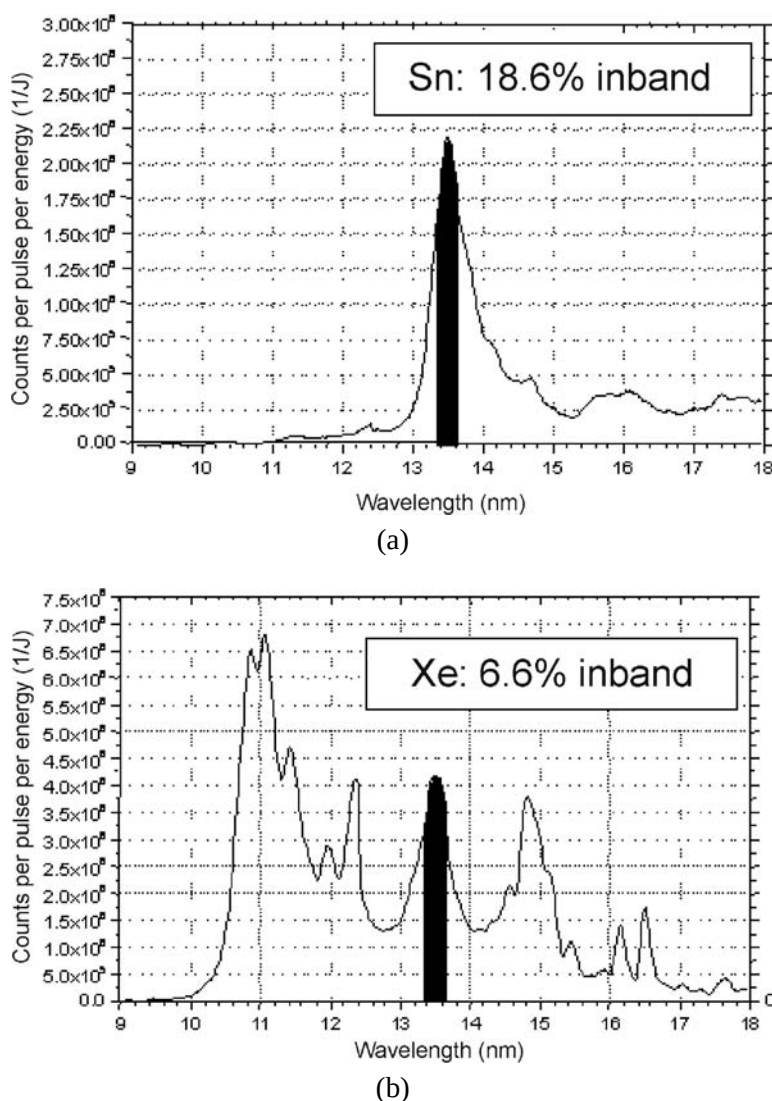


Figure 13.5 EUV spectra for Sn (a) and Xe (b) between 9 and 19 nm. The shaded areas in the graphs show the 2% bandwidth around 13.5 nm; the percentages are the fraction of inband versus total EUV intensity.

inband photons that can be processed by the scanner. The reference point is the intermediate focus. Determining factors are the etendue match between the source and the scanner, and the geometrical and material properties of the collector. The numerical aperture (NA) of the projection system and the size of the scan field ultimately determine the etendue requirements of the scanner. In practice, however, etendue loss may occur in the illuminator, so that the theoretical etendue acceptance cannot be fully met. Today's specifications by scanner manufacturers vary between 1 and $3.3 \text{ mm}^2 \text{ sr}$. The lamp etendue must match this value; otherwise

EUV photons are wasted, since they cannot be collected. Figure 13.6 shows model calculations of collection efficiencies, out of 2π sr, for collector openings of 1.8 and π sr and two etendue requirements (2.7 and $6.5 \text{ mm}^2 \text{ sr}$). The model assumes a pinch with an axisymmetric shape and a Gaussian intensity distribution along both the long and the short axes. The short axis has a FWHM of 0.5 mm in diameter; the FWHM for the long axis is the parameter that is varied in the model.¹⁸ Full etendue matching is achieved only for source lengths below $1\text{--}2 \text{ mm}$. The detailed analysis, also for non-Gaussian distributions, is given in Ref. 18.

This stringent etendue requirement is a very severe design restriction, since all the radiation energy must come out of a small volume, typically 1 mm^3 . This volume must be stable in space and, for thermal and sputter reasons, stay as far as possible away from any walls and other parts of the system.

Figure 13.7 shows experimental results for two different pinch plasmas, one operating on Xe and the other on Sn. The figure shows pinhole pictures recorded on a CCD camera through a zirconium-coated silicon nitride filter. The filter has broadband characteristics and hence images all wavelengths between around 10 and 16 nm . An alternative measurement method is to image via a MLM filter with a smaller bandwidth around 13.5 nm . Comparison of the two methods has led to almost identical results; hence pinhole images can be considered as representative for the spatial inband energy distribution of the source. Figure 13.7 shows the CCD intensity distribution and a line scan through the long axis of the pinch. The CCD image is taken at a fixed angle; the line scan is a direct scan of the CCD signal, so the length scale is divided by the sine of the observation angle to obtain the true length of the pinch. In all cases, the pinch is not well represented by a simple Gaussian intensity distribution. Just looking at FWHM values may hence be misleading. Calculating the true collection efficiencies according to the full optical model leads to a collection efficiency of 17% in the case of the Xe pinch, and 26% in the case of the Sn pinch, both for the case of a 1.8-sr collector opening and a $2.7\text{-mm}^2 \text{ sr}$ etendue requirement.

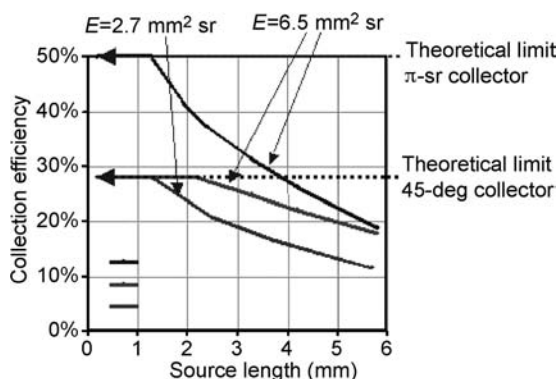


Figure 13.6 Collection efficiency over 2π sr as a function of pinch length for a 0.5-mm pinch radius and two different collector designs according to Ref. 18.

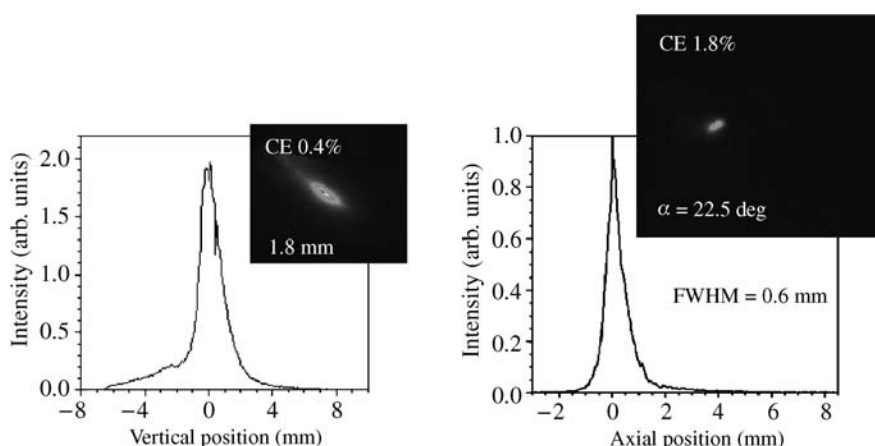


Figure 13.7 CCD pinhole pictures of a Xe pinch with FWHM of 1.8 mm (left) and a Sn pinch with FWHM of 0.6 mm (right). The plots are line scans through the long axis, recalculated to display the true length of the pinch.

13.3.4 Electrode lifetime, debris, and collector lifetime

The lifetime of the lamps is largely determined by the lifetime of two critical components: electrodes and collector.

The electrodes are subject to excessive heat load, sputter load, and current load. It is important to note that sputter and current load also occur when the lamp is operated at relatively low average power. Sputter load occurs on all surfaces exposed to the plasma, and is proportional to the number of plasma pinch events generated over time. Current load depends on the accumulated amount of charge transported through the system, again strictly proportional to the number of pinch events accumulated over time.

Thermal load, by contrast, is a property of average and peak load. Heat is dissipated during a time interval of 100 ns, i.e., with a duty cycle of 1:1000 in the case of 10-kHz operation. Because of the very short exposure time, the surface can reach a very high temperature during the pulse. This temperature rise can amount to as much as 2000 K above the steady-state temperature. The physical process is determined by the heat capacity and density of the material and the thermal conductivity. During the 100 ns, the heat is mostly stored in a very thin surface layer and conducted away on a much longer time scale. In Fig. 13.8 a typical model calculation for W electrodes, 3 J pulse energy, and an electrode-to-pinch distance of 5 mm is shown. The background temperature is assumed to be 1400°C. It can be seen that the surface temperature can rise up to the melting temperature of W (≈ 3400 K), while the temperature rise of the material as little as 10 μm below the surface is only 100 K. It is important to note that improved cooling technology can only reduce the average background temperature, not the pulsed surface heating. The only way to cope with this phenomenon is to reduce the surface heat load (e.g., by lowering the pulse energy, extending the pinch duration, or increasing the plasma-to-wall

distance) or to increase the thermal conductivity and heat capacity of the material. In practice however, the material choice is limited because of the required high melting temperatures. Refractory materials like W and Mo are good compromises.

As a result of electrode damage, the lamp will change its performance over time. As a general rule, we have observed that the overall generation of EUV with good CE is tolerant of even severe changes in electrode shape. On the other hand, the size and position of the pinch are highly sensitive to the detailed electrode shape. In practice, this means that collection efficiency is the more critical parameter to watch than CE. The biggest progress achieved so far has been the distribution of the current over a large surface by introducing the multiple-borehole concept. In Fig. 13.9, the results are presented for a life test of 200 million shots.

Another severe lifetime problem is damage to the collector. For the collector design we are using grazing-incidence nested collector shells. The shells are coated with metal layers of (e.g.) Au, Pt, Pd, Ru, or Mo and have a reflectivity that is strongly dependent on the reflection angle. In practice, angles above 20 deg will not have acceptable reflectivity. The reflectivity is dependent on surface roughness and contamination. The pinch plasma creates, in addition to EUV photons, high-energy ions and neutrals of the radiating species (Xe, Sn). The energy of the particles can be as high as several keV. Furthermore, metal vapor or clusters will leave the pinch in all directions. The metal vapor originates either from the electrodes or, in the case of a Sn discharge, from the radiating species itself. High-energy particles will quickly sputter the collector surface. Metal vapor eventually deposits on the surface and reduces the reflectivity. All of this damage must be prevented by an effective debris mitigation system. Such a system is not easy to build, nor is a concept available yet that satisfies the lifetime requirements of the industry. The subject will remain a research topic for quite some time.

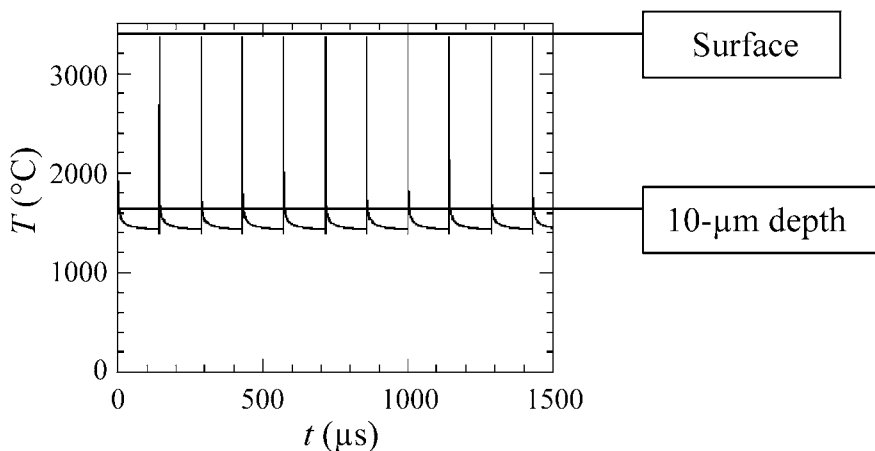


Figure 13.8 Peak temperatures at surface and at 10- μm depth during the pulsed operation of the lamp. Energy dissipation is 3 J with a 5-mm wall distance during 100 ns on a tungsten surface with a base temperature of 1400°C. Peak temperatures can go as high as the melting temperature of tungsten at the surface, but remain very flat a few microns below the surface.

Figure 13.10 presents results of a 0.5-billion-shot experiment. It can be seen that the sample shows hardly any loss in reflectivity. The sample was exposed at a position 12 cm away from the pinch and under a representative grazing angle. Details on the diagnostics for the grazing-incidence reflectivity will be published elsewhere.

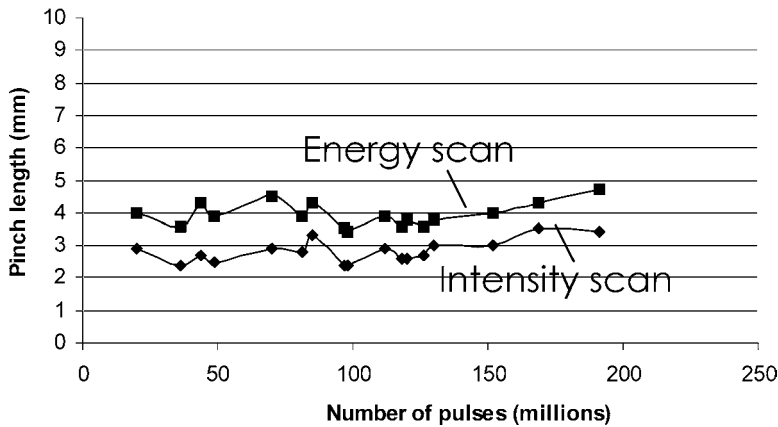


Figure 13.9 Pinch size as a function of pulse number for a Xe discharge. “Intensity scan” denotes the FWHM of the line scan as described in Fig. 13.7. “Energy scan” denotes the scan where the intensity is first integrated along lines perpendicular to the scan line, and only then is the line scan executed through the integrated values. The latter procedure is more representative for the collection efficiency. The frequency is 1 kHz, and the pulse energy 3.6 J.

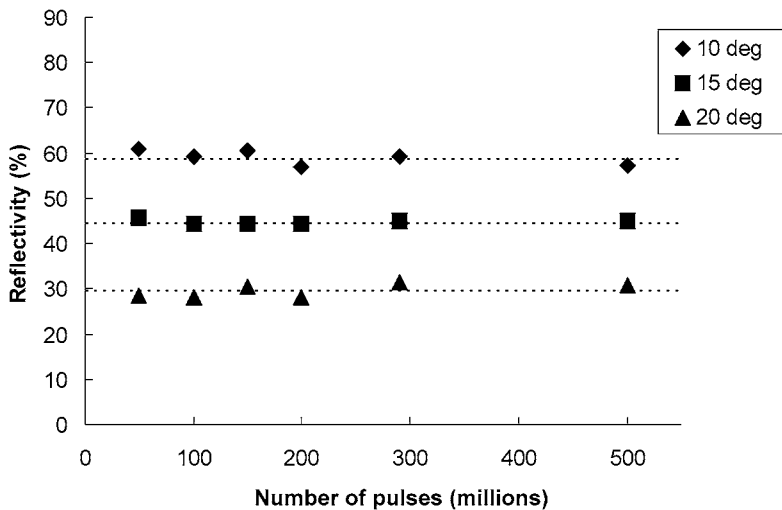


Figure 13.10 Reflectivity data on a collector witness sample after exposure to up to 0.5 billion shots with a suitable mitigation system. The sample was at a representative distance and angle to the pinch. The frequency is 1 kHz, and the pulse energy 3.6 J.

13.4 Summary and Outlook

The HCT concept has proven successful in a number of relevant parameters. Frequency scaling up to 8 kHz was demonstrated. Thermal and cooling properties were successfully demonstrated to power levels in excess of 15-kW input power. Further, an electrode lifetime of 200 million shots and a collector lifetime of at least 500 million shots were demonstrated. All of this makes the concept well suited to meet HVM specifications. Progress, however, is needed in all relevant parameters. The following combination is targeted as the final specification:

Input power:	30 kW
CE:	> 2%
Collection efficiency:	> 25% of 2π sr, meaning a collector with 3 sr opening and an average reflectivity of 60%
Debris mitigation:	Light transmission of 80%

Together, these parameters will lead to >120 W of usable light at the IF. It is important to stress that progress is needed in all parameters, since one parameter can hardly compensate shortage in another one. A CE of 0.5% for Xe with an acceptable short pinch length below 3 mm for xenon discharges is achieved, but it is not expected to increase the xenon efficiency much above 1%. In particular, it means that xenon is not an option for HVM sources because of its intrinsic low CE due to the spectral distribution of the EUV light. In Sn pinch plasmas, a CE higher than 2% and also a higher collection efficiency than with current xenon pinches have been successfully demonstrated.

The authors believe that the employed source concept is well suited to meet the targeted specifications. As this will be necessarily based on a Sn discharge, the main challenge will be handling of metal vapor and corresponding protection of the collector. Since every concept will have to use metal vapors, a generic solution to serve all sources might soon become an option.

Acknowledgments

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See Chapter 7 for a biography of Thomas Krücken. See Chapter 34 for a biography of Günther Derra. No other author biographies were available for this chapter.

Chapter 14

High-Power GDPP Z-Pinch EUV Source Technology

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14.1 Introduction

The timely availability of EUV light sources, measurement tools, and integrated test systems is of major importance during the development phase of EUVL for use in high-volume chip manufacturing, which is expected to start in 2009. The cost

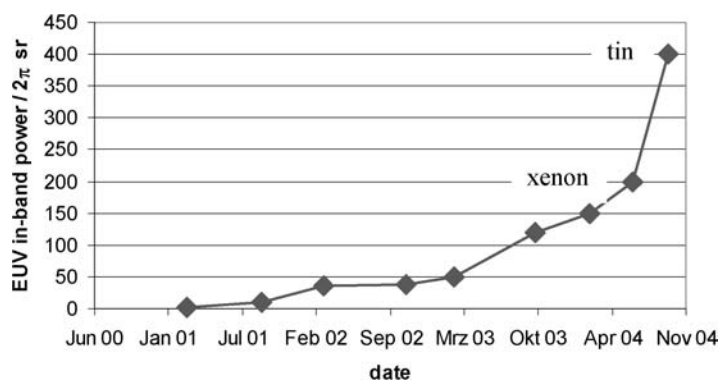


Figure 14.1 Historical evolution of EUV inband power emitted into 2π -sr solid angle in continuous operation from GDPP Z-pinch EUV sources. The power for all data points is emitted from a plasma volume of the same size.

estimates of an EUV exposure tool in combination with sophisticated throughput models lead to a throughput requirement of 80–120 wafers (300-mm diameter) per hour for economic use of EUVL. The projection for the necessary EUV output power from the light source is 115 W at a 13.5-nm wavelength at the entrance of the illuminator system for an estimated resist dose of 5 mJ/cm². The EUV power requirement, in combination with the necessary lifetimes of source components and collector optics, has made source technology one of the most critical issues in developing EUVL.

Gas-discharge-produced plasma (GDPP) EUV sources that are based on so-called Z-pinch arrangements are a promising technological approach to critical technical issues in EUV sources. GDPP Z-pinch sources have been proven to possess a high intrinsic efficiency and very good stability as well as low complexity. Since 2001 the EUV output power of Z-pinch sources at XTREME technologies GmbH has been increased by two orders of magnitude to 400 W in 2π sr in continuous operation (see Fig. 14.1). Thus Z-pinch sources are currently the most powerful EUV sources for lithography development. Their EUV output power is likely scalable to high-volume manufacturing (HVM) requirements. Moreover, with appropriate electrode design, the lifetime requirements of source components also seem to be reachable.

This chapter gives an overview of GDPP Z-pinch source basics and an update of the development status of these EUV light sources at XTREME technologies GmbH, operating in Jena and Göttingen, Germany, including some recent achievements (early 2005). Opportunities, challenges, and risks in developing Z-pinch GDPP sources to HVM lithography specifications are discussed as well.

14.1.1 Roadmap

The roadmap for the development of EUV sources for lithography up to the level of HVM requires so-called microexposure tools, α tools, and β tools as well as

early pre-HVM tools for the development of the technology. Leading semiconductor companies expect the ramp-up of EUVL for HVM to start at the beginning of 2009. It is also expected that for the 32-nm node of the *International Technology Roadmap for Semiconductors* (ITRS), EUVL will be used in parallel with 193-nm immersion excimer laser lithography. To support this roadmap, first microexposure tools with small field size were installed in the semiconductor industry as technology pathfinders in 2004; α tools will need to be equipped with sources supplying EUV power of up to 5 W at the IF, and β exposure tools will require sources with 10–20-W IF power in late 2005 or early 2006. Pre-HVM EUV exposure tools will need the integration of sources with 25–50-W IF power in late 2006 or early 2007. Finally, HVM sources with 100–115 W IF power will be needed for EUVL starting in 2008.¹

14.1.2 Requirements on EUV sources for HVM

Lithography exposure tool manufacturers have agreed on joint top-level specifications of the EUV source performance for HVM using EUVL.² The specifications for various EUV source parameters are summarized in Table 14.1.

The listed specifications of the EUV source parameters are defined for the focal plane behind the first source collector optics. This optics module separates the source from the EUV exposure tool. The focal plane defines a clear interface between source and exposure tool—it is usually called the *intermediate focus* (IF). This interface definition allows the coupling of differently designed sources to the EUV scanner without changing the illumination optics.

The power requirements for EUV sources are tremendous. This becomes clear when the beam path in the source collector from the plasma to the IF is considered. A schematic layout and beam path of the GDPP source collector module are shown in Fig. 14.2.

The EUV emission from the plasma is incoherent and, for the source developed at XTREME technologies, nearly isotropic over the 4π -sr solid angle of emission. The collector mirror used for GDPP sources is usually of grazing-incidence multiple-nested-shell reflector design (the so-called Wolter design).

Table 14.1 Requirements for EUV source parameters to be installed in EUVL HVM tools.² The specifications are for a plane of the IF behind the first source collector optics, which belongs to the EUV source. The collector optics module separates the plasma EUV generator from the illumination optics.

Source parameter	Requirement
Central wavelength	13.5 nm
EUV power (inband) at IF	115 W
Repetition frequency	$\geq 7,000$ to $\geq 10,000$ Hz
Integrated energy stability (3σ , >50 pulses)	<0.3%
Maximum solid angle of input to illuminator	0.03–0.2 sr
Etendue (area $\times$ solid angle)	3.3 mm ² sr
Source cleanliness at IF	30,000 h

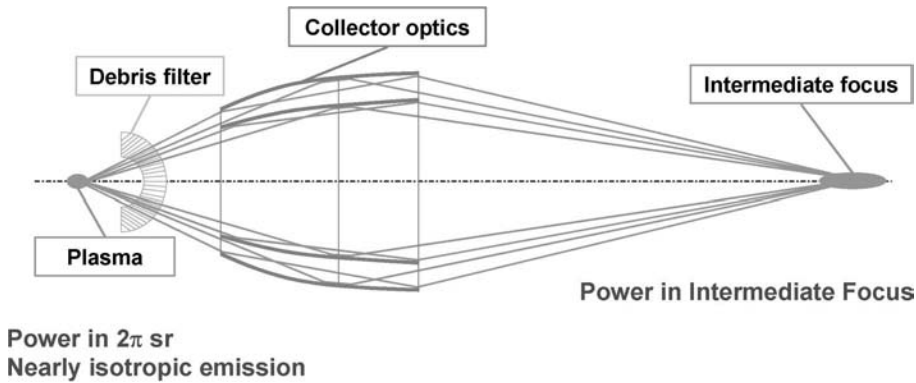


Figure 14.2 Schematics of the GDPP source collector unit.

There are several factors that determine how much EUV power from the plasma is necessary for generating the required power at the IF.

The first factor is the collector mirror design and the etendue of the EUV scanner. The etendue E of the optical system of an EUV exposure tool, which is the product of the area of the beam in focus and the solid angle of the beam, determines the optimum combination of the EUV source size and the collection angle:

$$E = \int_A \int_{\Omega} dA \cos \alpha d\Omega = \text{constant for any optical system.} \quad (14.1)$$

Because the etendue of the optical system is constant, the collectible plasma size decreases as the collection solid angle increases. Practically the etendue of the exposure tool is equivalent to an aperture in the IF plane according to the numerical aperture at the IF side. With I as the intensity in the IF plane and R as the radius of the etendue-equivalent aperture, we define the *available IF power* and *usable IF power* as

$$\text{available IF power} = \int_0^{2\pi} \int_0^{\infty} I(r, \varphi) r dr d\varphi, \quad (14.2)$$

$$\text{usable IF power} = \int_0^{2\pi} \int_0^R I(r, \varphi) r dr d\varphi. \quad (14.3)$$

The available IF power is dependent only on the collector design and the input power from the EUV source. The usable IF power is dependent on the etendue of the optical system of the EUV exposure tool and therefore on the diameter of the etendue-equivalent aperture in the IF plane. Because the IF is an image of the EUV-emitting plasma, the IF diameter decreases as the size of the plasma decreases. If the etendue-equivalent aperture at the IF is smaller than the real focal spot in the IF plane, only a fraction of the available IF power can be used.

We define the *etendue acceptance factor* as

$$\text{etendue acceptance factor} = \frac{\text{usable IF power}}{\text{available IF power}}. \tag{14.4}$$

This factor describes what fraction of the power delivered to the IF complies with the etendue restrictions imposed by the optics design of the EUV scanner. In the ideal case the etendue acceptance factor is 1. In this case the plasma is small enough to give an image on the IF plane with diameter smaller than the diameter of the etendue-equivalent aperture. In the case of a larger plasma size, which is often observed in GDPP sources, the etendue transmission factor may decrease to 70% or even less (see Sec. 14.4). In Table 14.2, estimates of the necessary EUV power emitted into 2π -sr solid angle are made for GDPP sources, based on the 115-W EUV power specifications at the IF for HVM sources.

In addition to the etendue-related losses, additional geometrical losses occur because of the practical limits on possible collection angles of typical collector optics. For GDPP sources the practical maximum collection angle may be at π -sr solid angle. For larger angles the collector optics cannot reflect the EUV radiation with two grazing-incidence reflections to the IF with sufficiently high reflectivity. Typical grazing-incidence reflectivities for EUV radiation are on the order of 80%, which leads to a total reflection efficiency below 70% for optics with two reflections.

The second factor that determines the necessary input power into the collector is losses related to the gas absorption over the optical path length (about 15%) between plasma and IF plane, and transmission losses in the debris filter system (about 80% transmission may be practicable) that is needed to protect the collector optics. Taking these effects into account, the required power from the EUV source into 2π sr is between 615 and 1230 W, depending on the etendue transmission factor for GDPP sources. The improvement of collection efficiency of the source collector module is one of the important topics in GDPP source development.

Table 14.2 EUV power emitted into 2π -sr solid angle necessary for HVM GDPP sources to achieve 115-W power at the IF, which is the entrance of the illuminator optics system of the EUV exposure tool.

EUV source parameters	GDPP source
Etendue acceptance factor	1.0–0.5
Transmission of debris mitigation tool	0.8
Transmission of gas in collector module	0.85
Required power from the source in collection angle	169–338 W
Geometrical collector efficiency with respect to 2π sr	0.5 ($\Rightarrow \pi$ -sr optics, ± 60 -deg opening angle)
Angle-averaged collector reflectivity	0.55
Required power from the source emitted into 2π -sr solid angle	615–1230 W

The third factor is that input power requirements from the source may increase because exposure tools may need a spectral filter in the beam path for reducing the emitted power in the tool outside the 13.5-nm EUV spectral band. Because of the limited transmission of potential spectral purity filter designs, this could increase the power requirements on the source by another factor of 1.25 to 2.0. For source fuels such as xenon or tin, the use of a spectral purity filter may be necessary. Optical designs are under consideration using one of the optical elements in the EUV scanner simultaneously as imaging element and spectral purity filter. This would be the most efficient solution.

In general, all estimates of power requirements from the source are dependent on the sensitivity of the photoresist (assumed for all simulation models to be 5 mJ/cm²) and the transmission of the scanner optics. Because of unavoidable line edge roughness, it might be that the resist sensitivity needs to be lower than expected. This would clearly lead to a higher required source power.

From today's perspective we expect, because of resist sensitivity and spectral-purity-filter losses, between 115 and 400 W of IF power to be needed for later stages of HVM. Higher optical transmission of the illumination and/or projection optics would result in a reduction of the necessary power.

14.2 Physics of the Z-Pinch Discharge and EUV Generation

14.2.1 Physical principle

A well-known and the most efficient method of plasma generation is an electrical gas discharge—for example, a spark or flash. Unfortunately, to generate EUV radiation the densities and temperatures of conventional gas discharges such as those used in discharge lamps or excimer lasers are not sufficient. However, a cold low-density plasma can be compressed by magnetic fields to a hot, high-density plasma with maximum intensity at an emission wavelength of 13.5 nm. The effect used is that of self-compression of a cylindrical plasma by the azimuthal magnetic field generated by the axial discharge current. This effect is called the *pinch effect*, and the compressed plasma is called a *pinch plasma*.

Its discoverer, Willard H. Bennet, described the pinch effect as magnetic self-focusing in a plasma with electrical current flow. The plasma temperature can be estimated from the balance between the pressure of the magnetic field (P_{mag}) and the thermal pressure of the plasma (P_{plasma})³:

$$P_{\text{mag}} = P_{\text{plasma}} \Rightarrow \frac{B^2}{2\mu_0} = (\langle Z \rangle + 1)n_i \cdot kT \Rightarrow kT = \frac{\mu_0 I^2}{8\pi(\langle Z \rangle + 1)N_i}, \quad (14.5)$$

where B is the magnetic field of the discharge current I , μ_0 is the magnetic field constant, n_i is the ion density, $\langle Z \rangle$ is the average degree of ionization, kT is the plasma temperature, and N_i is the line density. Here, $N_i = n_i \pi r^2$ and $B = \mu_0 I / (2\pi r)$.

Recent experiments to generate 13.5-nm radiation with GDDP sources have been made with xenon gas as the emitter.⁴ From the above relation and the requirements for EUV sources for lithography (plasma diameter about 1 mm, almost spherical) the current I necessary to generate a plasma temperature kT of 20 eV can be estimated at about 20 kA for gases such as xenon. The magnetic field is about 20 T and compresses the plasma cylinder to about 2000-bar pressure. The total energy in the magnetic field, plasma, and external circuit can be estimated as 5–10 J. A stable plasma cylinder would possess a resistance of 50 m Ω . The plasma is heated with some 10^7 W due to its ohmic resistance. Because of the heating of the plasma, the current decreases significantly after several hundred nanoseconds. The discharge can be operated only in a pulsed regime.

A typical design for such a discharge unit, which generates pinch plasmas with high efficiency, is currently under investigation at XTREME technologies—the surface-discharge pre-ionized Z-pinch discharge^{5,6} (see Fig. 14.3). The plasma generator consists of two cylindrical electrodes that are properly shaped to achieve the desired plasma size and emission angle. A cylindrical insulator separates anode and cathode. The design of the Z-pinch source supports an accessible emission solid angle for collection of more than π sr, i.e., ± 60 deg. Gas or vapor is used as the target material, which is typically continuously flowing through the discharge region. When the gas is converted to the plasma state and heated, EUV light is emitted. Key for the high emission stability of the Z-pinch source is a highly efficient surface-discharge pre-ionization device included in the source. The operation of the device can be separated into four steps. The pre-ionization of the working gas is spatially separated from the main discharge region. A high-voltage pulse is applied to an electrode system, which is isolated by a ceramic insulator. By collisions of free surface electrons with bound electrons on this surface, a cloud of electrons is generated. This electron gas ionizes the ambient gas phase and forms a cold plasma with low density. From this plasma, charged particles as well as ultraviolet radiation are propagating into the main discharge region of the Z-pinch assembly (step 1). A short time after the pre-ionization, a pulsed high-current discharge is ignited close to the insulator walls (step 2) and immediately compressed to a hot high-density plasma column (step 3). After the current pulse, the plasma pressure becomes higher than the magnetic pressure due to the decreasing magnetic field. Then the plasma starts expanding into the vacuum phase in both radial and axial directions (step 4).

In the Z-pinch design the length and diameter of the EUV-emitting volume can be varied by changing the separation between anode and cathode, as well as their shapes, and the gas dynamics. This is necessary to match the specific illuminator optics design. The possibility of scaling the emission volume from 0.8-mm length and 0.25-mm diameter to more than 6-mm length and 1.3-mm diameter has been demonstrated.

The most important technologies and components for GDPP Z-pinch EUV sources are

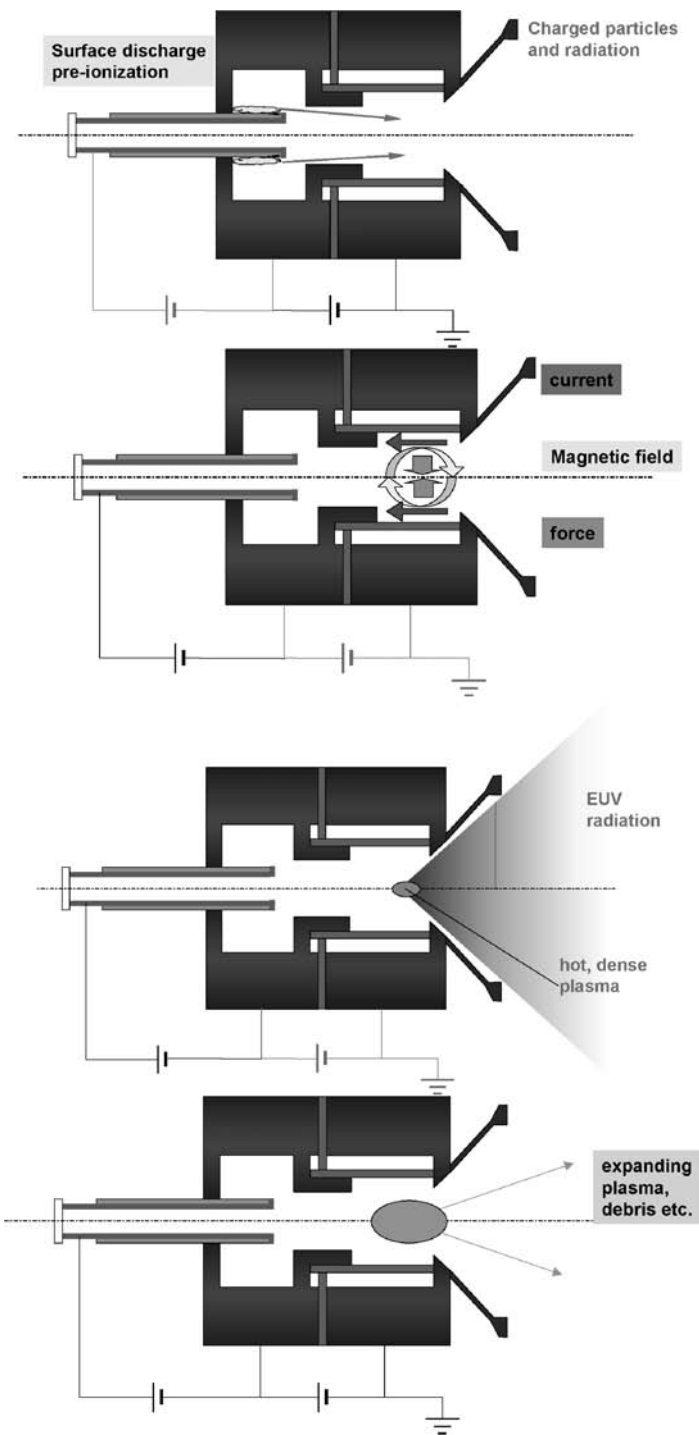


Figure 14.3 The four phases of operation of a Z-pinch GDPP EUV source.

- the emitter material (also called fuel, target, or working gas) and emitter supply,
- the discharge electrode system configuration for efficiently collectible plasma volumes,
- the pulsed-power electrical energy supply circuit,
- the discharge-electrode thermal management technology,
- the control of electrode and wall erosion,
- the debris mitigation and collector-optics protection system,
- the collector and source-collector contamination cleaning system.

In the following sections the above-listed technologies and components are discussed in more detail.

14.3 Emitter Materials for 13.5-nm Z-Pinch Sources

The emitter wavelength is determined by the Mo/Si multilayer-coated mirrors in the illumination and imaging beam path of the EUV scanner and by convention of the community to be 13.5 nm. The convention also reflects the fact that certain emitter materials are available with strong emission transitions at this wavelength.

Several groups have investigated the efficiency of EUV generation from low- Z elements, such as Li, O, and F, which emit only a few separated lines in a narrow band at 13.5, 13, and 12.8 nm, respectively,^{7–10} mostly with laser excitation. With increasing efforts in the development of GDPP sources, investigations of emitters in such sources have also been performed on a larger scale.^{11–13}

For LPPs a conversion efficiency (CE) into 2π sr of close to 0.5% was achieved with a fluorine-rich target excited with the second harmonic of a Nd:YAG laser.⁸ Recently Hanson et al. reported a CE of 2.7% obtained with lithium targets under laser excitation.³³

A systematic experimental survey of medium- and high- Z elements was performed in the mid-1990s to evaluate the efficiency of EUV plasma emission at 13.5 nm.¹⁴ In order to allow easy experimental access, selected elements with atomic numbers Z ranging from 13 to 82 were excited by a Nd:YAG laser with a pulse width between 7.5 and 30 ns. The EUV efficiency was recorded in a narrow channel around 13 nm. Figure 14.4 gives a graphic summary of the measured efficiency as a function of the atomic number.

As a general trend it was observed that the efficiency increased with increasing atomic number. Pronounced maxima appear around atomic numbers of 26 (Fe) and 50 (Sn), respectively. The highest efficiency was achieved with tin and antimony, while high- Z elements such as gold were slightly less efficient.

The maximum efficiency at $Z = 50$ can be explained by a manifold of strong 4d-4f transitions that fall into the 13.5-nm band for a range of ionization stages between 8+ and 13+. This emission feature is called an *unresolved transition array* (UTA), since several thousand transitions occur in a narrow band of roughly

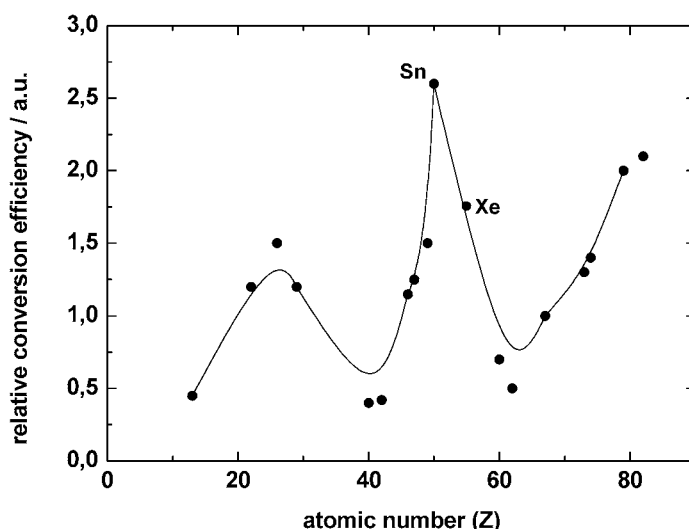


Figure 14.4 Relative CE into 13.5-nm radiation as a function of the atomic number of the emitter.¹⁴ The highly efficient tin ($Z = 50$) and the frequently used xenon ($Z = 54$) are marked.

0.5-nm width.¹⁵ The emission characteristic of high- Z elements is a spectral quasi-continuum with lower spectral brightness.

However, the choice of the emitter material for EUV sources is not governed by the requirement of high efficiency alone, but also driven by stringent requirements on source cleanliness. Because the first source-collector optics is only 10–20 cm away from the plasma (see above), one of the inherent requirements of lithography sources is that no condensation of the target material on the optical surfaces is allowed. Kubiak et al.¹⁶ suggested, as a compromise between efficiency and condensation properties, using xenon as target material in order to eliminate condensation of target material on the collector optics. The theoretical efficiency of xenon is lower than that of tin because the strong 4d-4f UTA peaks at about 11 nm, while the 13.5-nm radiation originates from a weaker 4d-5p UTA.¹⁷ Because of its condensation-free operation, xenon has been used widely in the development of GDPP EUV sources.^{5,6,18–22,40} Xenon is simply supplied in its gaseous state to the pinch region at pressures of approximately 1 Pa.

After substantial progress with xenon GDPP sources, more recently tin sources have been investigated in more detail to explore the limits of the EUV power that can be generated in GDPP sources and to study the debris contamination with tin. Tin has been supplied to the discharge region also in gaseous form after evaporation from solid tin or tin compounds. XTREME technologies' Z-pinch GDPP sources have achieved CEs of 1.0% with xenon and 2.0–3.0% with tin. For details see Secs. 14.8–14.10. An interesting approach to tin supply is the laser-assisted GDPP EUV source principle as described in Ref. 34, where a laser evaporates tin from electrodes or a separate target and an electrically excited gas discharge uses this tin as target gas. Detailed configurations, which use in the simplest case rotating

electrodes, are described for a rotating-disk-electrode GDPP source by Borisov et al.,^{35,36} and for a laser-triggered multiplexed source by Banine,⁴¹ Koshelev et al.,⁴⁶ and Pankert.⁴²

In view of the high CE of lithium under laser excitation reported in Ref. 33, lithium may be reconsidered as a fuel for GDPP sources also. The required density may not be achieved with pure GDPP arrangements. Therefore, laser evaporation is a likely approach for the target supply.

14.4 Discharge Electrode System, Source Collector, and Electrode Lifetime

As explained in Sec. 14.1.2, the limited etendue of the optical system of the EUV scanner and the numerical-aperture specification at the IF limit the usable size and volume of the EUV-emitting plasma. The smaller the plasma size, the larger is the allowed opening angle of the source collector optics (see Sec. 14.1.2). Today, available Wolter-type grazing-incidence collectors have a maximum opening angle of 1.8 sr, i.e., ± 45 deg. Wolter telescopes with π -sr opening angle as EUV source collectors are in principle producible.

Usually the diameter for GDPP sources in general and for Z-pinch sources specifically stays well below 1 mm. With both tin and xenon GDPP Z-pinch sources, we have achieved plasma diameters for full width at $1/e^2$ between 0.6 and 0.9 mm. Therefore, the numerical aperture (NA) and etendue allow geometrically the transmission of the entire EUV energy of the diameter. Because of the cylindrical symmetry of all GDPP sources, the shape of the EUV-emitting volume can be approximated as an ellipsoid with the main axis typically longer than the diameter. With Z-pinch sources using both xenon and tin, XTREME technologies' Z-pinch sources have generated lengths between 1.0- and 8.0-mm full width at $1/e^2$.

In Fig. 14.5 the etendue acceptance factor according to Eq. (14.4) is depicted for a Wolter-type multishell collector optics with input collection angles of 1.8 and π sr, respectively, and with a NA at the IF side of about $NA = 0.10$, depending on the length of the EUV-emitting plasma, for an etendue of the optical system of $3.3 \text{ mm}^2 \text{ sr}$. As soon as the length of the emitting plasma volume exceeds the collectible plasma length, the geometrical energy transmission decreases. While for the 1.8-sr collector the geometrical transmission for the 1.6-mm-long plasma is above 95%, for the π -sr collector it is decreased to 65%. Because of the constancy of the etendue [see Eq. (14.1)], the increase in the collection angle $\Omega_{\text{collector}}$ is compensated by the decrease of the collectible plasma length $l_{\text{collectable}}$. Therefore, the geometrically transmitted power into the IF with right etendue increases only weakly with increasing collector angle as soon as the plasma length reaches $l_{\text{collectable}}$. The use of collectors with larger opening angle requires the generation of a sufficiently short plasma. For the current development status a collector opening angle of approximately 2 sr seems to be the most efficient and practical solution.

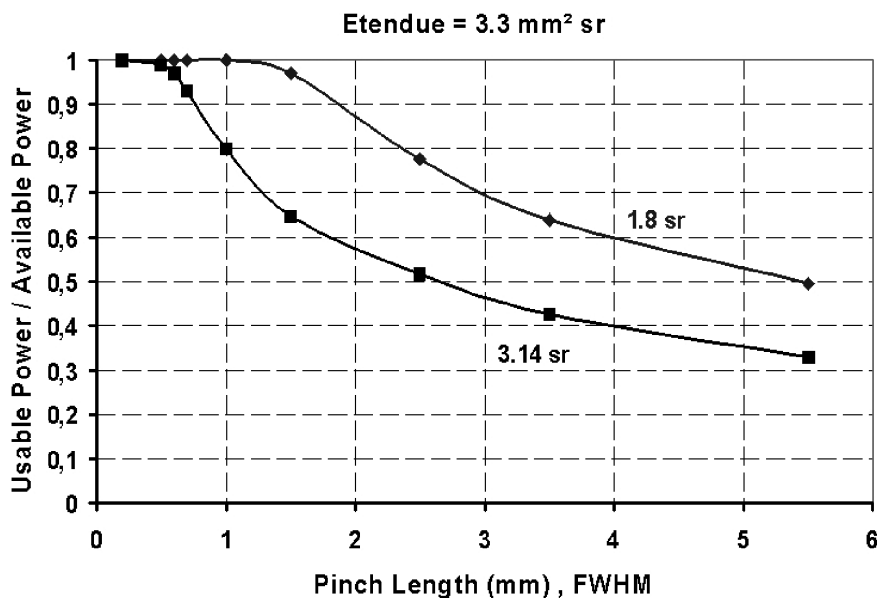


Figure 14.5 Geometrical energy transmission of Wolter-type multishell collector optics with 1.8- and π -sr collection angle in dependence on the length of the EUV-emitting plasma ellipsoid.

According to the discussions above, the development of highly efficient GDPP EUV sources has the goal to keep the plasma size, for efficiency reasons, below the etendue limits of the EUV scanner. For reasons of higher stability and better uniformity of the illumination in the EUV scanner, however, the plasma size should be somewhat larger than the etendue limit (so-called overfilling of the illumination system). An etendue transmission factor of 80–90% seems to be a reasonable goal as a practical compromise according to our calculations. For a π -sr collection angle this requires a plasma length of 1 mm or less.

In order to maximize the usable power at the IF, appropriate electrode discharge systems for Z-pinch EUV sources have been developed at XTREME technologies as depicted in Fig. 14.6. The anode of the Z-pinch discharge allows an obscuration-free emission solid angle of 2.0 sr. The distance between the plasma and the closest wall of the insulator is approximately 10 mm. The total plasma facing surface has a size of roughly 10 cm². For reasons of improved spatial and temporal stability of the plasma generation and EUV emission, a pre-ionization electrode is added to the Z-pinch discharge electrode system. Pre-ionization (i.e., uniform seeding of the plasma discharge volume with electrons prior to the initiation of the main discharge) is necessary in order to form a uniform glow discharge, so as to avoid arcing and to allow a homogeneous pinching effect. The parameters that affect the pre-ionization, such as threshold value, seed electron density, and uniformity, are heavily dependent on the design of the discharge electrode system, such as the type of electrode and profile, gas pressure of the target material, duration of pre-ionization, electron loss processes, time delay between pre-ionization

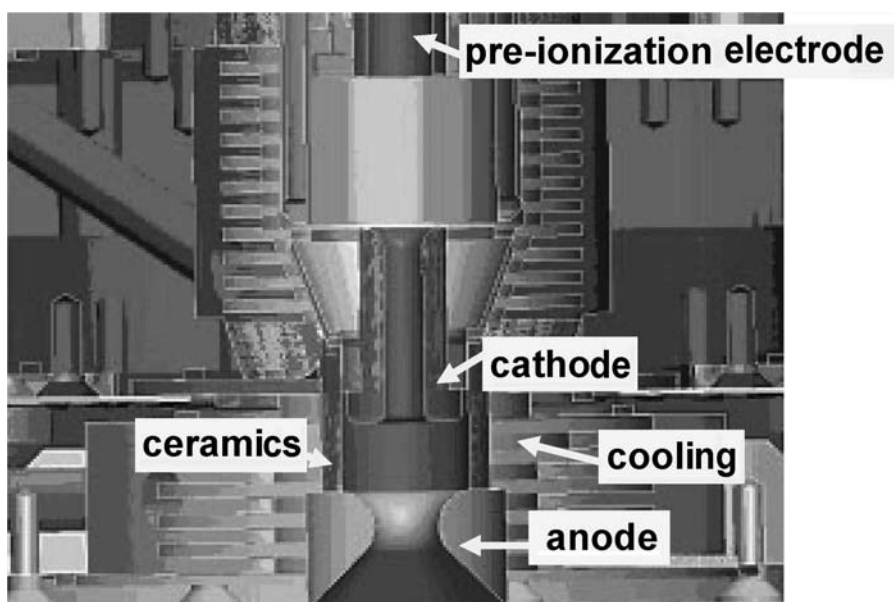


Figure 14.6 Schematic drawing of a cross section of the electrode discharge system configuration for optimum plasma size according to etendue, NA, and uniformity specifications.

and main discharge, and rise time of the discharge voltage, as well as on the overall discharge-system geometry. XTREME technologies Z-pinch sources use a sliding surface-discharge pre-ionization, which improves the energy stability over the non-pre-ionized operation of the Z pinch by a factor of 4. For experimental data on energy stability, see below.

With this type of pre-ionized Z-pinch discharge unit the EUV-emitting plasma ellipsoid size of $<0.6\text{-mm}$ diameter and 1.0-mm length (FWHM) is sustainable, which corresponds to approximately 80% etendue acceptance for a $\pi\text{-sr}$ collector at $3.3\text{-mm}^2 \cdot \text{sr}$ etendue. Maximum etendue acceptance factors of above 95% have been realized.

The most critical issue in GDPP EUV source technology is the lifetime of the electrode discharge system. In the following we discuss simulations that show that the distances between plasma and walls should be maximized to increase the lifetime of the discharge electrode system and also to improve the heat management of the discharge unit. In Fig. 14.7 the temperature at the surface of the electrode has been calculated for an example of discharge geometry after switching on the Z-pinch EUV source at a repetition rate of 1000 Hz. At each excitation pulse with approximately 5-J energy input into the plasma, the temperature at the electrode surfaces rises very fast by about 2500 K. Because of the finite heat transfer time, the background temperature of the electrode surface increases before the next excitation pulse is delivered to the discharge. The background temperature level saturates because the energy delivered into the surface volume of the discharge electrode by a single excitation pulse decreases relative to the total amount of energy originating

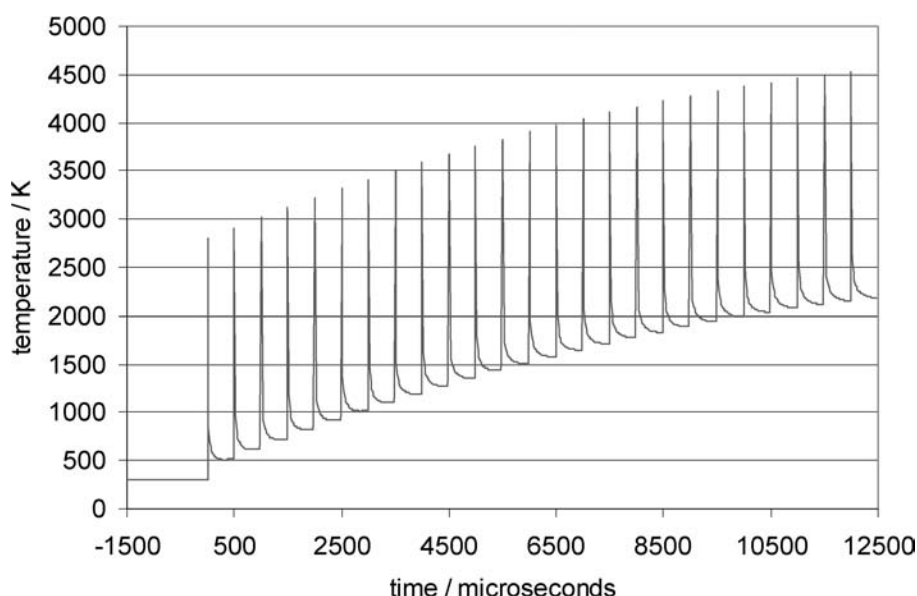


Figure 14.7 Temperature at the surface of the electrodes for an example Z-pinch EUV-source discharge configuration.

from all previous excitation pulses. The limit on the total average excitation power (product of excitation pulse energy and repetition frequency) that can be delivered into the discharge unit is that the maximum surface temperature of the electrodes should be lower than the melting temperature of the electrode material. Otherwise, at higher temperatures the mass loss is increased significantly by the emission of droplets from the electrodes.

With similar simulations of the surface temperature of the discharge system and the melting-related mass loss of the electrodes, we have calculated the lifetime of the electrode system for three different configurations of Z-pinch discharge units. The results for the simulation for 5-J input energy into the plasma are shown in Fig. 14.8. The electrode lifetime is defined as the number of EUV pulses generated in the system until the mass loss of the electrodes has led to a significant change of the electrode shape. Because of the linear increase of average excitation power with increasing repetition rate, the electrode lifetime decreases accordingly. The three configurations differ in geometry by the size of the discharge system. At the normalized distance d the electrode lifetime stays well above 10^9 pulses up to 4-kHz repetition frequency. For a plasma-wall distance of $d/3$ the lifetime decreases by more than two orders of magnitude. If a configuration with 3 times larger plasma-wall distance is possible, the lifetime of the electrodes increases to above 10^{10} pulses. Experimentally achieved discharge-unit lifetimes for XTREME technologies' GDPP Z-pinch sources are discussed below.

Unfortunately, without additional means of plasma confinement, these discharge configurations produce larger plasma volumes and therefore have lower CEs. Additional means to confine the plasma are necessary. A very promising ap-

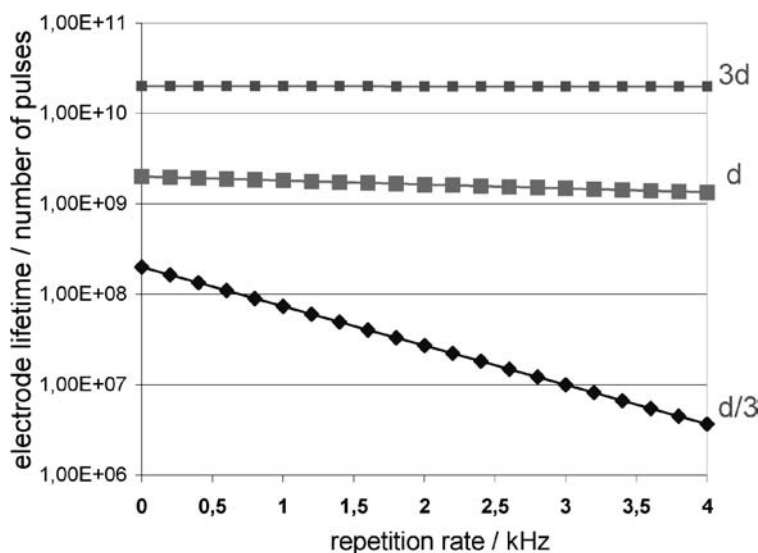


Figure 14.8 Lifetime of the electrode discharge system of GDPP Z-pinch sources in dependence on the repetition rate for three different distances between EUV-emitting plasma and discharge electrode system.

proach is the combination of localized laser evaporation and excitation of the target with subsequent GDPP EUV power generation.³⁴ In this approach the target can be injected separately from the electrodes in several ways (for example, as droplets, as discussed in Chapter 19 in this volume), or the electrode itself can be used as the target supply. The locally confined target-material evaporation supports small plasma volumes, which are to a certain extent independent of the electrode size.

The laser-assisted GDPP EUV source principle of Ref. 34 can be applied not only with stationary but also with moving electrodes, because the laser beam fixes the location of the tin vapor in this configuration. Moving the electrodes extends the static increase of the discharge electrode dimension to a serial dimension because different electrode locations are used in a temporally multiplexed way as described by Borisov et al.,^{35,36} Banine,⁴¹ Koshelev et al.,⁴⁶ and Pankert.⁴² The rotating electrodes in laser-assisted GDPP sources give the potential of increasing electrode lifetimes by orders of magnitude to the required HVM lifetime specifications.

14.5 Pulsed Power Excitation of Z Pinches

As discussed in Sec. 14.2, the GDPP EUV sources require pulsed electrical excitation of the discharge because of the EUV plasma physics. To realize the pinch effect in a low-pressure gas discharge and to allow efficient emission at the 13.5-nm EUV wavelength, the target atoms such as xenon or tin must be highly ionized. For tin the ionization state of ions contributing to the 13.5-nm band is between 8+ and 13+. The contribution to the 13.5-nm emission from xenon comes from the 10+ ionization state (Xe xI). For efficient EUV emission an ion density of

$(3-6) \times 10^{15} \text{ cm}^{-3}$ is necessary. Such concentrations can only be obtained by very high pump energy densities, on the order of $1-3 \text{ J/cm}^3$, supplied in a short time interval of about 10^{-7} s , usually by a high-power discharge pulse. GDPP sources are therefore invariably pumped by a power supply that delivers the stored electrical energy directly into the gaseous target material. The pumping schemes are well developed, for similar schemes have been applied over more than 20 years to excimer laser pumping. They involve efficient switching of the stored electrical energy into the discharge system in a very short time and with a well-defined spatial and temporal profile (for an overview see Refs. 23 and 24). This determines the discharge uniformity and—in turn—influences the spatial and temporal stability of the extracted EUV light. The excitation conditions needed impose severe requirements on the pumping scheme of GDPP sources in terms of peak currents and voltage rise times. Besides the charging section, the power supplies of GDPP EUV sources usually consist of a network of inductors and capacitors (discharge circuit), which is designed to closely match the dynamic behavior of the gas discharge, where the ohmic resistance is rapidly changing with time due to the plasma pinching and heating.

The discharge circuit used for the excitation of GDPP Z-pinch sources is either the capacitor transfer (*C-C transfer*) circuit or the inductor-capacitor inversion (*L-C inversion*) circuit. While a *C-C transfer* circuit is the simplest design for low-repetition-rate Z pinches, efficient Z-pinch excitation circuits use one or more magnetic pulse compression stages to shorten the driving pulse of the plasma.

The conventional *C-C transfer* circuit (see Fig. 14.9) employs simple matched energy transfer from a storage capacitor C_1 , which is initially charged to the required high voltage, to the discharge peaking capacitor C_2 . Once the voltage on C_2 and with it the pinch electrode voltage has risen to the level necessary for discharge initiation, the energy is switched into the discharge. The loop inductance L_2 consists of the stray inductance of the pinch electrode system and can be kept at a few tens of nanohenrys, resulting in a fast current pulse and extreme power deposition levels.

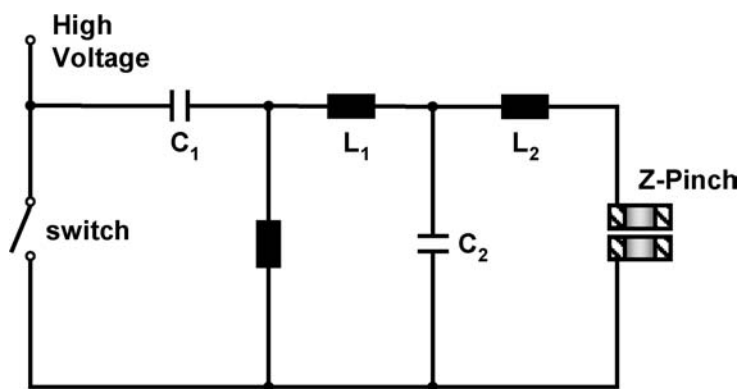


Figure 14.9 Schematic layout of a *C-C transfer* GDPP EUV-source electrical excitation circuit.

The simplest high-voltage switch for use in combination with the circuit in Fig. 14.9 would be a thyatron, i.e., a low-pressure hydrogen- or deuterium-filled electron tube with cathode, anode, and control grid. The lifetime of thyratrons in high-power operation, however, is rather limited. Therefore, high-voltage semiconductor switching devices such as thyristors or integrated gate bipolar transistors (IGBTs) are used in high-power Z-pinch sources. This all-solid-state switching technology constitutes a major advance toward highly reliable industrial systems, since semiconductor solid-state switches have practically unlimited lifetime. Because of the longer current rise times of semiconductor switches, subsequent pulse compression is needed. To compress the switching pulse from the semiconductor switch, magnetic pulse compression is used for high-power Z-pinch EUV sources. A corresponding circuit layout for *C-C* transfer with magnetic pulse compression is depicted in Fig. 14.10.

In magnetic pulse compression circuits the electrical energy is not delivered to the Z pinch in a single step (as, e.g., in the case of the simple *C-C* transfer circuit), but is initially transferred on a slow time scale by the semiconductor switch from the primary energy storage capacitor C_1 to an intermediate energy storage capacitor C_2 , from where it is transferred rapidly to C_3 and the discharge electrode system by the magnetic switch (L_{MS}). Because of the low initial transfer rate, peak currents carried by the semiconductor switch can be reduced, allowing it to operate well below its rise-time and peak-current limits and therefore not being lifetime-limiting.

The magnetic switch is realized by a saturable inductor employing ferrite or amorphous metal as core material. The nonsaturated, high inductance of the inductor does not permit significant current flow and therefore constitutes the open position of the switch. Switch closure is effected by driving the inductor into saturation, which reduces the inductance to close to the equivalent air-core value. Total energy transfer between successive loops is achieved if the energy transfer time from C_1 to C_2 is matched to the time required for the inductor L_{MS} to be driven into saturation (holdoff time). The pulse compression ratio δ between the loops is

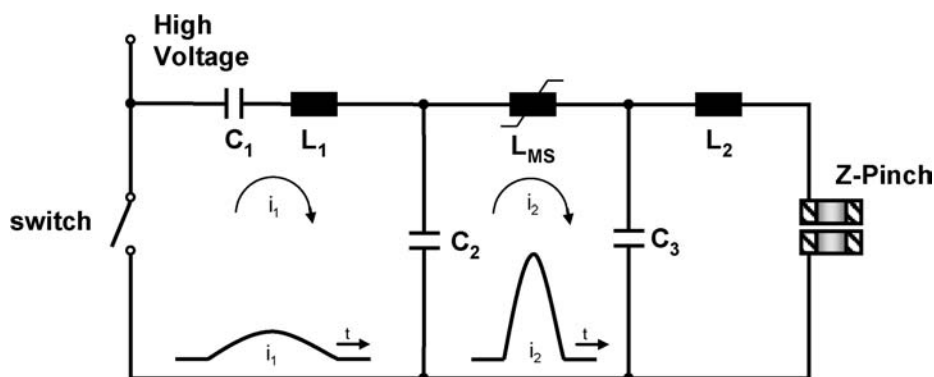


Figure 14.10 *C-C* transfer circuit with single-stage magnetic pulse compression (magnetic switch).

defined as

$$\delta = \frac{t_2}{t_1} = \sqrt{\frac{L_1}{L_{MS}^{\text{sat}}}}, \quad (14.6)$$

where t_1 and t_2 are the transfer times of loops 1 and 2, respectively, and L_{MS}^{sat} is the saturated inductance of L_{MS} . Typically achieved compression ratios for a single stage range from 2 to 5, and several stages can be cascaded to achieve overall pulse compression ratios of several orders of magnitude.²⁵ Since saturable inductors are passive switching elements, they can be designed for very high peak currents and holdoff voltages and have a virtually unlimited lifetime.

An excitation circuit for Z-pinch GDPP sources that can use lower input voltages at the semiconductor switch is the L - C inversion circuit. Figure 14.11 shows the circuit diagram of an L - C inversion circuit with single-stage pulse compression. The L - C inversion circuit has the advantage of voltage doubling and therefore halves the operating voltage for the switch. The associated disadvantage of increased switching currents at the lower voltage is compensated by the addition of one or more pulse compression stages.

Practical values used in XTREME technologies' Z-pinch sources are 2–20 J of electrical energy per pulse, stored in the first capacitors switched by high-voltage, high-current switches such as thyristors or IGBTs, with fast current rise of up to 100 kA/s. Discharge breakthrough voltages range from 2 to 10 kV, depending on the storage capacity. Impedance matching is the design goal to achieve low losses in the pulsed power circuit. Typical values for the impedance are 20–30 m Ω . Typical voltage, current, and EUV output waveforms are shown in Fig. 14.12. The EUV pulse is emitted after the voltage at capacitor C_3 has reached the negative maximum. The EUV signal shown in Fig. 14.12 is the response of the photodiode. The duration of the EUV pulse is approximately 100 ns.

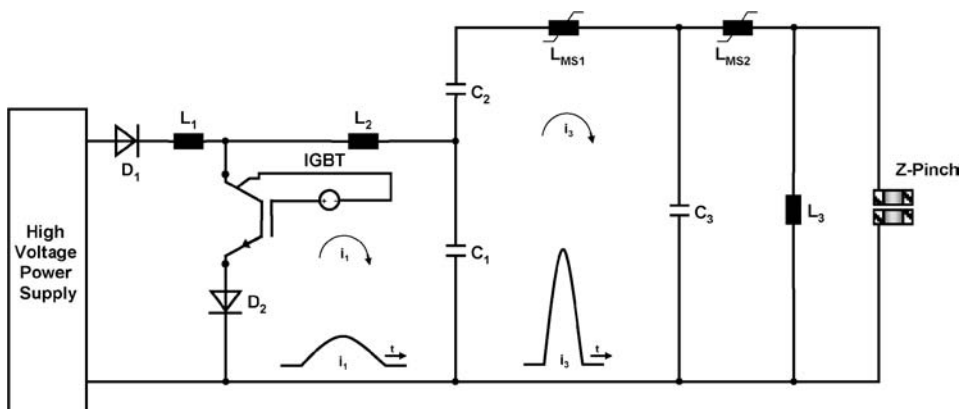


Figure 14.11 Semiconductor-switched L - C inversion circuit with single-stage magnetic pulse compression.

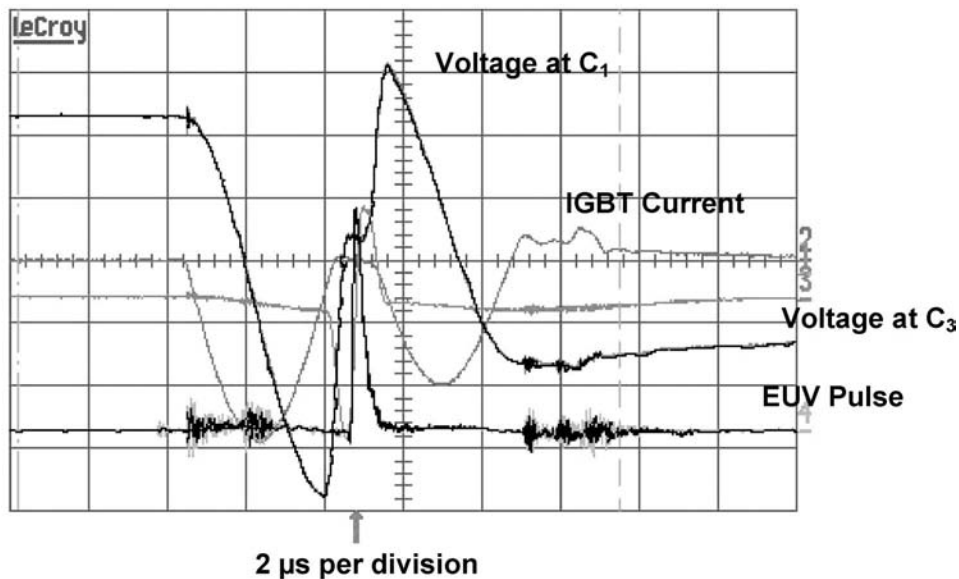


Figure 14.12 Waveforms at different points in the pulsed power circuit of Fig. 14.11. The EUV pulse is emitted after breakthrough of the voltage at C_3 .

With the above parameters, electrical pulsed-power-circuit losses (which are easily managed thermally) amount to less than 30%. EUV emission efficiencies of 1% to 2% from power deposited into the Z-pinch plasma to 13.5-nm EUV output have been realized, depending on the emitting fuel (see below).

14.6 Discharge-Electrode Thermal Management Technology

From the power requirements for GDPP EUV sources for high-volume chip manufacturing derived in Sec. 14.1.2, one can estimate the cooling requirements for the discharge electrode system. Under the assumption of 3% CE (estimate for tin-fueled Z-pinch sources) from electrical power to EUV inband radiation, between 23 and 46 kW of electrical power must be removed from the discharge system. The development of efficient cooling systems for Z-pinch sources is therefore targeting a heat removal of up to 50 kW at heat fluxes of up to 5 to 10 kW/cm². Because the discharge electrodes are connected to high voltage, the cooling system must be electrically isolated. Thermal cycling of the discharge electrode system from room temperature to above 1000°C will occur.

Several cooling arrangements for the discharge electrode system have been developed and tested with XTREME technologies' Z-pinch EUV sources.

In the simplest arrangement the electrodes are in good thermal contact with a liquid- (water- or oil-) cooled heat sink. With such arrangements up to 5 kW of heat could be removed from the discharge region.

In a more complex arrangement the electrodes have been designed to be directly liquid-cooled. Direct liquid cooling offers the potential for high heat flux.

The electrodes are designed with flow channels. Water or oil is injected into and removed from the system via these channels. With optimized liquid-cooled Z-pinch discharge designs a heat removal of up to 12 kW has been achieved.

A further significant improvement of the cooling efficiency is achieved by employing a cooling technology called porous-metal cooling. In this technology, highly efficient heat removal is obtained through use of a porous medium with microchannels for extended surface heat transfer (see Fig. 14.13). Parts of the electrodes are manufactured of porous metal with a very large surface, similar to a sponge. Water is forced by high pressure through the porous metal, and high heat

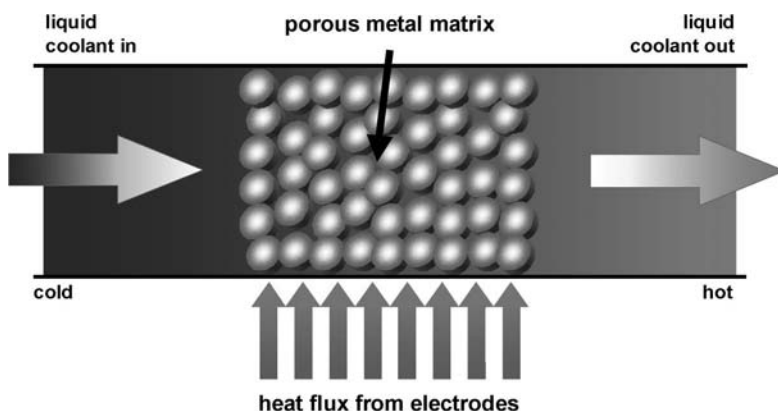


Figure 14.13 Porous-metal heat exchanger in cross section. Coolant liquid is pressed through the porous metal matrix.

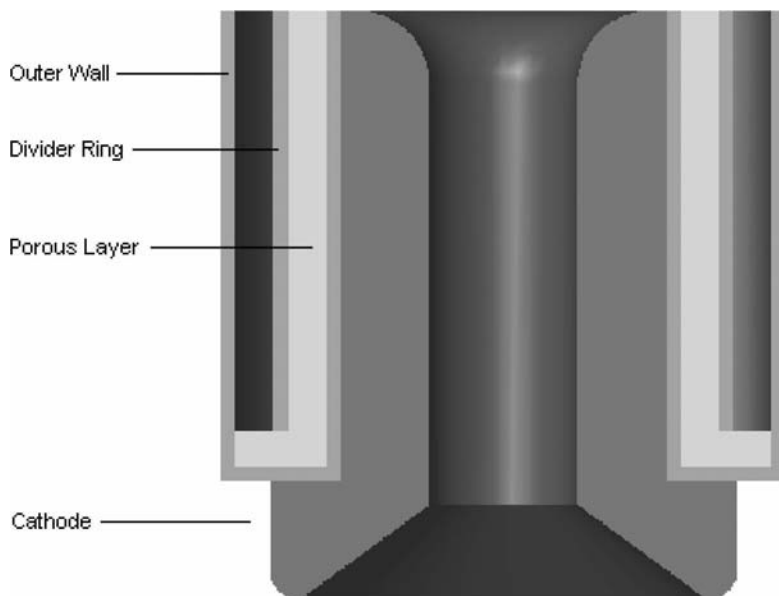


Figure 14.14 Water-cooled electrode design with porous-metal heat exchanger.

exchange from the surface to the water is obtained. The porous-metal heat-sink version of an electrode assembly is shown in cross section in Fig. 14.14. Key components include an inner copper shell, an outer copper shell, a divider ring, and the porous metal layer. The water coolant flows into the annular porous layer from the top. As it flows through the layer, it absorbs heat conducted from the tip through the inner wall. As it reaches the bottom of the assembly, the coolant is redirected around the divider ring, and then passes upward and out of the assembly. With the current technical realization, heat removal of up to 20 kW has been obtained from the discharge electrode assembly of XTREME technologies' GDPP Z-pinch sources.

14.7 Debris Mitigation and Collector-Optics Protection

The EUV-emitting plasma is a source of high- and low-energy particles such as ions, atoms, and electrons with a wide range of energies from a few electron volts up to several times 10 keV. The interaction of these particles with the collector-optics surface depends on the emitting material, i.e., xenon or tin. While xenon at room temperature is in the gaseous state, tin is in the solid state, and tin tends therefore to condense on the optical surface. In addition, because of erosion of the discharge electrode system, material from the electrodes may reach the collector-optics surface and, depending on the energies, either erode the collector surface or also condense there. All these interactions lead to a limited lifetime of the collector optics. To achieve sufficient lifetime of the source collector optics, collector protection and debris mitigation is one of the crucial tasks in EUV source development.

To measure debris-related effects that limit the lifetime of the source collector optics, two types of measurements are routinely carried out. One is the quartz-crystal microbalance technique, which is a well-developed and mature diagnostic metrology method. It allows one to measure the change of mass, either loss or deposition, of detectors coated with relevant grazing-incidence collector coating materials. The quartz crystal oscillator vibrates at a certain frequency in the megahertz range. The change of the frequency caused by sputtering (mass loss) or contamination (deposition of material) is measured. As mass is deposited on the surface of the oscillator, the frequency of the oscillator decreases. Sputtering of the oscillator coating material results in increasing oscillation frequency. The second kind of measurements uses small optics witness samples made with the manufacturing technology of grazing-incidence source collector optics. The relative or absolute reflectivity and its change are measured with 13.5-nm EUV detectors. While optics sample irradiation experiments are time-consuming (irradiation of samples may take weeks) the microbalance method gives results after short measurement times (a few tens of minutes).

With the above diagnostic techniques we came to the following conclusion: The dominant effect that limits the lifetime of the source collector without any means for debris reduction between EUV-emitting plasma and collector is sputtering of the optics surface by high-energy ions and atoms. This is true both for

xenon and for tin fuel in the source. For collector-optics samples placed at a distance of 11 cm from the pinch plasma the reflectivity decreases by 5% on exposure to 50,000 pulses of the xenon target source. The EUV inband energy per pulse amounts 35 mJ, so that the total EUV dose accumulated during 50,000 pulses is 1.75 kJ.

Debris filters have been developed at XTREME technologies that allow significant reduction of the sputter rate at the optics surface. For a debris filter device as shown in Fig. 14.15 the sputter rate has been measured and compared with the sputter rate without a filter. The comparison is given in Fig. 14.16. With the debris filter in place the sputter rate at the optics is reduced by a factor of approximately 5000.

Currently collector-optics lifetimes from several hundred million pulses up to 1 billion pulses have been achieved with a collector distance of 11 cm for an EUV source with 35-W power at 1000-Hz repetition frequency (see below). For HVM, a 3000-h collector lifetime should be the target specification. At 10 kHz this corresponds to 1.1×10^{11} pulses. To increase the optics lifetime of the source collector to these values, several design criteria have to be implemented in the collector.

First, one may increase the distance between plasma and collector to the highest technically possible values. The flux of fast particles decreases quadratically with increasing distance from the plasma, for geometric reasons. The larger space between plasma and collector can be used to efficiently mitigate debris. Second, research into sputter-resistant materials for collector coatings must be intensified. Third, the use of additional means for ionization of fast particles in combination with debris filtering by electric and/or magnetic fields may be necessary to reduce the sputtering effects further.



Figure 14.15 Photograph of a debris filter (foil traplike structure).

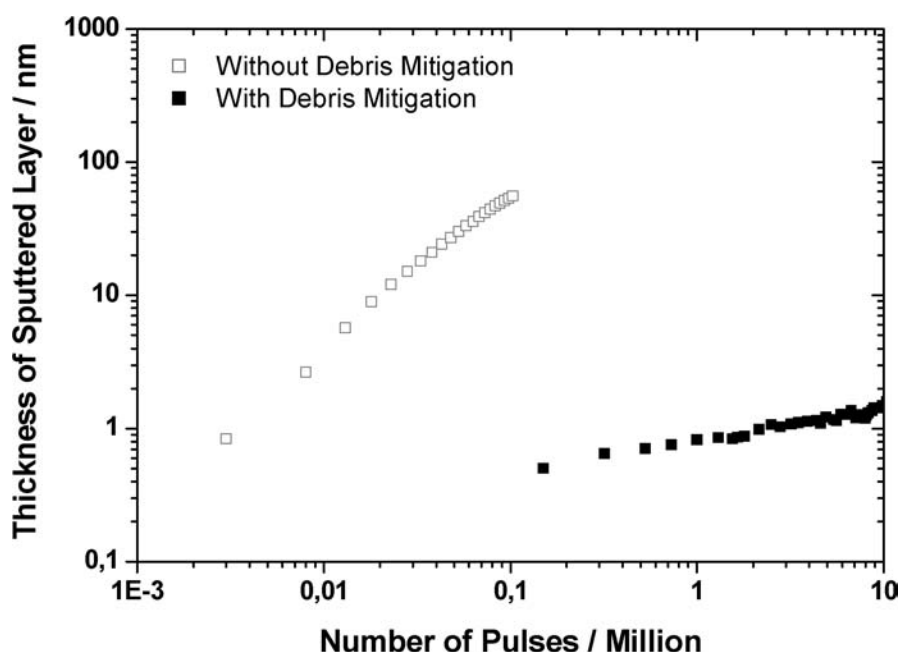


Figure 14.16 Sputtering effect of the plasma with and without debris filter in place. The sputter rate is reduced by a factor of approximately 5000.

Using projected debris-filter collector optics design configurations suited for β tools, an optics lifetime of 5–10 billion pulses can be extrapolated from experiments with the microbalance device. This is already one-tenth of the HVM optics lifetime requirements.

Once sputtering is reduced to the required level, contamination of the optics by electrode material and, in the case of tin, also by the target material itself may play the most important role (see below and Refs. 37, 38). These effects must be studied in further detail to achieve the required collector lifetime.

14.8 First Commercial Sources for Exposure Tools—EUV Source XTS 13-35

The development program for Z-pinch EUV sources at XTREME technologies has led to the completion of the first commercial GDPP EUV source prototypes of the type XTS 13-35 (see Fig. 14.17). The sources operate with xenon as fuel. They have been integrated into the EUV microstepper MS 13 developed by EXITECH, Oxford, UK.^{26,27} The source design is modular. The plasma generator (discharge head) must be connected to the vacuum beamline of the EUV exposure tool. A first part of the pulsed-power excitation circuit is directly integrated into the EUV discharge head. A first supply module contains fast high-voltage electronics of the pulsed-power circuit, which must be installed adjacent to the EUV source head. A second supply module, which contains power supplies and computer control,

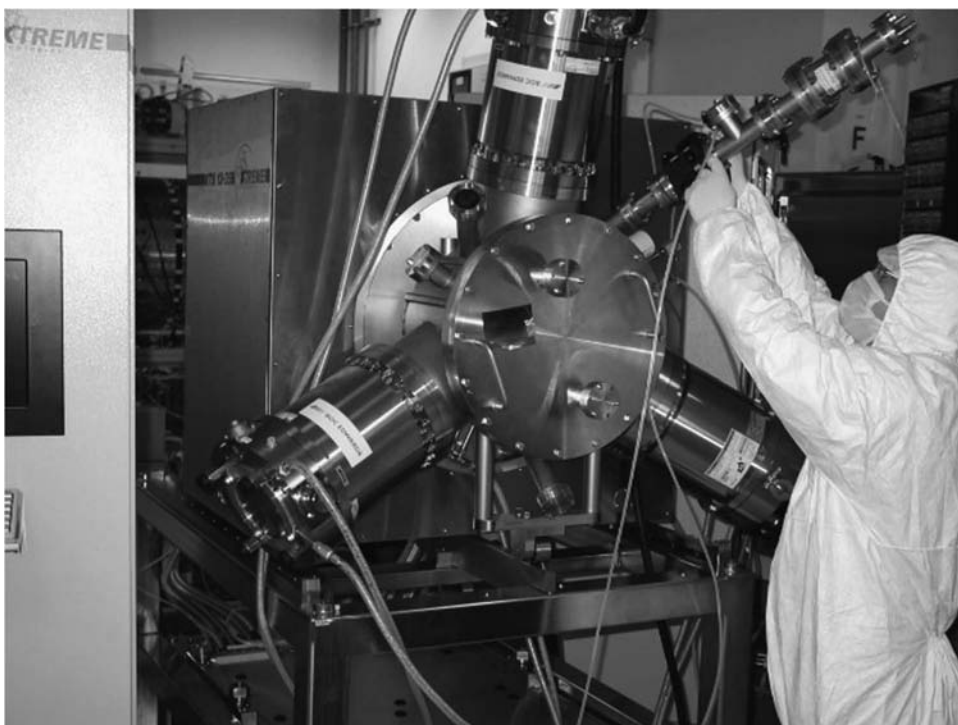


Figure 14.17 Photograph of the EUV source XTS 13-35, which has been integrated into the EUV microstepper developed by EXITECH, Oxford, UK.

can be installed at a larger distance from the source head. The source is equipped with a debris mitigation system, which was developed at XTREME technologies and extends the optics lifetime (until the reflectivity drops below 90% of the initial value) to more than 100 million pulses. The collector optics used with the source was designed and manufactured by Carl Zeiss, Oberkochen, Germany. The EUV microstepper with the XTS 13-35 EUV source will be used for process development in the semiconductor industry. Intel has announced the installation of the EUV microstepper and recently presented first promising imaging results.^{28,39} A second EUV microstepper is installed at the International SEMATECH ISMT-North facility in Albany, USA.

The main performance parameter of the source is the output power of 35 W of EUV inband radiation (2% bandwidth) into a solid angle of 2π sr. The nominal repetition rate is 1000 Hz, and the pulse-to-pulse stability is $3\sigma < 20\%$ (see Fig. 14.18). Theoretically the combination of the source with a collector optics module with 10% total efficiency would lead to 3.5-W EUV inband power at the IF.

A typical emission spectrum of the xenon-fueled source is shown in Fig. 14.19. The emission spectrum of the radiation is routinely measured with a reflection-grating spectrograph, which consists of a flat-field grating and a CCD detector.

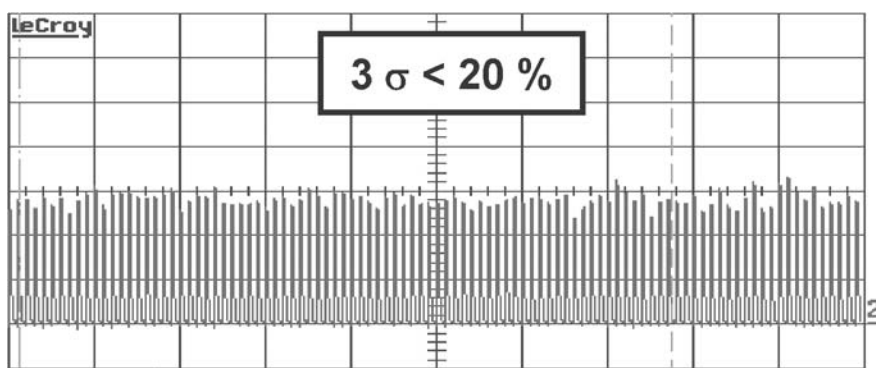


Figure 14.18 Pulse-to-pulse fluctuations of the XTS 13-35. An energy stability 3σ of $<20\%$ is achieved with a free-running source without active energy stabilization.

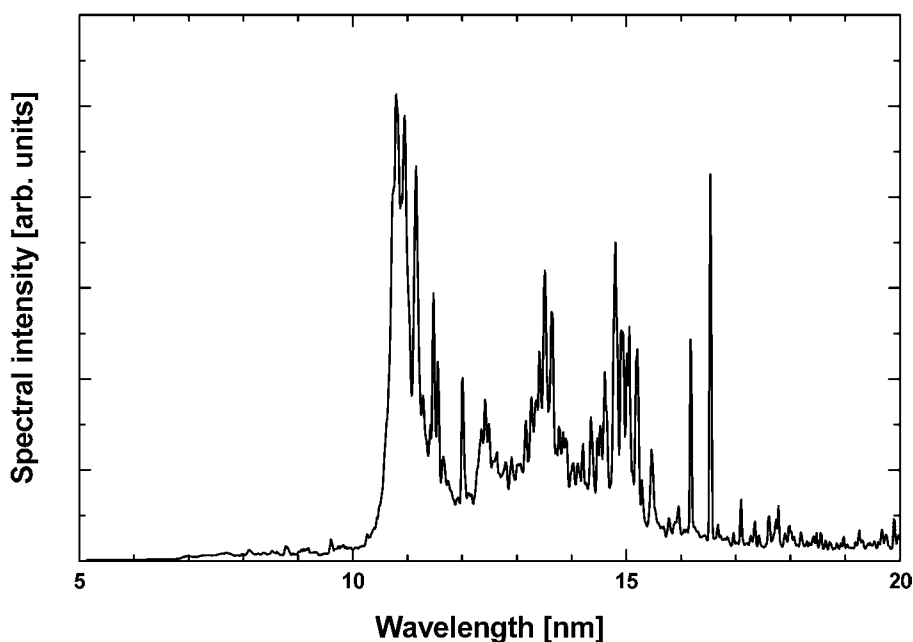


Figure 14.19 Spectral emission characteristic of the Z-pinch EUV source with xenon fuel.

The spectrum of the Z-pinch source shows a distinct peak around 13.5 nm. The CE into the 13.5-nm band of 2% bandwidth and 2π -sr solid angle is 0.7%.

Extensive lifetime testing of components and optics has been performed with the XTS 13-35 to evaluate the performance and the reliability of the system. Power stabilization, which keeps the output power constant, was simulated by controlling the high voltage of the discharge manually. Running the source at its nominal output power of 35 W into 2π sr, a discharge lifetime in excess of 100 million pulses was achieved (see Fig. 14.20). With recent improved configurations

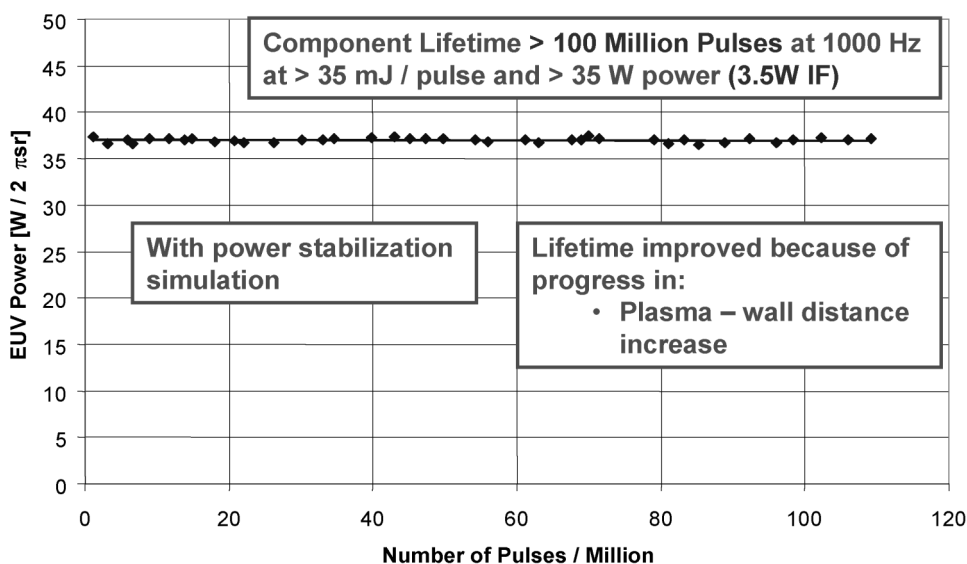


Figure 14.20 EUV output power of the XTS 13-35 monitored over more than 110 million discharges. The output power was kept constant by controlling the value of the discharge voltage.

with larger electrode dimensions the lifetime of the electrode system could be improved to 80 h at 1-kHz repetition frequency, which is equivalent to 300 million pulses.

To estimate the expected collector optics lifetime, samples of grazing-incidence collector optics were placed at 110-mm distance to the plasma. The reflected radiation at grazing incidence was monitored using an EUV inband energy monitor²⁹ equipped with two multilayer mirrors, a freestanding filter, and a photodiode. A reference signal was monitored simultaneously with an identical detector, which faced the plasma directly. The ratio of the two signals corresponds to the normalized reflectivity of the optics sample. Running the source at the nominal output power of 35 W, the sample reflectivity was kept constant for more than 170 million pulses (see Fig. 14.21).

The noise of the measurement data is related to the online measurement with the two EUV inband energy monitors directed through the debris filter. One of the monitors is behind the optics sample; the other directly measures the inband energy of the source. The normalized reflectivity curve in Fig. 14.21 was calculated by dividing the signals of the two detectors.

Further progress in debris mitigation at XTREME technologies has led to optics lifetimes derived from quartz-crystal microbalance devices in the above collector configuration of between 500 million and 1 billion pulses for advanced XTS-type sources with xenon fuel. The achieved lifetime is mainly determined by erosion of the optics surface as discussed in Sec. 14.7.

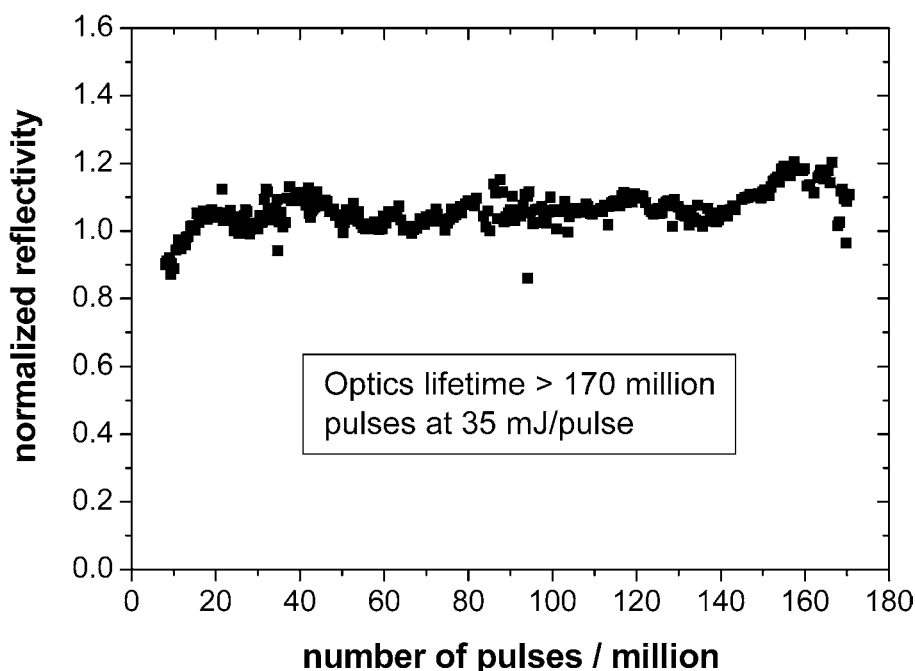


Figure 14.21 Optics-sample reflectivity as a function of the pulse number. The sample reflectivity was normalized to a reference signal of a monitor that faced the plasma directly.

14.9 Scaling of Z-Pinch Power and Lifetime Performance to β -Tool and HVM Requirements

14.9.1 β -tool source requirements and performance for xenon fuel

EUV-source power and lifetime scaling, including collector power handling and collector lifetime scaling, is the major critical issue in the development of EUV technology. Because of the contamination-free operation available with xenon, the development efforts in the past have been directed to a large extent to xenon-based EUV sources to explore the limits of the technology.

With 20-kW electrical power deposited in the plasma (limited by the cooling capabilities; see Sec. 14.6), the repetition rate of the discharge source can be increased to 4500 Hz in continuous operation. The electrical input energy per pulse is kept constant by adaptation of the pulsed power supply circuits. Also the CE was preserved at the same value as at low repetition rates. The output power curve for the sources operated with xenon fuel shows a linear dependence on the repetition rate, and 200-W output power into 2π sr is achieved (see Fig. 14.22). This is currently the highest power obtained in continuous operation over several hours from a xenon-fueled GDPP EUV source.

Figure 14.23 shows the output power and high voltage at the discharge electrode system. The adjustment of the high voltage allows one to stabilize the output

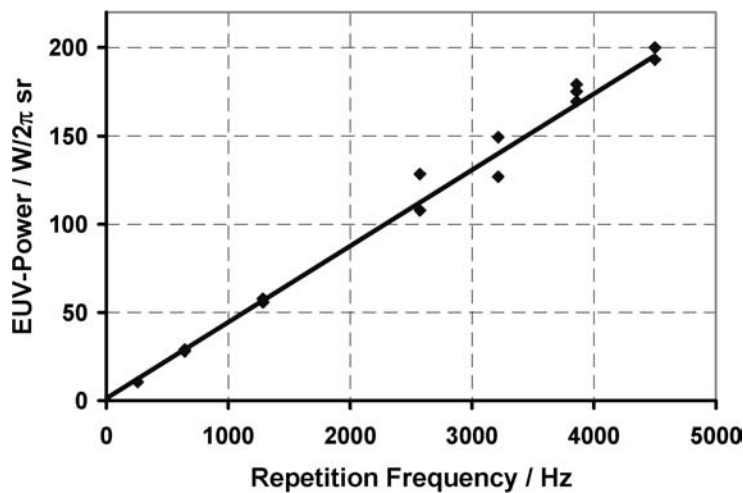


Figure 14.22 EUV output power as a function of the repetition rate of the discharge. The linear dependence indicates constant CE for all repetition rates.

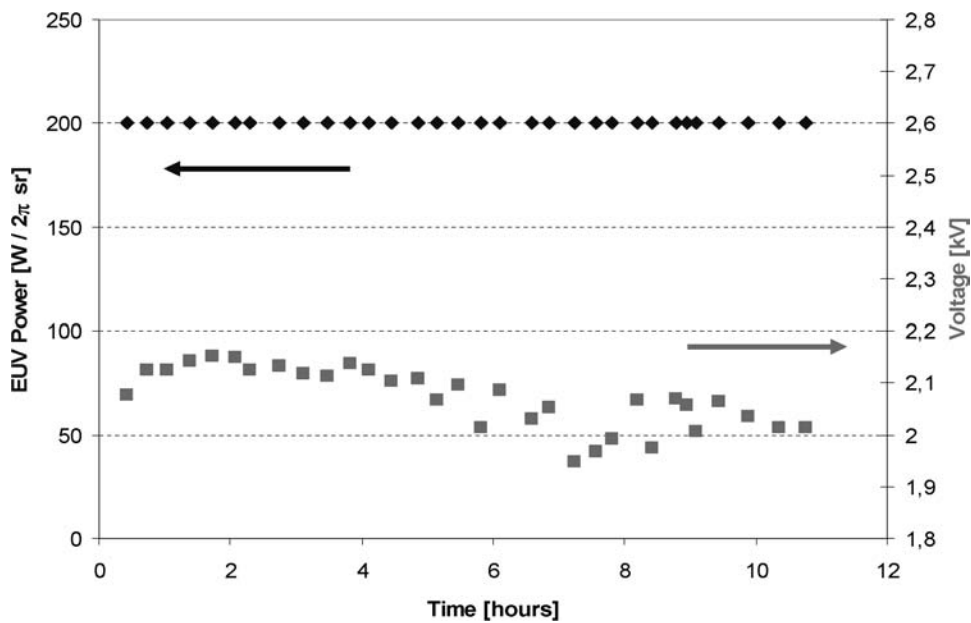


Figure 14.23 EUV output power stabilized to 200 W into 2π sr at a 4-kHz repetition rate by adjustment of the voltage at the discharge electrodes for each measurement point. The source was in continuous operation mode.

power at 200 W. The inband EUV power of 200 W into 2π -sr solid angle corresponds to an available IF power of 25 W for the existing 1.8-sr source collector design, taking into account the losses due to the debris filters, shadowing by mechanical parts in the beam path, and residual-gas absorption in the source collector module. In the etendue of β -tool optical systems, 10–20 W of the available IF

power can be used. Xenon-fueled Z-pinch sources are therefore well suited for β -tool use. They have the significant advantage of having no problem of optics contamination by the inert xenon. Debris filters to suppress fast-particle sputtering of the collector mirror have been tested at XTREME technologies for β -tool source-collector designs. These tests indicated collector lifetimes achievable by suppression of sputtering amounting to 5–10 billion pulses, i.e., 350–700 h at 4 kHz. The development of source collector mirrors for β -tool use is focused on implementing efficient cooling technology at the collector mirror to enable the handling of the thermal load introduced by the high input power from the source.

With designs of larger electrode discharge systems, electrode lifetimes of several billion pulses are also projected for xenon-fueled β -tool sources. Taking into account all these parameters, xenon-fueled Z-pinch sources will enable the timely adoption of EUV β tools in semiconductor fabs to prepare for manufacturing integrated circuits with EUVL.

14.9.2 Scaling of performance to HVM requirements

In order to estimate the potential and limits of xenon-fueled sources with respect to HVM requirements, we predict the following possible improvements in development:

1. Improvement of the cooling technology and enlargement of the dimensions of the discharge electrode system will allow heat removal of 30–50 kW from the discharge region.
2. A CE of 2% from electrical power deposited into the plasma to EUV inband radiation can be reached.

Under these provisions we estimate a maximum EUV power achievable with xenon Z-pinch sources of 600–1000 W emitted in a solid angle of 2π sr. This is the order of magnitude that was estimated to be needed for HVM sources in Sec. 14.1.2.

However, because of the size of the EUV-emitting plasma and the observed EUV spatial background of xenon-fueled sources under real conditions with debris mitigation schemes, it is unlikely that etendue acceptance factors above 80% can be achieved without additional means of plasma confinement. The maximum IF power achievable from xenon sources we estimate at 40–80 W. On the way to HVM sources, more efficient emitters will likely have to be used.

As discussed in Sec. 14.3, because its emission spectrum is well matched to the reflectivity of the 13.5-nm optics, tin is the most promising candidate for a GDPP source fuel.^{18,30,38,39} Tin-vapor-based GDPP EUV sources have been built at XTREME technologies. At the same electrical input energy, the CE for tin was measured to be higher than for xenon by at least a factor of 2. Emission spectra from tin and xenon under the same excitation conditions are shown in Fig. 14.24. The intensity of the 13.5-nm emission peak for tin is 2 times higher than that for xenon. Absolute CEs into the 13.5-nm band vary from 1.7% to 2.9%, depending

on the method of tin vapor generation: by gaseous supply or by electron-beam or laser-beam evaporation.

In Fig. 14.25 the output power of the tin-fueled source is given in comparison with the xenon-fueled source under identical excitation conditions. The tin-based

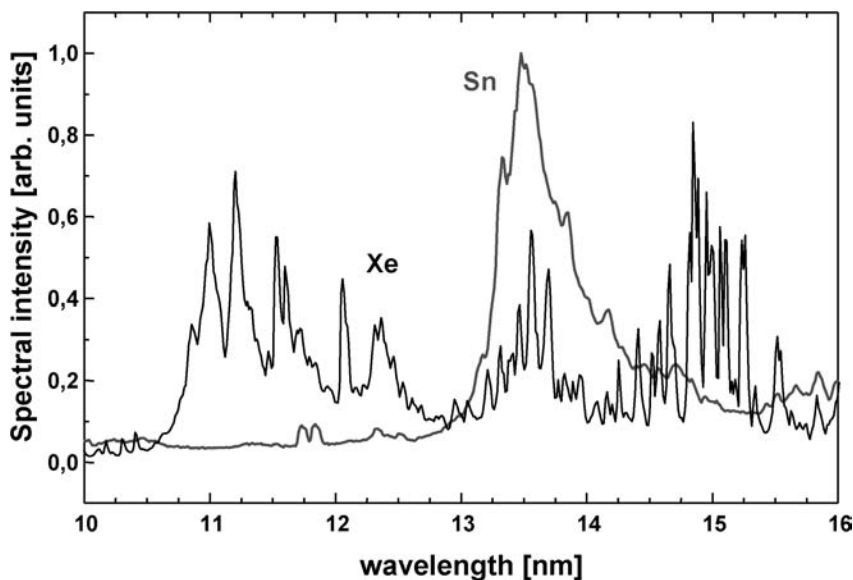


Figure 14.24 Emission spectra from a Z-pinch GDPP source working with tin in comparison with the xenon spectrum under the same excitation conditions.

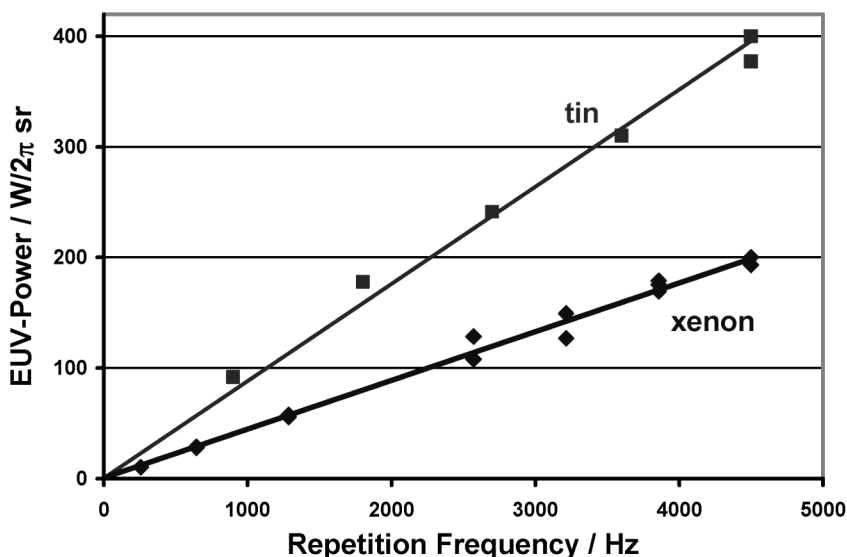


Figure 14.25 EUV inband output power of tin-fueled source compared with xenon-fueled source in dependence on the repetition rate of the source. An output power up to 400 W into 2π sr is achieved by the tin-fueled source. With manufacturable source collector mirrors of about 2-sr collection angle, an available IF power of 50 W is expected from the source.

EUV source can be operated at the same maximum repetition frequency as the xenon source. This repetition frequency is given by the maximum heat removal capability of the porous-metal-cooled electrode discharge unit, which is 20 kW. The maximum power from the tin source amounts to 400 W into 2π sr for 20 kW of power dissipated in the plasma at 2% CE. With existing and manufacturable source collector mirror designs, the power into 2π sr corresponds to 50 W of available power at the IF plane.

In comparing the tin-fueled with the xenon-fueled sources, it is important to emphasize that the spatial emission from the tin source is more concentrated. In Fig. 14.26 the EUV-inband-emitting plasma shapes are depicted for the xenon source (a) and the tin source (b) under identical excitation conditions. The scale of both inband images of the pinches is the same. It can be seen that the xenon plasma is more smeared while the emission of the tin plasma has sharp edges and a rather homogeneous intensity distribution. The spatial background emission in the xenon source contains significant energy. The tin plasma shows no visible background radiation. This means that the etendue acceptance factor for the tin source is larger than that of comparable xenon sources. For HVM sources it is also expected to reach values of around 0.9. Therefore, overall collection efficiencies from plasma to IF well in excess of 10% are expected for HVM tin sources.

From currently achieved data, 45 W of the available EUV power could be used in the EUV scanner, provided the collector can withstand the high input power load.

Despite the high usable IF power of tin GDPP sources, contamination of optics by tin fuel is a new challenge that comes in addition to requirements for optics protection against fast particles, which is also needed for xenon sources. Because the mass and ion energies of tin are comparable to those of xenon with respect to sputtering, similar protection schemes are necessary (see above). As for xenon, optics lifetimes of 350–700 h, i.e., 5–10 billion pulses, are projected for β -tool sources today. The application of the developed protection schemes leads to similar results for optics lifetimes in tin sources with respect to sputtering. Because of the well-developed protection against sputtering, the lifetime of optics in tin sources is limited only by contamination today.

Figure 14.27 shows the normalized reflectivity measured online during irradiation of grazing-incidence collector-optics samples versus the number of pulses while applying both contamination protection and sputtering protection. The reflectivity stays nearly at the same level for about 20 million pulses. The fluctuations in the signal are related to the reference measurement of the pulse energy behind the debris filters. The lifetime is limited by contamination of the optics by tin compounds. With further development of existing contamination protection schemes, lifetimes in excess of 100 million pulses are expected for mid-2005. This lifetime is about 2 orders of magnitude below the optics lifetime in xenon sources and 3 orders of magnitude below HVM requirements. We discuss this gap further below.

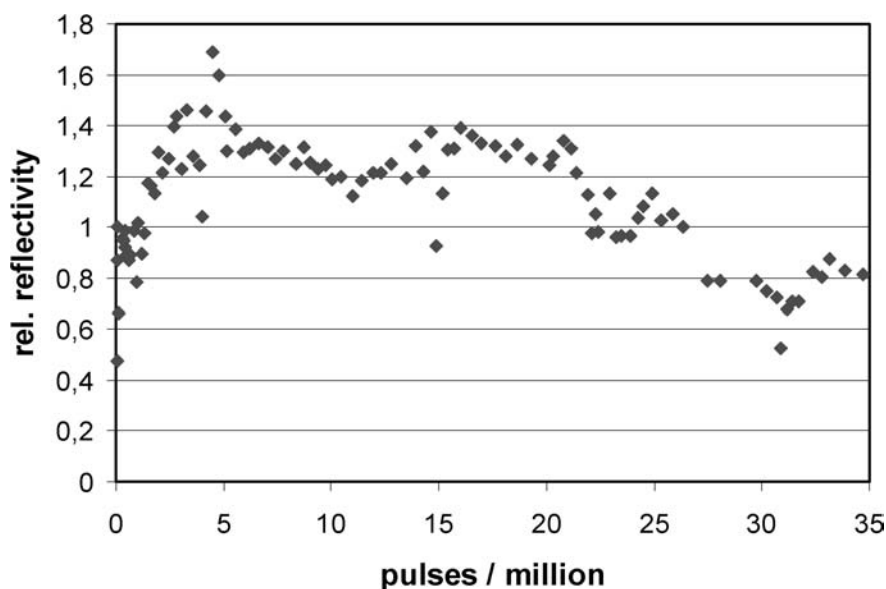


Figure 14.27 Online-measured normalized reflectivity of grazing-incidence collector-mirror samples against number of pulses used for irradiation in a tin-fueled GDPP source. The fluctuations in the signal are related to the reference measurement of the pulse energy behind the debris filters.

14.10 Path to Meet Remaining Challenges for HVM GDPP Sources—Lifetime Improvement of Discharge Electrode System and Source Collector Optics for Tin Fuel

In consideration of the results and estimates described above, we conclude that the IF power specification of 115 W and above for HVM EUVL will be met with tin-based Z-pinch sources without the need for additional inventions. The current status of both xenon- and tin-fueled GDPP sources is summarized in the first columns of Table 14.3.

With xenon sources the β -tool power requirements of 10–20-W usable IF power are met. With tin sources more than twice this IF power is available today. For the projected possible improvement in power, two steps will be taken:

1. Increase of average CE to 3%.
2. Increase of heat extraction from the discharge electrode system to 40 kW.

Conversion efficiencies of 2.9% have already been measured. The step to sustain 3% CE on average is very reasonable. The increase of heat-load extraction from 20 to 40 kW needs the enlargement of the discharge electrode system's surface by a factor of 2 or more. Such discharge electrode systems are already operational at XTREME technologies. With these two improvements the usable IF power will reach levels between 123 and 154 W, depending on the etendue and the etendue acceptance factor.

Table 14.3 Currently achieved performance of xenon- and tin-fueled GDPP sources and roadmap for tin sources toward HVM requirements. No losses in a possible spectral purity filter are included.

Fuel	Xenon status 9/2004	Tin status 9/2004	Tin on the roadmap with collector of today	Tin on the roadmap with improved collector
Heat removal from discharge (kW)	20	20	40	40
CE (%)	1.0	2.0	3.0	3.0
EUV power into 2π sr (W)	200	400	1200	1200
Transmission of debris mitigation	0.8	0.8	0.8	0.8
Collection solid angle (2π sr)	0.3	0.3	0.3	0.5
Average reflectivity of collector	0.63	0.63	0.63	0.55
Gas transmission in collector module	0.85	0.85	0.85	0.85
Available IF power (W)	25.7	51.4	154.2	224.4
Etendue acceptance factor	0.5–1.0	0.7–1.0	0.8–1.0	0.5–1.0
Usable IF power (W)	12.8–25.7	36.0–51.4	123.4–154.2	112.2–224.4

An additional step to increase the IF power is to increase the input collection angle of the source collector mirror from the current 1.8 sr to π sr. This type of collector will be manufacturable on taking the right development steps in the near future. IF power levels of 112–224 W are projected for this combination. Progress in the confinement of the EUV-emitting plasma will lead to higher etendue acceptance and therefore to IF power close to 200 W.

With the HVM power requirements achievable with GDPP sources, the next two challenges that must be addressed to achieve HVM performance are:

1. Discharge electrode lifetime.
2. Collector-optics lifetime in a tin environment.

To achieve the required electrode lifetime at a given total current through the discharge, there are three topics onto which development work is currently concentrating:

1. Enlargement of the area of the electrodes in order to reduce the current density and temperature at the surface.
2. Improvement of cooling efficiency to reduce the temperature of the surface below the melting temperature of the electrode material.
3. Recycling of electrode material loss toward the electrodes.

The development of larger electrode configurations with static electrodes led to several-billion-pulse electrode lifetimes in 2005. It may find a limit in lifetime

around 5 billion pulses while maintaining the required small plasma size. For HVM GDPP sources operating at 10-kHz repetition frequency, this would mean replacing the electrode system 20 times a year. The design of the electrode replacement can be engineered to achieve about 15 min or less of downtime per exchange.

As an alternative to the static increase of the discharge electrode dimension, the implementation of moving (rotating) electrodes, as described above, gives the potential for increasing electrode lifetimes by another order of magnitude, but at the expense of greater complexity of the design. It has the advantage, however, of also providing possibilities of electrode material recycling. Lifetimes of these kinds of electrode systems are expected to reach the order of 1000 h. This would require replacement about 3 times per year under HVM conditions.

The above developments will enable electrode lifetimes that are sufficient to support the use of GDPP sources for HVM using EUVL. The approach that is most suited for HVM EUVL will depend on downtime and related costs.

In order to achieve the required source collector optics lifetime, the development work is currently concentrating on

1. collector-optics protection against erosion by highly energetic particles,
2. collector-optics protection against contamination by tin fuel,
3. collector-optics protection against contamination by electrode material,
4. *in situ* cleaning procedures for collector optics to remove material deposits.

Progress in collector protection against erosion has been described above. It is expected to permit lifetimes of 10 billion pulses (i.e., 700 h) for β -tool source collectors. With further engineering of the existing protection schemes and collector designs, lifetime limits with respect to erosion are projected to rise to 3000 h, i.e., 1 year of operation for HVM sources.

Contamination effects related to the use of tin as well as from erosion of the electrodes require the development of additional contamination protection schemes as described above. Collector lifetimes of 20 million pulses have been demonstrated. Lifetimes of 100 million pulses are expected for mid-2005.

When the limit of active protection of the source collector against contamination has been reached, *in situ* cleaning procedures are needed to prolong the collector lifetime. These types of procedures are referred to as plasma cleaning or halogen cycling. The principle consists in cleaning the collector *in situ* by applying such methods after the reflectivity of the optics is reduced below a certain value by contamination with tin compounds. During cleaning, contamination layers on the optics are removed, leading to collector reflectivities close to the original value. Descriptions of the cleaning methods as well as results have been given recently.^{32,42–45}

The combination of the above-described collector protection and cleaning methods is expected to enable the required source-collector lifetimes for HVM use of tin-fueled GDPP EUV sources.

14.11 Summary and Conclusion

Z-pinch EUV sources at XTREME technologies are currently the most powerful GDPP sources in the world. Prototypes of commercial machines with xenon as emitter and an EUV power of 35 W into 2π -sr solid angle have been developed and are integrated in EUV microsteppers. These EUV microsteppers are used as pathfinders for EUVL in the semiconductor industry. The microstepper EUV source XTS 13-35 is equipped with a debris filter to protect the grazing-incidence collector optics. An optics lifetime exceeding 100 million pulses at 1-kHz repetition frequency is achieved. The same lifetime is obtained for the components of the discharge system itself.

On a laboratory scale, xenon-fueled GDPP sources have been developed with an available EUV inband power increased by more than 2 orders of magnitude over the status 3 years ago. The progress has resulted in a continuous EUV power of 200 W into 2π sr at 4.5-kHz repetition rate. The usable IF power for these sources is in the range between 12 and 26 W, depending on the collector optics design, on the transmission of the optical path to the IF, and on the etendue specification. The plasma shape of xenon sources, however, will likely prevent transmission through the source collector with sufficient efficiency to support HVM.

Because of their favorable plasma shape and spectral emission characteristics, Z-pinch sources with tin fuel have been developed. These sources have demonstrated 400-W EUV output power into 2π sr at 4.5 kHz in continuous operation. The IF power for existing collector designs is calculated to range between 36 and 50 W inband EUV power, depending on etendue specifications. The power requirements for HVM EUVL will be met without additional inventions.

Significant progress has also been made in the lifetime of the discharge electrodes and the source-collector optics. Current development projects lead to the projection that the lifetimes required for HVM use of GDPP sources will also be reached. The research programs at XTREME technologies are focused on demonstrating required HVM lifetimes in 2006.

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Chapter 15

Star Pinch EUV Source

Malcolm W. McGeoch

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15.1 Generic EUV Source Factors

This chapter begins by looking at the *first-wall* erosion problem for EUV sources and proceeds in Sec. 15.2 to introduce the concept of a *directed discharge*, which allows the hot EUV-emitting plasma to be held at a sufficient distance from the first wall to yield industrially acceptable component life while maintaining the high efficiency and low cost of a DPP source.

15.1.1 Pulsed plasma conditions

In EUV sources of the plasma type, either LPP or DPP, the challenge is to achieve rather hot and dense plasma conditions repetitively for at least 10^{10} pulses without damaging the illumination or collector optics, chamber walls, and (in the DPP case) electrodes. As an example of typical plasma conditions, the Star Pinch, which is driven by multiple converging plasma channels, dissipates 10 J in less than 500 ns within a 0.7-mm^3 volume, reaching an estimated electron density of $4 \times 10^{19} \text{ e cm}^{-3}$ and a temperature greater than 30 eV. At its hottest, the plasma radiates broadband EUV power at the rate of 20 MW, so it cannot be sustained continuously. In the case of xenon plasma discharges, approximately 20% of the dissipated energy is released promptly in a 50-ns burst of radiation, most of it in the 10–15-nm band. The remaining energy is carried by the expanding plasma toward the facing walls, where ion sputtering is the main erosion mechanism.

The typical plasma particle energy impacting the wall is roughly between 300 eV and 1 keV. We reach this number by considering the case of a plasma comprising Xe^{10+} ions (the ionization state that contributes most strongly to 13.5-nm radiation) that expands adiabatically from an initial temperature of 30 eV without recombination. At asymptotic distances the electron kinetic energy is low and Xe ions carry the energy formerly stored by the electrons, totaling 300 eV. In practice, di-electronic recombination occurs very rapidly through many of the xenon ionization stages before the plasma has even doubled in diameter. As that occurs, the electron density is reduced, but the electron temperature tends to be raised. Highly excited ions produced in recombination further heat electrons via superelastic collisions, but most of this electron energy is then imparted to the ions as electron pressure drives the expansion. The net effect is for much of the xenon ionization energy (totaling 807 eV)¹ to be added into the radial kinetic energy and for the expected asymptotic ion energy range to lie roughly between 300 eV and 1 keV.

15.1.2 First wall

The temperature jump due to the combined effect of prompt radiation and plasma impact must not melt the first wall; otherwise small droplets of wall material can be ejected. The prompt radiation temperature jump is determined by distance from the hot plasma, the absorption depth in the wall, and the thermal constants of the wall material. We consider several wall materials interacting with either the xenon 10–15-nm band² or the tin 12–16-nm band.³ Typical metal wall materials are copper and tungsten, and insulators are pyrolytic boron nitride and silicon carbide (the latter is partially conductive).

As an example relevant to the Star Pinch with xenon operated at 10-J input, 2 J of radiation in the 10–15-nm band is incident in a 50-ns pulse on the nearest surface at 9 mm from the plasma. This surface, which is that of the central insulator, has temperature jumps of 450°C in pBN and 305°C in SiC. Typical operation in the future will be with 5-J input at distances in the range 12–15 mm, leading to much-lower surface heating transients due to radiation.

Results similar to those of Table 15.1 apply to the temperature jump due to delayed impact of plasma particles, because the particle absorption length of a few nanometers is very much less than the thermal diffusion length on the relevant time scale. The plasma motion in the Star Pinch is not isotropic, so it is more difficult to estimate the heat load on a particular surface region. As a first approximation, the duration of the plasma impact is roughly equal to the transit time from the plasma location to the wall, which varies between 500 ns and 2 μ s in the Star Pinch. If the expansion were to be assumed isotropic, a typical copper surface at 25 mm from the plasma would have 1- μ s exposure to the 8 J of residual plasma energy. Scaling from Table 15.1, the temperature jump is estimated to be only 22°C. In the equatorial direction, magnetic insulation reduces the intensity of the plasma impact by several times (evidenced by a reduced erosion rate, discussed below), so the equatorial insulator, at 9 mm, is estimated to respond to the 8-J plasma with a temperature jump of less than 100°C.

When a pulse of energetic exhaust ions strikes the first wall, there is heating, but also sputter erosion. There are many deleterious effects of sputter erosion: (1) changing the shape of the wall (in extreme cases breaking through to cooling channels); (2) evaporating (sputtering) wall material that can leave the source and reduce the reflectivity of the collection optics; (3) introducing new radiating species into the plasma that dissipate energy but may not contribute at 13.5 nm; (4) in the case of multilayer collector mirrors, eroding layers and reducing reflectivity; and (5) in the case of grazing-incidence collector optics, degrading the smoothness of the surface, reducing reflectivity. Sputter erosion is of equal concern in LPP and DPP sources, in each case being the main limiter of source life.

Drawing on experience from DPP sources, sputter erosion can be incorporated into a simple model for source life. Erosion is proportional to the number of ions in the plasma times the number of pulses, N . We estimate the number of ions in the expanding plasma based on the known initial gas density (considering xenon for

Table 15.1 Temperature jump ΔT at surface in response to a 100 mJ/cm², 50-ns radiation pulse at 13.5 nm. The surface temperature jump scales inversely as the square root of the pulse duration and linearly with the specific deposited energy.

Wall material	Cu	W	pBN (<i>a</i> axis)	SiC
13.5-nm absorption length (nm)	17	26	126	229
Thermal diffusivity α (cm ² s ⁻¹)	1.17	0.69	0.57	1.18
Characteristic diffusion length in 50 ns (μ m)	2.4	1.8	2.8	2.4
ΔT (°C) for 100 mJ cm ⁻² in 50 ns	98	153	228	156

now) and the estimated volume swept into the pinch. For a Star Pinch dissipating 10 J, the initial gas density is approximately 2×10^{15} atoms cm^{-3} and roughly 1 cm^3 is swept into the pinch, giving an estimated 2×10^{15} xenon ions in the pinch plasma. In order to scale the ion count to energies other than 10 J, we use data from earlier PLEX Corporation work on an inertial Z pinch,² in which all of the pinch gas is collected in the ingoing shock wave. We found that the amount of gas needed for optimum 13.5-nm emission was roughly proportional to the dissipated energy, the scaling being at constant drive-pulse duration. Although application of the same scaling to the Star Pinch is still speculative, we will make the approximation that the number of ions is proportional to the pulse energy. Comparison of the 807-eV energy needed to create the 10th ionization state of xenon¹ plus ion and electron energies of 11×40 eV, totaling 1.25 keV, with the 10-J energy dissipated shows that the maximum ion count could have been as high as 4×10^{16} , 20 times more than the actual ion count at this energy. We can introduce an ion utilization factor $U = 20$ and express the ion count as $C = (1/U) \times E/(1.25 \text{ keV})$.

In the case of isotropic plasma expansion, which is not always true for DPP as discussed below, the erosion δ of a surface at radius R from the plasma is $\delta = SNC/4\pi R^2$, where S is the volumetric sputter removal coefficient. Substituting for C and rearranging, the number of pulses to erode to depth δ is

$$N = 1.6 \times 10^4 \delta U R^2 / SE, \quad (15.1)$$

in which δ and R are in millimeters, E is in joules, and S is in cubic millimeters per coulomb (assumed singly charged ions).

Figure 15.1 shows N derived from this relationship for measured sputter coefficients S relevant to 300-eV singly charged xenon ions incident on either tungsten⁴ or pyrolytic boron nitride,⁵ both relatively resistant materials. The magnitude of the sputter erosion problem is apparent.

A component life in excess of 10^{10} pulses is required, but even at 100-mm distance from the plasma, without mitigation, the erosion approaches 1 mm after this exposure. Depending on the ion utilization factor for mass-limited LPP plasmas, sputter erosion can be just as severe for DPP plasmas. Figure 15.1 shows a Star Pinch data point for a surface at 9 mm from the plasma in an equatorial location relative to the pinch. The erosion rate in this direction is about 5 times less than we would expect for isotropic expansion, because there is effective magnetic insulation by the pinch magnetic field, which persists at a relatively high level during the initial plasma expansion. The ion stream is directed by the magnetic and electric fields toward the cathode end of the pinch in a beam of solid angle less than 1 sr. The distance to the nearest surface at the cathode end of the Star Pinch can be increased arbitrarily until erosion is not the life-limiting factor. The distance to the equatorially located insulator in the Star Pinch can be increased to at least 15 mm, and in the case of tin as the fuel, using an argon buffer, there can be less sputter erosion than for pure xenon, suggesting that 10^{10} pulses will be achievable in this device, as discussed in more detail below.

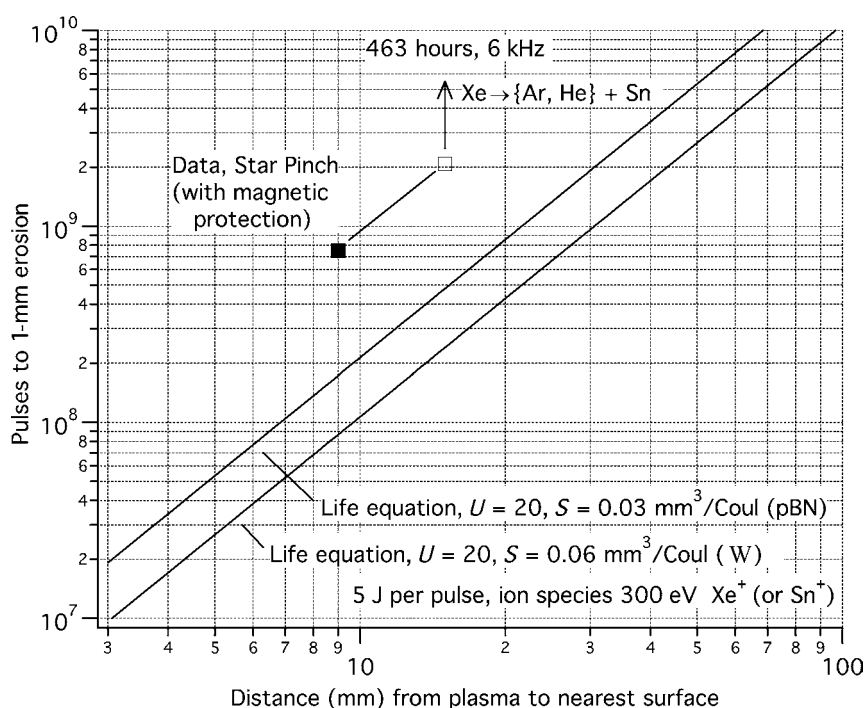


Figure 15.1 Sputter erosion scaling for 5-J pulse energy. The number of pulses to 1-mm erosion is displayed versus the distance of the eroded surface from the plasma. The Star Pinch data point is scaled to 5 J from the actual data at 10 J, doubling the number of pulses to 1-mm erosion.

15.1.3 Magnetic insulation

By definition, the magnetic field around the pinched plasma is sufficient to radially confine it at the relevant density and temperature for 13.5-nm emission. In fact, the peak azimuthal magnetic field is approximately 15 T in the Star Pinch. In addition, a very useful degree of radial confinement is available for several hundred nanoseconds after the peak-current moment (when 13.5-nm emission occurs), with the result that the early plasma expansion is directed more toward the poles than toward the equator. The effectiveness of this magnetic insulation is greatest when the duration of the current pulse, τ_I , exceeds the characteristic time τ_x for axial plasma expansion. For a plasma of charge state Z , ion mass m_i , temperature T , and axial dimension h , the expansion time is $\tau_x = h(m_i/ZT)^{1/2}$, which is of the order of 400 ns for typical Star Pinch conditions. The full duration of the current pulse is 600 ns, with 13.5-nm emission occurring halfway through, thereby providing 300 ns of insulation as the current and magnetic field decay. Magnetic insulation is not ideal in this case, but the erosion data show substantial anisotropy (further details discussed below). The initial axial expansion that occurs during the magnetic field pulse has the effect of lowering the plasma temperature, so that once radial expansion is free to occur, the resulting terminal radial ion velocity is less than

the axial ion velocity, leading to a lower sputter coefficient on equatorially located surfaces. Without either magnetic insulation or another form of plasma barrier, the life limit imposed by sputter erosion of first-wall components is very severe for both LPP and DPP sources. A magnetic field barrier of 0.6 T has been shown to be partially effective at slowing down the energetic ions from a laser-produced tin plasma.⁶

15.1.4 Discharge cathode

The geometry of the Star Pinch, described below, allows the discharge cathode to be located in a compartment outside of the first-wall enclosure, meaning that the cathode can be optimized, in terms of material and geometry, quite independently of the choice of first-wall material. Moreover, very little of the material that is inevitably sputtered from the cathode enters the first-wall enclosure, so that the load of unwanted material on the collection optic is reduced.

For different reasons, sputtering is also the life-limiting process in cathodes. The integrated discharge current in 10^{10} pulses at 25 kA, with 600-ns duration, is close to 10^8 C. Thermionic cathodes are not suited to the production of such high peak currents, and moreover would be susceptible to contamination in the relatively high-pressure source environment. In order to produce this large amount of charge we have chosen to use hollow cold cathodes, and moreover, many parallel cathodes with large total surface area. There has been focused investigation into the life of xenon hollow cathodes for use in ion thrusters for space propulsion, with a report of 1.2×10^9 C released from a xenon hollow cathode^{7,8} and the development of keeper electrodes to mitigate cathode orifice wear.⁹ Elements of this technology will be useful in the design of Star Pinch cathodes for industrial life. The geometry of a cathode successfully used in a 10^8 -pulse test of the Star Pinch is discussed below.

15.1.5 Gas barrier and collection optic

Although 13.5-nm multilayer mirrors (MLMs) facing the plasma have been used to collect light from an LPP source,¹⁰ the erosion rate due to xenon ion sputtering was fast,¹¹ and means to protect mirrors in this location have yet to be demonstrated. The ASML *alpha tool* lithography demonstrator uses grazing-incidence collection^{12,13} with surfaces such as ruthenium, of nanometer smoothness, exhibiting 60% reflection at grazing angles up to 22.5 deg. Because the grazing-incidence reflectivity drops precipitously with increasing incidence angle, the collection solid angle tends to be less than for MLMs, but a compensating advantage is that there is more space between the plasma and the collector for a gas buffer that completely brakes the plasma motion, preventing collector erosion, or even contamination. The operation of this barrier will be briefly discussed.

The barrier gas would probably be argon, because it has relatively low EUV absorption and yet sufficient mass to slow fast xenon or tin ions down within a few collisions. The elastic collision cross section at low energies is 2×10^{-14} cm², so

in principle a rather low density-pathlength product will provide these collisions. However, a separate criterion is that the gas barrier has to absorb the momentum of the energetic source particles without being accelerated into the collection optic. If we limit the averaged momentum transfer to the amount that will redirect an argon blanket with thermal velocity of 0.025 eV, then each xenon ion at 1 keV will need to have its momentum absorbed by 360 argon atoms. The barrier must be continually replaced at an argon flow rate correspondingly related to the number of xenon ions impinging on it, requiring a flow rate proportional to the source power. A rough estimate of the gas-barrier argon flow for a 5-J, 6-kHz xenon plasma is 2×10^{21} argon atoms per second.

15.2 Directed Discharges

A new approach to pinch discharges, the Star Pinch,¹⁴ was introduced in order to develop very high power DPP 13.5-nm sources with life exceeding 10^{10} pulses at 5-J dissipated energy. The two main problems that had to be overcome were first-wall temperature rise and first-wall sputter erosion, both of which mandated an increased distance between the plasma and the first wall. A third problem, that of cathode life, was solved in the process of solving the first two. A fourth problem, the need for volumetric ignition, was the key to taking the next step: toward directed discharges. Early in PLEX's development cycle on Z pinches it had been found that even with a symmetrically preionized cylindrical plasma² the distance of the first wall could not be increased much beyond 12 mm before the positional stability of the emitting plasma began to degrade. This was more related to spatial (azimuthal) inhomogeneity of the high-current plasma than to any nonuniformity of preionization. It was exacerbated by the need to evolve to lower-pulse-energy and higher-repetition-rate operation, when lower gas density became essential, and ignition began to be dominated by discharges feeding on the release of surface material rather than using gas available volumetrically. The state of the surface began to have a significant influence on the discharge azimuthal uniformity, and also on the 13.5-nm stability. Experiments then began with a type of discharge previously studied for possible use in high-current closing switches¹⁵ that had shown volumetric ignition at lower pressures than possible with the Z-pinch geometry.

15.2.1 Intrinsic properties of astron hollow-cathode discharge

The *astron* discharge, shown in Fig. 15.2, comprises multiple *pseudospark* discharge channels with through-cathode ion beams intersecting at a common central point. A feature of this compound discharge is that all channels light simultaneously at much lower gas pressure than any one channel would by itself. There is ignition reinforcement that depends on the discharge particles from every channel having access to the region of intersection. Completely altered characteristics, with high-voltage and higher-pressure ignition, are obtained when that location is filled

by a solid rod to prevent communication between the channels.¹⁵ This type of discharge (without the rod) satisfies the criterion for volumetric ignition at sufficiently low gas density to allow 13.5-nm emission from a low-energy (<10 -J) pinch.

A typical ignition characteristic is shown in Fig. 15.3. This curve was obtained with the inner electrode fed at -5 kV via a $300\text{-k}\Omega$ current-limiting resistor. The diameter of the inner electrode shell was 50 mm, and the separation between shells was 6 mm. Ignition extends down to 20 mTorr, whereas efficient 13.5-nm emission can be obtained in the range 40–100 mTorr in the related Star Pinch discharge discussed below. This 32-channel cooperative curve is in marked contrast to a single-

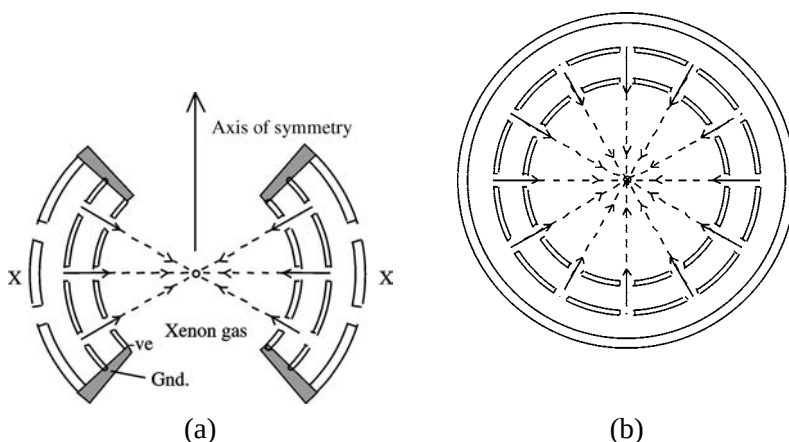


Figure 15.2 Schematic view of a multiple-channel hollow-cathode discharge: (a) vertical section showing negative inner shell with aligned channels; (b) transverse section X-X. The design shown has 36 intersecting discharge channels.

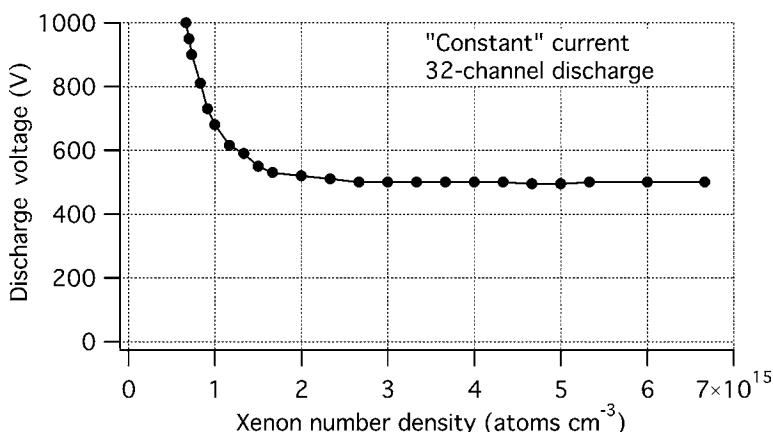


Figure 15.3 Voltage versus number density for an astron discharge fed by 5-kV supply in series with $300\text{-k}\Omega$ resistor. Typical current on flat part of characteristic is 15 mA.

channel reference curve,¹⁶ in which, for example, at a density of 2×10^{15} Xe atoms cm^{-3} , the breakdown voltage is approximately 7 kV.

15.2.2 Colliding-beam plasma source

Experiments were performed with a pulsed astron discharge to attempt to form a hot plasma at the intersection of the many through-cathode ion beams, which were known to be very intense in single pseudospark channels.^{17–19} The first necessity was simultaneous ignition of all channels, which was found to occur after minimal conditioning when the pulsed discharge was preceded by a dc discharge. It was estimated that the required ion count of $>10^{15}$ ions could not be delivered to the central location without substantial neutralization, either by resonant charge exchange or by copropagating electrons; otherwise a high positive potential would repel many of the ions. The resonant charge-exchange cross section is very large²⁰ and able to provide substantial neutralization at the xenon density of interest. Experiments with this colliding-neutral-beam device²¹ yielded a warm plasma that was not sufficiently hot and dense to yield 13.5-nm radiation from xenon. As a method to estimate the plasma conditions, an argon spectrum was analyzed in the 40–120-nm region, and ions up to Ar^{3+} contributed plentifully to the emitted radiation (Fig. 15.4). The plasma diameter was less than 3 mm, even although the nearest wall was 25 mm away. This prototype directed discharge led directly to the

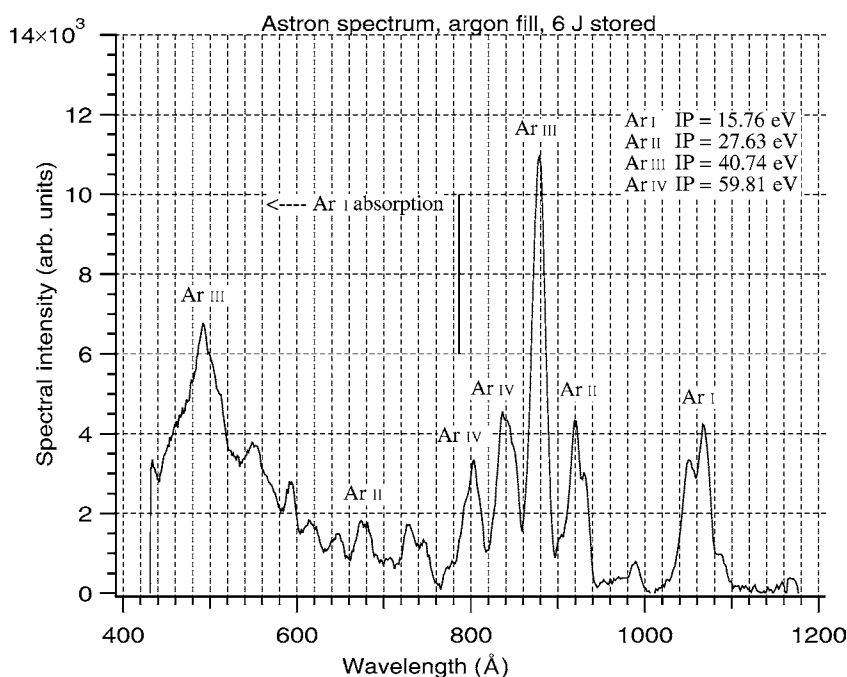


Figure 15.4 Spectrum of pulsed astron discharge of geometry shown in Fig. 15.2. The plasma diameter was less than 3 mm at 25 mm from the nearest solid surface.

development of the Star Pinch discharge, in which a heating pulse was introduced at the time the pulsed astron plasma had formed, to additionally pinch and heat the plasma to the temperature and density for 13.5-nm emission.^{22,23}

15.2.3 Star Pinch concept

An external electrode was employed in order to supply the required heating pulse to the astron, initially in the type of configuration shown in Fig. 15.5. The astron discharge of Fig. 15.2 is driven by the voltage V_1 , to be followed at an interval of approximately 3 μs by activation of the voltage V_2 , which drives a current of up to 25 kA between one of the internal shells and an external electrode. The resulting small central plasma is less than 1 mm in diameter and ranges between 2 and 4 mm in length (measurements given below).

15.2.4 Star Pinch with separate, distributed cathode

Many variations of the Star Pinch discharge have been explored, but one that we have found very suited to high-power, long-duration 13.5-nm generation is the relatively symmetrical arrangement shown in Fig. 15.6. In operation the top and bottom internal shells initially carry a common negative voltage relative to the anode and cathode rings (shown in cross section). The astron discharge locates a relatively low density and low temperature plasma at the center of the chamber. The cathode ring is then pulsed negative to the anode ring to establish a high-current discharge through the preformed astron plasma, heating it to produce 13.5-nm emission. The central insulator serves to aid rapid ignition and allows the amplitude of the heating current to be reduced. Its internal diameter can be increased to at least 30 mm without compromising the stability of the plasma. With development, the astron phase

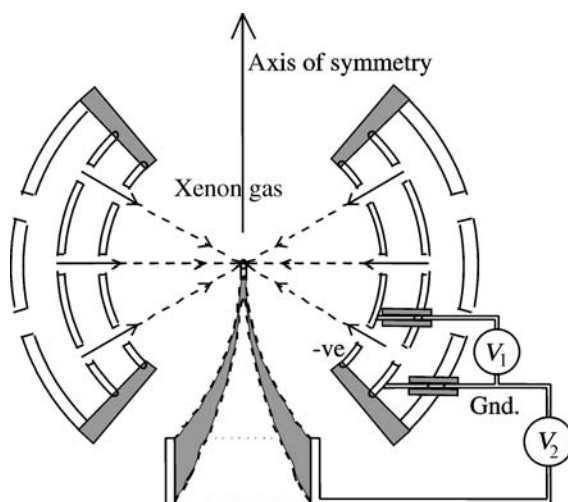


Figure 15.5 Prototypical Star Pinch discharge, showing a cylindrical external electrode driven by the voltage generator V_2 .

of the discharge has been reduced to consume only 5% of the energy input, the balance being supplied during the high-current heating pulse. The anode and cathode each operate with as much as 70 cm^2 of active surface, providing high power and long life capability. In particular, the cathode becomes a separated entity, not exposed directly to the radiation or plasma heat of the pinch, allowing specialized development for long life, with much flexibility in geometry.

The *beam dump* in Fig. 15.6 is a deeper part of the first wall that is designed to absorb the directed beam of ions that results from the combined action of magnetic insulation together with the anode-cathode driving potential of up to 1 kV that exists in the pinch. The surface area of the beam dump is increased by surface grooves so that heat is removed more rapidly from the plasma. The *foil comb* is a slotted structure that is very transparent to 13.5-nm radiation but presents a high impedance to the flow of xenon from the discharge chamber into the propagation space. In this design xenon is supplied to the chamber to maintain a pressure in the range of 40–100 mTorr, but the foil comb allows a pressure of 1–2 mTorr to exist in the propagation space, depending on the installed pumping speed, so that absorption of radiation is tolerable over propagation lengths up to 100 cm.

Typical waveforms are shown in Fig. 15.7. The pulsed 25-kA current is generated in a solid state switched modulator with magnetic compression. The top trace in that figure shows the recovery of 70% of the stored charge, representing 50% energy recovery in the modulator. The middle trace shows the 600-ns heating current pulse, with some ringing at late times on the diagnostic that does not represent plasma current. The bottom trace shows the time-integrated 13.5-nm signal. The

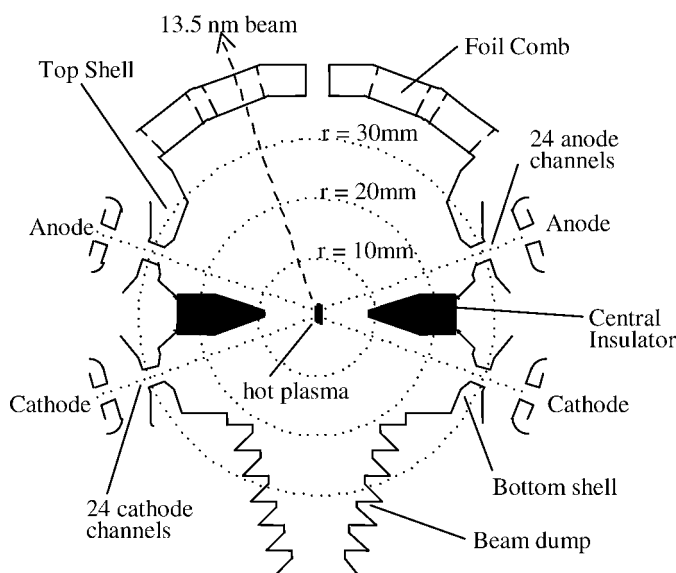


Figure 15.6 Star Pinch with heating pulse supplied between symmetrical anode and cathode rings (shown in cross section), each having 24 channels to carry the preionizing astron discharge.

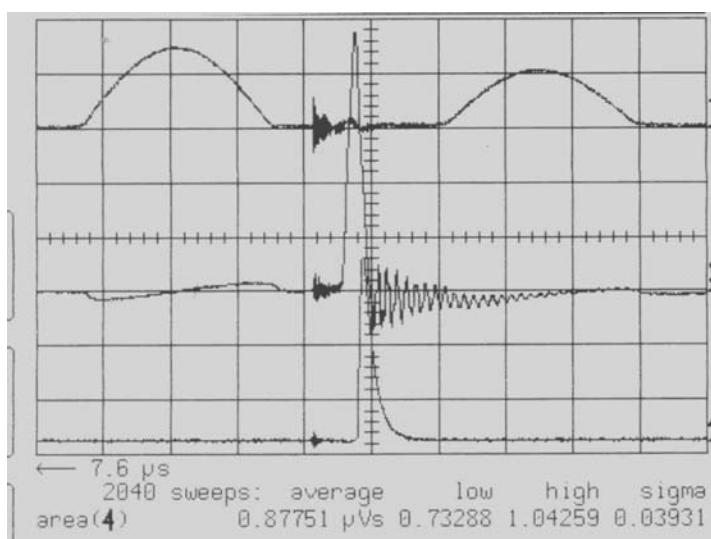


Figure 15.7 Pinch waveforms and 13.5-nm diode signal. Top trace: primary modulator current, outgoing and returning (2 μ s/div). Middle trace: current waveform in plasma load, amplitude 5 kA/div. Bottom trace: 13.5-nm diode signal integrated with 600-ns time constant.

emission begins just after the peak of the heating current, and closer inspection of the leading edge of the signal shows that the 13.5-nm radiation is emitted in approximately 50 ns, after which the charge slowly leaves the diode, with a 600-ns time constant.

A typical xenon spectrum at 0.14-nm resolution, optimized for 13.5-nm output, is shown in Fig. 15.8. The 2%-bandwidth fraction of the whole radiation band that is usable in an EUVL tool is only about 12%. When source power is quoted, it refers to the 2% fractional band centered on 13.5 nm. It is interesting to compare this spectrum with the optimized spectrum from a higher-energy 4-cm Z pinch,² which can be tuned to have 13.5 nm as the highest peak. In the latter case the axial plasma temperature distribution is believed to be very uniform, resulting in more exact tuning into the 10th xenon ionization state, which makes the dominant contribution to the 13.5-nm feature.²⁴

At a set peak current and stored energy the 13.5-nm signal can be optimized via variation of the xenon density, which effectively tunes the ionization state. Some data relating to this tuning are shown in Fig. 15.9, where the repetition frequency is varied. It is expected that the optimum xenon density should be the same at each repetition rate. The differences in optimum flow relate to changes in the exit flow rate of xenon, which, at constant density, should be proportional to the square root of the gas temperature at the foil-comb location. The average gas temperature may have increased to approximately 1000°C at 2 kHz, according to this interpretation. The plasma power at 2 kHz is 20 kW. Although the chamber has a large internal surface area (165 cm²), these data suggest that even larger internal surface area will be desirable at the 30-kW power estimated for high-volume manufacturing (HVM) with tin in an argon buffer, discussed below.

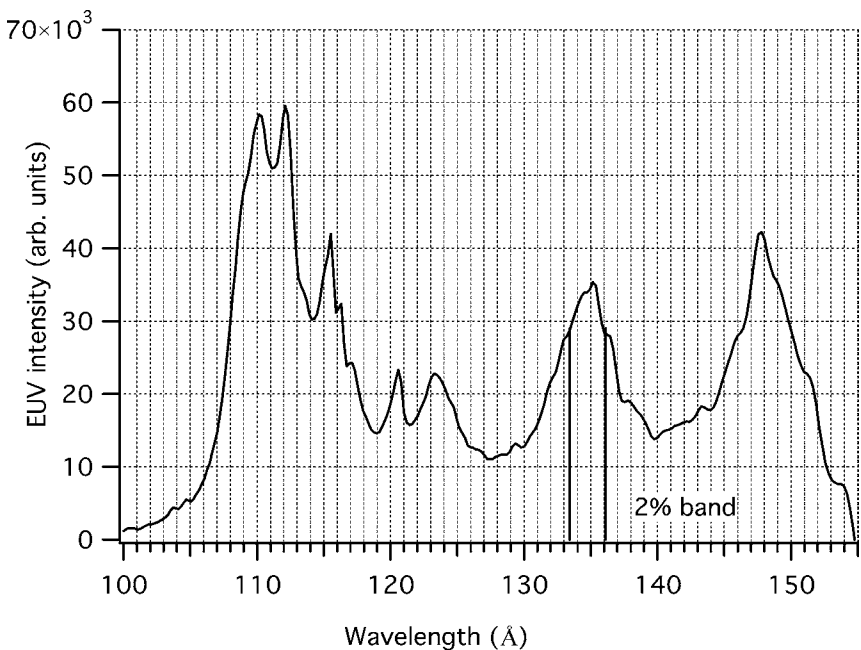


Figure 15.8 Spectrum from Star Pinch with xenon, optimized for 13.5-nm output.

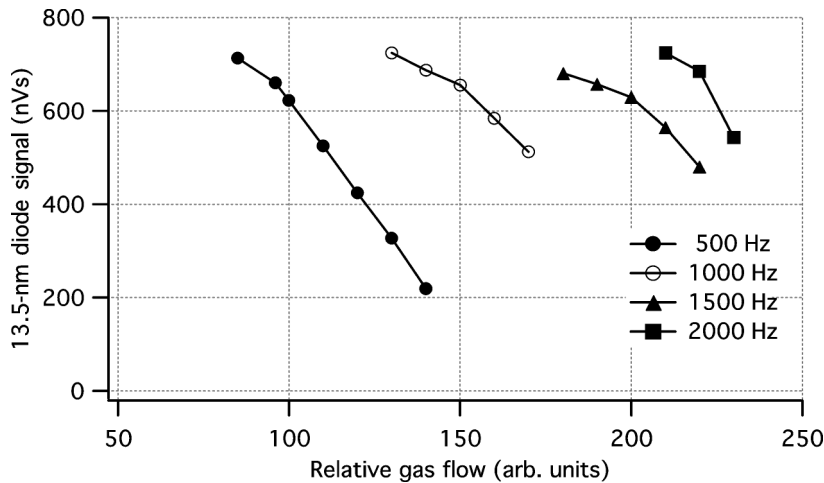


Figure 15.9 Optimization of 13.5-nm signal with gas flow rate as a function of repetition frequency.

15.3 Current Star Pinch Performance

The following data, coming from tests in early 2004, represent an intermediate stage in the development of this source, the ultimate limits of which are discussed in Sec. 15.4.1 below. A comprehensive measurement set was taken on the Star Pinch in December 2003 by the Flying Circus standards team and has been pub-

lished as a report by International SEMATECH.²⁵ Included in that report are many parameters not mentioned below, such as the angular distribution of radiation (close to isotropic) and out-of-band radiation in the DUV, visible, and IR.

15.3.1 EUV power and efficiency

As of early 2004, the Star Pinch repetition frequency had been scaled to 2 kHz at a dissipated energy of 10 J, corresponding to a power of 20 kW deposited into the plasma. This level of power could be maintained for several seconds, and 10 kW could be maintained continuously until parts of the adjacent uncooled vacuum chamber became too warm after approximately 10 minutes, with outgassing and some degradation of 13.5-nm output due to dilution of the xenon fuel. Continuous operation at 500 Hz, or 5 kW, could be maintained for hours. These limits only represented the current state of system engineering design and were not due to fundamental plasma-chamber problems such as surface melting. The hottest surface in the present design, the inside of the central insulator, is estimated to have an average wall temperature of 660°C and a maximum transient wall temperature of only 810°C at 20-kW input.

The distribution of power within the Star Pinch was measured by calorimetry. Running steadily at 300 Hz, with 25 J stored and 10 J recovered (40%), the flow rate and temperature rise in the different cooling systems were measured. With reference to Fig. 15.6, the heat removed was as shown in Table 15.2.

In extensive work at 2 kHz, after many runs in which the surfaces were able to outgas, an energy of 8 mJ/sr per pulse was seen, representing 0.40% conversion efficiency (CE) into 2π sr and 2% bandwidth. If the electrode heat losses are extracted (13.7% of total), an intrinsic efficiency of 0.47% is seen. Similar numbers are documented in Ref. 25. The pulse-to-pulse amplitude stability was in the range of 5%–10% (1σ), and the start-up transient comprised three or four subaverage pulses before the average output became established. The main reason for this slight delay is the response of the xenon density to the step in chamber wall temperature as repetitive pulsing begins. In order to have the correct density at the higher operating wall temperature there must be excess density when the walls are cool, leading to lower plasma temperature and less 13.5-nm output in the first few pulses. The inband 13.5-nm power in 2π sr was 100 W.

Table 15.2 Power measured in Star Pinch components at 300 Hz with 12.5-J total dissipation in the device and 2.5 J lost in the modulator (not registered in this measurement).

Cooling circuit	Power (W)	Percentage
Cathode	299	8.0%
Anode	212	5.7%
Foil comb	502	13.4%
Main chamber	2731	72.9%
Total	3744	100%

15.3.2 Plasma size and stability

Plasma size and positional stability are very important parameters entering into the usable source etendue that determines what fraction of the 13.5-nm energy measured from the whole plasma can be used in the illuminator optic and projection optic of the scanner. We have used a 13.5-nm imaging tube²⁶ that reimages at 1:1 magnification, via two reflections off 13.5-nm mirrors, onto a Ce-doped YAG crystal. The crystal is in the form of a 15-mm-diameter, 0.5-mm-thick disk with a 200-nm overcoating of Zr on the incident face to block visible light. This crystal is an efficient fluorescer,²⁷ giving a yellowish-green fluorescence that allows real-time plasma observation at 13.5 nm, a feature that has proved extremely useful in the development process. We usually observe the plasma at 40 deg to the axis so as to obtain both length and diameter information from one measurement. Typical views of the plasma at 1.0, 1.5, and 2.0 kHz are shown in Fig. 15.10. The dark central disk is the outline of the Zr coating, which is 14.5 mm in diameter. Each image in Fig. 15.10 was exposed for $\frac{1}{4}$ s, resulting in the superposition of 250, 375, and 500 pulses.

This set of images had the plasma dimensions shown in Table 15.3, as measured in 13.5-nm emission.

An improved design has an axial length of 4.0 mm at full power and 2.0 mm at half power. It is found that increasing the xenon density above the optimum for 13.5-nm emission reduces the plasma length significantly, but at the cost of a

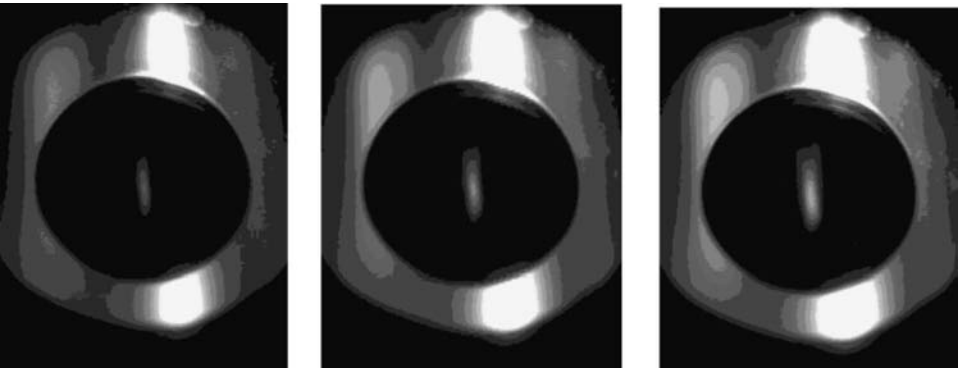


Figure 15.10 Images of xenon Star Pinch plasma at 40 deg in fluorescence from 13.5-nm light. Left to right, 1.0, 1.5, and 2.0 kHz at 0.25-s exposure in each case.

Table 15.3 Measurements of plasma size in xenon 13.5-nm emission.

Repetition rate (kHz)	Diameter (μm , FWHM)	Apparent length (mm, FWHM)	True axial length (mm, FWHM)
1.0	650	2.9	4.1
1.5	780	3.1	4.4
2.0	850	3.5	4.9

proportional reduction in 13.5-nm output. The plasma transverse stability is of the order of 50 μm (1σ) when successive images are measured. This is to be compared with the 25-mm length by which the directed-discharge plasma is separated from the electrodes supporting that discharge, and the 9 mm (in these data) from the plasma to the central insulator. The original choice of 25-mm standoff for the directed discharge was dictated by an estimate of the distance required for discharge powers in the range of 50–100 kW and life greater than 10^9 pulses. It seems possible that much greater standoff distances will be achieved in the future.

15.3.3 Life testing

It is expected that the sputter erosion rates estimated in Fig. 15.1 will apply to both DPPs and mass-limited LPPs. In our DPP xenon work we estimated 2.5×10^{14} xenon ions per joule (see above), and in a mass-limited tin-containing LPP target²⁸ the tin complement was 5×10^{13} ions per joule in a situation where the optimum appeared to be higher than this, possibly in the range of 10^{14} ions per joule. Both approaches have comparable ion loads and need to minimize sputtering of structures near to the plasma.

An 80-million-pulse life test, at 10 J per pulse and 500 Hz, has been performed with the Star Pinch in order to measure erosion rates. At the end of this test there was minor erosion (390 μm) of the innermost surface of the silicon carbide central insulator (9 mm from the plasma) and somewhat more erosion of the cathode, particularly at the entrances of the hollow-cathode cups, which had enlarged from an initial diameter of 2.5 mm to a new diameter of 3.4 mm. These entrances faced holes of 3.2-mm diameter in the bottom shell (Fig. 15.6), and it is possible that the cathode-directed ions during the high-current pulse were channeled through the bottom shell in beamlets of this diameter that caused the erosion. The bottom shell itself had negligible erosion, likewise the top shell. The beam dump, which was of copper in this experiment, showed 300 μm of erosion in the central 5 mm, where the magnetic field of the pinch had directed the most intense ion flux. There is nothing to prevent relocation of this surface to a greater distance than the 45 mm of this experiment, and/or replacement with a lower-sputter material. The largest amount of eroded material, that from the cathode entrances, had all deposited on nearby surfaces of the cathode structure and the outside-facing surface of the bottom shell, with apparently no significant amount entering the discharge chamber itself. Copper sputtered from the beam dump had mostly redeposited higher on the beam-dump wall, with some vapor possibly escaping from the chamber together with the flow of xenon. The sputtered silicon carbide insulator material had darkened the inside of the top shell. There was no change to the anode, which looked pristine after 80 million pulses. A strictly unipolar current flow was ensured by the final magnetic core of the pulser, and this prevented cathode-type erosion from occurring in the anode.

At the 80-million-pulse point in the life test the 13.5-nm emission intensity was unchanged, and plasma size, shape, position, and positional stability were all unchanged as well.

At this point the design under test is estimated to have a more than 500-million-pulse life, when the dissipated energy is scaled from 10 J down to the 5 J energy that we believe will be used in HVM (discussed below). Beyond this, solutions to all of the present erosion hot spots are available, including operation of the plasma more than 9 mm from the central insulator, lengthening the current pulse to maintain magnetic insulation further into the plasma expansion, resizing the cathode cavities, and, finally, the use of argon or helium as a buffer gas, with reduced sputtering, when tin replaces xenon as the working fuel. These scaling directions are illustrated in Fig. 15.1.

15.3.4 Alternative fuels

Xenon gas has been shown to have 0.5%–1.0% efficiency in discharge excitation. Other substances, including tin and indium, have transition arrays with higher efficiency than xenon in the 13.5–14.5-nm band.^{3,29} The estimated plasma temperature for optimum emission is close to 30 eV in the case of both xenon and tin. Both tin and indium are low-melting-point metals (232°C and 157°C, respectively) with very low vapor pressure at or near to room temperature, so new techniques have to be used to create the required vapor density of these fuels in the Star Pinch. Several approaches that have been considered include:

1. Heating the whole discharge apparatus to $>1200^{\circ}\text{C}$ to achieve the desired vapor density. The technical difficulties are extreme, not least being the need for a low-inductance, high-current electrical feed connecting the pulsed power source with the discharge electrodes.
2. Introduction of tin as a gas in the form of stannane (SnH_4). The gas decomposes at room temperature, so it is difficult to supply. If stannane were fed into a high-power discharge, the intense UV light of the discharge would very rapidly decompose it, depositing tin near to the entry point. A by-product of the use of stannane is hydrogen, which must be handled carefully.
3. Operation of the Star Pinch with a buffer gas and placement of a solid tin target at the beam-dump location in order to sputter the required amount of tin into the vapor phase. In preparation for this experiment, xenon was studied in a helium buffer gas and shown to emit efficiently at 13.5 nm down to a concentration of 5% (Fig. 15.11). The tin sputter source was successfully attempted by PLEX, but the desired lighter buffer gases, argon and helium, did not sputter at a high enough rate to reach the desired tin density. Xenon was more successful as a sputter source gas, with up to 44% enhancement of the 13.5-nm intensity compared to the xenon case without tin. But several drawbacks were evident. There was a delay of several seconds until the tin vapor reached an equilibrium density, making the use of intermittent 13.5-nm exposure inefficient. The tin migrated away from the center of the beam-dump surface after a half hour of operation at 500 Hz and 1 kHz, implying that a continually refreshed tin surface would be necessary at the

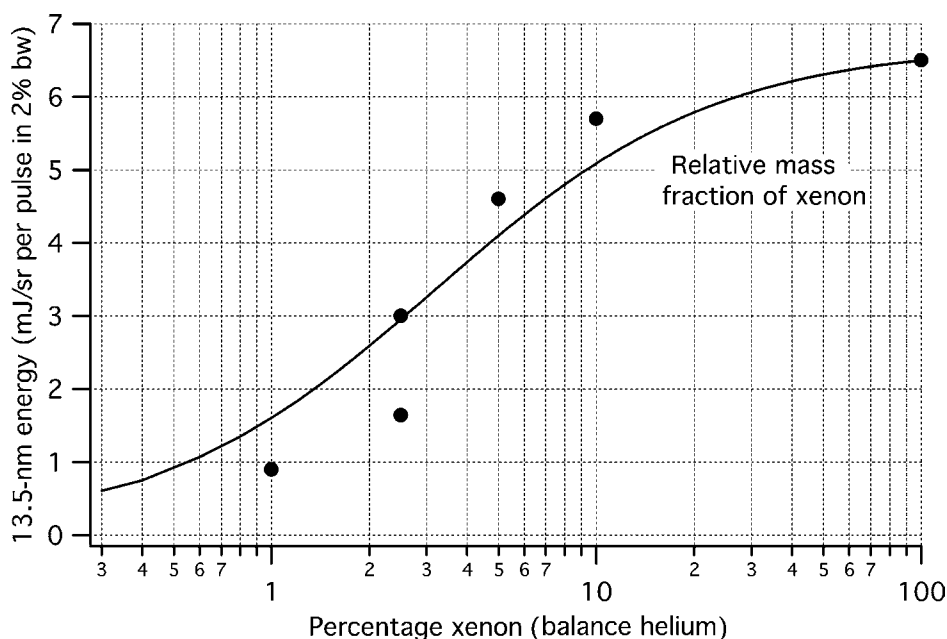


Figure 15.11 Dependence of optimized 13.5-nm output on fraction of xenon in helium buffer, 10 J dissipated. Solid line is relative mass fraction of xenon in the mixture.

sputter location. It was estimated that once the beam-dump surface had been moved close enough to the plasma to obtain a high enough sputtering rate with the lighter buffer gases, the heat load would be difficult to handle.

4. Location of a hot tin vapor generator in a stream of entering buffer gas. This is a continual tin source that would create a greater tin disposal problem than otherwise. Additionally, the plasma dimension would be expected to be comparable to that for xenon in a buffer gas (for example, 5% Xe in He), which we have measured to be similar to that for pure xenon, and too large to be collected within the scanner etendue.
5. An approach that has been explored by others is production of tin vapor by laser pulse evaporation from a solid tin surface,³⁰ but a disadvantage seems to be that the discharge tends to be close to the surface and the resulting intense surface temperature jump can melt the tin surface, with ejection of more tin than desired.

The method we have explored in the most detail is injection of small tin droplets into the Star Pinch while it is running on a low-Z buffer gas.³¹ The advantages are:

1. The tin target is mass-limited, just as for the LPP concept.²⁸
2. With on-demand injection, the use of tin is minimized and the correct number of tin atoms is available on the first pulse of a pulse burst.
3. The tin fuel is located initially within a droplet of approximately 40- μm diameter, and there is not much time for expansion during the 100-ns hottest

phase of the pinch when evaporation and ionization occurs. The resulting 13.5-nm emission volume is expected to be rather small,³² between that for an LPP source and a small pinch discharge.

4. A theoretical advantage of the more gentle heating than in the LPP case is the possible avoidance of breakup of the tin droplets in a laser-induced shock, which can generate small tin particles.
5. If the placing of tin droplets can be precise, there will be a degree of positional stabilization of the emitting region, which might make it more stable than the 50- μm measured stability of the xenon plasma.
6. Introduction of tin at the precise central location will make its subsequent migration more predictable. It is expected to be mostly ejected toward the beam-dump location, where it can be condensed and removed as a liquid.

In Ref. 32 we have discussed the rate of heat flow from a pinch discharge into a small metal droplet and conclude that heat fluxes of the order of 10^9 W cm^{-2} exist for 100 ns in the Star Pinch, sufficient to ionize a 30- μm -diameter tin droplet into the 7+ to 12+ charge states that radiate at 13.5 nm. The tin plasma when it reaches these states is estimated to be 600 μm in diameter.

15.4 Scaling to High-Volume Manufacturing

Although a Star Pinch discharge in lithium vapor has now become the focus of our efforts, one route to a 13.5-nm source with more than 100 W of usable power appears to us to lie in the use of the Star Pinch with argon or helium as the buffer gas and tin injected to the central location as a mass-limited droplet prior to the heating pulse of the discharge. We now estimate the ultimate limits on EUV life and power for this concept.

15.4.1 Ultimate limits on life and power

The distance from the hot plasma to the beam dump at the cathode end of the Star Pinch can be increased arbitrarily until erosion of that surface is not a life-limiting factor. The combined internal surface area of the hollow cathode can be substantially increased above its current 70 cm^2 by making the cathode cavities deeper, and details of the cathode entrance design can be improved by field shaping so as to minimize the entrance erosion experienced in the long-duration test. The parallel nature of the cathode effectively multiplexes the current without the need for moving parts. The anode shows negligible erosion at 10^8 pulses, and may extend to the 10^{10} -pulse range without further improvement. The distance to the equatorially located insulator in the Star Pinch can be increased to at least 15 mm from the 9 mm used in the long-duration testing that is discussed above. This will increase the central insulator life to the 2×10^9 pulse level (5-J pulses), assuming inverse-square-law scaling. Improved magnetic insulation, with a longer current

pulse, may be able to contribute another factor of 2 in protection. Finally, the replacement of xenon by argon or helium as the primary discharge gas will reduce the sputter erosion rates by another factor, which could be several times in the case of helium, leading to a likely 10^{10} pulse life for the central insulator and cathode.

The use of tin brings additional complexity to the evaluation of system life. One necessary condition for long life with tin is the absence of systematic deposition at any place within the structure except the beam dump. Much of the first wall is kept clean by sputtering. For example, when using tin in the xenon sputter source, we observed that the central insulator was constantly cleaned of tin by discharge sputtering, so its insulating function was not compromised.

EUV power, or more precisely, plasma power, is limited by the peak surface temperature, which must be somewhat below the surface melting point for every component of the first wall. It is readily shown that the most critical heat load in the Star Pinch is on the inside wall of the central insulator. Although our current design will remove 640 W cm^{-2} from this wall at an average surface temperature of 700°C , future improvements to handle 1 kW cm^{-2} are possible. Moreover, the surface can be located up to at least 15 mm from the plasma. If the plasma power flow is assumed isotropic, the figure of 1 kW cm^{-2} at 15 mm corresponds to a plasma power of 28 kW. Magnetic insulation will protect the insulator and extend the upper limit on plasma power to at least 60 kW.

Repetition rates up to 2 kHz have been demonstrated in the Star Pinch without any loss of efficiency. Further repetition-rate scaling, possibly to 6 kHz, is required to satisfy dose uniformity criteria in lithography. We believe that the scale of the individual pseudospark channels sets the recovery time for the device. Unlike the single-channel triggered hollow-cathode Z pinch, which has a recovery time determined by ambipolar diffusion of the plasma to the cathode walls,³³ the Star Pinch does not need to recover full voltage holdoff between pulses. However, it is conjectured that partial holdoff is required in order to accelerate ions toward the center during the predischARGE. The same basic physics should therefore apply to the Star Pinch recovery time, and by analogy a repetition rate of the order of 10 kHz would be achievable. When lighter buffer gases are used with tin injection, the channel recovery should be faster than this. In this case, the velocity of tin injection may become relevant, depending on the survivability, as they approach the central location, of tin droplets in the plasma exhaust from previous pulses. This problem is fairly similar to that in the case of an LPP mass-limited tin target, and will be the subject of further study.

Table 15.4 summarizes the present and likely future EUV power using xenon and tin in the Star Pinch. The two most significant improvements of tin over xenon relate to efficiency and etendue match. It is assumed that the tin droplet plasma will be less than 1 mm in length.

More recently, on-demand Sn droplet generation has been found to be intrinsically unreliable when droplets as small as $30 \text{ }\mu\text{m}$ are generated.³⁴ Star Pinch development is currently focused on operation with lithium vapor.³⁵

Table 15.4 Present and projected 13.5-nm power from the Star Pinch. The tin projection is for injection of tin droplets into the Star Pinch.³²

	Present Xe	Ultimate Xe	Ultimate Sn
Input power (kW)	20	60	60
CE (%)	0.5	0.9	2.5
13-nm power at source (W)	100 (2π sr)	540	1500
Collection solid angle (sr)	2	3.14	3.14
Etendue match (%)	40	50	100
Optical transmission to intermediate focus (%)	40	40	40
Power at IF (W)	5	54	300

15.4.2 Cost of ownership

This breaks down into capital and running costs. The pulsed power and discharge chamber are not much more complex than for excimer laser DUV sources. Additional components such as a tin injector and gas buffer system are probably going to be required. Not considering replacement of condenser optics, the achievement of a 10^{10} -pulse life in discharge components would translate into about two months of HVM operation before the plasma head would need refurbishment. Plasma-head components and other items such as vacuum pumps would entail approximately \$90,000 (U.S.) per year of upkeep. The source system capital cost would be in the range of \$1.5 million.

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Chapter 16

Xenon and Tin Pinch Discharge Sources

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16.1 Introduction

This chapter discusses the results of investigations of DPP sources for EUVL based on the pinch effect in Xe and Sn vapor. In the SRC RF TRINITI (formerly a branch of the Kurchatov Institute of Atomic Energy) in the Moscow region of Russia,

these investigations have been carried out since 1999. Up to that time the institute had already had experience in the development of high-power single-pulse radiation sources based on the pinch effect and capable of producing EUV power of $\approx 5 \times 10^{12}$ W,¹ and also in the study of pulse power systems used for high-repetition-rate (≈ 6 kHz) excimer lasers.² The part of this work devoted to the creation of EUV sources was supported by XTREME technologies GmbH.

The analysis of the discharge configurations that permit the plasma to be heated up to the temperatures (about 30 eV) required to emit EUV radiation around 13.5 nm has resulted in our choice of such known discharge configurations as the classical Z pinch³ and the dynamic (or spouting) pinch.⁴ These configurations permitted removing a high-temperature plasma area from the electrode and dielectric surfaces and thereby reducing plasma-surface interactions. However, in such configurations a small size (~ 1 mm) of plasma pinch radiating in the EUV range is needed. Started from large-size plasma pinches of 20-mm length and 1-mm diameter,^{5,6} we then matched the pinch size and the emission angle^{7,8} to the requirements of a high-volume manufacturing (HVM) lithography tool.⁹

In this chapter the characteristics of DPP sources with different electrode configurations using Xe or Sn are described. The concepts of the rotating multidischarge unit (RMDU) source using Xe or Sn and the rotating-disk electrode (RDE) source using Sn, which allow significant reduction of the heat load on electrodes, are discussed.

16.2 Pinch Effect

The pinch effect arises from compression of a previously created plasma by the magnetic field of its own current. The phenomenon of plasma compression was first described in 1934 by W. H. Bennett.¹⁰ The mechanism and characteristic features of a pinch effect can be usefully considered using the examples of the classical Z pinch (Fig. 16.1) and the spouting pinch (Fig. 16.2). In the classical Z pinch the current flows along the Z axis of a cylindrical plasma volume. The lines of force of the magnetic field **B** created by the current look like concentric circles arranged on planes perpendicular to the Z axis. The resulting electrodynamic force **F** acting on a unit gas volume with a current density **j** is equal to $c^{-1} \mathbf{j} \cdot \mathbf{B}$, where c is the light velocity. **F** is directed inward along the radius to the cylinder axis and causes compression of the current channel. The magnetic compression of the plasma is counteracted by the gas-kinetic pressure of the plasma. At equilibrium the moving boundary of the pinch is a surface of equal pressure. From this condition the so-called *Bennett equilibrium* follows: $B^2/8\pi = 2nkT$, where T is the plasma temperature and n is the gas concentration. However such a mechanism of pseudo-steady compression contradicts the experimental data, and the model offered by Leontovich and Osovets¹¹ is more correct. In accordance with this model, after the breakdown of an electrode gap the discharge is displaced to the walls of the insulator due to the skin effect, after which the surface plasma layer, under the

action of electrodynamic forces, is accelerated toward the axis. The equation of motion during the initial phase of compression is thus

$$\frac{d}{dt} \left[\left(1 - \frac{r^2}{r_0^2} \right) \frac{dr}{dt} \right] = - \frac{I^2(t)}{c^2 M r}, \quad (16.1)$$

where r and r_0 are the present and initial radii of the plasma layer, respectively, $M = \pi r^2 \rho$ is the mass of gas per unit length, and ρ is the gas density. In this model the inertial forces are taken into account, and it is assumed that during the whole compression there is no equality of magnetic and gas-kinetic pressure. The model allows one to calculate the time of compression, which agrees well with experimental data, including the data obtained for our experimental conditions. However, even such a description, considered within the framework of magnetohydrodynamics (MHD), is rather simplified and cannot explain repeated compression processes in a plasma pinch or various plasma instabilities that may arise.

The intensive investigation of high-power installations on the basis of the pinch effect began in the 1950s within the framework of controlled-fusion programs.³ The initial investigations at Kurchatov Institute of Atomic Energy were based on electrode systems similar to that shown in Fig. 16.1. The anode and the cathode are insulated from each other by the ceramic tube with diameter D . The low-inductance capacitor battery was connected to electrodes separated by a distance L . Z-pinch configurations with dimensions L and D up to several tens of

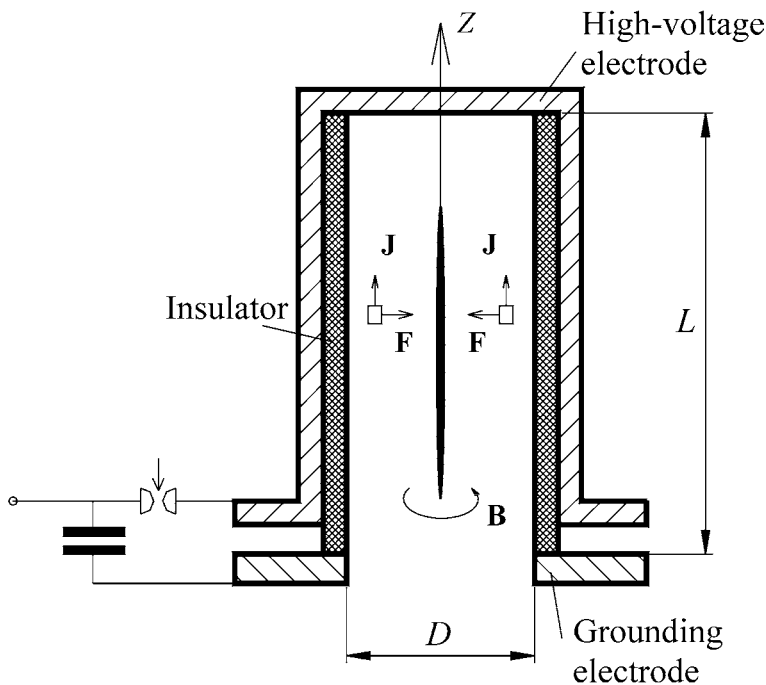


Figure 16.1 Schematic drawing of the Z-pinch discharge.

centimeters were investigated. The energy stored in the capacitor battery could reach about 10^6 J, so through the gas at pressures of 10^{-3} – 10^{-4} Torr a current of 10^4 – 10^6 A was obtained. Researchers who were trying to obtain neutrons from Z-pinch plasmas registered the compression of the plasma toward the cylinder axis during the first phase of the discharge. Then they registered the development of plasma instabilities in the current channel. Plasma instabilities limited the lifetime of the high-temperature plasma volume, and that was one reason amongst others why the attempts to obtain a thermonuclear effect in a Z-pinch plasma were unsuccessful.³

The more stable spouting pinch was obtained in Ref. 4. As shown in Fig. 16.2, the ring electrodes connected to the capacitor battery were separated by a ceramic disk with a central hole. The discharge volume was isolated from the external atmosphere by two glass caps. When a 130- μ F capacitor battery charged up to 20 kV was switched onto the ring electrode, the spouting pinch was observed as shown schematically in Fig. 16.2. Investigation of the discharge dynamics⁴ has shown that a bright central current cord (pinch) moves behind the plasma front with a speed of $\approx 3.3 \times 10^6$ cm/s. The pinch closes the electrodes through a coaxial plasma shell. In the experiments,⁴ the pinch, with a diameter of ≈ 2 cm and a length of ≈ 65 cm, was stable without any necks during the few microseconds of the first half period of the discharge current. No measurements of EUV radiation were made in Ref. 4; nevertheless, the form and features of the spouting pinch have brought us to a better understanding of plasma pinch dynamics and also to the development of the new discharge configuration described in Sec. 16.4.1.

The most attractive works dealing with the classic Z pinch as a source for EUVL are McGeoch's investigations. He reduced the energy dissipated in the dis-

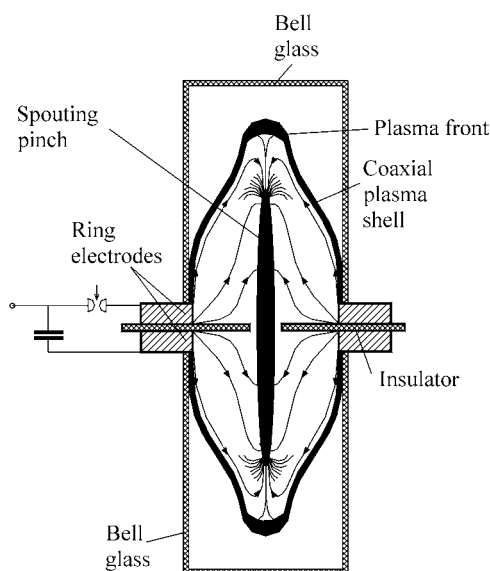


Figure 16.2 Schematic drawing of spouting pinch discharge.

charge while keeping the initial plasma uniformity by the use of radio-frequency preionization.¹² For an electrode system similar to the ones shown in Fig. 16.1, McGeoch used a ceramic tube with $D = 25$ mm and $L = 40$ mm. At a stored energy of about 240 J the brightness of the source was found to be $9.4 \text{ J sr}^{-1} \text{ cm}^2$ per pulse.

In the present day the pinch effect is widely used for the development of DPP sources with different electrode configurations, such as the noncylindrical configuration of the Z pinch, or *dense plasma focus* (DPF),¹³ the hollow-cathode triggered Z pinch (HCT-Z),¹⁴ the capillary Z pinch,^{15,16} and the Star Pinch.¹⁷

16.3 EUV Source Using Xe

16.3.1 Optimization and performance

We take into account the fact that in accordance with the HVM lithography tool requirements the pulse repetition rate of the EUV source should be 7–10 kHz, so the energy dissipated in the discharge (E_d) should be not too high (~ 10 J). The first step of our research, with the use of configurations similar to the ones in Figs. 16.1 and 16.2, was to understand how the reduction of E_d would affect the conversion efficiency (CE). The study of EUV energy as a function of E_d for the electrode configuration as shown in Fig. 16.1, with L ranging from 28 to 2 mm and D from 16 to 8 mm, have shown that the Z-pinch plasma can effectively radiate around 13.5 nm with E_d of about 5–10 J, depending on D and L .

It is known that ideally EUV radiation should be isotropic in a solid angle of $\approx 1.8 \text{ sr}$.⁹ Our measurements of the angular distribution of EUV radiation from a Z-pinch plasma for different electrode distances L ($D = 9$ mm, $E_d = 10$ J) have demonstrated⁶ that the EUV radiation becomes more isotropic with reduction of L . However, in the process of decreasing L it is more difficult to match the pulsed power system with the discharge load. Our experiments have shown^{5,6} that for $L > 13$ mm the pulsed power system is well matched to the discharge load ($E_d/E > 86\%$). When L was decreased, E_d/E was decreased also; for example, we found $E_d/E = 45\%$ for $L = 2$ mm.

Schematically, one of the electrode configurations with $L = 4$ mm is shown in Fig. 16.3. In order to create uniform plasma we have proposed¹⁸ and implemented^{5–8,19–22} preionization by an auxiliary creeping discharge. Preionization leads to the ignition of a uniform discharge in the main discharge gap, repeatability of EUV energy, and increased CE. The pulsed power system included two stages of magnetic compression and allowed variation of the stored energy from 10 J up to 30 J. The highest voltage (≈ 6 kV) was used for ignition of the auxiliary creeping discharge. Such preionization provides lower voltages (< 4 kV) in the main discharge gap. It reduces the electrical loads on the ceramic insulator separating the cathode and the anode, and it magnifies the lifetime of the EUV source. With stored energy of ≈ 20 J, the pulsed power system provided a discharge current with an amplitude of ≈ 50 kA. The appearance of EUV radiation correlated with the timing of a dip

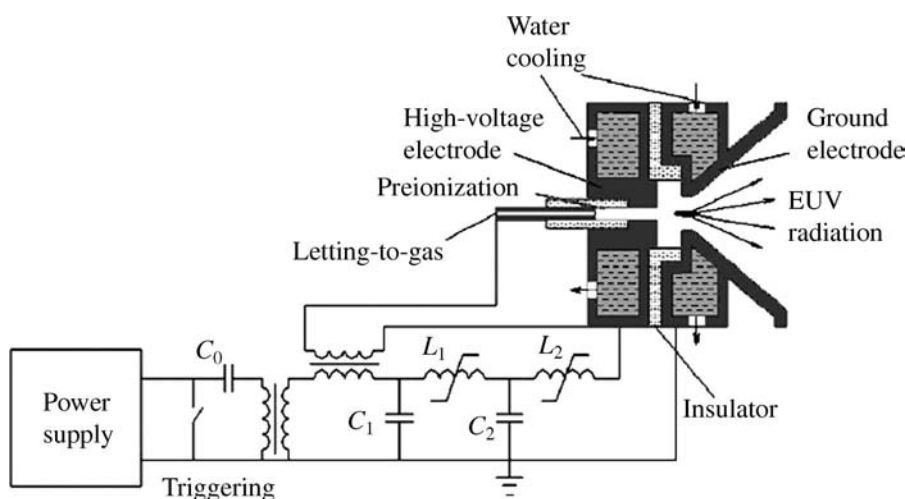


Figure 16.3 Schematic of the Z-pinch DPP EUV source.

in the discharge current oscillogram. The duration of EUV radiation (FWHM) was about 40 ns.

The inband EUV energy per pulse was measured using a calibrated diagnostic device equipped with Mo-Si multilayer mirrors (MLMs) and a photodiode (IRD Inc. AXUV-100G) produced by XTREME technologies.

16.3.2 EUV power and conversion efficiency

Figure 16.4 shows the dependences of the inband EUV power (in 2% bandwidth at 13.5 nm into a solid angle of 2π sr) on the pulse repetition rate. Curves 1 and 2 were obtained when the measuring device was placed at distances H from the pinch of 1.2 and 0.80 m, respectively. Curve 3 was obtained when EUV radiation on its way from the pinch to the measuring device passed a distance $H = 0.2$ m through Xe gas filling the main chamber and $H = 0.6$ m through He gas filling a special tube in order to reduce the absorption of the measured EUV signal. Curve 4, obtained from calculations taking into account the absorption of EUV radiation by Xe, gives the value of the EUV power close to the plasma pinch.²¹

Evidently, the value of the measured EUV power depends on the conditions such as the Xe pressure in the chamber and the distance from the pinch to the measuring device, determining the absorption of EUV radiation by Xe. These conditions are different for various EUV sources; therefore, the EUV power close to the plasma pinch region is of most interest. As seen from curve 4 in Fig. 16.4, the EUV power within the pinch region reaches an inband value of about 200 W.

We defined the intrinsic conversion efficiency (ICE) as the ratio of the EUV power close to the plasma pinch region to the electrical power dissipated in the discharge. Figure 16.5 shows the dependence of the ICE on the electrical energy E_d dissipated in the discharge. Optimum values of E_d were in the range 10–16 J/pulse,

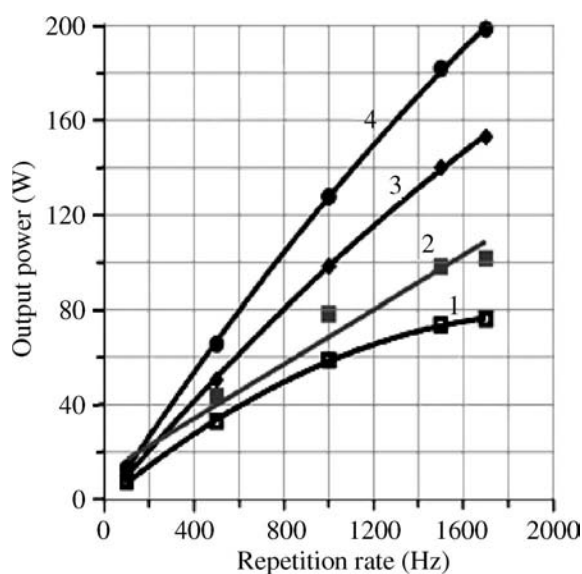


Figure 16.4 EUV output power (2π sr, 2% bandwidth) in dependence on the repetition rate.

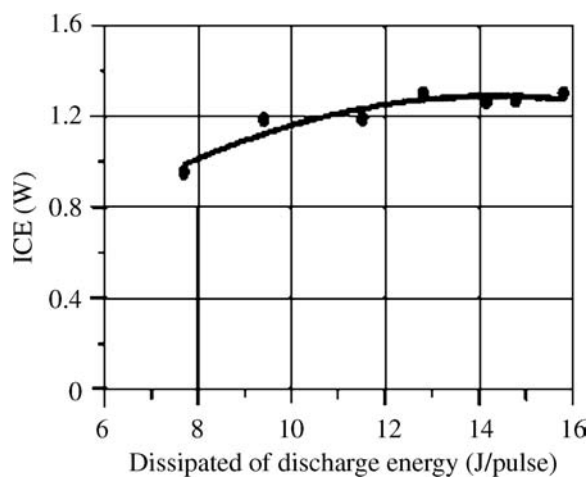


Figure 16.5 ICE (2π sr, 2% bandwidth) in dependence on the dissipation of the discharge energy.

for which the maximum ICE of $\approx 1.2\%$ was reached. In the developed pulse power system the discharge current was not oscillating, and just after the end of the discharge pulse, part of the initially stored electrical energy remained in the pulsed capacitor C_2 shown in Fig. 16.3. By means of a special recovery circuit, this remaining energy then was returned to the storage capacitor C_0 to be used for production of the next discharge pulse.

16.3.3 Emission spectra, source size, and energy stability

The Xe emission spectrum measured in Ref. 7 for the electrode configuration with $L = 4$ mm is shown in Fig. 16.6. The 2% bandwidth around 13.5-nm wavelength corresponding to the effective reflection band of the series of Mo/Si mirrors in an EUVL tool is marked by two vertical lines in Fig. 16.6.

Images of the pinch emission area were made with an EUV-sensitive pinhole camera employing a back-illuminated CCD array and a 0.2- μm freestanding Zr filter covering the pinhole of 0.1-mm diameter in order to cut off radiation emitted in the visible and UV region. The pinhole camera was equipped with software to determine the plasma size, the standard deviation of the size, and the pointing stability. Using the pinhole camera technique, we managed to obtain a source image in a single pulse or by integrating 2–20 pulses in both burst mode and continuous operation at repetition rates up to 1000 Hz. Our measurements have shown that the EUV source size depends on the electrode configuration, the amount of electrical energy dissipated in the discharge, the Xe pressure, and the polarity of the high-voltage electrode (HVE). Only in the case when the HVE was the cathode did we measure almost invariable intensity of EUV radiation flux at various angles to the pinch axis—namely, 12.5 mJ/sr (2% bandwidth) on axis, and 13.7–13.9 mJ/sr between 7 and 40 deg off axis—which testifies to an isotropic angular distribution of EUV radiation. This EUV source image, taken at an angle of 40 deg to the pinch axis and by integrating 20 pulses at 1000 Hz, is shown in Fig. 16.7. The plasma pinch diameter was determined as 0.22 mm (FWHM) and 0.54 mm (FW $1/e^2$). The length of the plasma pinch was determined as 1.1 mm (FWHM) and 3.1 mm (FW $1/e^2$).

The diagnostic used to measure the EUV power was equipped with software permitting one to determine the stability of the EUV output signal as well as other pulse-to-pulse statistics. Figure 16.8(a) demonstrates good pulse-to-pulse stability,

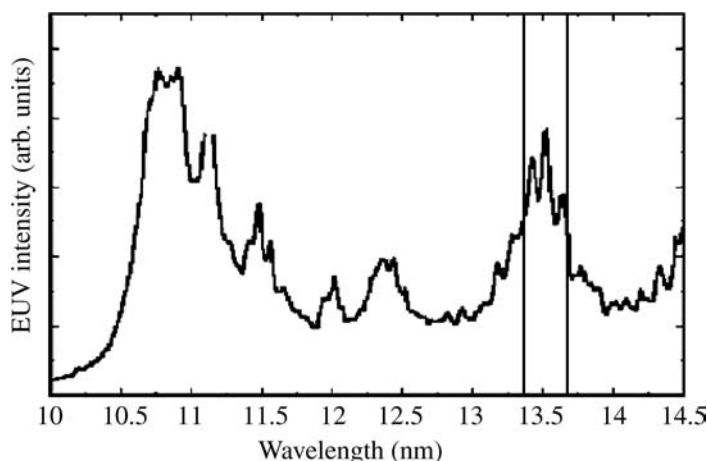


Figure 16.6 Emission characteristic of the Z-pinch EUV source filled with xenon.

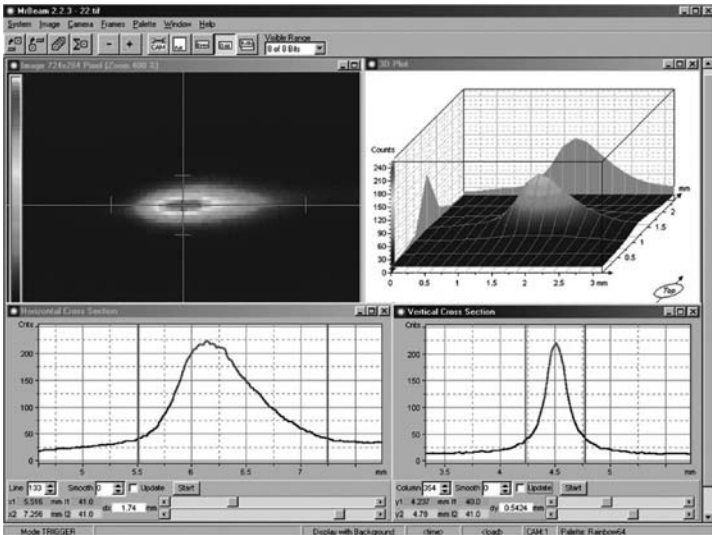
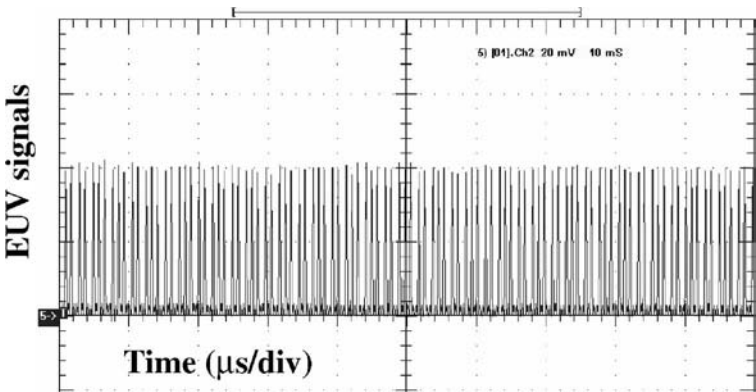
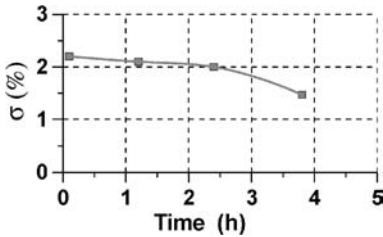


Figure 16.7 Image of the EUV plasma region taken at an angle of 40 deg to the axis.



(a)



(b)

Figure 16.8 (a) Pulse-to-pulse repeatability of the EUV emission; (b) standard deviation of EUV energy in dependence on the operation time (1000 Hz, 25 W, 1.8 sr, 2% bandwidth).

corresponding to a standard deviation $\sigma = 1.9\%$ measured at a pulse repetition rate of 1000 Hz. The behavior of σ during long-time operation is shown in Fig. 16.8(b).

16.3.4 EUV source lifetime, electrode erosion

The lifetime of the EUV source is determined first of all by electrode erosion, which is determined by the whole collection of interdependent physical processes on the electrodes under the action of both high discharge current and high power radiated from the plasma. Investigation of the character of anode surface destruction in the initial stage of the pulse discharge has shown that under electron bombardment in the presence of an electric field, it involved such phenomena as plastic strain of the surface layer, its melting and the growth of hanging indentations (microhillocks) from the melt, and evaporation or breakoff of the tops of the microhillocks.²³ The radiation from the hot plasma pinch forming in a later stage of the discharge leads to further heating of the electrodes and to evaporation of their surface layers. A typical model consideration for a tungsten electrode ($E_d = 4$ J) shows that during the discharge pulse about 70% of all deposited energy remains in an electrode surface layer of a few micrometers' thickness. During the discharge pulse the temperature of tungsten electrode surface layer jumps by approximately 200 K if the plasma-wall distance is 10 mm, and by more than 2000 K if it is 2.5 mm. So increasing the plasma-wall distance is an effective way to reduce the electrode surface temperature. During continuous operation of an EUV source at a high repetition rate, the surface electrode temperature can attain the melting temperature of tungsten (3650 K). If the average electrode temperature comes close to the melting temperature, the whole of the radiation energy coming from the plasma and being absorbed in a thin surface layer will be spent in intensive vaporization, causing significant electrode mass loss.

Our experiments have shown that the lifetime of the discharge system depends on the geometry and material of electrodes and dielectric, the method of cooling, the amount of electrical power dissipated in the discharge (W_d), and the parameters of the pulsed discharge (E_d , current, pulse duration). In our experiments both the anode and the cathode were fabricated from copper and reveted with tungsten. The electrodes were separately cooled by water at a total flow rate of up to 5 L/min.

We studied the electrode mass loss for different conditions during continuous operation of the EUV sources. The results of one test among those we have carried out are shown in Fig. 16.9. During the test the EUV source operated at different pulse repetition rates f and accordingly at different levels of W_d . For each level of W_d the electrodes were weighed before and after the test run. Thus the mass loss of the electrodes (their erosion) for each level of W_d was determined.

As can be seen from Fig. 16.9(a), the EUV source using Xe can provide about 250 W of inband EUV power close to the plasma pinch region in continuous operation. After 45×10^6 pulses the EUV power began to be significantly decreased even at $W_d = 10.5$ kW and $f = 1.11$ kHz, and after 85×10^6 pulses the decrease of the EUV output was 13%. Inspection of the EUV source after 85×10^6 pulses

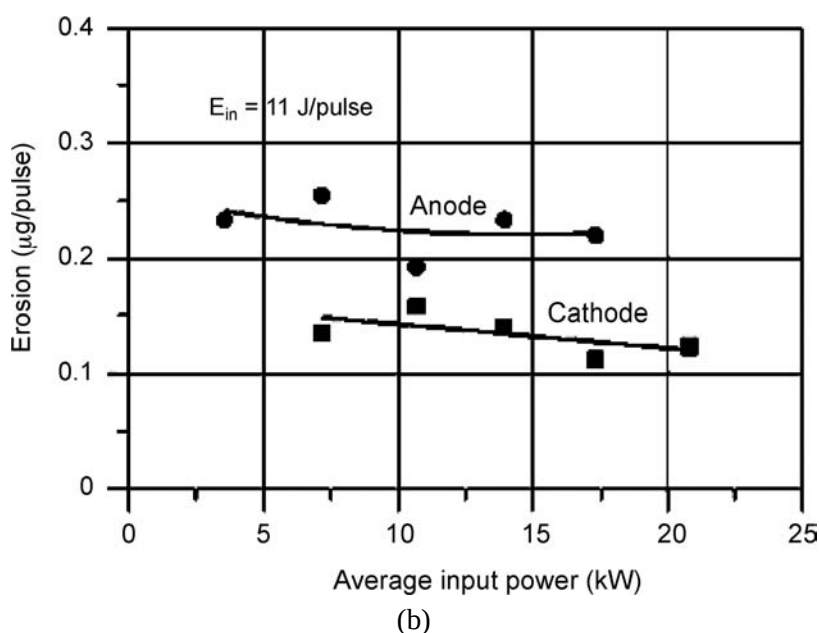
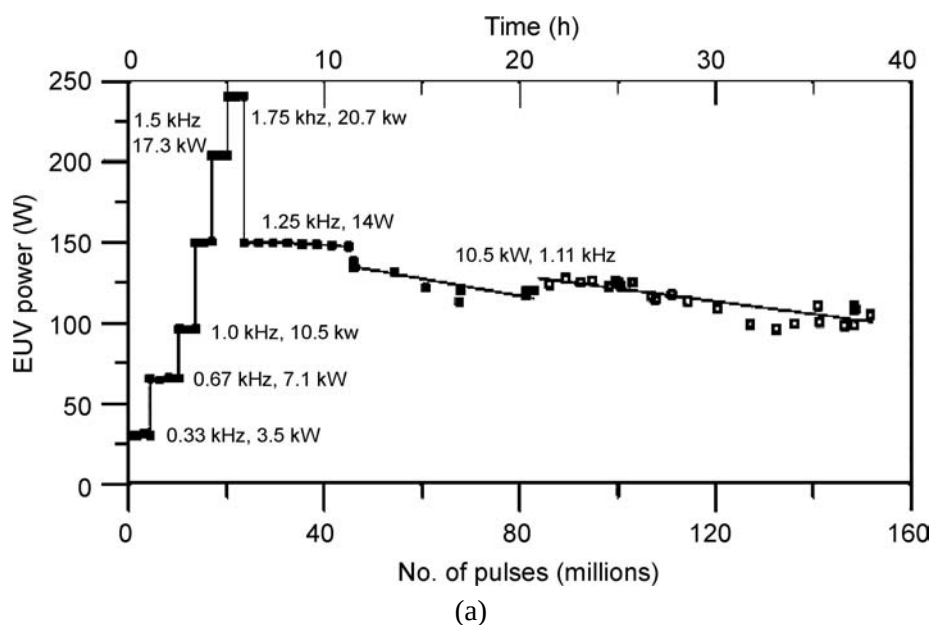


Figure 16.9 (a) EUV output power ($2\pi \text{ sr}$, 2% bandwidth) in dependence on the time of operation at different pulse repetition rates; (b) rate of electrode erosion in dependence on the average input power.

has shown that the mass loss of the cathode is substantially due to erosion of the walls of the central hole through which both injection of gas and preionization were performed. After replacement of the cathode, the level of the EUV power at

$W_d = 10.5$ kW was essentially restored and the source produced an additional 75 million pulses at 1.11 kHz. In this test the anode operated for 150 million pulses. The values of mass loss for both cathode and anode measured during the test at different W_d are shown in Fig. 16.9(b). The anode erosion was higher than the cathode erosion. That difference had already been noted in a number of publications, for example in Ref. 23. From Fig. 16.9(b) it also follows that the increase of W_d from 5 to 20 kW does not result in an increase of erosion per pulse. This result contradicts the common notion that the increase of W_d should result in non-linear growth of erosion. Probably it is possible to explain this by a phenomenon known as *vapor shielding*, which was studied in detail in Ref. 24, for example. The essence of the phenomenon is that under the interaction of high-power plasma fluxes with a wall it starts to evaporate intensely. The vaporized wall material is ionized under the action of external radiation and forms a plasma wall layer. This layer protects the wall surface against plasma fluxes. Now it is not clear whether such a phenomenon takes place in the EUV source, and further detailed research into the electrode erosion mechanism is necessary.

16.4 Some Approaches to Meet HVM Requirements

16.4.1 Increase of effective electrode surface

Evidently, in order to increase both the EUV power and the electrode lifetime, it is necessary to enlarge the distance between the pinch and the electrodes as well as the effective surface of the electrodes. These measures allow reduction of the density of the discharge current, plasma fluxes, and radiation acting on the electrodes. Enlargement of the electrode surface can be achieved with an electrode configuration similar to the one utilized to create the spouting pinch (Fig. 16.2). The electrode configuration that we started to investigate in the year 2000 is shown in Fig. 16.10. The high-voltage electrode (usually the cathode) was made as a metal flange with a spherical concavity of radius R . A ceramic insulator with hole diameter D separated a high-voltage electrode from a grounded ring electrode. The preionizer was introduced into the high-voltage electrode to provide a highly stable homogeneous pinch discharge. The gas was injected through a central hole in the preionizer. In our initial experiments the electrode configuration with $R = 25$ mm and ceramic disks with a central hole of 3-mm diameter were utilized. The study of this electrode configuration during ≈ 3 million pulses has shown that the erosion of the electrodes is really insignificant; however, the diameter of the hole in the ceramic disk (made of Si_3N_4) was rather rapidly increased. In later experiments with this electrode configuration we enlarged the diameter D of the hole to 20 mm. The results of our research on the plasma size at $D = 20$ mm have shown that the length of the plasma pinch for a single pulse was 1.7 mm (FWHM). The pinch length (integrating 20 pulses) was 4.6 mm (FWHM) at 800 Hz, which illustrates the pointing instability along the Z axis.

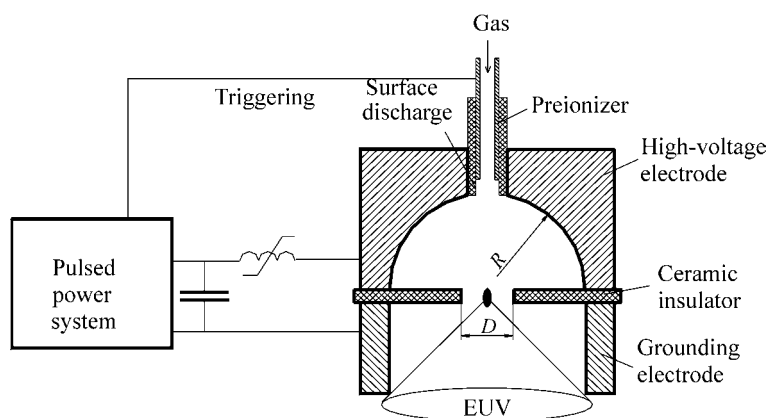


Figure 16.10 Schematic drawing of the Z-pinch discharge unit with enlarged surface of electrodes.

Nevertheless, the optimization of the dimensions R and D as well as the form and material of the ceramic insulator in an improved electrode configuration similar to that shown in Fig. 16.10 allows one to obtain a reasonable pinch length (≈ 2.8 mm FWHM) and diameter (≈ 0.4 mm FWHM) at high repetition rate. Research on the improved electrode configuration in continuous operation has demonstrated a significant decrease of electrode erosion ($< 5 \times 10^{-8}$ g/pulse) in comparison with the electrode configuration shown in Fig. 16.3. The CE, defined as the ratio of the EUV power measured at the distance 1.2 m from the plasma to the electrical power dissipated in the discharge, was around 0.5% inband into 2π sr. The EUV power measured at 1.2 m from the plasma was 55 W inband into 2π sr at 1200-Hz continuous operation.

To obtain the required EUV power of 115 W in the intermediate focus (IF) using the EUV source, with Xe it is necessary to dissipate about 100 kW in a discharge unit.⁸ Besides, in accordance with the requirements,⁹ an HVM EUV source should provide a pulse repetition rate of ~ 10 kHz and a lifetime of $\sim 10^{10}$ pulses. Our experience with various discharge configurations operating with Xe shows that it is unlikely to achieve these parameters in an EUV source with a single discharge unit.

16.4.2 Rotating multi-discharge-unit source

One of the approaches to meet the requirements for the HVM EUV source can be to utilize a source containing many discharge units triggered sequentially so that the total EUV power will be provided by the sum of the EUV power emitted by all the discharge units. The principle of the RMDU source with many rotating discharge units²⁵ consists in the fact that the discharge happens in one of N discharge units positioned on two metal disks separated by a dielectric (Fig. 16.11). Both disks are rotated by an electric motor with rotational speed ν . The N pairs of coaxial holes in which the discharge can be produced are positioned on a circle with diameter

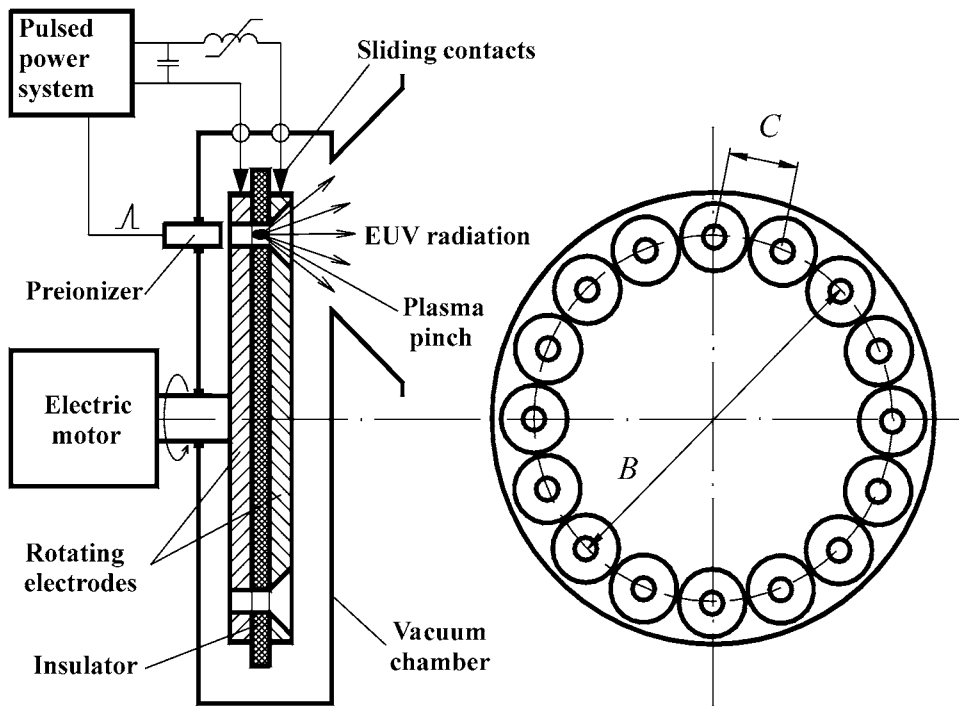


Figure 16.11 Schematic drawing of the rotating set of discharge units in the EUV source.

B on the disk. The discharge is initiated in a fixed location by means of a fixed ignition system (preionizer). The next discharge is initiated in the same location in the volume restricted by another set of holes. The holes inside which the discharge took place will be used again to produce the discharge after a complete rotation of the disks. Thus in the RMDU source the heat load on the electrodes can be reduced by a factor N . The dependence of the pulse repetition rate f on the main parameters of the RMDU source is determined by the following relation:

$$f = \frac{\pi B v}{C} = N v. \quad (16.2)$$

For the RMDU source with Xe the dimension C can be ≈ 3 cm, and at moderate $B = 0.5$ m the rotational speed of the disks should be as high as 200 rev/s to provide $f \approx 10$ kHz. Preliminary research has shown that at such high rotation speeds a serious technical problem of electrode vibration—and, accordingly, of pinch point-to-point instability—appears.

Another approach to reduce heat loading on a discharge unit is the use of N spatially fixed discharge units equidistant from a rotating mirror, which reflects radiation from each discharge unit onto one common axis.²⁶ The rotating mirror is installed near to N intermediate foci, symmetrically distributed around a common axis, at which the EUV beams are focused by means of N optical collectors. The total EUV flux reflected by the rotating mirror onto the common axis will be the

sum of the N fluxes from all discharge units, and the resulting pulse repetition rate on the common axis will be a factor N higher than the pulse repetition rate of each discharge unit. Thus in the EUV source containing N discharge units and a common rotating mirror, the heat load on the electrodes can be greatly reduced. Despite the attractiveness of this approach, it may meet with numerous difficulties on the way to its implementation because of its complexity and high cost.

One obvious step toward creating an HVM EUV source is to increase the CE. Research has shown that a considerable increase in CE is possible through utilization of an alternative medium, such as Sn vapor, which will be considered in the following section.

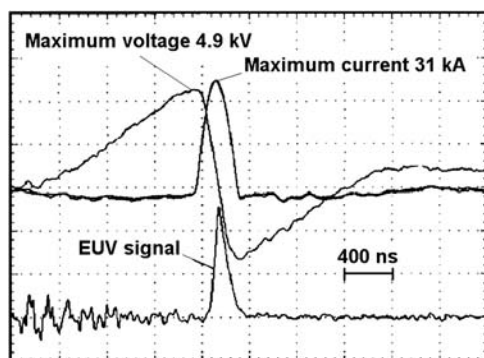
16.5 Pinch Discharges Based on Sn Vapor and Gas Mixtures

16.5.1 Principle of operation and characteristics

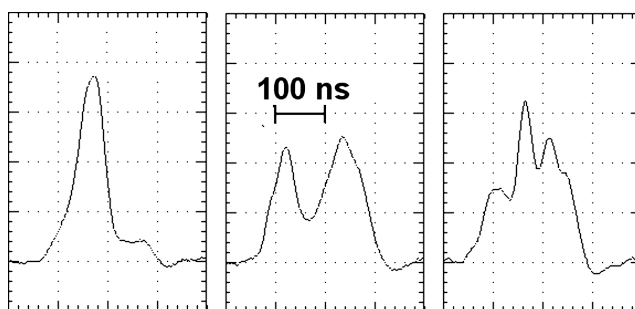
It is known that EUV radiation with a wavelength of around 13.5 nm is generated by Xe^{10+} ion lines. As the peaks of these lines are not very intense (see Fig. 16.6), according to Ref. 27 we cannot expect CEs much greater than 1% inband. On the other hand, it is known that tin ions have a very intense peak at 13.5 nm over a wide range of plasma parameters. In contrast with Xe, the peak of Sn radiation around 13.5 nm is formed by radiation from many excited states of ions such as Sn^{+7} , Sn^{+8} , Sn^{+9} , Sn^{+10} , Sn^{+11} , and Sn^{+12} , and in DPP sources it is possible to expect a CE much greater than 1%. Preliminary information regarding the achievement of a CE $\approx 2\%$ with a vacuum spark in a Sn plasma was given in Ref. 28.

In the first experiments with Sn begun by us in 2002, we used the same electrode configuration as for Xe. The difference was that the axis of symmetry of the electrodes (Z) was vertical and the Sn insert was located at the center of a high-voltage electrode as shown in Fig. 16.15(a). The gas feed and preionization by the auxiliary discharge radiation were carried out through 10 holes surrounding the Sn insert. The origin of the EUV radiation can be presented as the result of two discharge stages. In the first stage the pinch is formed in the gas. In the second stage the dense hot plasma interacts with the Sn insert, producing Sn vapor. The Sn atoms are ionized in the discharge near the Sn insert surface, and the ions in states Sn^{+7} – Sn^{+12} radiate in the EUV band, including 13.5 nm.

We used various gases (He, N_2 , Ar, Xe) to create the plasma pinch evaporating the Sn, but it appeared that the difference in EUV radiation was not great. Experiment confirmed that the generation of EUV radiation was due to the Sn ions. The typical waveforms of the voltage, current, and EUV pulses are given in Fig. 16.12(a). It is necessary to note that for different discharge conditions the pulse of EUV radiation can have one or two, or even three peaks [Fig. 16.12(b)]. Probably, along with the single compression, there can be two- or even three-fold compression of the discharge during the first half-wave of the current pulse. It results in a multipeak mode of the EUV radiation pulse.



(a)



(b)

Figure 16.12 (a) Waveforms of voltage between electrodes, discharge current, and EUV signal, and (b) waveforms of EUV signal under different experimental conditions for a source based on tin DPP.

Research into EUV sources with different polarity of the high-voltage electrode (HVE) has shown that if the HVE with tin is the anode, then the EUV energy can be much greater (Fig. 16.13) for the employed gases. When the HVE is the anode the dependence of EUV energy on the gas pressure has a prominent maximum at 40–80 mTorr. The CE, calculated as the ratio of the maximum EUV energy measured at a distance of 1.2 m from the pinch to the energy dissipated in the discharge, is 1.4%. The polarity change and gas pressure have an effect upon the dimensions of the EUV radiating plasma. If the HVE is the anode and the EUV energy is at a maximum, the plasma size (integrating 16 pulses) at 400 Hz is 1.3 mm (FWHM) in diameter and 2.8 mm (FWHM) in length.

16.5.2 Continuous operation of the EUV source using Sn

Figure 16.14(a) shows the EUV power of the EUV source using He + Sn as a function of repetition rate, and Fig. 16.14(b) shows the time dependence of the EUV energy during two hours of continuous operation at 200 Hz. Operation of the EUV source was stopped after most of the Sn was evaporated. The evaluation of the Sn consumption is $\approx 1.8 \times 10^{-6}$ g/pulse at 200 Hz. If the repetition rate was

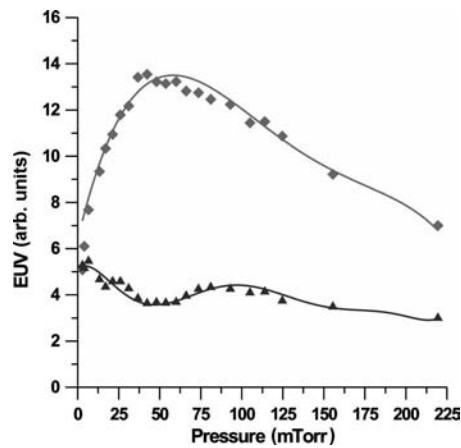


Figure 16.13 EUV energy in dependence on gas pressure for different polarities of the high-voltage electrode.

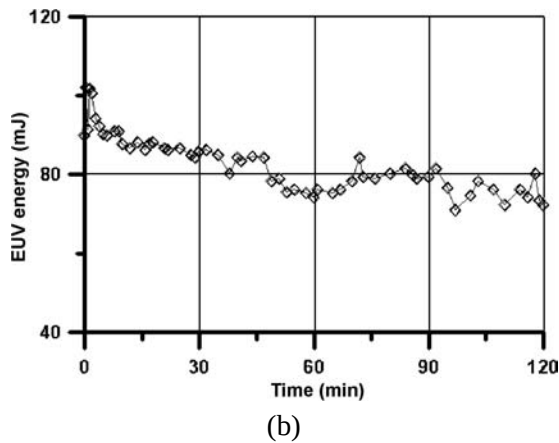
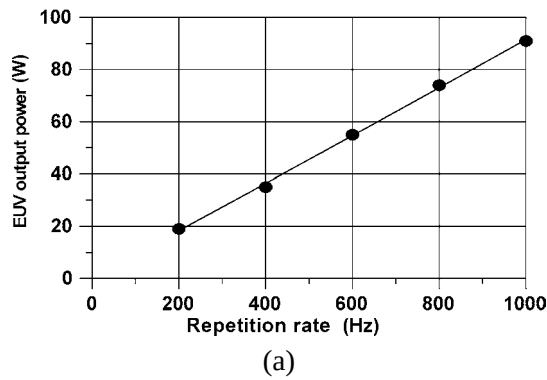


Figure 16.14 (a) EUV power (2π sr, 2% bandwidth) in dependence on the repetition rate, and (b) EUV energy (2π sr, 2% bandwidth) in dependence on the time of operation, for a source based on tin DPP.

increased, the resulting increase of Sn consumption was almost linear. Thus, it was 3.6×10^{-6} g/pulse at 400 Hz.

Examination of the electrodes after their long-term operation at different repetition rates has revealed a complex picture of Sn behavior. For example, in the case when the HVE was the anode, Sn mass transfer onto the grounded electrode (cathode) was observed, and the hole in the grounded electrode became clogged with settling Sn, as shown in Fig. 16.15(b). This phenomenon can play a positive role through increase of the electrode lifetime. A layer of Sn covering the electrode is created and then evaporated during long-term operation of the EUV source while the basic electrode metal conserves its mass and form. The HVE surface around the Sn insert also was covered with a Sn layer, and a crater was formed in the Sn insert after long-term operation [Fig. 16.15(c)]. The Sn mass transfer processes illustrated in Fig. 16.15(d) probably have an essential influence upon EUV radiation stability.

The pulse-to-pulse repeatability of the EUV emission is shown in Fig. 16.16 at 500, 800, and 1000 Hz. Evidently the repeatability is worsened with increasing pulse repetition rate. Introduction of a continuous Sn feed to compensate for Sn consumption will probably improve the repeatability of EUV emission.

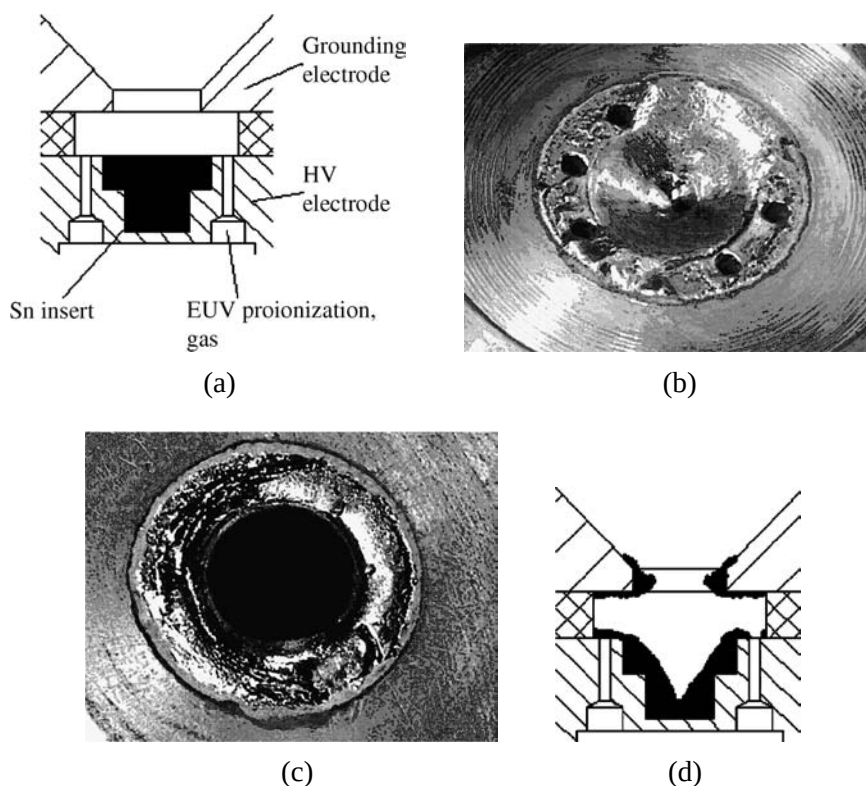


Figure 16.15 Schematic drawings of the electrode system (a) before, and (d) after an operation using a tin source; photographs of a (b) grounding electrode, and (c) high-voltage electrode after an operation.

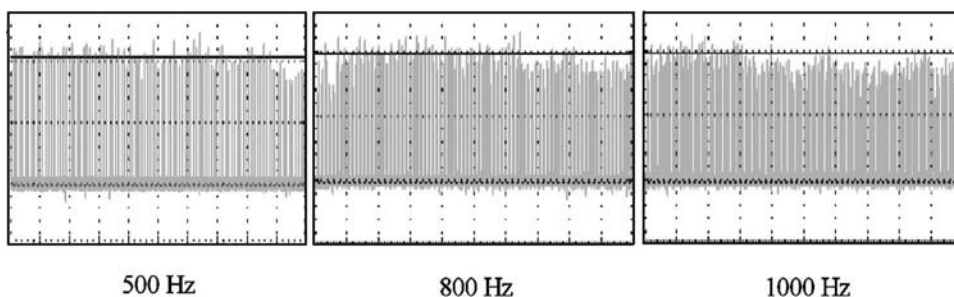


Figure 16.16 Pulse-to-pulse repeatability of the EUV emission for a source based on tin DPP at different pulse repetition rates.

We carried out experiments with the electrode geometry shown in Fig. 16.15(a), in which the initial Sn vapor was created by an electron beam. The miniature electron gun was placed on the axis of the grounded electrode so the electron beam hit the center of the Sn insert. The use of an electron beam has allowed us to increase the CE to 2.6%.

16.6 Excimer-Laser-Initiated Pinch Discharge in Sn

16.6.1 EUV source consisting of a single discharge unit

The occurrence of laser-induced vacuum-gap breakdown has long been demonstrated.²⁹ We used in the experiments an available KrF laser that can operate with a pulse repetition rate of up to 6 kHz.² Figure 16.17 shows the outline of the EUV source with laser Sn vaporization. The excimer laser radiation was focused by the lens on the Sn insert in one of electrodes placed in the vacuum chamber. The electrical pulse was applied to the electrodes from the pulsed power system with a certain delay after a laser pulse. The EUV radiation could be monitored on the source axis and at an angle of 40 deg to the axis, for which purpose there were appropriate flanged branches in the vacuum chamber. The maximal energy of laser radiation was 90 mJ, the optical system transmission was about 60%, and the focal length of the lens was ≈ 500 mm. The laser beam divergences were 3×10^{-4} and 9×10^{-4} in two mutually perpendicular directions that resulted in a spot size of 0.15×0.45 mm² on the surface of the Sn. The maximum power density of the laser radiation was $\approx 2.2 \times 10^9$ W/cm². It is necessary to emphasize that the excimer laser radiation initiated the Sn vaporization and vacuum-gap breakdown only. The main energy dissipated in the discharge and the plasma pinch evolution occurred owing to electrical energy stored in the pulsed power systems.

The experimental dependences of the EUV energy on the laser power density that were obtained have allowed us to reach the following conclusions:

1. There is a threshold of laser power density sufficient for the vacuum-gap breakdown that equals 0.6×10^9 W/cm².

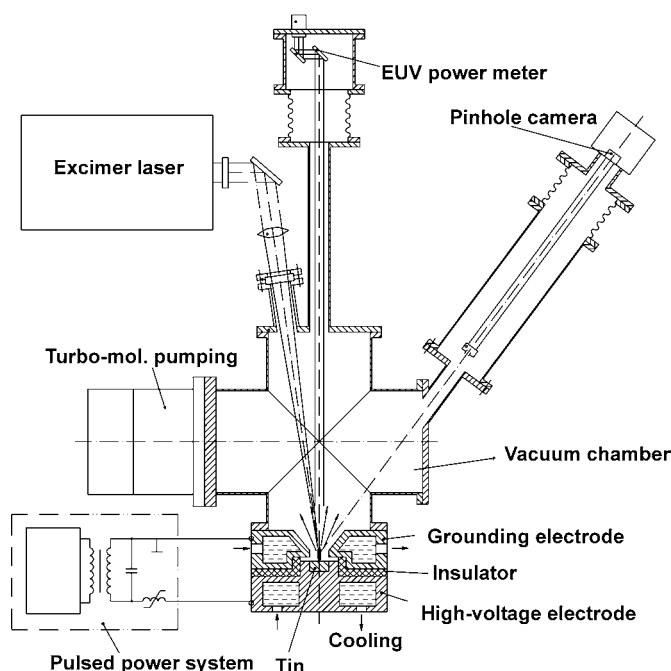


Figure 16.17 Schematic of EUV source based on tin DPP with excimer laser initiation of tin vapor.

2. There is a growth of the EUV energy with increase of the laser radiation power density from 0.6×10^9 to 1.3×10^9 W/cm².
3. Further increase of the laser power density does not result in additional growth of the EUV radiation energy.

Figure 16.18 shows the time dependences of the discharge current in the Sn vapor and the EUV radiation signal measured by the fast *pin* diode. The KrF laser radiation pulse is seen on the bottom curve. The optimum delay between the discharge current maximum and the KrF laser radiation pulse was ≈ 1.2 μ s.

The experiments have shown that the EUV radiation energy depends in a complicated manner not only on the HVE polarity of the Sn insert, but also from a lot of other source parameters. The maximum CE was about 2.2% in 2% bandwidth at 13.5 nm into 2π sr, which was calculated from the ratio of the EUV energy measured within a distance of ≈ 1.2 m from the plasma to the electrical energy dissipated in the discharge for optimum conditions. But the pulse-to-pulse repeatability of the EUV emission was rather bad. The experiments showed that the initially flat Sn insert was warmed up during continuous operation of the source and a crater was formed owing to the Sn evaporation. Thus, we have assumed that one of the reasons for the observed poor pulse-to-pulse repeatability could be the change to the Sn surface on which the laser beam was focused. We have tried to reduce the instability by substitution of a solid Sn insert for the previously melted Sn placed

in the HVE. However, that has not essentially improved the pulse-to-pulse repeatability of the EUV energy. This problem is now under investigation.

Measurements with the pinhole camera have demonstrated that when the HVE was the anode, the plasma size in the EUV band was too great, especially by the $1/e^2$ measure.²⁵ When the HVE was the cathode, a very small plasma size was observed (Fig. 16.19). Namely, the diameter was 0.29 mm (FWHM) and 0.62 mm (FW $1/e^2$), and the length was 0.54 mm (FWHM) and 1.08 mm (FW $1/e^2$). That meets the requirements⁹ quite well.

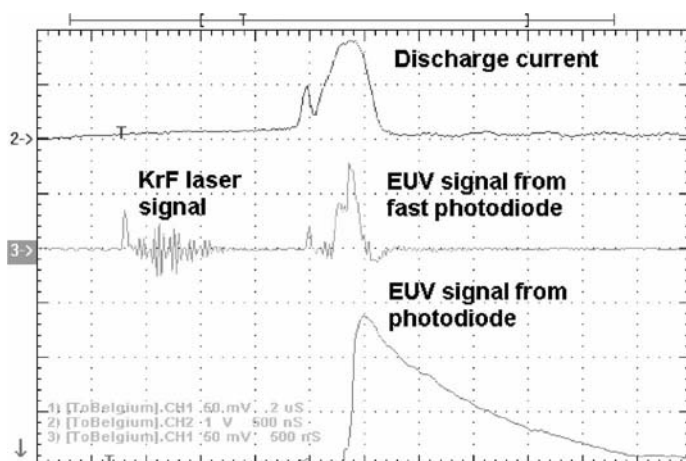


Figure 16.18 Waveforms of discharge current and EUV signals for the EUV source with excimer laser initiation of tin vapor.

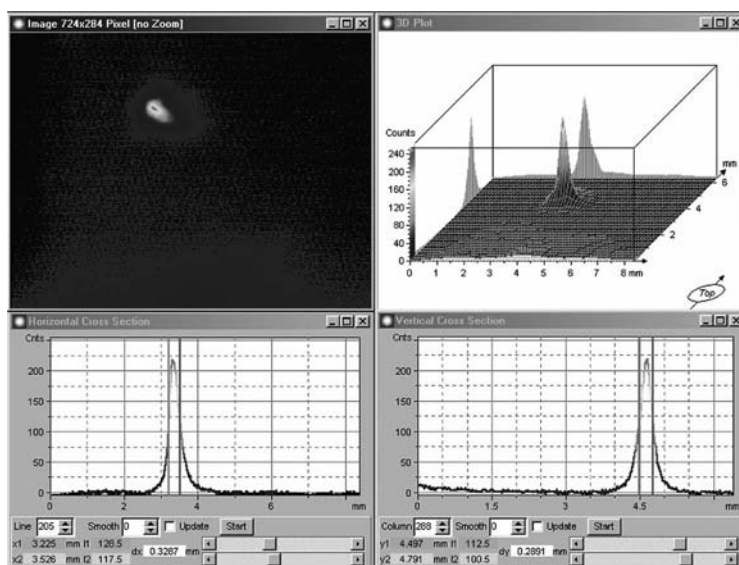


Figure 16.19 Image of the EUV tin plasma region taken at an angle of 36 deg to the pinch axis.

16.6.2 Rotating-disk-electrode EUV source

Variants of the multiplexed Sn source were discussed at the EUVL Source Workshop in 2003.^{21,22,30} To avoid the defects characteristic of RMDU sources discussed in Sec. 16.4.2, we developed a new approach³¹ based on a non-axially-symmetric electrode configuration, viz., a configuration with the discharge produced between the edges of rotating-disk electrodes. In this *edge* configuration we can use the EUV radiation from the plasma pinch in a direction perpendicular to the Z axis of the plasma pinch. This approach was presented first in Ref. 22.

A schematic drawing of an EUV source with the edge electrode configuration is shown in Fig. 16.20. The metal disk anode was separated by the insulator from the metal disk cathode. The disks and the insulator were rotated together by an electric motor. The pulsed power system was connected to the disks by the sliding contacts. The electrical energy was delivered to the plasma after breakdown of the electrode gap was initiated by a laser beam focused on the disk edge, which was covered with Sn by an apparatus for that purpose.

Measurement with the pinhole camera has shown that the image of the emission region of the plasma [Fig. 16.21(a)] is located near the Sn surface irradiated by a focused laser beam, and its size is as small as in Fig. 16.19. If the disks were not rotated and the laser beam was focused on the same point of the solid Sn surface during many pulses, the EUV energy measured perpendicular to the Z axis decreased from pulse to pulse, even at 10 Hz [Fig. 16.21(b)]. This decrease could be explained by the formation of a crater on the Sn surface. The depth of the crater is increased from pulse to pulse, and the plasma emission region descends to the crater bottom. In this case a part of the EUV radiation does not reach the measuring device. When the Sn was preliminarily heated and vacuum-melted, the drop of the EUV energy became not so sharp [Fig. 16.21(b)].

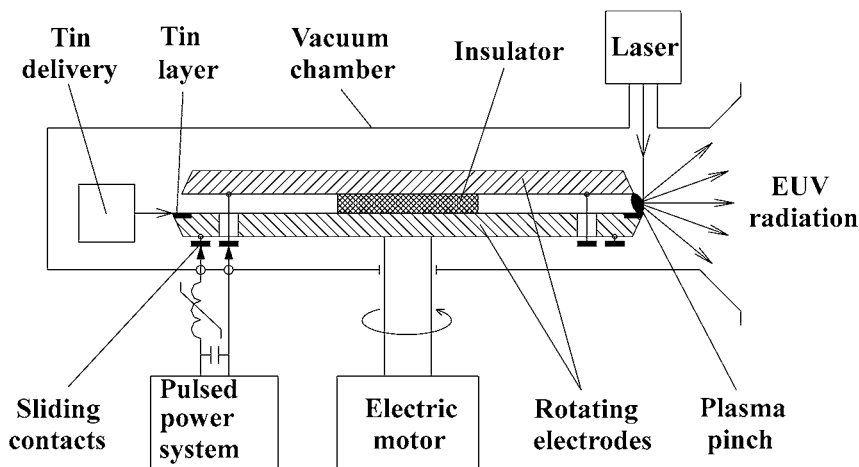


Figure 16.20 Schematic drawing of the rotating-disk electrode (RDE) EUV source.

Figure 16.22 demonstrates a sequence of EUV signals emitted from the source shown in Fig. 16.20 at 3 kHz when the disks were rotated at a speed of 1 rev/s and the edge of the grounded disk was covered with solid Sn. The bad pulse-to-pulse stability for 4 s after the source operation starts can be explained by the change of the tin state from solid to liquid. The average EUV power of approximately 180 W in a 2% bandwidth around 13.5 nm into a 2π -sr solid angle have been measured at the distance 1.2 m from the plasma at 3 kHz.

Because the lost Sn can be replenished from the apparatus for delivering Sn, the Sn-covered disk electrode can have a long lifetime. When the disks are rotated, the surface heat load on the other (not Sn-covered) disk electrode is also sharply reduced, because a fresh region on the electrode surface is used for every new discharge, and therefore the effective electrode surface becomes large.

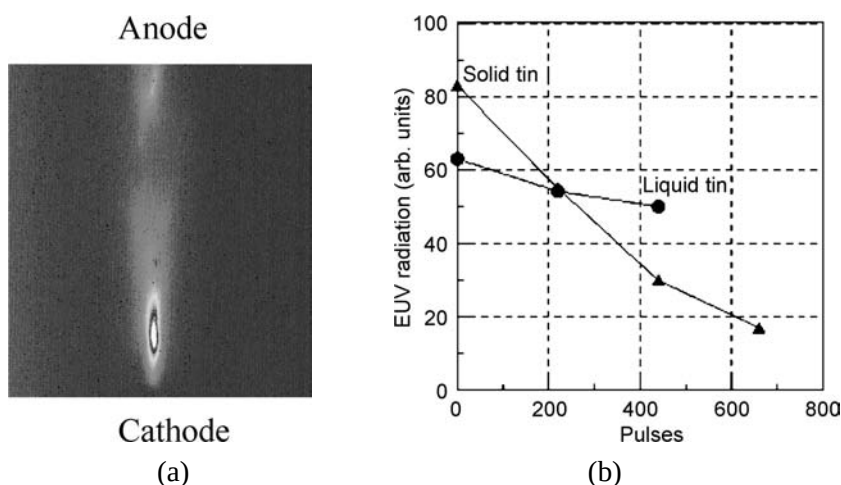


Figure 16.21 (a) Image of the EUV tin plasma region taken at an angle of 90 deg to the pinch axis. (b) EUV energy in dependence on the time of operation.

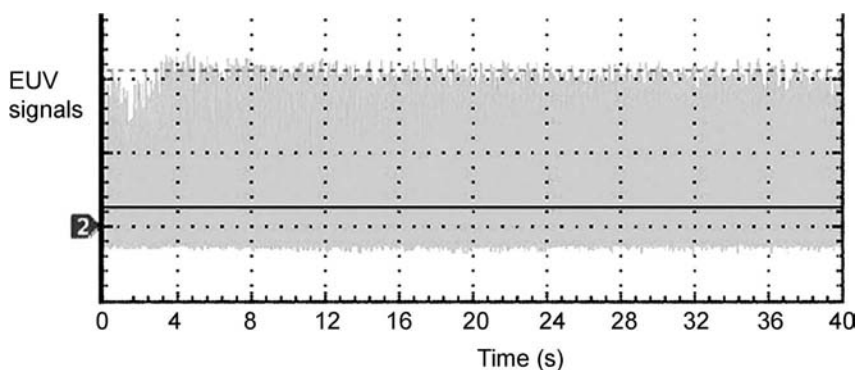


Figure 16.22 Pulse-to-pulse repeatability of EUV emission obtained with RDE EUV source at 3000 Hz.

Taking into account a transverse size of the discharge equal to about 1 mm ($C = 1$ mm) and in accordance with the formula (II), we can produce each discharge in a fresh region of the electrode gap between the edges of the rotating disks at a pulse repetition rate of about 10 kHz if the rotation speed of the disks with diameter $B = 0.5$ m is only 6.4 rev/s. For the approach illustrated in Fig. 16.20 the name “RMDU source” is no longer quite correct, because there are no separated discharge units and neighboring discharges can partly superimpose one on the next. A more appropriate name for the source shown in Fig. 16.20 would be the rotating-disk electrode (RDE) EUV source.

16.7 Conclusions

DPP sources based on the pinch effect in Xe and Sn vapor were investigated at SRC RF TRINITI as a potential exposure tool for HVM EUVL. For the source using Xe, an EUV power close to the plasma pinch of about 250 W in 2% bandwidth around 13.5 nm into a solid angle of 2π sr was obtained for continuous operation at 1700 Hz. In this case an intrinsic CE of 1.2% was obtained. The measured erosion of tungsten covering the copper electrodes amounted to 2×10^{-7} g/pulse for the anode and 1.4×10^{-7} g/pulse for the cathode. It was possible to reduce erosion of the electrodes to 0.5×10^{-7} g/pulse in another electrode configuration where the distance from the plasma pinch to the walls of the electrodes and ceramics was increased.

Investigation of EUV sources using Sn showed that it was possible to obtain a CE within the range 1.4%–2.6% by utilizing different methods of Sn vapor creation. The use of a KrF laser to produce the initial concentration of Sn vapor provided extremely small sizes of radiation plasma: the diameter was measured to be 0.29 mm (FWHM) and 0.62 mm (FM $1/e^2$), and the length of the plasma pinch was measured to be 0.54 mm (FWHM) and 1.08 mm (FM $1/e^2$).

Despite the progress that has been achieved, our estimates and experience indicate a serious restriction determined by the limit of the heat load on electrodes (approximately 30 kW) for a DPP source with a single discharge unit. The heat load on electrodes could be lowered considerably if many discharge units were to be switched one after another. In this case the EUV power would be the sum of the EUV power produced by each discharge unit. This chapter has looked into the concepts of RMDU sources for use both with Xe and with Sn vapor.

We have investigated an EUV source in which a Sn layer was put on the edge of one of two rotating disks. An excimer laser beam focused on the edge of the rotating disks was used as the device to initiate the breakdown by Sn vapor production. In such a RDE source the disks can be rotating slowly enough to ensure a pulse repetition rate of 10 kHz, so its design is not too complicated. The mean heat load on electrodes in the RDE source is many times smaller than with a single-discharge-unit source. Thus the problem of the required electrical power input and heat dissipation of critical source components in the Sn RDE source seems solv-

able. So far an average EUV power of approximately 180 W inband into 2π sr has been achieved with an RDE source at 3 kHz.

The key problem of the EUV sources that use Sn is the high level of debris, which limits the lifetime of the collector optics. Finding a solution to this problem is the main focus of our efforts now.

Acknowledgments

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Chapter 17

Capillary Z-Pinch Source

Yusuke Teramoto, Hiroto Sato, and Masaki Yoshioka

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17.1 Introduction

EUV is expected to be used as a light source in the next generation of lithography. In order to meet the joint requirements¹ for commercialization, researchers and engineers working on EUV sources must satisfy many needs: for increased EUV power, high repetition rate, stability, improved source figure, and so forth. Compared with a source using an LPP, one based on a DPP has important advantages, such as its direct conversion from electrical energy to photon energy and, especially, its lower cost of ownership. The largest disadvantage of the DPP source is the need for tight debris mitigation because of erosion or sputtering of the electrodes and dielectric surface. Because debris easily damages EUV optics, the research and engineering effort has concentrated on the effect of debris generation on EUV source performance.

Although several schemes are available to create a high-energy-density plasma, such as the dense plasma focus (DPF),² hollow-cathode-triggered Z pinch (HCT-Z),³ capillary discharge,⁴ and Z pinch,^{5,6} the source we are developing employs a combination of capillary discharge and Z pinch in view of their simplicity

and stability. Capillary discharge can maintain a high-temperature plasma for a relatively long time because a small-diameter capillary (dielectric tube) is used, and a low-amplitude and long-duration current pulse drives the load. A conventional Z-pinch plasma, in contrast, is created in a large-diameter dielectric tube or vacuum. A large current pulse creates an azimuthal magnetic field around the cylindrical initial plasma or gas, and magnetic pressure compresses the plasma toward the central Z axis.⁷ The capillary discharge is good with respect to stability, but the Z pinch is better with respect to radiation brightness and the lifetime of the dielectric wall. Thus our source employs a medium-diameter capillary and a large-amplitude and short-duration current pulse, so that we are able to obtain high-power, high-brightness, and stable EUV radiation even at high repetition rates.

In this chapter the current development status of the capillary discharge, debris mitigation system, and collection optics and their evaluation will be described briefly.

17.2 Discharge Head and Magnetic Pulse Compression Generator

Figure 17.1 shows the cross section of the discharge head. The head consists of an anode, capillary, cathode, vacuum interface, and coaxial current feed. Both electrodes are cooled by circulated deionized water. The electrode material determines the heat and debris generation. Since tantalum has good thermal conductivity and sputtering resistance, currently tantalum electrodes are applied. A silicon carbide (SiC) disk is used as the capillary body. The capillary diameter and length are among the important parameters for a Z-pinch discharge. They must be chosen together with the pulse shape of the driving current, because the magnetic field induced by the current is determined by the current amplitude and the capillary diameter. The radiation energy and its spatial and spectral profiles also depend on the capillary length. Although several geometries were tested to examine their charac-

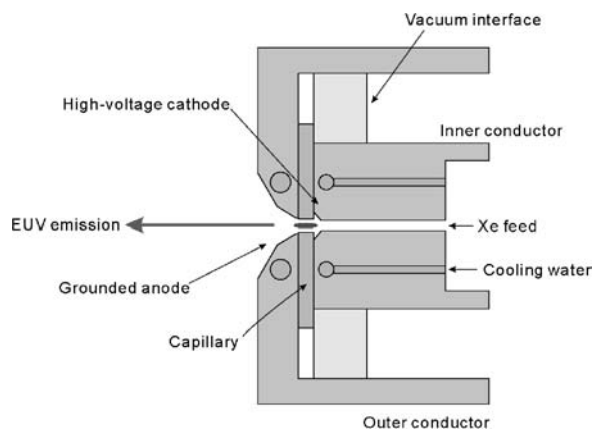


Figure 17.1 Schematic cross section of the discharge head.

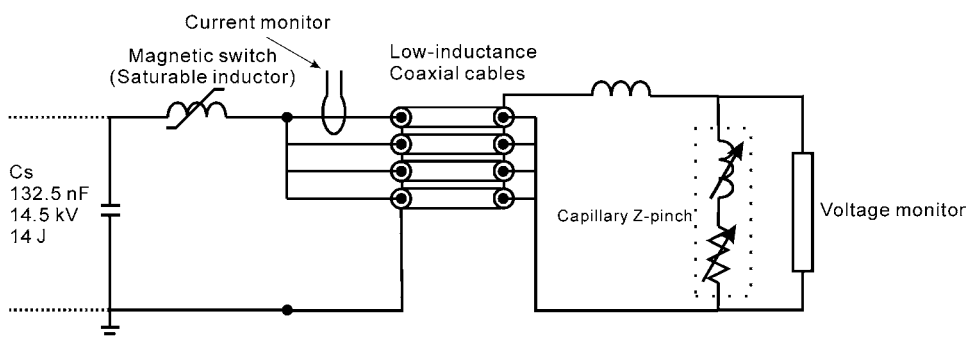


Figure 17.2 Circuit diagram of the magnetic pulse compression (MPC) generator. Only the final stage is shown.

teristics, in this section only the results obtained from a capillary of diameter and length 5 and 9 mm will be described.

The discharge head was installed in the vacuum chamber. Xenon gas was fed from the cathode side and evacuated from the anode side. The capillary could serve both as the discharge space and as an orifice for differential pumping, because the diameter of the capillary was small enough to maintain the pressure of the downstream region low enough to avoid absorbing the EUV radiation.

Figure 17.2 shows a circuit diagram of the magnetic pulse compression (MPC) generator. The final compression stage of the 5-stage MPC generator is shown in this figure. The final capacitor of 132.5 nF was charged to 14.5 kV, which is equal to 14 J of electrical energy storage. In order to decrease the output inductance, 16 coaxial cables were used to connect the MPC and discharge head. The all-solid-state MPC generator allows very stable operation at up to 2 kHz. Depending on the circuit resistance and inductance, a typical current amplitude and duration were 17 kA and 350 ns, respectively.

17.3 Diagnostics

Figure 17.3 shows the vacuum chamber in which the discharge head and diagnostic apparatus were installed. The chamber is 1.3 m wide and 2.2 m long, and has 11 ports for diagnostics from different angles. Inside the chamber, a nine-channel angular distribution monitor (ADM) was installed. Each ADM unit consists of a Mo/Si plane mirror, a windowless silicon photodiode (IRD Inc., AXUV-100G), and a 150-nm-thick zirconium filter (Luxel Corp.). The Mo/Si mirror was set at a 2-deg angle to the perpendicular incident angle. Each ADM allows simultaneous measurement of the inband EUV radiation profile at the source plasma or at the intermediate focus (IF). In order to make precise and absolute measurement of inband EUV radiation, a Flying Circus-II (FC-II, Scientec Engineering) EUV monitor and a grazing-incidence spectrometer were attached at 10-deg ports. Also, in order to make time-resolved measurements of EUV pulses, a fast photodiode was set at a 30-deg port.

Figure 17.4 shows a typical reflectance of the Mo/Si mirror used in the diagnostics. The bandwidth of the mirror is more than 2% around 13.5 nm, which is the requirement for a lithography source. Therefore, using the reflectance data and the observed spectrum, the EUV energy within a 2% bandwidth was recalculated. However, only reflectance data ranging from 13 to 14 nm are available so far, so

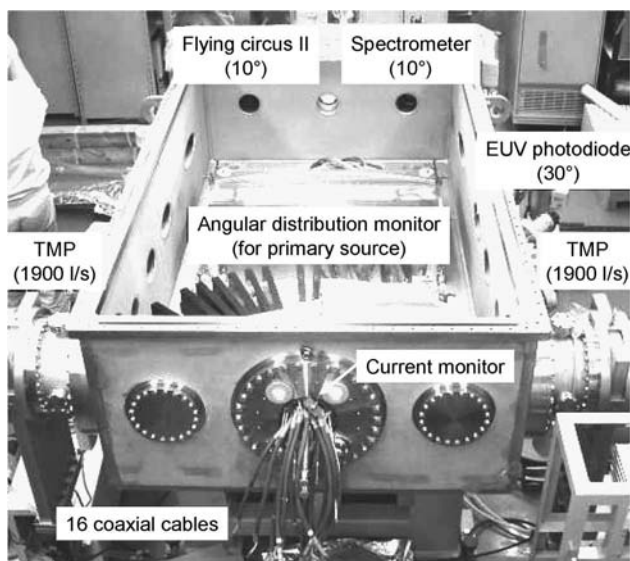


Figure 17.3 Diagnostics vacuum chamber.

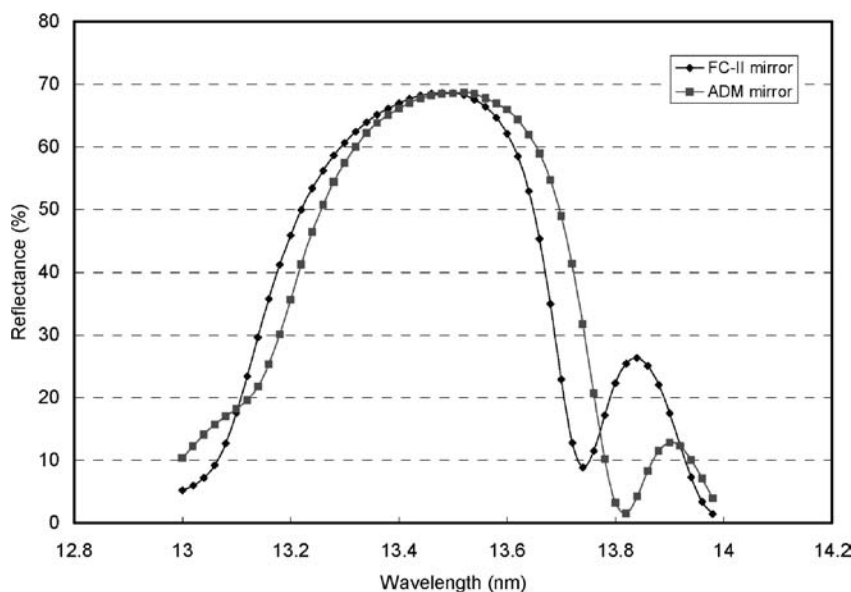


Figure 17.4 Reflectance of Mo/Si mirror used in the FC-II and ADM.

that some small calculation errors are possible. The on-axis EUV energy in a 2% bandwidth around 13.5 nm was calculated by the following equation⁸:

$$E_{\text{EUV}} = \frac{\int V_{\text{SC}} dt}{R_{\text{SC}}} \frac{1}{\eta_{\text{PD}}} \frac{1}{\Omega \cdot \tau_{\text{Zr}} \cdot \tau_{\text{MS}} \cdot R_{\text{ML}}} \cdot \eta_{\lambda} \quad (\text{mJ/sr, 2\% BW}), \quad (17.1)$$

where V_{SC} , R_{SC} , η_{PD} , Ω , τ_{Zr} , τ_{MS} , R_{ML} , and η_{λ} are the photodiode signal amplitude at the oscilloscope input, impedance of the oscilloscope input, responsivity of the photodiode, solid angle of the detector, transmittance of the zirconium filter, transmittance of the mesh support, reflectance of the multilayer mirror (MLM), and 2%-bandwidth coefficient, respectively.

It is very important to know the size of the source that is radiating inband EUV, since the source size determines the collection efficiency of a collector mirror. In order to take a picture of the source image, a back-illuminated CCD camera (Andor Technology Ltd., DO434) was used. In front of the CCD, two plane Mo/Si mirrors and a zirconium filter were placed. With the help of a small pinhole, the inband radiation image was focused on and recorded by the CCD.

Using the diagnostic apparatus described above, together with current-voltage measurements, the electrical energy input to the discharge, on-axis EUV energy, angular distribution of the EUV radiation, and EUV spectra were measured at low and high pulse repetition rates for several xenon flow rates.

Two turbomolecular pumps pumped the chamber out during the experiment. Cooling water flowing in the electrodes was maintained at 20°C temperature and 6.5-l/min flow rate. The discharge current and voltage were measured with a current monitor (Pearson, Model 5046) and a voltage monitor (Lecroy, PPE20KV), respectively. All the signals were recorded by four-channel digital oscilloscopes (1.5 GHz, 2 G samples/s, Lecroy WavePro960).

A debris mitigation system was also installed, and its effectiveness was examined by several diagnostics. The debris mitigation system and collection optics will be discussed in a later section.

17.4 Experimental Results

17.4.1 On-axis EUV energy

Figure 17.5 shows typical waveforms of the current, voltage, and EUV pulse. In this case, 17.5 kA of peak current and 350 ns of pulse duration were observed. A MPC generator transfers the electrical energy to the load when the final magnetic core saturates. Since there was no active preionizing system used in our experiment, the initial impedance of the capillary was high. Therefore, before the magnetic switch saturated, a voltage appeared across the capillary a few hundred nanoseconds prior to the current. After this voltage fell, a small current flowed in the capillary. This *prepulse* yielded preionization, and protected the capillary from dielectric breakdown. The high-frequency oscillation seen in the voltage waveform

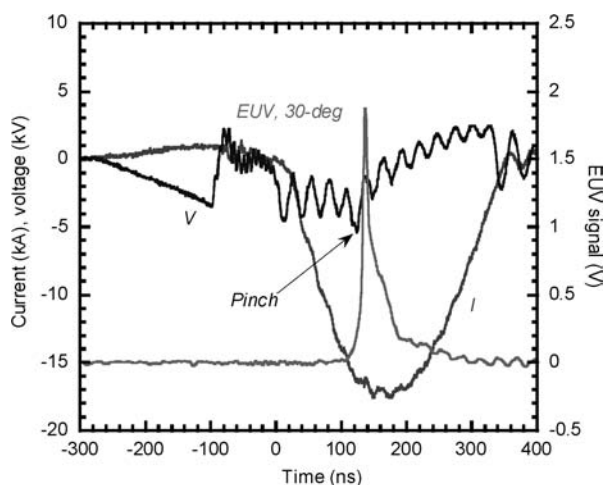


Figure 17.5 Typical waveforms of current, voltage, and EUV signal.

was due to the interaction between the final capacitor and the cable capacitance. When the Z-pinch implosion occurs, the inductance of the plasma rapidly rises, and a voltage spike sometimes appears in the waveform, as seen in Fig. 17.5.

Almost at the same time as the voltage spike, the EUV pulse was measured by the photodiode. In this system the timing of the EUV pulse was delayed with increasing gas flow rate. The reason was considered to be that the gas density inside the capillary was forced to increase with increasing gas flow rate from vacuum performance. In Z-pinch plasmas, an azimuthal magnetic field compresses the initial plasma column against the internal plasma pressure, so that an increase in the gas density prolonged the implosion time. This results in an increase in the radiation energy in the broadband EUV, as described later.

Figure 17.6 shows the typical spectra observed with 9, 21, and 40 sccm of gas flow. Although it is not discussed in detail here, the shape of the EUV spectrum was different from that of the LPP source. Comparing the spectra of DPP and LPP sources, it can be said that one advantage of a DPP source is its higher spectral efficiency in the 13.5-nm region. The shape of the spectrum varied with the gas flow rate. It is noteworthy that the highest CE from electrical to EUV energy was achieved when the spectral efficiency for 13.5-nm EUV was highest.

Figure 17.7 shows the on-axis inband EUV energy and broadband EUV energy as a function of gas flow rate when the pulse repetition rate was 1 Hz. Each plotted point represents averaged data obtained from 10 shots. At 9-sccm gas flow rate, the highest EUV energy of 5.87 mJ/sr (2% bandwidth) was obtained. At lower gas flow rates than 9 sccm, the EUV energy decreased rapidly with decreasing flow rate. At such flow rates, the gas density is very low, and the Z-pinch plasma, consequently, is expected to be unstable. At higher flow rates, a stable Z-pinch plasma is expected, but the higher gas density results in a decrease in inband EUV radiation energy. In contrast, the broadband EUV (5–20 nm) radiation energy increased almost linearly in proportion to the gas flow rate. Inband EUV (2% bandwidth around

13.5 nm) emission is caused only by Xe^{10+} ions. The total number of Xe^{10+} ions depends on the temperature and density of the Z-pinch plasma, and hence on the gas flow rate.

In addition to the EUV energy, the CE is very important, because it determines the necessary capacity of the pulsed-power generator and the thermal sink of the discharge head. The CE was calculated by the following equation:

$$\text{CE} = \frac{2\pi E_{\text{EUV}}}{E_{\text{input}}} \times 100 = \frac{2\pi E_{\text{EUV}}}{\int V(t)I(t)dt} \times 100 \quad (\text{mJ/sr, 2\% BW}), \quad (17.2)$$

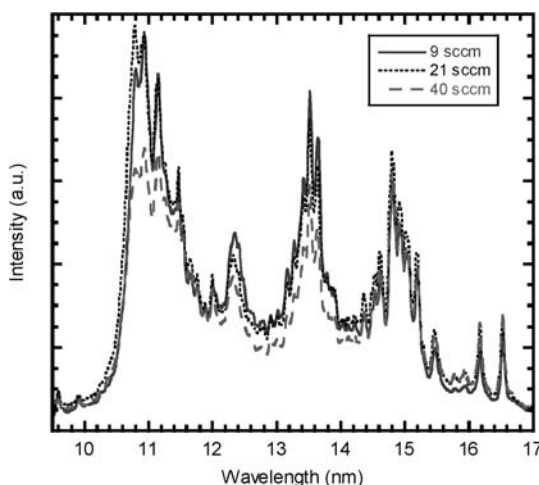


Figure 17.6 EUV spectra obtained with 9-, 21-, and 40-sccm xenon flow rates.

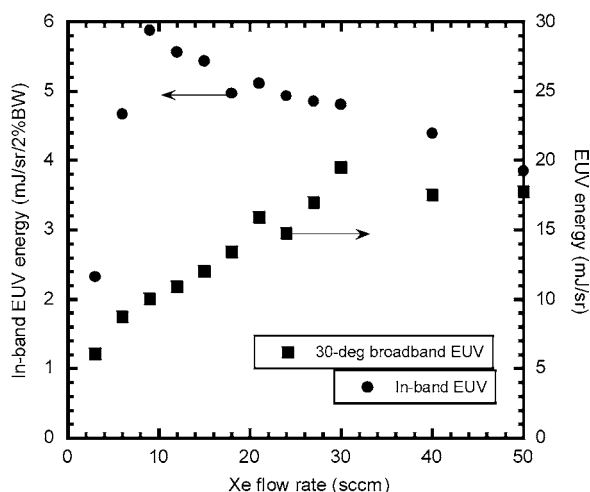


Figure 17.7 Inband and broadband EUV energy as a function of xenon flow rate obtained at 1-Hz operation.

where E_{EUV} , E_{input} , $V(t)$, and $I(t)$ are the on-axis EUV energy, electrical energy input, voltage across the discharge, and current flowing through the discharge, respectively. In this equation, uniform radiation is assumed and 2π sr of solid angle is used.

Figure 17.8 shows the dissipated electrical energy and CE. At 9 sccm, the electrical energy dissipation and CE were 3.5 J and 1.04% (2π sr, 2% bandwidth), respectively. Except for low gas flows, no large differences were seen in the dissipated energy and CE. The energy density (temperature and density) of the Z-pinch plasma is affected by the gas flow rate. Therefore, the spectral energy of the 13.5-nm EUV changes when the gas flow rate changes; Figs. 17.7 and 17.8 show this plasma-dynamics variation.

Although it is important to understand the basic characteristics of EUV radiation at a low repetition rate, characterization at a high repetition rate is also of great interest, because 7-kHz operation will be required in the future. For this purpose, the same measurements were made at 2-kHz repetition rate. The EUV energy stability is shown in Fig. 17.9, and summarized data are listed in Table 17.1. In the specifications for a commercial EUV source, the dose stability of EUV energy over 50 pulses is included. The data in Fig. 17.9 are accordingly integrated EUV energies over 50 pulses. Experiments were carried out at gas flow rate of 9 sccm (highest EUV yield in a 1-Hz experiment) and at 21 and 40 sccm. The data shown here are based on the first 200 pulses of a 2-kHz burst. It is very interesting that the experiment at 9 sccm resulted in a dramatic decrease in EUV energy from the beginning of the burst. Among these three cases, 21 sccm yielded the highest on-axis EUV energy and the lowest fluctuation. The difference in EUV energies between low- and high-repetition-rate operation became smaller when the gas flow rate was high. The EUV radiation energy characteristics were then quite different. When the repetition rate is 2 kHz, pulse interval is just 500 μ s, and thermal input causes

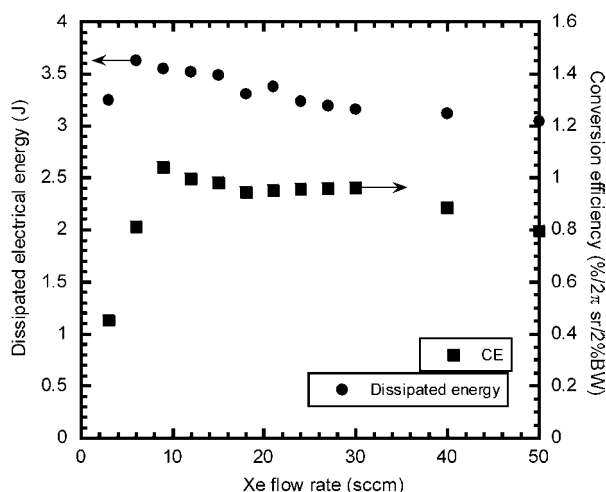


Figure 17.8 Dissipated energy and CE obtained at 1-Hz operation. CE was calculated with 2π sr of solid angle and dissipated energy.

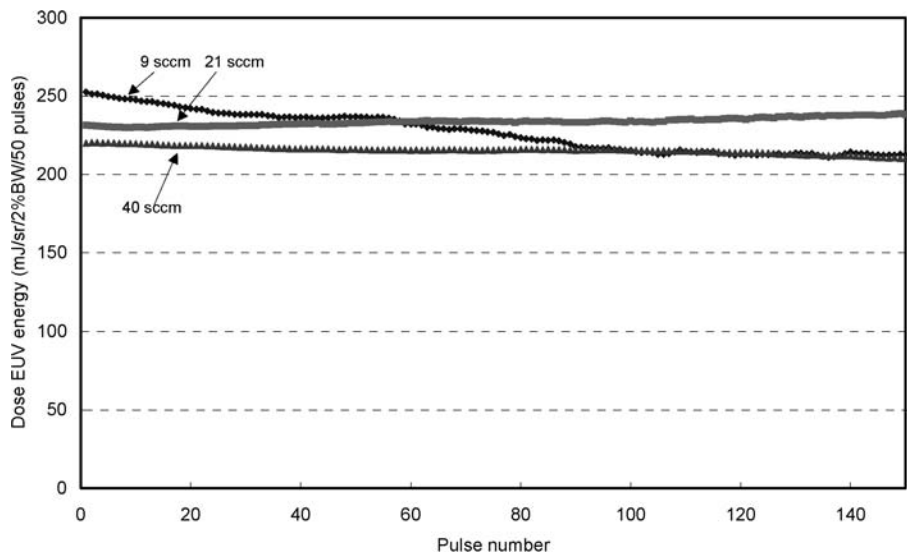


Figure 17.9 Dose EUV energy stability at 2-kHz operation for 9-, 21-, and 40-sccm xenon flow rates. Each data point indicates EUV energy integrated over 50 pulses.

Table 17.1 Summarized data on EUV output.

Xe flow rate	9 sccm		21 sccm		40 sccm	
	1 Hz	2 kHz	1 Hz	2 kHz	1 Hz	2 kHz
Repetition rate						
Averaged EUV energy (mJ/sr), 2% bandwidth	5.87	4.58	5.11	4.68	4.39	4.31
Dissipated energy (J)	3.55	3.43	3.38	3.54	3.12	3.26
Pulse-to-pulse stability σ (%)	6.88	10.8	5.75	3.96	2.54	2.80
Dose stability σ (%)	—	5.6	—	0.98	—	1.1

a temperature rise of the gas and surrounding material (capillary and electrode). With regard to the replacement and properties of the target gas, the flow dynamics and temperature of the gas must be well considered.

17.4.2 Angular distribution of EUV radiation

In the case of the DPP source, almost all schemes seem to have a nonuniform radiation profile. Since a 9-mm-long capillary was used in our capillary Z-pinch plasma, a nonuniform distribution had been expected. In order to confirm it, the EUV energy was measured at different angular positions using ADMs and an FC-II (Fig. 17.3). ADM units were placed at 0, 5, 15, 20, 25, 30, and 40 deg. Altogether eight channels were used simultaneously, including the FC-II (at 10 deg). Figure 17.10 shows the 200-shot-averaged angular distribution of EUV energy in millijoules per steradian (2% bandwidth) for 9-, 21-, and 40-sccm gas flow rates. Only data obtained at 2 kHz are provided here. At each flow rate, there was not a

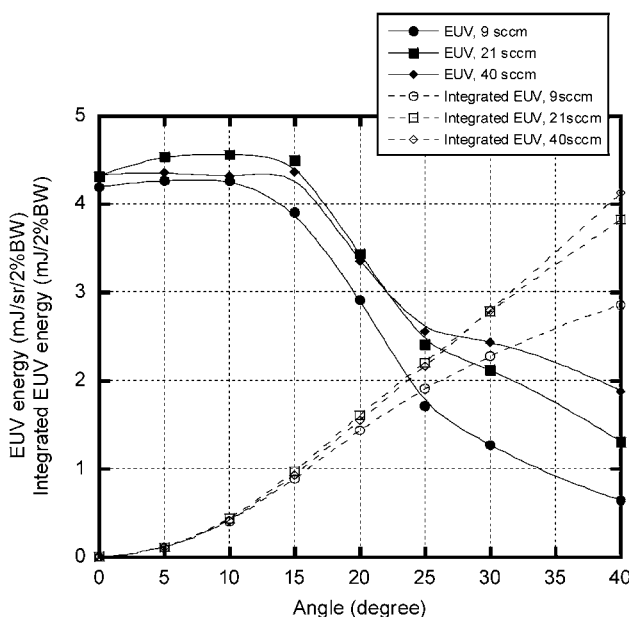


Figure 17.10 Angular distribution of inband EUV radiation observed in 2-kHz operation with 9-, 21-, and 40-sccm xenon flow rate. Integrated EUV energies within 40 deg are also shown (dashed lines).

large difference in the EUV energy from 0 through 15 deg. At larger angular positions, it was clearly seen that a higher flow rate made the profile broader. Therefore, the highest EUV energy (in other words, the highest equivalent solid angle) was obtained at 40 sccm, although the on-axis EUV energies did not differ from each other. On comparing these data with the previously measured data,⁹ the distribution profile was expected to fit the previous data at angles above 40 deg. Therefore, it can be estimated that EUV radiation existed in the region from 0 through about 70 deg. The integrated EUV energy, found by simply summing the EUV energy up to the designated angle, is also shown in Fig. 17.10. According to the following equation,¹⁰ the equivalent solid angle was calculated to be 1.45 sr:

$$\Omega_{\text{eq}} = 2\pi \int_{\theta_{\min}}^{\theta_{\max}} E_{\text{norm}}(\theta) \sin \theta d\theta \quad (\text{sr}), \quad (17.3)$$

where E_{norm} is the normalized EUV energy at each angular position.

Figure 17.11 shows the inband EUV radiation image taken by a pinhole CCD camera from 40 deg off axis. The horizontal and vertical axes indicate the longitudinal and radial directions of the capillary. This figure indicates a very interesting feature of the Z-pinch plasma. The diameter of the radiating plasma ranged from 500 to 600 μm , depending on the gas flow rate. When the gas flow rate was low, the radiating plasma was located upstream inside the capillary. With increasing gas flow rate, it came to cover the whole capillary. Surprisingly, a small portion of

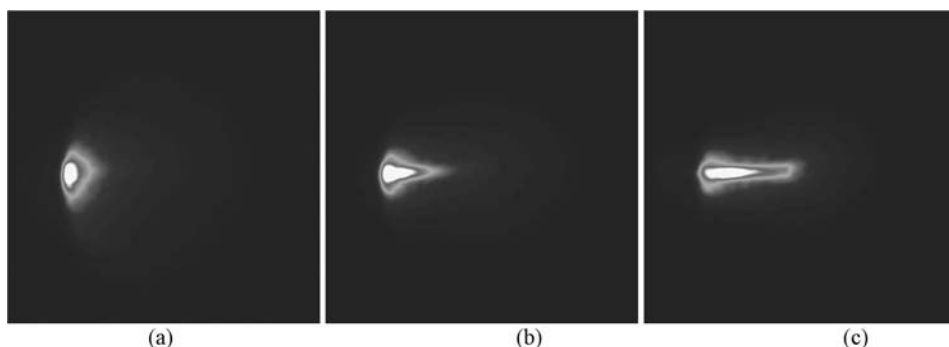


Figure 17.11 Inband EUV radiation images taken by a pinhole CCD camera with two Mo/Si mirrors, for xenon flow rates of (a) 9, (b) 21, and (c) 40 sccm.

plasma ejected from the capillary was observed at 40 sccm of gas flow rate. The length of this plasma ejection was estimated to be a few millimeters. The edge of the capillary is completely open, so that plasma can be ejected to the outside of the capillary during and after the Z-pinch implosion. The broader angular distribution of higher-gas-flow shots was in good agreement with this plasma location. From the viewpoint of collection efficiency of the collector mirror, it is an advantage that radiating plasma is located outside and near the electrode. Also, the higher gas flow rates seemed likely to yield better EUV energy stability. However, the plasma ejection might cause a difficulty. In a DPP EUV source system, a debris-mitigation system must be placed in front of the capillary to prevent debris from damaging the collector mirrors. Plasma ejection, however, could damage the debris shield. There is thus great concern about the interaction between the plasma jet and the debris shield. Further investigation of this EUV image should allow good understanding of the physics of EUV-radiating Z-pinch plasmas.

17.4.3 Total EUV power

Knowing the characteristics described above, we can calculate the EUV power from the source plasma as shown in Table 17.2. All data were obtained from the results of 2-kHz operation. It was experimentally found that the EUV energy increases as I^2T , where I and T are the current amplitude and the current pulse duration. Modifying the output inductance resulted in shortening of the pulse and increase of current amplitude. The value I^2T increased by a factor of 1.5, which almost equals the factor of increase of the EUV power from previously acquired data.

17.4.4 Performance on debris mitigation

The basic concept of the debris mitigation system in a DPP is the change of direction of debris by collision with a gas flow curtain and successive debris trapping on the surface of debris shield plates. A sketch of the debris mitigation system is

shown in Fig. 17.12. A picture of the debris shield plates on the capillary Z-pinch EUV source is shown in Fig. 17.13.

To assess the performance of the debris mitigation system, a contamination analysis of the witness plate surfaces was carried out by a scanning electron microscope (SEM) and by energy dispersive x-ray spectroscopy (EDX). From the data analysis of EDX, a typical result is shown in Fig. 17.14. In this figure the ordinate is a detected amount ratio of contaminants to the substrate material of the witness plate. The results in former sections were obtained mainly with the previous debris

Table 17.2 Latest EUV source output.

Electrical stored energy	14 J/pulse	Equivalent solid angle (0–70 deg)	1.45 sr
Pulse repetition rate	2 kHz	EUV power (2π sr)*	54.4 W
Dissipated electrical energy	3.26 J/pulse	Effective EUV power**	12.6 W
Dissipated electrical power	6.52 kW	CE (2π sr)*	0.83%
On-axis EUV energy	4.33 mJ/sr	Effective CE**	0.19 %
EUV energy stability over 50 pulses (σ)	~1%		

* 2π sr uniform radiation assumed.
**Equivalent solid angle used.

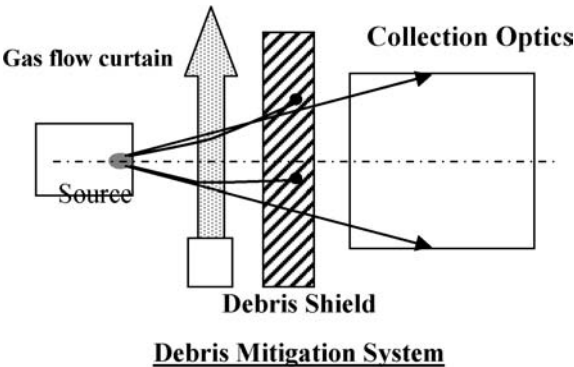


Figure 17.12 Sketch of debris mitigation system applied to an EUV source.



Figure 17.13 The debris shield plates on the capillary Z-pinch discharge EUV source.

shield design. However, its performance has been remarkably improved by optimizing the gas flow rate, the gas outlet location, and the debris-shield design. To date one may say that debris from the capillary Z-pinch source is controllable.

17.4.5 IF profiles of inband EUV radiation

Joint requirements on EUV sources were announced and opened to the public.¹ These requirements are only a provisional guideline for EUV source developers, but without them source developers would lose the direction and sight of the target.

In the joint requirements the EUV source power is specified only at an IF point according to the collector optics for EUV sources. This specification is presumably based on the difference in collector-optics designs and tasks between LPP and DPP sources.

Two types of typical collection optics for capillary Z-pinch EUV sources are shown in Fig. 17.15. In general, a grazing-incidence collector has better collection efficiency than a Schwarzschild collector. However, a Schwarzschild collector consisting of a Mo/Si multilayer has intrinsic wavelength selectivity for inband radiation, while a grazing-incidence collector does not. To date, EUVA has introduced

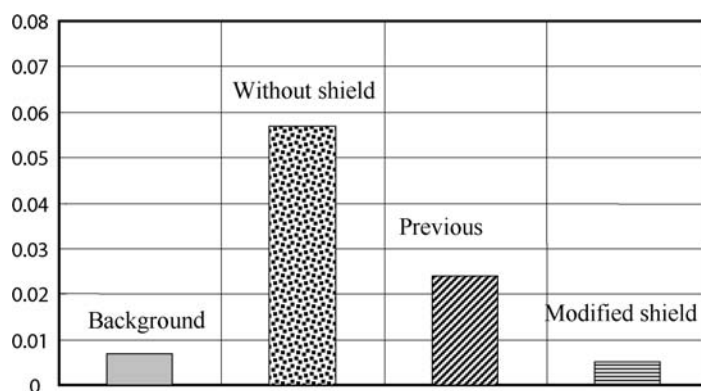


Figure 17.14 Contamination analysis of witness-plate surfaces by SEM/EDX.

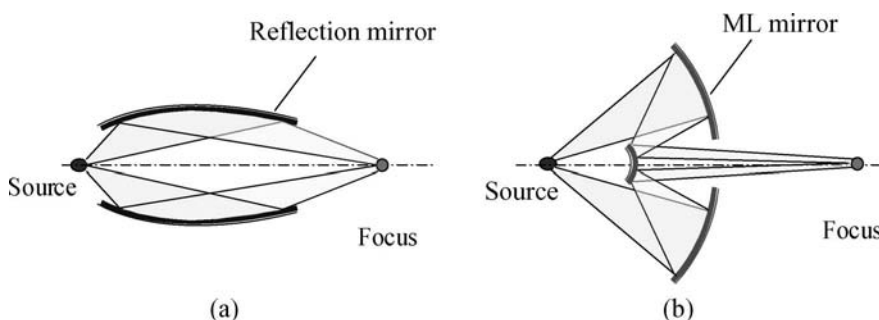


Figure 17.15 Two types of typical collection optics: (a) grazing-incidence collector; (b) normal-incidence collector (Schwarzschild type).

both types of collectors and has established experimental evaluation and simulation tools. The basic procedure of evaluation of the collector optics is shown in Figs. 17.16 and 17.17. Collector mirrors can be aligned in all the directions shown in Fig. 17.16.

IF images can be stored via a CCD camera with a $\text{Zr/Si}_3\text{N}_4$ filter. These images can be analyzed and compared with simulation results. In Fig. 17.17, the slit, which was specially designed as a position index of radiation flux, was inserted between a gas curtain and a collector when a grazing-incidence collector was evaluated.

Typical focus images and analyzed data on energy density distributions are shown in Figs. 17.18, 17.19, 17.20, and 17.21. In Fig. 17.19 the analyzed experimental beam profile at the IF was in good agreement with the simulation results. It has been shown that the focusing capability is good as designed. Adequacy of our simulation tools was also confirmed. In Fig. 17.21 the slight discrepancy at radii larger than 5 mm is due to the absence of part of the focused image from the CCD detector.

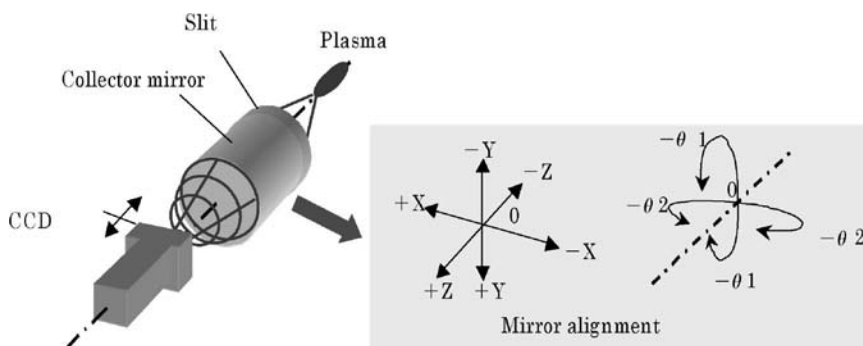


Figure 17.16 Procedure of evaluation of collector mirrors. Mirror alignment parameters are also shown.

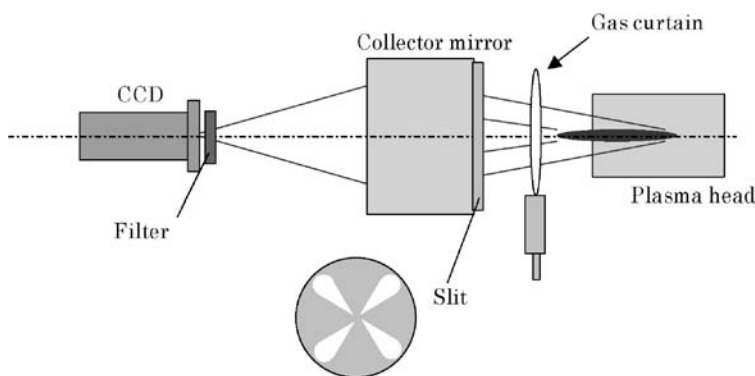


Figure 17.17 Schematic sketch of the evaluation system for collector mirrors. The slit was used only for grazing incidence.

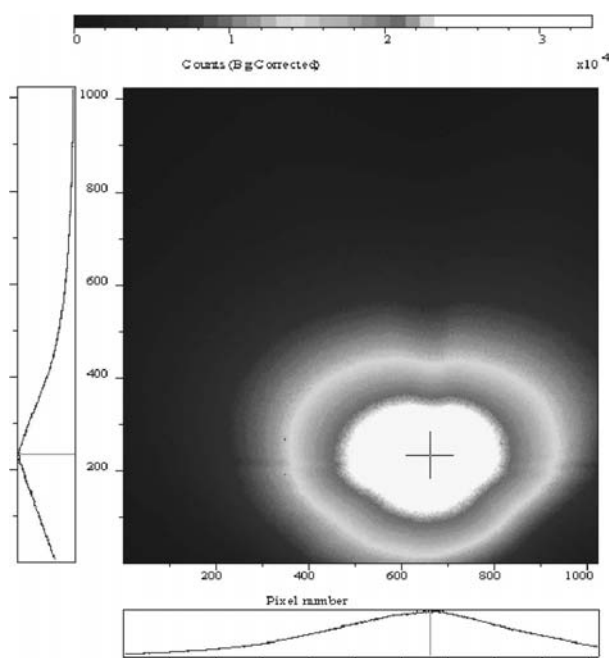


Figure 17.18 Typical IF image observed with a normal incident collector (Schwarzschild type) by using a back-illuminated CCD camera with a $\text{Zr/Si}_3\text{N}_4$ filter.

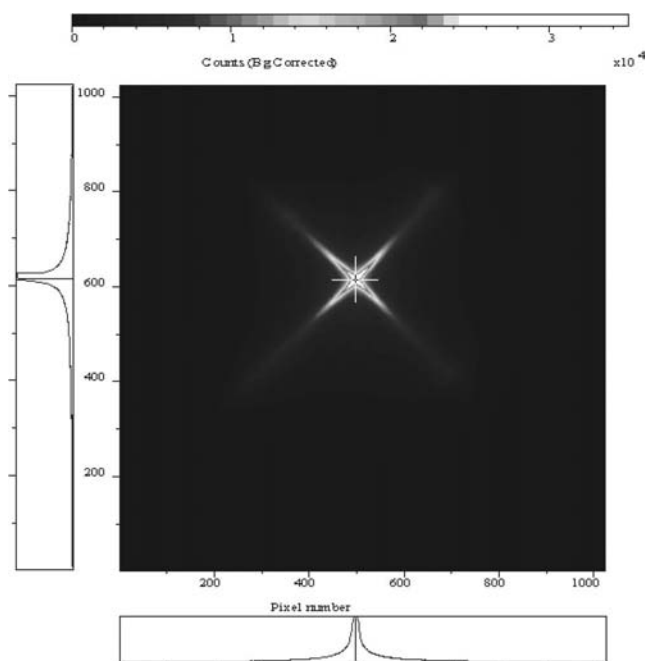


Figure 17.19 Typical IF image observed with a grazing-incidence collector by using a back-illuminated CCD camera with $\text{Zr/Si}_3\text{N}_4$ filter.

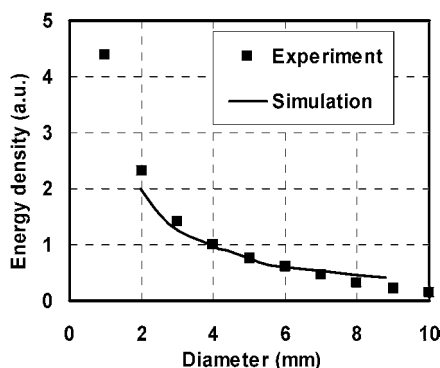


Figure 17.20 Comparison of experimental beam profile at IF with a simulation in the case of a grazing-incidence collector. The result was in good agreement with the simulation.

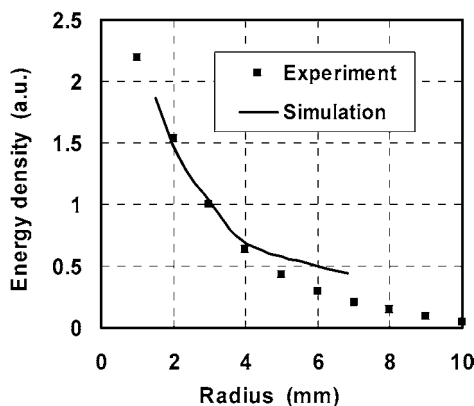


Figure 17.21 Comparison of experimental beam profile at IF with a simulation. The result was in good agreement with the simulation in the case of a normal-incidence collector (Schwarzschild type).

17.5 Conclusions

This chapter described features and characteristics of the capillary Z-pinch EUV source. An EUV source power of 54.4 W (2π sr, 2% bandwidth) was achieved in 2-kHz operation. At this time, a power of 121 W (2π sr, 2% bandwidth) has been achieved with a newly developed source in 7-kHz operation. An IF power of 8.4 W has been obtained with the use of a single grazing-incidence mirror. Lifetime tests for electrodes and collector mirror have started, and a component lifetime of more than 10^7 shots has been checked so far. Although the lifetime of neither electrodes nor collector optics meets the requirements yet, the causes of the problem have always been identified.

Using our experimental test stand, many aspects of the radiation characteristics were evaluated. The properties of the EUV output power in 2-kHz operation were different from those at low repetition rate. The angular distributions of inband EUV

radiation were explained, and the equivalent solid angle was calculated as 1.45 sr. Inband EUV images taken by a pinhole camera showed very interesting behavior of the radiating plasma in the capillary and explained the angular distribution of radiation. Moreover, two types of collectors were introduced, and EUVA has established experimental evaluation and simulation tools.

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Chapter 18

Plasma Capillary Source

Željko Andreić, Samir Ellwi, and H.-J. Kunze

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18.1 Introduction

Capillary discharges provide a simple means to produce hot and dense plasmas that are brilliant radiators in the EUV and soft x-ray spectral regions. Early investigations by Bogen et al.¹ revealed strong line emission down to 3 nm, and McCorkle was the first to point out a possible application to lithography.²

Capillary discharges are usually compact, allow efficient energy coupling, and are characterized by a small diameter-to-length ratio. The radiating hot plasma is either produced from a gas filling the discharge tube or, when operated at near-vacuum, from material ablated from the wall by an initial sliding spark, radiation from the hot plasma and heat flow to the wall providing further wall ablation. The smaller the capillary diameter, the stronger the wall ablation is. Also, a two-step operation employing a prepulse to evaporate wall material for the main discharge has been demonstrated.³ Gas-filled capillaries have diameters typically larger than 1 mm, the diameters of ablative setups being 1 mm and smaller.

The high current through the capillary results in pinching of the plasma to form the hot plasma column along the axis. In fast discharges this pinch effect is preceded by a cylindrical shock wave with consequent heating. Although in quasi-steady state, standard Z pinches are inherently unstable against the growth of the

$m = 0$ sausage and the $m = 1$ kink instability over an Alfvén transit time, in capillary discharges weakly ionized plasma and/or the influx of ablated wall material more or less bridges the region between the wall and the hot plasma column and stabilizes the latter. Exceptions are possible, and the plasma becomes unstable if conditions can be found under which the plasma indeed is fully detached from the wall.⁴

Capillary discharges can be characterized also by the period of the discharge and consequently by the current driver. Extremely fast discharges with a first half-cycle duration of the current well below 100 ns are driven by transmission lines, which are pulse-charged by appropriate Marx generators. Operation of such fast discharges is usually at high voltages. The fast rise time is mandatory for driving collisionally excited soft-x-ray lasers,⁵ but the short duration of EUV emission discourages application to lithography, where the delivered radiant energy is important. An extraordinarily short duration of emission, 5 ns, has been achieved in a device that combines the features of a transient hollow-cathode discharge with the inherent characteristics of a capillary discharge.⁶ Half-cycle durations of 100 ns and above are achieved by conventionally discharging capacitors but in carefully designed low-inductance arrangements. Rather straightforward designs of the discharge circuit are used for pulse durations of 0.5 μ s and longer.

18.2 Theoretical Modeling

Modeling of capillary discharges is, in principle, modeling of Z pinches, which is extensively discussed in Secs. 18.2.4 to 18.2.6 of this chapter. Depending on the degree of sophistication, this involves solving either a simple shock-wave or snowplow model⁷ combined with the equation of the electrical circuit, or solving the complete magnetohydrodynamic (MHD) fluid equations.⁸ Through a particle source term and a radiative loss term, the plasma equations are coupled further with the set of kinetic rate equations governing ionization and recombination of the atomic species in the plasma and the excitation of their levels and hence the emission of radiation. At high plasma densities radiative transport must be considered too. In contrast to most classical Z-pinch discharges, the main process that must be taken into account in addition in capillaries is the ablation of the wall material. It is heated and ionized, which can lead to a significant redistribution of the electric current and thus to a change of the pinch dynamics. In general, most simulations describe the plasma formation in capillaries sufficiently well and thus may be used for scaling and design purposes.

18.3 Gas-Filled Capillaries

Tubes of gas-filled capillaries are usually of polyacetal $[(CH_2O)_n]$, of quartz, or of a ceramic, the last leading to the least contamination of the hot plasma by impurities, the dominant one usually being oxygen. For applications in the VUV at sufficiently long wavelengths, capillary discharges can be designed to emit at the

blackbody limit within a narrow wavelength interval at selected wavelengths. The resulting radiant energy thus depends only on the temperature of the plasma and the duration of emission. The crucial quantity is the optical depth of a line, which in the case of Doppler broadening is given at the line center λ_0 by

$$\tau(\lambda_0) = \pi r_e \lambda_0^2 f_{qp} n_i(q) \ell \left(\frac{Mc^2}{2\pi k T \lambda_0^2} \right).$$

Here r_e is the classical electron radius, f_{qp} is the absorption oscillator strength from the lower level q to the upper level p , $n_i(q)$ is the population density of the lower level q , M is the mass of the ion, and ℓ is the length of the emitting plasma. For $\tau(\lambda_0) > 3$ the radiance of the line has approached the Planck curve to better than 5%.

The emission of such a pseudo-Planck radiator at four wavelengths between 70 and 80 nm was demonstrated by Juschkin et al.⁹ The capillary was a 9-cm-long ceramic tube of aluminum oxide with an inner diameter of 6 mm. The capacitor bank was selected to be 4.8 μF , which corresponds to an initial electrical energy of 240 J when charged to 10 kV. With a resistance of the plasma channel of 0.2 Ω , the discharge was strongly damped; the current rise time was 0.7 μs with a total duration of $\approx 2 \mu\text{s}$.

Discharges with argon and neon filling or mixtures of both were analyzed with initial filling pressures of 5 to 100 Pa; filling pressures around 20 Pa were found to be optimal. The duration of emission was up to 700 μs . Figure 18.1 shows a

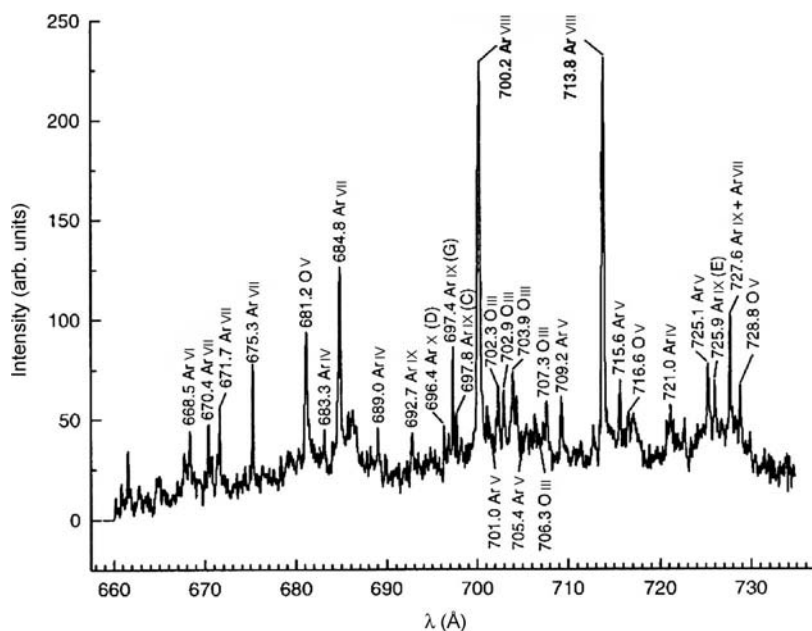


Figure 18.1 Spectrum of a discharge with argon filling (20 Pa). (Reprinted from Ref. 9 with permission from the Institute of Physics Publishing Ltd.)

time-integrated spectrum between 66 and 73 nm. Both resonance lines of Ar viii at 70.0 and 71.4 nm emit at the Planck limit. The intensities of the two lines are equal; in the optically thin case their intensity ratio is 2:1. The results for the Ne viii resonance lines at 77.0 and 78.0 nm were similar. Time-resolved studies showed a duration of the line emission up to 700 ns.

It is rather straightforward to calibrate the emission at these wavelengths, since a standard VUV source is available. It is a calibrated high-current hollow-cathode source operated at a constant current of 1 A.^{10,11} The emitted energy per unit solid angle in each of the four lines is 0.37 mJ sr^{-1} . A slit installed for differential pumping to reduce absorption by the filling gas limited the usable solid angle; it was determined to be $2 \times 10^{-2} \text{ sr}$.

Studies of discharges with krypton and xenon filling¹² were carried out with the capillary length reduced to 6 cm, which reduced the resistance of the capillary plasma channel to $\approx 0.15 \Omega$. The floating electrode of the spark gap, which serves as the cathode of the discharge after triggering, was changed to a hollow-cathode type: bore diameter 5 mm, depth 9 mm, exit hole 2 mm in diameter. This improved the plasma formation. The emission was recorded in the wavelength region from 5 to 35 nm employing a flat-field spectrograph. The initial filling pressure was varied in the range 10–150 Pa; the charging voltages changed from 5 to 10 kV.

The absolute calibration of the flat-field spectrograph including the microchannel plate (MCP) detector posed some problems, since the reference hollow-cathode arc displays only an extremely weak emission in this spectral region, hardly above the noise level of the MCP. Some approximate calibration was carried out, therefore, by indirect means: spectra both from the arc and from the capillary discharge were recorded on film and compared with each other, taking into account the different exposure times. Figure 18.2 shows spectra of Kr and Xe taken at the time of maximum emission for several charging voltages. It is important to mention that the spectrum in Fig. 18.2 was generated under a different operation regime from that of Juschkin et al.¹²

18.4 Ablative Capillary Discharges

Ablative capillaries allow us to exploit plasmas of solid materials and thus expand our choice of ions capable of producing EUV radiation. The discharge device is even simpler than the one needed for gas discharges, because a fast switch is not needed to apply the high voltage (HV) to the capillary electrodes. The HV can be applied directly to them, and triggering is done by a low-energy HV pulse between a small auxiliary electrode and one capillary electrode. On the other hand, a lot of debris is produced, and capillaries have limited lifetime, both of which effects seriously restrict the utilization of such a device in applications where a high repetition rate and/or absence of debris are required.

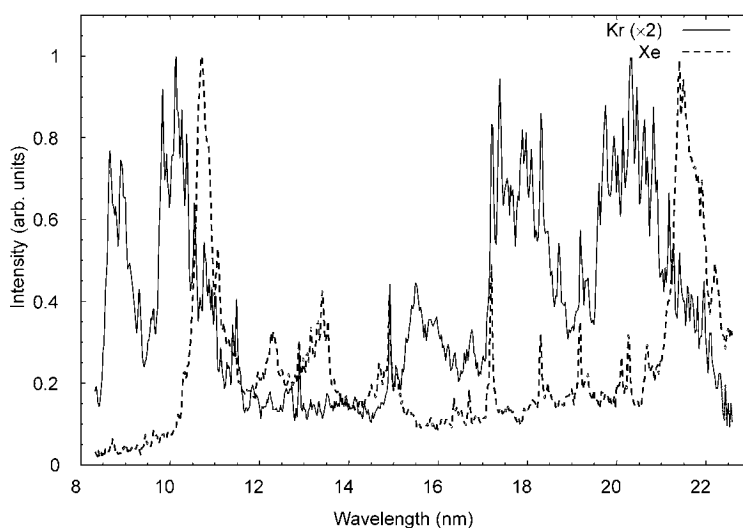


Figure 18.2 Kr and Xe spectra in the EUV region.

18.4.1 Polyacetal capillary

Polyacetal (POM) is a standard material for ablative capillaries. It is robust, withstands many discharges, and does not produce too much debris. In the last few decades ablative capillary discharges utilizing POM as the capillary material have been extensively studied in connection with EUV lasing of the C VI Balmer α line at 18.2 nm. The noncoherent spectrum of a plasma produced in a POM capillary is dominated by strong O V and O VI lines. Similarly, capillaries made of polyethylene are almost oxygen-free, and their spectrum is dominated by carbon lines. The broad peak around 13.5 nm is composed of individual C VI and C V lines, some of which are lines of shorter wavelength whose higher spectral orders appear here. The intensity of this “peak” is very low, and hence the polyethylene spectrum in Fig. 18.3 was multiplied by factor 5 relative to the POM spectrum to make details visible.

The spectrum of the POM plasma is of some interest for us because POM is often used as the capping material for the PVC capillaries and thus contributes to some extent to the EUV spectra of such composites.

18.4.2 PVC capillary

A few years ago¹³ we found out that capillaries made of PVC, which was never used before in such applications, are capable of producing intense bursts of EUV radiation around the very interesting wavelength of 13.5 nm. Figure 18.4 shows a typical spectrum recorded at the time of maximum emission. The narrowband emission at 13.5 nm matches the reflectivity curves of Mo-Si mirrors. The same peak is also seen at 27 nm in the second spectral order of the spectrograph

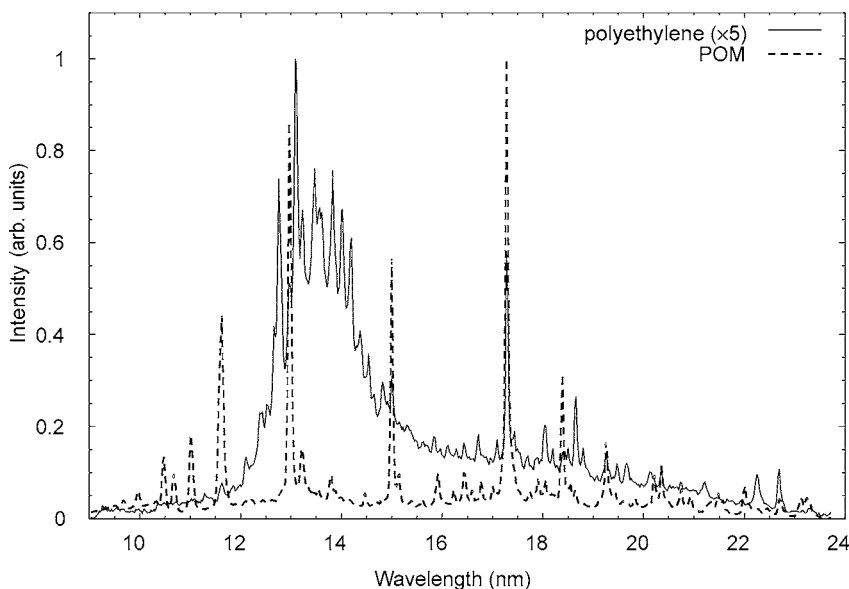


Figure 18.3 Typical EUV spectra of a polyacetal (POM) and a polyethylene capillary. The intensities of the polyethylene spectrum are multiplied by a factor 5 relative to the POM spectrum.

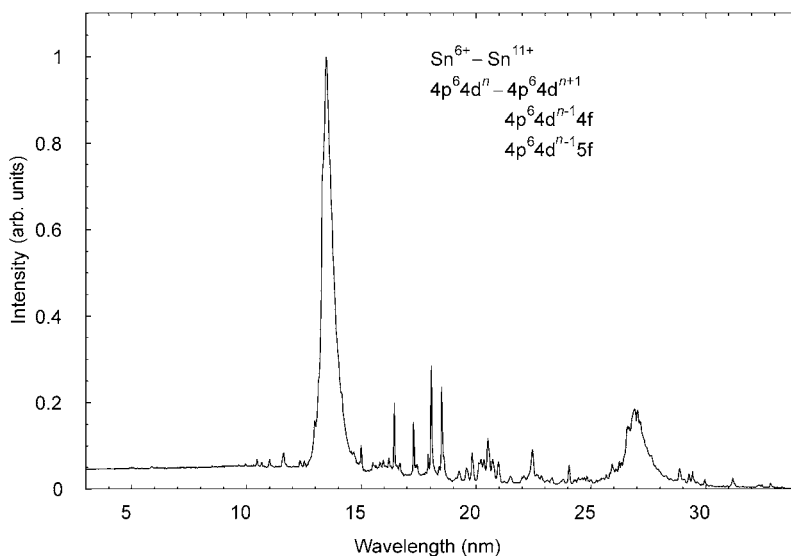


Figure 18.4 EUV spectrum of a PVC capillary at the time of maximum emission. The 13.5-nm peak is also seen at 27 nm in the second spectral order.

employed.^{14,15} The remaining weak lines correspond as before to strong transitions in O V and O VI. The great advantage of this source over other sources is evident from the figure: apart from the strong 13.5-nm band, very little EUV radiation is produced in the spectral region shown. As a consequence the source has the

potential of very high efficiency, and, in addition, the thermal load from the out-of-band radiation on any collection optics is greatly reduced for the same inband power.

On comparing this spectrum with spectra of LPPs,^{16–18} it becomes evident that the emission band corresponds to unresolved transition arrays (UTAs) of the type 4p-4d, 4p-4f, and 4d-5f in multiply ionized Sn^{Z+} ions, where Z is between 5 and 12. The extremely narrowband emission (FWHM of about 4%) is in striking contrast to the emission of LPPs. Studies done by O'Sullivan and Faulkner on LPPs with a varying amount of Sn in the plasmas¹⁷ suggest that this is connected with the low concentration of Sn in PVC. For example, the concentration of Sn in the PVC we used is around 0.4%.

Extensive studies showed that, for the device used, capillaries with bore diameters around 0.8 mm and lengths between 20 and 40 mm are optimal. PVC alone produces a lot of debris, which after a few shots also causes triggering problems. This specific problem was solved by using composite capillaries (Fig. 18.5), where a PVC capillary is capped at both ends with short pieces of POM capillaries. Such a form of construction reduces triggering problems, extends the lifetime of the capillary almost tenfold, and allows the use of larger discharge energies. The comparison of spectra recorded with a bare PCV capillary and those from composite capillaries having the same length of the PVC part showed that the 13.5-nm peak



Figure 18.5 Construction of a typical PVC capillary. The end caps are typically 5 mm in length, while the PVC section in the middle has a length between 20 and 30 mm.

is hardly affected by the capping. The only observable effect is that the intensities of the O V and O VI lines are increased by about 30%.

Figure 18.6 shows the spectrum at the time of maximum emission for various discharge voltages. At higher voltages the intensity of the 13.5-nm band rapidly increases, but the lifetime of the capillary decreases drastically. Above 14 kV only a few shots are possible before capillary breakdown. Also, the conversion efficiency (CE) at higher voltages starts to drop. The CE is defined here as the ratio of total inband EUV energy (integrated over the time of the discharge) to the total electrical energy initially stored in the discharge capacitors. Figure 18.7 displays this efficiency as a function of the electrical energy. A maximum is observed at the input energy of 5 J, corresponding to a charging voltage of 10 kV.

Lifetime studies were performed at a charging voltage of 8 kV and are shown in Fig. 18.8. After 300 discharges the EUV emission has dropped by about a factor of 2 and the inner diameter of the capillary has increased from 0.8 to 1.2 mm, which reveals an average wall erosion of $0.7\text{ }\mu\text{m}$ per discharge, or an ablation of about $10\text{ }\mu\text{g}/\text{cm}^2$ per discharge.

The absolute calibration of the emission was done with recently developed tools: a multilayer (ML) calibration setup known as Flying Circus (Sec. 18.5.1) and an energy monitor constructed by AIXUV, optimized for 13.5 nm and 2% bandwidth (Sec. 18.5.2).

With both calibration tools the emission characteristic was also determined: it is more or less fixed by the geometry of the capillary setup, and the FWHM of the radiation cone is about 40 mrad. This corresponds to inband radiant energy of $0.48 \pm 0.02\text{ mJ}/\text{sr}$.

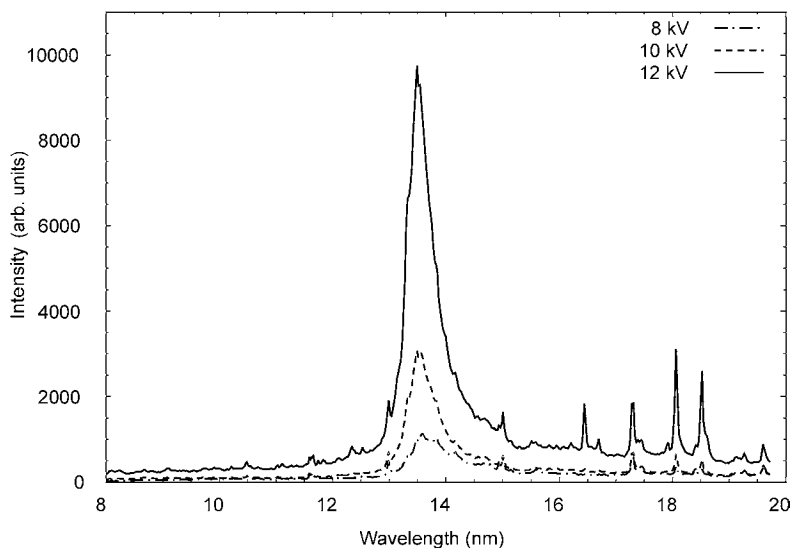


Figure 18.6 EUV spectrum of a PVC capillary at time of maximum emission for different discharge voltages.

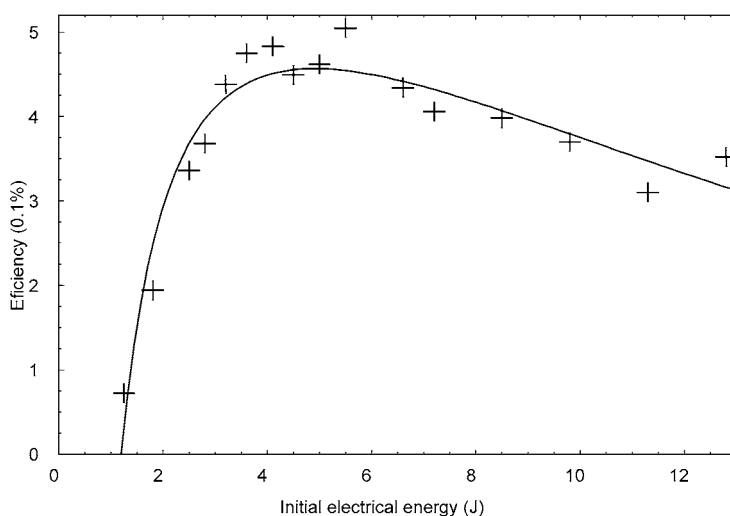


Figure 18.7 The CE as a function of input electrical energy.

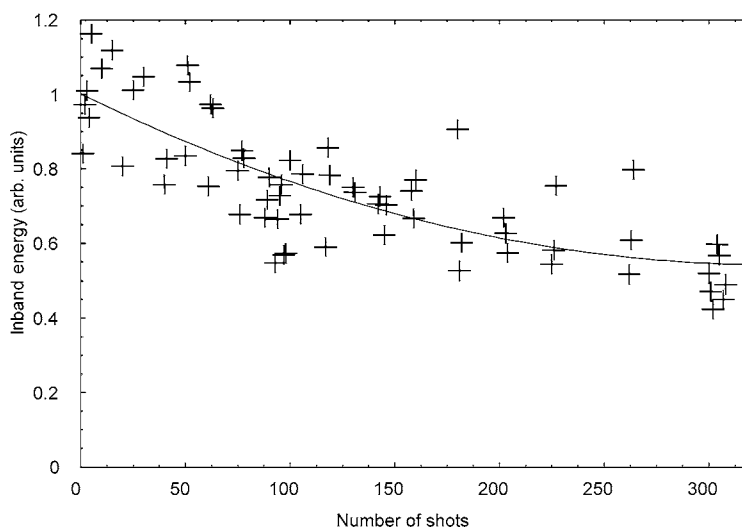


Figure 18.8 Variation of inband energy as a function of the number of shots done through the particular capillary.

18.5 Different Additives

Sn is not the only candidate for EUV-band emission. By using additives with Zn content^{19,20} we were able to produce emission bands at 10 and 15.5 nm, and these are certainly not the only possibilities (see Fig. 18.9). One very attractive possibility is to shift the emission band to shorter wavelengths and to enter the “water window,” which is of great interest for future EUV microscopy of biological spec-

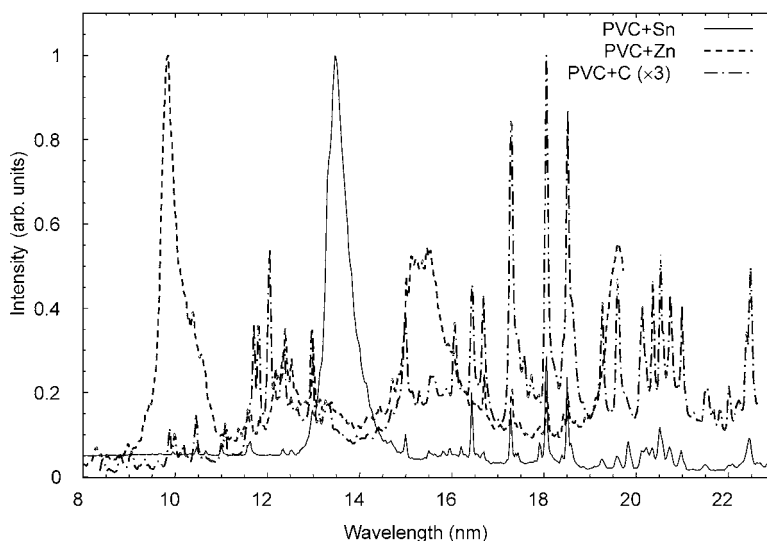


Figure 18.9 Different chemical elements in PVC additives can produce very different EUV spectra, or even suppress the band radiation totally.

imens. Research on this topic is in progress. On the other hand, the addition of carbon in the form of soot (a standard procedure to make black PVC) kills the band emission totally and leaves the usual EUV line spectrum similar to that of POM.

18.6 Conclusion

In conclusion, inband EUV radiation can be produced with high efficiency by employing a PVC ablative capillary discharge. However, these discharges are only suitable where low EUV power is asked for—as, for instance, for EUV MLM calibration, EUV mask inspection (which requires high power and high brightness), and EUV spectrometer calibration. It will be extremely difficult to develop this into a source for EUVL because of the ablation from the wall of the capillary, which limits the lifetime, causes problems with the discharges themselves, and last but not least, produces debris that will damage the MLM optics. These features are certainly inherent in all ablative capillary discharges. As the spectrum showed no indication of self-absorption, it is possible in principle to increase the efficiency further by simply employing PVC with a higher concentration of Sn. A CE of 2.4% with a Sn concentration of 2% in PVC seems entirely feasible.

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Chapter 19

Technology for LPP Sources

Uwe Stamm and Kai Gäbel

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19.1 Introduction

The availability of EUV light sources, measurement tools, and integrated test systems is of major importance for the development of EUVL to be used in high-volume chip manufacturing, which is expected to start in 2009. For economic use of EUVL, a throughput of 100 wafers per hour will be necessary, as estimated from the cost of an EUV exposure tool in combination with sophisticated throughput models. This means that light sources will be necessary that deliver an EUV output power of 115 W at 13.5 nm at the entrance of the illuminator system. The choice of the wavelength is derived from a general convention to use Mo/Si-based reflection coatings on the near-normal-incidence mirrors of the lithography system. The power specification in combination with the required lifetimes of source components and collector optics makes the source technology the most critical issue in developing EUVL. LPPs as sources for EUV radiation are a promising technical approach because of their physical principle, which allows one to manage the

thermal load of source components to provide sufficient component lifetimes. As a result, the EUV output power seems to be scalable to high-volume manufacturing (HVM) requirements.

At XTREME technologies GmbH—a joint venture of Lambda Physik AG, Göttingen, and Jenoptik LOS GmbH, Jena, Germany—EUV sources based on the generation of a plasma by an electrical gas discharge and by laser excitation have been investigated and developed since 2001. This chapter gives an overview of the basics of LPP EUV sources and their technology, the development roadmap, and the current state of the art of these light sources at XTREME technologies. An overview of GDPP EUV sources at XTREME technologies is contained in Chapter 14.

19.1.1 Roadmap

The roadmap for the development of EUV sources until the stage of HVM using EUVL requires so-called microexposure tools (α and β tools), as well as early pre-HVM tools, for the development of the technology. Some of the leading semiconductor manufacturers are expected to ramp up EUVL for HVM at the beginning of 2009, in parallel with 193-nm immersion excimer laser lithography. To support this roadmap, first microexposure tools with small field size were installed in the semiconductor industry as technology pathfinders in 2004. α tools needed to be equipped with sources with 5-W output at lithography exposure-tool manufacturers in 2004. β exposure tools required 15-W EUV sources in 2005. Pre-HVM EUV exposure tools will need the integration of sources with 25–50-W power in late 2006. Finally, HVM sources with 115 W power will be needed starting in 2008.

19.1.2 Requirements for EUV sources for HVM

Lithography exposure-tool manufacturers have agreed to joint top-level specifications of the EUV source performance for HVM using EUVL. The specifications for various EUV source parameters are summarized in Table 19.1. The collector optics module separates the plasma EUV generator from the illumination optics.¹

The specifications of the EUV source parameters listed in the table hold for the focal plane behind a first-source collector optics. This optics separates the source from the EUV exposure tool. The focal plane defines a clear interface between source and exposure tool—it is often called the *intermediate focus* (IF). How tremendous these power requirements on LPP EUV sources are becomes clear when the beam path in the source collector from the plasma to the IF is considered. A schematic view of the LPP source collector module is shown in Fig. 19.1.

The source collector to a large extent surrounds the LPP EUV plasma source and is therefore deeply integrated into the source. In Table 19.2, estimates of the necessary EUV power emitted into a 2π -sr solid angle are made, based on the 115-W EUV power specification in the IF for HVM LPP sources. Problems in achieving the necessary power may result from the requirement that the EUV emission volume must show a diameter of about 1 mm or smaller because of the etendue limit defined by the optical system of the exposure tool (see Table 19.1). EUV light

Table 19.1 Requirements for EUV source parameters to be installed in EUVL HVM tools.

Source parameter	Requirement
Central wavelength	13.5 nm
EUV power (inband) at IF	115 W
Repetition frequency	≥7000–10,000 Hz
Integrated energy stability (3σ, over 50 pulses)	<0.3%
Maximum solid angle of input to illuminator	0.03–0.2 sr
Maximum etendue (area × solid angle)	3.3 mm ² sr
Illuminator optics lifetime (behind IF)	30,000 h

Table 19.2 EUV power emitted into a 2π-sr solid angle necessary for HVM LPP sources to achieve 115-W power at the entrance of the illuminator optics system (IF) of the EUV exposure tool.

Etendue acceptance factor	1.0
Transmission of debris mitigation/obscuration	0.95
Transmission of gas in source collector module	0.9
Angle-averaged collector reflectivity	0.50
Required power from the source within the collection angle	269 W
Geometrical collector efficiency with respect to 2π sr	0.8
Required power from the source emitted into 2π sr	336 W

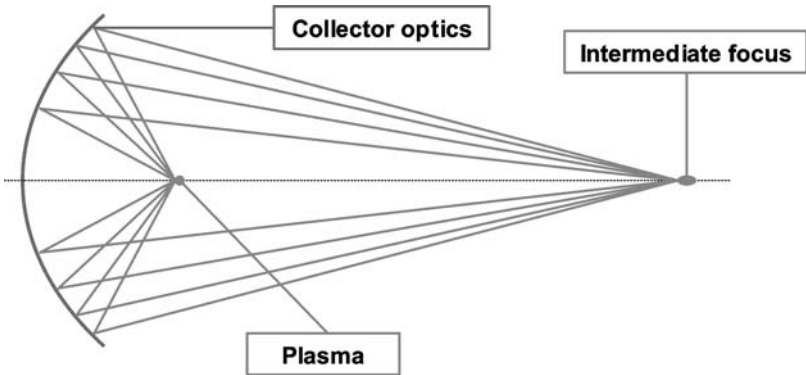


Figure 19.1 Schematic view of an LPP collector module.

emitted from larger volumes cannot be transmitted through the optical system of the EUV exposure tool. The optical system of the exposure tool determines which fraction of the EUV volume in the IF can be used. Ideally, the *etendue acceptance factor* is 1. Laser plasma sources excel in high brightness and small plasma dimensions (see below), and hence are advantageous with respect to the etendue as compared with DPP sources, which tend to generate a plasma of larger dimensions (see Chapters 12, 13, and 14). For the HVM EUV sources an etendue acceptance factor equal to 1 is therefore realistic.

Additional geometrical losses occur because of the limited collection angles of typical collector optics, which collects only a fraction of the EUV emission from

the plasma. Because of the small, high-brightness plasma, LPP collectors may be designed to collect radiation emitted into a solid angle of up to 5 sr. This is about 80% of the power emitted into a solid angle of 2π sr. Further losses arise from the limited reflectivity of the collector optics, about 50% averaged over all angles. The absorption by the gas around the target—which is used for debris stopping—is expected to amount to about 10%. Debris stopping is needed to protect the collector optics from degradation by energetic particle bombardment. Taking into account these losses, the required power from the EUV source into 2π sr amounts to about 340 W for the HVM LPP sources. Also under discussion is the possible need for an additional spectral filter in the beam path, which could increase the power requirement by another factor of 2. However, because of the additional loss of 50%, the use of a spectral purity filter is likely not an option for EUVL. Compared, for example, to 193-nm excimer laser lithography, where 20 to 40 W of power out of the laser is available, the power requirement for EUV sources is extremely high.

19.1.3 Challenges for HVM EUV sources

For LPP HVM sources we see two major challenges. The first challenge results from the required power. As discussed above, the necessary output power for HVM sources amounts to 340 W in 2π sr in 2% bandwidth at 13.5 nm. The conversion efficiency (CE) from laser light into EUV inband radiation in 2π sr is expected to reach 1% or slightly higher values for HVM sources with xenon targets, or 3–4% with metal targets such as tin or lithium, based on experimental data achieved today (see below). Metal-fueled sources, however, will likely require mitigation devices to prevent the deposition of metal on the collector optics. Today it is not clear how much loss these devices will introduce into the EUV beam path. In the most optimistic prospect, no additional losses will be introduced; in a more realistic one, additional losses may reach 50%. Therefore the driver lasers should have about 34,000 W (8500 to 24,000 W) of power to excite a xenon (a tin or lithium) target. The most powerful commercial solid state lasers have been developed for machining applications such as welding. These lasers operate continuous wave (cw) with an average power of up to 6 kW. However, pulsed Q -switched laser systems with single-pulse duration of about 10 ns are required for the EUV source application. Hence, it will be crucial for EUVL source development based on LPP technology to build highly efficient lasers with reliable modules of proven design.

The second challenge of any LPP EUV source is to ensure a long lifetime of the collector mirror, which faces the plasma directly. Mitigation of debris (e.g., particulate emission from the source) and related effects on collector lifetime are currently under intense investigation, not only at XTREME technologies. Although debris mitigation schemes (see sections below) to realize reasonably long collector lifetimes look very encouraging, the final achievement and the verification of these lifetimes will require considerable effort, because only rather limited data at high-average power are available today, and measurement procedures are not yet adequately established; furthermore, almost no experience exists with respect to

the long-term behavior of optics under the harsh radiative conditions of a lithography source.

19.2 Physics of LPP-based EUV Generation

19.2.1 Physical principle of LPP

At XTREME technologies, the most promising approach for EUVL sources—the excitation of a very hot plasma—is employed. This is a well-known method that has been used in research laboratories for many years. The spectral emission properties of the plasma are approximately described using Planck's formula for blackbody radiation. The temperature T of the plasma determines the maximum emission wavelength $\lambda_{\max}$:

$$\lambda_{\max} = \frac{2898 \text{ } \mu\text{m K}}{T}$$

or

$$\lambda_{\max} = \frac{250 \text{ nm eV}}{T}.$$

For the emission maximum to be positioned at 13.5 nm the temperature of the plasma must be about 220,000 K. This plasma temperature can be reached either by excitation through a pulsed electrical discharge (gas DPP) or through pulsed laser radiation (LPP). In comparison with the excimer laser radiation currently applied in DUV lithography, the plasma emission is incoherent and more or less isotropic (emission over 4π -sr solid angle).

Exciting a plasma with a laser beam is a promising approach for an EUVL source, because the EUV-emitting plasma can be generated at a large distance from any hardware. So thermal control is readily achieved, and a large solid angle around the source is accessible with the collector optics, allowing high collection efficiency.

When a laser beam impinges on a solid-density target, the leading edge of the laser pulse generates free electrons—in the case of a Nd:YAG laser and a xenon target, via multiphoton absorption. The free electrons are accelerated by the laser field; the mean kinetic energy E_{osc} of the oscillating electrons is $E_{\text{osc}} = (\frac{1}{4})e^2 E_0^2 / (m_e \omega^2)$, with $E_0^2 = 2I_L / (c\epsilon_0)$ the square of the electric field strength in the laser beam of intensity I , e the elementary charge, ϵ_0 the dielectric constant, m_e the mass of the electron, and ω the frequency of the light. The laser beam penetrates into an electron gas below a critical density $n_{\text{crit}} = \omega^2 m_e \epsilon_0 / e^2$ at which the refractive index becomes imaginary and the light will be reflected. The critical density varies with the laser wavelength; typical numbers are 10^{19} e/cm^3 for a CO₂ laser (wavelength of 10 μm) and 10^{22} e/cm^3 for an excimer laser (wavelength of 248 nm). The electrons collide with ions, and the plasma is heated. For

laser pulses not too short and for sufficiently high densities (e.g., for collisionally dominated energy transport), electrons and ions can be characterized locally with a common temperature.

Inverse bremsstrahlung (the electrical field accelerates electrons individually) is the dominant absorption mechanism for laser intensities below 10^{13} W/cm², which are typical of those used to drive an EUV plasma. The absorbed energy is transferred into radiation, excited by collisions or recombination, and into kinetic energy of the ions, e.g., in plasma expansion. Since the efficiency of inverse-bremsstrahlung absorption (IBA) decreases rapidly for densities below the critical density, the expansion leads to a diluted plasma, which becomes transparent to the laser light. This sets an upper limit on the pulse width of the driver laser of the order of 10 ns.

The CE of laser energy in a narrow EUV band was estimated by Silfvast et al., assuming the plasma as a blackbody radiator.² At a blackbody temperature of slightly above 20 eV the spectrum peaks at 13.5 nm. It should be noted that the emitted energy scales directly with the duration of the excitation, i.e., the laser pulse duration. The associated laser intensity is estimated, by the scaling law for a collision-dominated plasma and by using an experimental factor for typical EUV plasmas, as $T = 2.8I_L^{4/9}$.³ According to this calculation, the maximum CE of about 1.5% is obtained at a laser intensity of 2×10^{11} W/cm². Although a very simple model was used to derive the CE and the laser intensity, both values agree surprisingly well with experimental data.

For more detailed theoretical descriptions, we refer readers to the modeling chapters in Section II of this book. Modeling an EUV plasma requires advanced numerical methods because of the gradients of the density and the temperature, their dependences on the laser wavelength, the radiation transport in the plasma, and the hydrodynamics, which vary with the detailed experimental conditions.

19.2.2 Emitter materials for LPP sources

So far the laser intensity has been estimated that optimizes blackbody radiation in a narrow band at 13.5 nm. The radiative properties of the plasma can be further tailored by the selection of the emitting element.

Several groups have investigated the efficiency of EUV generation from low-*Z* elements, such as Li and O-F, which emit a few separated lines in narrow bands at 13.5 and 13 nm, respectively.⁴⁻⁷ The highest CE into 2π sr, close to 0.5%, was achieved with a F-rich target excited with the second harmonic of a Nd:YAG laser.⁵

A systematic experimental survey of medium- and high-*Z* elements was performed in the mid-1990s to evaluate the efficiency of EUV laser plasmas as a function of the target element.⁸ Selected elements of atomic number *Z* ranging from 13 to 82 were excited by a Nd:YAG laser with pulse widths between 7.5 and 30 ns, and the EUV efficiency was recorded in a narrow channel at 13 nm. Figure 19.2 gives a graphical summary of the measured efficiency as a function of the atomic number. It should be noted that the highest efficiency for all investigated elements was found at a laser intensity of about 2×10^{11} W/cm².

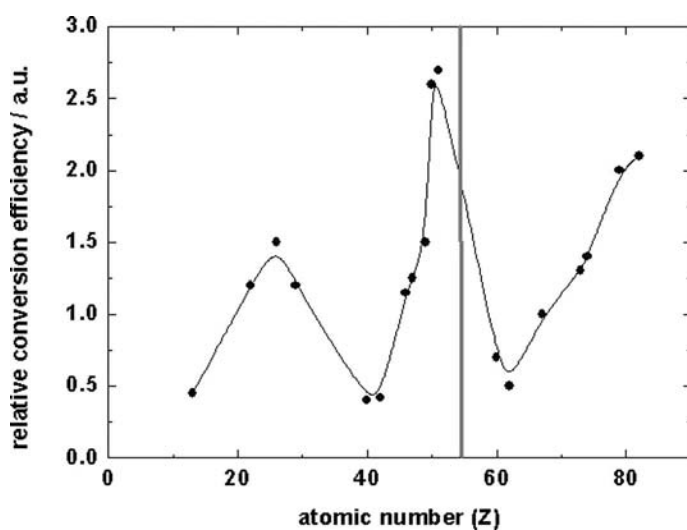


Figure 19.2 Relative CE into 13.5-nm radiation as a function of the atomic number of the emitter. The vertical line represents the atomic number of xenon. Data were taken from Ref. 8.

As a general trend it was observed that the efficiency increased with increasing atomic number. Pronounced maxima appear around atomic numbers 26 and 50. The highest efficiency was achieved with tin and antimony; high- Z elements such as gold were slightly less efficient.

The maximum efficiency at $Z = 50$ can be explained by a manifold of strong 4d-4f transitions that fall into the 13.5-nm band for a range of ionization stages between 8+ and 13+. This emission feature is called an unresolved transition array (UTA), since several thousand transitions occur in a narrow band of roughly 0.5-nm width.⁹ The emission characteristic of high- Z elements is a spectral quasi-continuum with lower spectral brightness.

Recently Hanson et al. reported a CE of 2.7% obtained with lithium targets. The choice of the emitter material is not alone governed by the requirement of high efficiency but also driven by stringent requirements on source cleanliness. One of the inherent requirements on lithography sources is to collect the emitted power in a large solid angle at a wavelength that is highly absorbed in any material. Thus the collection optics must face the plasma without any protective membranes; this implies that the emission of any material that condenses on the optics should be limited to an absolute minimum.

Kubiak et al.¹⁰ suggested the possibility of eliminating condensation of target material on the collector optics by using xenon as the emitter, which offers reasonably high efficiency. The theoretical efficiency of xenon is lower than that of tin, because the strong 4d-4f UTA peaks at about 11 nm, while the 13.5-nm radiation originates from a weaker 4d-5p UTA.¹¹

Nonetheless we have demonstrated a CE of 1% in 2π sr and 2% bandwidth with quasi-mass-limited (see below), xenon-based laser plasma sources at XTREME

technologies. This can be compared with a tin source operated in a very similar geometry of a regenerative tin jet as reported by Jansson et al.¹² A CE of 2.5% in 2π sr and 2% bandwidth was achieved, but during the exposure of only a few thousand pulses tin layers of several nanometers' thickness were condensed on optics samples. Condensation was completely absent in xenon sources. A general discussion of the debris of xenon laser plasmas will be given below.

To address the condensation problem with metal-fueled sources, several advanced concepts have recently been introduced. A diluted tin target with a tin content below 10% was reported with a CE of about 1%, but the condensation was not quantitatively evaluated.¹³ A similar concept of supplying Sn clusters of submicron particles either in a gas flow or in droplets was suggested by Tomie.¹⁴

According to the experimental results obtained so far and assuming realistic experimental progress in the near future, we believe it possible to achieve a CE into 2π sr from dissolved Sn droplets of 3–4%, i.e., 3 to 4 times higher than expected from Xe. Despite the higher efficiency of tin, it may not be possible to use it in laser-plasma lithography sources owing to the difficulties of handling it, the potential losses due to tin or lithium debris, and the resulting short optics lifetimes.

19.3 Laser Target Modifications and Target Handling

While many principal investigations of the EUV emission of laser plasmas were performed with slab targets, the demand for continuous target supply in a lithography source prevents the application of this kind of target. Moreover, the requirement of low debris production in the source cannot be fulfilled with slab targets. The reason is a shock wave, which propagates in the thick slab and causes the ejection of tremendous amounts of material from the bulk.¹⁵ A major improvement can be achieved with tape targets, which can in principle be operated over long periods of time and also reduce the debris ejection, since the shock waves break through the rear surface and eject most of the material there.¹⁶ However, the low-intensity region of the laser beam at the edge also interacts with target material and generates debris in the forward direction.

As a general solution to excessive debris production, the concept of the *mass-limited target* was introduced in the early 1990s.¹⁷ The basic idea of the mass-limited target is to supply only the amount of target material that contributes to the EUV radiation. This ideal target was suggested to consist of a stream of ~ 100 - μ m disks with a submicron thickness that corresponds to the ablation depth. Based on energy considerations, we estimate 5×10^{14} to 5×10^{16} ions per laser pulse as an approximate value for the required emitters, depending somewhat on the exact emitter species and the irradiation conditions.

The most promising method to generate a practical mass-limited target is a stream of droplets of some 10- μ m diameter that is injected into the laser focus.¹⁸ Such a droplet stream is generated by forcing a liquid through an injection system in the EUV chamber. In the case of negligible thermodynamical effects, a continuous liquid cylinder leaves the exit orifice of the injector and decays due to capillary

forces into individual droplets.¹⁹ This decay process is usually enhanced by a resonant pressure modulation to stabilize the frequency of droplet formation.

If an element with a high vapor pressure, such as xenon, is injected into a vacuum chamber, the rapid evaporation of the material leads to freezing of the liquid cylinder before any droplet formation takes place. For example, Hansson et al. used such a continuous frozen xenon needle, commonly called a xenon jet, as a target for an EUV plasma.²⁰ Such a target has the major advantages that the target material can be supplied for an arbitrary period of time, the amount of material that is excited by the laser beam is small compared to that for slab and tape targets, the continuous cylinder does not require any synchronization of the pulsed laser with the target, and a high target density is provided at large distances from the injection nozzle. The large standoff distance leads to a long lifetime of the injection system. The high target density is required for efficient absorption of the laser beam.

The drawback of the continuous needle is that along the needle axis additional material is supplied, which interacts with low-intensity regions of the laser beam. This interaction generates larger debris particles, which impinge on surrounding source components. Moreover, in high-repetition facilities the additional xenon blow-off imposes an unnecessary gas load. Since the target is coupled to the injection system, shock waves excited by the laser pulse might drive the target unstable under the conditions of a lithography source that operates at high average power and high repetition rates.

Figure 19.3 shows these two types of xenon targets that are being investigated at XTREME technologies: the continuous xenon needle and frozen xenon droplets. Today, frozen droplets are the favored solution for a production lithography source, because they constitute a real mass-limited target, and excitation is performed each time on individual, hydrodynamically decoupled volumes. The directional stability of our targets allows for EUV-plasma generation with very low shot-to-shot fluctuations up to standoff distances of several centimeters.

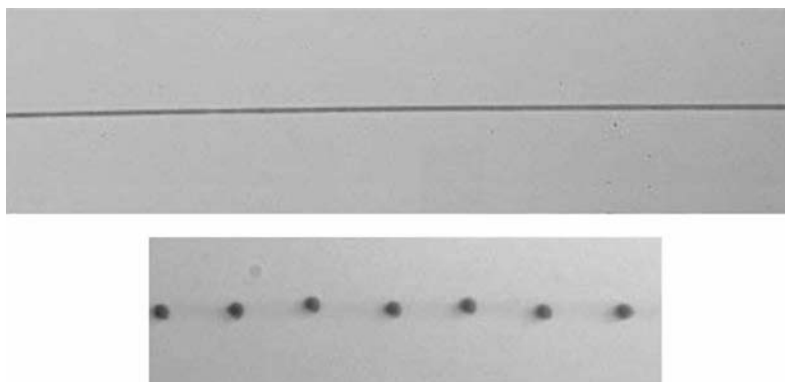


Figure 19.3 Different modifications of xenon targets (top: continuous frozen needle; bottom: frozen droplets) that are being investigated as targets for EUVL sources at XTREME technologies.

It should be mentioned that several low-density targets have been investigated in the past, including gas puffs,²¹ cluster targets,²² and spray targets.²³ These targets have in common that the mass stream is divergent, which allows for efficient laser absorption and EUV generation at distances of only a few millimeters from the nozzle. The small standoff distance, however, leads to high erosion rates at the injector nozzle and prevents thermal control at the power level, which will be required in a production-lithography source.

19.4 Laser-Driver Technology for LPP EUV Sources

The laser technology depends on the pulse parameter values needed to excite an EUV-emitting plasma under optimal conditions and requires technologically robust solutions to generate a stable, high-average-power laser system. Ranges of laser parameters such as the pulse width and intensity were already derived in Sec. 19.2.2.

Since the CE depends on the ion density, and thus the electron density, in the plasma during the emission, optimization can be achieved by choosing the appropriate laser wavelength. An optimum target density was derived from opacity requirements by Tomie¹⁴ for a Sn plasma with 3×10^{18} ions/cm³, and by Masnavi²⁴ by considering transient effects in a Xe plasma with several times 10^{17} ions/cm³. Assuming a mean ionization state of 10+ in both cases, the associated electron density is in the range of about 5×10^{18} to 5×10^{19} cm⁻³, which implies a laser wavelength > 1 μ m. These theoretical predictions are experimentally supported by slightly higher CEs for Sn plasmas with a Nd:YAG laser that is operated on the fundamental frequency rather than on the second harmonic.⁸

Since it is very likely that the required laser power of between 17 and 34 kW will not be achievable with a single laser, multiplexing of several lasers is required to bring the necessary total laser power onto the target. The spatial beam quality of a single laser necessary to achieve the above-mentioned intensities at the target depends on the kind of multiplexing and therefore cannot be specified in a general form. The required beam quality depends to a great extent on the particular scheme for superimposing individual lasers on the target, on the detailed focusing optics, and on the laser wavelength.

Principal candidates for pulsed high-power lasers to drive an LPP EUV source are gas lasers, such as excimer lasers and CO₂ lasers, and diode-pumped solid-state lasers.

DUV excimer lasers are widely used in optical lithography, flat-panel display manufacturing, and ink-jet nozzle drilling in industry. They have been developed into reliable machines, which makes these lasers good candidates for driver lasers for LPP EUV sources. However, we see two reasons why excimer lasers are not the best candidates for LPP driver lasers. First, because of their short emission wavelength in the UV, excimer lasers are by physical principle much less efficient than comparable lasers operating at longer wavelengths. Because the ratio between spontaneous emission loss and stimulated emission is inversely proportional to the

cube of the wavelength, it is about 80 times more difficult to generate the population inversion in a 248-nm excimer laser than in a 1064-nm Nd:YAG laser.

Secondly, as mentioned above, it is probably not possible to achieve the power level required for HVM EUVL from a single excimer laser within the next couple of years, if it is possible at all. The excimer lasers developed for DUV optical lithography in master oscillator–power amplifier (MOPA) configurations have an output power of less than 0.1 kW. The commercial excimer lasers with the highest output power as used in flat-panel display manufacturing have an output power of about 0.3 kW operating at 300-Hz repetition frequency with 1-J pulse energy (for an overview of excimer lasers, see Ref. 25). In research laboratories 1-kW output power has been demonstrated for MOPA excimer lasers. The beam cross section of the high-power excimer lasers is about 30×10 mm.

To get an idea how to achieve the necessary HVM laser power of between 8.5 and 34 kW, one has to consider that the output power of excimer lasers scales linearly both with repetition frequency and with beam cross section. Both parameters are limited by the fact that stable operation of excimer lasers and excimer amplifiers requires the exchange of about 3 to 5 times the gas volume of the beam cross section between two subsequent light pulses. Therefore the maximum power of excimer lasers is limited by the maximum gas velocity in them. Today gas velocities in excimer lasers are in the range 20 to 40 m/s. With future development efforts we believe it might be possible to achieve 100 to 200 m/s in reasonable-size industrial machines. This probably limits the power achievable from a single excimer laser to about 2 kW with a footprint of about $3\text{--}5$ m². For HVM laser power levels, 4 to 17 of these lasers would have to be multiplexed. We believe this will not be feasible with reasonable technical effort and space requirements.

The other gas-laser candidates, the CO₂ lasers, have reached more than 40-kW cw power and are commercially available with 50- to 100-ns pulses and 2-kW average power. However, the repetition rate is limited to a few hundred hertz at this power level, which would require temporal multiplexing of a large number of lasers to obtain the required repetition rate, >7 kHz, for a lithography production source. Moreover, the 10.6- μ m laser wavelength imposes serious constraints on the focusability of the beam. The beam quality ranges between $M^2 = 10$ and 20 for one laser, so that a focal spot as small as that of a Nd:YAG beam, for example, may be difficult to achieve. The most serious concern, however, is the temporal pulse shape, which consists roughly of a 100-ns spike, containing half of the energy, followed by a tail of several hundred nanoseconds' duration. Such a pulse shape does not meet the requirements of efficient EUV generation. It should be noted that the parameter values given are typical ones that could be improved; however, any significant alteration would be accompanied by a decrease of the total efficiency to a value well below 10%.

Because of the serious limitations of gas lasers as the drivers for an LPP EUV source, most of the research is focused now on solid state lasers.

Regardless of concept details, any advanced pump scheme for solid-state lasers is based on continuously operating laser diodes. This pump mode offers low heat

deposition in the active medium, as compared to flashlamp pumping, and long lifetimes of the pump diodes, as compared to pulsed-diode operation.

A more general consideration is the system layout, comprising either a manifold of individual pulsed lasers²⁶ or a few multiplexed MOPA systems.²⁷

In the following we will focus on the most promising concepts to obtain the necessary laser power from systems based on the MOPA architecture. To our knowledge the realization of all required system parameters simultaneously with a single oscillator of several hundred watts would be extremely difficult.

The principal setup of a MOPA laser driving an LPP EUV source is shown in Fig. 19.4. A master oscillator is employed to define the short (nanosecond) pulse width and the repetition rate. The oscillator seeds the amplifier chain via a Faraday isolator. In the shown setup two continuously diode-pumped amplifiers are used to preamplify the injected pulses in a double-pass configuration. The preamplified pulses reach saturation in a single pass through two power amplifiers and are finally focused in the vacuum chamber for EUV generation. Several optics between the amplifiers serve to suppress amplified spontaneous emission and thermal birefringence. Such a laser system was developed in a collaboration between XTREME technologies and the Fraunhofer Institut für Lasertechnik (ILT) in Aachen. The design of the amplifier modules is based on high-power cw laser heads such as are used in commercial welding lasers. The commercial cw lasers achieve an average power of 2 kW in a four-head configuration with an M^2 of about 40. A photograph of one amplifier module is shown in Fig. 19.5. The amplifier uses a Nd:YAG laser rod, which is side-pumped by cw laser diodes.

In the final setup that was employed to drive an LPP EUV source, the beam path was changed so that all amplifier heads are double-passed. The laser generates a maximum power of 500 W at a repetition rate of 10 kHz. The repetition rate can be set to any arbitrary value up to 10 kHz. The pulse width is weakly dependent on the repetition rate and reaches a maximum value of 15 ns at 10 kHz. The beam quality was determined with $M^2 = 2$ at all repetition rates.

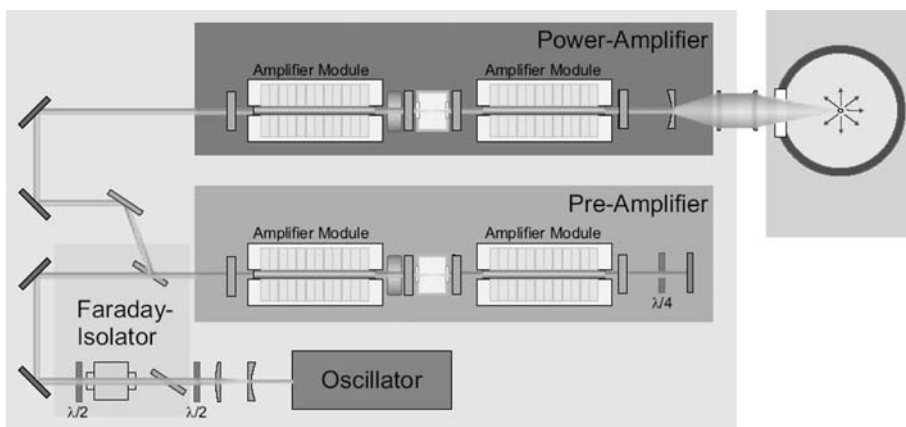


Figure 19.4 Schematic of a high-power MOPA laser driving an LPP EUV source.

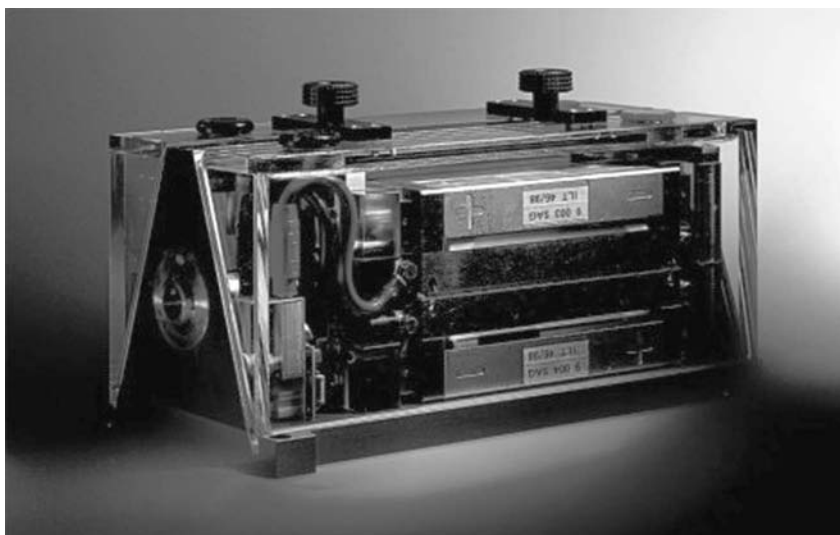


Figure 19.5 Photograph of a rod amplifier module.

The advantage of this laser design is that it is based on a commercial high-power system and that all modifications required for pulsed operation were integrated on the optical bench of the commercial cw laser. This laser was used over more than a year to drive our high-power LPP EUV source with high reliability. The reduced output power compared to the cw system is directly related to the high beam quality of the pulsed system. Due to thermally induced aberrations, the energy in the outer regions of the amplifier rod can only be extracted partially. It should be noted that thermal aberrations are inherent in all high-power lasers.

Based on this architecture, a second laser was developed with an average power of 1.2 kW at a repetition rate of 10 kHz. The higher power was achieved mainly by doubling the number of amplifier heads. Another major improvement was achieved in the seed power and in the beam guiding optics, which allow us to propagate a beam with $M^2 = 10$ through the amplifiers. This beam quality is consistent with our optics scheme for spatial multiplexing of several high-power lasers on the target to achieve the necessary power for a production lithography source. The optical efficiency of this laser (pulsed power divided by diode power) is 7.5%. Figure 19.6 shows a photograph of the high-power laboratory setup with the 1.2-kW laser on the left-hand side and the control panel in the foreground.

Finally we will discuss alternative laser schemes that are based on diode-pumped solid-state gain media with the laser wavelength at 1 μm . A zigzag slab geometry was already investigated in the mid-1990s as a very promising scheme for an LPP driver laser. The slab geometry offers lower thermal aberrations than the rod geometry because of the zigzag beam propagation, which averages over thermal distortions. Moreover, the good cooling access through the slab faces is advantageous for high-power operation. The drawback of a zigzag slab is the requirement of high optical quality of the slab faces used for the internal reflections



Figure 19.6 Photograph of the 1.2-kW laser (left-hand side, in the background) in XTREME technologies' high-power LPP EUV laboratory.

to generate the zigzag beam path in the slab. Because of these optical surfaces, the zigzag slab geometry is prone to parasitic modes, which limit the gain. However, one laser demonstrated 200-Hz operation with a pulse energy of 360 mJ in 1993. To achieve a beam that was ≈ 1.5 times diffraction-limited, a stimulated Brillouin scattering (SBS) mirror²⁸ was used in the amplifier beam path. Such a nonlinear mirror serves as correction optics for thermal aberrations. An alternative approach for aberration correction is the use of adaptive mirrors. Although zigzag slab lasers have not yet found their way into the commercial market, prototypes have been used successfully as EUV driver lasers, as described elsewhere in this book.

Another scheme that was recently introduced commercially in multikilowatt cw lasers is based on the disk laser geometry.²⁹ The laser employs an Yb:YAG disk of about 200- μm thickness, which is pumped longitudinally. The laser beam propagates in several passes through the pumped central part of the disk. The disk is efficiently cooled at one face, so that thermal lensing is almost completely suppressed. In practical realizations the cooling is technologically demanding, since the mirror coating must be deposited on the cooling surface. Using Yb:YAG as the lasing medium enhances the quantum efficiency as a consequence of the reduced wavelength difference between pump and lasing wavelengths; thus, less heat is released in the laser crystal. The large saturation fluence of Yb:YAG might limit the optics lifetime in pulsed systems, because the laser must be operated closer to the damage threshold of optical coatings.

Continuous-wave fiber lasers have recently shown dramatic progress for high-power operation, are commercially available, and could thus be considered as candidates for a pulsed laser driving an LPP EUV source. However, the small mode cross section limits the pulse energy to about 5 mJ at the required pulse duration. This limit is given by the onset of nonlinear effects and by the damage threshold. Thus, to obtain the pulse energy for a production lithography laser (see Sec. 19.7)

several hundred fibers would be required, which seems unrealistic. Moreover, and in contrast to all previously discussed laser schemes, the small cross section requires a high-brightness pump source, which is a considerable cost factor.

Summarizing this section, it seems likely that three principal laser schemes are capable of achieving a pulsed average power of 2 to 5 kW per MOPA unit and, by multiplexing of these units, of achieving the required total power of 8.5 to 34 kW. Especially the disk and the slab scheme, but also the rod scheme in combination with aberration correction, can be expected to reach an optical efficiency in the range of 20% to 30% at the time of EUV ramp-up in 2009.

19.5 CE and Output Power—Experimental Data

At XTREME technologies xenon targets in two types of modification—frozen xenon needle and frozen xenon droplets (see above)—are used as targets for high-power laser excitation. Diode-pumped Nd:YAG lasers based on commercially proven amplifier modules have been developed to generate the EUV-emitting plasma at the xenon target.³⁰

One of the most crucial tasks in LPP source development is to achieve maximal CE of laser energy into the desired EUV band centered at 13.5 nm within a 2% bandwidth (see above). High CE values are required

1. To minimize the heat that is dissipated in the source and that must be removed by cooling,
2. To minimize debris emitted from the plasma, and
3. To minimize the drive power of the laser system.

By improving the target systems and adapting the laser pulses to optimize the plasma emission of inband EUV radiation, a peak CE of 1% (assuming isotropic emission) in a 2π -sr solid angle is actually achieved.

Figure 19.7 shows two emission spectra from the LPP EUV source with xenon target. The spectrum with the lower intensity (lower curve) was generated using direct plasma excitation by nanosecond pulses. The spectrum with the higher intensity (upper curve) was emitted when the temporal excitation of the plasma had been optimized by shaping of the laser pulses. The optimization criterion for the pulse shaping was the CE at 13.5 nm. First of all, one can see from Fig. 19.7 that the intensity of the band at about 11 nm is significantly higher than that of the band at about 13.5 nm. This is a general feature of LPP xenon plasma EUV emission. Secondly, it can be seen from the spectra that the intensity of the emission around 13.5 nm is approximately three times higher in the case of optimum pulse shaping, while the increase of the intensity at 11 nm is only 50%. Obviously, pulse shaping allows the optimization of the emission spectrum for the 13.5-nm band.

With the frozen xenon targets the plasma is typically generated at a distance of 5 cm from the nozzle orifice (target injector), which is the closest hardware surrounding the actual EUV source. Due to the high spatial stability of the targets, the

average CE, which is achieved over bursts of several hundred pulses, is approaching the peak value and amounts currently to 0.8%. Further optimization is expected to allow average CEs of 1.0% and above.

The good spatial stability of the target and the laser beam results also in good energy and dose stability. Figure 19.8 shows an EUV dose stability of $\sigma = 0.9\%$, which is achieved with such an injection system. This value is close to the dose stability of the laser system itself. It means that the spatial stability of the target does not introduce additional variations.

The EUV output power generated by the EUV source with 0.5-kW laser driver amounts to 2.5 W in 2π sr. This power corresponds to 1-W inband power, which can be achieved in the IF by using a 5-sr collector mirror. The power delivered to the IF must be achieved while complying with the etendue restrictions imposed by the optics design of the EUV scanner.

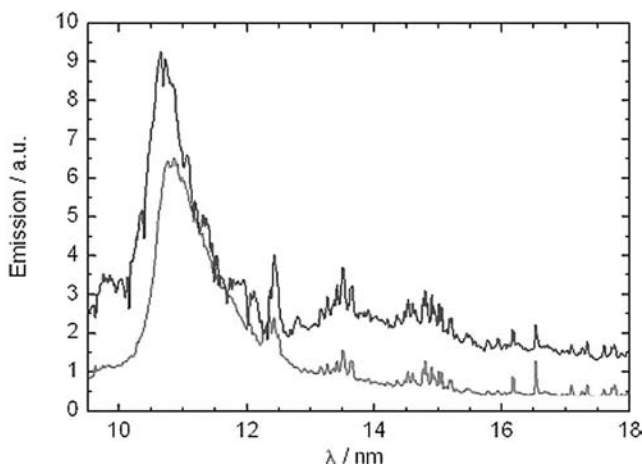


Figure 19.7 Xenon spectra of an LPP EUV source generated under different pulse-shaping conditions.

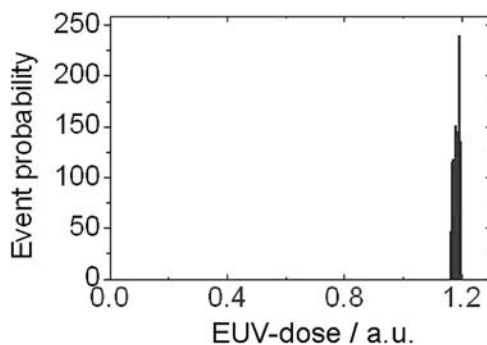


Figure 19.8 EUV dose stability $\sigma = 0.9\%$ (50-pulse moving average) of an LPP source operated at 5-cm standoff distance from the target injector.

Recently, with the 1.2 kW driver laser an EUV inband power of up to 10 W emitted into 2π sr has been generated. This power corresponds to an inband power of approximately 3.5 W in the IF. A lifetime of the nozzle of the injection system of 5 billion pulses was achieved.

19.6 Etendue, Source Size, and Source Collector

The etendue of the optical system of an EUV exposure tool, defined as the product of the area of the beam in focus and the solid angle of the beam, determines the optimum combination of the EUV source size and collector:

$$\text{Etendue} = \Omega A = \text{constant for the optical system.}$$

The etendue specifications for HVM EUV sources vary between 1 and $3.3 \text{ mm}^2 \text{ sr}$. To collect as much power as possible from the spatially more or less isotropic emission of the EUV-emitting plasma, the angle of collection of the optics should be as large as possible. Because the etendue of the optical system is constant, the collectible plasma size decreases as the collection solid angle increases. The power delivered to the IF must be achieved while complying with the etendue restrictions imposed by the optics design of the EUV scanner. For LPP sources the plasma size can be sufficiently small to support rather large collection angles. Figure 19.9 shows a picture of the spatial EUV intensity distribution of the LPP source. Also, the shape of the EUV distribution is quasi-Gaussian, which implies that 86% of the energy is emitted from a volume about $275 \text{ }\mu\text{m}$ in diameter. It should be noted that the dimensions of the source in this case are well below any etendue limit as long as the collection angle of the collector is below $\approx 10 \text{ sr}$. The angular distribution of

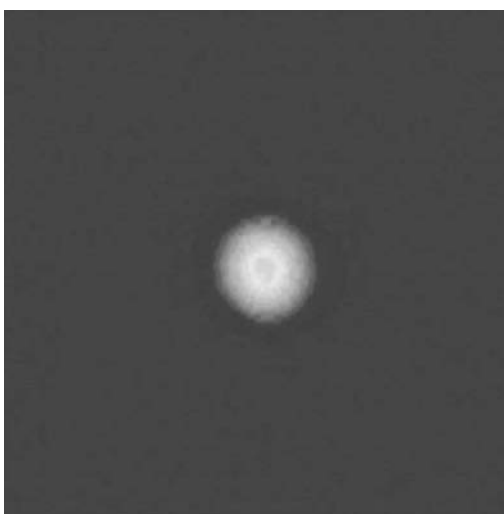


Figure 19.9 Spatial EUV distribution of an LPP source averaged over 20 pulses. The $1/e^2$ diameter is $275 \text{ }\mu\text{m}$. Single-pulse images have the same size.

the EUV emission indicates (see Fig. 19.10) that the anisotropy is relatively small in a plane perpendicular to the laser axis, but becomes significant in a plane parallel to the laser beam. A continuous xenon needle target was employed in these experiments. Most recent results indicate that the isotropy of the source emission can be considerably improved by spatial beam adaptation, which implies that nearly isotropic emission will be achieved within large collection angles.

Since for large collection angles the distance between plasma and collector cannot be too large (typically 10 to 20 cm), the source must be sufficiently clean (low debris) to provide a long lifetime of the collector optics. For LPP sources it is likely that the collector mirror for HVM sources will be a normal-incidence Mo/Si mirror.

We have evaluated the lifetime of Mo/Si mirrors by exposing witness plates, which consisted of a Mo/Si multilayer on a Si substrate, to the EUV plasma. The witness plates were arranged at different angles and at different distances to the plasma. The reflection off one witness plate was monitored during exposure with an EUV detector, and the plates were analyzed “post mortem.” The major effect of the source on an EUV mirror is erosion of the multilayer. The number of removed layers depends on the distance from the plasma as well as on the angle relative to the laser axis. Figure 19.11 shows a summary of these exposure experiments, performed with a continuous xenon needle target.

Typical numbers relate to an optics lifetime, defined as 10% reflectivity loss, of 1 million pulses under the most violent conditions (at 10-cm distance and close to the incident laser beam) without any debris mitigation. By using a background buffer gas, we were able to prevent erosion significantly. The lifetime of the collector mirror due to erosion could be extended to 5 billion pulses. It must be noted that

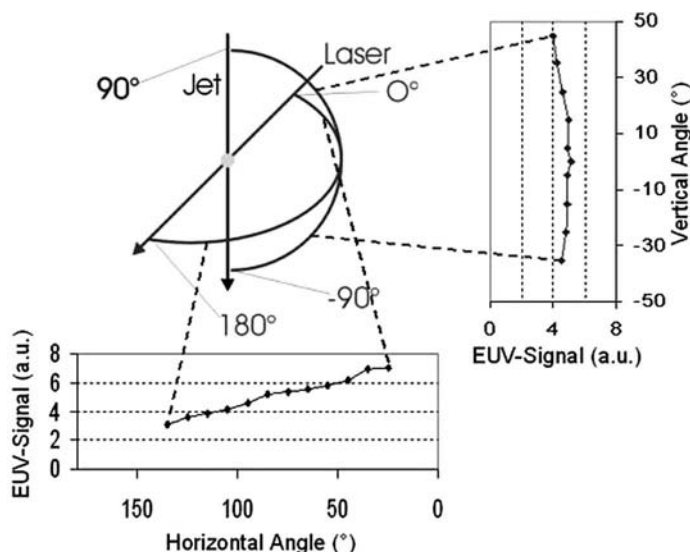


Figure 19.10 Angular distribution of the EUV emission of an LPP source.

no other materials were found on the witness plates, which implies that secondary erosion of source components and condensation of their material on the witness plates is negligible.

Since the power specification of system integrators is defined at the IF, we developed a collector design based on a normal-incidence mirror to project the emitted power of a π -sr solid angle into the IF. The characterization of the IF—power and dimensions—to be obtained with the π -sr mirror is scheduled for the near future. To qualify the mirror manufacturing as well as the alignment procedures, first we employed test mirrors that collect 0.35 sr. A photograph of one of these mirrors is shown in Fig. 19.12. The integration of the 0.35-sr collector mirror in the LPP source chamber showed mirror reflectivities exceeding 60%.

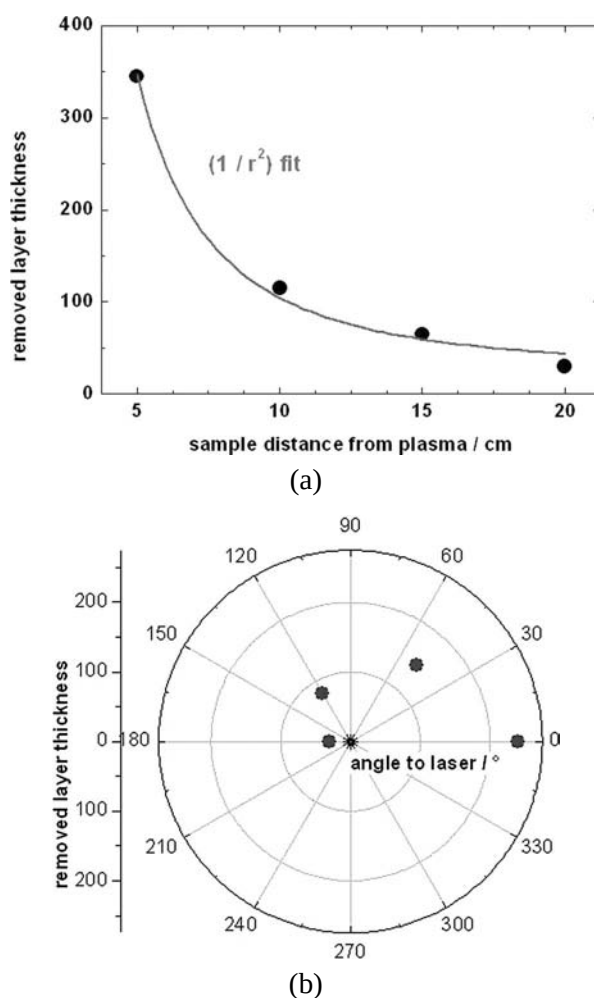


Figure 19.11 (a) Distance dependence, and (b) angular dependence of erosion rate. The two measurements were performed independently, i.e., the distance dependence was measured with samples placed at (almost) identical angles, and vice versa.

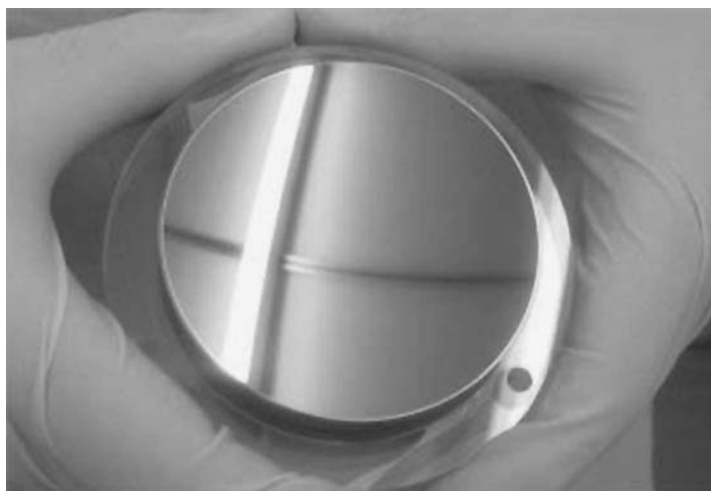


Figure 19.12 Photograph of a coated 0.35-sr collector mirror.

19.7 Scaling of Performance to HVM

In this section we will derive some estimates, technical and economic, of a production source with the requirements of Table 19.1, based on today's experimental data and some projections of future component prices.

The cleanest source today is based on xenon fuel and has demonstrated a CE of 1%. Assuming that the spatially and temporally averaged efficiency of a production source will also be 1%, the required laser power amounts to 34 kW (see above). The first concern relates to the thermal power load per unit area that must be removed from hardware components surrounding the plasma. Figure 19.13 shows a photograph of the EUV plasma in one of XTREME technologies' development sources. The closest component is the injection nozzle, which is generally placed at least 5 cm away from the plasma. Assuming that 99% of the laser power is isotropically dissipated, a power density of about 100 W/cm^2 is calculated at a 5-cm distance. This power density is an order of magnitude below the value that is typically handled in a gas-discharge source. Hence heat dissipation in a production source is not expected to be a limiting factor for an LPP EUV source.

However, a serious concern relates to the target itself. If we assume that the target consists of a continuous stream of individual droplets or frozen xenon balls, the droplets are much closer to the plasma than any hardware. A 34-kW laser with a repetition frequency of 17 kHz will require 3-mm-spaced droplets that move with a velocity of 50 m/s. Each laser pulse dissipates 2 J of energy. The fraction absorbed by the neighboring droplet is calculated from the solid angle subtended by it. For a droplet of about 100- μm diameter (say 5×10^{15} xenon atoms), this energy is 150 μJ , while the energy to vaporize the droplet is only half of that. However, only 3 to 5 sacrifice droplets between successive target droplets are required to dissipate the excess energy. Because the natural droplet distance is only a few droplet

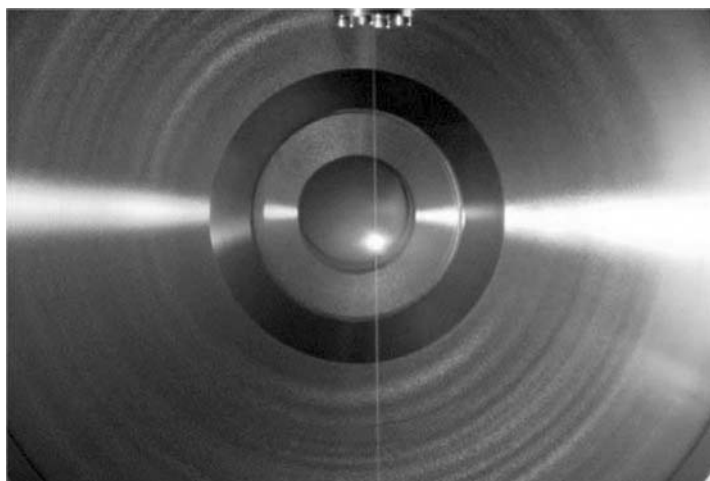


Figure 19.13 Visible-light photograph of an LPP EUV source at XTREME technologies.

diameters, sacrifice droplets are available in abundance; thus the following target droplet is protected and can be used for EUV generation.

Dose stability, positional stability, and the stability of the angular emission distribution require a very stable target. The target stability depends critically on the quality of the orifice of the injection nozzle. The lifetime of the nozzle today is large compared to that of the mirror in our sources, even without any debris mitigation, and will benefit equally from the optics protection schemes in a production source. Moreover, compared to costs of other source components, which will be discussed later, the injection nozzle is inexpensive and can be replaced within a very short downtime of the order of one hour. Thus we conclude that from a technical point of view the LPP EUV sources are very promising with regard to the requirements of a production source.

Most other issues relate to the economical viability of the sources under production conditions, i.e., close to 100% uptime each year. As derived in Sec. 19.4, the driver laser will very likely be a Nd:YAG laser with an optical efficiency between 20% and 30%, resulting in 115- to 170-kW power of the laser diodes. Using current values of diode prices and expected diode lifetime values, the operational cost originating from the laser diodes is in the range of \$3000 (U.S.) per billion pulses. Other laser consumables are estimated to add \$35,000 per billion pulses. This means the regular cost because of laser diode replacement is less than 1/10 of the total laser operational cost.

The next major contribution to the cost will arise from the collector mirror. Based on experimental data (see Sec. 19.6 for details), we expect to achieve a lifetime of more than three months for the collector optics in a xenon-based production source. Together with the estimated optics cost, this leads to an estimate of the regular cost for collector consumption in the range of \$15,000 per billion pulses.

Because of the relatively expensive xenon target, a recirculation and purification system is used in XTREME technologies' LPP EUV sources. Based on 90% efficiency, the annual xenon cost of a production source is estimated for such a system, using the throughput values, target droplets, and sacrifice droplets as described above. With an estimated xenon price of \$8 per standard liter, the target cost amounts to about \$700 per billion pulses.

It seems a realistic assumption that progress in laser and EUV technology will result in considerable cost reduction until the ramp-up in 2009, and that engineering efforts will result in a more efficient recirculation system. Thus we estimate the total operational cost of a xenon-based LPP EUV source in 2009 to be below \$50,000 per billion pulses. This is comparable to the running cost of current 193-nm excimer lasers.

It should be noted that the lower cost of using a Sn or Li target, with 2–3 times higher CE, mainly results from the reduced laser power and related lower laser and laser-diode costs. Because the optics lifetime of Sn-fueled laser-plasma EUV sources suffers from target condensation and is not well quantified today, any estimates of optics-associated cost in an HVM source are inaccurate. It has still to be demonstrated that the optics-associated cost and potentially longer downtimes will not cancel the reduction of running cost due to the higher CE.

19.8 Summary and Conclusion

LPP EUV sources with diode-pumped solid-state driver lasers are promising candidates for HVM lithography light sources. With respect to the required power and lifetime, these sources do not show physical limitations in principle that might prevent the achievement of the required specifications. The driver-laser design is based on diode-pumped solid-state lasers. The most reliable target material in practice is xenon, the use of which should allow sufficiently long optics lifetime of the lithography exposure tool. Experimentally 2.5-W inband power was achieved in 2π sr and 2% bandwidth, which corresponds to an IF power of 1 W. With a recently developed 1.2-kW laser, a demonstration of 3.5-W IF power is in preparation. The necessary laser power for HVM sources based on xenon is estimated to be 34 kW.

The more efficient target material tin would reduce the laser-driver power needed to 8.5–24 kW and therefore reduce the cost of ownership (CoO) of the laser. However, because of condensation on the optics the use of tin may impose fundamental restrictions with respect to the lifetime of the optics. This may finally override the laser CoO reduction by far. Research to clarify this question is currently going on. A choice of tin, lithium, or xenon fuel is expected for 2006 to support the introduction of LPP-based HVM EUV sources in 2008.

Acknowledgments

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Uwe Stamm. See Chapter 14.



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Chapter 20

Spatially and Temporally Multiplexed Laser Modules for LPP Sources

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20.1 Introduction

EUVL is considered to be one of the most attractive candidates to succeed conventional optical lithography in the coming years. This will permit reduction of structure sizes in semiconductor devices to less than 45 nm. To enable this technology, a light source is required that emits in the spectral range around 13.5 nm. The LPP EUV source has great potential to be the future source for EUVL, and offers several advantages over discharge-based EUV sources. These advantages can be summarized as power scalability through tuning of laser parameters, low debris, pulse-to-pulse stability (optimum dose control), flexibility in dimensions, spatial stability, minimal heat load, and large solid angle of collection.

The main objective of the EUV program at Powerlase is to develop a high-power, cost-effective source able to deliver enough usable power for use in the microlithography process. We have successfully generated a high-power EUV source using an LPP scheme. In this scheme, we spatially multiplex (combine) several of

our lasers and focus them onto a xenon target. To achieve this we have recently made significant steps forward in the performance of the laser-driver module employed in our LPP EUV source. We have increased the average power output from the laser whilst minimizing the overall cost of ownership (CoO) and footprint of the system.

In addition to sustained laser development, we are taking the responsibility of developing an appropriate target to achieve what we have projected in our EUV development source roadmap. The target development is not restricted to Xe solid jets, but other targets materials are also investigated in order to increase the inband EUV conversion efficiency (CE). The combination of highly efficient lasers and high CE of the inband EUV through target development drives down the CoO of the EUV source.

20.2 Laser Technology

20.2.1 Design parameters

A key element in the design of an LPP source is the choice of laser-driver parameters. Certain parameters, such as the laser pulse energy, pulse duration, and beam quality (as quantified by the parameter M^2) must be chosen in order to optimize the CE of laser radiation into inband EUV radiation. The choice of target (particularly its initial size and composition) and knowledge of optimum plasma conditions must also be taken into account when choosing these parameters.

Other parameters, such as the average output power and repetition rate, are chosen in order to satisfy the EUV output requirements specified by the lithography tool manufacturers. In the next sections these parameters are discussed in detail.

20.2.2 Laser parameters for efficient EUV generation

In this section, physical arguments are used to estimate the optimum values of those laser parameters influencing the CE of laser radiation into inband EUV radiation (for a more detailed discussion of laser-plasma interactions, see Ref. 1). The parameters should be chosen such that an optically thick plasma is formed and maintained at the correct temperature for EUV generation near the Planck limit.

The optimum plasma temperature can then be estimated from the simple formula $T \sim E_{\text{ph}}/3$, where E_{ph} is the photon energy associated with the wavelength of maximum emission. For EUVL the wavelength of interest is 13.5 nm, corresponding to $E_{\text{ph}} = 92.1$ eV and therefore an optimum temperature $T \approx 30$ eV.

Following this reasoning, the required focused laser intensity I (W cm^{-2}) can be estimated by equating it to the emitted intensity of a Planckian radiator. This leads to the expression $I \sim \sigma T^4$, where σ is the Stefan-Boltzmann constant and T is the plasma temperature. For $T \approx 30$ eV, this yields $I \sim 10^{11} \text{ W cm}^{-2}$.

The laser pulse duration defines the plasma heating time scale and must be carefully chosen in order for deposited energy from the laser to be efficiently con-

verted into EUV radiation. This is because there are other time scales associated with the evolution of the LPP that dictate the choice of pulse duration.

For instance, there is a relaxation time scale corresponding to the time required for the plasma ionization (which can be regarded as an internal degree of freedom) to reach steady state: In the early stages of the interaction, free electrons are produced via high-field ionization to produce a cold plasma, after which laser energy is deposited primarily into the electrons through collisional absorption. Further ionization occurs when energy is transferred from the electrons to the ions via inelastic collisions. This process continues until a steady ionization state is reached. For temperatures of interest here, this time scale is ≈ 0.5 ns.²

Another time scale concerns the time taken for the expanding plasma to become optically thick to its own emitted radiation (which for $T \approx 30$ eV means primarily EUV radiation). The optical thickness τ of the plasma can be estimated from the formula for the optical thickness of a Doppler-broadened line:³

$$\tau \sim 30 \left(\frac{\lambda}{13 \text{ nm}} \right) \left(\frac{m}{131} \right)^{1/2} \left(\frac{30 \text{ eV}}{T} \right)^{1/2} \left(\frac{n_i}{10^{20} \text{ cm}^{-3}} \right) \left(\frac{L}{10 \text{ } \mu\text{m}} \right) \left(\frac{f}{0.1} \right), \quad (20.1)$$

where λ is the emission wavelength of interest, m is the ion mass measured in atomic mass units, n_i is the ion density, L is the thickness of the plasma layer, and f is the oscillator strength of the line.

The characteristic electron density of the plasma is of the order of the critical density $n_{\text{cr}}[\text{cm}^{-3}] \sim 10^{21}/\lambda_l^2[\mu\text{m}]$ (where λ_l is the laser wavelength), assuming that the majority of the laser radiation is deposited in the region of the critical surface. For a laser wavelength $\lambda_l = 1.064 \text{ } \mu\text{m}$ (typically produced by solid state Nd:YAG lasers) and an average ion charge state $Z \approx 10$, the corresponding characteristic ion density $n_i \sim 10^{20} \text{ cm}^{-3}$.

The thickness L of the plasma layer as a function of time t can be estimated from $L \sim c_s t$, where c_s is the plasma sound speed given by $c_s = (ZkT/m)^{1/2}$. The physical thickness of the critical-density plasma layer is required to evolve to the point where $\tau \gg 1$. Taking $\lambda = 13 \text{ nm}$, $m = 131$ (for xenon), $T = 30 \text{ eV}$, $n_i = 10^{20} \text{ cm}^{-3}$, $f = 0.1$, it follows that $\tau \approx 30$ for $L = 10 \text{ } \mu\text{m}$. Using the sound-speed formula, this occurs at $t \sim 1 \text{ ns}$.

The two time scales discussed above determine the time taken to create the optimum plasma state for EUV emission, and therefore place a lower limit on the laser pulse duration. However, the optically thick, critical-density plasma has a finite lifetime t_{max} due to hydrodynamic expansion, dependent on the initial size of the target, d [Eq. (20.2)]. For times much larger than t_{max} , the characteristic plasma density drops below critical density, and the laser energy is no longer efficiently absorbed in the plasma. The time scale t_{max} therefore places an upper limit on the laser pulse duration, and can be estimated from the following expression for a 3D

expansion⁴:

$$t_{\max} \sim \left(\frac{n_{e0}}{n_{cr}} \right)^{1/3} \cdot \frac{d}{c_s}, \quad (20.2)$$

where n_{e0} is the electron density of the initially unperturbed plasma, and c_s is the plasma sound speed. The above expression can be rewritten using characteristic values as follows:

$$t_{\max} \sim 15 \left(\frac{n_{e0}}{10^{23} \text{ cm}^{-3}} \right)^{1/3} \left(\frac{10^{21} \text{ cm}^{-3}}{n_{cr}} \right)^{1/3} \left(\frac{10}{Z} \right)^{1/2} \left(\frac{m}{131} \right)^{1/2} \left(\frac{30 \text{ eV}}{T} \right)^{1/2} \times \left(\frac{d}{50 \text{ } \mu\text{m}} \right) \text{ ns}. \quad (20.3)$$

In the case of the high-density xenon filament target currently under development at Powerlase (discussed in a later section), $d \approx 50 \text{ } \mu\text{m}$. Taking $Z = 10$, $m = 131$, $T = 30 \text{ eV}$, $n_{e0} = 10^{23} \text{ cm}^{-3}$, and $n_{cr} = 10^{21} \text{ cm}^{-3}$, the above expression gives $t_{\max} \approx 15 \text{ ns}$. It follows that the optimum pulse duration for EUV generation using this target is of the order of 10 ns.

The laser focal spot size is often dictated by the initial size of the target from which the plasma is formed. For targets with $d > 30 \text{ } \mu\text{m}$, the beam quality specification of the laser can be relaxed, for the laser is not required to be focused to a diffraction-limit spot. The laser driver can then be designed to operate at a higher M^2 value, which has the advantage that stored energy can be more efficiently extracted from the gain modules containing the optically pumped Nd:YAG rods.⁵ Larger targets are also favorable from the point of view of increasing the EUV CE (for example, the expansion tends to a 1D limit as the target and associated laser spot size increase, thereby limiting hydrodynamic losses), but this point must be balanced by the fact that debris production also increases with target size.

20.2.3 Powerlase Starlase laser system

Having considered the optimum laser parameters for efficient EUV generation, the laser solution under development at Powerlase is now presented.

The Starlase range of lasers is based on completely solid state technology that employs diode pumping of Nd:YAG rods in order to generate laser radiation at a wavelength of $1.064 \text{ } \mu\text{m}$. The system currently under development for EUV generation utilizes electrooptical (EO) switching to generate short laser pulses with 9-ns duration, and is therefore ideal for use with micron-scale, solid-density targets. At the present time, the laser is capable of producing an average output power of up to 1 kW at a repetition rate of 3.5 kHz, and operates with a beam M^2 of 12.

One key feature of the laser technology is that very high electrical-to-optical CE has been achieved. This is a consequence of three important factors. First, the CE of electrical power to optical power provided by the pump diodes is excellent

at approximately 50%. Second, careful gain module design has been employed in order to optimize and homogenize the coupling of diode pump power to the Nd:YAG rod (Fig. 20.1). Third, continued development of the laser configuration and improved switching technologies allow power to be efficiently extracted from the gain modules. As mentioned earlier, by relaxing the beam quality requirement of the laser, the extraction efficiency of power from the gain modules can be further enhanced. Figure 20.1 also shows an example of beam quality data used to determine M^2 . This is done by scanning a CCD camera through the beam waist of the focused laser beam in order to measure the beam size at a number of positions, and then fitting the points with a curve generated from Gaussian beam propagation theory.⁶

Within the context of the complete EUV light source, a key efficiency factor is the CE of laser energy into inband EUV radiation. To date, we have measured an EUV CE of 0.8% (2π sr, 2% bandwidth) using the Starlase system to irradiate a jet of xenon clusters a short distance (~ 1 mm) away from the gas supply nozzle. However, in order to reduce source-induced debris and increase CE, work has begun on developing a high-density xenon filament as the next stage in LPP target development. This type of target has been shown⁷ to exhibit an EUV CE of up to 0.95% (2π sr, 2% bandwidth). We have so far demonstrated a CE of up to 0.8% (2π sr, 2% bandwidth) using a 50- μ m-diameter xenon filament. Table 20.1 shows a section of the Powerlase EUV source roadmap, which was prepared in response to industry demands. This illustrates that advanced target and laser technology, both of which have already been demonstrated at the present time, can be combined to produce an EUV source capable of satisfying industry requirements.

The current EUV source power requirement is 115 W at the position of the intermediate focus (IF) following the collection optics. This requires 15–25 kW of

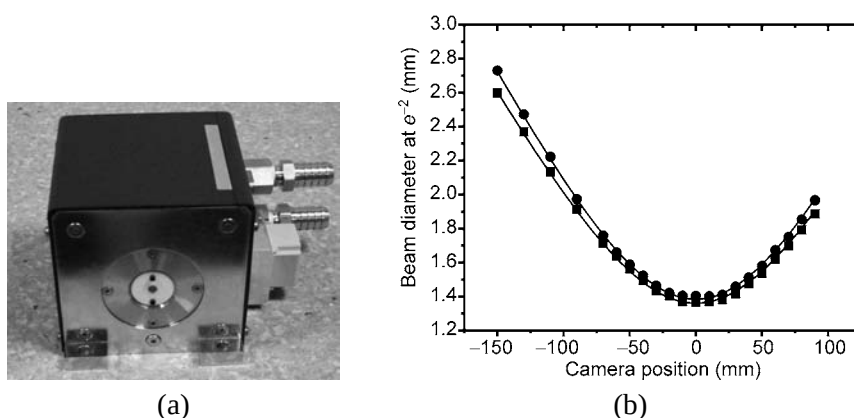


Figure 20.1 (a) Powerlase gain module, and (b) beam size data used to infer beam quality. Two M^2 parameters can be defined for the beam (one for each Cartesian direction in the cross-sectional plane of the beam). The lower curve (square data points) and upper curve (circular data points) can be used to determine M^2 in the x direction (in this case the direction parallel to the laser bench) and y direction, respectively.

Table 20.1 Section of EUV source roadmap illustrating laser-driver power requirements.

	Oct. 2002	2003	End of 2004	2005	Future	
					Xe	Sn
Solid state laser driver (kW)	0.450	1	3.6	8.5	25	15
Net CE (%)	0.5	0.8	0.9	1	1.2	2.5
EUV power in 2π sr (W)	2.25	8	32.5	85	300	375
Collection angle (sr)	5	5	5	5	5	5
Collector efficiency	40%	40%	40%	45%	45%	45%
EUV at IF (W)	1	2.6	10.5	30	110	135

laser input power, depending on the choice of target in the final stages of source development. In order to produce the required level of laser power and be able to deliver it to the LPP target, Powerlase is continuing to increase the output power of the EO-switched laser module whilst employing spatial multiplexing (discussed in the next subsection) to combine multiple beams on target. The output power of the laser module is scaled up using a combination of increased repetition rate with enhancements to key laser components such as the cavity, gain module, and switch.

20.2.4 Spatial multiplexing

The approach of increasing the pulse energy on target using multiple laser beams has been demonstrated extensively in laser fusion work, for example at Rutherford Appleton Laboratory (RAL) and Lawrence Livermore National Laboratory (LLNL). These pulses are coupled to the fusion target from different directions in order to compress the target before igniting it with a shorter laser pulse (*fast igniter* scheme).⁸ However, this method will not be valuable for our EUV work, where collection of the EUV light will be difficult to achieve (due to laser entry from different windows in the vacuum chamber that contains the EUV target). Therefore, at Powerlase we have taken a different approach where we overlap three or four focused beams on target using a single optic. Complex lens-assembly architecture designs have been developed at Powerlase (patent pending) with minimum restriction on the EUV light collection.

In spatial multiplexing schemes, several laser sources are spatially combined using mirrors and other optics in order to create a single effective laser source, which is then imaged onto the LPP target using a focusing optic (Fig. 20.2).

In order to allow for differences in path lengths between the combined beams, conditioning optics (e.g., expanding telescopes) can be used to adjust the beam divergence so that the corresponding focal spots are all equal in size. The effective focal spot can be monitored in real time by taking a small fraction of the laser light and focusing it onto a CCD camera (Fig. 20.3).

Similarly, the lasers can be timed to arrive simultaneously on target using timing pulse generators to allow for path-length differences. However, it is also possible to temporally interleave the pulse trains of one or more lasers in order to increase the effective repetition rate of the system.

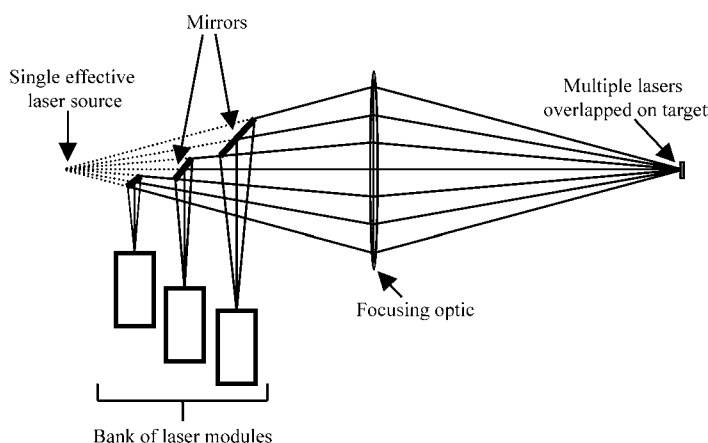


Figure 20.2 Principle of spatial multiplexing.

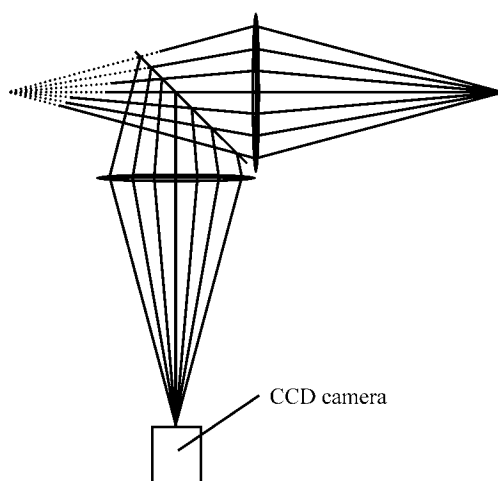


Figure 20.3 Use of CCD camera to monitor multiple beam overlap in real time.

It can therefore be seen that spatial multiplexing of laser modules offers greater scale-up flexibility than LPP schemes that employ a single high-power laser. Also, by sharing the power requirement over several laser modules, the power per module is reduced and the laser design can be simplified. Furthermore, spatial multiplexing has the advantage that in the event of failure of one of the laser modules, the EUV source can continue to operate, albeit at a reduced output power.

This method of spatial multiplexing has previously been demonstrated successfully,⁹ when three 150-W beams were spatially multiplexed on target in order to deliver 450 W of laser power. Figure 20.4 illustrates the image recorded on the CCD alignment camera, showing three overlapping, equal-size focal spots.

The next stage in the development of the LPP EUV source will be to spatially multiplex three 1–1.2-kW Starlase systems. When they are combined with a high-density xenon target (described in the next section), the EUV power at the IF is expected to be 10.5 W (Table 20.2).

Finally, we can summarize the advantages of spatial and temporal multiplexing as follows:

- 1. One can scale up the laser power intensity on target until the CE of the EUV is optimized by spatially multiplexing N laser modules.
- 2. Combining multiple lasers using the spatial multiplexing method offers several advantages over using a single high-power laser as an LPP driver. First, greater flexibility is offered in scalability. Second, if a fault occurs on one of the multiplexed modules, the EUV system can continue to run (albeit at slightly reduced output power). This is in contrast to the single-laser solution, in which a laser fault would lead to a shutdown of the whole EUV system.
- 3. The average power can be scaled up independently of the power intensity on target (i.e., we can increase the average power on target without increasing the power intensity on target).
- 4. The combination of spatial and temporal multiplexing offers a way to scale up the laser’s average power output. This can be achieved by using spatial multiplexing to obtain sufficient power intensity on target per pulse that optimum CE of EUV radiation is achieved, and then scaling up the average power using temporal multiplexing.



Figure 20.4 CCD image showing multiple overlapping beams.

Table 20.2 Laser-power roadmap illustrating scale-up method using spatial multiplexing.

	2002	2003	End of 2004	2005
Average power (kW) per module	0.150	1	1.2	1.2
Rep rate (kHz)	3.5	3.5	6	6
Number of multiplexed beams, n	3	1	3	7
Total average power for multiplexing (kW)	0.450	1	3.6	8.4

20.3 Target Design and Vacuum Environment

20.3.1 High-density xenon target

The principal objective of LPP target design is to create a localized region of high-density material such that laser absorption is maximized, whilst absorption of the generated EUV radiation in the chamber environment is minimized. Furthermore, if a nozzle is used to deliver the target material, the plasma must be created far enough away from the nozzle that nozzle debris does not limit the lifetime of the collection optics.

The target should be refreshable and able to support the high repetition rates (>3.5 kHz) that are produced by the Starlase range of lasers and are required for optimum EUV dose control during the lithographic process. The source environment must also be debris-free, and the hydrocarbon and water levels must not exceed specified limits.

A promising method of achieving these requirements is provided by a cryogenic, high-density xenon filament target. In the system currently under development at Powerlase, a high-density xenon filament with diameter of $50\text{ }\mu\text{m}$ is injected into the vacuum system shown in Fig. 20.5. This system uses two 3000-l s^{-1} turbopumps to achieve an ultimate pressure of 5×10^{-10} mbar and a background pressure of 5×10^{-4} mbar when operating the xenon target.

The xenon is recycled in a closed loop employing continuous gas filtration in order to achieve extremely low levels of contamination. Residual gas analyzer (RGA) measurements indicate hydrocarbon levels of $\leq 5 \times 10^{-10}$ mbar (for molecular masses $\sum 45\text{--}200$) and a water level of $\sim 10^{-9}$ mbar. The recycling system is capable of delivering a stable xenon pressure of up to 50 bar at the nozzle inlet.

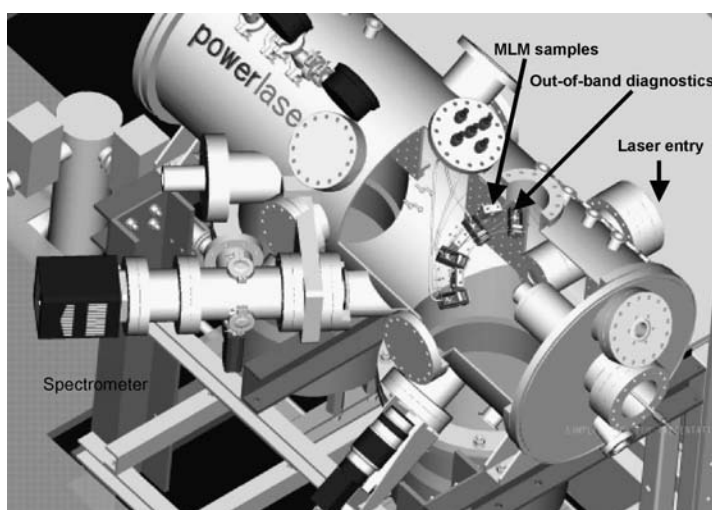


Figure 20.5 EUV source chamber showing pumps and plasma diagnostics. (Courtesy of Powerlase Ltd.)

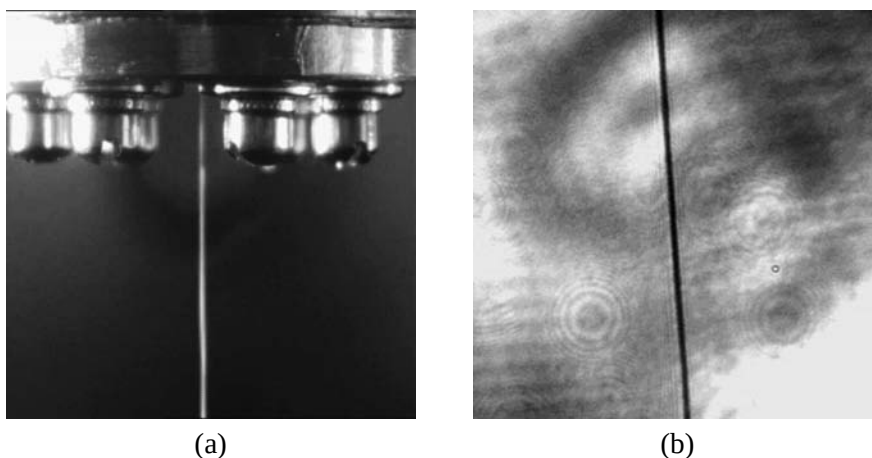


Figure 20.6 Images of the xenon filament target: (a) taken using a CCD camera with zoom lens, and (b) a shadowgram produced using a low-power, 10-ns-pulse-duration laser as the illumination source.

Figure 20.6 shows two images of the xenon filament. The main issue currently being addressed is the stability of the target, as changes in the filament direction can lead to substantial variations in the EUV output.¹⁰ However, several strategies exist to circumvent this problem, and they are currently being investigated.

In order to determine the angular distribution and the out-of-band (OOB) radiation, we have assembled a photodiode array at a distance of 110 mm from the EUV source. The diode assembly is also equipped with multilayer mirror (MLM) samples to study debris from the source. A cross section of our vacuum chamber illustrating these diagnostics is shown in Fig. 20.5. OOB measurements using a Xe target showed that almost 60% of the emitted plasma radiation is in the region 5–20 nm. The OOB measurements were conducted using combinations of different filters such as Al, Si, Zr, and CaF_2 with XUV diodes. Angular distribution measurements, shown in Fig. 20.7, exhibit less than 10% variation of the EUV intensity.

20.3.2 Tin target

Tin is an alternative target material that offers a higher EUV CE than xenon targets. A typical EUV emission spectrum for tin is shown in Fig. 20.8. We have demonstrated a CE of 2% (2π sr, 2% bandwidth) from tin (concentration 20%), using a low-repetition-rate laser with similar pulse parameters to those of our high-repetition-rate laser. Furthermore, there is plenty of scope for further optimization, and theoretical modeling suggests that CEs approaching 3% (2π sr, 2% bandwidth) can be obtained.¹¹

However, macroscopic tin targets are difficult to implement in high-repetition-rate EUV sources because of the need to refresh the target and, more importantly, the high level of debris produced. One proposed solution¹² uses tin-doped droplets

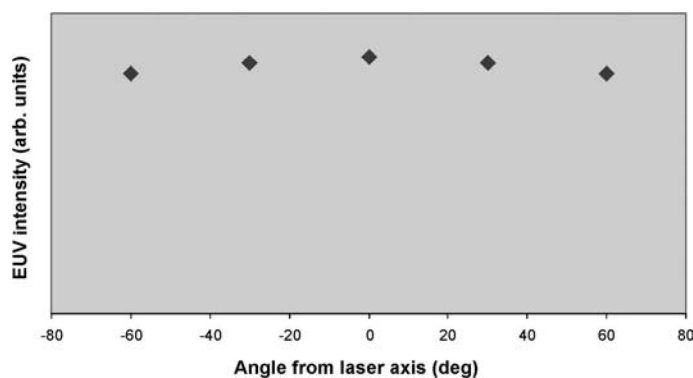


Figure 20.7 Angular distribution of the EUV source.

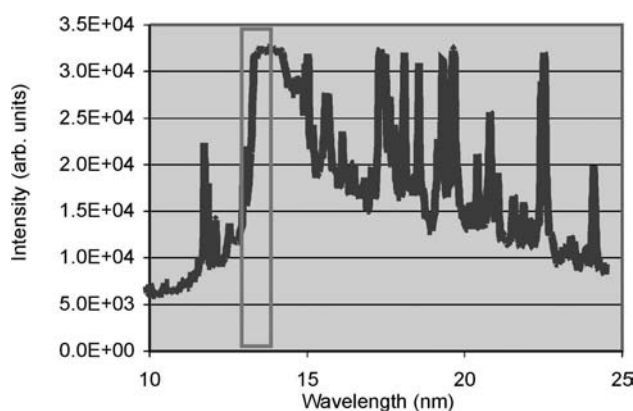


Figure 20.8 Tin spectrum taken using flat-field spectrometer. The vertical lines indicate the wavelength band of interest.

with a diameter of $35\text{ }\mu\text{m}$ in order to make use of the EUV emission characteristics of tin, whilst minimizing the quantity of debris produced and simplifying management of the target material. This type of target is thoroughly discussed in Chapter 26. This method supports laser repetition rates in the range 20–100 kHz and therefore provides a promising alternative to xenon targets. Our method of temporal multiplexing can be employed to achieve system repetition rates greater than 20 kHz in a straightforward manner, and is therefore well suited to the tin droplet target. This target has a higher CE than xenon targets, and if it could be successfully integrated into the EUV system, this would lead to a dramatic reduction in the total CoO of the LPP source.

Furthermore, this target method is only associated with the LPP sources. However, in Chapter 18 the use of tin in the DPP method was discussed. The conclusion was that tin is a very good target for both DPP and LPP, but there may be contamination problems—which, of course, is true for both approaches. However, another issue is that in the case of DPP the stability of the pinch was absolutely uncon-

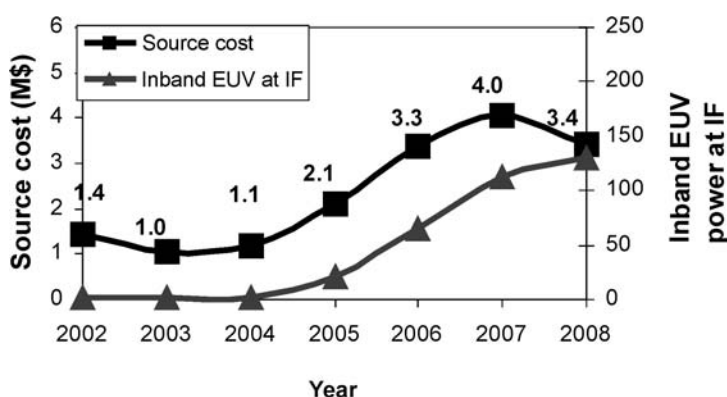


Figure 20.9 Projected capital cost of source: squares show projected cost, and triangles show power at the IF.

trollable (because conducting debris tends to self-trigger the discharge, thereby limiting the repetition rate).

20.3.3 Cost of ownership

In order to demonstrate the commercial viability of the LPP EUV source, a CoO model was prepared.¹³ This is summarized in Fig. 20.9, where available EUV source output power (in watts at the IF) and corresponding source capital cost are plotted over the next few years.

These projections are based on the cost of laser diodes, the laser design, and the choice of target. Note that a production-level source using xenon will be available by the end of 2006 at a projected cost of approximately \$4 million (U.S.) according to our CoO model. If tin target technology can be introduced so as to dramatically improve the EUV CE (Table 20.1), the cost of the EUV source can be reduced. With continued development work, we estimate that the source cost in the EUV production tool will be approximately \$3 million. Improvements in other influencing factors, such as the efficiency of the EUV collection optics and the photoresist sensitivity, will help to further drive down the CoO.

Figure 20.10 shows our progress from 2002 to date with projections to 2008. It clearly shows that the cost per watt has been reduced dramatically, and by 2008 the cost of 1 W of EUV at the IF will be approximately \$26,000 (U.S.). Note that at the moment the DPP CoO has not been projected; however, we think it is most important to compare LPP with DPP in the final stages approaching large-scale production, as this is where the superior scalability of LPP technology will be decisive.

20.4 Conclusion

LPPs provide a flexible and scalable route toward a production-level EUV source for lithography. The key technological components of the EUV source, namely the

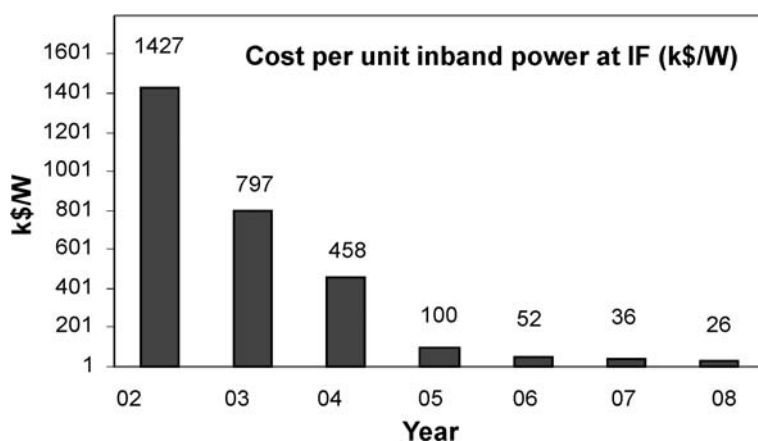


Figure 20.10 The cost per watt at the IF, based on real data from 2002 to 2004 and projected data from 2005 onward.

target and (most importantly) the laser-driver solution, have already been demonstrated to be technically viable. In addition, CoO calculations indicate that the LPP source is a commercially viable solution that will satisfy the requirements specified by EUV scanner manufacturers.

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Samir Ellwi. See Chapter 18.



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Chapter 21

Modular LPP Source

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21.1 Introduction

For more than a decade, research on plasma light sources in the EUV spectral range has been the subject of intense efforts all over the world.^{1,2} This extensive work is motivated by the planned 2009 introduction of EUVL to high-volume chip manufacturing, operating at a wavelength of 13.5 nm. The scientific and technical challenges are indeed tremendous in achieving sources that are both powerful and clean and that also present very small source spots of less than 1 mm in diameter. Since the start of the development of EUV sources in the early 1990s, the

requirements in terms of EUV power needed by the industrial lithography tools have been raised from a few watts to more than 100 W, and the lifetime of the critical components such as the collector optics must today exceed 10^{11} shots. From an industrial point of view, EUV sources must present very high conversion efficiencies (CEs) between the incoming exciting power of the emitter plasma and the outcoming EUV power in order to keep the heat load of the system at an acceptable level. Other important constraints are linked to the economic viability of the proposed source concepts and to their adaptability to run at high repetition rates with exceptional reliability.

Two main families of EUV sources are currently developed for industrial EUVL tools, which mainly differ in the plasma-exciting mechanisms employed. On one hand, DPP sources use electrical sparking in a low-density gas target to achieve EUV generation. On the other hand, LPP sources use very dense targets that are irradiated by tightly focused laser light. Each of the two concepts presents its own advantages and drawbacks, which will be discussed later, but it is clear that so far neither has yet reached the required specifications, in particular with regard to EUV power and critical component lifetime. Actually, tremendous efforts are still necessary to overcome these important challenges, and the risk of failure is not negligible, since the unavoidable time-to-market law governs the introduction of innovative technologies into industrial high-volume production.

The Exulite consortium, as a member of the European MEDEA+ program, decided in 2002 to develop a power source for EUVL based on the LPP concept. This source prototype is called ELSAC, which stands for “EUV lithography source apparatus cw.” Within Exulite two laboratories of the French Atomic Energy Commission (CEA) collaborate with Thalès Laser and Alcatel Vacuum Technology/Adixen, which is also the coordinator of the consortium. The main working fields are the development of innovative laser technology (CEA/SCP and Thalès Laser) and system-related technical solutions (CEA/SPAM and AVT/Adixen).

Within the frame of the MEDEA+ project until mid-2005, Exulite will concentrate on xenon target technology, although alternative materials such as tin are also being closely studied. Finally, Exulite has also performed numerous theoretical studies on the complex atomic physics of xenon and tin (see Chapter 10) and on the plasma dynamics to optimize the laser-target interaction (Sec. 21.2.2).

21.2 Designing a Modular LPP Source

21.2.1 The global approach chosen by Exulite

The ELSAC prototype is a modular LPP source that uses spatial multiplexing of several identical power laser modules that are focused on the same source spot. Such a modular approach presents several advantages, in particular in terms of power flexibility, power efficiency, and reduced costs in development and maintenance. It is a matter of fact that LPP sources are much cleaner than DPP sources for a given target material, and DPP sources generally suffer from power limitation

arising from dramatic thermal heat load and reduced lifetimes of vital components such as electrodes and the EUV collector. For essentially these reasons, Exulite decided in 2002 to launch the development of a highly innovative LPP concept on a reasonable economic basis. Finally, a modular approach for LPP, typically involving 10–20 laser modules, is in our opinion unavoidable when considering the ultimately requested laser power levels, approaching tens of kilowatts, in order to achieve the requested EUV output.

21.2.2 Optimizing the laser-target interaction

In the framework of the PREUVE project³ we have developed a target composed of a dense and collimated spray of xenon microdroplets.^{4,5} This target has been optimized for cw operation during the Exulite project and is a sort of compromise between a liquid microfilament and a cluster jet. First, the spatial stability and the density of the target are *a priori* not a problem, since a large number of droplets are present in the laser focal volume. Second, the collimated spray allows focusing the laser far away from the nozzle exit, thus limiting the heat load.

The first studies concerning EUV emission at 13.5 nm have been performed during PREUVE using a 50-Hz, 1-J, 8-ns-pulse-duration laser at 1.064- μm wavelength. The EUV yield was measured using a calibrated device consisting of a MoSi multilayer mirror coupled to a Zr-filtered XUV photodiode. The measurements were performed at 14 deg from the laser axis. The signal was normalized to 2π sr, assuming isotropic emission, and to 2% spectral bandwidth. Figure 21.1 shows the variation of the CE as a function of intensity at FWHM in the case of a pulsed droplet spray. Each point represents the mean value of 100 shots, and the error bars give the standard deviation. Those vary from 6% up to 13% when the

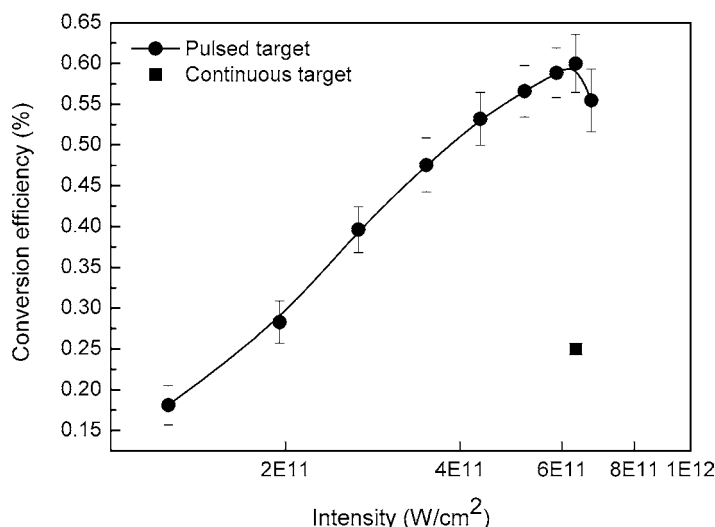


Figure 21.1 Evolution of the CE in 2π sr and 2% bandwidth as a function of laser intensity for a pulsed droplet target (circles) and for a continuous target (square).

CE is low. After a rapid increase of the EUV yield with laser intensity, the highest CE achieved is 0.6% at $6 \times 10^{11} \text{ W/cm}^2$ and then decreases. These results have been obtained with a target of 200- μm diameter and a 100- μm focal-spot size. The pressure is between 20 and 30 bars, and the temperature of the nozzle between -95 and -110°C . A measurement based on Mie^{6,7} diffusion suggests a mean droplet size of about 10 μm under these conditions.

We have also indicated in Fig. 21.1, by a square, the highest CE obtained in the same conditions but using a continuous droplet jet. Under these conditions the CE drops to 0.25%. The reduction of the measured EUV yield is mainly due to the fact that it has not been possible to produce a well-collimated continuous flow of droplets as in the pulsed-jet case. Briefly, as a consequence, the density of the jet is lower, thereby limiting the number of droplets in the laser focus and thus lowering the absorption of the laser light. Moreover, the poorer jet confinement prevented us from reaching satisfactory vacuum conditions in the ELSA interaction chamber using the inverse differential pumping scheme developed during PREUVE. Reabsorption of the emitted light at 13.5 nm is therefore much higher with the continuous target than with the pulsed jet.

Generally, CEs are extrapolated to $2\pi\text{sr}$, which is correct when assuming isotropic EUV emission. However, no target produces such emission.^{8–10} Actually, the hydrodynamic expansion of the plasma and its opacity determine the resulting spatial distribution of the EUV emission. Figure 21.2 shows the angular distribution of the EUV emission, for the experimental conditions giving the highest CE. Using a motorized support under vacuum, a Zr-filtered photodiode can move

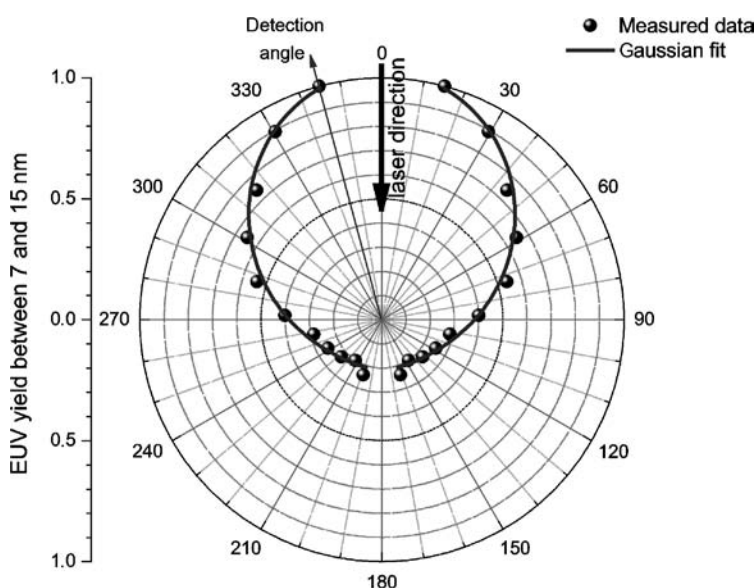


Figure 21.2 Experimental angular distribution of the EUV yield integrated between 7 and 15 nm (solid circles) and Gaussian fit (curved lines).

around the emitting plasma. The signal is integrated over the spectral bandwidth of the filter, between 7 and 15 nm.

The main part of the emission is directed toward the incoming laser pulse, and the angular distribution is essentially contained within π sr. The experimental data can be fitted with a Gaussian function. The total EUV emission energy can then be calculated starting from these measurements. This leads to a spatially integrated energy of 1.9 mJ/pulse at a laser energy of 740 mJ/pulse, which is equivalent to a CE of 0.3% per pulse with the pulsed jet target and only 0.13% per pulse with the continuous target. Such an analysis shows that most CEs in the literature are actually overestimated. Nevertheless, the angular distribution of the EUV emission in the case of a plasma produced using a small microfilament⁸ (diameter 10 μm) approaches isotropic emission over 2π sr. In this last case, CE is then overestimated by only 20%.

The laser pulse duration is one of the major parameters affecting the efficiency of the laser-target coupling.¹¹ As previously discussed, before starting the Exulite project, we used a commercial 50-Hz Nd-YAG laser delivering 8-ns pulses at 1.064 μm . We tried to determine the influence of increased pulse durations on the interaction through numerical simulations. We used the 1D1/2 Lagrangian hydrodynamic code CHIVAS¹² developed by the CEA, which was coupled to a post-processor code we developed in our laboratory at CEA/SPAM. The postprocessor is based on a simple collisional-radiative model¹³ and calculates the population density of the ionic species supposed to be responsible for the emission around 13.5 nm (Fig. 21.3). In particular, we estimated the bound-bound radiation losses¹⁴ due to Xe^{9+} – Xe^{11+} ions.¹⁵ The ratio between this value and the delivered energy

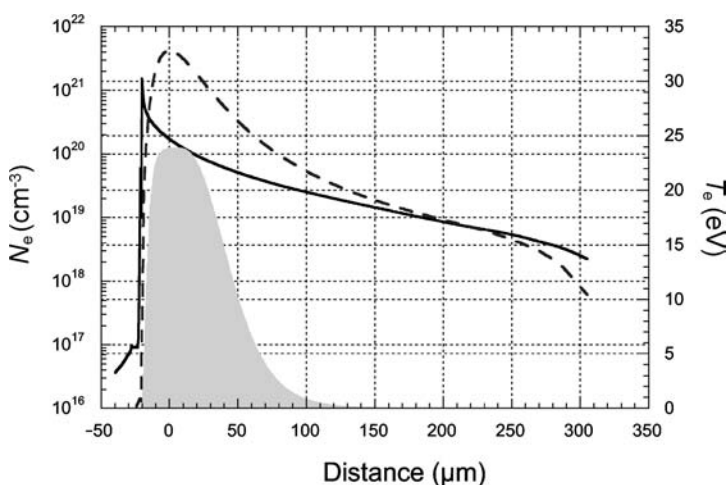


Figure 21.3 Spatial evolution of the electron density (solid line), electron temperature (dashed line), and Xe^{10+} population density (shaded area in arbitrary units) as calculated by CHIVAS at the laser peak of an 8-ns pulse in the case of a 1.2- μm -thickness liquid xenon target for a 5×10^{11} -W/ cm^2 laser intensity. The origin of the x axis corresponds to the initial position of the target surface. The laser beam is coming from the right.

was used as a kind of virtual CE. For simplicity, we considered a planar slab of solid xenon as target. For each pair of pulse duration and energy, the target thickness was properly chosen in order to avoid making the plasma transparent to the incoming laser radiation before the end of the pulse.

Figure 21.4 presents the results of the calculations for the CE as a function of impinging laser intensity for three different pulse lengths. At the optimum intensity, around $6 \times 10^{11} \text{ W/cm}^2$, the CE decreases not more than 30% when the pulse length is increased from 10 to 35 ns. Due to the roughness of the postprocessor for estimating EUV emission, it is hard to compare quantitatively the numerical predictions with the experimental data. Nevertheless, one can note that our result is close to that shown by Spitzer et al.¹⁶ Those authors performed an experiment using a plane slab of tin where the laser pulse duration was increased from 7.5 to 30 ns. At a laser intensity of about $2 \times 10^{11} \text{ W/cm}^2$, they report a weak loss in CE of 15%.

We have tried to further confirm the efficiency of such longer pulses by reproducing the experiment of Spitzer et al. and using well-characterized 3-, 8-, and 18-ns pulses and a planar solid tin target. This experiment was realized in collaboration with the Intense Laser Irradiation Laboratory (ILIL) at the CNR/IPCF in Italy. Unlike Spitzer et al., we used the Nd-YAG fundamental frequency. In Fig. 21.5, the measured CE is shown as a function of the laser peak intensity for the three different pulse durations. Despite the broad data dispersion, one can note that the maximum CE is almost the same for all durations. It is interesting to note that the laser intensity required to reach a given CE is higher for the shortest pulse duration and comparable for the two longer ones (8 and 18 ns).

We performed an additional experiment at the ILIL, to study the effects of longer pulses on our continuous xenon droplet spray target. The laser at ILIL allows

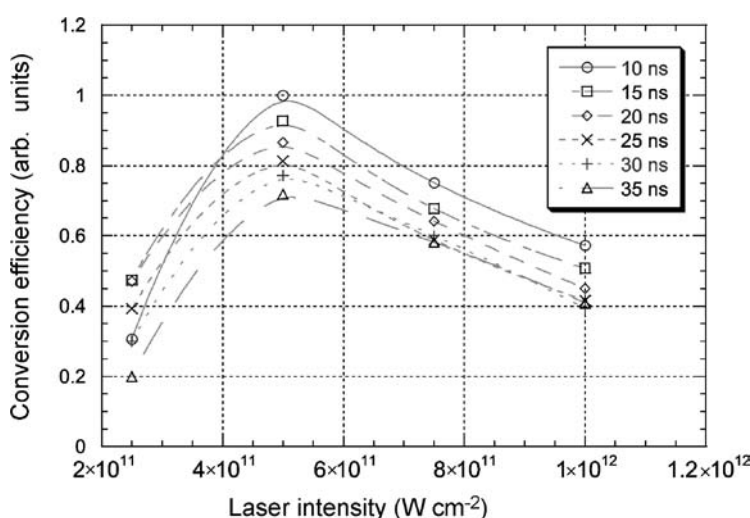


Figure 21.4 Calculated evolution of CE as a function of laser intensity for different pulse lengths.

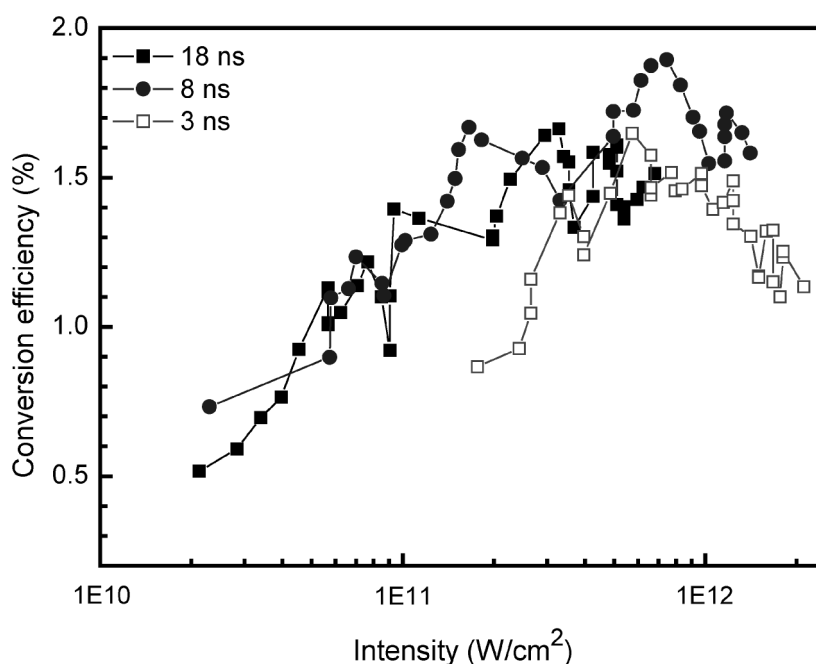


Figure 21.5 Evolution of the conversion efficiency of a tin solid target as a function of laser intensity with 3-ns (open square), 8-ns (full circle), and 18-ns (full square) pulse durations.

us to tune the pulse duration between 8 and 42 ns after each amplification stage. A pulse energy of a few joules was available, and the repetition rate of the laser was one shot every 5 min. The laser was focused on a 50- μm -diameter focal spot. The CE obtained for pulse durations of 8, 35, and 42 ns as a function of laser intensity is shown in Fig. 21.6. The CEs are given in arbitrary units, since we had no calibrated detection system for this experiment. Each point is averaged over 15 laser shots, and the error bars show that the standard deviation is varying between 13% and 30%. The fluctuation of the EUV yield is directly related to the fluctuation of the number of droplets in the focal volume. Considering the size of the droplets (10 μm), we estimate that the maximum number of droplets heated by the laser was only about 5. It is obvious that any small variation of the size, of the position with respect to the beam axis, or of the number of droplets will lead to high EUV emission instability. Nevertheless, the effect of the pulse duration on the EUV yield can be easily observed. Unlike bulk targets, in a droplet spray the effect of the pulse duration on the EUV emission is important. For a given laser intensity, the CE drops respectively by a factor of 2 and 3 when the pulse duration is increased from 8 to 35 ns and from 8 to 42 ns. It is thus clear that the droplet-spray target, unlike solid targets, is not suitable for efficient EUV emission when using long laser pulse durations. For this reason we have decided to abandon the development and further optimization of the xenon droplet spray although this target gave excellent results during the PREUVE project when using low-repetition-rate lasers.

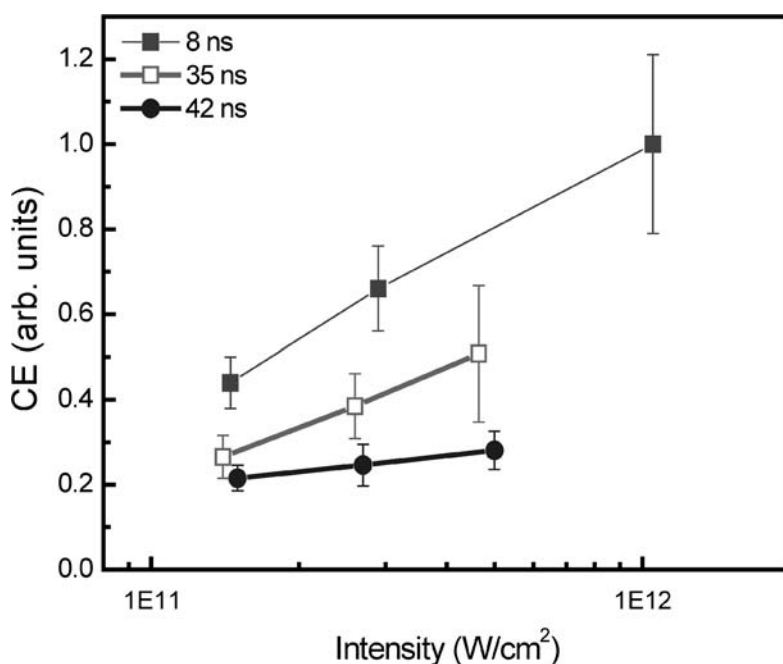


Figure 21.6 Evolution of the EUV yields at 13.5 nm as a function of laser intensity for 8-ns (full squares), 35-ns (open squares), and 42-ns (full circles) laser pulse duration.

An obvious disagreement appears between the numerical results, predicting an almost constant evolution of the CE, and our experimental data. We believe that the inhomogeneity of the spray is at least partially responsible for this lack of consistency. The plasma hydrodynamic expansion of a droplet is completely different from an ideally 1D plasma expansion such as we can simulate with CHIVAS.

In order to study qualitatively the influence of the laser pulse duration on the heating and the subsequent expansion of a single microdroplet, we developed a simple self-similar plasma expansion model in spherical geometry based on the initial approach of Haught and Polk.¹⁷ This model was coupled to a ray-tracing code, which calculates the energy deposit and the propagation of the laser through the droplet. We report in Fig. 21.7(a) the time evolution of the electron temperature (solid line) and density (dotted lines) obtained for an 8-ns duration and a 700-mJ laser pulse focused at 5×10^{11} -W/cm² peak intensity on a 12- μ m-diameter droplet of xenon. The intensity peaks at time $t = 0$. One can see that the maximum density and temperature are achieved very early in the pulse. When the maximum intensity is reached, the plasma has expanded and the electron density has dropped. Therefore, the coupling of the laser light with the plasma is very weak. This effect depends dramatically on the pulse duration, as shown in Fig. 21.7(b), which gives the time evolution of electron temperature (solid line) and density (dotted lines) for a 35-ns-duration and 5×10^{11} -W/cm²-intensity pulse. The maximum coupling occurs still earlier in the pulse and the maximum temperature is lower than for the 8-ns pulse duration. The model predicts that for 35-ns pulse duration, the maxi-

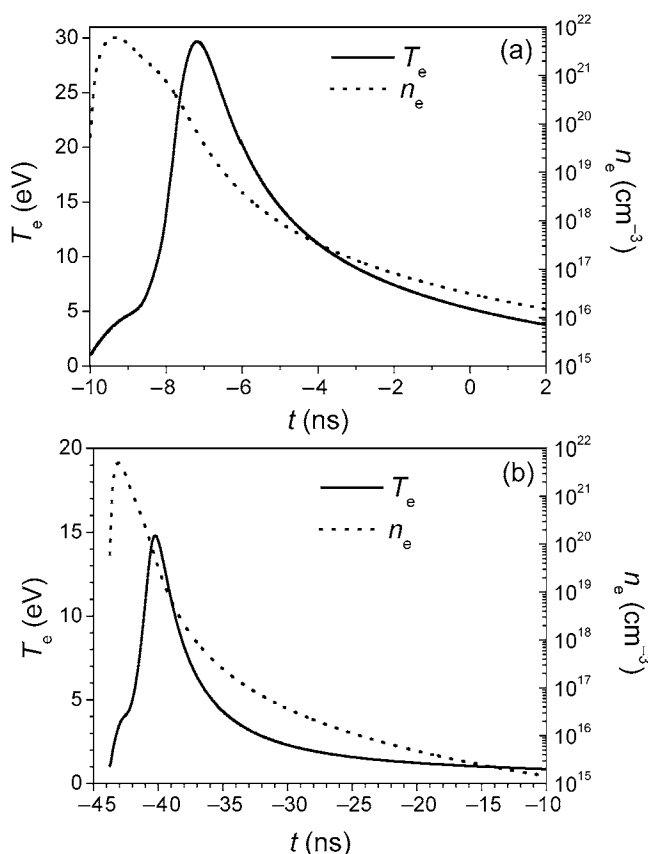


Figure 21.7 Time evolution of the electron temperature (solid line) and density (dotted line) for (a) 8-ns and (b) 35-ns pulse duration. The maximum laser intensity is 5×10^{11} W/cm² in both cases, and it is reached at $t = 0$.

imum temperature is 16 eV and the ionization degree is only 6+. Consequently, no or at least not much EUV light near 13.5 nm should be produced at 5×10^{11} W/cm² laser intensity. This result is confirmed by the experimental results given in Fig. 21.6.

As presented previously, the Exulite LPP prototype is based on lasers with high repetition rates (10 kHz) and long pulse durations (35 ns). Regarding the different experimental results and calculations, a filament target seems to be the best compromise to produce an efficient EUV source. Indeed, this target is very close to being a solid one, and the achievement of high conversion efficiencies with long pulses appears possible (Fig. 21.4). In addition, a liquid microfilament target is renewable and presents almost isotropic EUV emission and low reabsorption. This makes high-repetition-rate EUV generation possible.⁸ Such a target is now in operation in our laboratory. We now routinely produce filaments of about 40- μm diameter with a spatial peak-to-peak stability of ± 5 μm at a nozzle distance of 20 mm. The first results, obtained at quite low laser intensity (3×10^{10} W/cm²)

using a single laser module delivering 35-ns pulses, are very promising for the future, when several kilowatts will be focused on the target.

21.2.3 Laser development for the modular LPP source

The laser system is by far the most expensive part of an LPP source. Thus the designers have to take into account not only its technical performance but also such essential characteristics as cost, efficiency, reliability, and industrial availability.

In the present state of the art, the maximum CEs achieved with commonly used xenon and tin targets are respectively 1% and 3%. To fulfil the throughput requirements of EUVL production tools, the laser system of an LPP source must deliver, in the most optimistic case, at least 20 kW of average power. In our opinion, this can hardly be obtained with only a few laser chains. Starting from this consideration, we have proposed¹⁸ the concept of a modular LPP source based on the use of 10 to 20 identical, moderate-power laser chains (with typically 1.5 to 2 kW each) that are simultaneously focused on the same spot.¹⁹

Among other advantages, this leads to a simpler, more compact laser-chain concept and to a more robust system with enhanced redundancy (e.g., still allowing EUV operation when one chain is down). Another advantage is the possibility of accurately controlling the EUV dose on the wafer, as explained later in Sec. 21.2.6.

To develop a laser chain suitable for an LPP source, we considered a Nd:YAG rod as laser material, pumped by high-power cw diode bars. As a matter of fact, to obtain high repetition rate (>3 kHz), cw pumping is more efficient than pulsed pumping, due to the lifetime of the upper laser level. Moreover, the lifetime of cw diode bars may approach 20,000 hours—much longer than that of quasi-continuous-wave diodes—and cw diodes are at least 2 times cheaper for the same average power.

In order to obtain a good optical-to-electrical efficiency we have chosen to develop a power oscillator–power amplifier (POPA) configuration instead of the standard MOPA (master oscillator–power amplifier) system. In the POPA there is no need for preamplifiers, because the output from the oscillator efficiently extracts the energy stored in the first amplifier.

The beam quality of the power oscillator must be a compromise between good system efficiency and good focusability to generate sufficiently high intensities on the target. The beam quality^{20,21} should be on the order of $M^2 = 10$ –15 and maintained throughout the amplification chain.

The power oscillator is based on specially developed, now commercially available pump modules.²² These modules exhibit excellent pump uniformity to limit the spherical aberration and a high (90%) transfer efficiency, defined as the ratio of the light absorbed by the rod to the light emitted by the diode bars. In a short cavity, the cw output power of a pump module is 450 W for 1100-W pump power, yielding 40% optical-to-optical efficiency and 17% optical-to-electrical efficiency for the optical pumping structures.²³

Particular efforts were devoted to the management of the thermal effects. Briefly, we use two identical pump modules in combination with a polarization

rotator to compensate for the induced birefringence.²⁴ The spherical aberration, mainly due to pump inhomogeneities and the temperature dependence of the thermal conductivity,²⁵ limits the efficiency of the oscillator. The spherical aberration was measured, and we found typical values between 0.5λ and 1.6λ rms at the maximum pump power, depending on the diode cooling temperature, i.e., the pump profile. Unlike the birefringence, the spherical aberration cannot be easily compensated and should be minimized.

For Q switching of the laser, we use acousto-optical (AO) devices. They allow simple, reliable, and cost-effective switching for unpolarized cavities at high (multikilohertz) repetition rates, but two of them are necessary to hold off the relatively high gain ($g_0 \approx 1.8$).

A schematic diagram of the laser resonator is given in Fig. 21.8. Two divergent lenses are used to reduce both the divergence of the beam (so as to improve the hold-off of the Q -switch system) and the power density on the mirrors.

Figure 21.9 shows the average laser output power as a function of the repetition rate. It ranges from 480 W at 10 kHz to 550 W at 30 kHz. The pulse duration (Fig. 21.9) is linearly dependent on the repetition rate and can be as low as 32 ns. This leads to peak densities on the order of 75 GW/cm^2 on a $50\text{-}\mu\text{m}$ -diameter spot. The measured beam quality is 13 and mainly limited by the spherical aberration. The optical-to-optical and the optical-to-electrical efficiencies of the laser module are respectively 21% and 7%. The time jitter of the laser is 1.2 ns rms, and the power fluctuations less than 3%.

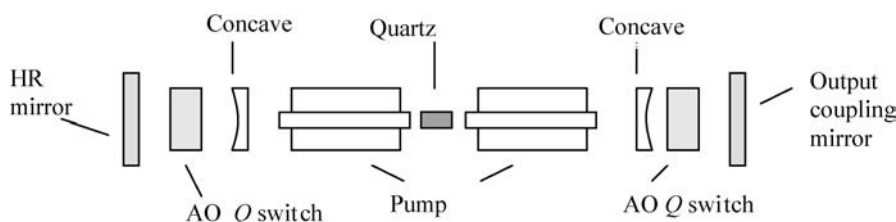


Figure 21.8 Schematic diagram of the oscillator resonator with two pump modules and birefringence compensation.

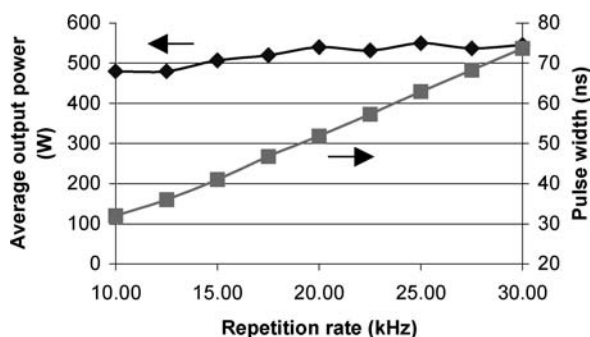


Figure 21.9 Average output power and pulse width as function of the pulse repetition rate.

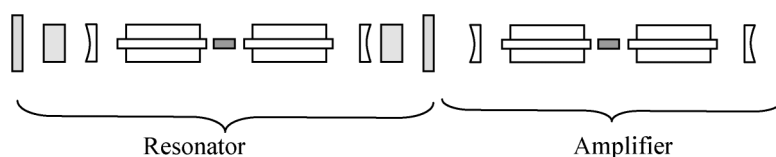


Figure 21.10 Schematic of an oscillator and an amplifier stage in a POPA configuration.

To increase the laser power of each module, we will add amplifier stages to the oscillator. The amplifier is a duplicate of the oscillator design without the mirrors. The schema of the POPA design is given in Fig. 21.10. The authors of Ref. 26 have shown that in this way the power can be doubled without degradation of the beam quality. First calculations show that the extraction in the first amplifier can be as high as 70% of the stored energy with 50-mJ input, and in the second one 80%.

21.2.4 Multibeam laser focusing

The multibeam focusing technique that has been developed by Exulite is the so-called spiderlike side attack on the target. In it, as shown in Fig. 21.11, the laser beams run outside a grazing-incidence EUV collector. This side attack is chosen in such a way that an optimized collection efficiency for EUV is obtained. In particular, our optimized design takes into account both the EUV angular distribution of the target and the collector efficiency as a function of the incident angle of the incoming light rays.

Because of the large angle chosen for EUV collection (at least 120 deg), the incident laser beams are almost perpendicular to the average collecting axis, which corresponds to the axis between EUV source and intermediate focus (IF).

It is important to consider the needed numerical aperture (NA) of the laser focusing units, since the beams must reach the target within the space defined by the outer EUV collector shell and the target injector device. For a given beam quality of the laser, M^2 , the full angle of divergence D for focusing is given by $\Phi D = 4M^2\lambda/\pi$, where Φ is the beam diameter at focus, and D and Φ are defined at $1/e^2$. For example, with $\Phi = 100\ \mu\text{m}$, $M^2 = 10$, and $\lambda = 1.064\ \mu\text{m}$, the full angle divergence $D = 0.136\ \text{rad}$, which corresponds to an opening angle of 8 deg.

The present design for an LPP EUV source is even adapted to the case of quite poor beam quality of the exciting lasers together with relatively low mean powers where the requested intensities on target call for very small spot diameters. However, the opening angle will be smaller for the powerful industrial source.

Concerning our choice of the laser focusing device, we considered the critical issue of the heat load induced by the EUV and thermal power emitted by the source spot. For a lens with cooling on the circumference, the absorbed power would generate wavefront distortion leading to longitudinal and lateral defocusing and enlarging of the focused spot. We have also considered the possibility of laying out a transparent heat shield (e.g., sapphire or diamond), but we preferred a focusing mirror, which allows for efficient and homogeneous cooling from the rear of the

optimized substrate and thus avoids a large increase of temperature on the front and a steep gradient in temperature profile (cf. Sec. 21.3.7).

The shape of the focusing mirror must be consistent with the desired image quality at the focus. One can use a mirror of either parabolic or ellipsoidal form. However, the ellipsoidal mirror limits the housing needed to protect against stray beams around the entrance window. Moreover, with such a mirror it is easier to lay out a protecting screen against the flux coming from EUV source in front of the entrance window without increasing the off-axis angle (Fig. 21.12).

In the frame of Exulite, we have also studied the beam transport from the laser to the focusing optics. In order both to limit the housing for all focused beams around the source and to maximize the laser transmission at the focusing mirror, the laser waist is imaged on the focusing mirror, which is the optical aperture of the system. The modular multibeam LPP source requires excellent spatial stability of the laser foci on target. To this end, a closed-loop feedback control is used to compensate slow drift due to thermal effects and also to minimize the effect of system vibrations, even though the very short equivalent focal length of the focusing optics tolerates poor beam-pointing stability.

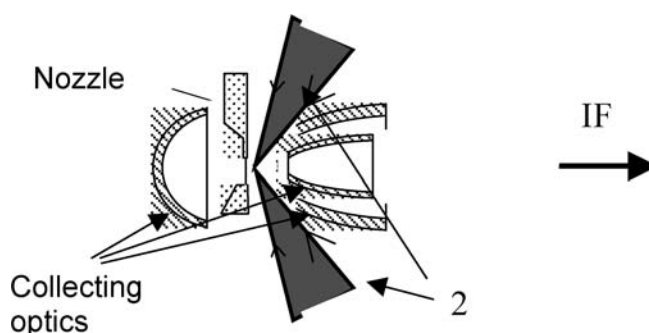


Figure 21.11 Simplified scheme of the spiderlike side attack on the target with two focusing beams (2) and the EUV collection optics according to the Exulite design.

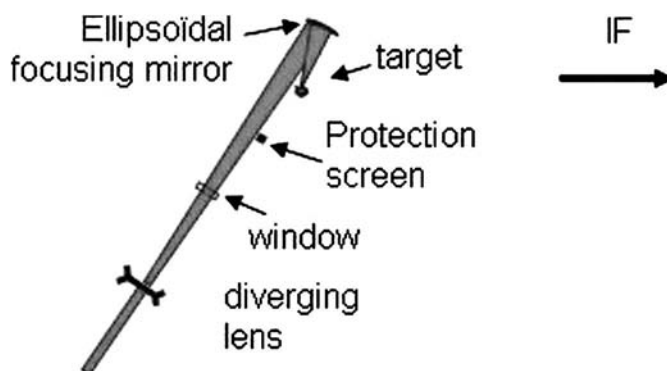


Figure 21.12 Optical scheme for the focusing of a single laser beam on a target.

21.2.5 EUV collection

A key requirement of the EUV collection system is to ensure high collection efficiency even with an increasing number of lasers. A system with a laser beam propagating along or close to the collector axis is not suitable, since for an increasing number of lasers the central part of the collection system, which is also the most efficient part, will be obscured. We have developed a system where the lasers do not obscure the collection elements (see Sec. 21.2.4). Indeed, with our modular LPP source, the maximal EUV emission will be along the symmetry axis although the laser beams are arranged in a spiderlike configuration.

Two types of collecting mirrors are generally used, namely, grazing-incidence metallic mirrors, and normal-incidence multilayer coated mirrors. Our approach uses both types of mirrors to benefit from the advantages of both technologies.

Consider first the half-space that contains all the laser beams that are focused on the target. In this first part, we use a set of grazing-incidence mirrors. Those mirrors have a shape designed to reflect the rays from the point source to the IF. It is a general property of ellipsoids that all the rays coming from the first focus are reflected within the ellipsoid to the second focus. Nevertheless, as the reflectivity of the surface varies greatly with the angle of incidence, it is very ineffective to use only one ellipsoid. In order to collect effectively the rays whose angle with the collector axis is greater than 40 deg, we use a Wolter objective.²⁷ The Wolter objective combines a hyperboloid with an ellipsoid. An advantage of this combination is that the two reflections (first in the hyperboloid and second in the ellipsoid) are realized at smaller angles and the surface reflection is thus greater (approximately 80% for each surface, depending on the material).

If we combine an ellipsoid with a Wolter objective, we can calculate the reflectivity curve of this system, as presented in Fig. 21.13. This system can collect effectively rays between 0 and 65 deg, which is the reason why we have required the incident angle of the laser beams to be greater than 65 deg.

The second part of the EUV collection system is located in the other half-space on the opposite side of the source spot. Here we use a simple spherical mirror whose center of curvature is the EUV source point. This part is a MoSi mirror whose reflectivity is around 68% for almost normal incidence. The rays coming from the point source arrive normal to the surface mirror and are reflected back to the point source (or very near) so that they can be collected with the first part of the system. A global description of this system is presented in Fig. 21.14.

We have used ray-tracing software to evaluate this optical system. This software is also used to check whether the specifications for the second focus are achieved, viz., numerical aperture <0.2 sr and etendue $<3 \text{ mm}^2 \text{ sr}$. The results of this study are reported in Table 21.1.

Using grazing-incidence mirrors and a multilayer coated mirror, this multi-element collection system can collect a very considerable solid angle despite our

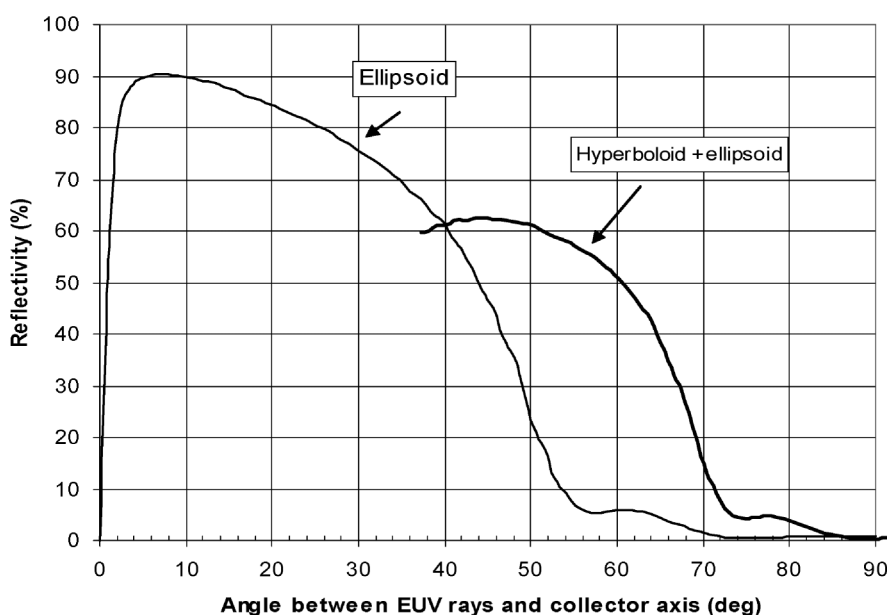


Figure 21.13 The reflectivity calculated with the surface equation using the properties of the material.

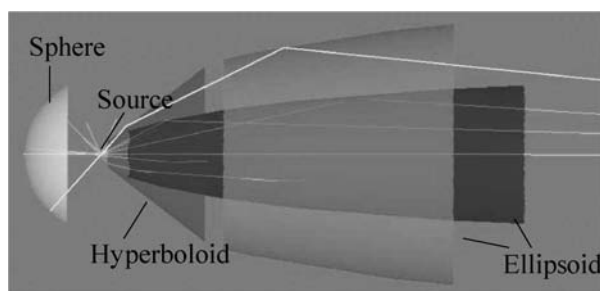


Figure 21.14 Ray-tracing software was used to evaluate the collecting system. Various parameters, such as the source emissivity and the surface reflectivity (which depends on the grazing angle), are integrated in the calculation.

multibeam laser-plasma configuration. Interestingly, it is also an advantage to use the grazing-incidence collector as an additional vacuum chamber and take advantage of differential pumping. Then the gas transmission of EUV can be higher in the collector chamber than in the main chamber with the xenon jet.²⁹

21.2.6 EUV dose control

Each part of the wafer must receive a well-defined energy dose in order to be correctly exposed for the lithographic process. With an EUV source power of 115 W at a repetition rate of 10 kHz, the correct dose corresponds to 50 pulses and the source dose stability has to be $\pm 0.30\%$ in 3σ .³⁰ Without an energy-dose control

Table 21.1 Comparison of a simple ellipsoidal collector, an ellipsoidal collector combined with a Wolter objective (see text), and our EUV collection system with the alpha-tool requirements.²⁸

Collector	Ideal geometrical collection efficiency ^a η (%)	Mean reflection R (%)	Transmission ηR (%)
Alpha tool	28	65	61
Ellipsoid	36	61	22
Ellipsoid + Wolter objective	40	67.5	27
Global	80	46	37

^aCollection solid angle divided by 2π .

system, this requirement is hard to achieve, due to the multiple instabilities of the different source systems. Hitherto, common EUV sources have been much less stable, approaching only 2% in 3σ over 50 shots, despite the fact that they still do not have enough power.^{32,33} Thus, a specific system allowing one to control the dose stability is essential. To do so, one must consider in detail how the scanner proceeds. During the continuous translation of the exposure slit on the wafer, only one different-energy pulse is delivered between two consecutive doses of 50 pulses each. Using LPP sources, the EUV energy is a particular function of the injected laser power, which means that the delivered EUV dose can be adjusted with the laser power. It is very difficult to adjust, quickly and precisely, the output power from a single laser chain without having any thermal problems. The approach we propose is straightforward when using a modular, multibeam LPP source.

Our dose control system is based on the principle³¹ that the EUV pulse energy can be modified quickly and precisely with the number of lasers that is effectively contributing to the plasma heating. Whereas it is not recommended to vary quickly the power of a laser module for thermal reasons, it is easy to shift temporally the pulse trigger instant or to shift spatially the focus point with a moving mirror. We have preferred the solution based on temporal shifting. As the EUV energy produced by a single laser is quite low, the energy of the temporally shifted laser does not disturb the EUV source, if the temporal shift is judiciously chosen. The way that our dose control works is actually quite simple: the system measures the energy of the first 49 pulses, calculates the pulse energy necessary to obtain the energy dose, and commands the number of lasers to be used. In practice, the problem is a little more complicated in that, between two consecutive energy doses, there is only one available different-energy pulse. So we must use algorithms to reduce the noise level and to decide the next pulse energy. Different simulations were needed to choose the best algorithms and to calculate the performance according to the different parameters: maximum EUV power, ratio of the EUV power with the laser power, and shot-to-shot stability. The results of these simulations (Fig. 21.15) show

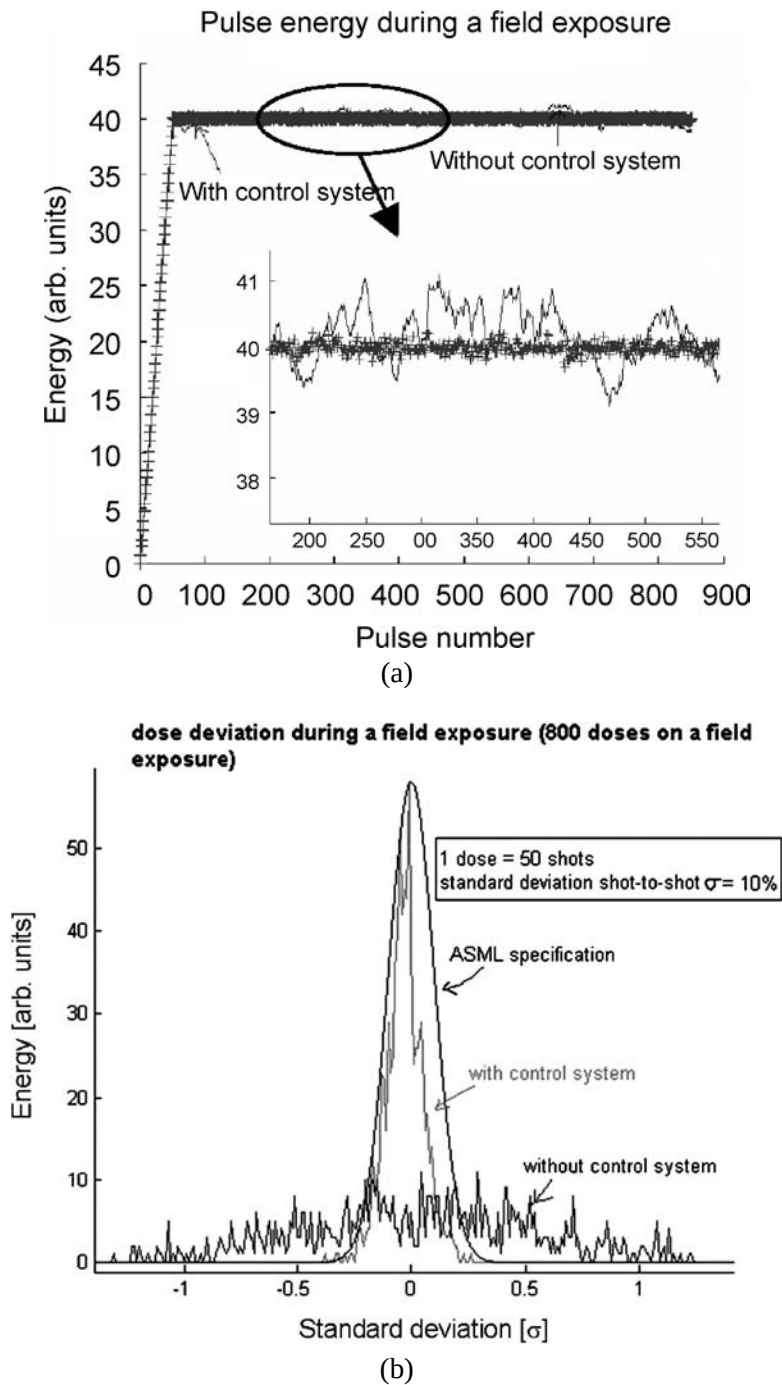


Figure 21.15 Comparative study with and without a control system. The results are obtained with a shot-to-shot source stability $\sigma = 10\%$ during 800 energy doses.

that even with an EUV source presenting 5 times more shot-to-shot instability than other existing sources,^{32,33} we can meet the tough stability requirements.

Of course, this method works with more pulses per dose, or with more lasers, or with a different pulse repetition rate. However, good stability can be achieved only if the average EUV power necessary for the lithographic process is below the maximal useful EUV power of the source. For this reason, a system to optimize the EUV power has also been developed within Exulite. This system, between wafer changes, looks for the best working point of the LPP source and its lasers. The modular LLP source is thus an excellent concept to apply for a simple and efficient EUV dose control system.

21.3 The ELSAC LPP Source Developed by Exulite

21.3.1 The ELSAC source architecture

Right at the beginning of Exulite, the main idea was to take into account the constraints on all subelements of the ELSAC source and those generated by the relationship between those elements. This architecture optimization was achieved thanks to a complete functional analysis of the source and of all subelements: the target vacuum chamber, the injection system, the laser module, the xenon pumping and recycling system, the laser-beam transportation and focusing system, the EUV collector, and the global control system.

First of all, the design takes into account the injection and optical systems. For example, the mechanical implantation of the injection system is modular. It allows using either a droplet spray or a filament jet. Both systems lead to injecting a high flow of xenon in order to generate a dense target.

A second priority was to keep the pressure in the source chamber low to avoid both the reabsorption of the generated EUV light and the contamination of the laser-focusing and EUV-collecting optics.

To meet these specifications, a special differential pumping system³⁴ was designed and installed. Notice that this system is related to the choice of a grazing-incidence collector. We also choose special aluminum with a very low specific outgassing rate for the source chamber in order to meet the severe pressure and contamination requirements.

Moreover, thermal management of the chamber with all subunits is a crucial issue, because the injection of 5-kW laser power produces significant out-of-band radiation. Thermal modeling was performed to evaluate these constraints precisely. The result of these studies is that the ELSAC main chamber is a massive part made of aluminum to facilitate the extraction of this heat load. Because the focusing optics and the collector are particularly sensitive to heat load, the main chamber and the collector chamber include cooling areas, specifically designed to optimize the cooling of these elements. Furthermore, the injector has its own integrated temperature control system. Note that the choice of a massive chamber also permits us to

reach the required positioning precision of the focusing mirrors and to facilitate the implantation of all necessary windows for the inlet and outlet of the laser beams.

Finally, the second chamber for the EUV collecting elements has lower mechanical and thermal constraints. Its design was optimized to be modular in order to accept a complete set of diagnostics and thereby allow numerous different studies. Figure 21.16 shows the resulting architecture for ELSAC.

21.3.2 The high-power laser system

The concept of 10 spatially and temporally multiplexed laser modules of 500-W average power in the infrared is chosen to reach the total power of 5 kW. We believe that this solution is the best adapted to higher-power LPP sources, because of (1) cost optimization of each individual module, (2) easy and fast replacement of a module in case of failure, (3) no interruption of the EUV process with one module offline, (4) cw diode technology for low cost of ownership, and (5) satisfactory beam quality of high-power modules through innovative design.

The 500-W laser module design is based on patented homogeneous pumping structures, used in Thalès Laser commercial lasers, and which represent the technological base of Thalès Laser. The main specifications of the 500-W laser module developed in collaboration with the CEA/SCP, and currently prepared for industrialization by Thalès Laser, are: 1064-nm wavelength, 6- to 20-kHz pulse repetition rate, average power 500 W at 10 kHz, beam quality M^2 better than 15, and pulse durations shorter than 40 ns.

The SHINE module, shown in Fig. 21.17, will be the first product that combines high average power and beam quality in a reliable compact diode-pumped solid state (DPSS) laser. The highest energy densities in the laser cavity are located on the oscillator mirrors and are far from the damage threshold of the standard optical components, thus ensuring safe use in an industrial context. The cavity size is compact enough to be representative for the future laser units needed for EUVL.

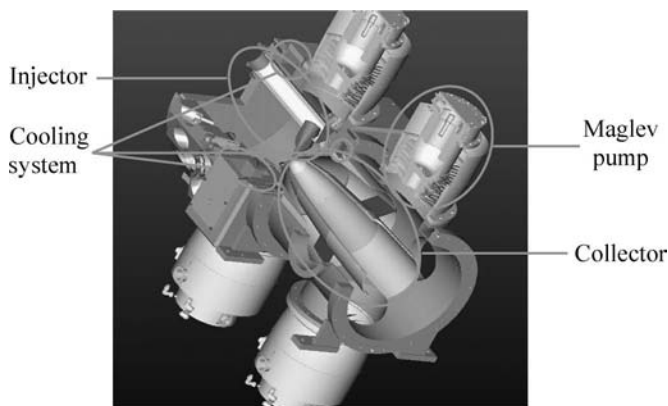


Figure 21.16 Overall view of the ELSAC chamber with all its elements.

A picture of the SHINE cavity is given in Fig. 21.18. The heart of the system consists of two diode pumping structures (Fig. 21.19). Each structure is pumped by 30 cw laser diodes manufactured by Thalès Laser. The total pump power per head is 1200 W cw.

SHINE laser heads and electronic devices benefit from a user-friendly design with computer control, assuring all the different verifications that are needed. The Thalès Laser software drives the master clock, which gives the timing for the 10 lasers and allows for synchronizing of all modules. This is essential to ensure precise EUV power control for the photostepper (cf. Sec. 21.2.6 on EUV dose control).

21.3.3 The laser-target optical interface (spider configuration)

The laser-target optical interface—the so-called spider configuration—has been developed by Exulite for 10 independent beams that are focused all together on the xenon target on a spot $50\text{ }\mu\text{m}$ in diameter ($1/e^2$). The interface will couple 87% of the incoming pulse energy into the nominal focus of the ELSAC source. With typical 50-mJ pulse energy per module and 35-ns pulse length, the result-



Figure 21.17 Compact housing of the 500-W SHINE laser module (maximum length is about 1 m).



Figure 21.18 Twin-laser-head cavity design to increase beam quality and output power of SHINE.



Figure 21.19 Diode pumping structure.

ing peak intensity on the target is $7 \times 10^{10} \text{ W/cm}^2$, but, depending on the laser beam's far-field profile, the peak intensity can reach up to twice the above value, i.e., $1.4 \times 10^{11} \text{ W/cm}^2$. It is also possible to change the spot diameter by adjusting the transport and defocusing unit (consisting of three lenses), thereby changing the beam diameter on the focusing mirror. The maximum full angle of a beam is around 24 deg, which is limited by the mirror size and the corresponding power loss. As shown in Fig. 21.20, the present spiderlike laser-target optical interface, developed for ELSAC, couples focusing beams at an angle of 75 deg with respect to the EUV collecting axis.

The two foci of each ellipsoid are respectively 100 mm (source spot) and 625 mm (first focus) away from the mirror center. The design and shape of the mirror together with its mounting have been optimized to facilitate both the realization of the mirror and its precise mounting within the ELSAC vacuum chamber. The optics company SESO has realized the mirrors on a silicon substrate. The laser entrance window of ELSAC is 300 mm away from the EUV source spot. The whole optical system has been toleranced. A result of the thermal studies is that beam pointing will be stable enough when thermal load is increased up to maximum power. A closed-loop control device has been developed for the beam pointing and the beam position on the focusing mirror (less important). The beam is monitored either to preserve the reference parameters during the alignment phase or to keep the EUV power at a maximum.

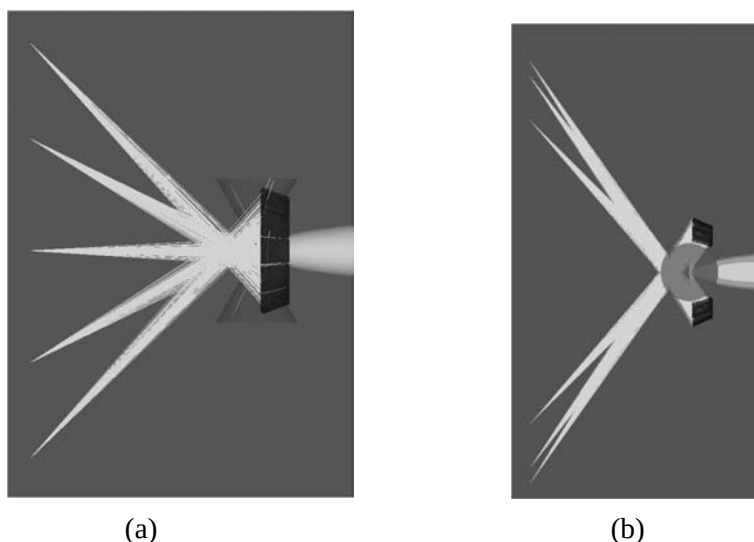


Figure 21.20 Optical scheme of the 10 laser beams, showing (a) the optical path drawn from the first focus of each ellipsoidal mirror to the common second focus, and (b) another side view from the perpendicular direction. The main EUV collection axis is in the paper plane and horizontal in both views. The violet cones (a) and circle (b) indicate the position of the target injector and catcher.

21.3.4 The EUV collector

The designed EUV collector will not be built during the first phase of Exulite, which runs until mid-2005. For the realization of ELSAC, we intend to use a rough collector module that mimics the future optical collector without presenting an optimal optical surface (with respect to shape, roughness, and treatment).

21.3.4.1 The xenon pumping system

Vacuum and contamination controls are key issues for the production of EUV light. First of all, for current systems using xenon, the reabsorption of EUV light by residual contamination gas and in particular by residual xenon strongly affects the useful EUV generation. Therefore, the source chamber partial pressure of xenon should be limited to 10^{-3} mbar on the EUV light path. Second, contamination could be critical for the optical components' lifetime. Indeed, EUV sources contain optical components, such as focusing elements or collector modules, that are fragile and very sensitive to contamination. Therefore the partial pressure of water and hydrocarbons must be kept as low as possible, typically below the 10^{-9} mbar range.

However, due to the physical properties of xenon (small thermal expansion coefficient and large atomic weight), this gas is difficult to pump. To meet the EUV source specifications, Alcatel designed an innovative pumping system based on three differential pumping stages and on advanced pumps optimized for xenon.

The main part of the xenon jet is directly pumped through a catcher by a dry primary pumping system based on advanced multistage Roots pumps. The evaporated xenon in the source chamber is pumped by magnetically levitated turbomolecular hybrid pumps, which are directly connected to the plasma chamber and to the EUV collecting chamber. Figure 21.21 summarizes schematically the ELSAC pumping system for xenon and shows all subunits.

The diaphragm between the two chambers is optimized so that only a small amount of evaporated xenon can flow through it toward the collector. Thus, the pressure in the collector chamber remains one order of magnitude below that of the plasma chamber, thereby keeping EUV-light absorption at a negligible level and limiting contamination of optical elements.

This optimization was first made with simple conductance calculations, and then detailed with a 3D computational-flow-dynamics modeling of the whole vacuum system. In particular, our modeling is based on a stationary approach assuming monophasic gaseous xenon (i.e., no liquid phase), and finally the xenon target is taken as a dense, gaseous xenon flow out of the injector nozzle. Note that the results of the global thermal study of the source have been injected into this fluid modeling (see Sec. 21.3.7).

The calculated gas flow chart in Fig. 21.22 shows very fast expansion of xenon due to injection of a high flow rate of gaseous xenon under vacuum. Optimization of the vacuum systems was obtained by combining gas flow modeling with experimental tests.

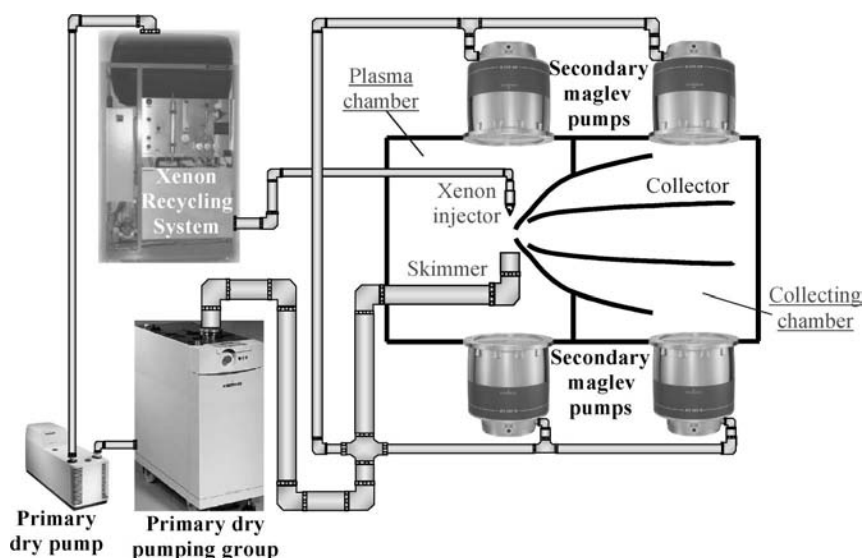


Figure 21.21 Scheme of the advanced xenon pumping system for the ELSAC source developed by Alcatel.

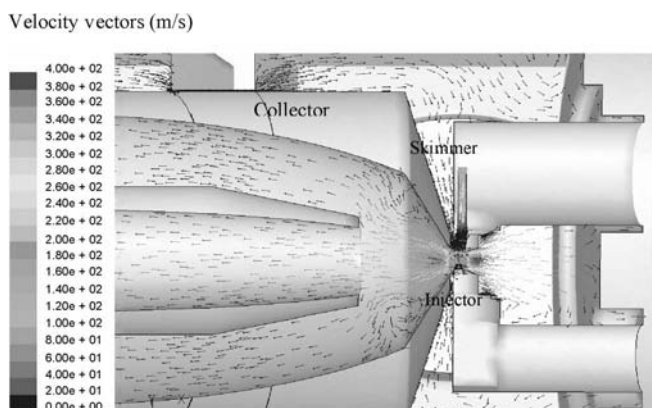


Figure 21.22 Gas flow modeling for vacuum system optimization: velocity vectors in the vertical symmetry plane.

21.3.5 The xenon recycler

Since xenon is a rare and expensive material, a recycling and purifying system is crucial to keep the cost of ownership for an industrial LPP source at a reasonable level. Alcatel Vacuum Technology/Adixen developed a xenon recycling system, and a first prototype has been working continuously since 2002 at the CEA labs. The specifications for the second system for the ELSAC source prototype have been set much more severely in terms of purity (1 ppm H₂O; 1 ppm O₂; 1 ppm C_xH_y; 1 ppm NH₃, Cl₂, and F₂; 10 ppm N₂ and rare gases; 1 ppm for all other trace gases), in terms of injection pressure (up to 50 bars), in terms of xenon charge (up

to 400 L), and in terms of flow rate of xenon (up to 3 slm), thereby keeping the leak rate below 10^{-9} mbar L/s. This system has continuous automatic flow operation, for potential every-day and round-the-clock operation. The physical principle of the recycling system is illustrated in Fig. 21.23.

The xenon is extracted from the exhaust of the dry pumping system in a gas phase to a buffer gas tank. This xenon gas is then purified through chemical filters to eliminate H_2O , O_2 , and C_xH_y molecules. Liquefaction is performed in the next phase in one of the three reservoirs by cryogenic means. At the same time, another reservoir is in evaporation mode and is delivering xenon gas at room temperature to the source injector. The third reservoir is in transition mode between liquefaction and evaporation, so that the cyclic system is able to deliver purified xenon gas in continuous flow. The output pressure delivered is regulated by a mass flow regulation system. The entire machine is controlled by an automatic device and a supervisor computer.

21.3.6 Thermal studies

The injection of 5-kW laser power into the xenon jet target produces, beside the useful EUV power, important amounts of out-of-band radiation, which heats up the ELSAC chamber together with all subunits. For this reason, thermal management is crucial to avoid deformation and degradation of the whole system. In particular, the cryogenic xenon injection system and various optical elements are very sensitive to thermal stress. For example, the temperature and pressure of the injection system, and particularly of the nozzle, must be precisely controlled to obtain a stable cryogenic filament jet.

Specific thermal and thermomechanical modeling have been performed to study the heat load of the system and possible solutions. Figure 21.24 shows the deformation of the laser-beam-focusing mirrors, of their supports, and of the chamber

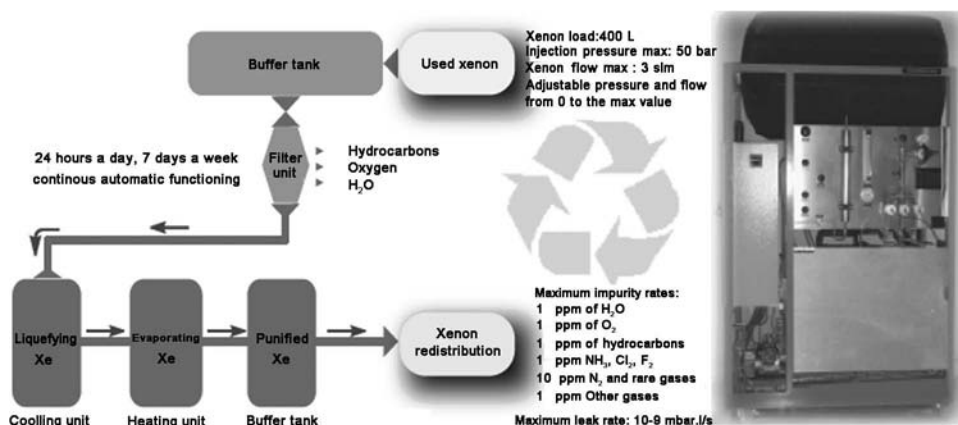


Figure 21.23 Functional scheme of the Alcatel xenon recycling system developed for EUV LPP sources.

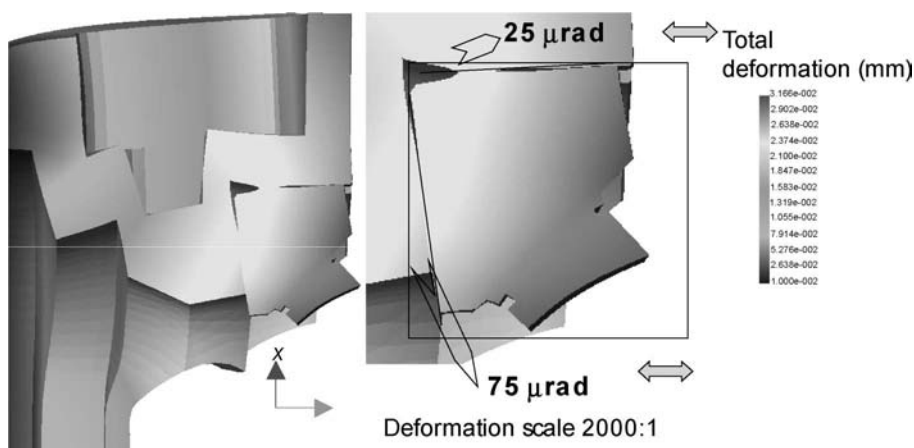


Figure 21.24 Deformation of the focusing mirrors, their supports, and a part of the ELSAC chamber.

wall itself. This result was obtained in two steps. First, we calculated the temperature field in the whole source with a 3D thermal modeling. Second, the results of the first modeling were input to a mechanical study to calculate the deformation of the chamber and of the focusing optical elements.

The results of these studies have led to a novel configuration for the focusing optics, to the choice of well-adapted materials for the focusing optics and the xenon injection nozzle, and finally to the design of an optimized cooling system.

21.4 Conclusion

Within the frame of the European MEDEA+ T405 project, the Exulite consortium is currently developing a modular LPP source based on spatial multiplexing of several laser beams. This innovative approach using many identical, compact power-oscillator modules was first proposed by Exulite partners in 2000 to overcome the economic constraints of common LPP sources. This chapter summarizes in a condensed way the spectrum of efforts at Exulite that allow us to propose technical solutions concerning lasers, EUV optics, and system-oriented aspects, including for example thermal studies, pumping and recycling of xenon, tolerancing of the multibeam optical interface, and EUV dose control. The LPP prototype (ELSAC) is currently built and will be fully operational on an intermediate EUV power level in mid-2005 with 3-kW laser power on the target.

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Chapter 22

Driver Laser, Xenon Target, and System Development for LPP Sources

Akira Endo

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22.1 Introduction

The Extreme Ultraviolet Lithography System Development Association (EUVA) was established in Japan in July 2002. Association members are the companies Canon, Fujitsu, Gigaphoton, Komatsu, NEC, Nikon, Renesas, Toshiba, and Ushio. EUVA is funded through the Japanese Ministry of Economy, Trade, and Industry (METI). The target of the EUVA project is the development of an EUV light source and of EUV exposure-tool projection optics. The light-source development project includes DPP sources and LPP sources. The EUVA project will end in March 2006, i.e., at the end of the Japanese fiscal year 2005. By that time DPP and LPP EUV light sources with an IF inband power of 10 W will have been developed. More detailed information related to EUVA can be found elsewhere.¹

The “driving force” for EUVL light sources is the aspect of semiconductor evolution that favors smaller feature sizes because they allow for more tasks to be done at higher speeds. Optical lithographic technologies have been used so far for semiconductor production, meaning that the wavelength of the light source must follow the trend to smaller sizes, i.e., to shorter wavelengths. Current high-end light sources are KrF and ArF excimer lasers oscillating at 248 and 193 nm, respectively. These lasers enable the 90-nm node (KrF), and may still be used in the 45-nm node

(ArF) if immersion technology can be successfully applied. The status of the F₂ laser (157 nm) as a lithography light source is therefore open, because the currently favored technology for the 45-nm node and below is EUVL. EUVL incoherent light sources will be used at 13.5 nm because the current Mo/Si multilayer mirror (MLM) technology provides optics with about 70% reflectivity at normal incidence at this wavelength, with a FWHM bandwidth of about 4%. EUVL sources will be based on DPPs or LPPs optimized for the emission at the required wavelength. The main constraint on the light source is the increased power requirement that is due to the limited reflectivity (e.g., using six mirrors for the projection optics results in a transmission of only 0.12) and to the low resist sensitivity (5 mJ/cm²). Whereas currently KrF and ArF laser powers of 20–40 W are sufficient, an EUVL light-source power of 115 W is required at the IF,² i.e., the interface point between the light source and the illuminator of the scanner. The required power estimation of 115 W is based on a 300-mm wafer throughput of 100 wafers per hour, which is considered necessary for profitability. Another quite severe specification is due to the critical dimension control, which requires an integrated energy stability of 0.3% (3 σ) for a moving average of 50 pulses.³ Ota et al. present the current EUV source requirements from the lithography system makers ASML, Canon, and Nikon in detail in Chapter 2.

This chapter will briefly describe the development of an LPP light source for lithography done at EUVA. First, the driver-laser and plasma-target development will be outlined, then the current system performance will be presented.

DPP and LPP light sources are being developed simultaneously at EUVA; the research facilities are, however, at different locations. The LPP development is outlined in this chapter; the DPP development is presented by Teramoto et al. in Chapter 17.

22.2 High-Power Driver Laser

The conversion efficiency (CE) of laser energy to inband EUV energy determines the laser power level necessary to generate the required 115-W inband power. A CE of 1% (related to a solid angle of 2π sr) in the case of xenon requires a minimum laser power of 11.5 kW. Assuming a collector mirror reflectivity of 0.7 and a collector angle of 1.5π sr, the laser power requirement increases to 22 kW. (Losses due to eventually necessary spectral purity filters, as well as absorption and other losses, are still not taken into account.) The solid-state laser technology that is well established and closest to this power requirement is the Nd:YAG laser technology. However, at this power level no ready-to-use lasers are commercially available, and therefore laser development is yet to be done for LPP EUVL applications.

The Nd:YAG laser system developed at EUVA is a master oscillator–power amplifier (MOPA) system. A photograph of the system is shown in Fig. 22.1. The master oscillator has a pulse energy of 7 mJ at a repetition rate of 10 kHz, thus delivering an average power of 7 W. The wavelength is 1064 nm, and the FWHM laser pulse width is 6 ns. A fiber-coupled laser diode pumps the oscillator longitudinally

at the given repetition rate. The power amplifier consists of four preamplifiers and four main amplifiers followed by four booster amplifiers. All amplifier modules are continuously pumped with laser-diode stacks in the transverse direction. Figure 22.2 shows the amplifier output power versus the oscillator input power. The maximum output power currently obtained is 1 kW. The initial (oscillator) FWHM pulse width of 6 ns remains unchanged after amplification.

Evidently, the high-power laser must have good beam quality, because the laser beam must be focused onto the plasma target, which has a size of several tens of microns in the case of a xenon jet or droplet target. At the required power levels, however, thermal effects inside the solid state laser rods deteriorate the beam quality. One possibility to correct the beam quality is the use of deformable mirrors. A schematic of such a mirror is shown in Fig. 22.3. The mirror consists of a silicon nitride membrane that is coated with a high-reflectivity dielectric multilayer film. The clear aperture of the mirror is 18 mm. The mirror surface can be adjusted to the laser-beam wavefront via 37 electrostatic actuators, to which high voltages are applied. The focal-spot size of a small fraction of the laser pulse energy is the pa-

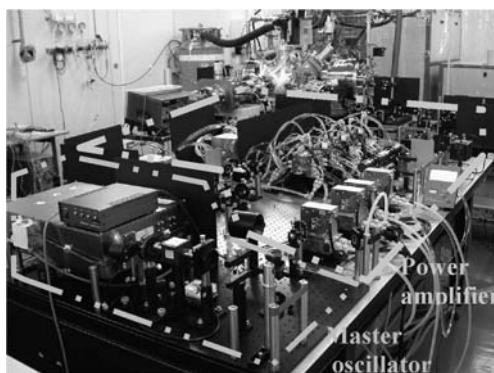


Figure 22.1 MOPA laser.

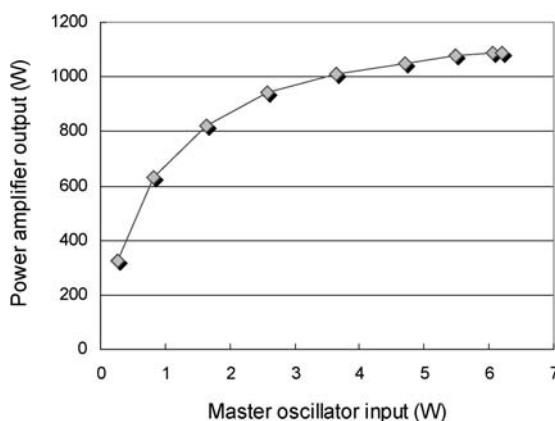


Figure 22.2 MOPA output power versus oscillator input power.

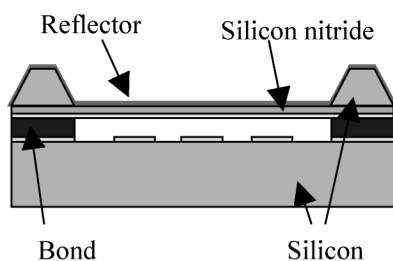


Figure 22.3 Schematic of a deformable mirror.

parameter of the feedback loop that the controller of the deformable mirror system minimizes. The performance of the mirror system has been tested at our laboratory, and an increase of the laser intensity at the focus of more than a factor 2 has been observed, thus proving the efficiency of the deformable-mirror system.

22.3 Xenon Targets

The main plasma targets currently being discussed for EUVL are tin (Sn) and xenon (Xe). Tin is very attractive due to its high CE of several percent, as reported by different groups;^{4,5} see also Chapter 5 by O'Sullivan et al. The main drawback of a tin plasma light source is its high debris content, which is difficult to control and severely limits the lifetime of the collector mirror, which is placed close to the plasma. Xenon, on the other hand, has a lower CE of about 1%, but the debris problem is less severe due to the inertness of xenon at room temperature.^{6–8} Hence, xenon was selected as the target material.

A high-density target is required for high EUV inband power. The xenon is therefore liquefied under high pressure and injected into the vacuum chamber as a liquid microjet having a diameter of several tens of microns. Since the liquid xenon phase does not exist under steady-state conditions at a vacuum pressure of about 0.1 Pa, the jet will consequently undergo a rapid phase transition. The phase transition is driven by the xenon vapor pressure, i.e., by evaporation, which further cools and finally freezes the liquid xenon jet. Hansson and Hertz describe this process in detail in Chapter 23.

Besides the microjet target, a droplet target is currently being developed. On adjusting the droplet frequency to the laser frequency, less target material is needed than with a continuous jet flow. This also reduces the gas load of the vacuum-chamber pumps. As is well known, the Rayleigh instability will cause an initially uniform-diameter liquid jet to become nonuniform and eventually to break up into droplets. In the case of the droplet source, the Rayleigh instability is driven by a piezoelectric ceramic (PZT) attached to the nozzle. On applying an oscillating voltage with a frequency in the kilohertz-to-megahertz range, the nozzle tip oscillates longitudinally with an amplitude of the order of several microns. With the appropriate nozzle oscillation frequency for a given droplet speed and nozzle diameter, uniform droplets can be generated.⁹ As mentioned before, liquid xenon droplets in

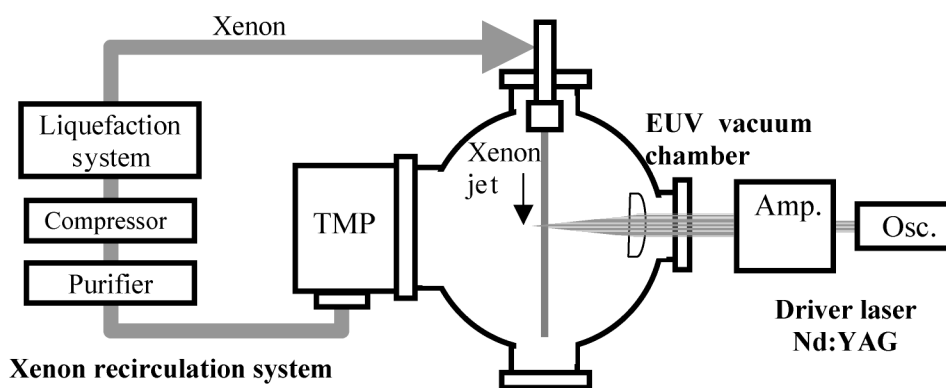


Figure 22.4 Xenon system schematic.

high vacuum evaporate at a high rate, making the process very unstable. The idea is therefore to slow the evaporation rate by using a lower vacuum and then inject the generated xenon pellets (solid droplets) into a high-vacuum chamber.

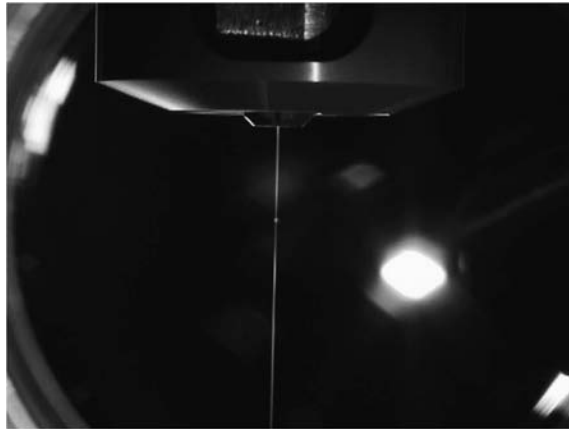
The xenon liquefaction system currently used for the xenon jet target operates at a maximum backing pressure of 5 MPa and at a xenon temperature between 160 and 190 K. A schematic of the whole xenon system, including the liquefaction and recirculation unit, is shown in Fig. 22.4. The liquid xenon is vertically injected from the top into the vacuum chamber through a nozzle having a maximum diameter of 50 μm . Two turbomolecular pumps (TMPs) with a total xenon pumping speed of 4200 l/s are used to keep the pressure inside the vacuum chamber below 0.1 Pa during xenon injection. The xenon exhausted from the pumps is recycled in order to reduce the xenon consumption cost. Figure 22.5 shows (1) a xenon jet inside the vacuum chamber, and (2) an LPP with the laser beam entering horizontally from the right-hand side. Figure 22.6 shows an example of a xenon droplet train. In first experiments with this droplet target a CE of 0.4% was obtained.

An important specification for plasma targets in the form of jets and droplets is their spatial stability. Evidently, the overlay between the laser focus area and the jet position must be sufficiently stable for the final target to have an (integrated) inband energy stability of 0.3% (3σ , 50-pulse moving average). In a recent paper by Endo,¹⁰ considerations of jet stability and laser pointing stability are discussed in detail.

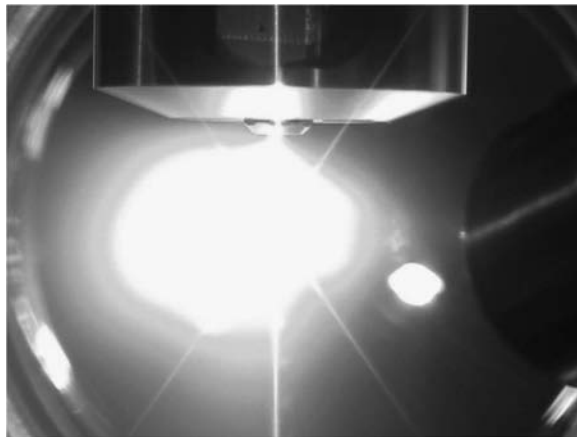
22.4 Light-Source EUV Characteristics

The current status of the LPP EUVL light-source development at EUVA, viz., the characteristics of the current light source, will be briefly outlined in this section. More detailed information about the development, including fast plasma ions, ion sputtering of optical components, ion mitigation, and collector-mirror lifetime, can be found in several papers^{11–14} and in Chapter 37 by Klebanoff et al.

Generally, LPP light-source development is done at two different laser repetition rates. A high-repetition-rate laser, as described in Sec. 22.2, is used for the



(a)



(b)

Figure 22.5 (a) Xenon jet, and (b) xenon plasma.



Figure 22.6 Xenon droplet train.

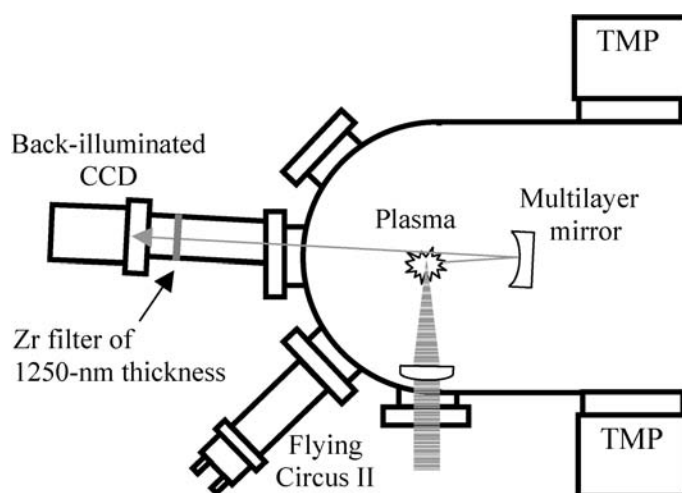


Figure 22.7 Experimental setup.

actual light-source system development, whereas a low-repetition-rate laser is used to investigate fundamental aspects of the laser-plasma interaction, e.g., the CE. In the following the main characteristics of the current light source, including its energy, CE, and emission spectrum, will be briefly outlined.

The energy emitted at 13.5 nm is measured absolutely with an energy meter from Scientec Engineering, generally known as the Flying Circus.¹⁵ The meter uses a concave EUV MLM that images the plasma onto an absolutely calibrated photodiode from International Radiation Detectors (IRD, AXUV-100G).¹⁶ Two measurement channels are included that, in combination with a filter wheel in front of the diodes, allow one to measure inband and out-of-band contributions simultaneously. The energy meter is placed at 135 deg to the laser-beam propagation direction (see Fig. 22.7). The Nd:YAG laser is focused onto the xenon jet using a 50-mm lens placed inside the vacuum chamber. The laser intensity at the jet position is estimated to be about 2×10^{11} W/cm². An average EUV inband power of 4 W (2% bandwidth, 2π sr) with an integrated energy stability of 1.6% (3σ , 50-pulse moving average) has been measured. The power of 4 W corresponds to an estimated power of 1.6 W at the IF, assuming the parameters of Ref. 17 except that the spectral purity filter has been omitted. The CE from Nd:YAG laser power to EUV inband power is 0.44%. Figure 22.8 shows the inband EUV pulse-to-pulse and integrated energy of 200 continuous plasma pulses produced with a laser power of 0.9 kW at 10 kHz.

The emission spectrum of the light source in the range between 10 and 20 nm is shown in Fig. 22.9. The spectrum was measured with a flat-field grazing-incidence spectrograph that includes a toroidal mirror (Shinseiki, Japan). The variable-line-spacing grating (Hitachi) has an average line density of 1200 lines/mm. The detector is a back-illuminated CCD (Andor) with a pixel size of 13.5×13.5 μ m. The spectrum shows the characteristics of a xenon LPP with the main emission peak at

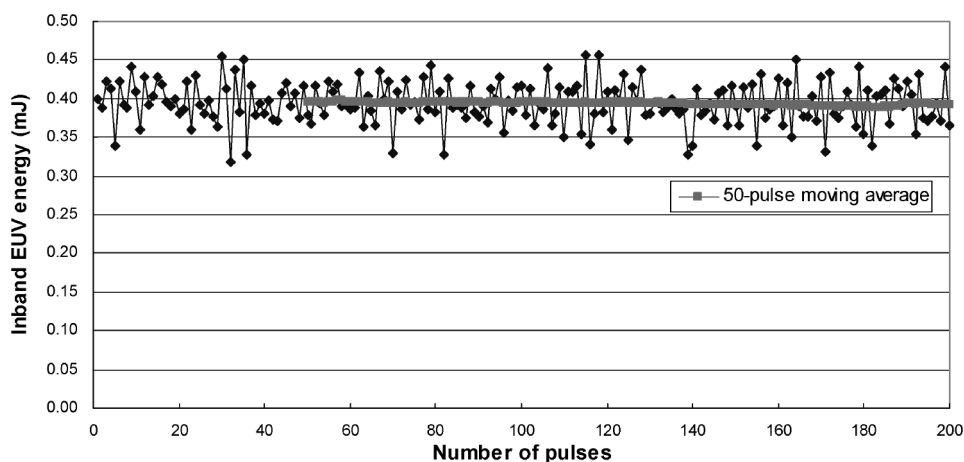


Figure 22.8 Pulse-to-pulse and integrated inband energy.

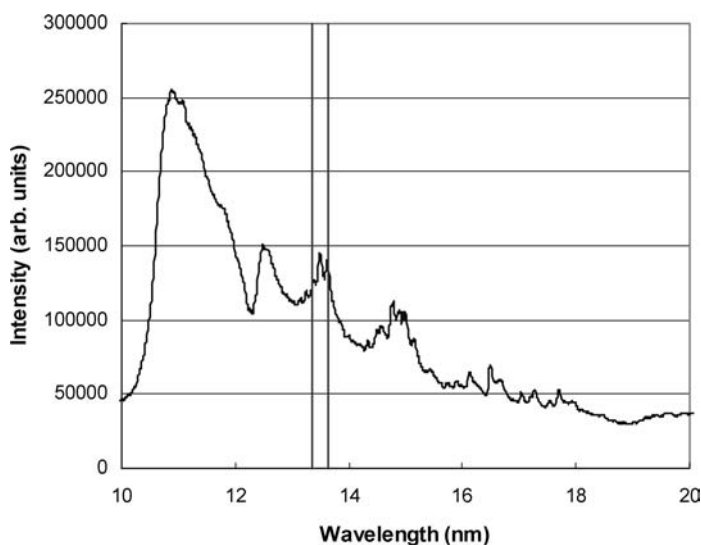


Figure 22.9 EUV xenon spectrum.

11 nm. The emission inside a 2% (full) bandwidth at 13.5 nm is indicated with two lines. This illustrates that only a small fraction of the power is emitted within the usable wavelength range. Calculated xenon spectra presented in a paper by Sasaki et al.¹⁸ are in good agreement with measured spectra. The calculations are based on a local thermodynamic equilibrium (LTE) plasma and include a simple model for radiation transport, viz., the assumption of an optically thick plasma.

Finally, the *etendue* is an important EUVL light-source parameter and is defined as the product of the source size and the acceptance angle of the collector mirror. The maximum acceptable etendue is currently $3.3 \text{ mm}^2 \text{ sr}$ in order to efficiently transfer the light-source power into the illuminator.² With the experimental

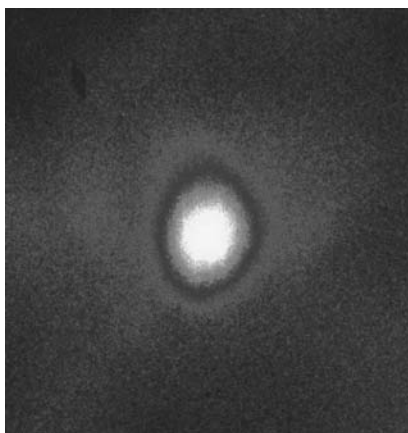


Figure 22.10 Inband plasma image.

setup shown in Fig. 22.7, the size of the inband emission area has been measured at 10-kHz repetition rate for a xenon jet with a diameter of 30 μm . A concave EUV MLM with an aperture of 10 mm images the plasma onto a back-illuminated CCD with a magnification of 6. A Zr filter with a thickness of 1.25 μm is placed in front of the CCD in order to block the visible part of the emitted radiation. Figure 22.10 shows the monitored EUV plasma image at 10-kHz repetition rate and a CCD exposure time of 30 ms, i.e., averaged over 300 plasma emissions. The measured source size is approximately $115 \times 140 \mu\text{m}^2$ (horizontal $\times$ vertical, FWHM). The calculated etendue is therefore approximately $0.1 \text{ mm}^2 \text{ sr}$, thus fulfilling the etendue requirement.

22.5 Summary

The EU LPP light-source development for lithography currently done in Japan under the management of EUVA has been presented. A MOPA Nd:YAG laser system is being developed as a driver laser. The system has currently an average power of 1 kW at a repetition rate of 10 kHz. The FWHM pulse duration is 6 ns, and the wavelength 1064 nm. Xenon has been chosen for the plasma target to minimize debris and thus maximize optical-component lifetime. Xenon jet and droplet targets are being investigated; droplet targets are becoming more attractive for higher laser repetition rates. The currently developed light source delivers 4-W inband power at a repetition rate of 10 kHz. Important light-source characteristics such as the emission spectrum and the inband emission plasma size have also been presented.

Acknowledgment

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Chapter 23

Liquid-Xenon-Jet LPP Source

Björn A. M. Hansson and Hans M. Hertz

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23.1 Introduction

23.1.1 General background

The liquid-xenon-jet laser-plasma EUV source is one of the source types under development for EUVL. This chapter focuses on the initial development of the source type performed by the authors and their coworkers at the Royal Institute of Technology (KTH) and at the former company Innolite AB, both in Stockholm, Sweden. Where relevant, it also presents results on this source type achieved by others; results given without specific references were obtained at KTH or Innolite AB.

23.1.2 EUV sources

Synchrotron radiation from electron storage rings¹ is today the most common source of EUV radiation. However, it is difficult to install an electron storage ring in an existing fab, especially given the required radiation shielding, which weighs at least 100–200 tons.² Furthermore, a traditional synchrotron source cannot meet the power requirements of EUVL.^{2,3} Instead, all sources under consideration for EUVL are based on hot plasmas, and there are two major ways to generate the plasma: electrical discharge and laser irradiation. Since the various electrical-discharge sources are covered elsewhere in this volume, this chapter will mainly discuss the laser plasma. It should also be mentioned that other means to generate EUV radiation are available, including high-harmonic generation,^{4,5} table-top soft-x-ray lasers,⁶ and conventional electron impact sources,⁷ but since they are not expected to reach the specifications for EUVL, they are not discussed further here.

23.1.3 Laser plasma

In a laser plasma, the plasma is created through the interaction of short high-peak-power laser pulses with a target. Pulse energies on the order of 1 J with pulse lengths of a few nanoseconds are typically used, leading to peak powers in the range of megawatts to gigawatts. Furthermore, by focusing the laser pulses down to diameters in the 100- μm range, power densities of 10^{11} to 10^{12} W/cm² are achieved. These power densities are sufficient to raise the temperature of the plasmas to the several times 100,000 K needed to achieve emission in the EUV wavelength region.¹

23.1.4 Laser-plasma targets

For each new laser shot, fresh target material must be available at the laser focus position. Since a source for an EUVL scanner is anticipated to operate at a repetition rate of >7 kHz with 25% duty cycle for almost 24 hours a day,⁸ this puts high demands on the target delivery system. Traditionally, solid bulk targets have

been employed for laser-plasma generation. They are typically translated between shots to provide a fresh target surface and can therefore only operate for a very limited time until the whole surface is filled with craters. In addition, large fractions of molten material will be ejected due to the shock wave reflected in the bulk material.⁹

An alternative is to use a thin tape as a target, as illustrated in Fig. 23.1(a). The tape target limits the debris by allowing the shock wave to escape through the tape rather than be reflected back to the surface.⁹ However, the debris emission is still substantial from a tape target.¹⁰ In addition, tape targets are limited to materials that can be processed into a tape, and the tape will eventually run out during prolonged high-repetition-rate operation.

For gaseous target materials, the gas-puff target is an alternative as illustrated in Fig. 23.1(b).¹¹ The clear advantage is that no large debris particles can be ejected from the plasma target. However, the laser must be focused close to the nozzle in order for the target gas to have sufficient density for effective laser-plasma generation. This may lead to sputtering of nozzle material that, in turn, may coat sensitive components.¹² Under the right operating conditions, the gas will form clusters enhancing the EUV production from the gas target.^{13–15}

A similar target is the liquid-spray target [Fig. 23.1(c)], which can be applied to liquids or condensing gases, where larger droplets are formed. Compared to the gas/cluster target, this target has the advantage of higher density, which leads to improved EUV generation, and better collimation of the target flow, which allows for slightly longer working distances, although still in the few-millimeter range.^{16,17}

This chapter, however, describes the liquid-jet^{18,19} target [Fig. 23.1(d)]. It is formed by forcing a liquid through a small nozzle orifice, thereby creating a collimated jet. Normally, the jet will naturally break up into droplets after traveling

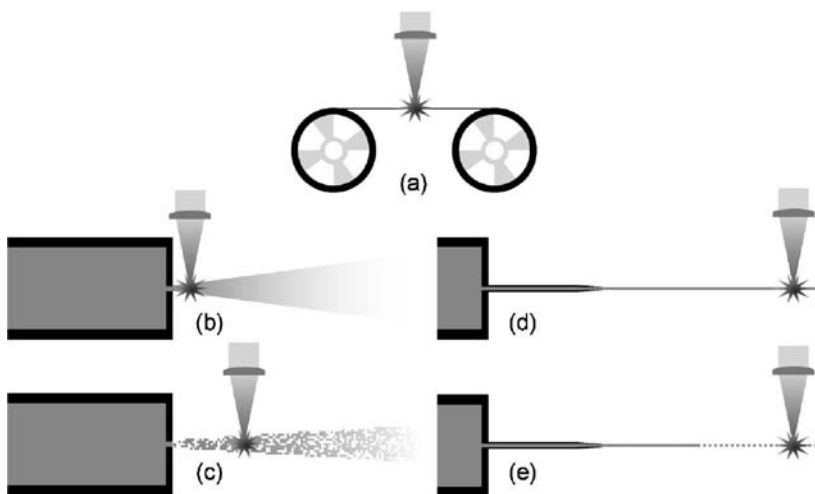


Figure 23.1 Different target geometries for laser-plasma generation: (a) tape target, (b) gas/cluster target, (c) liquid-spray target, (d) liquid-jet target, and (e) liquid-droplet target.

some distance, leading to a liquid droplet target²⁰ [Fig. 23.1(e)]. However, as will be discussed below, a liquid xenon jet may freeze before natural droplet formation, resulting in a solid jet, often referred to as a filament.

The liquid-droplet target was early shown to reduce the debris deposition, compared to a tape target, by a factor²⁰ of 200–300. It has furthermore been shown that the liquid-jet target yields as low deposition as the droplet target.¹⁸ A disadvantage of the liquid-jet and droplet target types is that not all substances can be used, but many are available that are not room-temperature liquids through various techniques, e.g., liquefied gases,^{21–23} molten metals,^{24,25} solutions,^{25–27} and liquids doped with metal in various ways.²⁸

23.1.5 Target materials

The choice of proper target material for laser-plasma EUV generation is based on many different factors. The most obvious is the spectral emission of the material, but of equal importance are its contamination characteristics.

As for the spectral output, a general emission feature of atoms of different weight is that lighter elements typically generate narrowband line radiation and heavier elements a broader quasi-continuum. This is due to the difference in the number of atomic transitions available. It is well illustrated by comparing the emission spectra of ${}_8\text{O}$ and ${}_6\text{C}$ from the water-methanol droplet laser plasma²⁹ shown in Fig. 23.2 with the emission from the heavier elements ${}_{50}\text{Sn}$ from a liquid-tin-jet target,²⁵ ${}_{53}\text{I}$ from a liquid-jet target of sodium iodine dissolved in water,²⁵ and ${}_{54}\text{Xe}$ from the liquid-xenon-jet target³⁰ shown in Fig. 23.3.

An advantage of using light-element narrowband emission as from the O VI line at $\lambda = 13$ nm is that the linewidth is significantly narrower than the bandwidth of Mo/Si mirrors. So far, however, a conversion efficiency (CE) of only about 0.1% into the line and 4π sr has been shown.^{31,32} The integrated CE over the bandwidth of Mo/Si mirrors is significantly larger from heavier elements such as those of Fig. 23.3. The spectra of Fig. 23.3 show similar narrow emission peaks for all materials, although the peaks are at shorter wavelengths for the heavier substances. Such peaks have been observed and explained in laser plasmas from elements ranging

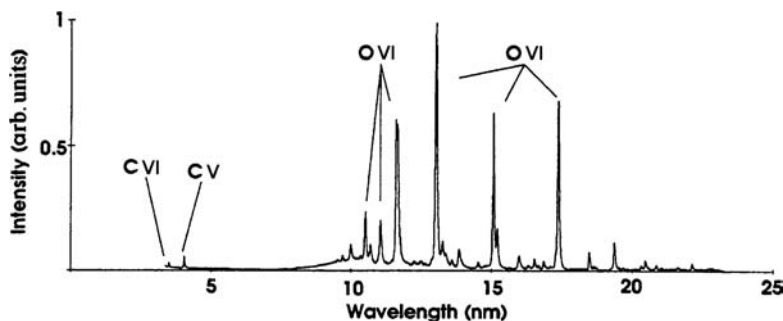


Figure 23.2 Emission spectrum from water-methanol droplets (reprinted from Ref. 29).

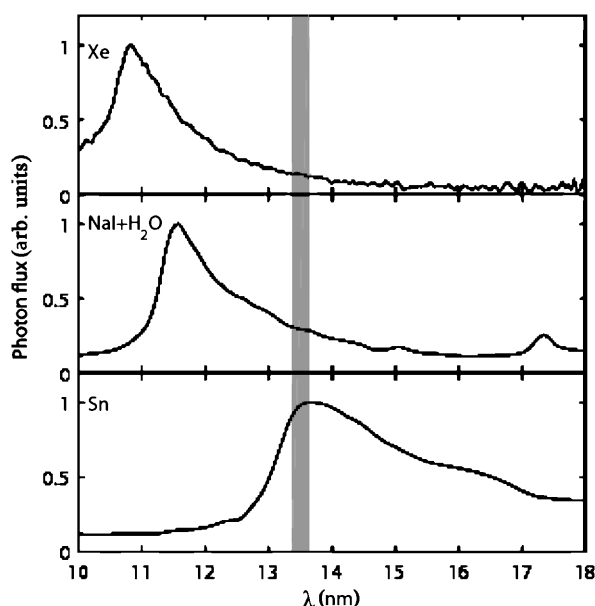


Figure 23.3 EUV emission spectra from xenon, iodine, and tin. Shaded area depicts the 2% bandwidth region around $\lambda = 13.5$ nm with high reflectivity in a Mo/Si multilayer system.

from ${}_{50}\text{Sn}$ to ${}_{82}\text{Pb}$.^{33–36} Figure 23.3 also shows the 2% bandwidth region around $\lambda = 13.5$ nm, of interest for EUVL. From the point of view of spectral emission alone, tin may be the optimal substance. A CE of 2.5% (2% bandwidth, 2π sr) at $\lambda = 13.45$ nm has been obtained for a liquid-tin-jet laser plasma,²⁵ compared to 0.95% for a liquid-xenon-jet laser plasma.³⁷

However, as will be discussed below, the demands on cleanliness of a source for EUVL make the operation of any target that might condense on or react with the optics, especially the collector mirror, difficult. Therefore, it may be preferable to use a noble gas as target material.³⁸ Thus, although xenon does not have optimal spectral emission, it could still be the best target from a total system perspective. Which target material will finally turn out optimal depends on both target characteristics and the effectiveness of different debris mitigation schemes.

23.1.6 General characteristics of liquid-xenon-jet laser plasma

A few general characteristics are important for the liquid-xenon-jet laser plasma in support of its use as a source for EUVL. The first major advantage is that the target material is a noble gas, so that the evaporated target material will not condense on room-temperature components such as a collector mirror. The second advantage is that the plasma can be operated far from any hardware component. This is possible because the target material is transported in a collimated fashion to the point of laser-jet interaction. Furthermore, this being a laser plasma, the drive power can be delivered without the physical proximity of, e.g., electrodes as for a discharge plasma. This has the advantage that the thermal load and potential sputtering of,

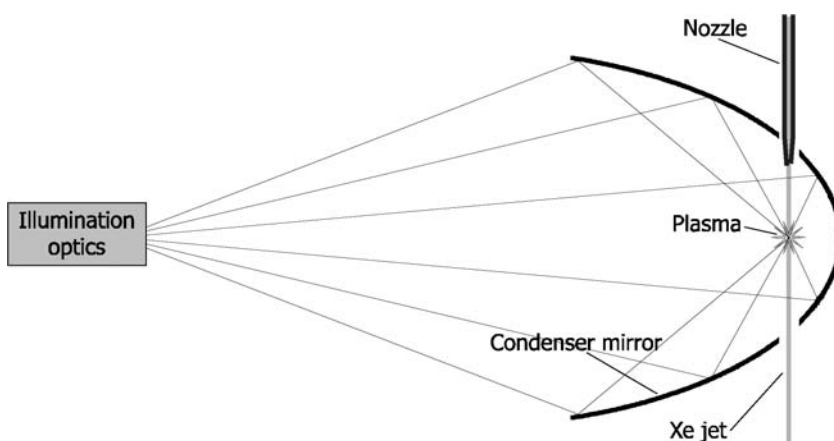


Figure 23.4 Illustration of how a liquid-jet target theoretically allows for very large collection angles (reprinted from Ref. 30).

e.g., the nozzle can be limited. Furthermore, the geometrical access to the plasma is excellent, allowing for application of large-solid-angle collectors as illustrated in Fig. 23.4. The small etendue of the source also supports large collection angles. However, a major problem that must be solved is the emission of high-energy ions and neutrals from the plasma that may destroy, e.g., the collector mirror, as will be discussed below. A way must be found to decelerate these atoms without limiting the available collection angle. Finally, a major problem of using xenon as a target is that the CE is not optimal. Tin, for example, shows significantly higher CE. It remains to be seen whether the noncontaminating nature of xenon is sufficient compensation for its lower CE or if novel debris mitigation schemes will make operation of condensing targets, such as tin, possible.

23.2 Liquid-Xenon-Jet Laser Plasma Generation

23.2.1 Typical source arrangement

A typical arrangement for operation of a liquid-xenon-jet laser-plasma target is as illustrated in Fig. 23.5. The liquid jet is formed by forcing xenon gas under high pressure into a reservoir cooled to liquefy the xenon. A tapered glass capillary nozzle with an orifice diameter of typically 10–30 μm is attached to the reservoir, producing a microscopic liquid jet into an ultrahigh-vacuum-compatible chamber. Vacuum is maintained by two ≈ 2000 -l/s turbomolecular pumps, resulting in pressures of 10^{-4} – 10^{-3} mbar during operation. The base pressure of the system, before jet operation, is typically in the 10^{-8} – 10^{-7} -mbar range, but could be further reduced through, e.g., baking of the system. To reduce the load on the turbomolecular pumps during operation, the nonevaporated part of the xenon jet is extracted from the chamber through a differential-pumping scheme. The xenon evacuated through both the turbomolecular pumps and the jet-extraction system is

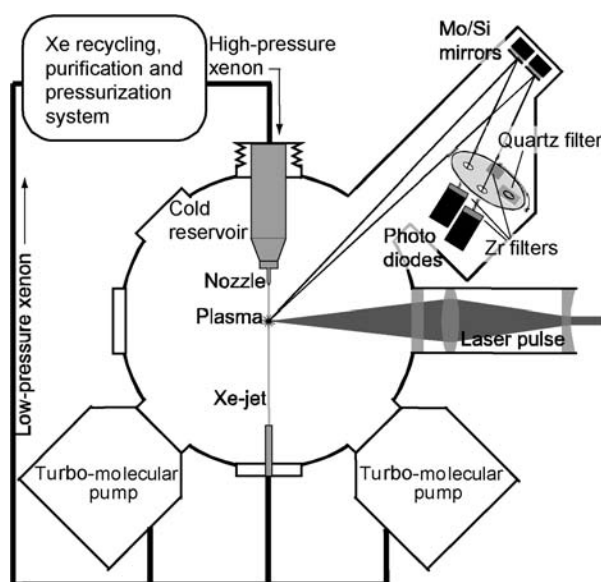


Figure 23.5 A typical experimental arrangement for liquid-xenon-jet laser-plasma generation and EUV inband-emission monitoring (reprinted from Ref. 37 with permission from the American Institute of Physics).

further collected by a recycling, purification, and pressurization system allowing for closed-loop usage of xenon. Without such a recycling system, the high cost of xenon strongly limits the experimental time. The plasma is typically generated by focusing Nd:YAG-laser pulses of $\lambda = 1064$ nm, ≈ 5 -ns pulse length, and up to 350-mJ pulse energy onto the jet through a focusing system theoretically capable of obtaining a FWHM-10- μ m spot. Finally, the EUV emission is generally monitored using a Flying Circus tool.³⁹

23.2.2 Liquid-xenon-jet generation

Figure 23.6 illustrates how xenon is liquefied by injecting it at high pressure into a reservoir cooled to a temperature where xenon condenses. An advantage of injecting xenon at higher pressures is that the available temperature span where xenon is liquid is larger. At 1 bar, xenon is liquid only between 161.45 and 164.78 K, but at 50 bar it is liquid between 163.35 and 282.14 K.⁴⁰ Even though the liquid range is large at high pressures, it is still preferable to operate the jet close to the freezing temperature of xenon to achieve a stable jet. This is further discussed by Hansson et al.⁴¹

The applied xenon pressure is also responsible for driving the jet through the nozzle. A high-speed jet is preferred in order to allow for high-repetition-rate operation, as discussed below. The relationship between driving pressure, nozzle shape, and achieved jet speed is explained in detail by Hemberg et al.⁴² However, for a

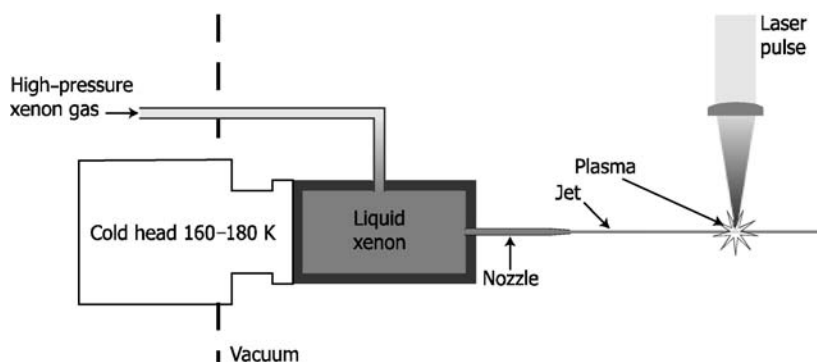


Figure 23.6 Sketch showing how xenon is liquefied and injected as a liquid-jet laser-plasma target (reprinted from Ref. 30).

20- μm xenon jet, the simple formula

$$v_{\text{jet}} = \sqrt{\frac{2p}{\rho}}, \quad (23.1)$$

which assumes that the whole pressure p is converted to kinetic energy, has been shown to give the right jet speed v_{jet} to within 5%, for pressures between 10 and 50 bar. Here ρ is the density of liquid xenon.

23.2.3 Liquid-xenon-jet freezing

Normally, a liquid jet will spontaneously break up into droplets.⁴³ However, highly volatile liquids, such as liquefied gases, may freeze due to evaporation-induced cooling before traveling the droplet formation distance, thereby avoiding drop formation. Whether droplets will form or not is therefore a question of the rate of the droplet formation process contra the rate of the jet cooling process.

The general theory for the droplet formation distance L is that of Weber^{44,45} as discussed in Hansson et al.⁴¹ The value of L is determined by

$$L > 3.5v \left[\left(\frac{\delta d^3}{\sigma} \right)^{0.5} + \left(\frac{3\eta d}{\sigma} \right) \right], \quad (23.2)$$

where the parameters are defined in Table 23.1.

The evaporative cooling and freezing of the jet may be modeled using elementary thermodynamic arguments. Assuming xenon with an initial temperature of 170 K and an injection pressure of 30 bars, the calculated cooling and freezing process as a function of distance from the nozzle orifice is illustrated in Fig. 23.7. Details of the model are described in Hansson et al.⁴¹ In addition, the minimum droplet-formation distance according to Eq. (23.2) is displayed in Fig. 23.7. As can be seen, the jet will rapidly freeze, thereby inhibiting droplet formation. The jet velocity is calculated from the injection pressure according to Eq. (23.1).

Although the cooling-freezing calculation contains some uncertainties as discussed in Hansson et al.,⁴¹ it is still clear that the model predicts that the jet freezes well before the droplet formation point. This is supported by experimental evidence shown in Fig. 23.8. Here the xenon jet is photographed several centimeters from the nozzle orifice. The image is taken through a microscope using a ~ 10 -ns laser pulse for illumination. At this distance, the jet is broken at several locations, but no sign of general droplet formation is visible. This behavior is possible only if the jet is in solid state.

Table 23.1 Parameters for droplet formation distance (for xenon at 180 K and 30 bar).

Parameter	Units	Values
Density	ρ (kg/m ³)	2854 ^a
Viscosity	η (10 ^{−3} Pa s)	0.409 ^b
Surface tension	σ (10 ^{−3} N/m)	15.7 ^c
Velocity of jet	v (m/s)	
Jet diameter	d (μm)	

^aRef. 40.
^bRef. 46.
^cRef. 47.

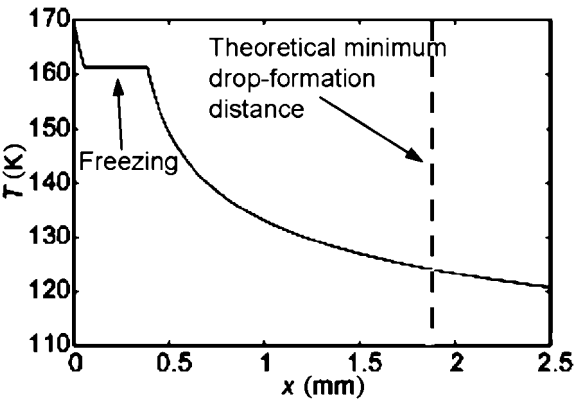


Figure 23.7 The calculated cooling process of a 10-μm xenon jet injected into vacuum at 30 bars, corresponding to ≈ 40 m/s. The theoretical model indicates that the jet freezes well before the droplet formation point, thereby inhibiting the formation of droplets (reprinted from Ref. 41 with permission from the American Institute of Physics).



Figure 23.8 A 10-ns flash photograph of a xenon jet several centimeters from the nozzle orifice. The jet is broken at several locations, but no signs of general droplet formation are visible (reprinted from Ref. 41 with permission from the American Institute of Physics).

23.2.4 Jet stabilization through nozzle heating

The stability of the xenon jet is very important in order to allow for stable plasma operation far from the nozzle. It was mentioned above that it is important to operate the jet at a temperature close to the freezing point of xenon in order to avoid spraying. However, apart from spraying, a directional instability of an otherwise stable jet can be present on occasion.^{21,23,48} This instability can be as large as 1 deg, and when it is present it makes stable plasma generation at practical distances from the orifice difficult.

This instability and a way to avoid it are discussed in Hansson et al.⁴¹ It is believed that the instability is due to some substance, most probably the liquefied gas itself, freezing in or around the nozzle orifice, and thus changing the flow characteristics at the orifice. One can assume that the rapid evaporation of the jet cools the nozzle to temperatures below the freezing point of the liquefied gas used. The cooling process could be due either to evaporation of the liquid that wets the edges of the orifice or to heat transfer from the jet, which in its turn is cooled by evaporation. Nozzle cooling has in fact previously been observed for normal liquids.⁴⁹

Localized heating of the nozzle tip is a possible way to avoid this problem and to achieve a stable jet.⁵⁰ The heating can, e.g., be applied through resistive heating at the tip with a thin wire, as is illustrated in Fig. 23.9. It is believed that this heating will keep the nozzle tip at a high enough temperature to avoid the freezing of material in the tip that may alter the flow profile and induce an instability. However, it is important to apply this heating very locally at the nozzle tip, since otherwise the liquid jet itself will be heated, leading to spraying. This is consistent with the observation reported above, that the jet will spray when the liquid is too warm.

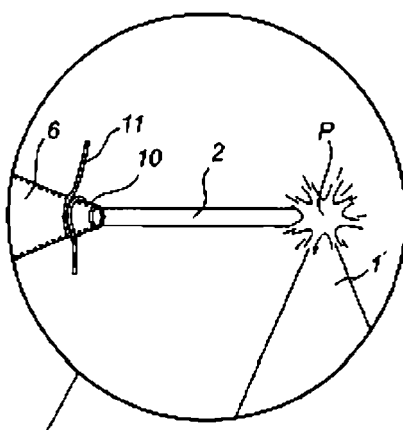


Figure 23.9 Running a current through a thin wire (11) applied around the tip (10) of the nozzle (6) heats the nozzle tip locally, leading to a stabilization of the liquid-xenon jet; P refers to the plasma formed by focusing the energy beam (1) on to the liquid-xenon jet (2) (reprinted from Ref. 50).

23.3 Source Requirements and Design Example

23.3.1 Source specification overview

An EUV source must meet very demanding requirements to be suitable for operation in production-scale EUVL scanners. An estimation of the final requirements on an EUVL-scanner source is given in Table 23.2, a list of requirements jointly published by the three major scanner manufacturers: ASML, Canon, and Nikon. The source specification is further discussed in Chapter 2.

23.3.2 Design example

The following is a brief example of how a liquid-xenon-jet laser plasma source could meet some of the main EUVL specifications above. The values are not achieved values, but rather examples to get a feeling of typical quantities that will be needed to meet the final source specification. Furthermore, the following section on source characterization will refer to the numbers of the design example. Where applicable, it will be discussed how experimental results indicate whether or not these numbers can be met.

Specification	Value
CE	1.2% (2% BW, 2π sr)
Laser pulse energy	1 J
Repetition rate	20 kHz
Laser power	20 kW
Power into 2π sr	240 W
Collector transmission	45%
No spectral purity filter	—
Power into IF	108 W

Table 23.2 The EUVL source requirements as jointly agreed by ASML, Canon, and Nikon (from Chapter 2).

Source characteristic	Requirement
Wavelength	13.5 nm
EUV power (inband)	115 W*
Repetition frequency	7–10 kHz***
Integrated energy stability	$\pm 0.3\%$, 3σ over 50 pulses**
Source cleanliness	$\geq 30,000$ h**
Etendue of source output	Max. $1\text{--}3.3$ mm ² sr***
Max. solid angle input to illuminator	$0.03\text{--}0.2$ sr***
Spectral purity:	
130–400 nm (DUV/UV)	$\leq 7\%$ ***
≥ 400 nm (IR/Vis) at wafer	TBD***

* At intermediate focus (IF).

** After IF.

*** Design-dependent.

23.4 Source Characterization

23.4.1 Conversion efficiency

The CE from laser power into EUV power that can be collected and transmitted through the optical system is of course a very important parameter. The laser power required will scale linearly with the CE and thus heavily influence the cost of ownership (CoO) of the source. The CEs of liquid-xenon-jet sources have so far reached 0.95% (2% bandwidth, 2π sr) as, e.g., reported by Hansson et al.³⁷ and Nikolaus et al.⁵¹ The CE has improved continuously over the years through optimization of several parameters, although the details remain confidential information of the different source developers. It is expected that the CE can be increased somewhat further, supported among other things by the fact that higher CE has been demonstrated for bulk xenon targets, e.g., 1.1% (2% bandwidth, 2π sr) reported by Shields et al.,⁵² and 1.4% reported by Mochizuki et al.⁵³ The assumed CE of 1.2% for the design example above should therefore be possible to reach in the future. Pulse energies as high as the 1 J specified in the design example have not been applied, but so far experiments at least show increasing CE with pulse energy in the range ≈ 100 –500 mJ, supporting future 1-J pulses.⁵⁴ The accuracy and comparability of inband-energy and CE measurements were previously a much-debated topic, but with the development of standard tools such as the Flying Circus³⁹ and the E-Mon,⁵⁵ measurements using these and similar tools are generally believed to be accurate.

23.4.2 Repetition-rate capability

At a given pulse-to-pulse emission stability, increasing the repetition rate of the EUV source will improve the dose accuracy and thus the critical dimension control. This is discussed through a simple model by Banine et al.⁵⁶ The current specification states that an EUV scanner source should operate at >7 –10 kHz with an integrated energy stability of $\pm 0.3\%$ (3σ) over 50 pulses.⁸ This means that at a higher repetition rate than the required >7 –10 kHz, more pulses can be integrated to achieve the $\pm 0.3\%$ stability.

It is believed that the limiting factor for the repetition rate of a liquid-xenon-jet laser-plasma source is the time after one plasma event until new unaffected target material is available at the laser focus point. This is influenced by the jet speed and the length of the jet that is destroyed by a plasma event. Figure 23.10 shows the jet just after a plasma event.⁵⁷ As can be seen in the image, the jet is basically unaffected at a point 1.3 mm upstream toward the nozzle. With a typical jet velocity of 50 m/s, this corresponds to a maximum repetition rate of 30 kHz. A similar experiment is reported by Shields et al.,⁵² arriving at a maximum repetition rate of 10 kHz, the lower value probably being due to lower jet speed.

In order to further investigate the maximum repetition rate, high-repetition-rate operation has been simulated in a double-pulse setup in which two plasmas were generated with a very short time separation.³⁷ By varying the time delay

between the two pulses and investigating the shot-to-shot EUV stability from the second pulse, the minimum time delay before the first pulse affects the second pulse could be found. For a jet velocity of 60 m/s, Fig. 23.11 illustrates how a significant stability transition from 3.8% (1σ) to 36% was found on changing the delay from 60 to 50 μ s, corresponding to an increase in repetition rate from 17 to 20 kHz.

At the shorter time separation, the second pulse is not always fired on an intact jet target, but rather on the jet region that may have been damaged by the first pulse. The experiment indicates that a liquid-xenon-jet laser-plasma source can be operated with a repetition rate of at least 17 kHz. Although this is below the result

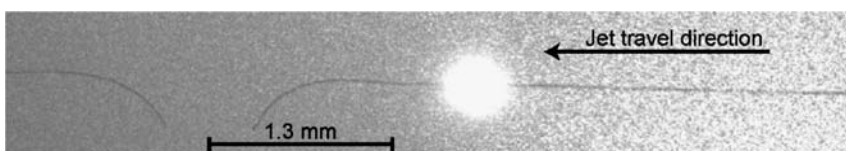


Figure 23.10 This image illustrates how only a small fraction of the xenon jet is affected by a laser shot. As can be seen, the jet is basically unaffected by the previous plasma at a point approximately 1.3 mm upstream toward the nozzle. Given a typical jet velocity of 50 m/s, this corresponds to a maximum repetition rate of 30 kHz (reprinted from Ref. 57).

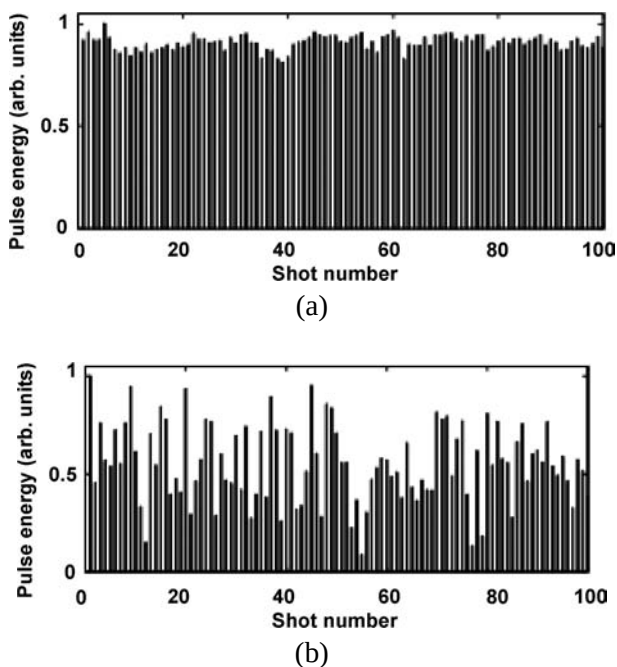


Figure 23.11 For a jet velocity of 60 m/s, two plasmas are generated with a small time separation. The pulse-to-pulse EUV stability of the second pulse is illustrated. In (a) the temporal delay is 60 μ s, corresponding to 17 kHz, and in (b) 50 μ s, corresponding to 20 kHz. The 1σ stability goes from 3.8% in (a) to 36% in (b) (reprinted from Ref. 37 with permission from the American Institute of Physics).

of the first study yielding 30 kHz, it is still well above the specified 7–10 kHz previously discussed. With a slight increase in jet speed, it should also be possible to reach at least the 20 kHz assumed in the design example above.

23.4.3 Emission stability

A pulse-to-pulse emission stability of $\pm 8.4\%$ (3σ) at plasma operation 50 mm from the nozzle has been reported.⁵⁷ As will be evident in the next section, the ability to operate a stable jet at a large distance from the nozzle is especially important to reduce the thermal load. This measured emission stability should correspond to $\pm 8.4\%/\sqrt{50} = \pm 1.2\%$ for a 50-pulse running average, to be compared with the specification of $\pm 0.3\%$. However, the repetition-rate specification is 10 kHz, and if a liquid-xenon-jet laser plasma source can be operated at 20 kHz, the specification should be given for a 100-pulse average, which means that the published stability would be $\pm 8.4\%/\sqrt{100} = \pm 0.84\%$. This number is within a factor of 3 of the specification, and it should therefore be possible to reach the final specification.

23.4.4 Thermal-load capability

It is evident from the design example above that drive powers of several tens of kilowatts will be required. It is a great challenge for any source to handle such powers. Since the plasma will be optimized to absorb most of the drive power, approaching 100%, basically the same amount of power that drives the plasma will be emitted from the plasma as broadband radiation and energetic particles. This means that the jet and the source hardware must be able to handle this power. The challenge is to predict if this is possible before the lasers become available, since so far only lasers in the few-kilowatt range have been available for laser-plasma experiments.^{54,58}

The main problem with the thermal load is that the source mechanics, especially the nozzle, may heat up and that the jet may be heated in flight. Simulation of the jet in-flight heating is difficult without an actual high-power laser, although one might use a burst-mode laser, as Vogt et al.³¹ demonstrated for a water jet, and possibly also operate at a lower jet speed in order to increase the integrated thermal load on the jet. However, to our knowledge no such experiments have been performed to date. The thermal load on the nozzle, on the other hand, can be simulated to some extent by operating the plasma closer to the nozzle. Figure 23.12 illustrates how a 50-W plasma is operated only 1.5 mm from the nozzle while maintaining a stable xenon jet. This should give the same thermal load to the nozzle tip as a 40-kW plasma operated at 50 mm from the nozzle. It therefore seems possible to operate very high average powers, such as the 20 kW assumed in the design example above, although more experiments certainly need to be performed.

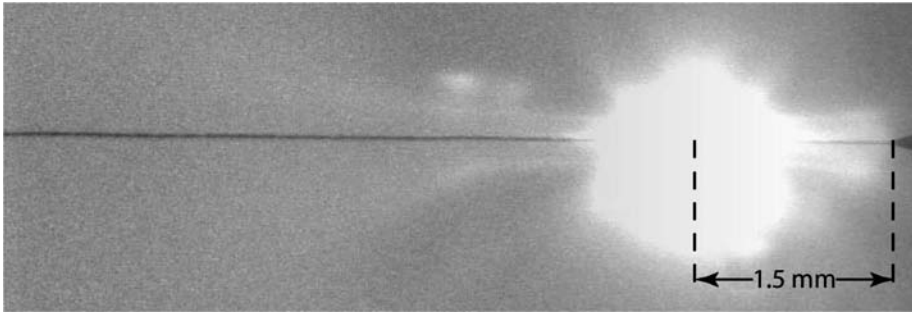


Figure 23.12 A plasma driven by 50-W laser power is operated 1.5 mm from the nozzle orifice while maintaining a stable jet. The power load to the nozzle compares to a 40-kW plasma operated 50 mm from the nozzle.

23.4.5 Source size, etendue, and shape

The size of the EUV-emitting plasma is critical, since the etendue of the system will limit the collectable fraction of the energy radiated from the plasma.⁵⁹ The etendue is given by the emitting source area A and the numerical aperture (NA) of the collector as⁶⁰

$$\text{etendue} = A \times \pi \times \text{NA}^2. \quad (23.3)$$

At the same time, the spatial emission profile is also an important input to the design of an illumination system of an EUV tool in order to achieve the desired illumination uniformity. The emission profile of plasmas have traditionally been imaged by pinhole cameras.¹⁸ The main disadvantage is that this technique is not wavelength-selective, and it has been shown that the EUV inband image of a plasma may not correspond to a broadband image.⁶¹ Moreover, it is difficult to obtain good spatial resolution using a pinhole camera, which is especially important when imaging very small plasmas. The size and shape of the liquid-xenon-jet plasma has therefore been measured using an EUV camera based on a spherical multilayer mirror (MLM) that was developed to obtain both wavelength selectivity and high spatial resolution simultaneously. The EUV camera arrangement with 8- μm resolution is illustrated in Fig. 23.13 and is further described in Hansson et al.³⁷

By focusing the laser as tightly as possible on the xenon jet, a very small plasma, $\approx 20 \mu\text{m}$ FWHM, can be obtained with a liquid-xenon-jet laser plasma as illustrated in Fig. 23.14(a). However, by using a first laser prepulse to expand the target and then defocus the main laser pulse, the size of the plasma can also be increased.⁶² A 200–270- μm FWHM plasma is shown in Fig. 23.14(b).

A disadvantage with the very small plasma is that the CE is typically somewhat lower than normal, e.g., $\approx 0.35\%$ (2% bandwidth, $2\pi\text{sr}$) for the case of Fig. 23.14(a). However, in certain applications this is well compensated by the fact that the smaller source results in a very high brightness ($\text{W}/\text{m}^2\text{sr}$). This is advantageous in applications with a small etendue, such as a microexposure tool (MET)⁶³

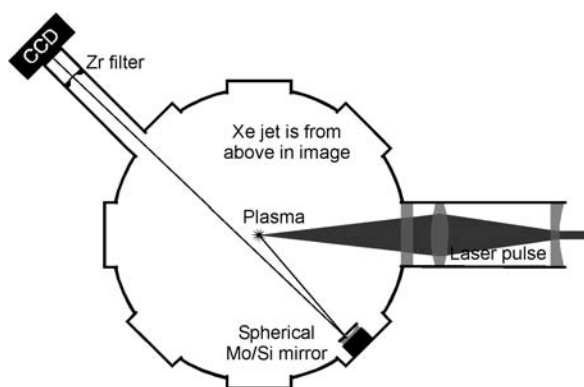


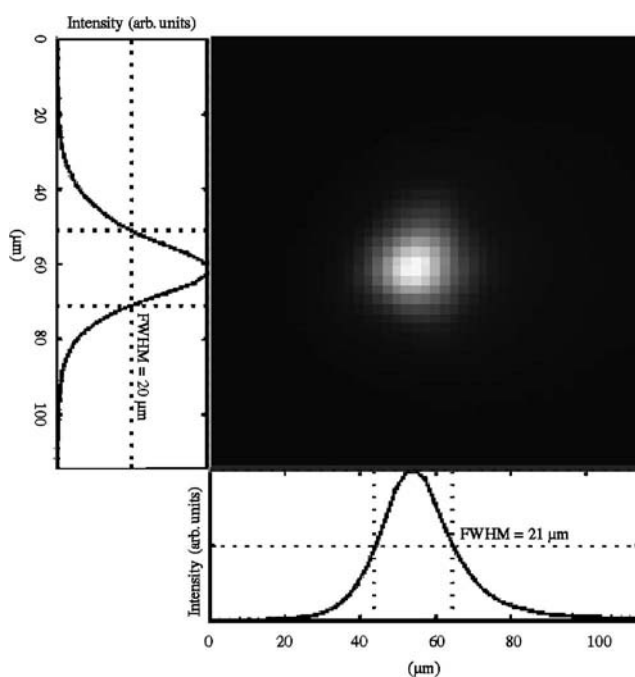
Figure 23.13 An EUV camera for EUV inband imaging based on a spherical Mo/Si mirror and a CCD detector (reprinted from Ref. 37 with permission from the American Institute of Physics).

or an aerial-image microscope (AIM)⁶⁴ (cf. Hansson et al.⁶⁵). A larger source, having optimal CE, is better suited for a high-volume manufacturing (HVM) scanner. Even if the full geometrical diameter of the plasma is considered ($d \approx 400 \mu\text{m}$) and a large collection angle of $2\pi \text{ sr}$ ($\text{NA} = 1$), the resulting etendue is $\approx 0.4 \text{ mm}^2$, which is well below the presently estimated maximum allowable source output etendue.⁸ Thus, no power from the laser-plasma source will be lost due to the etendue limitation. This is in contrast to the larger-diameter discharge sources, where such loss may become important.⁵⁹

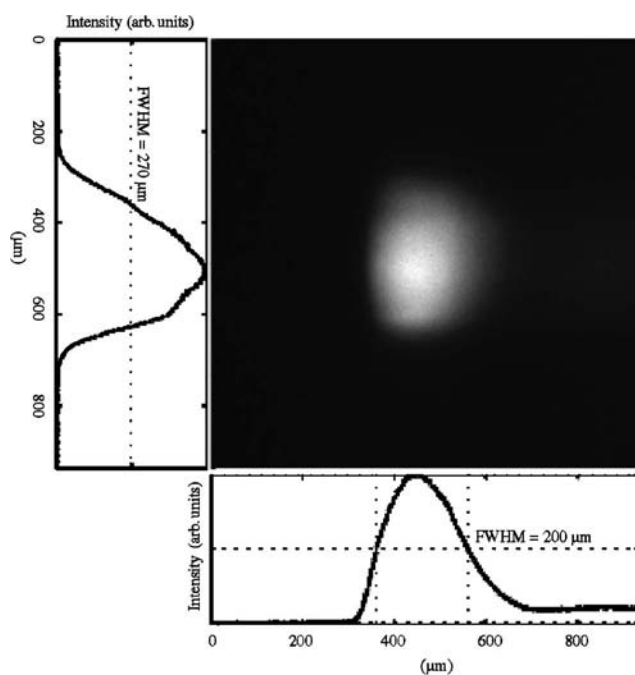
23.4.6 Out-of-band radiation

Unfortunately, the xenon plasma also emits radiation outside the desired $\approx 2\%$ bandwidth around $\lambda \approx 13.5 \text{ nm}$ that is transmitted by the optical system of an EUVL scanner based on Mo/Si MLMs. This out-of-band (OOB) radiation will degrade the EUVL system performance. The broadband soft-x-ray and EUV radiation may induce carbon growth and oxidation on mirror surfaces.⁶⁶ However, this OOB short-wavelength radiation will not be transmitted through the full system, since it is effectively absorbed in the first near-normal-incidence MLM it encounters. This will, though, lead to heating of this mirror. For longer wavelengths, $\lambda > 120 \text{ nm}$, the Mo/Si mirrors reflect radiation well.⁶⁷ The DUV radiation, $\lambda \approx 130\text{--}300 \text{ nm}$, is especially harmful, since it can expose the resist if it reaches the wafer. Furthermore, all radiation that is transmitted through the optical system will increase the thermal load on components throughout the system. If the specifications for OOB radiation cannot be met, a spectral purity filter, which also will attenuate the inband EUV radiation and thus lead to a higher demand for total power from the source, will be needed.

A measurement of the DUV radiation into the $\lambda = 130\text{--}400\text{-nm}$ wavelength range has been reported by Hansson et al.³⁷ The measurement was performed by combining spectrally integrated energy measurements obtained with a Flying Circus device with non-absolutely-calibrated spectral measurements. The resulting



(a)



(b)

Figure 23.14 Image of (a) a small plasma (5-shot average), and (b) larger plasma (40-shot average). The emission tail in (b) is an artifact due to the CCD having been read out during continuous exposure (reprinted from Ref. 37 with permission from the American Institute of Physics).

wavelength-dependant CE of DUV emission is illustrated in Fig. 23.15. The measurement gives a ratio of inband-EUV CE to DUV CE of 39%, which is 5.6 times higher than the required 7% according to the specification mentioned above.

An important point is, however, that the measured DUV radiation is emitted by the full plasma. A significant fraction of the DUV radiation will be emitted by the colder wings of the expanding plasma, although the actual size of the DUV-emitting plasma has not yet been experimentally determined. However, spatial filtering of the hot EUV-emitting core should improve the EUV/DUV ratio. In combination with optimization for low DUV emission and more accurate diagnostics, it is likely that the 7% DUV/EUV ratio can be met. This is supported by other published xenon laser-plasma data showing a DUV/EUV ratio at the secondary focus of 4%.⁶⁸

Finally, it should be noted that not only radiation from the plasma, but also IR radiation from heated source hardware in the line of sight of the optical system, may contribute to the total radiation budget. The freestanding nature of a liquid-xenon-jet plasma should, however, limit this problem.

23.5 Lifetime

23.5.1 General mirror lifetime issues

As discussed by Banine et al.,⁶⁹ a major factor that determines if a source is suitable for an exposure tool is its cleanliness. Especially if the collector must be replaced frequently due to contamination from the source, this will increase the CoO of the source significantly.⁵⁶

Degradation of mirror performance can occur for three main reasons: thermal, chemical, and impact-related damage. The thermal problems are due to the high drive power needed and are to some extent common to all source types, although high CE and large collection solid angle may limit the drive power needed.

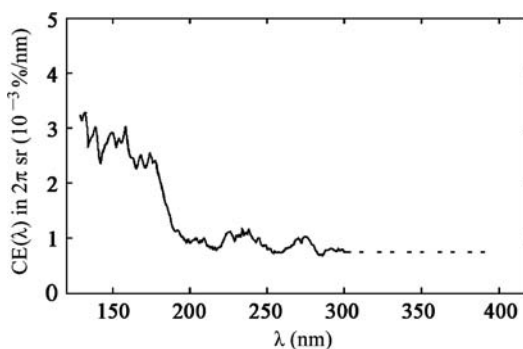


Figure 23.15 Wavelength-dependent CE of laser energy to broadband DUV emission. The dotted line represents extrapolated data (reprinted from Ref. 37 with permission from the American Institute of Physics).

The chemical problems are also to some extent common to all source techniques, since they are related to the interaction between the EUV radiation and residual gases. The EUV radiation creates secondary electrons, which dissociate the adsorbed molecules, especially hydrocarbons and water, at the mirror surface.⁷⁰ These species then react with the topmost layer, building oxide (SiO_x), and carbide (SiC) layers.⁷¹ Such contamination layers drastically reduce the reflectivity of the mirrors. A 10% reflectivity loss is observed after growth of just 1 to 3 nm of SiC or 0.5 to 1 nm of SiO_x .⁷² There are, however, ways to prevent this contamination, including keeping an ultraclean environment with, for example, the use of ultrahigh vacuum (UHV) techniques or the use of a capping layer on the mirror to reduce the reactivity^{73,74} of its surface. In-situ cleaning of the mirror^{75,76} may also be employed to remove the contamination, but only the carbide layers can be removed in this way.

The impact-related damage comprises the most source-specific types of degradation. Here one can discern three different types of impact damage: due to Xe fragments,⁷⁷ to sputtering by energetic Xe ions and neutrals, and to deposition/implantation of foreign materials. As is reported by Hansson et al.,⁵⁷ impact damage from Xe fragments has not been observed on Mo/Si mirrors exposed to a liquid-xenon-jet laser plasma. However, sputtering by energetic xenon ions is a major problem, as is illustrated in Fig. 23.16. First, the energetic ions may directly sputter the surface of the collector, reducing its reflectivity (primary sputtering). Furthermore, the ions may sputter other components in the vicinity of the plasma and in that way release material that may deposit on the collector mirror, also reducing its reflectivity (secondary sputtering). It is therefore important to understand both the ion emission characteristics of the xenon plasma and the energy-dependent sputter yield (number of knocked-out atoms per ion). A calculation of the sputter yield of xenon ions on a Mo/Si mirror is reported in Hansson et al.,³⁷ where it is

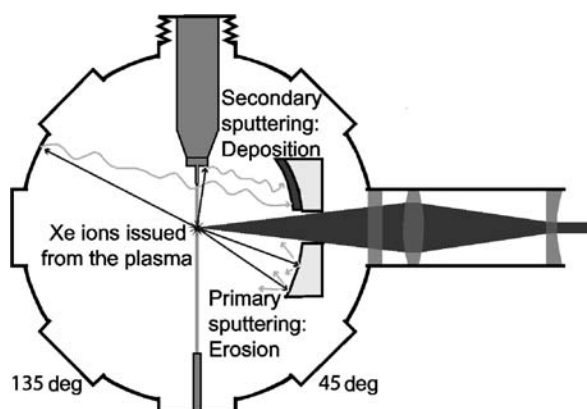


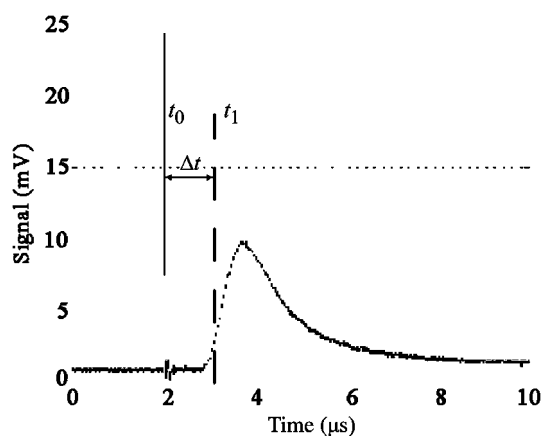
Figure 23.16 Energetic xenon ions from the plasma can lead to both direct sputtering (primary) of the collector mirror and sputtering (secondary) of other material in the vicinity of the source, releasing material that may deposit on the collector mirror (reprinted from Ref. 37 with permission from the American Institute of Physics).

found to be about unity for xenon ions in the keV range. It should, however, be noted that highly charged ions can have much higher sputter yields.⁷⁸

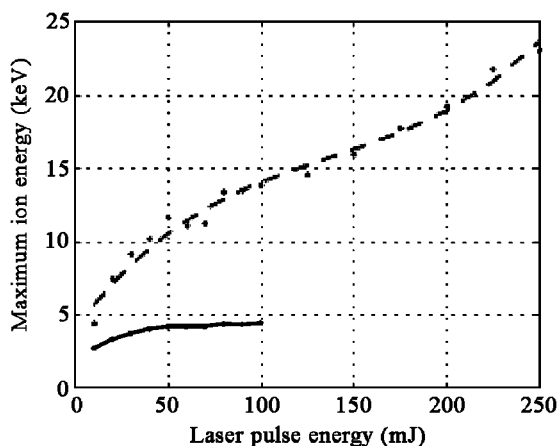
23.5.2 High-energy ion emission

The energies of the xenon ions emitted from the plasma have been reported by Hansson et al.³⁷ The energies were measured through a time-of-flight experiment with a Faraday cup as ion detector (cf. Daido et al.⁷⁹) with the Faraday cup mounted at both 45 and 135 deg to the laser direction (see Fig. 23.16).

Each pulse resulted in a voltage response as illustrated in Fig. 23.17(a). The maximum energy of the ions was determined through the time Δt between the first



(a)



(b)

Figure 23.17 (a) The voltage response of the Faraday cup for a typical plasma event. (b) The dependence of laser pulse energy on maximum ion energy. The dashed line was obtained with the Faraday cup at a 45-deg angle to the laser beam (cf. Fig. 23.16), and the solid line at 135 deg (reprinted from Ref. 37 with permission from the American Institute of Physics).

peak at t_0 , which is fully synchronized with the laser pulse, and the rising edge of the second peak at t_1 , corresponding to the arrival of the first ions.

The resulting maximum ion energies as a function of laser-pulse energy and direction of measurement are illustrated in Fig. 23.17(b). As can be seen, the peak energy of the ions is higher in the 45-deg direction than in the 135-deg direction. A long tail of lower-energy ions should also be present; however, this could not be experimentally determined with the existing arrangement. Furthermore, quantitative ion-flux numbers could not be obtained, since the average charge of the ions reaching the Faraday cup was not known. Future experiments should therefore also try to determine the charge distribution of the ions due to the higher sputter yield expected from highly charged ions as mentioned above. The presence of multi-keV xenon ions from plasmas created by several-nanosecond laser pulses has also been reported in other studies of similar targets^{68,80} and in solid bulk targets.⁷⁹ Multi-keV ions were not, however, found in a xenon-gas-puff target experiment.⁷⁹

23.5.3 Sputtering experiments

The existence of high-energy ions suggests that sputtering of the collector mirror and other components will be a major problem. The sputtering has also been verified by exposing witness plates (silicon wafers) to a liquid-xenon-jet laser plasma. In Hansson et al.³⁷ it is reported how silicon wafers were exposed to 10^6 plasma events generated by ≈ 330 -mJ laser pulses, where the wafers were placed 110 mm from the plasma, in both the 45- and 135-deg directions (see Fig. 23.16). The wafers were masked except for a small area, and the edges between the masked and unmasked areas were investigated with a surface profiler (KLA Tencor P-15) after the exposure. The unmasked area showed ≈ 10 -nm-deep sputtering in the 45-deg direction, and ≈ 27 -nm-deep sputtering [see Fig. 23.18(a)] in the 135-deg direction.

It is interesting to note that the sputtering rate is higher in the 135-deg direction, although the maximum ion energies are higher in the 45-deg direction as reported above. This probably indicates that a larger number of ions are emitted in the 135-deg direction, although with lower energies.

The sputtering ions and neutrals must be decelerated to nonsputtering energies before reaching the collector mirror or other components, in order to meet the lifetime specification. Furthermore, this must be done without significantly limiting the available collection angle, since otherwise more drive power will be needed. It has been reported that a background pressure can reduce the energy of the fast ions,^{81,82} so this could be a way to decelerate the atoms without introducing hardware that limits the collection angle. The result of a simple experiment was further reported by Hansson et al.,³⁷ where the turbomolecular pumps of the source chamber were stopped, increasing the xenon pressure in the vacuum chamber to > 1 mbar. Two silicon wafers were then exposed under identical conditions to the previously discussed sputter experiments. Indeed, no sputtering was observed, but rather a deposition of ≈ 4 nm in both the 45- and the 135-deg direction [see Fig. 23.18(b)]. The composition of the deposit, however, was not analyzed. Although the background pressure of > 1 mbar is too high (since it will absorb most

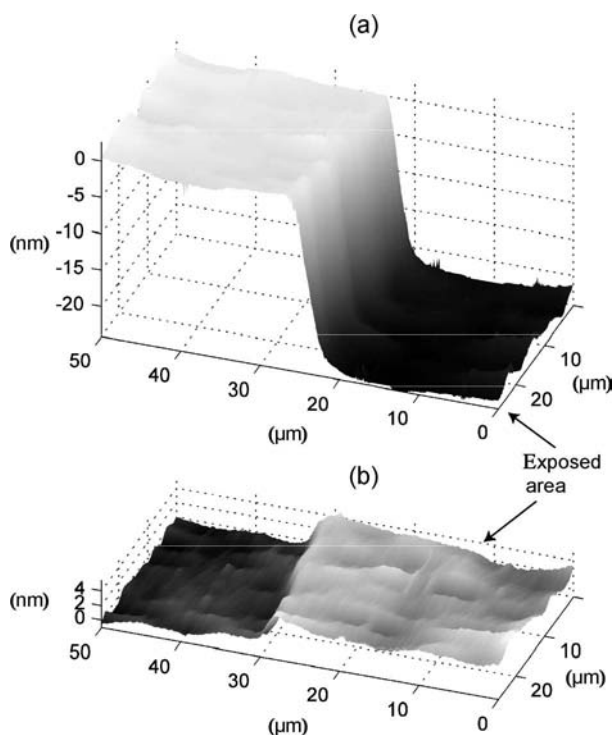


Figure 23.18 Edge between masked and unmasked areas of silicon wafer exposed to 10^6 plasma events: (a) in the 135-deg direction without increased background pressure, and (b) in the 45-deg direction with increased background pressure. Sputtering is observed in (a), and an unidentified deposition in (b) (reprinted from Ref. 37 with permission from the American Institute of Physics).

of the inband EUV radiation over a short distance), at least the concept was shown. Further experiments should be performed where the background pressure can be accurately controlled, and using other gases than the highly EUV-absorbing xenon. Other ion mitigation methods such as electrostatic repeller fields⁸³ or magnetic field shields⁸⁴ should also be investigated, though the introduction of such concepts without limiting the collection angle may be difficult.

23.6 Summary

This chapter has described the liquid-xenon-jet laser-plasma source, especially from the point of view of its applicability for HVM EUVL scanners. It has been shown how experiments indicate that many crucial requirements on such a source, e.g., source size, repetition rate, and thermal-load capability, can hopefully be met with this technology. However, it is also reported how the presence of high-energy ions from the plasma is a major problem, since they will significantly limit the lifetime of the collector. Finding a way to decelerate these ions to nonsputtering

energies before they reach any surface is probably the main challenge to meet for liquid-xenon-jet laser-plasma source technology.

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The authors gratefully acknowledge the significant contributions to the technology described in this chapter by former coworkers at both Innolite AB and the Royal Institute of Technology: Magnus Berglund, Oscar Hemberg, and Lars Rymell; and by former coworkers at Innolite AB: Hee-June Choi, Björn Jacobsson, Emmanuelle Janin, Sofia Mosesson, Jalmar Thoresen, and Martin Wilner.

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Chapter 24

LPP Source Development and Operation in the Engineering Test Stand

John E. M. Goldsmith, Glenn D. Kubiak, and William P. Ballard

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24.1 Introduction

The Engineering Test Stand (ETS) is a fully integrated, alpha-class, full-field (24×32 mm) EUVL step-scan tool that was developed for system and process learning in support of commercialization of EUVL. The overall system design is shown in Fig. 24.1, and is described in detail in Refs. 1–4. This chapter describes the high-average-power LPP EUV source that was integrated into the ETS, and the developments that led to this source.

The goal of the ETS source and associated collector and imaging optics was to demonstrate EUV optical throughput and associated wafer exposure rates equivalent to ten 300-mm wafers per hour. The EUV illumination-system requirements to support this throughput are listed in Table 24.1. The source is required to produce 15 W of 13.4-nm radiation integrated over a 2.5% spectral bandwidth (the appropriate bandwidth for the mirror configuration in the ETS optical design) and a 2π -sr solid angle. To achieve the required flux at the reticle plane, 4.4 W, or approximately 30% of the emitted radiation, must be collected by the first element of the condenser. The collection solid angle and the etendu of the projection optical system limit the source emission diameter to ≤ 150 μm FWHM.⁵ The

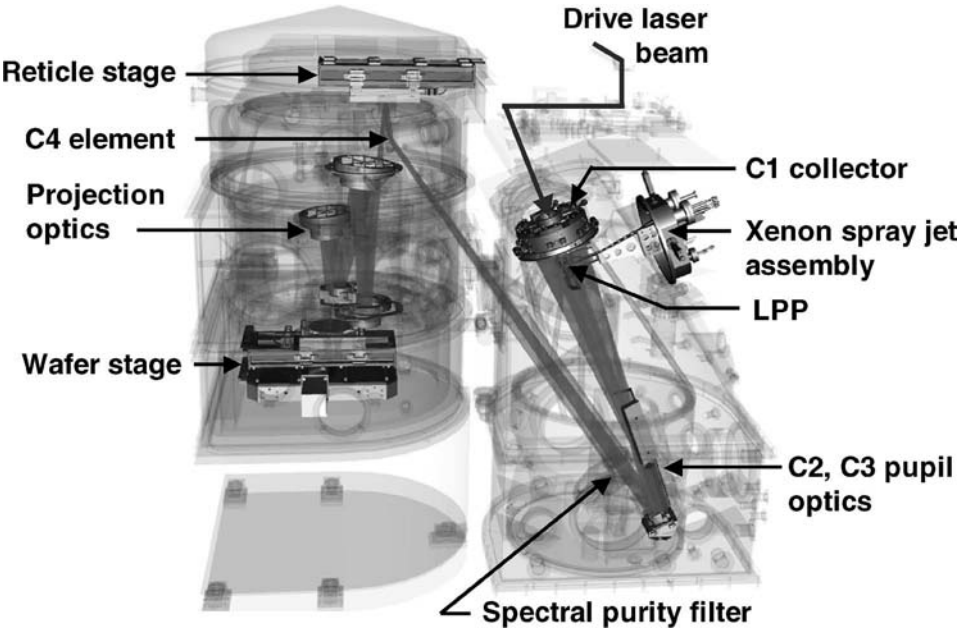


Figure 24.1 Cross-section of the ETS showing the major subsystem components.

Table 24.1 Illumination system requirements for the ETS.

System Characteristic	Requirement
Wavelength	13.4 nm
Total power incident on condenser	4.4 W over 1.8 sr and 2.5% spectral bandwidth
Power delivered to reticle	≥ 0.76 W
Repetition rate	≥ 3000 Hz
Illumination format	96 mm arc, ≤ 6 mm wide
Partial coherence	0.7
Illumination uniformity	$\pm 2\%$
Illumination stability	1% (1σ)
Source motion	$< \pm 25$ μ m
Condenser lifetime	$\leq 10\%$ reflectance loss after 10^{10} pulses

repetition-rate requirement derives from the illumination uniformity requirement of the scanned exposure. The illumination uniformity is measured over the full 24×32 -mm exposure field and is sensitive both to spatial nonuniformity along the length of the scanned exposure arc and to temporal illumination instabilities that lead to nonuniformities in the scanned direction. The tolerance to source motion is extremely tight, due, in part, to the high effective magnification of the condenser; slight source motions cause significant nonuniformities in the reticle plane and unacceptable motion of the illumination beams in the entrance pupil of the projection optic. The condenser lifetime requirement is derived from an intermediate goal of 500 h of operation before significant condenser maintenance is required. To significantly reduce the cost of ownership (CoO), the condenser lifetime requirement for

commercial EUVL tools is likely to increase to 10^{11} pulses or more, depending on the nature of the reflectance loss.

The path to satisfying these requirements required many developmental steps. An outline of the source developments at Sandia will be presented here.

24.2 Early Source Development at Sandia

Because of the need for high-density targets to effectively couple laser pulses into EUV-emitting plasmas, most early source work used metallic targets. The first imaging tool developed at Sandia employed a KrF (248 nm) laser system with a gold-drum target to produce EUV radiation for imaging with a $20\times$ reduction camera.⁶ It was immediately apparent that debris from sources of this type was a major threat to the lifetime of condenser optics. Two *mass-limited* targets were investigated at that time to reduce debris production: 0.3–1.0- μm -thick films of metals on Mylar tape, and solid Xe targets.^{7,8} Both were partially successful, but a copper-wire target was found to be superior to the tape-based system.

The first-generation $10\times$ imaging system was based on a KrF laser with a copper-wire target, using 200 mTorr of background He pressure to effectively stop atomic-scale debris.⁹ Parallel investigations at this time showed that the shorter pulses and higher beam quality produced by Nd:YAG (1064 nm) lasers were superior for efficient EUV generation, and all subsequent systems have used such lasers. The second-generation $10\times$ imaging tool, now referred to as the “ $10\times$ microstepper,” was first based on a Nd:YAG laser with a copper-wire-drive system, using a high-speed chopper to further reduce debris.^{9,10} This system is still in use today for resist studies, though with a Xe-cluster source (to be described below) and improved projection optics.^{11,12}

The debris-mitigation schemes used with these early laboratory systems were sufficient to enable a large variety of studies, but a major advance was needed to move well along the path to provide the many-orders-of-magnitude reduction in debris that would be required to operate a commercial EUV lithographic tool. This advance was the development of a debris-free EUVL source based on a xenon jet source.¹³ In this source, the target is provided by high-density xenon clusters formed in supersonic nozzle expansions (Fig. 24.2). The key features of this source are that the actual target is debris-free (inert xenon atoms), it has a conversion efficiency (CE) comparable to that of solid targets, and its geometry and operating characteristics are readily adapted to a commercial tool. Early studies were based on a moderate-repetition-rate (up to 100 Hz) Nd:YAG laser, and a pulsed jet compatible with this repetition rate was used to reduce xenon consumption and pumping requirements.

A key parameter of gas-jet sources is the standoff distance available between the laser focal point and the gas-jet hardware. Figure 24.3 shows the EUV yield as a function of separation observed in this study. The target material itself does not produce debris, but deposition of material eroded from the nozzle was found to be

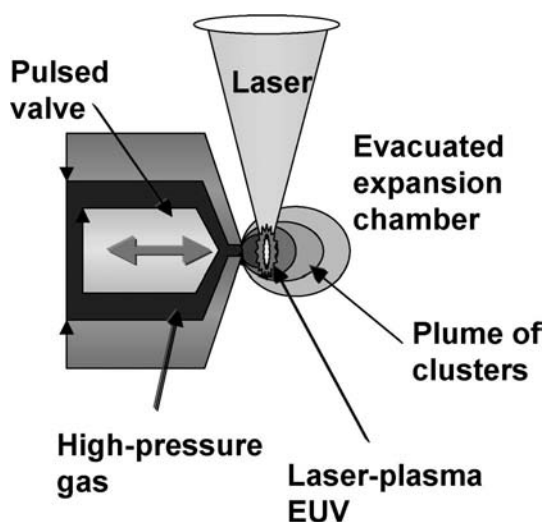


Figure 24.2 Schematic diagram of the pulsed cluster LPP source.

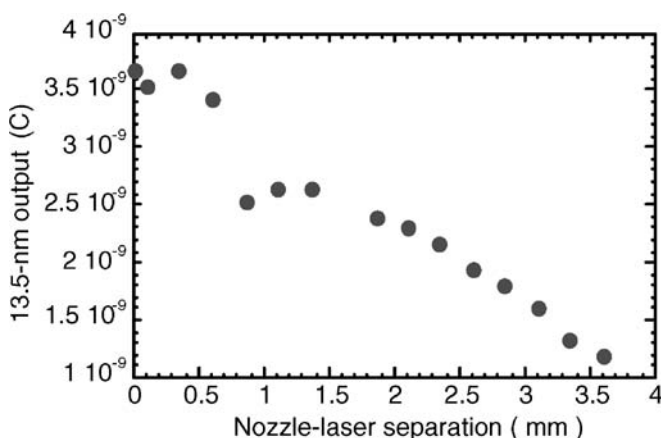


Figure 24.3 13.5-nm yield measured as a function of laser-nozzle separation for the pulsed cluster LPP source.

the major threat to condenser lifetime from this source, and the standoff distance of 1.5 mm was found to provide a reasonable trade-off between EUV output and condenser lifetime. At this standoff distance, the EUV output was 58% of that obtained from solid gold targets, but with an improvement of condenser lifetime by a factor of 10^5 over unprotected solid targets, and of 100 over solid targets with debris mitigation. Further progress on this source is described in Ref. 14, including additional improvements in condenser lifetime and measurements of output spectra, angular distributions, and source size. Figure 24.4 shows the progress in condenser lifetime achieved up to that time (1998).

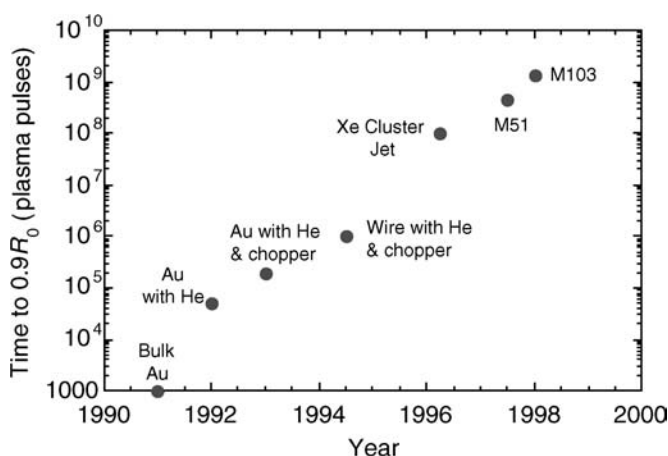


Figure 24.4 Progress on EUVL condenser mirror lifetimes, expressed as the number of plasma pulses required to reduce the original mirror reflectance by 10%.

24.3 ETS Source Development

By 1998, the majority of the source work at Sandia focused on implementing a high-power source to meet the requirements outlined in Table 24.1. This required a nearly 40× scale-up of laser power from 40 to 1500 W, accomplished entirely by increasing the pulse repetition rate of the laser source (in fact, with a modest decrease in pulse energy) from 100 to 6000 Hz. Because of overall schedule constraints, this work was accomplished using three parallel developmental paths: final development of a suitable high-power laser system, development of jet sources suitable for use with that system, and integration of a low-power source into the ETS for early imaging studies. These three paths will be described separately here.

The custom 1700-W laser was developed by the TRW Corp. (now Northrop Grumman Space Technology) and subsequently installed at Sandia for use with the ETS (Fig. 24.5). The laser is a diode-pumped, solid state Nd³⁺:YAG laser composed of three identical laser modules, each of which produces 570 W of time-averaged 1.06-μm power at repetition rates of 1667–2000 Hz. The beams from the three modules are multiplexed to deliver 285–342 mJ/pulse at a combined repetition rate of 5000–6000 Hz, or can be synchronized to deliver 900 mJ/pulse at a repetition rate of 1667–2000 Hz. The pulse duration for each individual chain is ~10 ns FWHM, and the beam quality, as determined by the focal-spot size in the far field, is 1.1–1.2 times the diffraction limit. Laser-beam pointing is actively controlled at the full laser repetition rate, achieving a total combined beam drift and jitter of approximately 0.25 times the diffraction-limited spot size. The output power stability is also excellent, exhibiting root-mean-square (rms) deviations ranging from 0.6% to 0.8%, depending on the output power.

Because of the need to increase the source repetition rate from 100 Hz to 5–6 kHz, the decision was made to change from a pulsed to a continuous jet expansion system. A continuous gas-jet system was designed and built by a division

of the Northrop Grumman Corp. to allow EUV source operation with the TRW laser.⁵ A model of the jet is depicted in Fig. 24.6, which shows the cooled nozzle mounted together in a cooling and support yoke with an efficient gas collection body to minimize pumping requirements. Also mounted on this structure are the laser recollimation lens and turning mirror, used to direct unabsorbed laser power out of the source chamber and into a beam dump. The nozzle support structure is mounted to an in-vacuum stage to allow precise alignment of the cluster beam with respect to the laser. To minimize the Xe partial pressure in the source chamber and the resulting EUV attenuation, two 3000-L/s magnetically levitated turbomolecu-



Figure 24.5 High-power Nd:YAG laser with two chains installed and one chain on loading rails. Controller can be seen in the background.

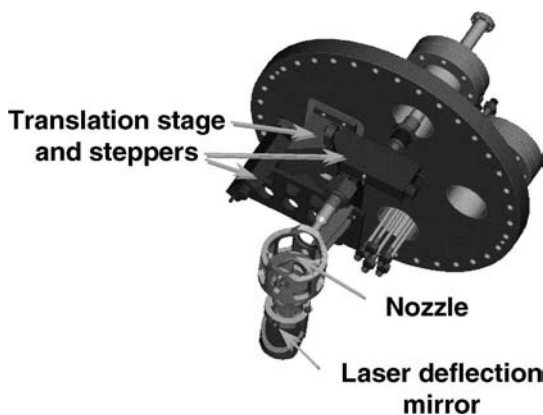


Figure 24.6 Model of continuous jet, showing nozzle, laser deflection mirror, cooling and support yoke, and translation stages.

lar pumps are used in combination with the gas-collection body. When a 150- μm -diameter nozzle throat is used, the ambient partial pressure of Xe in the chamber is 1 mTorr, transmitting 83% of the 13.4-nm power over the condenser path length. To reduce recurring Xe consumption costs, 100% of the Xe is recycled: recompressed, filtered, and delivered to the nozzle inlet for reuse.

An important design constraint for the continuous jet is that it must not interfere with the collection and delivery of EUV light by the condenser. Figure 24.7 shows a cross section through a common plane of the jet assembly together with cross sections of the six EUV beams as they reflect from the six “channels” of the first condenser element on their way to the second condenser element. As can be seen, the interfaces are tight but manageable. The continuous jet is designed to accommodate the full thermal loading of the spectrally integrated output of the plasma. Based on calorimetry measurements, up to 60% of the absorbed laser power is re-emitted as spectrally integrated radiant power. The nozzle region thus receives up to 65 W of radiated plasma power with 1500 W of laser power driving the plasma. Cooling is provided by a conical cooling jacket surrounding the nozzle and by proper choice of nozzle materials. For alignment stability of the nozzle during full-power operation, the support yoke is protected by a water-cooled radiation shield.

In the first phase of power scale-up, the continuous jet was integrated with a 200-W laser system operating at a maximum repetition rate of 500 Hz. It was anticipated that the expansion dynamics of the continuous jet would differ somewhat from the earlier pulsed jets, and that the details of EUV generation would be sensitive to these differences. Thus, the primary objective of this first phase was to establish the operating point required to optimize the fundamental source radiation properties such as CE, source size, angular distribution, and total power. A second objective was to validate the thermal management approaches.

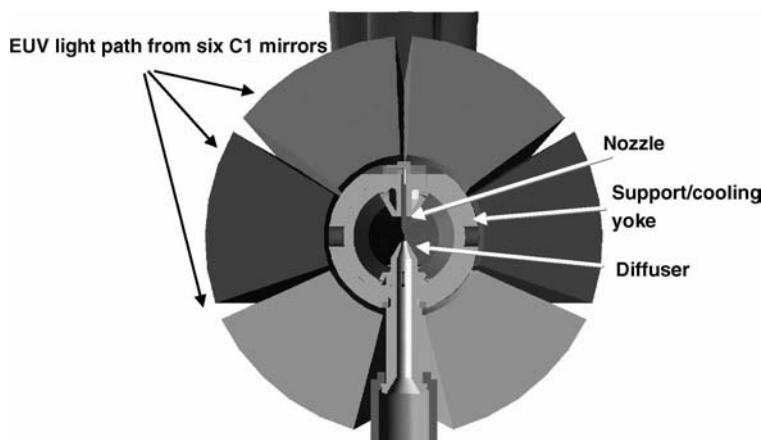


Figure 24.7 Cross section of six illumination channels and nozzle system hardware, showing condenser beam exclusion zone in the plane containing the nozzle axis and perpendicular to the laser propagation direction.

The 200-W laser system was composed of five commercial pulsed Nd:YAG lasers, each of which operates up to a maximum power of 40 W and repetition rate of 100 Hz. When properly synchronized and aligned, the result was a laser driver operating with a pulse duration of 3 ns and up to 200-W average power at a 500-Hz repetition rate. To illuminate the jet target, a single lens was used to focus all five beams to the far field. The five beams were aligned in a configuration in which one beam passed through the axis of the lens and the other four were arranged in a fourfold-symmetric pattern, each beam lying equidistant from the lens axis. To achieve a common focus with this arrangement, all five beams must remain parallel to within $\approx 30 \mu\text{rad}$. A CCD camera was used to monitor the degree of alignment and overlap of the five beams by viewing an equivalent focal plane with a microscope objective. For initial alignment and to compensate for long-term beam drift, computer-controlled pointing and centering mirrors were adjusted from calculations performed on images acquired from the alignment camera.

When the laser was focused properly 1.5 mm from the nozzle exit plane, a 13.4-nm CE of 0.56% was achieved, equal to that measured in the earlier pulsed jet to within the uncertainty of the experimental measurement. The CE value quoted here is integrated over a 2.5% spectral bandwidth centered at a wavelength of 13.4 nm and a 2π -sr emission solid angle, assuming a uniform emission angular distribution. Though the CE value of the continuous jet was equal to that of the pulsed jet, the nozzle and laser parameters required to produce this value were significantly different in the continuous jet. For example, we found that the EUV CE in the continuous jet is much more sensitive to nozzle geometry and inner-wall roughness than that in the pulsed jet. This may be due to the presence of a fully developed boundary layer in the continuous jet that does not contain a significant density of clusters. This boundary layer does not contribute to plasma formation and EUV generation, but instead partially obscures radiation produced by the plasma. Methods have been developed to fabricate nozzles meeting geometry and finish requirements to minimize these effects.

It is desirable to scale up the output power of EUV sources by increasing the pulse repetition rate rather than increasing the pulse energy, both to provide improved lithographic dose control and to reduce the risk of optical damage to the laser optics. Because the laser pulse significantly perturbs the local environment of the xenon jet, it is to be expected that the EUV CE will suffer if the temporal separation between the pulses becomes shorter than the time for the local environment to recover. The flexible triggering capability of the five-laser system made it straightforward to measure the EUV CE as a function of the effective laser repetition rate. Figure 24.8 displays the ratio of the EUV signal from the second laser pulse to that from the first laser pulse as a function of the delay between the two laser pulses. The ratio is constant for delays greater than $\approx 33 \mu\text{s}$, indicating that the EUV production is constant up to effective laser repetition rates of $\approx 30 \text{ kHz}$, and in particular showing that difficulties would not be encountered at the more modest 5–6-kHz repetition rates planned for the ETS.

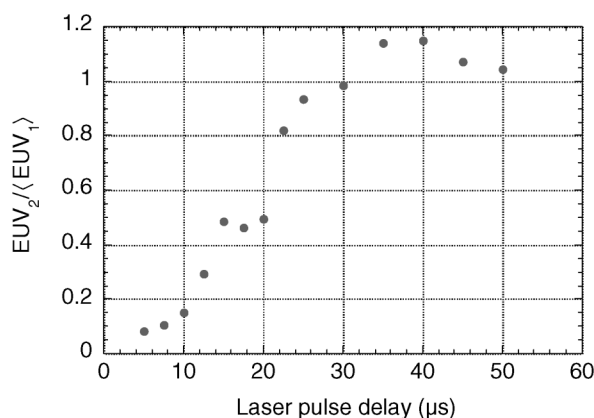


Figure 24.8 Ratio of the EUV output produced from two consecutive laser pulses as a function of the delay between the two pulses.

24.4 Integration of the High-Power Source into the ETS

During the time that the high-power laser and continuous gas-jet sources were under development, the ETS was operated with a continuous gas-jet source similar to that described above, but using a single 40-W Infinity Nd:YAG laser to generate the LPP. The system design of the ETS is described in detail in Ref. 1, and the use of the low-power source for first operation and static imaging is described in Ref. 2. Although the low-power source was used for the first demonstration of full-field scanned imaging in the ETS,³ the limited scan speed possible with this source required integration of the high-power source in order to continue making rapid progress.

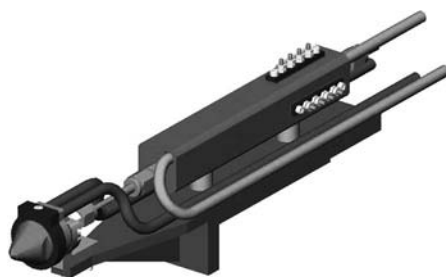
Following the operation of the continuous cluster-jet source using the moderate-energy laser system described above, the cluster jet was then irradiated with a single 500-W beam of the TRW laser operating at 1667 Hz. The additional cooling capacity added to the cluster jet assembly did not maintain the integrity of the clusters with this higher radiated power and ≈ 3 times longer laser pulse duration. Thus, the EUV output gradually degraded with time as the cluster density decreased, and it became clear that further progress with this source type would be difficult. During this same time period, a group at TRW Corp. had developed a liquid xenon spray jet for use in their LPP studies, and had demonstrated operation with a 900-W Nd:YAG laser system.¹⁵ We therefore chose to integrate a source based on this design into the ETS for high-power operation.

The TRW liquid spray jet was redesigned both to fit within the ETS geometric constraints and to use the ETS material guidelines. The spray-jet hardware must fit within a 30-deg space between two of the six primary condenser elements. In addition, the list of approved materials for the ETS is restricted because the jet hardware must be high-vacuum-compatible and baked before installation. A key difference between the cluster jet and the liquid spray jet is the lack of a gas recov-

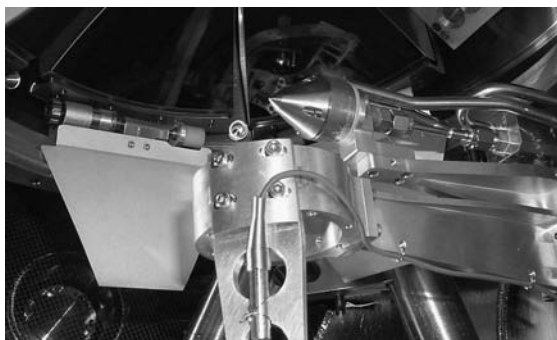
ery diffuser in the latter. Hence, higher background Xe pressures were anticipated and observed.

Gaseous Xe at high pressure (1–4 MPa) liquefies in a packed copper heat exchanger cooled by liquid nitrogen (Fig. 24.9). A 50-W heater and a thermistor embedded in the heat exchanger regulate the temperature through an external temperature controller that maintains the liquid-Xe temperature to ± 1 K. The liquid Xe enters the ETS through a 50- μm -diameter orifice made from a commercial electron-microscope aperture for accurate dimensional control. A graphite collimator with internal diameter 400 μm protects the orifice from direct plasma exposure and maintains a well-collimated spray of liquid Xe droplets. The collimator uses a separate heat exchanger and coolant lines so that its temperature can be maintained whether one, two, or three of the 500-W laser beams are used to irradiate the plasma without affecting the Xe liquefaction temperature. The laser beams are focused onto the jet with a 250-mm-focal-length lens, creating a Xe plasma producing EUV at 13.5-nm wavelength. The locations of the jet hardware and the laser beam can be remotely adjusted, thereby placing the EUV source at the focal point of the condenser optics.

A wide variety of additional ETS systems required modification to accommodate the liquid spray jet. The Xe recirculation system was modified, allowing Xe



(a)



(b)

Figure 24.9 (a) isometric view of the ETS liquid-xenon spray jet source, showing liquefaction heat exchanger with thermal feedback control; (b) liquid-xenon spray jet source as installed in the ETS.

stagnation pressures up to 3.5 MPa. A third 3200 L/min turbomolecular vacuum pump provided increased pumping capacity for the ≈ 0.2 g/s Xe gas flow. The existing water-cooling of the condenser optical assembly anticipated the higher thermal loads from the more intense plasma. A water-cooled witness sample holder installed in the condenser assembly made certain that the environmental witness samples observed the same environment as the condenser. After intercepting the gas jet, a water-cooled Mo absorber mounted below the jet hardware absorbed and dispersed any unconverted laser energy.

Initial operation of the spray jet source was readily established using temperatures (200–225 K) and pressures (1–4 MPa) provided by TRW from experiments conducted in their test chamber. Figure 24.10 shows typical long-term operation for a ~ 10 -million-shot environmental run and a plasma-nozzle separation of 4 mm. The three turbomolecular pumps maintain a background pressure of ≤ 0.7 Pa in the illuminator vacuum chamber of the ETS. Condensed Xe particles are observed in the chamber, and equilibrium between the formation and sublimation rates occurs after only a few minutes. Thus the system did operate successfully without a gas recovery diffuser, but incorporation of such a system would decrease the pumping requirements and/or permit operation at lower ambient xenon pressures.

Experiments performed with a single 500-W beam of the laser and the liquid spray jet showed a CE of 0.17% into 2π sr and a 2% bandwidth with 4-mm plasma-nozzle separation. This CE is an improvement of about a factor of 3 over the prior cluster-jet CE obtained with the 500-W laser beam yet with a greater separation (4 versus 1.5 mm) between the plasma and the nozzle. Experiments show no degradation of EUV output or increase in shot-to-shot standard deviation of the output during several hours of operation. On using all three 500-W laser beams, oper-

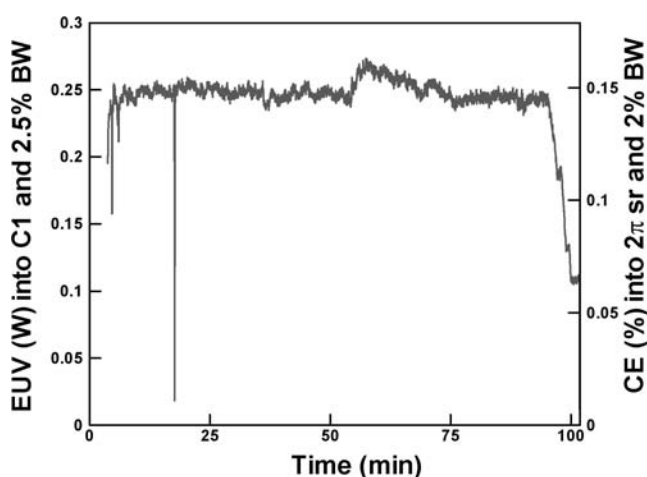


Figure 24.10 Long-term EUV generation for the liquid spray jet with single 500-W laser chain drive. The pause at ≈ 20 min was intentional to observe turn-on transient behavior. The left axis shows the EUV power collected by the condenser, the right axis the CE.

ated sequentially at a total average power of 1500 W, the EUV output increased by an additional factor of 3. The source shot-to-shot stability exhibited 11% standard deviation with one or all three laser chains operating. With two beams operating either synchronously or sequentially, the output power was virtually identical. Thus, no increase in CE was observed with additional energy in the pulse (from 260 to 520 mJ). It is expected that the EUV output should be a strong function of the distance between the laser and the collimator exit. As this distance increases, the Xe becomes more diffuse and the surrounding gas cloud expands, both of which decrease the net EUV output. This dependence was observed (Fig. 24.11).

The EUV output of the source should also depend strongly on the incident laser energy per pulse. A direct measurement of the output as the incident power varied confirmed this (Fig. 24.12). Additional studies with multiple chains of the laser also showed that the CE was unchanged as the amount of laser drive energy increased up to ≈ 520 mJ, indicating that the additional laser power increased the EUV linearly. Thus, the CE became constant above about 250 mJ. Measurements of the EUV pulse shape showed that the EUV FWHM and the laser FWHM were essentially identical (Fig. 24.13). This observation indicates that saturation with pulse width has not been reached, which explains why the chain-to-chain jitter did not adversely affect the EUV output. In contrast with many other LPP studies,^{16,17} the *Q*-switched laser used here had much longer pulses (≈ 12 ns FWHM) than were used in other studies (femtosecond to picosecond durations). The applicability of the conclusions of these other studies about saturation levels to longer pulses is unclear.

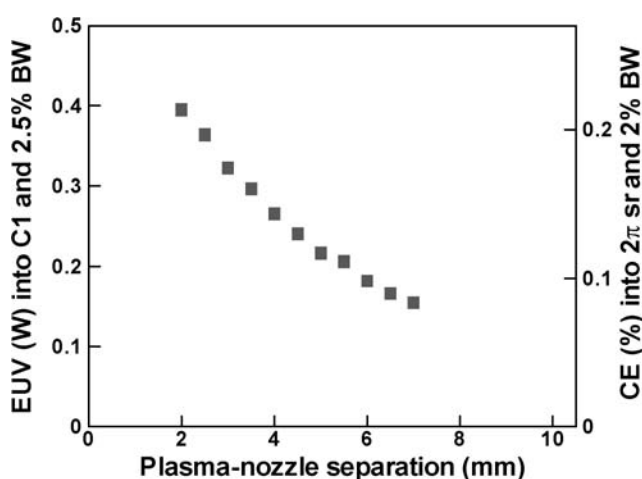


Figure 24.11 EUV output versus plasma-collimator separation for the liquid spray jet with single 500-W laser chain drive. The left axis shows the EUV power collected by the condenser, the right axis the CE.

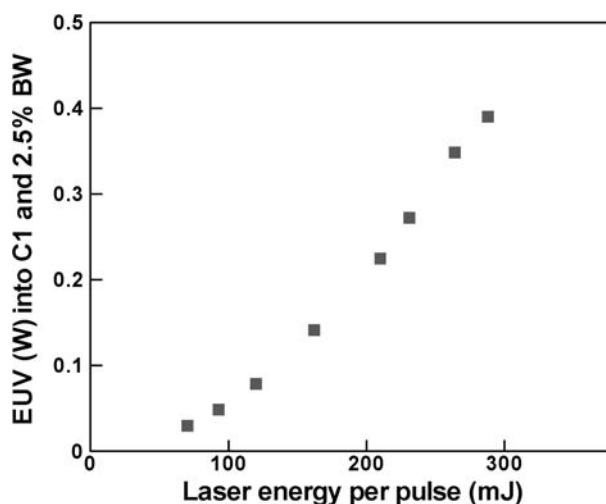


Figure 24.12 EUV output of the liquid spray source as a function of laser pulse energy at 2.5-mm separation between the plasma and the nozzle.

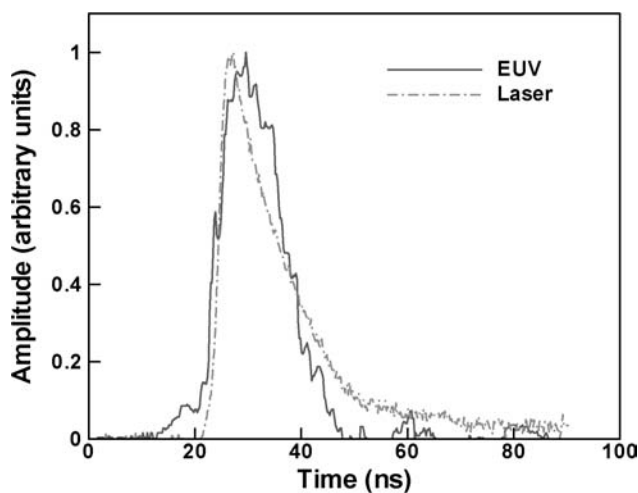


Figure 24.13 Time history of laser input and EUV output from the liquid spray-jet source.

24.5 ETS Operation with the High-Power Source

Demonstration of lithographic imaging followed shortly after integration of the high-power source into the ETS,¹⁸ and all subsequent source operations have used single or multiple 500-W chains of the TRW Nd:YAG laser rather than the 40-W laser originally used to qualify the ETS. The liquid Xe spray jet source operated with a CE of 0.2% into 2π sr and 2.5% bandwidth, appropriate for the ETS optical system. Significant compromises were made in ultimate source output to achieve acceptable condenser lifetime. The source reliability was over 90%, and the condenser erosion rate, measured over 300 million pulses, was approximately one

Mo/Si bilayer in 15 million laser pulses, translating to a condenser lifetime of approximately half a year at a throughput level of 20 full-field wafers per week with primary condenser optics using ~ 100 sacrificial multilayers.

The major challenge encountered with the high-power laser source was source drift during lithographic operation. Two in-vacuum EUV cameras monitor the position of the source. The drift of the x and y components of the centroid from one of these cameras (the xy view) is shown in Fig. 24.14. Temperature monitors on various components of the condenser-optics support truss showed that these trusses were heating differentially and significantly. One truss reached 60°C after extended operation with two laser chains driving the LPP. The original ETS design assumed that these trusses would all heat at the same rate; however, subsequent modifications of the system prevented this behavior. Additional cooling and thermal shielding were added to the trusses, resulting in the much smaller drift observed in Fig. 24.14.

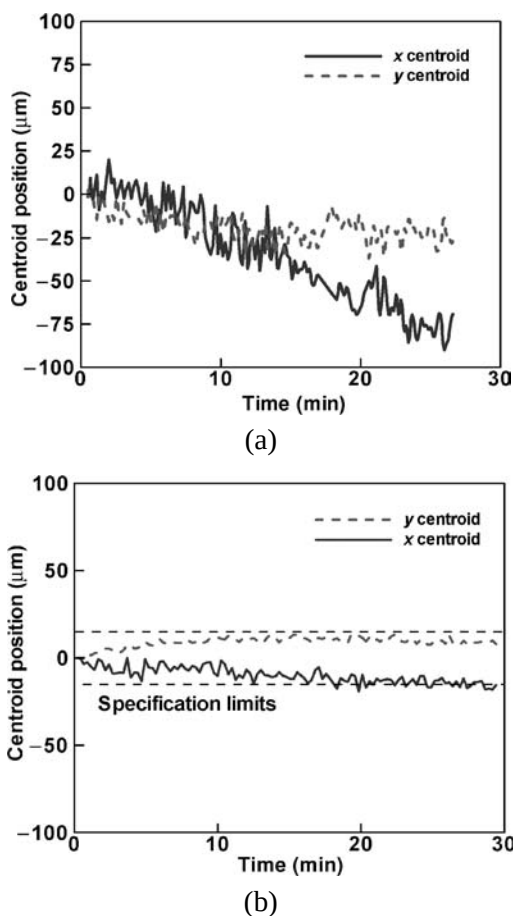


Figure 24.14 (a) Source centroid movement versus time as originally installed, and (b) after incorporation of additional cooling.

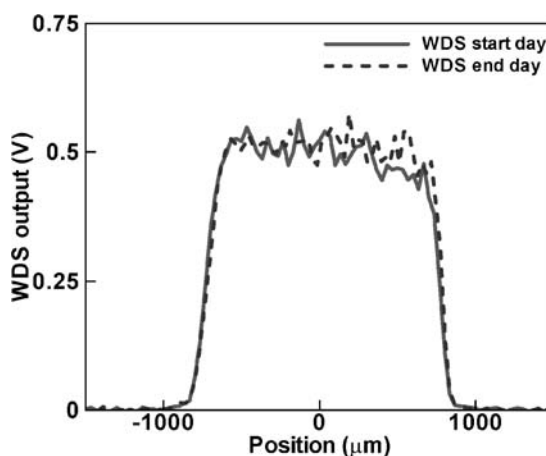


Figure 24.15 Wafer dose sensor scans at the beginning and the end of the day, showing long-term stability of source performance.

The addition of thermal shielding removed the long-term source movement, but there was still a short-term shift occurring as the jet hardware warmed up in the first tens of seconds after the laser was energized. An in-vacuum, fast EUV shutter was designed and installed, allowing the source to run for ≈ 20 s before EUV was admitted to the main chamber. In conjunction with additional shielding for scattered laser light at the injection mirror, the source drift was virtually eliminated.

A wafer dose sensor (WDS) measured the throughput of the entire system by sampling the EUV from a bright field on the reticle at the wafer plane, using an EUV-sensitive photodiode translated through the illumination field by the wafer stage. Studies have shown that it is most sensitive to the location of the source along the z axis (laser direction). With all of the source improvements, there is no change in source location in this dimension over the course of a day, as shown in Fig. 24.15. The variations in WDS output as it traverses the exposure area correlate with stochastic fluctuations in the source output, also observed by the condenser EUV sensors.

24.6 Conclusion

The high-power LPP based on a liquid xenon spray jet proved to be a robust source for ETS operations. Combined with the first implementation of a condenser system that efficiently mapped the small-volume LPP source into a ring-field optical system, it was critical to enabling full-field exposures of 200-mm wafers (Fig. 24.16) with sub-100-nm feature sizes (Fig. 24.17), and supported a wide range of system learning (thermal response, sensor development, environmental issues, magnetically levitated stage operation, system control) as well as imaging studies.^{19–23} In order to obtain high CE and larger standoff between the laser focal point and source-target-related hardware, it is very likely that an LPP for a commercial EUVL system would be based on a filament-jet or droplet-type target (as described

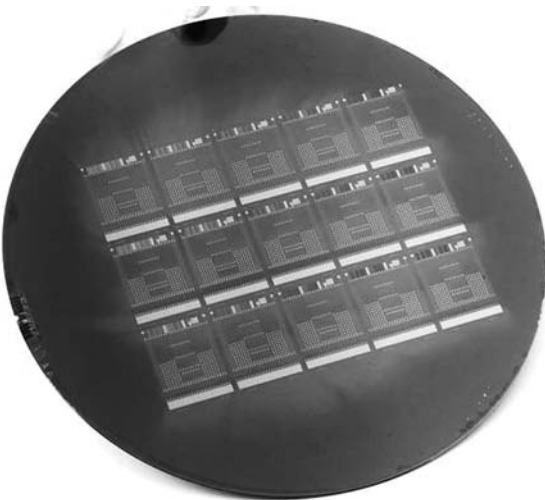


Figure 24.16 24 × 32-mm fields imaged by the ETS on a 200-mm wafer.

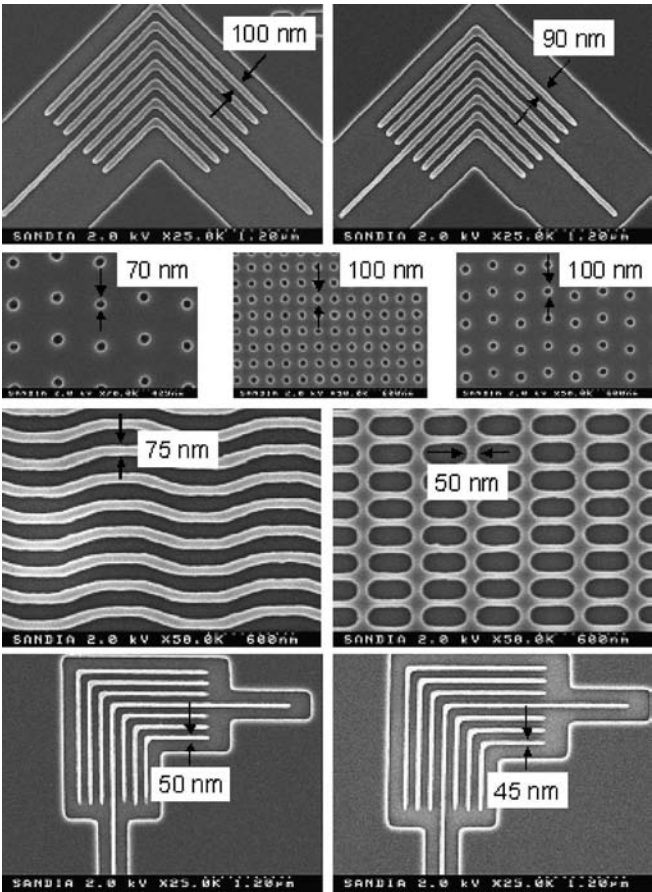


Figure 24.17 Sub-100-nm features imaged by the ETS.

elsewhere in this volume), but those sources were not ready for integration into a complete tool at the time that the high-power ETS source was needed, and the spray jet provided a valuable intermediate step in the progression of high-power LPP sources.

Acknowledgments

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Chapter 25

Xenon Target and High-Power Laser Module Development for LPP Sources

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25.1 Introduction

This chapter gives an overview of LPP EUV source development work at Northrop Grumman Corporation (NGC). The chapter covers development of the laser module, xenon target, and overall system.¹ The volume editor (V. Bakshi) prepared this chapter as a summary of information provided to him by NGC.

25.2 Laser Module

Lasers for LPP EUV sources are expected to produce tens of kilowatts of high-pulse-rate, high-pulse-energy, short-pulse-width, near-diffraction-limited output.

Such lasers will be focused onto a condensed jet of cryogenic xenon or tin targets to produce a plasma with sufficient temperature to generate EUV radiation. For the generation of the EUV-producing plasma, pulse widths of around 10 ns and pulse energies in the range of 0.5 to 1 J are required. High beam quality and low pointing error are required to maintain constant high intensity on the EUV source target so that the radiated EUV power and consequent exposure doses on the semiconductor wafer are uniform. Depending on the choice of target material, eventually pulse rates of at least 7500 Hz and laser powers of 10–30 kW will be required to ensure the required power collection at the intermediate focus (IF).

In 1999, NGC constructed a 1700-W diode-pumped Nd:YAG phase-conjugated master oscillator–power amplifier (MOPA) laser, designated EUV-Alpha, which was used in a lithography testbed at Sandia Labs in Livermore (see Chapter 24 for further description). Later NGC built an EUV-Beta laser (Fig. 25.1) that produced 4500 W and was operated at NGC's EUV source development facility at Cutting Edge Optonics (CEO). The Beta laser, a modular design for better maintainability, was twice as efficient and had two-thirds the footprint of the Alpha laser.

For this laser, NGC selected a MOPA architecture (Fig. 25.2) using stimulated Brillouin scattering (SBS) phase conjugation to compensate for aberrations, figure error, and thermal distortions in the Nd:YAG gain media. The output of a custom 12-W master oscillator (MO) was split in two with a polarizer and directed to two amplifier trains. Each amplifier train consisted of two diode-pumped zigzag slab amplifiers, image relay telescopes, shaping optics, and an SBS cell. After round trips through the two slab amplifiers, the two MO beams were brought to their full 750-W power in each train, and then polarization-combined for a total of 1500 W. In the Beta laser, there were three such 1500-W modules, which yielded a system total of 4500 W at 7500 Hz.



EUV Beta laser



Three 1500-W laser modules in enclosure

Figure 25.1 The 4500-W Beta laser. The left photograph shows the laser with a clean-room enclosure. The right photograph shows the three laser modules (top three shelves) and the pointing control and health monitor (bottom shelf).

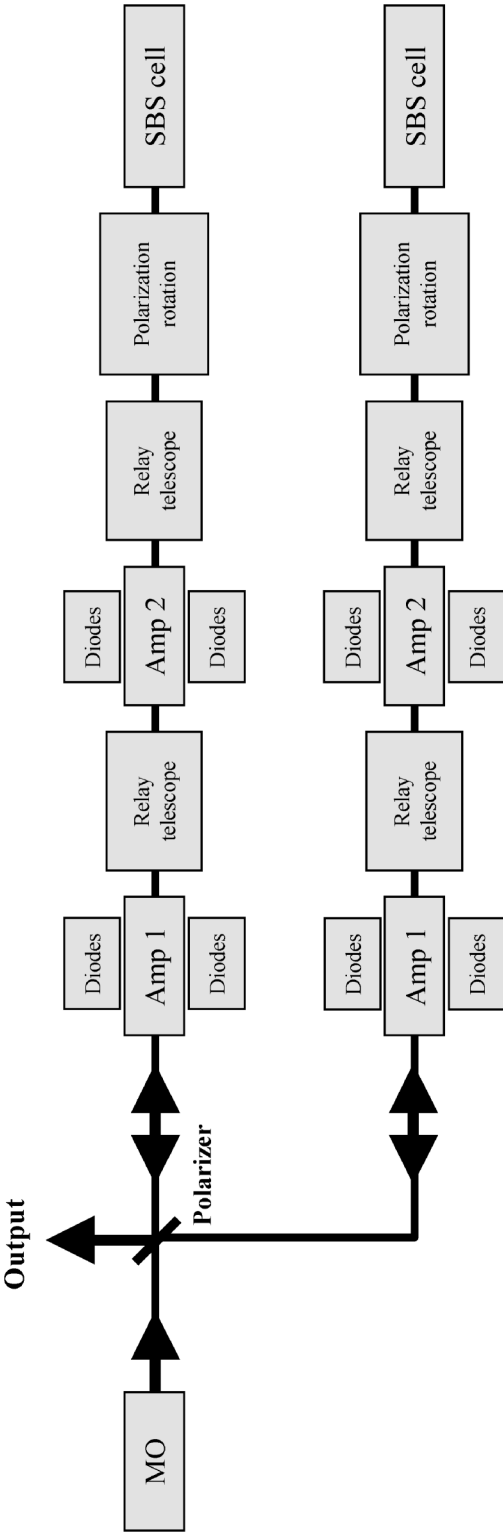


Figure 25.2 The EUV Beta laser uses MOPA architecture—a 12-W MO shared by two 750-W amplifier trains, and SBS phase-conjugated architecture for high beam quality, stable pointing, and short pulse output. Three of the modules depicted here constitute the 4500-W Beta system.

The laser was successfully installed in the EUV production facility at CEO and provided laser power for the EUV generation tests. It was integrated with a vacuum chamber that contained the xenon jet and facilitated the engagement of the laser with the jet. The laser operated at full power (Fig. 25.3) with a power stability within 0.7% (15 out of 4500 W). Because the laser consisted of three MOPA modules, three independent beams were coaligned and directed to a common focusing lens, which brought the three adjacent parallel beams to a focus at the xenon jet. Thermal management is a major issue in a multikilowatt laser; by using water-cooled laser slabs and cooled shrouds and beam blocks, long-running-time operation within the laser enclosure was achieved without thermal drift. Figure 25.4 shows the temporal profile of a laser pulse. In Fig. 25.5, the plot of extracted power as a function of pump diode current shows that the thermal uniformity was under control, since there was no power rollover at high diode current. Due to the precision of the gain modules housing the Nd:YAG slabs, the thermally induced

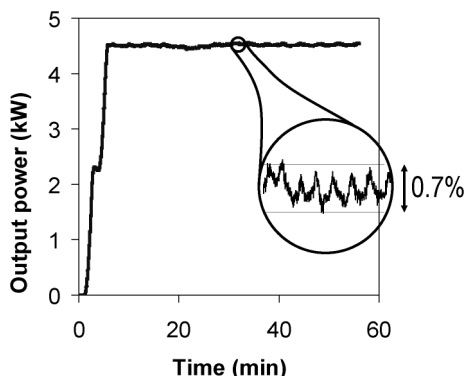


Figure 25.3 The power stability for 4500-W output power. Power was stable within 15 W out of 4500 W.

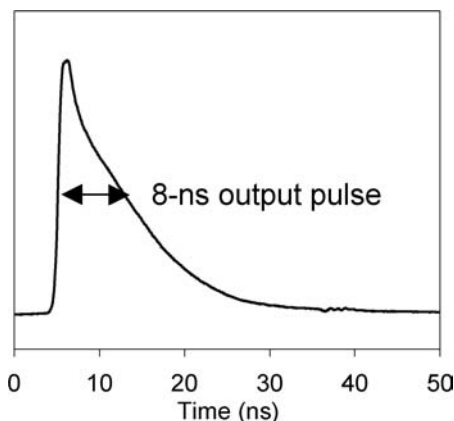


Figure 25.4 Temporal resolution of 0.6-J pulses per bench at 7500 Hz—three interleaved 2500-Hz benches were used to generate the 7500-Hz output.

aberrations were kept low, resulting in birefringence controlled to better than 2%, and a nearly diffraction-limited beam quality of approximately 1.25 times the diffraction limit (DL) (Fig. 25.6).

In addition to the laser itself, the system included all the support equipment necessary for operation. This equipment included custom diode power supplies developed by NGC specifically for driving pump diodes in high-power solid state lasers. These power supplies were computer-controlled to provide automatic protection against overcurrent, pulse spikes, and reverse voltages, as well as providing health monitoring to the system controller. The system controller provided the starting, warm-up, and operational sequences, and maintained a comprehensive array of interlocks, monitors, fault response, and communication to a higher executive controller. A significant issue with pulsed high-power lasers is optical damage, often driven by contamination; therefore, NGC controlled the purity of the assembly and operational environment with specially built class-1000 clean rooms to prolong optics life. Coolant-water heat exchangers, high-power transformers, and diode power supplies were enclosed in a standalone cabinet.

The packaging of the Beta system was part of a major effort to improve the reliability of the system in view of the highly stringent requirements of a semiconductor fabrication facility. In such facilities, downtime for scheduled and unscheduled upkeep is extremely costly, so systems must be designed for long life and rapid maintenance. To this end, the Beta system was a wholesale redesign of the Alpha system, incorporating lessons learned into both design and operations. Extensive use of castings, consolidated custom PC boards, sealed cells, and commercial components lowered the cost and simplified assembly and maintenance of the Beta system. Design selections were guided by a formal failure-mode and effect analysis (FMEA) and a materials and processes development effort to evolve the device from a flexible Alpha breadboard to a Beta product ready for customer use.

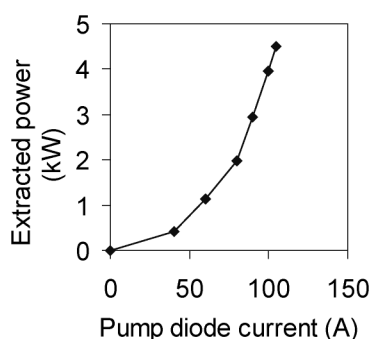


Figure 25.5 Plot of extracted power as a function of pump diode current shows that the thermal uniformity was under control with no rollover at high diode current.

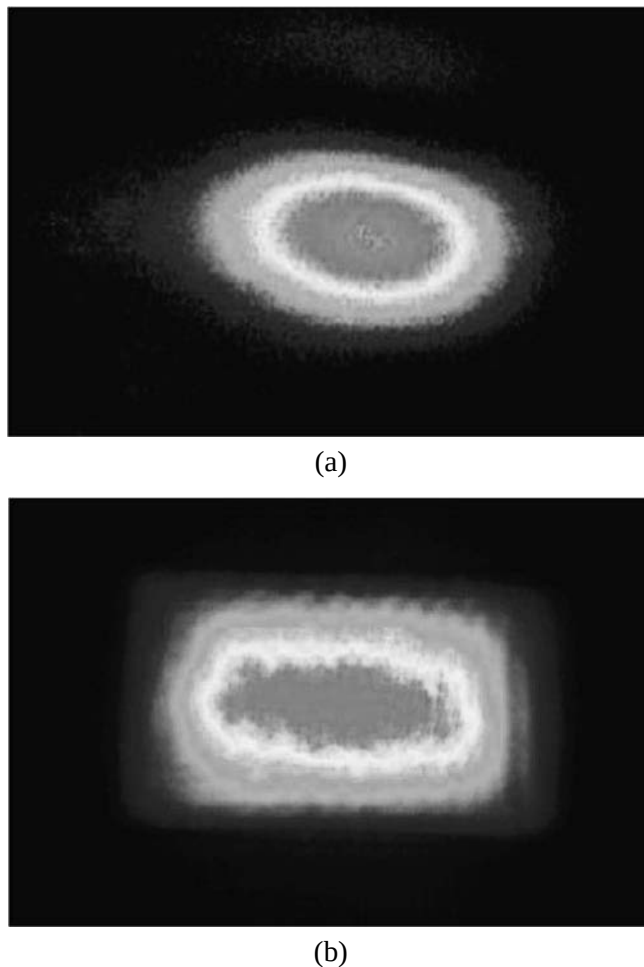


Figure 25.6 (a) Near-diffraction-limit beam quality in the far field ($1.25 \times \text{DL}$). (b) Uniformity of beam quality in the near field for three combined beams.

25.3 Xenon Target Development

In the development of the xenon target, five types of targets were investigated: cluster jets, liquid xenon spray jets, solid xenon targets, xenon droplets, and xenon filaments.

Cluster jets that produced 50-nm atomic xenon clusters from condensation cooling were simple and stable targets, but they suffered from low efficiency due to EUV absorption in gas-phase xenon and will not be described in this chapter. Liquid xenon spray jets (1- μm aerosols) were also simple and stable, and had somewhat better conversion efficiency (CE) but were also limited by high EUV loss from gaseous xenon absorption. Xenon droplets (50- μm drops) needed synchronization to ensure stabilization. Xenon filaments (10–100 μm) were found to be the most efficient target type, capable of large standoff distances from the laser to reduce contamination.

25.3.1 Xenon aerosol spray target

In a xenon aerosol spray jet,² xenon is cooled to condense behind a simple orifice and is sprayed through a short collimator tube into the laser focus region, as shown in Fig. 25.7. The collimator body acts as a shield to protect the orifice from heat and particle flux from the plasma. The laser-to-EUV CE was measured at 0.36 mJ/J eV sr (corresponding to 0.52% into 2.3-eV bandwidth and 2π sr) when laser pulses of 0.3-J energy were focused on the spray at a pulse rate of 2500 Hz and at a distance of 2 mm from the heat-shield tip. This type of spray nozzle was engineered for use in the ETS LPP source, as shown in the photograph in Fig. 25.8, and has been used to generate several watts of inband EUV power in that system with the 1700-W Alpha laser.

The xenon aerosol spray jet was operated over a broad range of temperature (from -50 to -75°C) and pressure [from 200 to 600 psi (gauge)], measured just

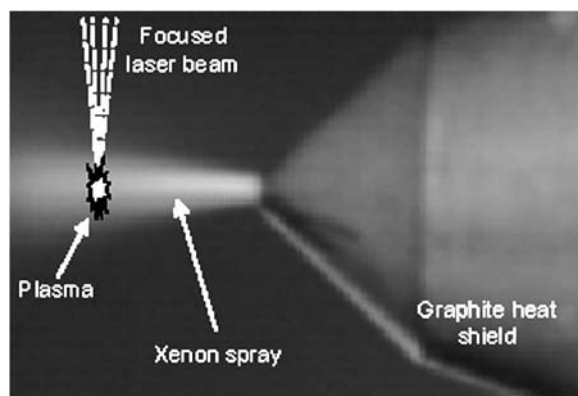


Figure 25.7 Xenon aerosol spray jet with plasma.

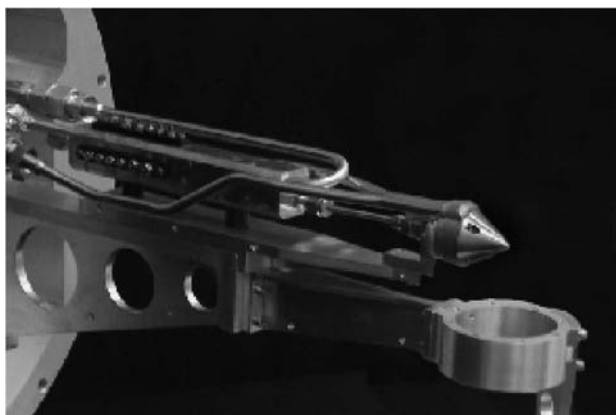


Figure 25.8 Xenon spray jet with tungsten heat shield in the ETS source assembly. (Photo courtesy of VNL.)

upstream of the orifice. The spray presented a large target area for the laser, typically ≈ 0.7 mm in diameter at the laser focus position. It was observed that the EUV output decreased as the distance from the heat shield to the laser focus was increased. This was most likely due to a reduced density of xenon aerosols in the plasma volume and to greater EUV absorption by xenon aerosols and vapor around the plasma region. Thus, for efficient EUV generation, the aerosol spray target required the plasma to be generated close to the heat shield, resulting in heating and plasma sputtering of the heat-shield material, which would limit the laser's power-handling capability. Two heat-shield materials were evaluated under conditions where a laser power of several hundred watts was focused into the plasma and the plasma was 2 mm from the collimator exit of the heat shield. One heat shield was fabricated from Poco graphite, because graphite is known to have a high energy threshold for sputtering from incident ions and atoms. This heat shield degraded rapidly in a test with an average laser power of 300 W, as shown in Fig. 25.9, but whether this was due to plasma sputtering or to abrasion by the spray of xenon particles was not established. Tungsten was used to fabricate a second heat shield, since this material has a high melting point and is resistant to erosion by larger particles (e.g., xenon clusters). This shield proved to be more rugged, and appeared in good condition after tests at 750 and 275 W.

A contamination test was carried out on the tungsten heat shield; several witness samples were exposed at a distance of 120 mm from the plasma (approximately the distance to the primary collector mirrors in the ETS), over a period of 10 million pulses at 275 W laser power. The witness sample consisted of a 100-Å silicon layer deposited on a chromium base. Auger depth profiling of these samples, shown in Fig. 25.10, and comparison with similar reference samples allowed effects of deposition, oxidation, and/or erosion to be observed.

Comparing the reference profile with the witness profile in Fig. 25.10, it is clear that significant quantities of tungsten and aluminum were deposited on the sample exposed to the plasma. The tungsten originated from the heat shield, and

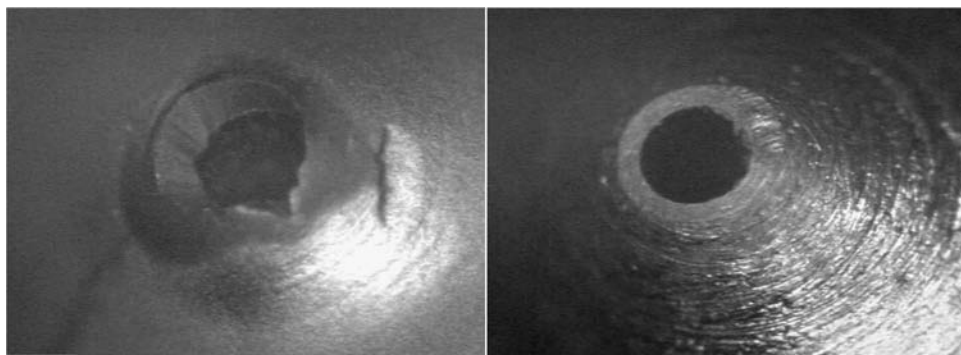


Figure 25.9 Micrographs of the aerosol spray heat-shield exit after exposure to a xenon LPP. The left picture shows a graphite heat shield after 2 million pulses at a laser pulse energy of 0.6 J at 500 Hz. The right picture shows a tungsten heat shield after 36 million pulses at 0.3 J and 2500 Hz, followed by 10 million at 0.55 J and 500 Hz.

corresponds to about 20-Å thickness at solid density. This thickness would result in a reflectivity reduction of 14% at a collector mirror located at 120 mm from the plasma. The aluminum was sputtered from foil located behind the heat shield at about 30 mm from the plasma. Scanning-electron-microscope analysis of this foil

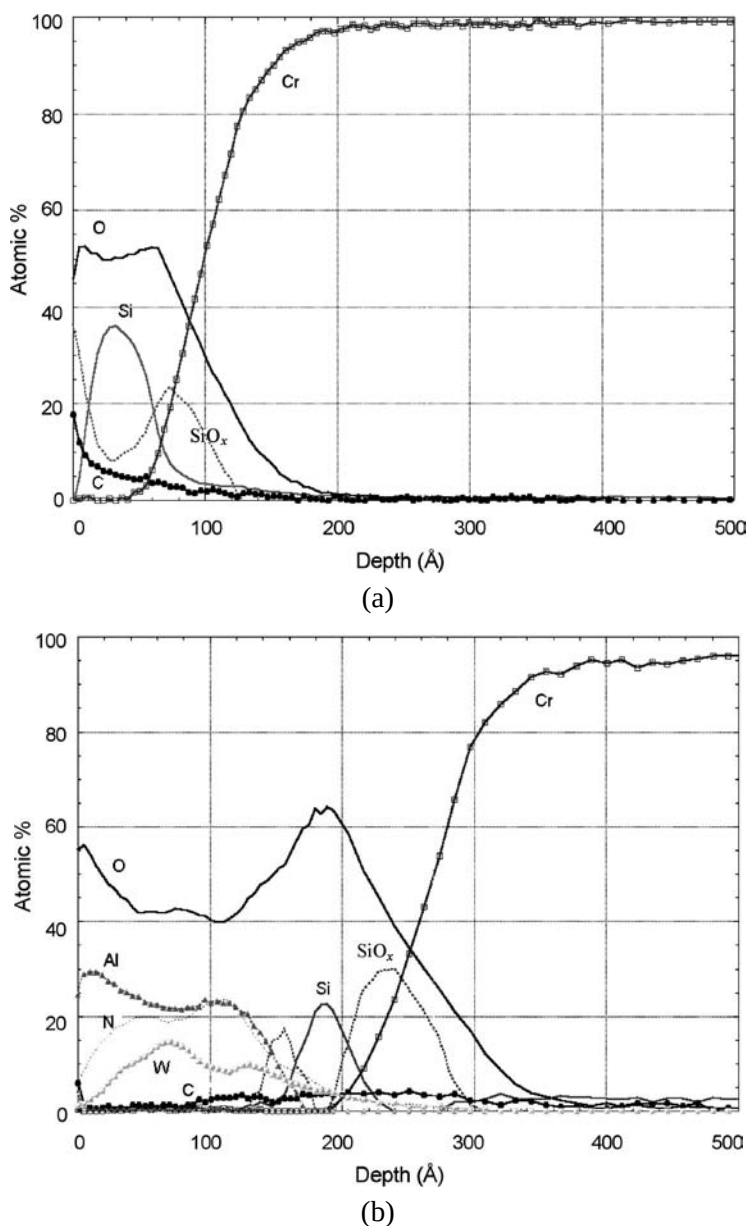


Figure 25.10 Auger depth profiles of Si-on-Cr witness samples. The profile (a) is a reference sample, which was not exposed to the plasma. The profile (b) shows the change in the surface constituents after exposure to 10 million plasma pulses. (Auger analysis courtesy of M. Clift and S. Haney at VNL.)

showed a columnar surface structure typical of plasma etching. The sputtered aluminum corresponds to a thickness of 40 Å at solid density (20% reflectivity loss), but this contamination source could be easily eliminated by minimizing exposed surfaces and by using more sputter-resistant material.

Reduction of the contamination rate due to tungsten deposition would appear to require more than the 2-mm separation of the plasma from the heat shield used in this work, but the consequent reduction in xenon density and EUV efficiency would limit the usefulness of this aerosol spray approach. While the Poco-graphite heat shield showed signs of degradation after only 2 million pulses, it is possible that harder forms of carbon (pyrolytic or diamond) might provide better sputter resistance, allowing the aerosol spray target to achieve reduced contamination rates and longer collector lifetime.

25.3.2 Planar solid xenon target

To investigate the upper limit of EUV CE that can be achieved using a xenon target, experiments were carried out where xenon gas was frozen onto a solid copper substrate at a temperature of ≈ 15 K. Solid xenon target films ~ 1 mm thick were grown slowly to achieve uniformity, which limited experiments to single-pulse laser operation. The Nd:YAG laser pulse energy was 0.7 J in a pulse duration of ≈ 12 ns FWHM, focused by a 500-mm-focal-length lens to a minimum spot diameter of 40 μm . Figure 25.11 shows the EUV CE for solid xenon measured into a 2.3-eV

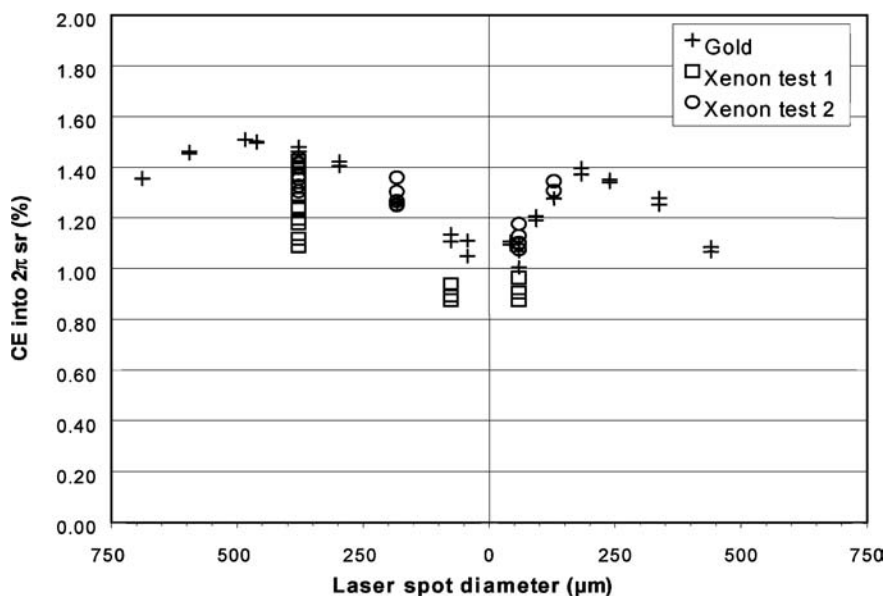


Figure 25.11 CEs measured for solid, planar gold and xenon targets as a function of spot diameter as the focusing lens is translated through focus. Points on the left correspond to the beam diameter at the target before focus is reached, and points on the right are beyond focus.

energy band and integrated over 2π -sr solid angle, as the laser spot diameter is varied by defocusing the lens. The CE for a thick gold foil is also shown over the same range of focal conditions. Points on the left-hand branch correspond to a converging laser beam striking the target before focus is reached, and points on the right correspond to an expanding beam hitting the target beyond the focus.

The xenon data in Fig. 25.11 show measurements made in two test runs. Differences between these runs, and the spread in data points for a given laser spot diameter, are most likely due to differences in the morphology of the xenon films. Comparison of the gold and xenon data shows a similar trend, with a minimum in the CE at the smallest spot diameter and asymmetric CE peaks on either side. For the laser pulse energy and pulse width used in this experiment, the largest CE measured for xenon was 1.4% at a spot size of 400 μm , with the target located in front of the laser focus. The CE for planar gold targets was previously reported by Spitzer et al.³ under similar laser operating conditions and with results that are consistent with the data of Fig. 25.5. These authors noted that CE for gold targets optimizes at lower laser intensity for larger spot diameters, over the range 15–600 μm , and that the peak CE is greater for larger spots. Thus, it appears that the 1.4% CE measured for xenon can be attributed to at least three factors:

1. The planar target allows the spot diameter to be optimized so that hydrodynamic cooling of the plasma is reduced and a larger fraction of the input laser energy goes into EUV output.
2. There is minimal EUV absorption by xenon vapor at the low vapor pressure associated with the solid target.
3. The target is at solid density for the duration of the laser pulse, allowing optimum laser absorption.

The drawbacks in pursuing a solid xenon target system are likely to be in growing the xenon film quickly enough to supply fresh target material at high laser pulse rates, and minimizing EUV optics damage due to particles of xenon “ice.” An approach has been described by Mochizuki⁴ where solid xenon was grown on a rotating cylinder, and demonstrated to operate with a laser pulse rate of 320 Hz.

25.3.3 Xenon filament target

Liquid xenon filaments have been proposed^{5,6} to meet the requirements of high xenon density to achieve good EUV CE and increased plasma-nozzle separation to reduce contamination due to sputtering of nozzle material. The filament is formed by pressurizing xenon behind an orifice at a temperature of about -100°C and ejecting a continuous jet of the liquid into vacuum. In order to limit the mass flow of xenon to a range that can be handled by vacuum pumps maintaining a background vacuum of ~ 1 mTorr, the orifice diameter must be less than ~ 100 μm . This places strict constraints on the beam quality and pointing stability of the laser, and on the positional stability of the filament. In addition, to support high laser pulse rates, the filament must rapidly recover between pulses.

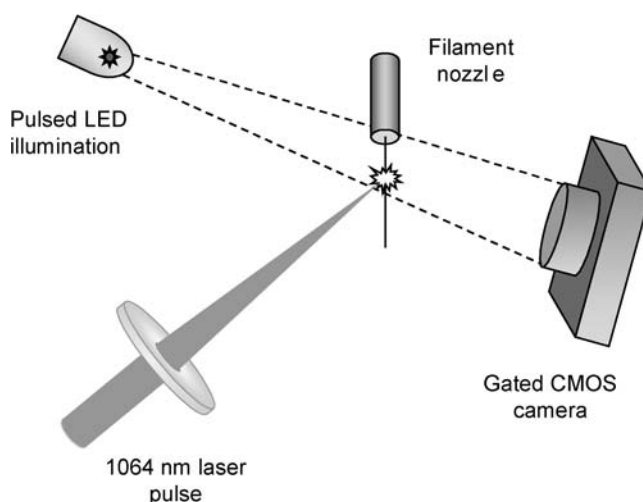


Figure 25.12 Schematic diagram of the imaging system used to study filament recovery and positional stability.

Measurements have been made of filament recovery and positional stability using the experimental arrangement shown in Fig. 25.12. A filament formed by a 60- μm orifice is imaged onto a gated CMOS array. The filament is backlit by a pulsed LED, which is triggered to fire at a controlled delay time after each laser pulse, and this time delay can be varied to capture filament images following the LPP pulse. The Nd:YAG laser is operated at a low pulse rate of 0.5 Hz, and a pulse energy of 0.7 J is focused to a spot diameter of 40 μm at the filament. Under these conditions, a laser-to-EUV output CE of 0.28 mJ/J eV sr (0.4% into 2.3-eV bandwidth, 2π sr) was measured.

Figure 25.13 shows a set of images of liquid xenon filaments over a period of ~ 100 μs . The first image shows the filament before the arrival of the laser pulse, with a HeNe alignment laser marking a position 8 mm downstream from the orifice. Subsequent images show that a piece of the filament about 1.3 mm in length is removed by the laser pulse, and is replaced as fresh filament advances. The filament is fully replaced in the laser illumination region after about 100 μs , consistent with operation at laser repetition rates up to 10 kHz. In addition to supporting high pulse rates, the filament allows the condensed xenon target region to be projected several centimeters from the delivery nozzle; by minimizing the area of the nozzle exposed to the plasma, a very low rate of sputtering of nozzle material is expected. A xenon filament was used in system demonstrations described below to achieve the highest production of EUV reported.

25.3.4 Xenon droplet target

Droplets of water and ethanol have been studied by several groups as targets for EUV LPP sources.^{7–9} Typically, droplets are formed by the spontaneous (Rayleigh) breakup of a continuous liquid stream, where the droplet diameter is ≈ 1.9 times

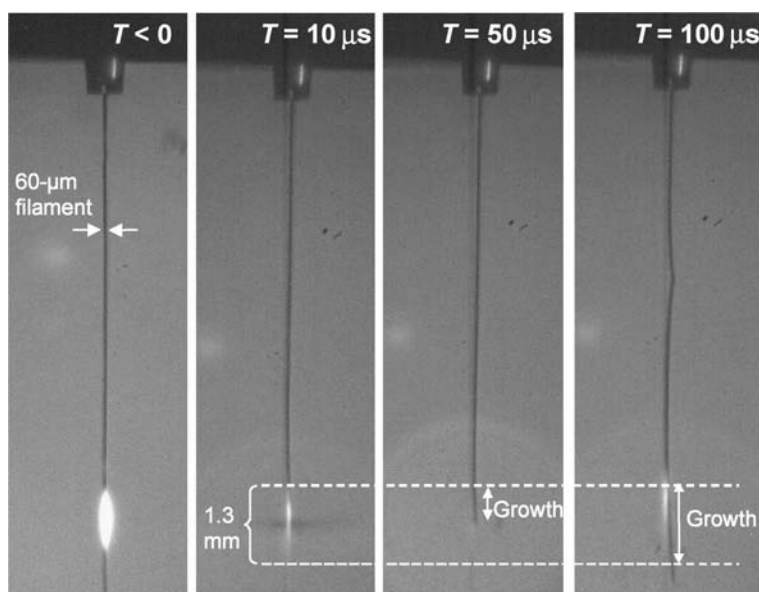


Figure 25.13 A series of images showing the recovery of a xenon filament following a laser pulse. Here $T < 0$ corresponds to the filament before the LPP is formed. The $T = 10\text{-}\mu\text{s}$ image shows a 1.3-mm section of filament removed by the laser during plasma generation. Subsequent images show the growth of the filament as it propagates from the orifice, with full recovery after $100\text{ }\mu\text{s}$.

the stream diameter, and the droplet spacing is ≈ 4.5 times the stream diameter. Thus, droplet targets have the potential advantages of delivering larger-diameter targets and smaller mass flow than the filament jet. In addition, the formation of frozen xenon droplets allows the possibility of achieving the high conversion of solid xenon and the debris-free operation of an isolated target.

Xenon droplets have been generated by periodic perturbation of a xenon filament, in a manner similar to that described by Tanimoto¹⁰ for cryogenic targets. The filament diameter was $80\text{ }\mu\text{m}$, resulting in a droplet diameter of $150\text{ }\mu\text{m}$ and a spacing of $\approx 400\text{ }\mu\text{m}$. Two experiments were carried out to measure laser-to-EUV conversion. In one experiment a 20-Hz Nd:YAG laser was used with a pulse energy of 0.69 J . The highest conversion measured with this system was 0.56 mJ/J eV sr (0.81% into 2.3-eV bandwidth and $2\pi\text{ sr}$). In the second experiment, two EUV detectors were mounted in the plane, including the laser axis, and perpendicular to the droplet stream direction—one at 12 deg from the laser axis, and the other at 45 deg . This arrangement allowed an estimate of the EUV radiation angular distribution to be made, assuming a $\cos^n \theta$ function. The laser pulse energy was 0.64 J at a pulse rate of 500 Hz . The EUV conversion, based on the 12-deg detector measurement, was 0.36 mJ/J eV sr (0.51% into 2.3 eV and $2\pi\text{ sr}$). Comparison of the signals from the 12- and 45-deg detectors indicated that the exponent in the $\cos^n \theta$ distribution was $n = 0.1$, corresponding to a nearly isotropic distribution. These CEs were lower than the 1.0% to 1.2% expected from the solid-planar-xenon data

(Fig. 25.11) at a laser spot diameter of 150 μm , but further optimization of laser intensity and spot size may lead to improved performance.

25.3.5 Summary of xenon target development

To meet EUVL manufacturing requirements, it will be necessary to develop an LPP source that demonstrates high CE, noncontaminating operation, and good pulse-to-pulse stability. Xenon-target LPPs are leading candidates to achieve these goals, and several xenon target concepts were studied to determine the best approach to meet EUV light-source requirements. This study has been preliminary in nature, and at this time there is no xenon target concept that meets all the requirements. The xenon aerosol spray jet provides relatively good pulse-to-pulse stability, but the CE is low and the proximity of the heat shield leads to considerable erosion and contamination. An LPP using a solid xenon target can realize high CE, but solid-xenon replenishment will be an issue for high-pulse-rate systems and this source may be too unwieldy to integrate into an EUV illuminator optical system. The filament source has the potential for clean operation. Further work is needed to improve its CE, demonstrate high-pulse-rate and high-power operation, and establish that the filament positional stability is adequate to meet EUV pulse-to-pulse dose stability requirements. The xenon droplet target also has great potential to meet the CE and clean-operation requirements, but stability will be a major challenge for this source. At this time, the aerosol spray jet and the filament LPP sources appear to be the most promising candidates to meet near-term needs, where EUV power and source-induced contamination are less demanding than will be required for high-volume manufacturing (HVM). For the longer term, filament and droplet sources seem to have the greatest potential for clean, high-power operation, but ongoing development is essential.

25.4 System Development and Performance

After the initial development of xenon targets, efforts were focused on the demonstration of a working prototype with a xenon filament source at the CEO facility. Table 25.1 shows the results on its performance over nine months.

Figure 25.14 shows the final system that was integrated with the 4500-W Beta laser. Figure 25.15 shows the EUV output as a function of laser input power. By estimating 55% optical collection efficiency and a 5-sr collector, the power at the IF was estimated to be 17 W for 4500 W of laser input. This power estimate remains the highest output power reported to date.

Table 25.1 shows the improvement in the peak efficiency, net efficiency, and isotropy, in parallel with the increase in the input laser power.

Figure 25.16 shows that the CE was observed to be constant at increasing input laser power. The increase of CE as a function of input pulse energy was noted, at lower pulse energy (Fig. 25.16). The CE became constant at 0.9% at the pulse energy of 500 mJ. Figure 25.17 shows the nearly constant EUV CE, indicating

Table 25.1 Estimated power at IF as a function of laser input power. EUV power in 2π sr was measured; power at IF was estimated.

Parameter	Oct. 2002	Feb. 2003	May 2003
Laser power at target (W)	2475	2475	4250
Peak efficiency, on axis (%)	0.6	1.0	1.0
Isotropy (%)	84	88	90
Net efficiency (%), 2% BW, into 2π sr	0.5	0.87	0.9
EUV power (W) into 2π sr	12	22	38
Collection angle (sr)	5.0	5.0	5.0
Optical transmission (%)	55	55	55
C1 reflectivity (%)	68	68	68
Polarization loss (%)	90	90	90
Xe transmission (%)	90	90	90
Debris filter (%)	100	100	100
EUV at output focus (W)	5.4	9.4	17

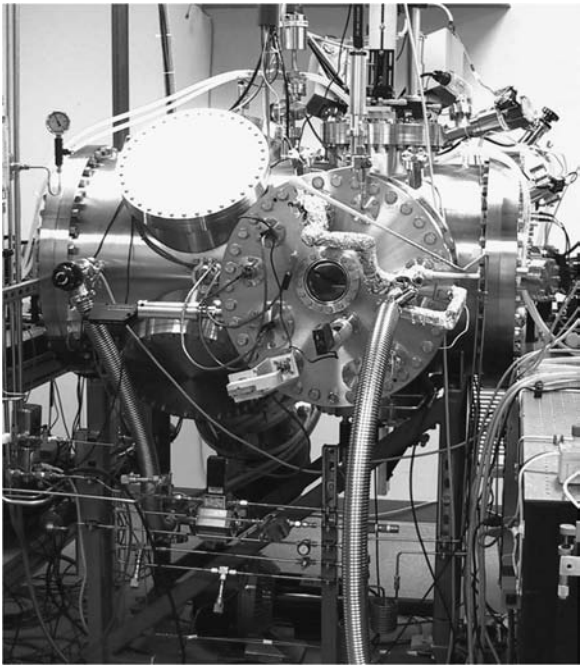


Figure 25.14 NGC's LPP system.

the dose stability for the source. Further improvement in source stability can be expected from automatic laser alignment.

Figure 25.18 shows that the EUV angular emission is nearly isotropic. It has been observed in the experiments that the emission uniformity improves with higher pulse energy.

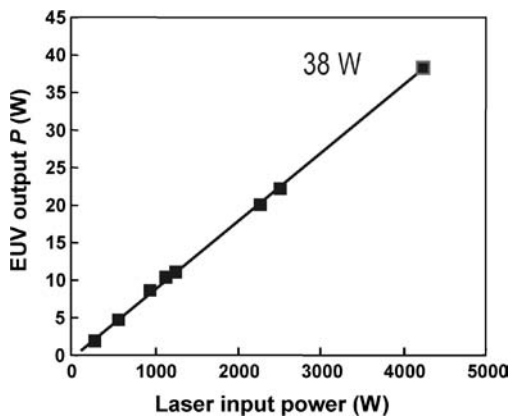


Figure 25.15 EUV output (2% bandwidth) as a function of laser input power. Here, 38 W of power was obtained from the 4500-W laser input power. No drop-off of efficiency was seen.

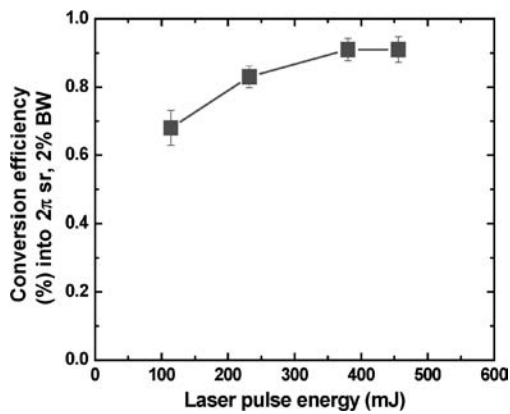


Figure 25.16 CE as a function of laser pulse energy. Trend shows the increasing efficiency with increasing pulse energy.

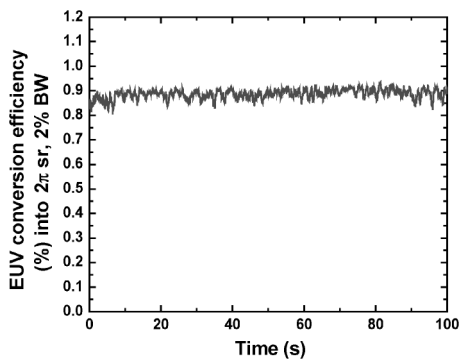


Figure 25.17 Nearly constant EUV CE shows the dose stability. Further improvement in source stability is expected from automatic laser alignment.

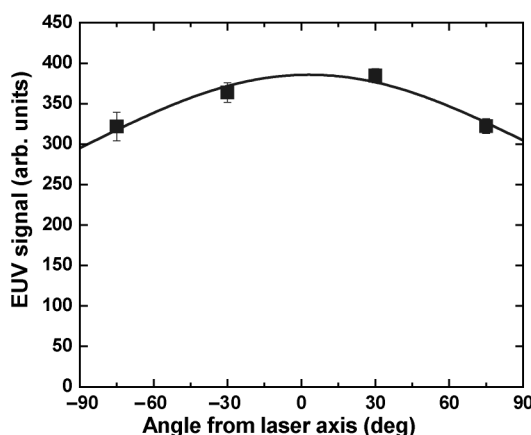


Figure 25.18 EUV angular emission is nearly isotropic and the emission uniformity improves with higher pulse energy.

25.5 Conclusions

A Xe-filament-based source with 4500-W input power, 38-W output in 2% bandwidth in 2π sr, and expected output of 17 W at the IF was demonstrated by NGC. A CE of 0.9% and isotropy of 90% were obtained.

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Vivek Bakshi. See Chapter 1.

Chapter 26

Laser Plasma EUV Sources based on Droplet Target Technology

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26.1 Introduction

The development of a source bright enough for EUVL, possessing the required long-term stability within a reasonable cost, is forcing plasma physicists to address

issues associated with dense plasmas that have up until now received scant attention. With both discharge plasmas and laser plasmas, addressing these issues has stimulated many new ideas and concepts for source design and measures associated with them. Although these new developments are currently directed toward satisfying the needs of next-generation lithography (NGL), it is likely they will also open new fields of application in the years ahead.

Early on in the development of EUVL sources, when the required source power (2π sr, 2% bandwidth) was ~ 10 W, we speculated that the so-called *debris problem* would be the most difficult to overcome.¹ It was for this reason that we proposed the notion of the mass-limited target for the laser plasma source.² In this scenario, the material supplied to the source should consist only of a mass sufficient to provide the minimum required number of atomic radiators.

26.1.1 Source requirements for EUVL

The complete set of diverse source requirements for EUVL is summarized in Chapter 2. This chapter concentrates on those requirements that present the stiffest challenges to the successful development of a source for EUVL, with particular reference to a laser-plasma source. Though the key requirements of inband power, stability, lifetime, and cost pertain both to discharge sources and to laser-plasma sources, their relative importance as threats to the collection optics differs. For instance, thermal loading on the electrodes will limit the maximum inband power available from a discharge source. Thus, any improvement in inband conversion efficiency (CE) will increase the maximum available power. Yet this thermal loading limit creates a practical maximum power above which discharge sources will not operate. The laser plasma, on the other hand, suffers no imposed limit on the available power. This can be increased simply by increasing the total laser power. In that case, however, low values of the inband CE will drive laser costs through the economically imposed ceilings on total scanner costs.

As the anticipated insertion date of EUVL into fabrication has receded, and both the assessment of its technology and its required performance level have matured, it is not surprising that the required source parameters have increased in magnitude—and maybe, too, in level of attainment. By far the most dramatic change has occurred in the required source power, jumping tenfold in the last six years (Fig. 26.1). Hopefully we will not be challenged by still higher fluence levels, since, in large part, the fabrication industry seems to have settled on 300-mm wafer formats running at ~ 100 wafers per hour. Other requirements have different degrees of difficulty for discharge and for laser plasmas. The maximum source size of 1 mm is easily met with laser plasmas, but not with discharge plasmas—likewise for the repetition rate, which affects the EUV dose stability. Out-of-band (OOB) radiation poses a threat for both sources.

By far the most difficult challenge after source power is the need to limit the effects of plasma and particulate debris on the collection optics. These must last for 30,000 h. Meeting this latter requirement can be approached in several ways. Particles and ions emanating from the source can be stopped by a number of means

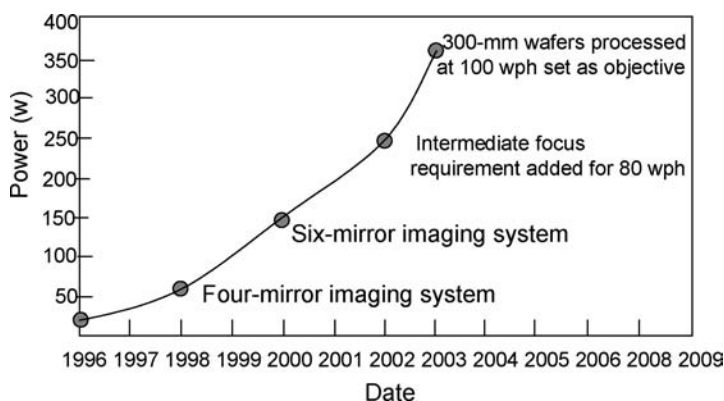


Figure 26.1 Progressive increase in source power [defined as inband (2%) EUV power emitted into 2π sr at the source with the assumption of one-third of the power collected at the IF] required since the inception of EUVL.

before they damage the optics. Gas curtains,³ mechanical shutters,⁴ electric and magnetic fields,⁵ and other devices can be the basis of a number of inhibition techniques. Moreover, the relative particle and ion fluxes depend greatly on the source materials and characteristics. Discharge sources tend to have higher particle fluxes, while the larger-solid-angle collection optics possible with laser plasmas place more stringent requirements on protection against ion erosion.

26.1.2 Inherent characteristics of laser plasmas

Laser-plasma EUV sources, like those produced with gas discharges, need to meet very high performance levels for EUVL to become a viable technology for the fabrication of computer chips at the 45-nm node and beyond. Apart from the requirement for inband power levels—at the intermediate focus (IF), >100 W of 13.5-nm light within a 2% spectral bandwidth, and collection-mirror lifetimes in excess of 30,000 h—issues of source size, stability, architecture, and finally costs are also important.⁶ Laser plasmas in principle have many attractive features for this application. The laser energy is delivered to the source by optical coupling, and therefore the laser and its associated infrastructure can be located away from the scanner itself—unlike a discharge source, which requires much of its cooling and power systems to be integral. Depending on geometry and laser architecture, laser plasmas can more easily extend to higher frequencies and therefore greater dose stability; source repetition rates of several tens of kilohertz do not stretch present technical limits. Moreover, the margins on source size are wider with laser plasmas. With expectations that all scanners will require an etendue of 1–3.3 mm²sr, which implies sources sizes of <1 mm, the likelihood increases that discharge source sizes will step out of this range as power levels rise. Since laser-plasma source sizes are much less than this, and higher powers can be achieved through increased repetition rates, this aspect is less threatening. Thus, despite the current imbalance

in performance between discharge sources, which have now demonstrated sustainable powers of ~ 10 W at the IF,⁷ and laser plasma sources, which have barely demonstrated one-tenth of this, we believe laser-plasma sources still offer an attractive long-term pathway toward a viable EUV source. In addition to the above considerations, there are arguably less-severe roadblocks to high powers with the laser-plasma approach, particularly bearing in mind the heat dissipation problems that discharge sources must contend with at source powers approaching those required at the IF. The most serious impediment the laser-plasma approach suffers from is cost, and more directly the CE of laser light to useful inband emission. Assuming a conservative a loss factor of 50% in transmitted light between the source and the IF [as would be expected with a double-mirror ($R = 70\%$) collection system] and hemispherical light collection, with a CE $\approx 0.7\%$ (2% bandwidth into 2π sr) for current Xe sources, implies a required laser power of ≈ 30 kW. Not only is this somewhat beyond current capabilities, but more importantly, its cost would probably be prohibitive. This estimate, moreover, does not take into account any costs in light transmission associated with debris mitigation.

26.1.3 Motivation for droplet sources

From the outset of our involvement in laser plasma sources for lithography, we have expressed concern for the effects of material debris from the target on the collection optics. Early investigations of tin as a source material, by others and ourselves,^{8,9} showed its potential as an efficient emitter at 13 nm, but simple witness-plate tests identified high-velocity, micron-size aerosols flying from the target,¹⁰ which convinced us and others of the danger of using solid metallic targets. Our approach has since been to configure the laser plasma from a mass-limited target, that is, one whose mass yields just the total number of required atomic radiators. With this target concept, for example, a 100-mJ laser pulse (energy $\approx 6 \times 10^{18}$ eV) will produce an ≈ 30 -eV plasma of $\sim 10^{15}$ atoms, taking into account the energy needed for ionization and excitation. Depending on the material, such a target will have a diameter of ~ 10 μm . Assuming that this target is uniformly energized, there should be no particulate debris at all. The sole problem will now be to protect the collection mirrors from the ions coming from the plasma. Ions can be controlled with electric and magnetic fields, and are slowed by recombination, in contrast with particulate neutral matter.

With this philosophy, we began investigating a water droplet target, which fortunately emits a strong narrow line at 13 nm (the 4d-2p transition in Li-like oxygen).^{2,11} Another approach, which quickly gained favor, was to use jets of liquid Xe atomic clusters produced by pulsed supersonic ejection through a microscopic nozzle.^{12,13} Xenon was recognized as a broadband emitter of EUV radiation from previous general studies of soft-x-ray emission from laser plasmas.¹⁴ It was felt that Xe, being a gas, would pose less serious threats to collection mirrors. Subsequently liquid jet¹⁵ and liquid Xe droplet¹⁶ targets have been developed.

More recently, we have introduced the tin-doped liquid droplet target, which combines the advantages of tin over xenon (see below) with the mass-limited target concept.¹⁷

In this chapter we describe the experimental and theoretical foundations for mass-limited droplet targets for EUV sources. We place special emphasis on our latest progress with the tin-doped droplet target, since this is showing some promise for satisfying the needs of EUVL. We describe the basic physics of the interaction leading to plasma generation, and the associated radiation physics. We place strong emphasis on using plasma fluid and radiation transfer codes to model the ion emission. Included are brief descriptions of our characterization of the evolution of the plasma, and comparisons made with hydrodynamic plasma code predictions of the plasma density and temperature. Calibrated spectroscopy and metrology of the 13.5-nm emission help to identify the optimum laser and irradiation conditions, and these are equated with the predicted plasma conditions. Details of the laser and target technologies used in precisely synchronizing the streaming microscopic droplet targets with the focused laser beam are summarized, and at-wavelength imaging of the target confirms a small, submillimeter source size. Extensive measurements of the energy of the ions emanating from the plasma, particularly those that can cause erosion of the collection optics, are summarized, as well as characteristics of the particulate emission. Measures to stop or inhibit this particulate and ion emission are described. Lastly, we summarize our current view of the expectations of this approach with respect to a high-efficiency EUV source and describe the developments needed to demonstrate its practicality.

26.2 Laser Interaction with Mass-Limited Spherical Targets

To first order, though not correctly in principle, the interaction of a high-intensity laser beam focused with high numerical aperture (NA) optics onto a spherical target can be described as a 1D interaction, and the expansion of the plasma can also be considered to be isotropic. This simplification allows for an elegant and comprehensive description of the plasma evolution. One-dimensional plasma models can be used. Moreover, for the most efficient EUV generation, a thermalized plasma is required. Collisional absorption, or inverse bremsstrahlung absorption (IBA), is the preferred absorption mechanism. This mechanism can be very efficient in converting laser energy into thermalized plasma energy. The CE can approach 100%, given appropriate plasma density gradient and temperature conditions.

26.2.1 Inverse bremsstrahlung absorption

Inverse bremsstrahlung absorption (IBA) occurs in a laser plasma when oscillating electrons, driven by the laser electromagnetic field, collide with ions, transferring energy from the field to the ions. The fraction of the incident energy absorbed from the electromagnetic field after traversing a distance L is given by¹⁸

$$\alpha_{\text{abs}} = 1 - \exp(-k_{\text{ib}}L),$$

where

$$k_{ib} = 3.10 \times 10^{-7} Z n_e^2 \ln \Lambda \omega_L^{-2} \left(1 - \frac{\omega_p^2}{\omega_L^2} \right)^{-1/2} \left[\frac{1}{T_e (\text{eV})} \right]^{3/2} \text{ cm}^{-1}$$

is the IBA absorption coefficient—the imaginary part of the field propagation vector. Here, ω_L is the laser frequency (rad/s); ω_p is the electron plasma frequency; T_e is the electron temperature; $\ln \Lambda$ is the Coulomb logarithm, which is related to the minimum impact parameter; and Z is the average charge per ion. Thus, IBA is more effective for high electron densities, low plasma temperatures, short laser wavelengths, and a highly ionized plasma. For these conditions and a sufficiently short plasma scale length ($\approx 20\lambda_L$), most of the laser energy is deposited near critical density.

26.2.2 Optimum ion population

The laser intensity and plasma parameters can be manipulated to produce optimum ion levels of a plasma for specific emission from a given target material. The relative population for a specific ionization state can be estimated using several ionization dynamics models.¹⁹ Figure 26.2 shows the estimated ion population of a tin plasma as a function of plasma temperature.

Estimating the detailed character of the emission spectrum from these plasmas is challenging, since it involves literally thousands of transitions. Our approach is to

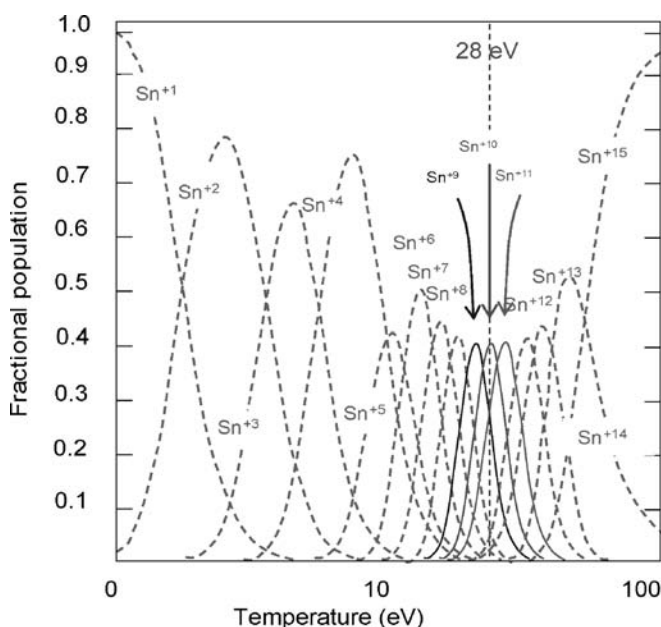


Figure 26.2 Relative ion abundance in a tin plasma as a function of plasma temperature.

couple a complex radiation transport model with a hydrodynamic plasma fluid code that models the laser coupling physics and the inertial expansion of the subsequent plasma.

There are many tin ions that emit radiation in the 13-nm region. Figure 26.3 shows Cowan-code calculations of the oscillator strengths of many of these transitions. For ions with a given temperature distribution in a laser plasma, many of these ions will be present. The total numbers of each ion in the emitting plasma will depend on the spatial distribution of the electron density and temperature and on its variation with time during the laser pulse. An indication of this can be seen from the 1D hydrodynamic plasma code predictions of the electron density and temperature shown in Fig. 26.4.

The temperature varies strongly as one goes down the density gradient. Consequently the relative ion population will also change considerably. For the spherical droplet plasmas we are studying, maximizing the 13-nm emission must be achieved through these considerations and through empirical measurements.

26.2.3 Sources of plasma emission

The spectral emission from a plasma can be categorized into continuum emission, which includes bremsstrahlung and recombination emission, and discrete line emission.²⁰ Bremsstrahlung radiation (free-free emission) is strongly dependent on the electron density and temperature. It is the dominant emission mechanism in low-atomic-number (hydrogen and helium) plasmas, and in high-atomic-number plasmas where the ions are fully stripped. The bremsstrahlung emission maximum occurs at $\lambda_{B,max} \text{ (nm)} = 620/T_e \text{ (eV)}$. For the bremsstrahlung emission maximum to occur at $\lambda = 13.0 \text{ nm}$, the plasma electron temperature should be $T_e \sim 48 \text{ eV}$.

Recombination radiation, or free-bound radiation, occurs when an initially free electron is captured by an ion. The energy of the emitted photon is $h\nu = \frac{1}{2}mv^2 + E_Z^n$, where the first term is the initial kinetic energy of the electron and the second term is the atomic binding energy of an ion of charge Z in a state having a principal quantum number n . The lowest value of the emitted photon energy is given by $h\nu = E_Z^n$ and corresponds to the recombination of a free electron having zero initial kinetic energy. The spectrum of recombination radiation will be characterized by recombination edges, which are characteristic of the binding energies associated with the different atomic states. In a high-density plasma, the edges are broadened by various mechanisms. Recombination radiation is also strongly dependent on the electron density, ionic charge, and electron temperature. The $1/n^3$ recombination-radiation dependence makes transitions to the ground state dominant for each ion. The ratio of the spectrally integrated recombination and bremsstrahlung energy densities is given by $W_r/W_B \approx 2.4Z^2E_H/(k_B T_e)$.²¹ For a lithium-like oxygen plasma ($Z = 5$), having $T_e = 30 \text{ eV}$, one finds that $W_r/W_B \approx 27$, which indicates that recombination radiation will dominate over bremsstrahlung.

Line emission comes from both resonance transitions and transitions between excited states; resonance transitions are generally the stronger of the two types.

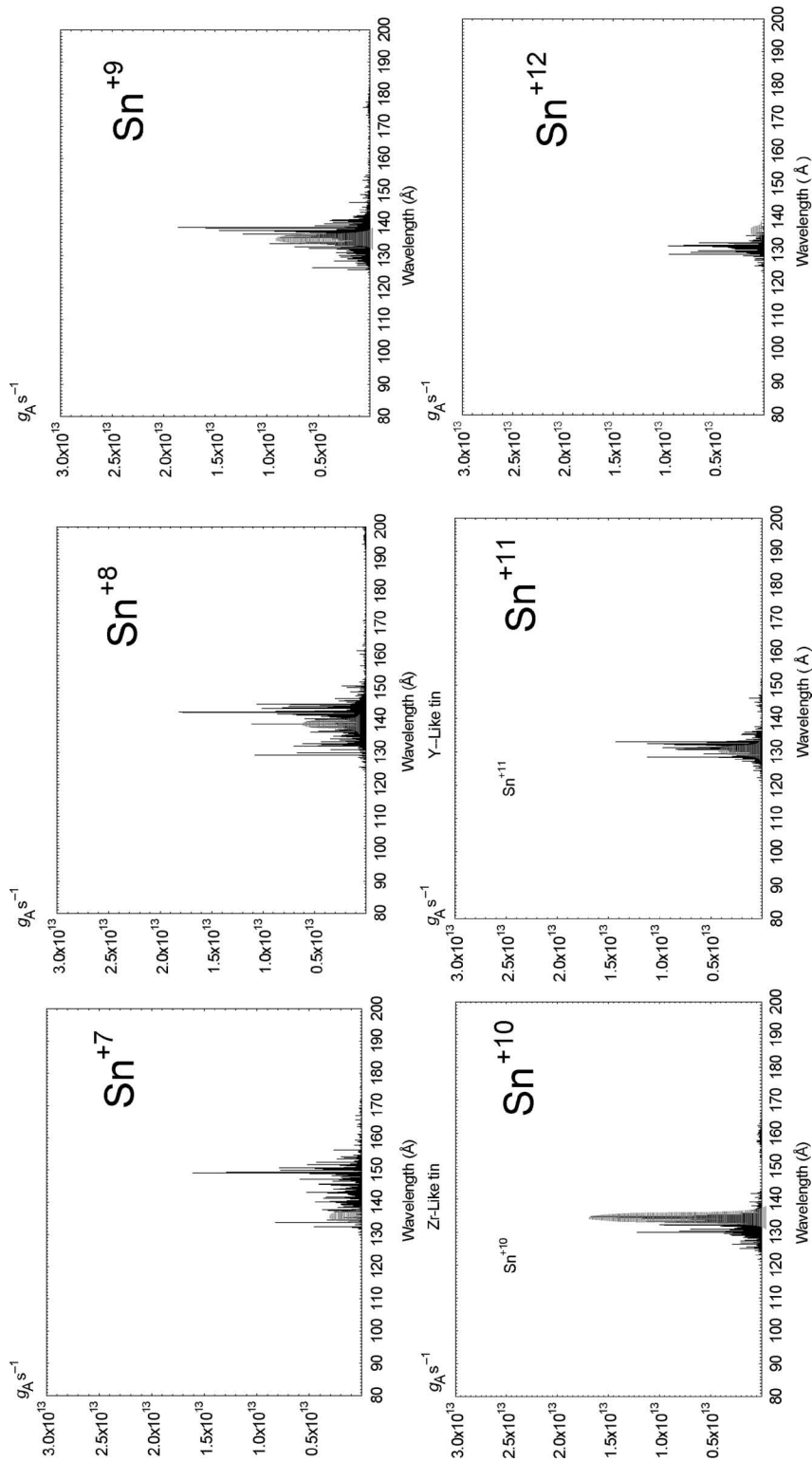


Figure 26.3 Predicted oscillator strengths of Sn ions that emit in the 13 nm.

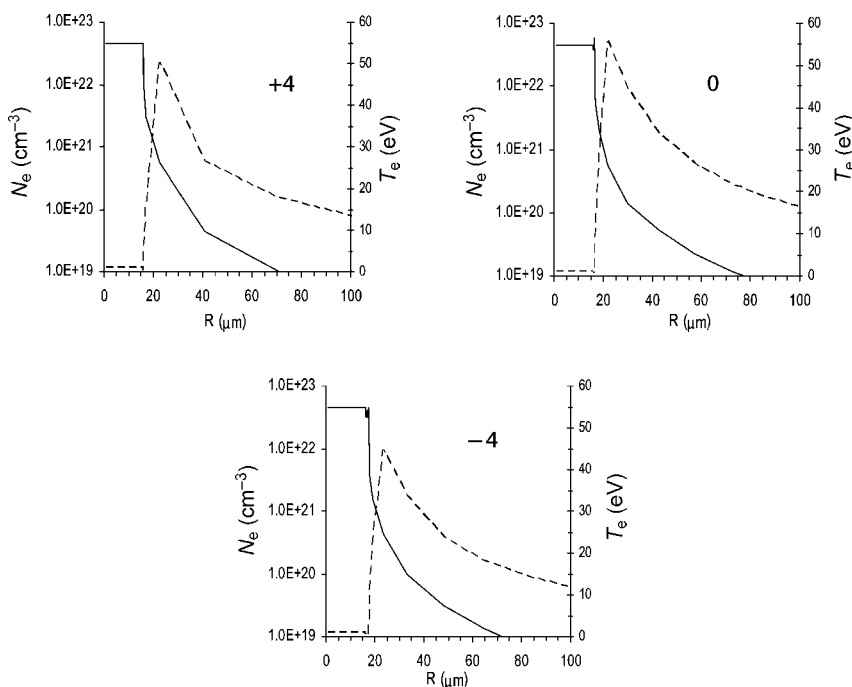


Figure 26.4 One-dimensional hydrocode predictions of electron density n_e and temperature T_e at different times (-4 , 0 , $+4$ ns) from the peak of a 10-ns laser pulse incident on a 35- μm -diameter O_2 target with $I_{\text{max}} \approx 5 \times 10^{11}$.

The emission coefficient for line emission from an upper level u to a lower level l is given by²¹

$$\varepsilon_\nu = \frac{h\nu_{u,l}}{4\pi} A_{u,l} N_u L(\nu - \nu_{u,l}),$$

where N_u is the upper level density of ions, $L(\nu - \nu_{u,l})$ is the line-shape function, $\nu_{u,l}$ is the central frequency of the transition, and $A_{u,l}$ is the spontaneous emission coefficient.

26.3 Plasma Dynamics of Droplet Laser Plasmas

Knowledge of the expansion dynamics of the plasma is particularly important for the limited-mass laser plasma source described in this chapter. In order to understand and maximize the coupling of laser light to the microscopic target, knowledge of the expansion of the plasma cloud is required. Moreover, since this plasma approximates an isotropic plasma, an accurate characterization of the electron density profile as a function of time, as shown in Sec. 26.3.1, can be compared with the predictions of hydrodynamic plasma fluid codes to understand other plasma properties.

26.3.1 Determination of electron density through interferometry

Interferometry is a powerful optical probe technique capable of providing high-resolution spatial and temporal information about an expanding plasma. We have employed the polarized-light interferometer to study the water droplet plasma expansion dynamics.^{22,23} Figure 26.5 illustrates the simplicity of this device. The lens L images the object O , the plasma, into the image plane. The Wollaston prism creates two orthogonally polarized images that overlap in the image plane and are separated by an angle ϵ . Interference between these two images is accomplished by a pair of polarizers, P_1 and P_2 , oriented either parallel or perpendicular to one another. In order to form high-contrast fringes in the image plane, P_2 is oriented so that the two originally orthogonal images will, after passing through P_2 , have the same polarization and intensity. The fringe separation in the object plane is given by $i = \lambda f / b \epsilon$, where λ is the wavelength, f is the focal length of the imaging lens, ϵ is the angle between the two deviated images, and b is the distance between the Wollaston prism and the lens focal plane.²¹ The fringe orientation can be changed by rotating the polarization elements, and the fringe spacing can be changed by altering the distance b between the focal plane of the lens and the Wollaston prism. The Wollaston prism used in our experiments is composed of quartz and has $\epsilon = 8.7$ mrad. Using a 7.5-cm-focal-length lens and $b = 37.7$ cm, the fringe spacing is calculated to be $12.1 \mu\text{m}$.

The cumulative phase difference between light rays passing through equal lengths of plasma and vacuum is given by²⁴

$$\Delta\phi = k_0 \int \left[\left(1 - \frac{n_e}{n_c} \right)^{1/2} - 1 \right] dl \approx \frac{k_0}{2n_c} \int n_e dl,$$

where the plasma index of refraction is $N = (1 - n_e/n_c)^{1/2}$, n_e is the electron density, and $n_c = m_e \epsilon_0 \omega^2 / 4\pi e^2$ is the critical density. In writing the expression on the right side, it was assumed that $n_e \ll n_c$. In the event that the plasma is spherically or cylindrically symmetric, one can extract the radial distribution of the electron distribution from the above chordal integral by applying the Abel inversion

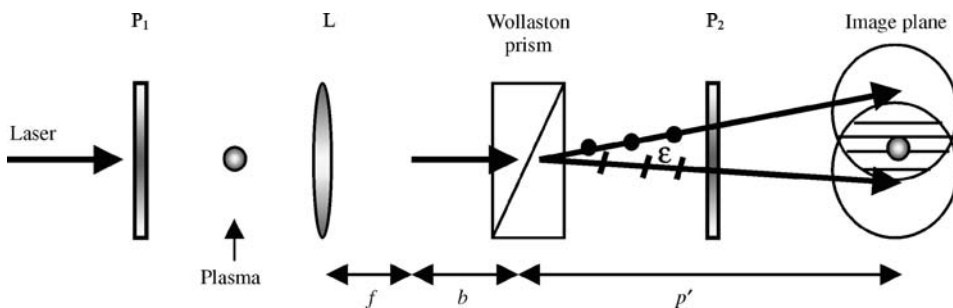


Figure 26.5 Polarized-light interferometer.

given by²¹

$$n_e(r) = \frac{n_c - 1}{k_0 \pi} \int_r^R \frac{d\Delta\phi}{dy} \frac{1}{\sqrt{y^2 - r^2}} dy.$$

Here, k_0 is the probe wave number, R is the plasma radius where $n_e = 0$, and y is the coordinate transverse to the axis of symmetry and the line of sight. The code Interferometric Data Evaluation Algorithms (IDEA) was used to calculate the plasma-induced phase shift and compute the Abel inversion.²⁵

Figure 26.6 illustrates the configuration used for the optical diagnostic experiments. The plasma is created by a 100-Hz Q -switched Nd:YAG laser providing 10-ns (FWHM), 270-mJ pulses.²⁶ A 10-cm $f/2$ lens focuses the beam to intensities of up to 4×10^{11} W/cm² on the target. Due to the rapid expansion rates of laser plasmas, a short probe pulse is necessary to avoid fringe blurring in the interferograms. The probe beam is initially formed by passing the Nd:YAG fundamental beam through a second-harmonic generator (SHG), producing a 6-ns, 532-nm beam. Following the SHG, the beam is spatially filtered to remove beam nonuniformities. The probe pulse is then shortened to a duration of about 1 ns by the application of a pulse-slicing technique.²⁷ A 5-kV, 10-ns-rise-time voltage pulse is applied to a LiNbO₃ crystal having a quadrupole electrode arrangement as the SHG pulse passes through. The high-voltage pulse produces a time-varying linear gradient in the crystal index of refraction, causing an angular deflection of the pulse. By placing the exit face of the crystal in the focal plane of a 1-m-focal-length lens, the deflected pulse is redirected parallel to the axis of the crystal. As this beam is swept across a 300- μ m pinhole, a short (1-ns) pulse is sliced out of the original 6-ns, 532-nm pulse. The plasma was imaged by an $f/3$ lens with a magnification of 17.75 and a spatial resolution of about 5 μ m.

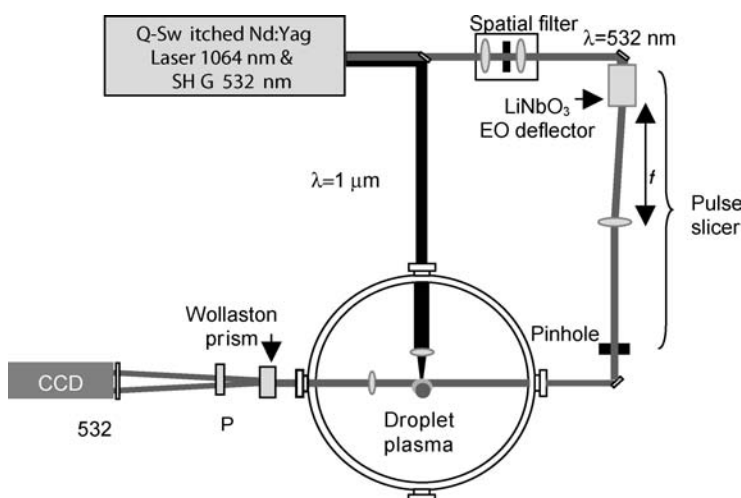


Figure 26.6 Experimental setup for interferometry of the laser plasma.

Figure 26.7 shows a typical sequence of interferograms for plasmas created from 35- μm -diameter water droplets by the laser described above.²⁸ Three interferograms are shown of the plasma at -4 , 0 , and $+4$ ns relative to the peak of the laser pulse.

Several features of these measurements are of value to the understanding of how droplet laser plasmas evolve. It can be seen that an overdense plasma, such as one having a density

$$n_e > n_c = \frac{m_e \omega_0^2}{4\pi n_e^2} = \frac{1.1 \times 10^{21}}{\lambda_0^2 (\mu\text{m}^2)} \text{ cm}^{-3},$$

expands rapidly from the surface of the spherical target to fill the focal volume of the irradiating laser. By the peak of the laser pulse, the expansion is reasonably spherical toward the laser beam. Also, since the fringes completely penetrate the target at the end of the pulse, the interferogram is no longer opaque in the center, which implies that the complete target is underdense and partially ionized. Other interesting features become visible, such as the apparent jetting on the rear of the target at later times.

Of considerable value is the measured electron density profile, which can be compared with that predicted by the 1D hydrodynamic code, as illustrated in Fig. 26.4. Using appropriate values for target and irradiation conditions, it is then

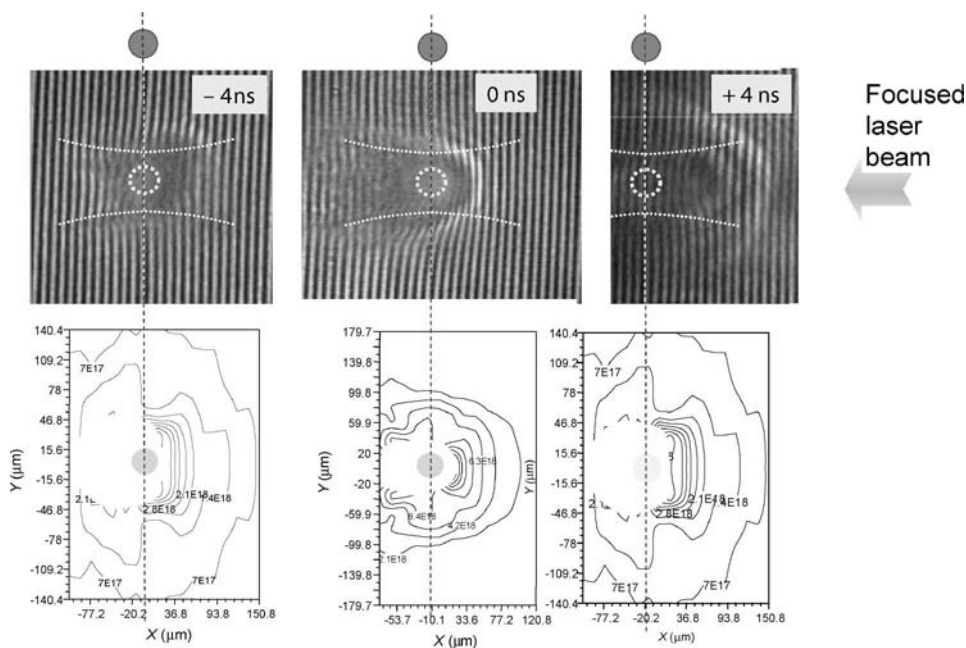


Figure 26.7 A series of interferograms of water droplet laser plasmas, and the electron density distributions deduced from them.

possible to use this comparison to estimate other parameters of the plasma, such as the electron temperature T_e .

26.3.2 Inference of plasma temperature from x-ray spectroscopy

Soft-x-ray spectroscopy is a powerful tool for the interpretation of the plasma state and the characteristics of its emission. In our studies we use two types of spectrometers: a transmission grating spectrograph (TGS),²⁹ and a so-called *flat-field* spectrograph (FFS) containing a variable-spacing (Harada) grazing-incidence grating. Both instruments were developed specifically for these EUV studies.

The TGS employs a freestanding 5000-line/mm (200-nm period) grating produced by XOPT Inc.³⁰ The grating bars are made of gold and are 0.5 μm thick. Due to the grating's submicron period, a wire mesh is used to provide mechanical support for the grating. The wire mesh is composed of coarse wires having 30- μm -wide bars with an effective period of 150 μm , and crossed fine wires having 1.7- μm -thick bars with an effective period of 4 μm . The support structure results in a 46% transmission through the grating. The diffraction efficiency of a similar XOPT 5000-line/mm freestanding grating has been measured.³¹

The FFS employs a Harada grating³² with radius of curvature $R = 5.649$ m, nominal groove spacing $d_0 = 1200$ lines/mm, and angle of incidence $\alpha = 87$ deg. The slit-grating-center distance is 237 mm, and the grating-center-image-plane distance is 235 mm.³³ The plate factor at $\lambda = 10$ nm is calculated to be 0.56 nm/mm. Using a slit width of 70 μm , the resolving power at 10 nm in first order is $R \approx 880$, corresponding to a minimum resolvable wavelength of $\Delta\lambda \sim 0.01$ nm. The diffraction efficiency of a similar grating has been measured.³⁴

The atomic physics radiation code Spectra has been used to model the EUV emission of the water droplet laser plasma.³⁵ Spectra assumes the plasma is in local thermodynamic equilibrium (LTE) and uses the atomic data in the Opacity Project database, which is available on the Internet.³⁶ The Opacity Project was implemented to calculate and compile the atomic data necessary for estimates of stellar envelope opacities for the astrophysically abundant elements (atomic numbers 1–26) from 1 to 1000 nm. The calculated line shapes are assumed to be Lorentzian, and the linewidths are based on the modified semiempirical method (MSEM).³⁷ Using the impact approximation, the width of an isolated line is given by

$$w = N_e \left[v \left(\sum_{j'} \sigma_{j'j} + \sum_{f'} \sigma_{ff'} \right) \right]_{\text{av}} + w_{\text{el}},$$

where $\sigma_{j'j}$ is the inelastic cross section for collisional transitions to state j' from levels j of the optical transition, and w_{el} is the line width of transitions induced by elastic collisions. The average is over the electron velocity v .

The Spectra code was executed at electron densities in the range of 10^{19} – 10^{22} cm^{-3} and temperatures in the range of 20–85 eV in order to achieve a good match with the oxygen FFS spectra. Figure 26.8 shows the FFS data along with

the synthetic spectrum (both normalized to the 13.0-nm line intensity) using parameter values $T_e = 45$ and 30 eV at an ion density of $t \times 10^{20} \text{ cm}^{-3}$ over the wavelength range 10–19.0 nm. The synthetic spectrum does not include the emission from continuum mechanisms, since they introduced significant structure into the spectrum that was not observed in the FFS spectrum. The best agreement for the O VI lines at 10.46, 11.02, 11.58, 12.99, 13.23, 15.01, and 18.39 nm was obtained at a temperature of 45 eV and an ion density of $5 \times 10^{20} \text{ cm}^{-3}$, which is in good agreement with the previous temperature calculation. As the temperature is lowered in the application of the Spectra code, the weaker structures—those from O V and O IV—in the FFS spectra begin to be produced by the Spectra code, and the line ratios of the main O VI lines begin to differ from those for the FFS spectra. At temperatures above 45 eV, structure that is not in the FFS spectra begins to appear and dominate the synthetic spectra. At ion densities slightly above or below $1 \times 10^{20} \text{ cm}^{-3}$ ($\Delta N_i = +1 \times 10^{20} \text{ cm}^{-3}$ or $\Delta N_i = -0.3 \times 10^{20} \text{ cm}^{-3}$), there was a notable discordance between measured and synthetic O VI linewidths, and the line-ratio comparison showed greater differences.

Figure 26.9 shows the LTE oxygen ionization distribution and average ion charge state for an ion density of 10^{20} cm^{-3} , calculated with the Spectra atomic physics code. From Fig. 26.9, the average charge state at $T_e = 45$ eV is found to be $Z_{\text{av}} \approx 5$. The electron density near the critical density is given by $N_e \approx Z_{\text{av}} N_i = 5 \times 10^{20} \text{ cm}^{-3}$.

Spectroscopy also reveals the effects of the detailed ion structure on the unresolved transition array (UTA) emission from Sn-doped targets. Figure 26.10 shows typical spectra. The broadband emission resulting from Sn^{+10} and other ions is observable, together with the sharp emission lines of O^{+5} .

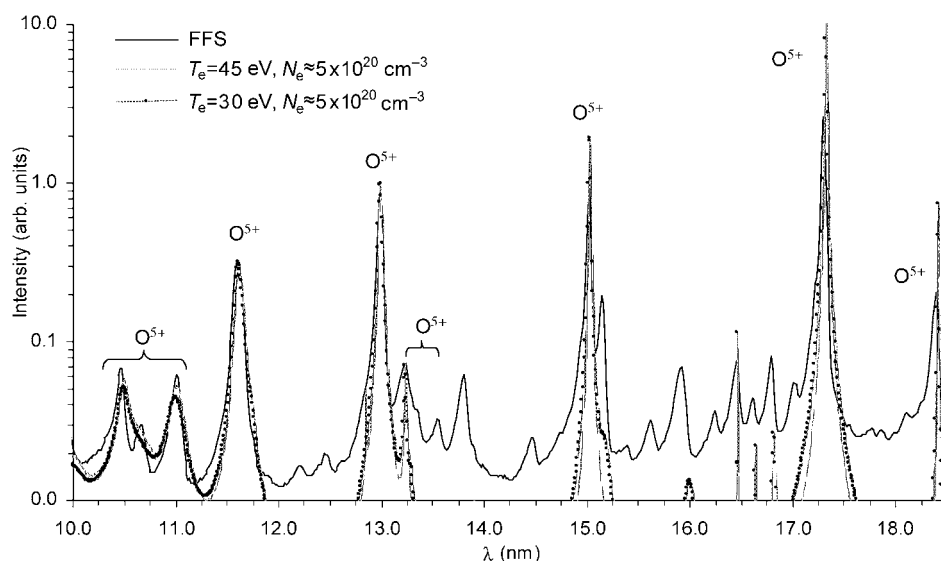


Figure 26.8 Comparison of experimental spectra from water droplet target and synthetic O spectra deduced from Spectra code.

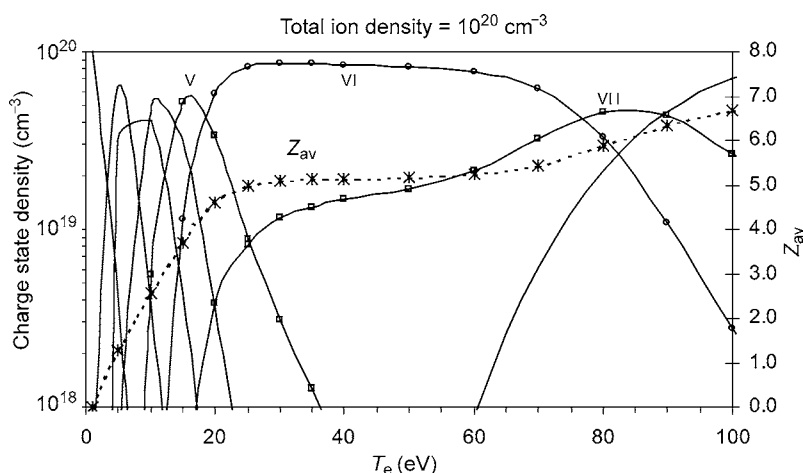


Figure 26.9 Variation of charge-state density of ions of O as a function of electron temperature.

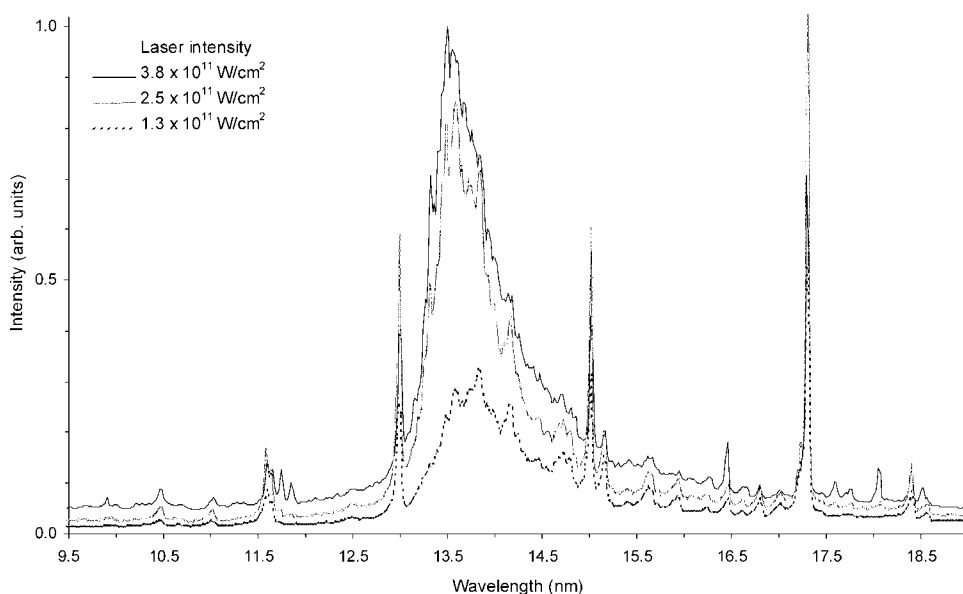


Figure 26.10 Spectra of tin-doped droplet targets.

26.4 EUV Emission from Laser Plasma Droplet Sources

We have adopted the same methods of EUV radiation metrology as the FOM Flying Circus (FC) group in estimating the effective CE of the source. Most of these recent studies have been with our tin-doped droplet target source.

The method that we used for calculating the CE is the same as the method employed by the FC2 team.³⁸ A numerical analysis program was developed for this purpose. The program takes a number of input files, uses a process of interpolation

to combine these files, and finally performs numerical integrations to calculate the source's EUV energy.

The EUV energy radiated by the source across 2π -sr solid angle and within the 2% bandwidth (centered on 13.50 nm) is given by

$$E_{\text{BW}} = \frac{2\pi A_{\text{scope}}}{\Omega R_{\text{scope}}} \left[\frac{\int_{\text{BW}} I_s(\lambda) d\lambda}{\int_{\text{all}} I_s(\lambda) T_g(\lambda) R_{\text{mir}}(\lambda) T_f(\lambda) \eta_{\text{diode}}(\lambda) d\lambda} \right],$$

where Ω is the collection solid angle of the FC mirror subtended at the source, A_{scope} is the integrated area under the EUV signal waveform displayed on an oscilloscope, R_{scope} is the impedance of oscilloscope channel, $T_g(\lambda)$ is the transmission curve of the gas in the vacuum chamber,³⁹ $R_{\text{mir}}(\lambda)$ is the calibrated mirror reflectivity curve, $T_f(\lambda)$ is the transmission curve of the filter(s) used to block visible light from entering the AXUV detector, $\eta_{\text{diode}}(\lambda)$ is the calibrated responsivity curve of the AXUV detector in the FC, and $I_s(\lambda)$ is the spectrum of the EUV source in arbitrary units.

The equation assumes isotropic emission from the source. The CE is the ratio of the EUV energy to the laser energy at the target. As a convention, the CE is quoted in the units of percent over 2π sr and 2% bandwidth (BW) at 13.5 nm.

Some of our latest data for the CE with Sn-doped targets are shown in Fig. 26.11. This data set includes results taken as part of a SEMATECH-sponsored FC calibration performed by the FOM EUV team.⁴⁰ These are the highest values of the CE for a viable high-repetition-rate mass-limited laser plasma source so far achieved. Peak values in excess of 2% are consistently obtained for the optimum laser and target conditions. Even higher CEs are obtained for solid tin targets irradiated under the same conditions and characterized by the same calibrated di-

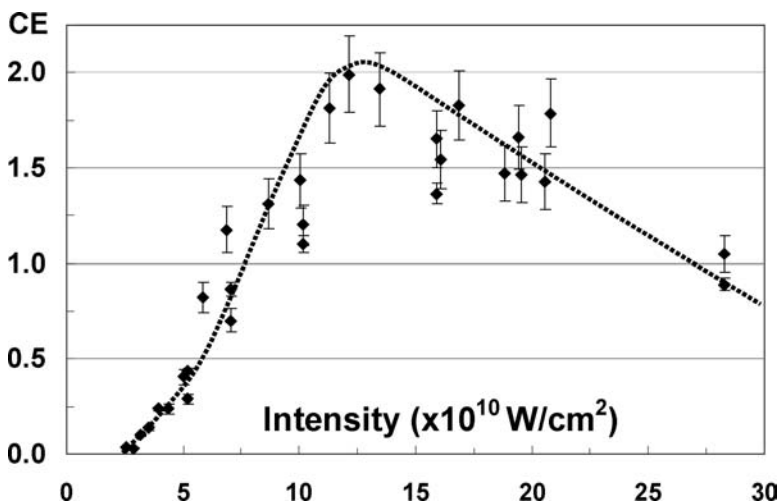


Figure 26.11 Variation of the average CE for Sn-doped targets as a function of laser light intensity at the target.

agnostics. These are shown in Fig. 26.12, which shows that CE values approaching 5% are achievable.

Measured values of the stability of the droplet source are largely dependent on the stability of the laser being used, currently $\sim 10\%$.

These recent results are very encouraging for the prospects of laser-plasma sources for EUVL. Assuming a required inband source power of ~ 200 W for a full-scale scanner, these results would imply the need for a laser power of ~ 10 kW. Q -switched, diode-pumped lasers of this power will soon be available. Moreover, we believe there is considerable merit in spatially and temporally multiplexing several Q -switched lasers to meet this power. This approach can be adopted with commercially available lasers today. Thus the viability of laser plasma sources for EUVL now shifts from the question of whether the required powers are achievable, to questions of costs, lifetime, and reliability. Further improvements in the achievable CE will increase the attractiveness of the laser-plasma approach by reducing still further the required laser power.

Greater understanding of the ion dynamics, excitation, and radiation manifolds within the plasma, we believe, can be obtained through precision spectroscopy of the 13-nm spectral emission band shown in Fig. 26.10. We have made a comprehensive study of the characteristics of this band as a function of laser and target irradiation conditions for both Sn-doped droplet targets and solid tin targets. Results from these studies will be reported in future publications.

Another important parameter associated with the EUV source is the fractional power emitted as radiation outside the 2% bandwidth specified by the EUV mirror characteristics, the so-called *out-of-band radiation*. Excessive short-wavelength (both shorter and longer than 13 nm) radiation, absorbed by the collimating mir-

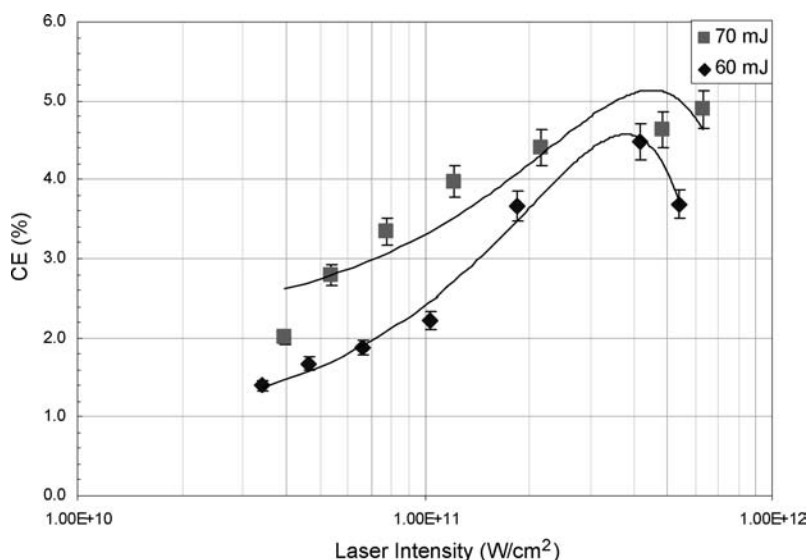


Figure 26.12 CE at 13.5 nm for solid tin targets.

rors, can lead to thermal distortions, and longer-wavelength (UV, visible, and IR) radiation is reflected through the system and can lead to background exposure of the wafer. Preliminary measurements of the OOB radiation have been made using the FC instrument outfitted with sets of different bandpass filters.⁴¹ We are now preparing to study this emission in depth using a range of calibrated spectrometers in the EUV, UV, visible, and IR regions of the spectrum.

26.5 Ion Emission from Droplet Laser Plasmas

A precise characterization of the ion emission from the plasma is imperative to meeting the requirements of laser plasma EUV sources. First, this characterization is necessary to assess the potential erosion effects of these ions, if they are allowed to expand freely, at the first collector mirrors. Second, a knowledge of the ion composition of the plasma and the relative ion velocity distributions will provide further understanding of the plasma state, the laser light coupling mechanisms, and the fractional ablation of the target material. To this end, we have established an experimental facility dedicated to quantitative ion measurements.

Two different approaches are currently being used to measure ionic emission. The first is a Faraday-cup ion probe (IP). Although the IP has limitations in estimating the spectrum of the ions emitted by the plasma, it is a very useful device for measuring the total charge, and therefore the approximate flux of ions, at points remote from the source. It can therefore be used to estimate the ion flux that would be incident on a collection mirror's substrate.

The second diagnostic is a custom-designed ion spectrometer configured as an ion energy analyzer (IEA). The IP and IEA configurations are shown in Fig. 26.13. Both of these techniques utilize time-of-flight (TOF) analysis and are both commonly used in many fields.^{42–44}

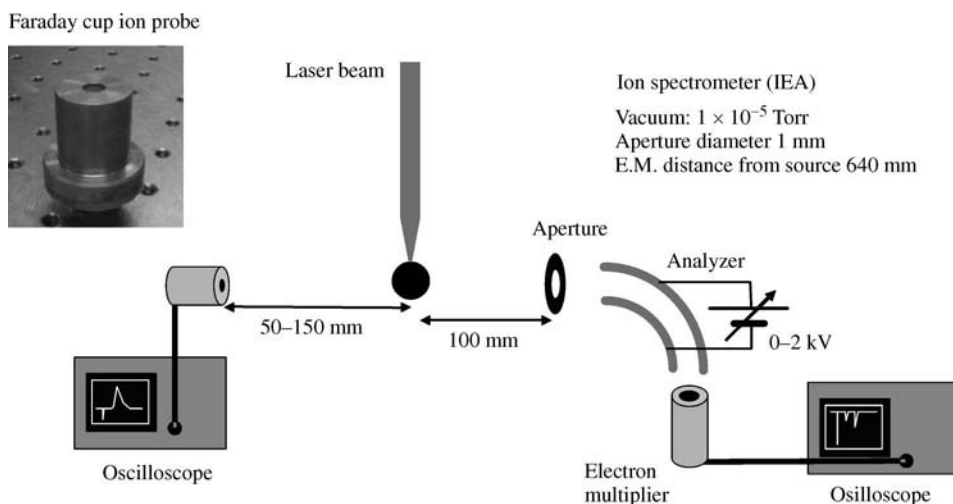


Figure 26.13 Two methods of ion measurement.

26.5.1 The ion probe detector

The IP collects various charged particles unless an electrostatic potential is applied to the grid located in front of the cup's electrode. To measure positively charged ions, a negative potential is applied, which is typically -60 V. At the beginning of the laser-material interaction, the IP experiences strong x-ray radiation from the source, generating photoelectrons on the cup electrode. This photoelectron signal determines the plasma event time used for the TOF measurements. The charge signal is detected when individual charged particles arrive at the cup's electrode. From the time delay, the TOF, and the distance between the IP and the source, the energy of the particles can be determined by assuming the particles fly at constant velocity. Were the source to be a single ion source, an IP would therefore provide a quantitative measure of the ion energy distribution. However, in a laser plasma, particularly in the multicomponent plasmas described here, IPs are of limited value because they cannot discriminate between different ion species. This shortcoming is avoided with the use of ion spectrometers, as described below. However, an IP can be used to estimate the total number of ions intercepted by the ion probe. Thus, for an isotropic source, it can be used to estimate the total ion flux at a given distance from the target plasma. This parameter is very important in estimating the number of ions that would intercept the surface of a collector mirror.

A typical ion signal is shown in Fig. 26.14. By integrating the signal across the $50\text{-}\Omega$ load, one can make an estimate of the charge accumulated. Taking the angular cross section subtended by the detector at 12 cm from the source, and assuming that each of the constituent atoms is doubly ionized when it reaches the detector, it is possible to deduce that only some $\approx 5\%$ of the total number of target atoms ($\sim 10^{15}$ atoms) reach the detector. Estimates of this sort are useful in determining the number density of ions contributing to erosion of the collector mirrors over time.

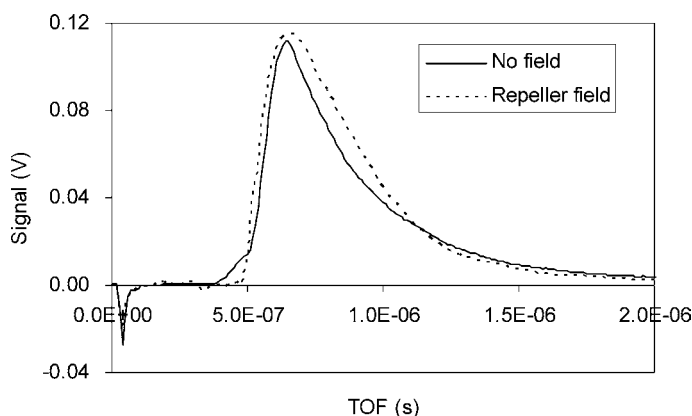


Figure 26.14 Ion probe signal with and without repeller field.

26.5.2 The ion spectrometer

The spectrometer consists of an ion-flux-limiting aperture, a field-free path for TOF analysis, an electrostatic ion energy analyzer (ESIEA), and an ion detector. The first two sections are simple in design. An aperture of 1-mm diameter is set at a distance of 10 cm from the source. After the aperture, a separate vacuum chamber is attached to the target chamber, and a field-free drift path is realized to separate the ion species, since they move at different velocities. A detailed description of this spectrometer, the ESIEA, and the ion detector is given elsewhere.⁴⁵ The vacuum in the entire ion spectrometer assembly must be kept below 1.0×10^{-6} Torr.

The primary elements of the ESIEA are a pair of electrodes with the shape of a circular quadrant. By changing the applied potentials on the electrodes, one can select the ions with the energy E but different charge states Z and mass M . The ion detector, placed right after the analyzer, detects filtered ions with the same E/Z and different TOFs. A single-channel electron multiplier (Burle Magnum 5900) is used for detecting the ions. This electron multiplier has many advantages over conventional ion detectors such as discrete-stage multipliers.⁴⁶ It has higher gain, longer lifetime, and smaller size. It also maintains the linearity of the gain over a wide range of the operating current. When the ions hit the surface of the multiplier, secondary electrons are generated, depending on the ion velocities. The efficiency of ion detection depends on the ion velocity, as has been previously characterized.^{47–49} The value of M/Z is proportional to the square of the TOF. Finally, the energy distribution of each charge state is obtained by scanning the electrostatic potential.

The ion spectrometer detects selected ions with a corresponding kinetic energy. Under the influence of the electrostatic force, the ions that fail to get through the IEA's geometric path are filtered out. The trajectory path is a circular quadrant illustrated in Fig. 26.13. The IEA passes only those ions with a specific kinetic energy E . With the same kinetic energy, the velocity varies for different elements due to their different mass. Thus the IEA first analyzes ions of higher Z and smaller mass, proceeding down to the lowest Z and the heaviest ions. The ions selected hit the electron multiplier's surface and generate secondary electrons, which are then multiplied to generate detectable signals. To use the electron multiplier properly, the vacuum of the entire ion spectrometer assembly must be kept below 1.0×10^{-6} Torr. By recording the ion spectra for different values of E for the same irradiation conditions and interpolating the data, a 3D map of the relative ion distributions can be created (Fig. 26.15).

The data, when analyzed in detail,⁵⁰ showed the ion charge state progressively moving to more highly ionized states with increased laser intensity. Similarly, as the laser intensity is increased, the individual ion energy distributions move toward higher energy.

This ion spectrometer, as described, provides a full description of the ion energy spectra by progressively recording data for different values of the electric field. An alternative spectrometer is a Thomson parabola spectrometer (TPS), which induces ion velocity dispersion with the aid of parallel electric and magnetic fields.

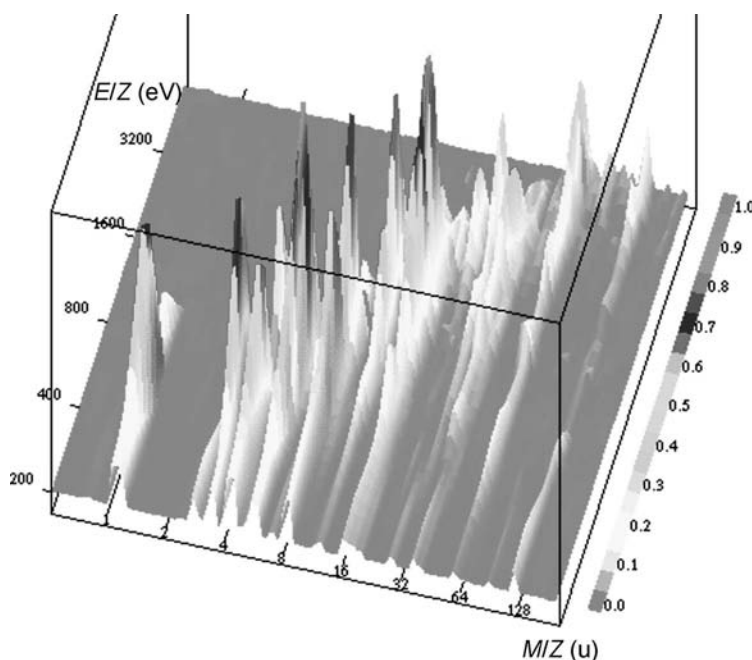


Figure 26.15 Interpolated ion spectra from IEA data taken at a constant intensity.

The spectra of all ions in the plasma are displayed in the image plane as separate parabolas for each ion, thus providing a full distribution of the ion velocity spectra for all ions in a single shot. We have utilized these spectrometers for many years in the diagnosis of laser plasmas, and are developing a similar^{51,52} system for these plasmas.

26.6 Particle Emission from Laser Plasmas

Our earliest investigations with solid-target laser plasmas for EUVL immediately identified the magnitude of the challenge to preserve the high-reflectivity multilayer-coated optics of the high-NA collection mirrors required in an EUV scanner.⁴ As was soon observed by others using solid metal targets, copious metal aerosols and fragments stream away from the plasma zone with a range of velocities as high as 2000 m/s.⁴ These arise indirectly from the creation of the radiating plasma and on time scales slower than the emitted EUV radiation (Fig. 26.16). Though not easily visible with the naked eye, and generally of little interest to physicists studying plasma phenomena, the collateral generation of this particulate matter is associated with plasmas created on large solid targets by almost all pulsed lasers. For high-repetition-rate laser sources, this becomes one of the most serious problems.

The particulate matter is generated from two primary mechanisms. The creation of a hot thermal plasma on the surface of the solid produces a rapidly moving

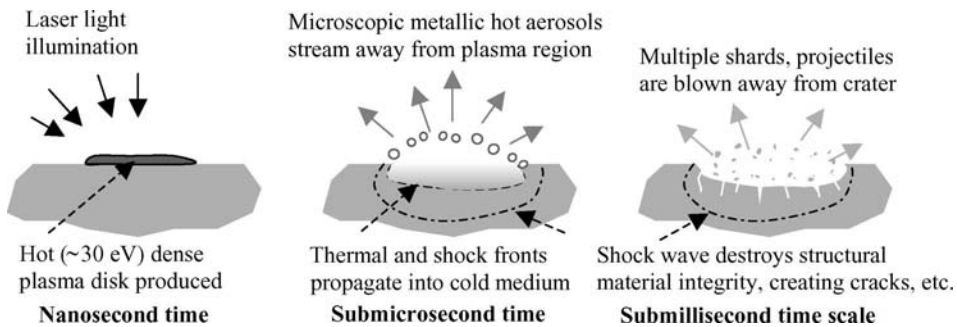


Figure 26.16 Creation of particulate debris from a solid target.

thermal gradient from the ablation region. At the time of the plasma creation, these temperatures are several thousands of K in magnitude and occur at very high pressures (kPa). With the evaporation of the laser plasma after the laser pulse, this superheated molten material explodes into the surrounding vacuum, disintegrating as high-speed aerosols that stream in all directions. Witness plates, such as microscope slides or Si wafers, will detect microscopic circular deposits of these aerosols as they impinge,⁵³ cool, and solidify on their surfaces. These aerosols are usually submicron in size, depending on the target material, and determined by the turbulent hydrodynamic flow of this exploding material.

Later in time, the consequences of the generation of the strong shock wave by the laser plasma as it propagates through the material become apparent. This shock wave, with pressures of many tens to hundreds of kPa, usually speeds ahead of the thermal wave, causing microscopic structural disassembly of the solid material, and results in the ejection of shards of solid material from cracks and disassembly of the surface, even after the propagation of the thermal wave. Many of these shards are then blown into the surrounding vacuum by the turbulent heated gases still resident in the crater of the interaction region. Some of these shards can have extremely high velocity, and, depending on the material, can have sizes up to tens of microns, or even 100 μm —that is, sizes even larger than the original laser spot size. The effects of these solid shards on the surface of a multilayer mirror (MLM) can be severalfold. With sufficient velocity, some shards embed themselves into the surface. Others cause an indentation, or actually chip off the surface before falling or bouncing off the multilayer.

Obviously it is imperative to eliminate all of these particle forms or prevent them from hitting the mirrors. This we are attempting to accomplish with the following strategies:

- **Mass-limited target approach.** By delivering to the focal region a microscopic spherical target of limited mass, we are hoping to avoid the production of aerosols and solid shards. As noted above, plasma studies and hydrocode estimates indicate that the shock and thermal wave should propagate through to the center of the target before the laser pulse has terminated.

- *Debris inhibition.* Doubtless some aerosols will be created. Our present experiments with tin-doped microtargets indicate the creation of some aerosols. Figure 26.18 shows a SEM image of a thin circular deposit of liquid material. The thickness in the center is only a few tens of nanometers, while the thin rim of the deposit is several hundred nanometers high. Although we are not sure yet of their origin, it is likely that in any practical system based on this target, some aerosols will occasionally be created. We therefore expect to deploy a combination of mitigation schemes that will prevent these particles from impinging on the mirrors.

26.6.1 Diagnosis of the particles

From careful diagnosis of the characteristics of witness-plate deposits of these aerosols, we can learn much about their origin and their physical characteristics. We have deployed a number of post mortem analyses of these deposits, using several materials analysis techniques. These include precision optical and SEM imaging of the size and nature of these deposits (Figs. 26.17 and 26.18), and also Auger electron microscopy (AEM) and spectroscopy (AES), to identify the elemental composition of these deposits (Fig. 26.19).

Atomic force microscopy (AFM, Fig. 26.20) is also very useful for making precise characterizations of the deposits. Auger microscopic spectroscopy indicates there is little tin deposited on the surface of witness plates, outside the deposits resulting from aerosols.

26.6.2 Effects of ions on MLMs

Even if particles are prevented from reaching the mirror surfaces, the effects of the free-streaming ions from the plasma will be deleterious to the lifetime of the mirror.

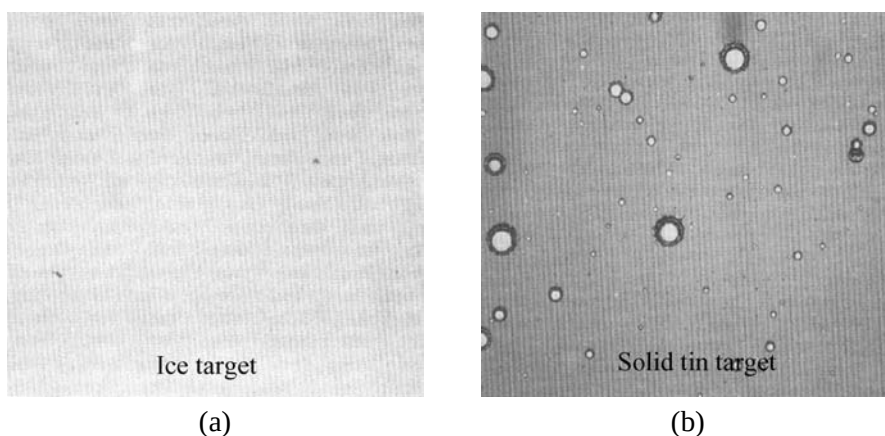


Figure 26.17 Glass-slide witness plates of particulate debris from (a) water ice, and (b) solid tin targets.

This was graphically shown several years ago⁵⁴ by SEM images of a MLM exposed at short range to oxygen ions from a water droplet target, partially shadowed by an aperture. This is reproduced in Fig. 26.21. The interfaces between individual layers of the MLM are easily observed after their erosion by the high-energy laser-plasma ions. Monte Carlo calculations⁵³ indicate the erosion rates are consistent with all the atoms in the target being ionized, that is, that few neutral atoms are left after the laser interaction.

26.7 Inhibition of Ion and Particle Emission

The previous section illustrates how imperative is the need to prevent both particles and ions from reaching the multilayer collection mirrors in any large numbers. This

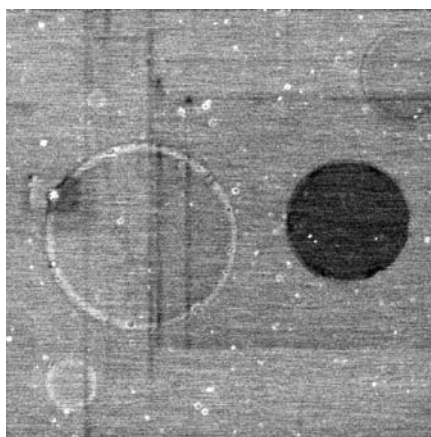


Figure 26.18 SEM image of solidified aerosols on a Si wafer from tin-doped droplet plasma.

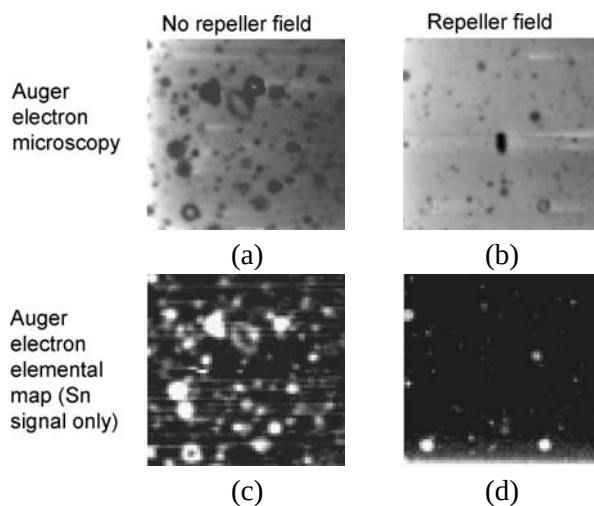


Figure 26.19 AEM of tin deposits.

is also the case for discharge sources, and may pose even a more serious threat in that case. Thus we have embarked on a multidimensional approach to mitigating damage to these mirrors. In earlier studies we examined the effects of mechanical shutters, spinning apertures, and other mechanical systems for intercepting debris.⁴ The use of the droplet approach radically reduces particulate debris. But ions can still threaten the mirror lifetime. This was demonstrated in our earlier studies with water droplets, which created no particulate debris (Fig. 26.17), but in which erosion by oxygen ions was observed (Fig. 26.21). We examined several methods to inhibit this erosion⁵³ including the use of electric and magnetic fields and the use of a transmitting background gas, helium. The latter we found did lead to reduction in erosion, but through x-ray photoelectron spectroscopy (XPS) surface analysis, we found it also led to an undesirable effect, oxidation of the top silicon layer of

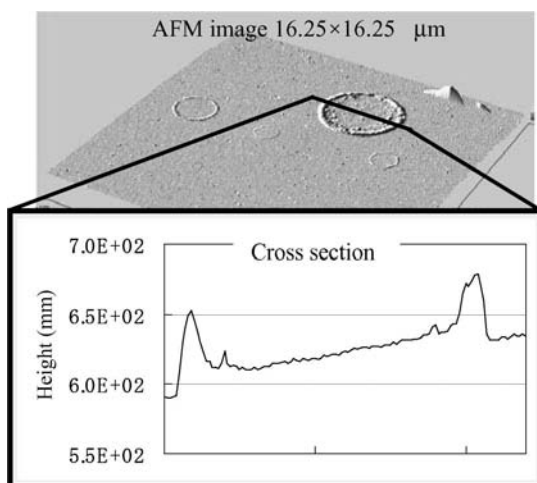


Figure 26.20 AFM analysis of the tin aerosol plates.

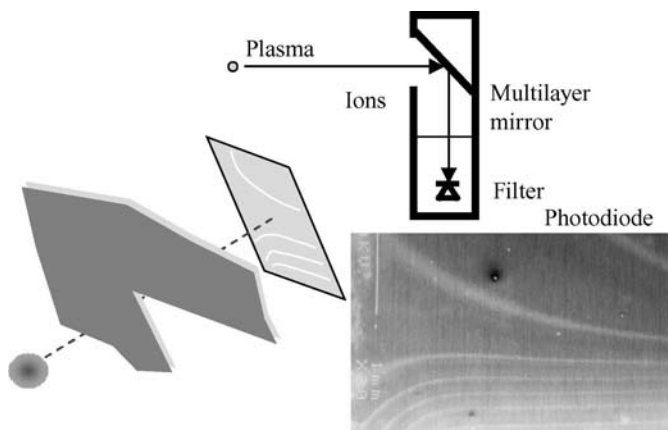


Figure 26.21 SEM image of the sputtered layers of a MLM after long-time exposure to oxygen ions from a water droplet plasma.

the multilayer. This effect had a more devastating effect on the mirror lifetime than did erosion. Magnetic fields helped steer ions to benign areas of the source facility, but we are concerned about the long-term presence of strong magnets in locations where precision optomechanical systems need to be located. The greatest effect on ions in mitigating mirror erosion we have so far found is through the use of electric fields, the so-called *repeller field* concept. We have demonstrated a more than order-of-magnitude improvement in mirror lifetime with simple embodiments of this concept. Moreover, we have recently found that it is effective in inhibiting charged particulate matter as well, as illustrated below. However, it is our view that this approach alone will provide insufficient protection to the collimating mirrors. It is most likely that a combination of techniques will be needed, and we are therefore investigating other approaches.

26.7.1 The repeller field

The concept of the repeller field was first demonstrated with water droplet targets.⁵³ Since then, we have examined other embodiments of this concept, and its effect not only on ions, but also on particles. A cylindrical version of this approach is illustrated in Fig. 26.22. In our studies with tin-doped targets we have obtained evidence of particulate matter on the surfaces of MLMs exposed to the tin-doped laser-plasma target.⁵⁵ This is illustrated in Fig. 26.19. Measurements made in 2003 showed that the repeller field was effective in stopping some fraction of these particles.⁵⁴ Our new setup allows us to investigate more precisely and more consistently the effectiveness of the field inhibition scheme by comparing two witness plates placed in one experiment: one without the field applied, and the other with the field applied. Figure 26.19 shows the images of the two witness plates (Si wafer) with surfaces area of $50 \times 50 \mu\text{m}$, after 3×10^4 laser shots, and a distance from the source of 64 mm. Figures 26.19(a) and (b) are AEM images, and Figs. 26.19(c) and (d) are the elemental maps of the tin signal of the same areas

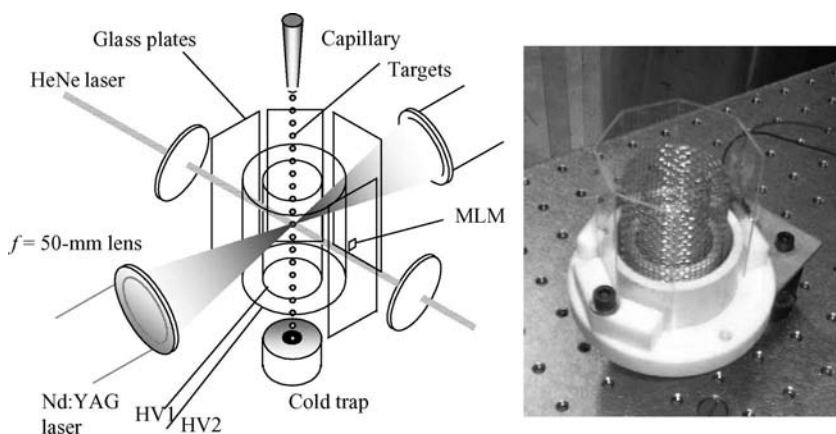


Figure 26.22 Cylindrical version of the repeller-field concept.

as in (a) and (b), respectively. Significantly fewer tin particle depositions are observed on the surface with the repeller field than without it. There are possibilities to improve the effectiveness of the inhibition by changing the configuration so that far less deposition is observed.

Recently we have examined the effect of the repeller field on the inhibition of high-energy ions. For this purpose a simple configuration was used (Fig. 26.23), utilizing an ion-probe detector and pure water droplet targets. Here we found that the repeller field was very effective in inhibiting the high-energy component of the ion spectrum (Fig. 26.14). The signal was averaged over eight shots in each configuration. Looking at the rise in the ion probe signal, just before $0.5\ \mu\text{s}$, the signature of the fastest ions appears as a step in the signal when no field is applied. This step, however, is not seen in the signal with the repeller field. From the ion spectral measurements, these are hydrogen ions. The hydrogen ions are stopped or slowed down so that they reach the ion probe at the same time as oxygen ions do. Thus, with the repeller field, we cannot resolve the hydrogen signal separately from oxygen ion signals. It is clear that the energy of the hydrogen ions is lowered. It is not seen in the ion probe signal that oxygen ions are slowed down, but that is expected to happen. Therefore the ion spectral measurements with the repeller field are necessary to verify the effectiveness of the repeller field for stopping ions.

Similar measurements were also made by replacing the ion probe with a MLM. Significantly reduced erosion was observed. More accurate measurements are now in progress.

26.8 High-Power and Long-Life Target Scenarios

Assuming that the required EUV power and lifetime requirements can be met, the ultimate selection of a source will be made by taking account of economic and strategic factors. No scanner supplier will be comfortable with a sole vendor of EUV light sources, so the technology must be sufficiently robust to ensure the involvement of multiple source suppliers. While it is possible that discharge sources might be able to meet the required source parameters, probably at a price lower than comparable present-day laser-based sources, the latter are less affected by thermal loading and will be able to attain high powers (possibly beyond the required 115 W at IF). The challenge then for laser source developers will be making their sources price-competitive. The concept described here is very conducive to a low-cost laser-based source.

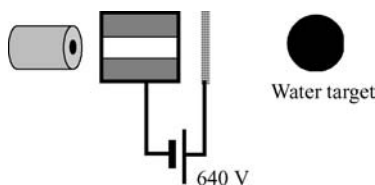


Figure 26.23 Measurement of ion signal with repeller field.

Reliable 2% CEs are achievable. A nominal 200 W (inband, 2π), with a collimator transmission of $\approx 50\%$, could provide close to 100 W of inband power with a laser power of ~ 10 kW. The latter is within the bounds of current technology. In the future we can expect the attainable CE to increase more, thus further reducing the required laser power.

The droplet source is ideally suited to very high repetition-rate sources. Simply extending the current results (CE = 2% for ~ 100 -mJ laser pulses at 1 Hz) by a factor of 10^4 will achieve the desired power. The current droplet source runs at frequencies of 30–100 kHz, and therefore we can anticipate source repetition rates of 10 kHz and higher. These high repetition rates favor a spatially and temporally multiplex laser system. Temporal multiplexing of the laser beams reduces the technology stress on operating *Q*-switched laser technology at very high frequencies. Multiplexing separate laser systems also provides redundancy and reliability in long-term operation. It could also lead to greater cost reductions, since the cost saving of volume fabrication of these lasers would affect total scanner prices at an earlier stage in their deployment.

26.9 Summary

This chapter describes a promising approach to the development of a high-power source for EUVL. It has evolved from the long-term efforts of a university group and its collaborators. Significant gains have been made in the efficiency of inband emission generation, and we believe further improvements can be made. There seems no impediment to running these sources at high repetition rates (> 10 kHz). A future high-power demonstration of this concept should substantiate this confidence. This source should easily satisfy the required levels of stability, average source size, and dose stability. Although not yet fully characterized, the level of OOB emission and the consequent heating of the first collimator mirrors are probably manageable. Studies of the ion emission and the particle emission from the droplet laser source show that long-term operation in conjunction with a multilayer collimator is possible, but that mitigation schemes will need to demonstrate greater effectiveness. We believe that a firmer understanding of MLM erosion by ions and greater effort devoted to the integration of mitigation schemes with this source will help this development.

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Chapter 27

Flying Circus EUV Source Metrology and Source Development Assessment

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27.1 Historical Overview of Metrology Development and Standardization

Soon after the first explorations of the potential of EUVL, it became obvious that the wafer throughput of future EUVL systems, and thus the EUV source brightness, was a key factor in the industrial value of this new imaging technology. The need for plasma-based light sources of moderate temperature, though strongly confined in space and critically optimized for emission at 13.5 nm, implied the use of suitable diagnostics, well adjusted for the particular application. Especially in the early days of EUVL development, a variety of source diagnostics were being used by the different source developers, each having backgrounds in different research and technology areas. These diagnostics ranged from uncalibrated grating spectrographs and luminescent detectors to broadband detection systems, such as filtered calorimeters and photocathodes, each detector obviously having its own characteristics.^{1–3} The measurement units applied varied correspondingly, ranging from $\text{J}\cdot\text{eV}^{-1}\cdot\text{J}_1^{-1}$ to percent.^{4,5}

From the data collected with these devices, extrapolations were then made to the most relevant quantity, namely, the true EUV power within the bandwidth and

the radiation acceptance angle of the total EUVL system. In order to allow a direct comparison of the performance of the different candidate EUV sources, in 2000 ASML sponsored a source metrology activity by FOM and Philips Research for which a portable, absolutely calibrated set of diagnostics was used. The approach was to assess each of the different sources with one single diagnostics set, circumventing any uncertainty introduced by the specific properties or calibration of the various metrology devices. In addition, the measurement procedure was standardized. Collecting data from sources on different locations worldwide, the activity became known as Flying Circus, or FC for short, and initially resulted in a full benchmark characterization of five candidate EUV light sources and the development of a common diagnostic standard.^{6,7} The follow-up project, Flying Circus 2 (FC2), sponsored by International SEMATECH, had the broader scope of further assessing the progress of EUV source performance, calibrating EUV source metrology equipment from different EUV source suppliers, and continuing the development of globally accepted EUV source measurement procedures. Nowadays, more than a dozen sources are characterized in this way, and the FC-type diagnostic has found permanent use at the majority of the source development laboratories. FC diagnostics are commercially offered by Scientec Engineering (www.scientec.nl). The general acceptance of the method and the continued program of on-site calibration using the portable FC equipment at the different source labs, as well as further-developed FC hardware, considerably assisted in the standardization of source performance representation.⁸

27.2 Metrology Concept

The choice for the FC metrology concept is based on results from applied physics research at various laboratories on characterization of laser-plasma XUV emission, as well as the development of appropriate XUV diagnostics.^{9–12} Notably, an early comparative study on plasma heating conditions for EUV generation and the progress in multilayer research contributed to the definition of the FC concept.^{13,14} Essential in the approach is the use of a multilayer optic as the main bandwidth-selective and light-collimating element.^{15,16} By adding a matched filter for the long-wavelength cutoff and a semiconductor junction diode, a versatile detector system is formed, enabling an accurate and straightforward calibration procedure (Fig. 27.1).^{17–19} The modular ultrahigh vacuum (UHV) construction of FC allows *in situ* alignment and *in situ* verification of detector linearity and absence of filter damage or contributions by out-of-band (OOB) radiation. The EUV light collimation by the curved multilayer allows either relatively long working distances with enhanced calibration lifetime, or enhanced filtering, both factors being helpful in the everyday practice of source monitoring. Collimation, adjustable by the use of different apertures, is also helpful in limiting the detector's acceptance angle, which is an advantage with respect to mirror lifetime and the determination of the value of the acceptance angle for the conversion to the standard solid angle of 2π sr. The use of a single mirror at near-normal incidence, similar to most of the multilayer

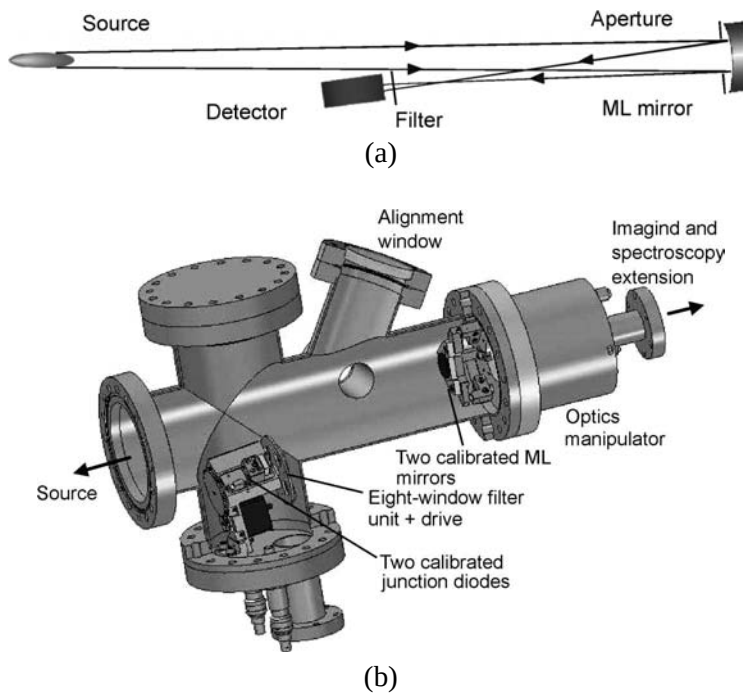


Figure 27.1 (a) Basic geometry of the FC EUV diagnostic. (b) Hardware schematics in the classic mode of operation of FC2.

optics in the EUVL tool, reduces the chance of polarization effects or alignment uncertainties, as compared to the use of multiple multilayer elements at off-normal incidence. The ability to do *in situ* alignment, finally, is of practical value, notably for source development use of FC.

In the classical mode of operation, the FC equipment allows direct measurement of the absolute inband EUV power, the pulse-to-pulse intensity stability, the OOB vacuum ultraviolet (VUV) and IR radiation, the maximum and steady-state repetition rate, the type and pressure of the surrounding gas, and the source-facing condenser's lifetime. Using an add-on source imaging extension, the inband source size can be measured within a few-percent-wide bandwidth around 13.5 nm, as well as the pulse-to-pulse spatial stability and the EUV intensity distribution across the plasma. Indirectly measurable are the average angular distribution of the radiation, the available collection solid angle, key risk areas for operating the EUV source and its critical component lifetime, and the electrical power dissipated by the source. These properties represent the range of source parameters currently agreed on for regular EUV source assessment.

27.3 EUV Source Metrology Calibration Procedures

The initial FC diagnostic allowed the measurement of the absolute EUV energy and average power in two wavelength bands, viz., 11.4 and 13.4 nm. In addition,

the pulse-to-pulse and long-term EUV stability of the source were assessed, as well as the contamination of multilayer optics exposed to the source. Nowadays, the focus is at 13.5 nm, the commonly accepted wavelength for EUVL. All optical elements are pre- and post-calibrated in a band including a wavelength by the Physikalisch-Technische Bundesanstalt at the storage ring Bessy II. A comprehensive description of the calibration procedure is found in Refs. 20 and 21, including an analysis of geometrical factors and the influence of the spectral emissivity of the source on the calibration. The calibration is performed for the centroid wavelength, for the full bandwidth of the diagnostic, and for OOB ranges (Fig. 27.2). The total uncertainty in the absolute calibration amounts to less than 5%, while the shot-to-shot repeatability is within 2%. This uncertainty is mainly determined by external factors such as the presence of a background gas and spectral source characteristics.²¹

The everyday practice of monitoring EUV source properties means that a number of other factors must be taken into account, such as contamination by source debris or background pressures, polarization effects, plasma and target gas EUV absorption, and detector linearity. The determination of the linear operating range of detectors was verified in the visible wavelength range using a method to generate pulses with a well-known pulse shape and length, both inherently calibrated.²² This method consists in sweeping a dc laser beam through a known aperture using a fast-rotating deflecting mirror. The sensitivity of the AXUV-100 photodiode, investigated this way, remained constant as a function of the pulse length at radiation intensities up to 118 mW, when applying a reverse bias voltage of 9 V in an electronic circuit suitable for pulse lengths up to 5 μ s. This is well within the normal

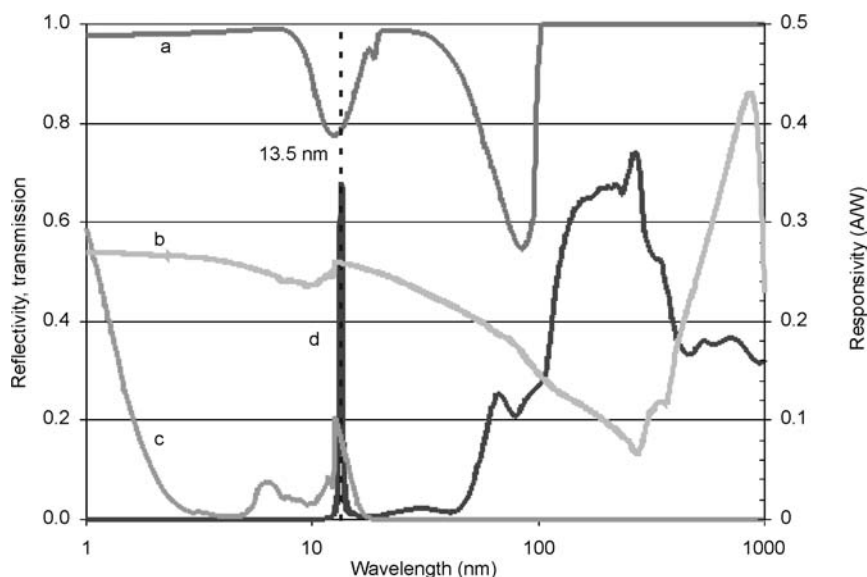


Figure 27.2 Example of the spectral response of the different metrology components: (a) Xe gas transmission, (b) AXUV-100 photodiode responsivity, (c) $\text{Si}_3\text{N}_4/\text{Nb}$ filter transmission, and (d) Mo/Si multilayer mirror (MLM) reflectivity for the wavelength range from 1 to 1000 nm.

working range encountered at most sources. Recent studies on the linearity of the photodiodes applied have confirmed a linear operating range up to typically 5 nC. The FC detection sensitivity is normally adjusted by scaling the mirror aperture or the overall source-to-detector distance. Linearity in the EUV range is argued to be similar, but remains to be verified.²³

At least down to the currently useful accuracy level of a few percent, there appears to be no need to calibrate the diagnostic as an assembled unit; due to the straightforward optical configuration, a separate calibration of the individual components (MLM, junction diode, filter) was shown to lead to at least the same overall accuracy as obtained using the full unit. A study performed at NIST showed that the responsivity based on separate component calibration agrees to within 1% with the responsivity of the assembled unit, with the total uncertainty of the beamline being 3.5% (1σ). This means that the total responsivity of FC2 and similar EUV metrology devices can indeed be derived from the calibration of the individual components. From a practical and cost point of view, individual component calibration is a preferred method for (re)calibrating EUV diagnostics. Ultimately (i.e., when applied at the final EUV scanners), verification of this procedure at much higher accuracy levels is desirable. This need can be foreseen for dedicated metrology tools or EUV dose monitors at (for instance) the wafer stage or intermediate points in the illuminator and projection-box optics. It can be argued that such dedicated monitors still need to allow regular cross-calibration with transfer standards.

Yet, a main issue in the everyday practice of source diagnostics is the need for frequent recalibration of components at appropriate EUV calibration facilities. The risks of contamination or damage of metrology components—e.g., by source debris or hydrocarbon or oxygen background pressures—calls for such possibilities, preferably available in the form of small-scale, lab-source-based metrology calibration setups.²⁴ Regular cross-calibration of such facilities with synchrotron-based setups, as well as correlation of results from different synchrotron facilities, will remain necessary in future, with accuracies typically within 1%.

Cross-calibration of EUV energy detector systems has been explored in detail using the FC2 system and also the E-MON system as developed by Jenoptik Mikrotechnik. Both detectors are intended for monitoring of EUV source characteristics.²⁵ A discharge and a laser-plasma EUV source were employed, developed by XTREME technologies. The FC2 and E-MON measurements showed agreement within 10%, in some setups down to 1%. The comparison showed a strong dependence on source properties (stability, isotropy, spectral emission) and measurement procedure (Xe absorption, triggering) when cross-calibrating two devices. The comparison also indicated that procedures for EUV absorption correction need to be standardized.

27.4 FC Source Progress Assessment

The initial FC activity resulted in a first comprehensive source benchmarking effort, with data reported on five EUV light sources, each of a different concept.^{6,20}

This benchmark, established in the first half of 2000, constitutes a point of reference in the development of EUV sources. The maximum power recorded then was 2.8 W, achieved by the Sandia laser plasma. The discharge systems investigated included the PLEX Z pinch, the Cymer plasma focus, the Sandia capillary plasma, and the Fraunhofer hollow-cathode source: all showed a power of less than 0.1 W in 2% bandwidth per collectable angle. By early 2004, the average power increased to an impressive level of several tens of watts, even while the required point of measurement was changed to the so-called intermediate focus (IF), i.e., including loss factors from collection optics or debris mitigation schemes. At the time of this writing, the power level achieved is typically up to several tens of watts in a 2% bandwidth at the IF, and several source developers are extrapolating to the lithography-required level of 115 W (Fig. 27.3).

The list of EUV sources either partially or fully assessed by FC over the past few years currently includes the following sources, listed in chronological order of the measurement: the laboratory gaseous-Xe-based laser plasma source at FOM, laser- and capillary-discharge plasma sources at Sandia National Laboratories, the Xe dense plasma focus at Cymer, the hollow-cathode-triggered (HCT) discharge source at the Fraunhofer Institut für Lasertechnik (Aachen), the Z-pinch and Star Pinch sources at PLEX LLC (Cambridge, MA), the discharge plasma at Philips EUV (Aachen), laser and discharge plasmas at XTREME technologies (Jena and Göttingen), an rf-excited plasma source at LBNL (Berkeley, CA), and a Sn-based

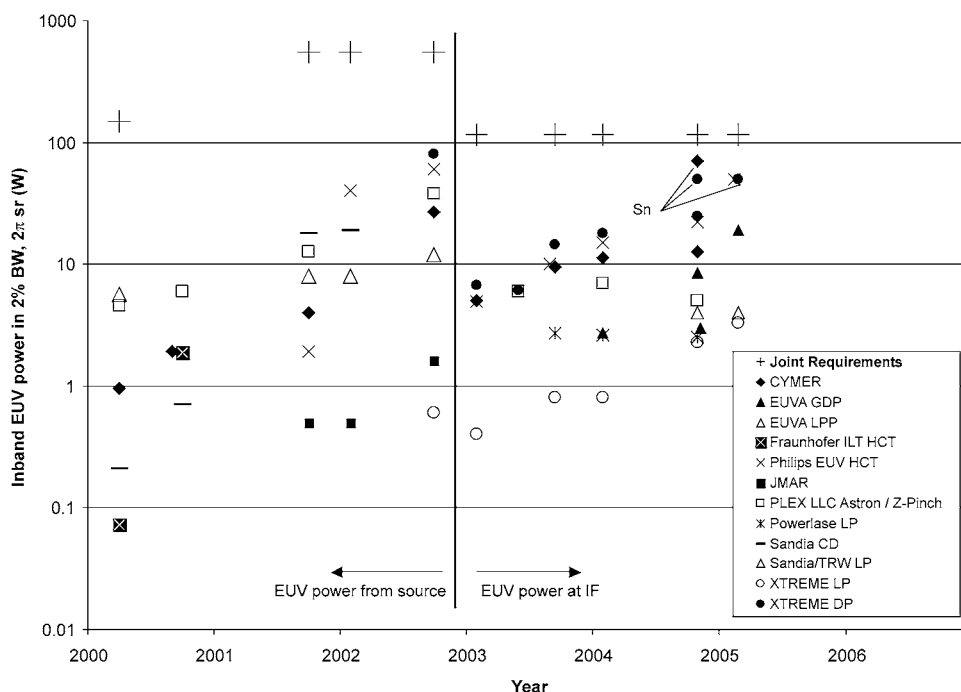


Figure 27.3 Summary of FC and supplier data on EUV source performance development. From 2002 on, the power values in the IF are shown.

laser plasma source at CREOL (Orlando, FL), many with individual reports available.

By way of example of the scope of typical FC source assessments, a summary of the results of measurements collected by the end of 2003 at the PLEX LLC Star Pinch is given (Table 27.1).²⁶ The table shows the main source properties as currently being quantified within the FC program, as well as the measurement units applied for each of the source characteristics. This listing also reflects the consensus among source and system developers on relevant source characteristics. The full report describes the equipment developments, the calibration and analysis procedure, and a discussion on the results.²⁶ It is noted that the data do not necessarily represent the latest performance of the particular source due to the rapid development of sources.

27.5 Diagnostic Extensions and New Developments

The FC optical concept of employing a curved multilayer optic enables an extension by a second multilayer optic, so that an EUV multilayer telescope is formed (Fig. 27.4). This can be used to image the EUV source onto a CCD camera at magnifications between 2 and 10. These narrowband images, showing only the EUV-emitting part of the plasma, can differ considerably from the widely used pinhole-camera images, which show the broadband source size. The latter can result in incorrect estimation of the collectable power due to limitations in the collection efficiency given a certain etendue of the collector optics. Experimental results show that there is no general relation between EUV size and broadband source size, so that one would have to verify the inband size when changing major plasma conditions. Imaging results on a gaseous Xe laser-plasma source at FOM showed a 40% smaller inband size than the broadband size, and studies at Philips Extreme UV showed an 18% broader source at 13.5 nm with a different energy distribution across the source.^{27,28} Larger inband sizes would result from plasmas that radiate primarily at wavelengths from higher ionization stages in the plasma, of which the radiation originates usually from a smaller core. The wavelength-band averaging occurring in pinhole cameras then can lead to a smaller size than for images from inband multilayer telescopes.

Source intensity measurements are normally based on one or two reflections from MLMs, resulting in data for a 3.9% and a 3.3% bandwidth, respectively. Additional spectral data are then needed to convert the intensity to the 2% standard

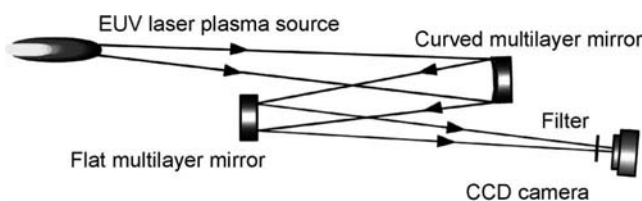


Figure 27.4 Imaging mode of FC operation.

Table 27.1 Typical measurement quantities and standardized units as assessed by the Flying Circus program.

Parameter	Unit	Value	Comment
Absolute collectible inband EUV power measured (2% BW)	mJ/sr	3.7–6.4	Measured at 500 Hz; energy values dependant on Xe flow
Max. collectible inband EUV power measured (2% BW)	mJ/sr	6.9	Measured at 1250 Hz
Estimated power at IF at steady-state rep. rate (2% BW, 500 Hz)	W	1.3	Assuming 2.5-sr collection from 1.6-mm length out of measured 4.8-mm source, and 50% optical efficiency to focus
Estimated max. power at IF (2% BW, 1.25 kHz)	W	4	(See above)
Estimated max. power at IF (2% BW, 2 kHz)	W	6	Assuming energy measured at 1.25 kHz is reproduced at 2 kHz
Angular emission uniformity, over 40-deg half angle	%	≤ 2	
Etendue of source output	mm $\times$ mm	4.8×0.8	Axial length $\times$ transverse length; supplier reports plasma length is reduced to 4 mm in post-FC upgrade
Demonstrated maximum rep. rate	Hz	2000	For duration of ≈ 2 sec
Demonstrated steady-state rep. rate	Hz	500	
Pulse-to-pulse spatial stability	–	–	Total volume within 4.8×0.8 mm
Pulse-to-pulse intensity and integrated energy stability	%	9.6	At 500 Hz for average of 500 pulses. Av. energy value of 4.5 mJ
Pulse-to-pulse angular stability	%	10	Average of measurements at 0, 20, and 40 deg
Dissipated power (steady-state rep. rate)	J/pulse	9.5	Out of 27 J per pulse, 9.5 J per pulse is dissipated in the plasma. Recovery of 14 J of energy in the system. 1.25-kHz operation
Estimated conversion efficiency	%	0.42	1.25 kHz
Out-of-band power, 160–325 nm	mJ/sr	0.55	12% of 4.5 mJ [EUV + (>160 nm) band energy]
Out-of-band power, 325–715 nm	mJ/sr	0.25	6% of 4.5 mJ (see above)
Out-of-band power, 715–850 nm	mJ/sr	0.15	3% of 4.5 mJ (see above)
Out-of-band power, IR (>850 nm)	mJ/sr	0.29	6% of 4.5 mJ (see above)
Type and pressure of surrounding gas	mTorr	2.1	Xe gas at 500 Hz, relative flow 240
Source-facing condenser lifetime	–	–	
Key risk areas	–	–	
Critical component lifetime (electrode)	–	–	Supplier data: no erosion at 2×10^7 pulses

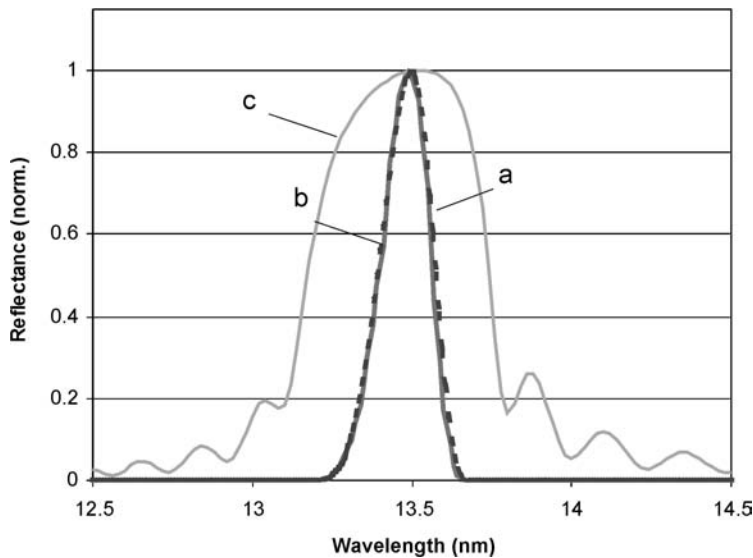


Figure 27.5 Reflectivity characteristics of a depth-graded MoSi/Si MLM (curve a) adjusted to the total response of an 11-mirror lithography system (b, dashed). Curve c represents the standard Mo/Si reflectivity response.

bandwidth. Obviously, a direct measurement within the 2% bandwidth, or even within the bandwidth of the total lithography optics, would be desirable.^{29,30} At FOM, specially designed MLMs were fabricated with a reduced bandwidth of 2%, consisting of 70 layer pairs of molybdenum silicide and silicon. The first samples showed a bandwidth of 2.1% FWHM and a reflectivity of 50.1% at 13.5 nm. A first demonstration of the use of such a mirror in the existing FC2 setup showed a more than fourfold reduction of the spectral correction. The next step would be to move to the in-system bandwidth corresponding to the bandwidth of a full, 11-bounce EUVL system. By applying specially designed multilayer optics, such a system bandwidth can be mimicked by a single mirror, which is then compatible with the FC detection concept (Fig. 27.5).^{30,31}

Apart from these evolutions in multilayer capabilities, the FC metrology equipment is also gradually evolving, incorporating for instance *in situ* EUV alignment using luminescent materials such as YAG:Ce crystals.³² Diagnostics are also becoming more compact, for example, as in the FC3 system, which combines the classic FC metrology concept and an EUV telescope for inband source size measurements in a single, more compact device (Fig. 27.6).

27.6 Summary and Future Directions

The rapid progress of EUV source development and an increase in commercial interest will have the consequence that a considerably larger fraction of the results becomes proprietary. In response, the nature of FC may gradually change into a more facilitating cross-calibration-like activity. For the coming years, though, a

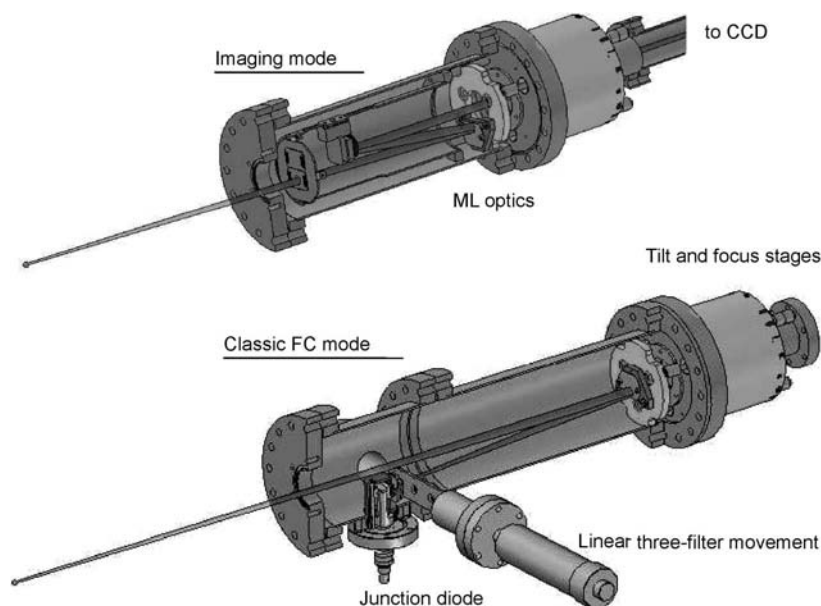


Figure 27.6 Latest version of the FC equipment, allowing EUV and OOB source characterization and EUV source imaging.

continued need to assess the progress of EUV source performance can be foreseen, as well as a need to have a noncommercial liaison activity on EUV metrology equipment in a position between EUV source suppliers and synchrotron-based or lab-scale calibration facilities. The FC formula is well suited for that purpose, though possibly with small adaptations.

In general, the range of available EUV metrology equipment is becoming noticeably broader, with more emphasis on the ability to monitor system-specific source parameters such as true inband power, inband source size, and spectral contributions in the VUV.³³ This development calls for an ongoing standardization effort in order to continue the development of EUV source measurement procedures.

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Chapter 28

Plasma Diagnostic Techniques

Eric C. Benck

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28.1 Introduction

In order for EUV plasma sources to become the next-generation lithographic (NGL) source, significant obstacles still need to be overcome. Improvements in conversion efficiency (CE), plasma stability, and component lifetimes are required. Although the final goal is to produce a suitable 13.5-nm light source, solving the full range of problems will require a more thorough understanding of the plasma than just the EUV optical emission. Because of the complex nature and extreme

conditions produced in the EUV plasma sources, many different plasma diagnostics are needed to fully characterize these EUVL sources.

Although the development of EUVL light sources is a relatively recent endeavor, similar plasmas have been utilized for many years for other applications. LPPs have been used for applications ranging from laser drilling to x-ray lasers. DPPs have been investigated as potential nuclear fusion sources and also as x-ray sources. Consequently, suitable plasma diagnostics have been developed over many years for the study of these types of plasma sources.

This chapter will concentrate on plasma diagnostics not based on optical-emission measurements. Although measurements of the optical emissions from these plasmas provide a great deal of information, many of these techniques have been discussed previously in Chapter 27. Consequently, this chapter will concentrate mainly on diagnostics of emitted plasma debris and other basic plasma properties such as electron density and temperature.

28.2 Surface Accumulators

Surface accumulators are typically designed to monitor plasma-surface interactions within the plasma. While extremely important, they provide very limited, indirect information concerning the actual plasma conditions. In EUVL plasmas, one of the goals is to minimize mirror degradation, and consequently plasma surface erosion or deposition is slow. Surface accumulators typically need to be exposed to the plasma for an extended period of time. Although some *in situ* measurements such as mirror reflectivity can be performed, most measurements that will provide information concerning plasma conditions require *ex situ* measurements of the accumulator. Typically, no spatial or temporal information is obtained using these techniques.

28.2.1 Witness plates

Although primarily used for monitoring the degradation of optical surfaces in EUVL sources, witness plates can also be utilized as a simple plasma diagnostic. Material ejected from the plasma can form a deposit on the surface or, if the particle energy is high enough, embed beneath the surface. Even if the surface is being etched, some of the plasma debris may still reside beneath or on the surface. After an extended exposure to the plasma, a post mortem analysis of the witness plate can be performed to identify the chemical identity of the deposited materials.

A wide variety of different surface analysis techniques can be applied to analyze the witness plates. The chemical composition of material on the witness surface can be obtained from such techniques as x-ray photoelectron spectroscopy (XPS) or Auger electron spectroscopy (AES). Surface sensitivities better than 10^{12} atoms/cm² for certain materials can be obtained.¹ Depth profiling of material embedded in the surface can be achieved by sequentially combining these techniques with ion milling. Even higher surface sensitivity can be ob-

tained using secondary-ion mass spectroscopy (SIMS), achieving sensitivities of 10^9 atoms/cm².¹

Microscopic analysis of the surface depositions can be very important as well. The presence of concentrated surface deposits instead of a uniform deposition layer can be evidence of large clusters or droplets being emitted from the EUV light source. Surface scanning techniques such as scanning electron microscopy (SEM) or atomic force microscopy (AFM) can provide very high spatial resolution, but probably will not have the necessary chemical discrimination between different materials. Reasonable microscopic imaging of the surface can be done with either SIMS or AES with spatial resolutions on the order of 0.1 and 1 μ m, respectively.¹

One problem involved with witness plates is that not all surface depositions are related to plasma-surface interactions. EUV radiation can crack carbon-containing molecules, resulting in surface deposits of carbon.² Hydrocarbon molecules can come from a variety of different sources, including outgassing from the photoresists.³ The presence of this deposition mechanism can be verified by inserting an EUV transmitting filter between the plasma and the witness plate. In many cases most of the carbon deposits can be attributed to this EUV cracking mechanism.⁴

28.2.2 Quartz crystal microbalances

Quartz crystal microbalances (QCMs) can provide slow time-resolved *in situ* measurements of the etching or deposition processes. The mass of material being added to or removed from the surface of a QCM can be monitored by changes in the crystal's resonant frequency. Because thermal, vibrational, and electrical noise can influence the measurement of the crystal resonant frequency, operating with an exposed-unexposed pair of QCMs can provide an *in situ* reference to improve measurements. The surface of the QCM can essentially be coated with any material desired for testing plasma-surface interactions. As with the passive witness plates, in order to determine what is causing the mass change to the QCM surface, *ex situ* surface analysis is typically required.

Although QCMs have been used to analyze many EUVL sources, the research group of Ruzic at the University of Illinois has been using both QCM and witness plates as an important diagnostic for plasma debris mitigation techniques.^{5,6} This work is described in more detail in Chapter 36. Ruzic's group has combined QCMs with a foil trap composed of foil tubes with a 5:1 length-to-diameter ratio. This trap acts as a collimator and allows limited spatial imaging of the material emitted from the plasma. This technique has been used to study the debris emitted from a large dense plasma focus (DPF) source. The group has been able to distinguish between debris emitted from the main plasma pinch and the rundown region plasma that occurs before the main plasma pinch.

28.3 Plasma Imaging

Plasma imaging techniques provide a direct measure of the spatial extent of the plasma. Not only does this type of technique provide important information concerning the evolution of the pulsed plasma, it is also important for understanding the optical properties of the emitted EUV radiation. Imaging of EUV plasmas is complicated by the lack of refractive materials for lenses. Therefore, lensless techniques such as pinhole cameras or mirror optics are required. Optical spectroscopy techniques can often be combined with plasma imaging, but these techniques are covered in more detail in Chapter 27.

28.3.1 Pinhole cameras

Because of its simplicity, one of the most widely used imaging diagnostics is the pinhole camera.^{7–17} Essentially all that is required is a pinhole and a 2D light detector such as photographic film or a CCD array. The magnification of the camera is determined by the ratio of the pinhole-detector distance to the pinhole-object distance. Normally, some type of foil filter is used to restrict the range of photon energies imaged by the camera. Even with a foil filter, the pinhole camera still images a significant amount of out-of-band (OOB) radiation.

The ultimate resolution of the pinhole camera is restricted by the interference properties of the imaged light. The image of a point object is transformed into a Fresnel diffraction spot of the pinhole on the image plane.¹⁸ But in addition to this fundamental limit, there can be other factors degrading the image, including the finite pixel size of the CCD and the response of intensifying microchannel plates (MCPs).¹⁹

28.3.2 Mirror imaging systems

An alternative imaging technique is to use reflective optics in the imaging system. Using mirrors coated with the same coating as the projection optics results in only the inband radiation being imaged. Diagnostics using either single or multiple mirrors have been used to measure the spatial extent of the 13.5-nm plasma.^{4,20–22} Significant variations in plasma size as measured between the filtered pinhole camera and mirror optics systems show that different plasma processes are involved in the optical emissions.

28.3.3 Shadowgraphs

A shadowgraph is a very common technique to monitor gradients in the index of refraction of a transparent medium. As a collimated beam of light passes through the sample, light rays are slightly deviated so that light bends toward regions of higher refractive index and away from regions of lower refractive index. The resulting image of the light formed on a distant screen will show light and dark regions corresponding to the inhomogeneities of the sample perpendicular to the

light beam. The technique was first used by Johannes Wiesel²³ in 1649 and is now commonly used with a variety of different applications ranging from the thermal convection in fluids²⁴ to the formation of shock waves.²⁵ In the case of EUVL plasmas, the plasma index of refraction is determined by the electron density, so the shadowgraph technique measures gradients in the electron density.

Although the technique was originally developed with an extended broadband light source, the development of high-intensity pulsed lasers has significantly increased its range of application. Using a pulsed laser enables measurements of transient plasmas such as those found in EUVL sources. Combining this with a CCD camera enables measurements of the electron density gradient from each plasma pulse. The technique is limited to the regions of the plasma that remain transparent. Consequently, portions of the plasma that exceed the critical plasma density cannot be probed using this technique.

Researchers at the University of Central Florida (UCF) have used this and other similar optical diagnostic techniques to study EUV LPP sources.²⁶ They have studied a variety of different targets, including water and water-tin droplets, in an LPP. A schematic of their experimental apparatus is shown in Fig. 28.1. The laser plasma was created with the fundamental of a Nd:YAG laser with a 9-ns FWHM duration focused onto the target droplet. The second harmonic of the laser, with a 2.5-ns duration, was then used to probe the plasma with a spatial resolution of 5 μm . The shadowgraph was then recorded with a CCD. The measurements indicate that the

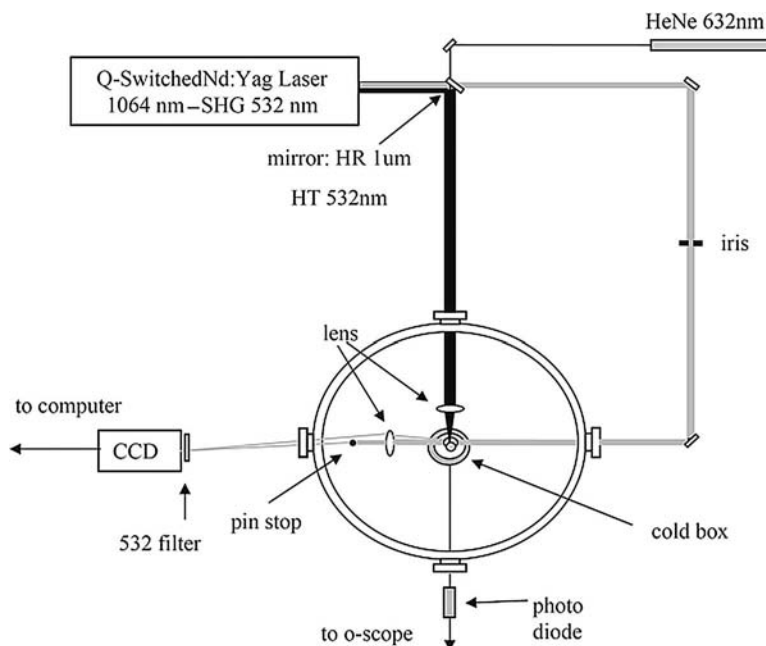


Figure 28.1 Schematic of a shadowgraph and schlieren imaging system used at UCF. (Reprinted from Ref. 26 with permission from The Institute of Pure and Applied Physics, Japan.)

plasma produced on the side of the incident heating laser formed symmetric fringes indicative of spherical symmetry.

Shadowgraphs have also been used to study DPF devices. Gupta et al.²⁷ from the University of Delhi, India, have used this technique to study a sequential DPF device that has a segmented anode. The plasma was illuminated by a homemade nitrogen laser ($\lambda = 337$ nm) with a 1-ns pulse width. The images were recorded with a high-speed Polaroid film. Jitter in the plasma focus times was a significant problem. A large number of images were required to record the complete temporal behavior of the plasma.

One variation of the standard shadowgraph is resonance shadow imaging. In this technique, a tunable pulsed laser is used as the illumination source. By tuning the laser into resonance with an atomic transition of material in the plasma, the atomic density within the plasma can be determined. In essence, the normal shadowgraph becomes overlaid with an absorption image. This technique has been used to study the laser plasmas from solid tin and lead targets at the University of Florida.²⁸ A 35-ps-duration Nd:YAG laser was used create the plasma on solid targets and also to pump a tunable dye laser for the diagnostic.

Another application of shadowgraphs for EUVL sources has been to monitor the stability of the laser target before irradiation by the laser. Lin et al.²⁹ used this technique to study a multikilohertz water-droplet LPP source. They utilized shadowgraph imaging to demonstrate that the laser-generated plasma did not destroy adjacent water-droplet targets.

28.3.4 Schlieren imaging

Schlieren imaging is very similar to shadowgraph measurements. The main difference is that the light transmitted through the sample is refocused and a focal-point stop blocks all nonrefracted rays. The refracted waves can then form interference patterns with light scattered off the focal-point stop. This results in a very high-contrast image in which the interference fringes are perpendicular to the index-of-refraction gradient. Since the index of refraction of the plasma is due mainly to the electron density, this diagnostic also measures the gradients in the electron density.

Researchers at UCF have also been using the schlieren imaging to monitor their EUV plasma sources.²⁶ The experimental diagnostic is essentially the same as that previously described for the shadowgraph, with the inclusion of a pin stop at the focal point of a $f/3$ imaging lens. This system results in a magnification of $18\times$ with a spatial resolution of about $5\text{ }\mu\text{m}$. These workers used both schlieren imaging and shadowgraph measurements to study a water-droplet laser-plasma source.

28.3.5 Interferometry

Interferometry of plasmas measures the optical phase shift in the light that traverses the plasma. It is typically assumed that the optical beam path is not being significantly deviated by optical gradients as in shadowgraphs and schlieren imaging. The optical phase shift is due to the optical index of refraction of the plasma, which is

related to the electron density. The phase shift is actually measured by interfering the probe beam sampling the plasma with an unperturbed reference beam. The resulting image of interference fringes provides a measure of the spatial distribution of electron density within the plasma.

A variety of different geometries can be used to create the probe and reference beams for interferometry measurements. One such configuration is the shearing interferogram and has been used by Qi et al. to study a DPF source.³⁰ A schematic of such an optical configuration is shown in Fig. 28.2. A 10- μ J, 3-ns-FWHM, 600-nm pulsed laser was used to illuminate the plasma. After passing through the plasma region, the light entered a 50:50 beamsplitter. A series of two mirrors directed the reflected and transmitted laser beams along similar paths but in opposite directions. The beams were then recombined onto a sheet of photographic film. The two beams were not perfectly aligned, and in the overlap region between the transmitted and reflected beams a series of parallel interference fringes formed in the absence of any plasma. The photographic images were later digitized for further data analysis. Clear measurements could be obtained during the rundown phase, but not within the actual plasma pinch. The current sheath was measured to have a current density of $3.3 \times 10^{18} \text{ cm}^{-3}$.

A very similar type of interference technique is the polarized-light interferometer. This has been used by the research group of Prof. Richardson at UCF to study LPPs.³¹ A schematic of this diagnostic is shown in Fig. 28.3. Two polarizers, P_1 and P_2 , were oriented either parallel or perpendicular to each other. After the laser light passed through the plasma, a Wollaston prism separated two beams with different polarizations. The beams were then partly overlapped on a CCD detector. Without a plasma, a series of parallel interference fringes formed in the overlap region, just as in the shearing interferogram. For these measurements, the

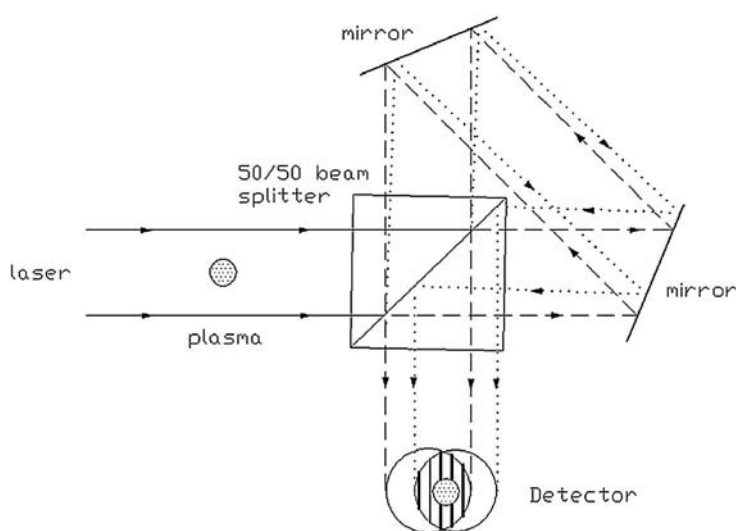


Figure 28.2 Schematic of a shear interferometry apparatus.

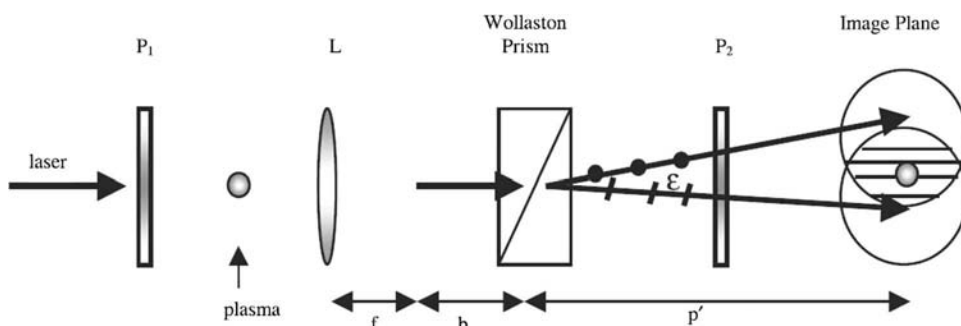


Figure 28.3 Schematic of a polarization interferometry apparatus. P_1 and P_2 are polarizers, and L is a focusing lens. (Reprinted from Ref. 31 with permission from the American Institute of Physics.)

laser source was the second harmonic of the same Nd:YAG laser used to create the LPP from water droplets. A special pulse-slicing technique was used to shorten the second-harmonic laser pulse to approximately 1 ns from the original 6 ns. A spatial resolution of about $5\ \mu\text{m}$ was achieved.

The resulting interferograms obtained by Prof. Richardson's research group showed fringes which, to first order, were spherically symmetric on the irradiated side of the droplet. On the rear of the droplet, there was evidence of some material jets and a low-density plasma. At the center of the image, the interference pattern was blocked by the plasma, which exceeded the critical density of $4 \times 10^{21}\ \text{cm}^{-3}$ for the laser probe. Because the plasma seemed to exhibit spherical symmetry on the illuminated side of the droplet, the resulting fringe shifts could be Abel-inverted to determine the actual spatial plasma density distribution. An example of such spatially resolved data is shown in Fig. 28.4.

28.4 Electron Diagnostics

Optical emission measurements have indicated that electron temperatures on the order of 30 eV occur in EUVL sources optimized for 13.5-nm emission from xenon. But it is the nonthermal electrons that drive many of the important plasma processes, including the generation of high-energy ions. Although the electrons are probably not directly responsible for much of the optics erosion found in EUV sources, they certainly play an important role in the ion and neutral-atom behavior. Several of the plasma imaging techniques described in Sec. 28.3 (shadowgraphs, schlieren, and interferometric imaging) provide information on the spatial distribution of the electron density. This section will discuss two additional nonimaging electron diagnostics that can provide information related to both the electron temperature and the density.

28.4.1 Langmuir probes

Langmuir probes were one of the fundamental techniques first used in plasma diagnostics. Essentially, a biased electrode was inserted into the plasma, and the result-

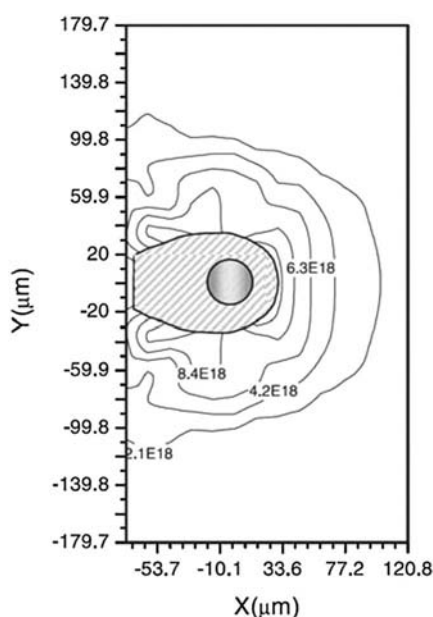


Figure 28.4 Electron density (cm^{-3}) distribution plot obtained by Abel-inverting polarization interferometry measurements from LPP water-droplet target. (Reprinted from Ref. 31 with permission from the American Institute of Physics.)

ing current provided information concerning the properties of the plasma. A great deal of information can be determined from this simple diagnostic, including electron and ion densities and electron distribution functions. Unfortunately, placing the biased electrode in the plasma can, under certain circumstances, significantly perturb the plasma, making the results unreliable.

Langmuir and other types of electrostatic probes have been used frequently to study LPP sources. Unfortunately, the quantitative results obtained from Langmuir probes in these plasmas are of questionable quality.³² Secondary-electron emission from the probe surfaces can significantly alter the measured signals. Over time, deposition or oxidation on electrode surfaces can change in an unpredictable manner the already poorly quantified secondary-electron emission coefficient.³³ Because the plasmas in EUV sources are rapidly expanding, a different theoretical treatment of the data is typically required, similar to that derived for moving probes. The ion saturation current I_i can be approximated by $I_i = (1 + \epsilon)eUA \sum n_i z_i$, where ϵ is the secondary-electron emission coefficient, U is the plasma velocity, A is the cross-sectional area of the probe perpendicular to the flow, n_i is the density of an ion j , e is the electric charge, and z_i is the charge state of the ion.³⁴

The research group at Sandia National Laboratories in Livermore, CA, has attempted to make Langmuir probe measurements of its LPP source.^{35,36} A stainless steel spherical Langmuir probe approximately 6.35 mm in diameter was located 12.7 cm from the laser focus. Ion saturation currents were monitored with a -350-V bias. The Langmuir probe data indicated the presence of ions long after

the laser shot. Such low-energy ions could contribute to a continuum ion background when a high-repetition-rate laser is used.

28.4.2 Thomson scattering

Thomson scattering measurements can provide information concerning the electron temperature, electron density, and average ion charge state of plasmas. This information is obtained from the frequency shifts of light scattered from the plasma. The scattered radiation is typically quite small and often difficult to measure. Great care also is needed to suppress scattered laser light from optical components and other surfaces within the plasma vacuum chamber. Carefully designed beam dumps, optical baffles, and polarizing filters are often used to help reduce the scattered laser light. In addition, the scattered radiation must be distinguished from the background of optical emissions from the plasma.

The spectrum of scattered light in a Thomson scattering experiment is determined by the parameter $\alpha = (\lambda/4\pi\lambda_D) \sin(\theta/2)$, where λ_D is the Debye length, θ is the scattering angle, and λ is the wavelength of the incident laser light. When $\alpha \ll 1$, the spectrum is directly related to the electron energy distribution function. If the plasma has a well-defined electron temperature, the scattered light will have a Gaussian shape. When $\alpha \gg 1$, the collective motion of the plasma becomes dominant. The scattered spectrum is dominated by a central peak at ω_0 and satellite peaks at $\omega_0 \pm \omega_p$, where ω_0 is the incident laser frequency and ω_p is the plasma frequency. The width of the central peak is associated with the ion motion and can be used to determine the ion temperature. The satellite peaks can form from both the electron (ω_{pe}) and ion (ω_{pi}) plasma frequencies. The plasma frequency is $\omega_{px} = (4\pi n_x e^2 / m_x)^{1/2}$, where n_x and m_x are respectively the electron ($x = e$) or ion ($x = i$) density and mass. Therefore, by measuring the plasma frequencies from the Thomson scattering spectrum, the charged-particle densities can be determined. The ratio of the electron and ion densities can then be used to estimate the average ion charge state in the plasma.

Thomson scattering has not been used widely as a diagnostic for EUV or other similar plasma sources. The intense optical emissions from these plasma sources make measuring the weak scattered light very difficult. The technique has been applied by Chenais-Popovics et al.³⁷ at the Laboratoire pour l'Utilisation des Lasers Intenses facility at École Polytechnique, France. They studied the properties of a laser-produced gas-jet xenon plasma. Instead of having a separate laser for the Thomson scattering, they measured the scattered light originating from the same laser pulse used to create the plasma. The xenon target was a sonic gas jet formed with a 1-mm-diameter nozzle. The nozzle created a parabolic density profile that was essentially uniform over the central 400 μm of the jet. A frequency-doubled Nd:glass laser was focused into a 160- μm -FWHM focal spot. The laser pulse was flat-topped with a 650-ps duration. The scattered light was collected at 45 deg to the incident laser beam and observed from a $200 \times 100 \times 100\text{-}\mu\text{m}^3$ volume. The estimated scattering parameter was $\alpha = 3.43$, and therefore the spectrum was

dominated by the collective plasma motions. Two separate spectrometers were used to measure the electronic and ion satellite peaks. A high spectral resolution (0.025 nm) was used to measure the ion plasma frequency, and a lower spectral resolution (10 nm) for the electron plasma frequency. They found for the condition measured that the electron temperature $T_e = 415 \pm 40$ eV, $\langle Z \rangle = 27.4 \pm 1.5$, and $n_e = (1.30 \pm 0.05) \times 10^{20} \text{ cm}^{-3}$. This LPP source is significantly different from other EUV sources in which electron temperatures on the order of 30 eV optimize the 13.5-nm radiation from xenon.⁴

28.5 Ion Diagnostics

It is expected that the ion flux from the EUVL sources will be the main factor in source problems involving optics degradation. Even small numbers of highly charged ions could have a big effect on surface erosion due to their high sputtering efficiency. In addition, unexpected ions could be present due to erosion or melting of electrodes or outgassing of materials such as resists. Being able to characterize the ion flux from the plasma can aid in source optimization and damage mitigation techniques.

28.5.1 Time-of-flight spectrometry

The pulsed operation of the various EUV light sources lends itself readily to time-of-flight (TOF) spectroscopy. Because of its simplicity, it has been used by many different research groups to measure plasma debris. This technique is based on measuring the amount of time required for charged particles to travel a known distance. The arrival time t of any ion depends on both its energy and mass according to the relation $t = d/(2E/m)^{1/2}$, where d is the distance of the detector from the plasma, E is the initial energy of the ion, and m is the ion mass. Therefore, this technique measures the E/m ratio of ions ejected from the plasma. If the mass of the ions is known, then the ion energy distribution can be determined.

Any factor contributing to the uncertainty in the timing of the ion signals results in an uncertainty in the E/m ratio. One such factor is the lifetime of the plasma. The creation time of the ejected ions must be significantly less than the spread in ion arrival times at the detector. For LPPs, laser pulse durations are typically 10 ns or less. DPPs can take hundreds of nanoseconds to form, but the actual pinch typically lasts for only tens of nanoseconds.^{4,38,39} Timing jitter of the actual pinch formation can also be a significant problem. The finite lifetime of the plasma can often be dealt with by choosing a sufficiently long ion path length. Typically, the ion path lengths have ranged from around 50 to 400 cm. In most TOF measurements, x rays create a spurious signal, coinciding with the ion creation time, that can be used to initiate the timing of the subsequent ion signals.

Another factor is the assumption inherent in these measurements that the ions travel with essentially constant velocity. This requires that the main accelerating electric fields be confined to a small distance compared to the total ion path length.

A very similar issue is ion energy loss due to collisions with the background gas. In a few cases, the background gas pressure can be kept low enough so that the collision mean free path is longer than the measurement length. But more frequently, the mean free path of ions is significantly less than the desired total ion path length. In these cases some form of differential pumping is required. A small aperture allows the ions from the plasma to enter a low-pressure region in front of the ion detector. If the aperture cannot be located less than a collisional mean free path from the detector, the distance in the low-pressure region should be many times longer than the path length in the higher-pressure plasma chamber. Otherwise, timing errors due to fast ions losing energy in collisions near the aperture will perturb the measurements. The presence of the entrance aperture has another benefit in that sheaths forming on the aperture will help shield the detector from lower-energy electrons. Otherwise such electrons could alter the apparent measured flux of high-energy ions.³²

Still another issue with TOF measurements is the acceptance angle to the diagnostic. Because a long path length is usually necessary after the entrance aperture, the acceptance angle of incoming ions is typically very small. Consequently, ions that have undergone collisions before entering the entrance aperture will often not be detected, since they are no longer traveling in a straight line from the initial plasma. Therefore, most of the TOF signal will arise from those ions that do not undergo collisions, and consequently the measured ion energy distribution will be skewed to higher energies.³⁵

The ion flux from most EUVL sources is sufficiently high that the ion current can be detected using a Faraday cup. The cups are typically biased at a negative voltage in order to collect all the ions and repel stray electrons. If care is not taken, the Faraday-cup signal is prone to uncertainty due to the emission of secondary electrons. This is a serious problem when highly charged ions are present, since the secondary-electron emission coefficient increases rapidly with ion charge state. It is possible to suppress the secondary-electron emission by a variety of different techniques. A negatively biased aperture or grid at the entrance to the cup can trap the secondary electrons. Secondary-electron emission can also be suppressed by choice of the materials of the Faraday cup.⁴⁰ Designing the cup with a large aspect ratio or filling its interior with a metallic honeycomb structure can also reduce the probability of the secondary electrons escaping.⁴¹

When the current flux is too small for the use of a Faraday cup, due either to a small entrance aperture or a long path length, amplified detectors such as a multichannel plate (MCP) or a channeltron can be used. MCPs have been used frequently for this application because their large surface area helps reduce problems with detector saturation. Variations in the secondary-electron emission can still be a problem, particularly when dealing with different ion charge states. The secondary-electron emission variations are less of a problem when the detectors can be operated in a single-ion counting mode, where the magnitude of each current pulse is not measured.

At UCF, TOF detection has been used to study an LPP source with water and water-tin droplets.⁴² The detector consists of a Faraday cup, typically biased to

–60 V, located 50 to 150 mm from the plasma. Differential pumping is not required because of the low operating pressure (1.3×10^{-3} Pa). Other than the entrance to the Faraday cup, there are no apertures restricting the ion beam. Since ions with significantly different masses (H, O, Sn) are expected from a water-droplet-based source, it is not possible to convert the basic TOF data into ion energies. These measurements were mainly used for comparison with the electrostatic-analyzer TOF data described in Sec. 28.5.2.

The LPP source at Sandia National Laboratories in Livermore, CA, also has a TOF detector to characterize the plasma.³⁵ A 1-mm aperture is located 15.7 cm from the laser focus, and the main vacuum chamber has an operating pressure ranging from 0.24 to 0.467 Pa (1.8 to 3.5 mTorr). A Faraday-cup detector was located at a distance of 109 cm from the plasma. Ion energies were found to vary with laser power. Although the peak of the ion energy distribution was around 10 keV, ions with energies as high as 60 keV were measured. Operating the source with the lower pressure (0.24 Pa) seemed to increase the number of low-energy ions.³⁶

The research group headed by Dr. Sublemontier from the EXULITE project at CEA Saclay has also been utilizing TOF measurements to characterize LPP plasmas.^{43,44} The ions traverse a distance of about 10 cm in the main chamber ($p < 0.1$ Pa) before entering a 1-mm aperture. The group has reported finding debris from a Xe-jet LPP source with a maximum ion energy of 15 keV.⁴⁴ More extensive work has been published involving TOF measurements of LPP with cryogenic Ar and N₂ jets. A 1-mm entrance aperture is located approximately 10 cm from the LPP, which was maintained with an operating pressure of about 0.1 Pa. It is followed by a 20-cm, independently pumped flight tube and a 50-cm free-flight section within the spectrometer, which is pumped to a pressure better than 10^{-4} Pa (10^{-6} mbar). An electron multiplier was used as the detector. A postacceleration voltage was sometimes applied in front of the detector, which enabled some discrimination between ion charge states for low-energy ions. A negatively biased entrance grid was used to verify that electrons made a negligible contribution to the signals. The measurements found very high energy ions being emitted from the plasma, some exceeding 200 keV for the Ar jet. The energy distributions varied significantly with laser pulse duration, with the highest energies found for a pulse duration of 2.25 ps. Although a complete data set was not obtained for the Ar jet, the energy distribution appeared higher than that from the N₂ jet. Analysis of the erosion of the jet nozzle suggests that additional arc discharges were occurring between the LPP and the nozzle, creating additional surface damage.

28.5.2 Electrostatic analyzer with TOF spectrometer

Electrostatic analyzers (ESAs) consist mainly of two curved deflection electrodes. These electrodes create a radially directed electric field through which entrance and exit apertures restrict the ions to travel along a circular path with a known radius. In terms of the applied voltage, assuming the ions travel midway between the plates,

the energy-to-charge ratio becomes equal to $E/q = V/\ln(b/a)$, where V is the applied voltage, q is the ion charge, and b and a are the radii of the deflection electrodes.

Typically, ESAs are not used alone but in combination with a mass spectrometer. The simplest combination is an ESA with a TOF spectrometer. Consequently, both the E/q and the m/q of the transmitted ions can be determined. Because the detector is no longer directed at the plasma, spurious signals due to x rays and fast electrons are not present. Consequently, an external timing signal from the plasma is necessary to measure the ion arrival times.

The research groups of both Richardson at UCF⁴² and Komori at EUVA⁴⁵ have used this technique. Schematics of their experimental apparatus are shown in Fig. 28.5 and Fig. 28.6, respectively.

The group at UCF uses a 90-deg ESA.⁴² The base pressure in the main vacuum chamber is below 1.33×10^{-2} Pa (1×10^{-4} Torr), and consequently does not require any differential pumping. In order for the electron multiplier detector to operate properly, the vacuum must be maintained below 1.33×10^{-3} Pa (1.0×10^{-5} Torr). The entrance aperture is 10 cm from the LPP with a total path length of 64 cm. The different ions could be easily distinguished by the detector at the measured energies of 250 and 313 eV.

The ESA at EUVA used by Komori's research group is a commercial device.⁴⁵ It is located in a separate vacuum chamber that is differentially pumped. The entrance aperture to the differentially pumped region is 42 cm from the LPP, and the ions traverse a total distance of 845 cm. The analyzer deflects ions through an angle of almost 180 deg, and they are then detected with an MCP detector. Excellent mass resolution is obtained, and the natural isotope abundance for each charge state can be easily resolved. The group has been using its ESA-TOF detector to study an LPP source using a Xe jet. A typical measurement is shown in Fig. 28.7. Only Xe ions have been observed, and the ion charge states were $\leq 6+$. The most

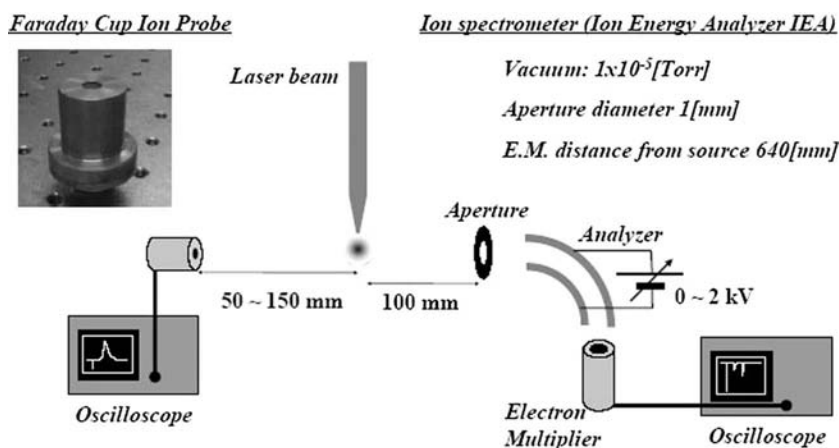


Figure 28.5 Schematic of TOF and ESA-TOF diagnostics at UCF (reprinted from Ref. 42).

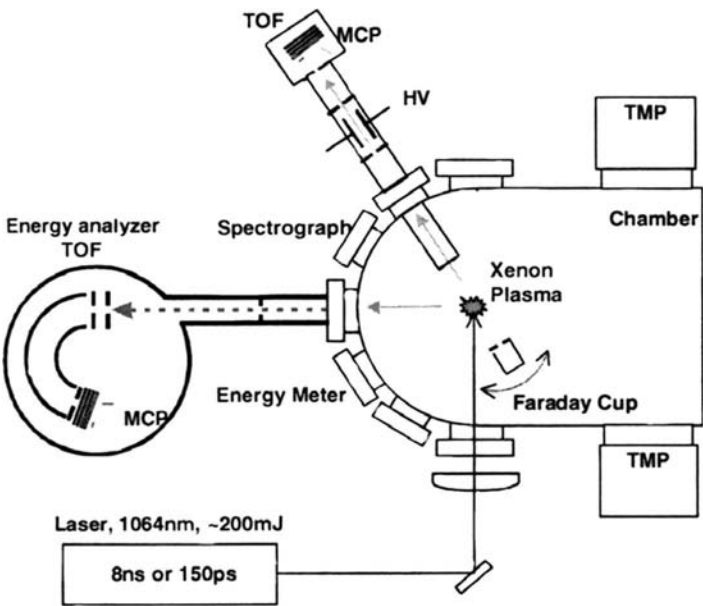


Figure 28.6 Schematic of the ESA-TOF diagnostic and neutral-atom detector at the Hiratsuka Research & Development Center, EUVA (reprinted from Ref. 45).

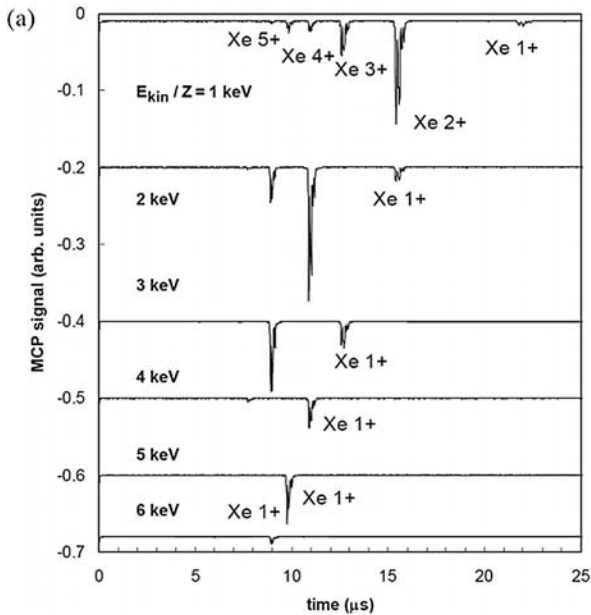


Figure 28.7 Typical ESA-TOF measurements from an LPP of a Xe jet with an 8-ns, 100-mJ laser (reprinted from Ref. 45).

abundant ion charge state was Xe^{2+} . The maxima of the ion energy distributions were approximately at 3 and <1 keV for the 8-ns and 150-ps laser pulse widths, respectively. The maximum ion energies were approximately 8 and >10 keV, respectively.

28.5.3 Electrostatic analyzer with quadrupole mass filter

One very powerful mass-spectroscopic technique is to combine an ESA with a quadrupole mass filter. Alternating radio frequency (rf) fields in the quadrupole transmit only those ions with a specific mass-to-charge (m/q) ratio. This technique has been used frequently to study mass-resolved ion energy distributions from a wide variety of plasmas. Unlike TOF spectroscopy, this technique does not depend on precise ion timing to make measurements. This enables the diagnostic to examine ions not directly created by the laser-droplet interaction or ions that have been undergoing collisions. The possibility of ions originating from longer-lived plasmas can be inferred from the Langmuir-probe data taken at Sandia^{35,36} and from the nozzle erosion patterns observed by Sublemontier's research group.⁴³ The technique can be utilized for the suppression of background noise as well as time-resolved ion flux measurements.

A commercial mass-resolved ion energy detector (the Hiden EQP mass-resolved ion energy analyzer*) is being utilized as part of an effort from NIST to study the ion fluxes from EUVL sources. A schematic of the device is shown in Fig. 28.8. It has been utilized for studying a variety of other plasma sources, including various semiconductor etching plasmas.⁴⁶ It has mass and energy ranges of up to 300 u and 1100 eV respectively. Previous TOF measurements of the Sandia LPP source have indicated that the peak ion energy is on the order of 10 keV.³⁵ In order to measure such high-energy ions, the entire mass spectrometer will be biased to approximately 10 kV. A high-voltage vacuum break will insulate the spectrometer from the grounded vacuum chamber, and optoelectronic isolators will be used to isolate the data-acquisition computer. One of the key advantages of utilizing this particular diagnostic is that the ESA is maintained at a constant voltage and the ion energy is selected by biasing the ESA, mass quadrupole, and detector. Therefore all the ions reach the detector with the same energy, and there is no variation in detector sensitivity with the initial ion energy. This detection scheme will be able to clearly distinguish between ions immediately ejected from the plasma during the laser pulse and those that might be emitted later from a decaying plasma in the chamber.

28.5.4 Thomson parabola spectrometer

The Thomson parabola spectrometer has the distinct advantage over other ion spectroscopy techniques that it can collect the entire ion energy spectrum from a single

*Certain commercial equipment, instruments, and materials are identified in this chapter to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

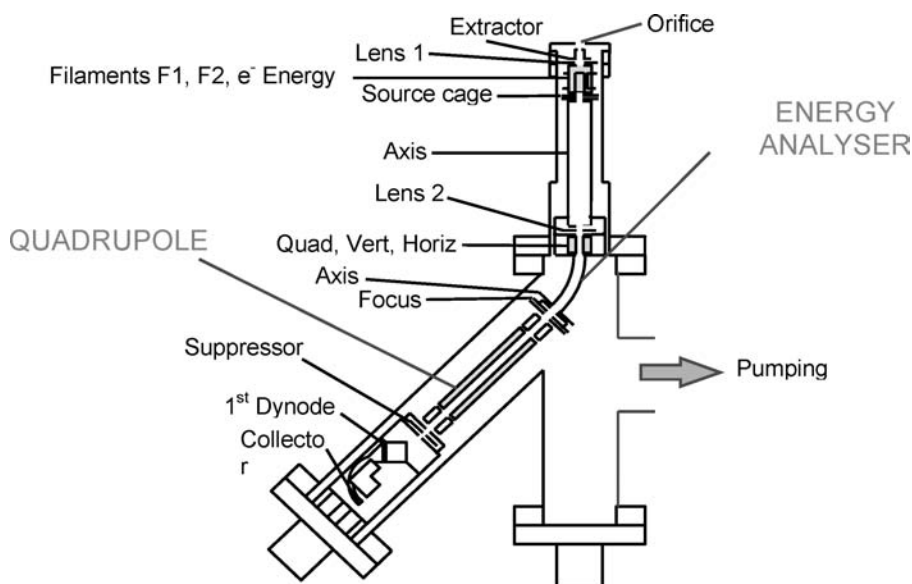


Figure 28.8 Schematic of a commercial ESA–quadrupole–mass–filter ion diagnostic. Device also includes ionizer for residual gas analysis (RGA). (Courtesy of Hidden Analytical Ltd.⁴⁶)

plasma pulse. Separate uniform magnetic and electric fields deflect an ion beam from the plasma into a parabolic curve on a 2D detector surface. Each type of ion will be deflected into a different parabolic arc, with the ion energy determined by the distance along the arc. Measuring the ion intensity as a function of distance along the arc determines the ion energy distribution function. It has been used frequently to study very high energy plasma sources.^{47–49}

Thomson parabolas are formed from three parts: collimator, deflection fields, and a 2D detector. The collimator is typically a series of apertures located at the entrance of the spectrometer. The diameter of the ion beam determines the thickness of the measured parabolic curve and limits the resolution between ions with different q/m ratios.

The choice of the magnetic and electric field strengths is very important. They need to be chosen to match the expected range of q/m and ion energy. To first order, the ions with a charge to mass ratio q/m will be deflected on the detector by $x = (q/m)(EL^2/2v^2)$ and $y = (q/m)(LB/v)$, where E is the electric field strength, B is the magnetic field strength, L is the distance from the fields to the detector, and v is the ion velocity. Ions with too low an energy will be deflected off the detector surface, and high-energy ions will be deflected too little to resolve the different q/m values. Typically, varying the electric field is easy, but the magnetic field is usually fixed by the strength of the permanent magnets.

Thomson parabolas designed for very high energy plasmas typically have used either photographic film or solid-state nuclear track detectors. Solid-state nuclear track detectors require ion energies typically > 100 keV and therefore will not work

with EUV plasma sources, where the maximum ion energies are on the order of tens of keV. Also, pulsed EUVL sources will need to operate at repetition rates on the order of 7 to 10 kHz, so that insertion and removal of the film begins to become a problem. Consequently, the best solution for a detector array is an MCP coupled with a phosphor. This will enable true single-shot measurements. Using a time-resolved imaging system with the MCP can also enable measurements of the time evolution of the plasma. Because an MCP requires a base pressure on the order of 10^{-4} Pa (10^{-6} Torr), the Thomson parabolas require differential pumping.

Regardless of the type of detector, the Thomson parabola needs to be well calibrated. The sensitivity of the detector array can vary significantly with ion energy and charge state. Stray fringe fields may also deflect the beam in unexpected fashion. As a result, calibration of the spectrometer with ion beams of known properties is important for interpreting the final experimental results.

Although there does not appear to be any published record of Thomson parabolas being used to study EUVL sources, there are plans in several research groups to do so in the near future. Martin Richardson's research group at UCF has assembled a Thomson parabola with a large-surface-area MCP detector, which should be capable of measuring ions in the range from 100 eV to 10 keV.⁵⁰ The research group at Sandia National Laboratories at Livermore have also been working to install a Thomson parabola on their LPP.³⁶ They are modifying a spectrometer designed for higher ion energies to work in the expected energy range of their LPP. The original high-energy nuclear track detector is being replaced with a MCP-phosphor detection system.

28.6 Neutral-Atom Detectors

Measurement of fast neutrals in EUV plasma sources is difficult. These fast neutrals can be produced by charge-exchange collisions with fast ions. Typical optical diagnostics are difficult to employ. Except for some of the faster optical transitions, the lifetime of most of excited fast neutrals is longer than the collision time with the plasma chamber. This makes more traditional optical emission and laser-induced fluorescence measurements difficult to perform in these short-lived plasmas.

There have been only a limited number of attempts to measure fast neutrals in EUV plasma sources. Doria et al. found some evidence of fast neutrals using a TOF spectrometer with a movable biased Faraday cup.⁵¹ They were measuring the plasma properties of an LPP formed with a XeCl laser on a solid copper target. At distances under 20 cm from the target, the application of high bias voltages would result in a plasma breakdown. The researchers attributed this to the arrival of neutral atoms at the Faraday cup. Near the source, the neutral flux lasted for approximately 300 μ s.

Komori's research group has utilized a better technique to measure fast neutrals from its EUV LPP source⁴⁵ (see Fig. 28.6). A pair of biased electrodes were

placed inside the TOF spectrometer to deflect all ions from the beam. The remaining signal with the bias voltage applied was interpreted as being due to the fast ions and is shown in Fig. 28.9. Komori et al. estimate that the neutral flux was approximately 20% of the ion flux, assuming similar neutral and ion gains in the MCP detector.

Another neutral-atom detection method that possibly could be applied to EUV plasma sources is pinhole imaging. The research of Kiwamoto et al. utilized a pinhole camera to measure energetic neutral atoms from a quadrupole-magnetic-mirror fusion plasma source.¹⁶ The camera had a 1.2-mm-diameter pinhole bored in a lead block.¹⁷ A MCP-phosphor screen detector was located 155 mm behind the pinhole for a magnification of 0.031. The spatially resolved neutral-atom flux was determined by the difference in images with and without filters.

A unique detector was developed by Sarraf and Woodall that could simultaneously detect the ion, electron, and neutral signals and was applied to LPPs from solid targets.⁵² The detector had an entrance aperture followed by a conductive tube that was bisected longitudinally. The two halves of the conductive tube were simultaneously biased up to 5 kV. These electrodes deflected the charged particles and acted as Faraday cups, which simultaneously measured the ion and electron flux from the plasma. In order to suppress secondary-electron emission, ring magnets at both ends of the detector created a weak longitudinal magnetic field. A pyroelectric calorimeter wafer made from lead zirconium titanate (PZT) was located at the end of the tube behind another aperture. The calorimeter detected in a time-integrated manner the total neutral flux, including neutral atoms and photons. Of the total energy emitted from the plasma, it was estimated that 15% to 20% was from ions, 15% to 20% from neutrals (atoms and photons), and 15% from energetic electrons. The detector operated properly only in plasmas with densities below a particular

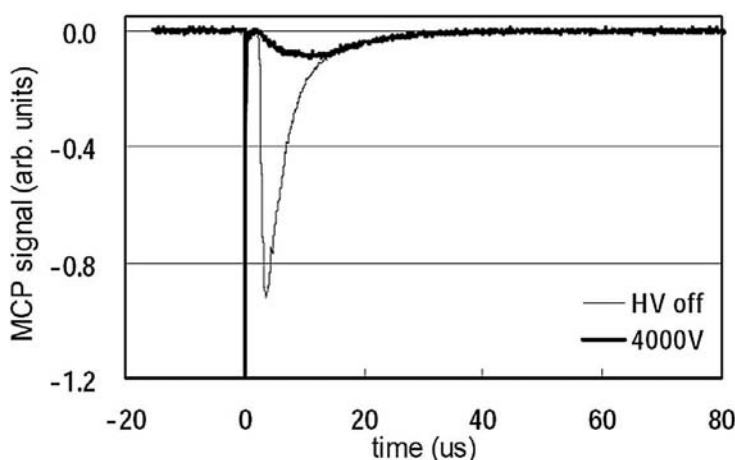


Figure 28.9 Sample time-of-flight measurement of ions and neutral particles. Only neutral particles should reach the detector with the 4-kV bias applied to a pair of deflection electrodes (reprinted from Ref. 45).

upper limit. When ion densities exceeded this limit, the detector began to fail due to the plasma shielding out the external electric deflection field. When this occurred, ions and electrons were not properly measured, and they perturbed the neutral-flux measurement.

28.7 Summary

In order for an EUV plasma light source to become the NGL source, many critical challenges still need to be addressed. An understanding of the plasma and the emitted plasma debris is critical for the optimization of EUV sources and suppression of plasma debris. This is important for achieving the necessary source intensity and component lifetimes for EUV plasmas to be an economically viable lithography source. Fortunately, a wide variety of different diagnostics are available for characterizing the plasmas found in EUVL sources. Many of these diagnostics have been developed previously for other high-energy plasma applications such as fusion and x-ray lasers. Each plasma diagnostic provides only a small piece of information concerning the actual plasma state. In order to fully characterize EUV sources, a variety of different diagnostic techniques need to be employed.

Acknowledgments

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Chapter 29

Metrology for EUVL Sources and Tools

Steve Grantham, Charles Tarrio, Robert Vest, and Thomas Lucatorto

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29.1 Introduction

The effort to develop EUVL has presented the metrologist with a set of unique challenges both in radiometry and in measuring reflectivity. Since the inception of the National Institute of Standards and Technology's (NIST's) EUV-detector-based radiometry program in 1970, there has been little need for accurate measurements of pulsed EUV sources, and the radiometric techniques in this spectral range were all tailored to continuous wave (cw) measurements. Now, however, EUV sources bright enough to be suitable for EUVL are all based on very high temperature plasmas that must be generated by extremely high power pulses. Recently some experience in pulsed radiometry has been gained through the creation of standards for pulsed radiometry connected with DUV lithography with its pulsed 248- and 193-nm laser sources.¹ However, important differences in the spectral, temporal, and spatial characteristics of the EUV sources as contrasted with the DUV laser sources necessitate specialized approaches, still under development, that are described in Sec. 29.3.

Soon after the demonstration in 1986 of the first practicable EUV mirror in the form of a Mo/Si multilayer,² NIST established a capability to measure the reflectivity of EUV mirrors for such applications as solar astronomy, plasma diagnostics, EUV laser development, and EUV microscopy. At that point, measurement accuracy of order 0.01 nm in wavelength and 2% in reflectivity seemed to provide more than adequate characterization for the applications at hand. However, the advent of EUVL made the demands much more stringent due to the imaging and illumination needs of the process.³ NIST has continued to perform EUV mirror calibrations since the program's inception, has increased its capabilities to meet many of the reflectometry demands of EUVL, and will continue to expand and improve the program to help meet the future needs of the industry.

29.2 NIST EUV Sources for Metrology

Calibration of EUV optics, detectors, and tools must be done with an EUV source that is well characterized in order to fully understand the meaning of the calibration. Effects from EUV-source instability and out-of-band (OOB) radiation both contribute to calibration uncertainty and must be accurately known and allowed for in order to incorporate a source as a calibration tool. The differences between the calibration sources and the sources that metrology tools are used with must be identified and compensated for in order to ensure accurate performance of a metrology tool. In this section the EUV calibration sources utilized by NIST are presented.

29.2.1 Synchrotron Ultraviolet Radiation Facility

Synchrotron radiation sources are the sources of choice for setting radiometric standards and calibration. This is because they are stable, calculable sources with

a smooth, spectrally continuous emission. An output spectrum of NIST's Synchrotron Ultraviolet Radiation Facility^{4,5} (SURF III) is shown in Fig. 29.1. It shows the continuous output spectrum as a function of wavelength for several different electron energies of the stored beam. SURF III is somewhat unusual in that it is possible to change the electron energy over a broad range and thereby tune the output spectrum as needed. This property is often exploited at SURF III to reduce the presence of higher-order and OOB radiation.⁶

Synchrotron radiation sources are generally considered cw sources; however, they are actually pulsed in nature. The radiation is pulsed at n times the synchrotron orbital frequency, where n is the number of electron bunches stored in the ring. At SURF III the radiation incident on a calibration sample is pulsed at 114 MHz. At all synchrotron-based calibration facilities, the pulse frequency is sufficiently high that the radiation is essentially a continuous stream of photons for all but the fastest detectors. Therefore, all EUV calibrations are performed in the cw mode.

Compared to the sources for EUVL, synchrotron radiation sources are extremely low-power devices. At SURF III the typical EUV power on a sample being measured rarely gets higher than a few microwatts. The low-power nature of synchrotron sources must be considered when calibrations are transferred from a synchrotron radiation source to a pulsed, high-peak-power EUV light source such as the DPPs and LPPs for EUVL, because nonlinear effects such as detector saturation will not be revealed with low-power measurements.

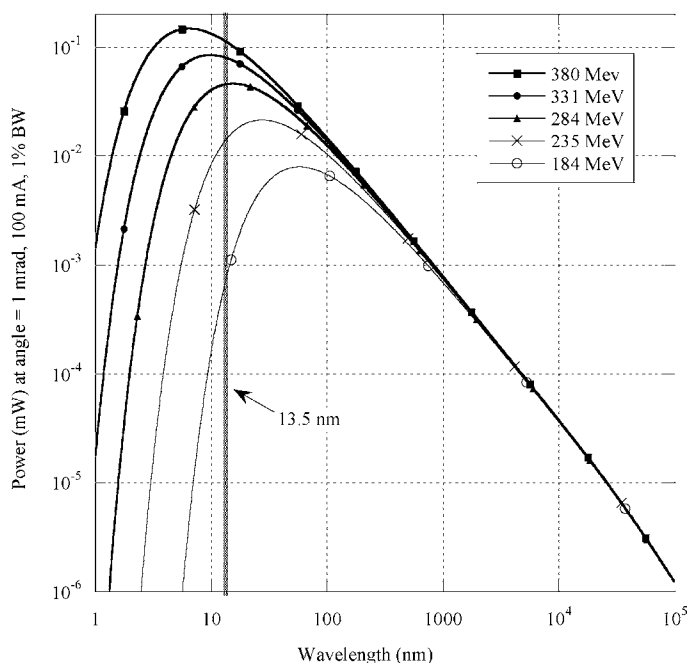


Figure 29.1 Calculated output spectrum of SURF III at various electron beam energies.

29.2.2 LPP source

NIST has assembled a Xe-based LPP source for use as a calibration tool for assembled metrology instrumentation. The source incorporates a 10-Hz Nd:YAG flashlamp-pumped *Q*-switched laser, which delivers approximately 800 mJ of 1.06- μm light in a 10-ns pulse on target. The target is a pulsed-valve Xe or Kr gas target operating at 1 Hz. The source can be cooled to cryogenic temperatures to facilitate droplet formation and increased EUV production. An identical pulsed-valve system is in place at the University of Maryland and is used to characterize the interactions of ultrashort laser pulses with clusters and droplets.⁷ Calibrations are done with a detector-based method by incorporating a working standard (WS) channel and a normalization channel for monitoring the shot-to-shot variability of source output. This method significantly reduces the measurement uncertainty by accurately mapping the shot-to-shot performance of the source.

This source has no grating monochromator, but uses the bandwidth of the Mo/Si multilayer mirrors (MLMs) to control the spectral throughput of the WS channel. A schematic of the system is shown in Fig. 29.2. The figure shows light from the LPP being collected by two separate Mo/Si MLMs and being relayed onto two detectors: one WS and one normalizing detector. Each detector has a directly deposited Zr-based filter that is approximately 300 nm thick and effectively minimizes the OOB light recorded by the detectors. After recording the ratio of the WS to the normalization detector, the WS detector's calibration can be transferred to an instrument by removing the WS detector and placing an instrument to be calibrated in the WS channel beam path. Despite fluctuations in laser intensity

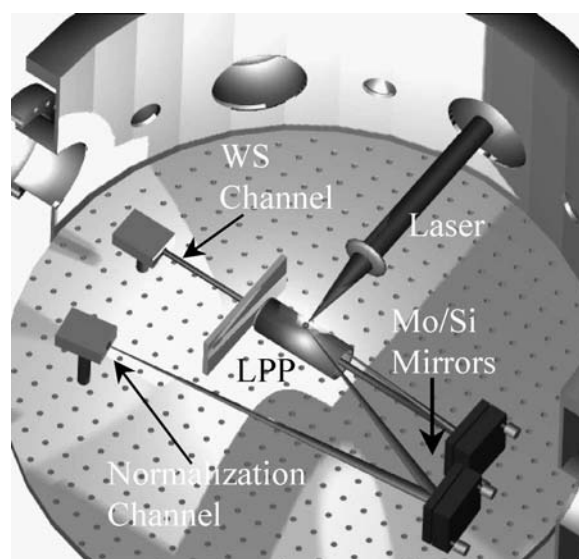


Figure 29.2 Diagram of NIST's LPP setup for EUV instrument calibration. The setup includes two Mo/Si mirrors, which relay EUV light onto a WS channel and a normalizer channel. This configuration permits the transfer of a WS calibration to EUV instrumentation.

and other shot-to-shot variations, the two-channel system is reliable and repeatable. The WS channel can insert as much as 100 nJ per pulse into a test instrument and can be varied to generate a continuous scale of input energies. A typical normalization run is shown in Fig. 29.3(A). It shows the ratio of the charge collected by the WS and normalization channels. The linear curve fit included shows that the shot-to-shot variation has little effect on the normalization and also shows that neither of the two channels is affected by saturation. Removing the WS channel and repeating the process with a test instrument in the WS channel generates a similar curve. The ratio of the slopes of the two curves determines the ratio of the

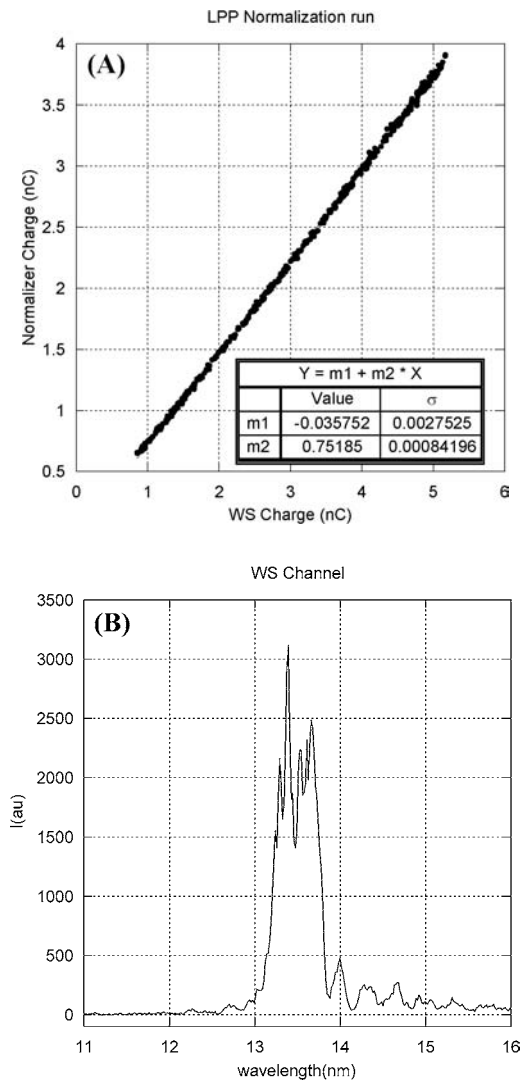


Figure 29.3 (A) Example of normalization run on an LPP calibration source, showing linear correlation between normalization and the WS channel. (B) Spectrum of the WS channel of the LPP calibration source.

inband responsivity of the WS and the test instrument, thus transferring the WS's calibration to the test instrument.

The output spectrum of the WS channel greatly influences the calibration of tested EUV instrumentation, so that spectrum has been measured and is shown in Fig. 29.3(B). In order to accurately transfer a calibration, the overlap between the WS channel's output spectrum and the test instrument's acceptance spectrum must be determined. Therefore the effects of individual components within a test instrument must be characterized to calculate the final absolute calibration. The characterization of these individual components is done at NIST on beamlines at SURF III and is described in the following sections.

29.3 Inband EUV Power Instrumentation

Instruments used for inband EUV-source power measurement are composed of four parts: a detector, a narrowband filter, a broadband filter, and a solid-angle-defining aperture. Typically, these elements take the form of, respectively, an EUV-sensitive silicon photodiode, an EUV Mo/Si MLM (or MLMs), a transmitting thin foil filter, and a precisely measured and placed aperture. Each component can be individually calibrated and their throughputs multiplied together to get a calibrated responsivity. This is the simplest technique, because the individual components are small, and typically calibration laboratories are set up to calibrate individual components for users. Calibration can also be done with a fully assembled instrument to minimize calibration errors due to misalignment and other unaccounted factors of the intact instrument. This topic is discussed in Sec. 29.6.

Since EUV exposure tools are predicted to have eight or more multilayer optics in the optical train, the effective spectral width of the throughput is reduced, because each subsequent optic in the train narrows the bandwidth. For example, eight identical mirrors would yield an inband throughput of 2% as opposed to the 4% inband reflection that is typical for a single mirror. Thus, a measurement of the usable source output requires accurate knowledge of both the original source spectrum and the spectral throughput of the optical path to the wafer plane.

It is important to know the effects of the EUV pulse duration and illuminated-spot size on a detector, since saturation effects can cause a decrease in the responsivity of a detector.⁸ It is often useful in high peak-intensity measurements to monitor the time-resolved output of the detector as one way of possibly detecting evidence of a nonlinear response. Care should also be taken to ensure that the instrument is aligned relative to the source in such a way that the actual solid angle of acceptance from the source is well defined and as insensitive as possible to movements in source position. Another reason alignment is critical is the dependence of the reflected wavelength on the angle of incidence for the MLM(s) in the radiometer.

The thin foil (typically Zr or Be) used as a broadband filter reduces the OOB radiation reflected from the MLM or scattered by optical elements within the filter radiometer by several orders of magnitude. The thin foil filters are typically 200 to

400 nm thick and can have small pinholes or spatial nonuniformities that can lead to systematic errors. One must also be concerned that background gas pressures in the optical path, especially of xenon in the xenon plasma sources, are low enough to prevent significant absorption.

Finally, it should be noted that the environment within a plasma-based EUV source is not ideal for the components of a radiometry tool. Although the sources are contained within vacuum systems, they have trace amounts of hydrocarbons and water. Both will cause the performance of a mirror, filter, or detector to change over time when they interact with EUV. In addition, ions, electrons, and debris from the plasma can also degrade the performance of the components of a metrology tool. Therefore, the assembled system or its individual components must be frequently recalibrated or even replaced to ensure accurate measurements.

29.4 Reflectometry

The NIST/DARPA EUV Reflectometry Facility was installed in the late 1980s to serve the community of multilayer optics developers. The earliest work took place on an existing beamline of what was then SURF II while a new beamline was being designed. The monochromator was designed with the goal of optimizing performance for measurement of Mo/Si MLMs. The wavelength coverage is 3 to 40 nm, with high throughput and modest resolution. The sample chamber was designed to measure actual EUVL optics. In 1994 the largest optics predicted for a commercial system were 35 cm in diameter. The goniometer was designed to be able to measure the entire surface of an optic 35 cm in diameter and 15 cm thick.

29.4.1 Monochromator

Figure 29.4 shows a schematic of the monochromator, which is described fully in Watts et al.⁹ A Ni-coated toroidal mirror is located 254 cm from the tangent point of

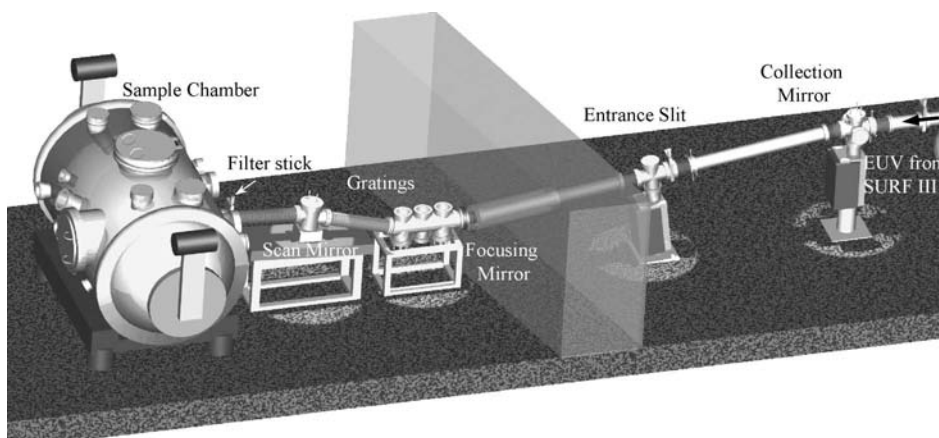


Figure 29.4 Schematic of NIST/DARPA EUV reflectometer facility at SURF III.

SURF III. This mirror collects virtually all of the vertical emission and 20 mrad of the horizontal emission of EUV radiation from SURF III. The radiation is focused 1:1 onto the entrance slit, then is deflected by a second toroidal mirror 325 cm downstream from the entrance slit. Both toroids operate at a 3-deg grazing angle. The gratings are 40 cm from the second toroid. The gratings are plane, varied-line-space ruled gratings with gold surfaces. The first operates at a 5-deg grazing angle, from 10 to 40 nm, with 600 lines/mm. The second operates at a 3.5-deg grazing angle from 3 to 14 nm, with 1500 lines/mm. Wavelength is scanned by rotating and translating a gold-coated plane mirror. The vertical focus is at the exit slit, which is 247 cm downstream from the gratings, while the horizontal focus is at the sample, 30 cm farther downstream. All reflections are in the vertical plane, and the radiation incident on the sample is 96% horizontally polarized.

Higher grating orders are reduced by the use of thin-foil filters. The following filters are currently in use in this system: 500-nm-thick carbon foil, used over the approximate range 4.5–8 nm; 500-nm-thick boron foil, 7–12 nm; 1000-nm-thick beryllium foil, 11.5–20 nm; 500-nm-thick aluminum foil, 17.5–34 nm. Scans can be made throughout the full range from 3 to 40 nm, and other filters appropriate for the expanded range can be inserted into the beam if there is interest from customers. Each of these filters rejects virtually all second-order radiation and provides radiation with less than 1% contribution from higher orders.

The spectral purity of the monochromator's output near 13.5 nm has been characterized by running it under various electron-beam and filtering conditions.⁶ In this study it was found that under standard operating conditions of 380-MeV stored beam energy, there is a contribution due to broadband scatter of 0.5%, with an additional contribution of higher-order radiation (third order and above) of 0.2%. It was also found that an additional narrowband scatter component can be deconvolved from the measured reflectivity and typically reduces the measured peak reflectivity of a 40-period multilayer by a relative amount of 1.1%. The root-sum-square expanded uncertainty in correcting for all of these factors, discussed completely in Ref. 6, is 0.35%. (All uncertainties in this chapter, unless otherwise stated, are given as the combined standard uncertainty with a coverage factor $k = 1$.) The characterization of the uncertainty of the NIST/DARPA EUV Reflectometry Facility in the 13-nm region was done in great detail and is fully addressed elsewhere.⁶

Figure 29.5 shows the throughput of this beamline. The data are normalized to the stored beam current. A typical average current is about 200 mA, with a peak current of 300 mA. Peak throughput in the region around 13 nm is about 10^{11} photons/s, corresponding to about 2 μ W. A typical EUV detector has a noise floor of a few picowatts, leading to a dynamic range in the beamline of over five orders of magnitude.

Reflectivity measurements are made by measuring the photocurrent generated in the detector when it is exposed to the incident beam and then the reflected beam. However, these measurements cannot be made simultaneously, and the stored beam current is continuously decaying. The output of the monochromator is normalized by incorporating a unique double-exit slit design. Two slits lie in the exit slit plane

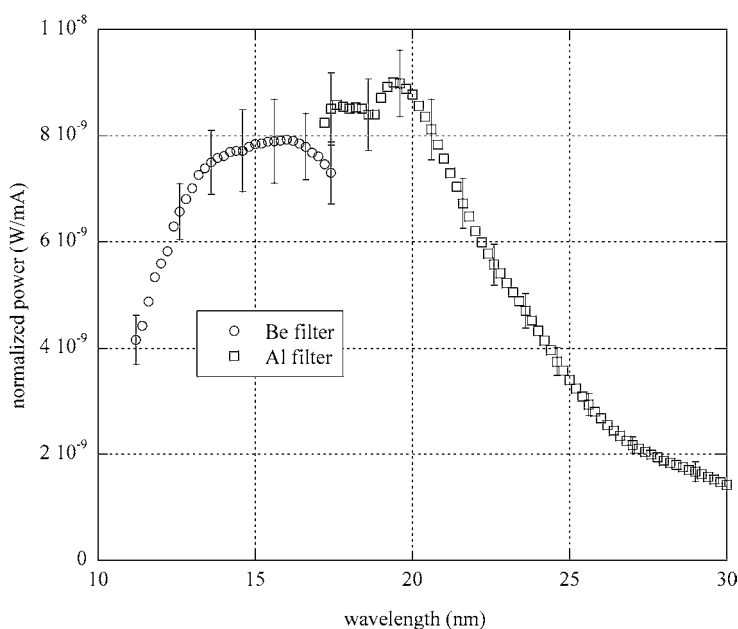


Figure 29.5 Optical throughput of the NIST/DARPA EUV reflectometer. Uncertainties are shown at the detector calibration wavelengths. Since there is little structure in the detector responsivity in this wavelength regime, a linear extrapolation of the responsivity is done between the calibration points. The uncertainty of extrapolation is negligible in comparison with the calibration uncertainty.

of the monochromator: one is open, and the second, 5 mm below the first, incorporates a detector that is butted directly at the slit's output. The open slit allows light to exit the monochromator and impinge on the sample plane 30 cm beyond the slit. The signal from the detector at the lower slit accurately follows the open slit's output with an uncertainty approaching 0.1%. This system allows for accurate tracking of the input power on a sample under test.

The spectral resolution of the monochromator is modest. The beamline is generally run with slit widths of 0.5 mm, which gives a resolving power of about 200. Resolving power up to 1000 can be achieved using the 1500-line/mm grating; however, this grating does not cover the full range of a typical EUVL MLM measurement.

29.4.2 Sample chamber

The reflectometer sample chamber is a large cylindrical vessel, which has a diameter of 2 m and a length of 3 m and houses six axes of sample motion. The linear stages allow ± 17 cm of motion in X , ± 10 cm of motion in Y , and ± 5 cm of motion in Z . The angular motions include ± 90 deg of pitch, continuous 360 deg of roll, and ± 30 deg of yaw. The chamber also houses a detector arm that rotates almost a full 360 deg and holds two EUV-sensitive photodetectors: one uncoated Si photodiode and one with a directly deposited Zr/Si filter. These detectors can

be interchanged and adjusted to record reflections up to 15 deg off axis. An EUV-sensitive CCD camera is also mounted on the detector arm, and is used to observe the incident and reflected EUV beams to determine sample alignment.

The large-scale motion stage allows for position-dependent reflectivity maps on large, complex-shaped optics. One example of this is shown in Fig. 29.6. This figure shows an EUV reflectivity map of a condenser optic used within Sandia National Laboratory's Engineering Test Stand (ETS).¹⁰ This map was obtained by setting the wavelength to 13.3 nm and making a series of azimuthal (roll) angle scans as a function of radius. For each radius, the sample height (z) had to be changed, as well as the yaw (sample surface slope) and pitch (operating angle of incidence) angles. The optic had been directly exposed to the plasma environment of the ETS's Xe LPP source. Exposure to the plasma damaged the optic and removed several of the Mo/Si bilayers on it, and the resulting reflectivity map shows a spatially dependent reflectivity. A plasma or EUV environment can reduce the reflectivity by sputtering, surface roughening, material deposition, heating, intermixing, and/or oxidation.

Another application for this beamline is the measurement of the transmission of EUV filters. These filters, typically based on Be or Zr, are used in radiometry instruments to filter out visible and OOB UV light to ensure spectrally pure EUV signals on detectors. The performance of a filter can also change when it is kept in a plasma environment, and it may need frequent recalibration. Figure 29.7 shows the filter calibration curves for an EUV radiometry tool. These curves show the transmission of the filters before and after they were used in measurements of a plasma-based EUV source. The transmission of the filters is reduced by about 2% due to the exposure to the EUV-source environment.

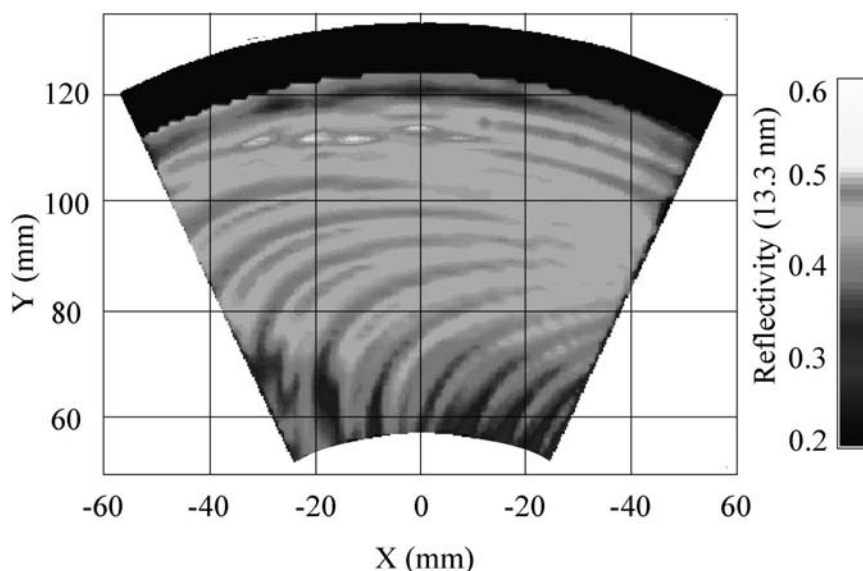


Figure 29.6 EUV (13.3 nm) reflectivity map of C1 petal used in the ETS.

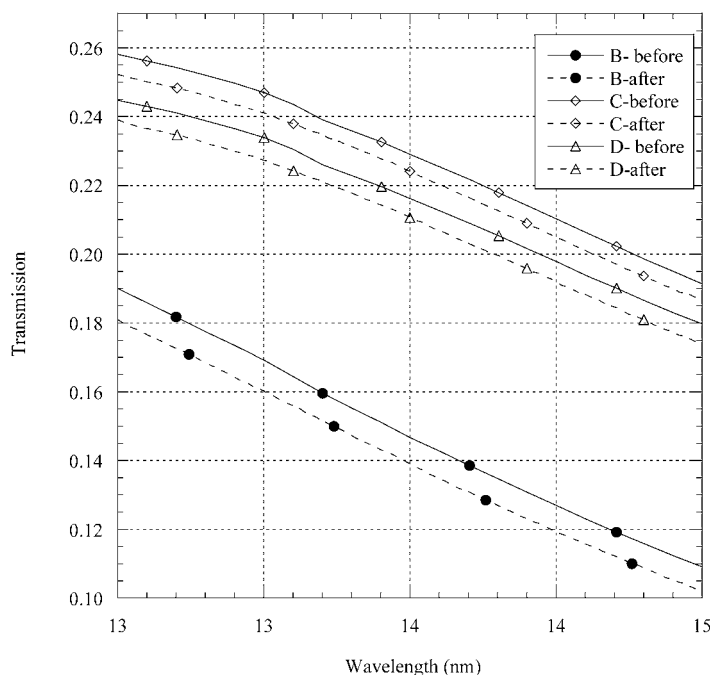


Figure 29.7 Measurements of transmission of EUV Zr-based thin foil filters before and after use within a radiometry tool deployed on a plasma-based EUV source. The uncertainty is 1%, which is less than the changes in transmission, which are >2%.

Another application of the NIST/DARPA EUV reflectometer uses grazing-incidence transfer optics placed within the sample chamber to bring the EUV radiation level and relay it out a port on the back of the chamber. The transfer optics included a plane mirror at a 2-deg grazing angle and a cylindrical mirror (50.4-mm radius of curvature) at a 4-deg grazing angle. This second optic reduces the horizontal divergence to about 1/10 its initial value and permits a small (4×4 mm) EUV spot to be relayed into an external end station. One such end station is an absolute cryogenic radiometer used for absolute detector calibrations in the EUV.²⁵ This procedure is outlined in the next section. End stations are also used for the calibration of assembled radiometry tools, as outlined in Sec. 29.6.

29.5 Detector Characterization

The heart of every radiometry tool is its detector. These devices convert the incident optical energy into an easily measurable—typically electrical—form of energy. For nearly two decades the workhorse of EUV radiometry has been the *np* Si photodiode^{11–14} with a thin, often radiation-hardened SiO₂ passivating layer and nearly 100% internal quantum efficiency. These devices combine efficient detection of the 13.5-nm wavelength radiation used for EUVL with good radiometric characteristics, including spatial uniformity, linearity, radiation hardness, and long-term stability.

Silicon photodiodes for use in the EUV are typically fabricated from *p*-doped epitaxial wafers. The front region is *n*-doped to create an *np* junction. The semiconductor heterojunction develops an internal electric field and a depletion region in the Si devoid of free carriers. Incident radiation is absorbed, generating electron-hole pairs. The pairs generated near the depletion region are separated by the internal electric field, with the electrons drifting toward the cathode and the holes toward the anode. The charge separation gives rise to an electric current flowing across the junction that can be measured by external electronics. The magnitude of this current is proportional to the intensity of the incident radiation. Detailed descriptions of the internal mechanisms of photodetection and the physics of semiconductor heterojunctions can be found in many textbooks (see, for example, Ref. 15).

Currently, all absolute EUV detector calibration facilities worldwide use synchrotron radiation from an electron storage ring as a source of radiation or use reference standards based on calibrations made at synchrotron radiation facilities. As stated in Sec. 29.2.1, these calibrations are essentially cw in nature, and since all EUVL sources are pulsed devices, the transfer of a cw calibration to a pulsed application is an important area of active research.⁸

29.5.1 Detector characteristics

29.5.1.1 Quantum efficiency

The external quantum efficiency of a photodetector is defined as the number of electrons flowing in an external circuit per incident photon. A typical quantum efficiency curve (measured at NIST) is shown in Fig. 29.8. There are several primary factors that influence the quantum efficiency of the device: the electron-hole pair creation energy, the transmission of surface films, and surface recombination. In the EUV, the electron-hole pair creation energy in Si is 3.66 eV,¹⁶ and is independent of wavelength. The transmission of surface films depends on the thickness of the passivating layer, the presence of bandpass limiting filters (discussed below), and any contamination that may have accumulated on the active area of the photodiode. A typical passivating layer is 6 nm of SiO₂ and has a transmission of 94% at 13.5-nm wavelength. The most common contamination on the surface is C; a 5-nm film of C transmits 97% of the incident 13.5-nm radiation.¹⁷

Surface recombination is a device-dependant loss mechanism that is important for radiation absorbed near the front surface of the photodiode. This loss mechanism can be considered as a reduction in the charge collection efficiency from the front region of the photodiode. Neglecting surface recombination and reflectivity, the quantum efficiency η of a photodiode is a function of the photon energy E and is given by

$$\eta(E) = \frac{E}{W_{\text{Si}}(E)} T(E), \quad (29.1)$$

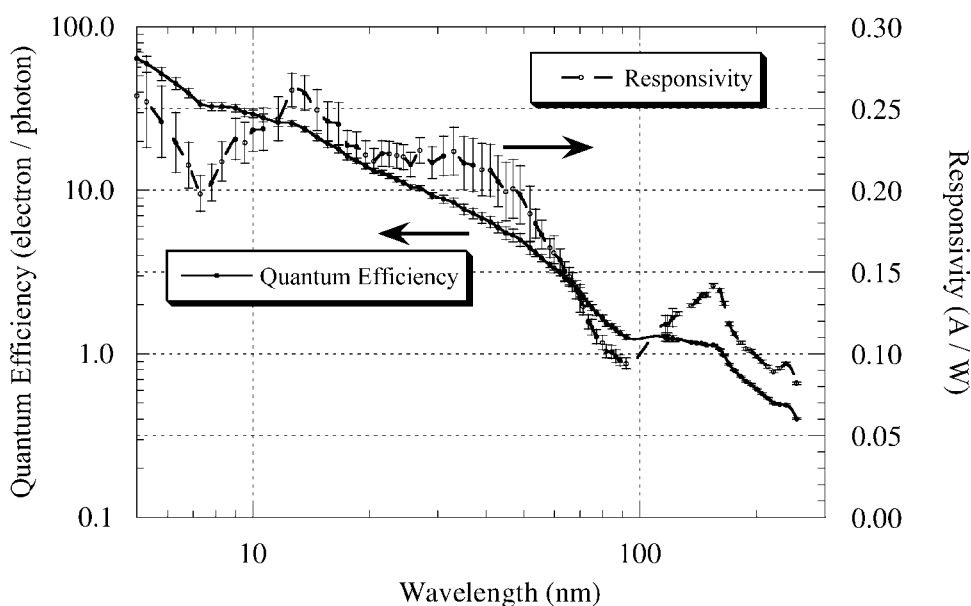


Figure 29.8 A typical quantum efficiency (filled circles; left axis) and responsivity (open circles; right axis) curve for a radiation-hardened, EUV-sensitive Si photodiode. Note that the quantum efficiency axis is logarithmic while the responsivity axis is linear. Only the VUV spectral region is shown here, but uncoated Si photodiodes respond to incident radiation from the x-ray region to the IR.

where T is the transmission of the surface films (i.e., the passivating layer, any bandpass limiting filters, and possibly a contamination layer), and W_{Si} is the electron-hole creation energy. The quantum efficiency is related to the photodiode responsivity R (current flowing in an external circuit per unit incident optical power) by

$$R(E) = \frac{\eta(E)q}{E}, \quad (29.2)$$

where q is the electronic charge.

29.5.1.2 Stability

The stability of the quantum efficiency will help determine the recalibration frequency for any radiometry tool. There are two types of stability that are important: temporal stability during storage, and radiation hardness during use. Si photodiodes with radiation-hardened passivating oxide layers exhibit significantly improved performance in both types of stability over native oxide passivated devices.

The native SiO_2 passivating layer on photodiodes is easily damaged by the incident radiation, particularly when there is strong absorption in the SiO_2 . The damage is a result of trap sites that form in the SiO_2 and collect at the Si-SiO₂ interface.¹⁸ The presence of these trap sites increases the surface recombination loss of photogenerated carriers and decreases the quantum efficiency of the device.

Incorporating nitrogen into the passivating layer significantly reduces the device's susceptibility to radiation-induced damage.¹³

The long-term stability of these devices when stored has been demonstrated by repeated calibration of detectors at NIST. Over the course of a year, the quantum efficiency of a family of three devices was observed to be constant, varying only randomly with a standard deviation on the order of 0.2%, which is the measurement repeatability. A high degree of stability has also been demonstrated in a 100%-relative-humidity environment over a four-week period.¹³ This resistance to water-vapor-induced degradation is a significant improvement over native oxides.

29.5.1.3 Speed

In a pulsed application, the detector's intrinsic speed is a significant factor. The response from one pulse must be completely discharged prior to the arrival of the next pulse, or pulse-stacking will occur. The device speed is determined principally by the junction capacitance, which appears with the load resistance as the RC time constant in a capacitive discharge circuit. Junction capacitance scales linearly with the photodiode active area, so smaller devices are faster devices. The capacitance can be decreased by reverse-biasing a photodiode, as described in Sec. 29.5.3. The calibration of small devices is problematic, since it is crucial for the detector to be underfilled during the calibration. Traditionally, 10×10 -mm devices have been used for transfer standards because of their large active area.

29.5.1.4 Uniformity

The spatial uniformity of quantum efficiency is another important detector characteristic. Errors in measurement will result when two photon beams (e.g., incident and reflected beams in a reflectometer) strike different parts of the photodiode. Errors will occur even if the two beams are both well centered if the intensity profiles of the beams are different, as may be the case in transferring a calibration from the NIST laboratory to the user's laboratory. The radiation-hardened Si photodiodes have been measured to have a peak-to-valley variation in quantum efficiency on the order of 1%¹¹ at 121.6 nm and 0.1%¹² at 11.3 nm over the full 100-mm² active area.

29.5.1.5 Linearity

At high signal strengths, the linearity of the photodiode is important. As saturation sets in, the quantum efficiency of the photodiode can change. Devices with 100% internal quantum efficiency [$\eta(E)/T(E)$] show good linearity at photocurrents in excess of 3 mA when unbiased and illuminated with visible cw radiation.¹¹ A lower internal efficiency indicates the presence of trap sites that lead to surface recombination losses. Devices with an internal quantum efficiency less than unity show an increase in quantum efficiency at low incident powers as trap sites are filled and the recombination losses are mitigated. At higher incident powers, the quantum efficiency falls dramatically. Saturation effects are a major concern in

the measurement of pulse energy, because the peak power of a short pulse is very high, even when the average power is low. This problem is discussed more fully in Sec. 29.5.3.

29.5.1.6 Out-of-band response

As seen in Fig. 29.8, Si photodiodes have an intrinsically broadband response. The 1.1-eV indirect bandgap means that the cutoff wavelength for absorption in the Si is in the IR portion of the electromagnetic spectrum at 1.1- μm wavelength. The short wavelength limit is determined by the transmission of the incident radiation beyond the depletion region of the device and is typically in the x-ray portion of the spectrum between 5- and 10-keV photon energy. Si photodiodes are therefore sensitive to OOB radiation from an EUVL source. The spectral response of a Si photodiode may be limited by depositing a thin film of filter material directly on the photodiode active area.¹⁹ Films of Zr- or Si-containing systems (e.g., Mo/Si or Zr/Si) make good spectral filters for isolating the 13.5-nm wavelength of interest for EUVL.

29.5.2 Synchrotron-based calibrations

29.5.2.1 NIST photodiode calibration facilities

The NIST photodiode calibration activities in the EUV are carried out at the EUV Detector Radiometry Beamline²⁰ at SURF III. This beamline is a grazing-incidence toroidal grating monochromator with a fixed exit slit. There are no collection optics at the front of the beamline, so the solid angle of collected radiation, and hence the beamline throughput, are quite modest (a few nanowatts). However, the monochromator exit beam is well collimated, allowing measurement stations to be separated by about 1 m of path length without significant change in the beam size. Also, effects arising from oblique incidence on the detector that are present in beams with a high numerical aperture are absent in this beamline. There are two interchangeable gratings, one covering the spectral region from 5 to 18 nm, and the other from 17 to 50 nm.

The beamline houses an ionization chamber for absolute measurement of the photon flux from the monochromator.²¹ A WS photodiode is calibrated against the ionization chamber, and then outgoing transfer standard detectors are calibrated against the WS by interchanging the two detectors in the photon beam. A second end station with an adjustable aperture can be installed to calibrate small photodiodes or to scan large-area detectors to measure the spatial uniformity of the quantum efficiency. The details of the calibration procedures are described elsewhere.²²

29.5.2.2 Ionization chamber

NIST has a calibration system²³ based on an ionization chamber that covers the entire region from 5 to 50 nm. The ionization chamber uses Ne as the absorbing rare gas and operates in the single-plate mode. Incident photons are absorbed in

the Ne and generate ion-electron pairs that are separated by an applied electric field. The ions are collected at the cathode, and the photocurrent is measured. From knowledge of the gas photoabsorption cross section, the path length in the Ne, and the gas density (usually calculated from pressure and temperature), one can derive the incident photon flux. A photodiode is calibrated by inserting it into the photon beam of known flux and measuring the photogenerated current.

29.5.2.3 Absolute cryogenic radiometer

The most accurate instrument for the measurement of optical power is an absolute cryogenic radiometer (ACR). This instrument is an electrical substitution radiometer (ESR) operated at liquid-He temperature. In an ESR, a receiver cavity is maintained at constant temperature with no incident radiation. For an ACR, that temperature, slightly above the liquid-He temperature (4.2 K), is maintained by a thermal link between the receiver cavity and a liquid-He bath and electrical heaters on the cavity. When the shutter is opened, the optical radiation is absorbed by the cavity and converted into heat, thus reducing the amount of electrical power required to maintain the constant temperature. The measured reduction in electrical power is equal to the optical power. A typical data acquisition sequence is shown in Fig. 29.9. The responsivity of a photodiode is measured by determining the power

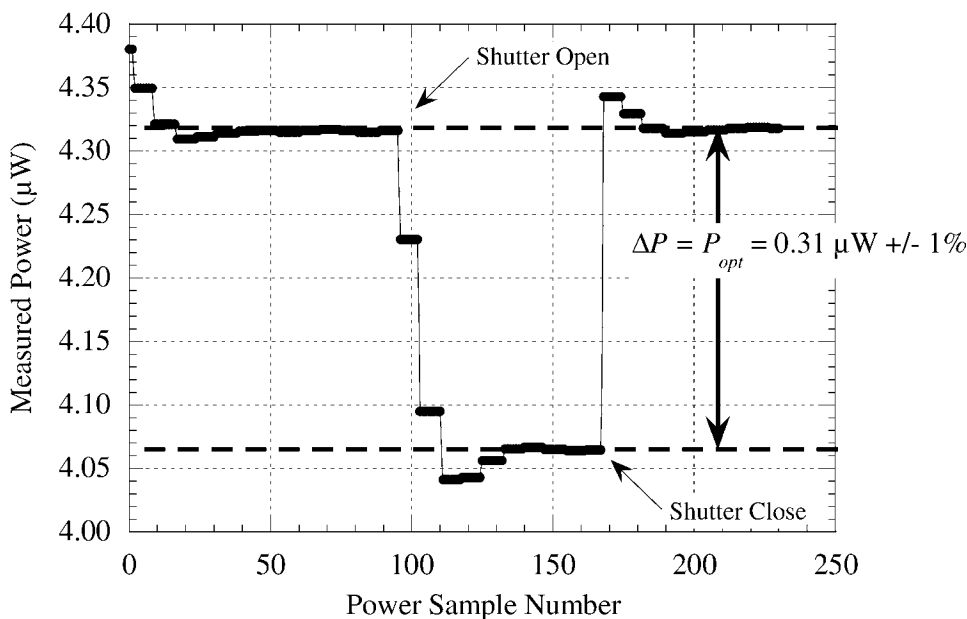


Figure 29.9 Data acquisition sequence for optical power measurement with an ACR. The electrical power required to maintain a constant temperature in the receiver cavity is shown. The ringing at the points where the shutter is opened and closed is due to the thermal time constant of the system and the control-electronics algorithm. Here ΔP is the change in power needed to maintain the ACR cavity at constant temperature and is equal to the optical power (P_{opt}) absorbed by the ACR cavity.

in an EUV beam from a monochromator with an ACR, then inserting the photodiode into the beam, and then measuring the photocurrent generated by the known power. The photodiode quantum efficiency can be calculated from Eq. (29.2).²⁴

NIST has recently implemented an ACR on the previously described beam-line normally used for reflectometry. A set of transfer optics steers and collimates the beam through the reflectometer.²⁵ The resulting beam spot is approximately 4×4 mm and is relayed to a chamber outside the reflectometer. Using this ACR-based system, NIST has calibrated an uncoated Si photodiode and a Si photodiode with a Si/Zr bandpass limiting filter. The relative combined standard uncertainty of the calibration is still under evaluation, but is on the order of 1%. The ACR-based calibration covers the wavelength range from 11 to 35 nm, which includes the 13.5-nm EUVL wavelength. The ionization chamber described above is used in conjunction with the ACR to extend the calibration range from 5 to 50 nm. Figure 29.10 shows the excellent agreement between the two calibration methods.

29.5.3 Pulsed response of Si photodiodes

Perhaps the greatest difficulty in EUVL radiometry is understanding the issues arising from the pulsed nature of the source. The number of electron-hole pairs initially generated per incident photon will be the same as in the cw case, but the high peak power in a short pulse may cause saturation effects even when the average power is modest, and at high source repetition rates pulse-stacking will occur. These effects may change the external quantum efficiency of the device.

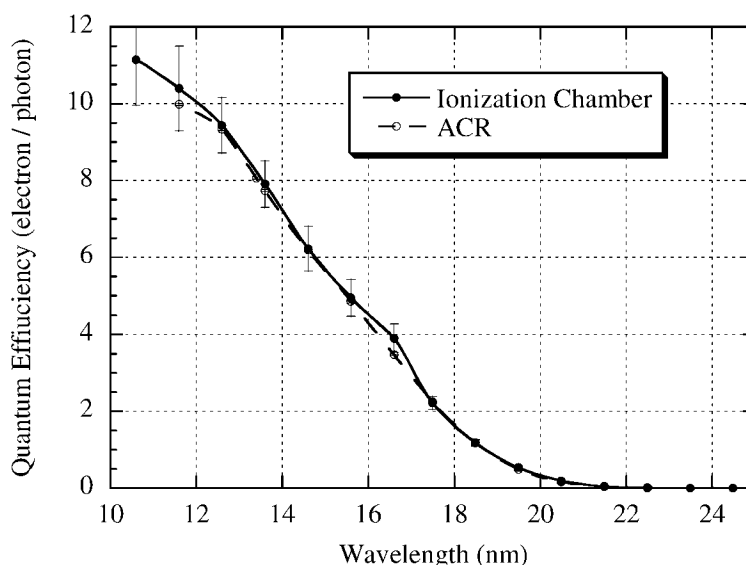


Figure 29.10 Quantum efficiency of a Ti-Zr-C-coated Si photodiode for use in EUVL calibrations. The difference between the efficiency derived from an ACR-based calibration and from an ionization-chamber-based calibration is well within the uncertainty of the calibrations. The uncertainty of the ACR measurement is 1%.

29.5.3.1 Bias electronics

In pulsed radiometry, the photodiode should always be reverse biased to increase the speed of the device. To fairly good approximation, the junction capacitance varies inversely as the square root of the reverse bias, and the time constant is linearly related to the junction capacitance. The bias circuit should provide an ac-coupled path to the measurement instrumentation (typically an oscilloscope) and a current-limited path from the voltage source. The capacitance and resistance values in the bias circuit must be chosen to minimize the effect on the load resistance seen by the photodiode and the reduction in the photodiode capacitive-discharge time constant. Additionally, the voltage supply must be able to restore the full reverse bias potential across the photodiode in the interval between pulses. Bias electronics design is not a trivial task and should be approached with some care.

29.5.3.2 Saturation

It has recently been demonstrated⁸ that the response of a Si photodiode to 10-ns pulses of visible (532-nm wavelength) radiation shows evidence of saturation effects at even the lowest peak power levels measured (1 nJ in 8.25 ns, ≈ 120 mW). The useful dynamic range of the photodiode depends on the accuracy required for the radiometry and the knowledge of the nonlinear dependence of quantum efficiency on power. A model has been developed that attributes the loss of efficiency to increased recombination loss of the photogenerated carriers. The presence of these photogenerated carriers is responsible for the decreased carrier lifetime in the semiconductor, and thus for the reduction in external quantum efficiency.

The model predicts, and experiment confirms, that the photodiode responsivity can be fitted with a curve that requires two calibration factors: one is the cw responsivity, and the other describes the saturation characteristics of the device. The responsivity R as a function of pulse energy E_{pulse} is⁸

$$R(E_{\text{pulse}}) = \frac{R_{\text{cw}}}{1 + \beta E_{\text{pulse}}}, \quad (29.3)$$

where R_{cw} is the responsivity measured in a low-power cw calibration system and β is the nonlinear calibration factor. NIST is currently developing methods for the measurement of this nonlinear response to pulsed radiation in the EUV.

29.5.4 Other detector technologies

There are alternatives to the radiation-hardened Si photodiodes for EUVL radiometry, but each alternative has drawbacks.

The radiation hardness of Si *np* junction photodiodes with the passivating oxide layer completely removed and replaced by a metal silicide (e.g., PtSi, HfSi) or diamondlike carbon is significantly better than that of oxide-passivated devices.¹¹ However, these devices have a quantum efficiency that is significantly lower than

the nitrided-oxide devices and are often noisier. Schottky barrier devices with a PtSi metal layer have also been fabricated,²⁶ but these devices can also be noisy.

The sensitivity to visible and IR radiation can be eliminated by using a semiconductor with a wider bandgap than Si. Significant material quality problems remain with the wide-bandgap semiconductors (e.g., SiC, GaN, AlGaIn).²⁷ Although progress is constantly being made, these materials are not yet suitable for radiometric applications.

Photoemissive devices are inherently insensitive to long-wavelength OOB radiation, and photoemission is an extremely fast process, but such devices have significantly lower quantum efficiency than solid-state devices, and their quantum efficiency is very sensitive to their surface condition. Especially in source evaluation, a windowless photoemissive device may not be stable, due to surface contamination from source debris.

29.6 Calibration of EUV Radiometry Tools

This chapter has mostly discussed the calibration of individual components, not assembled radiometry instruments. This is due to the fact that individual components are routinely calibrated at synchrotron radiation facilities, because it requires less effort to ship and calibrate components than to ship an assembled tool and possibly design custom hardware to interface the tool to an existing beamline. Therefore the cost and availability of individual component calibrations are more appropriate for the frequent calibrations necessary to maintain a well-characterized radiometry tool. With this said, it is still necessary to do an occasional calibration on a fully assembled calibration tool. Though the response of an assembled tool can be modeled through the responsivity of individual components, it may not reveal the full story of the calibration of the instrument. Apertures, filter and mirror nonuniformities, and mirror angle of incidence all have an effect on the total throughput of an instrument and its resulting responsivity. In this section a calibration of a fully assembled radiometry tool will be described.

29.6.1 Tool description

The Flying Circus 2 (FC2) is an instrument that has been in development for several years and is often used by EUV source developers to determine the performance of an EUV source under various conditions. It has been designed to measure the performance of sources under a variety of conditions and configurations. It is composed of a single-apertured MLM, thin foil filters, and an EUV-sensitive photodetector. The FC2's performance has been well documented.²⁸

29.6.2 Calibration setup and results

The calibration of an assembled FC2 requires the ability to place a measured amount of EUV light in the aperture of the instrument and record the signal at

its detector. This can be done at the NIST/DARPA EUV reflectometry facility with the use of the transfer optics described in Sec. 29.4. A schematic of the layout is shown in Fig. 29.11. It shows the transfer optics relaying an EUV beam into the FC2. The light is incident upon the Mo/Si MLM of the FC2, which reflects the beam to a filter on the *filter wheel* and subsequently to a filtered detector. In this configuration the FC2 incorporates three thin foil Zr filters in its filter wheel and a single static Zr filter directly in front of the detector. The detector is an EUV-sensitive photodiode. Typically an aperture is used at the mirror plane to define the solid angle of the radiometer; however, because the output of the transfer optics underfills the mirror of the FC2, this is unnecessary for the SURF calibration. In addition, these measurements were conducted using pristine MLMs that had not been used in previous source measurements in order to avoid possible nonuniformities that can be caused by exposure to a plasma environment.

The calibration is performed by inserting a filtered transfer standard diode, calibrated with the ACR described in the previous section, and recording the amount of incident signal for a given normalization signal (from the lower slit detector on the reflectometer described in Sec. 29.4.1) during a wavelength scan. The transfer standard is then removed, and the incident EUV enters the FC2 and is relayed to the detector plane. This is repeated for the four filter-wheel combinations (no filter, filter A, filter B, and filter C). These measurements can be directly compared with expectations based on individual component measurements and modeling of reflectivity changes due to angle. The values of some of these measurements and their predicted results are shown in Fig. 29.12. This figure shows responsivity curves versus wavelength. The curves are dominated by the reflectivity of the FC2's Mo/Si multilayer but also include effects from the filter and detector response.

The direct measurements and their modeled performance show good agreement, each lying well within the uncertainties shown in the individual figures. These experiments show that individual component calibrations can provide an adequate calibration of an assembled instrument. However, since the uncertainties of several individual calibrations add up in quadrature, the modeled uncertainty can be higher than that of a fully assembled calibration. Complementary measurements utilizing the LPP calibration source described in Sec. 29.2.2 are currently underway at NIST.

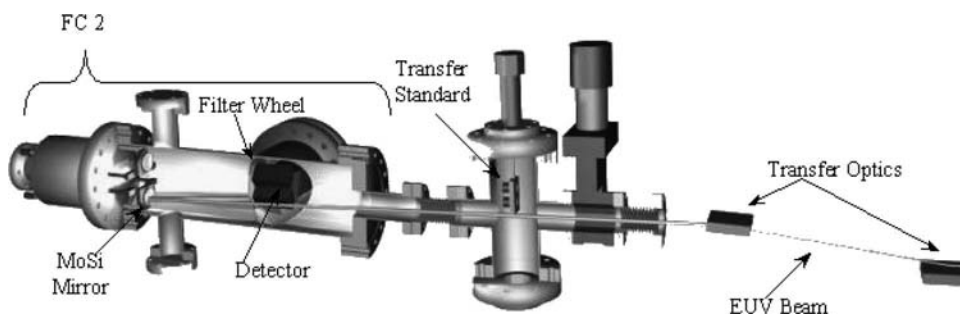


Figure 29.11 Schematic of the layout used for calibration of the assembled FC.

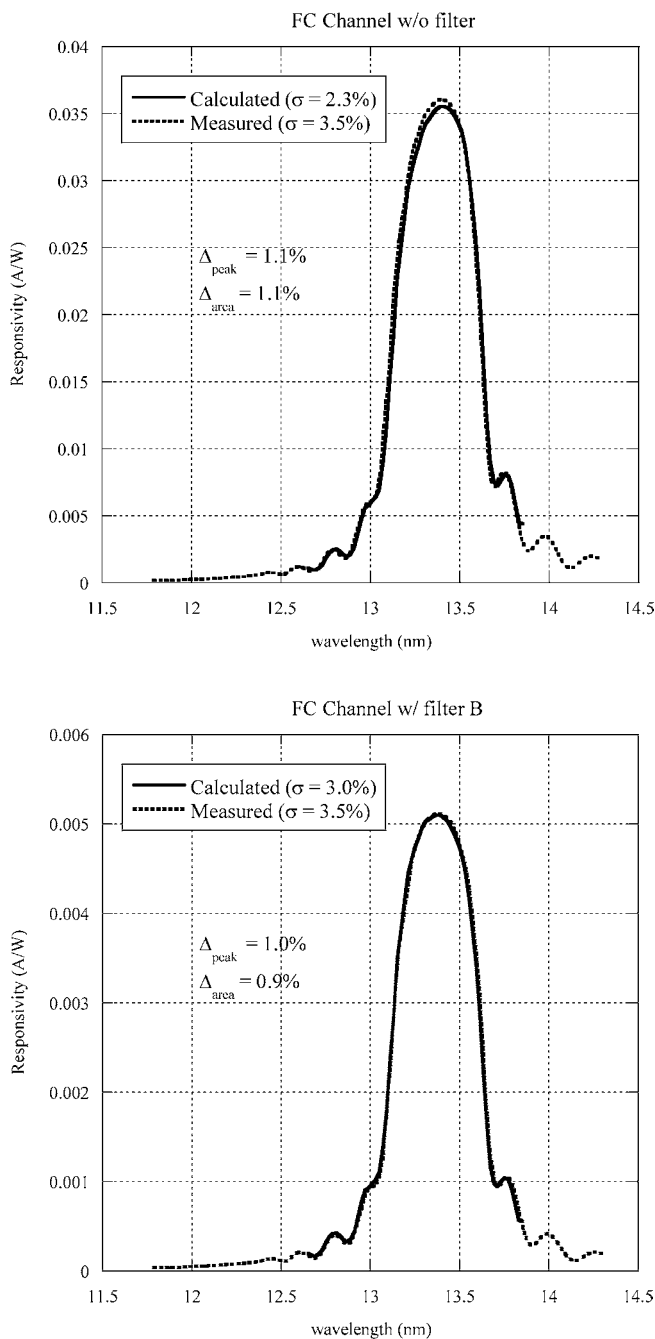


Figure 29.12 Results of assembled FC calibration compared with calculations based on individual component measurements made at NIST. Here, Δ_{peak} represents the difference between the peak responsivity values, and Δ_{area} represents the difference in the integrated responsivity over the 12.8- to 13.8-nm range.

29.7 Conclusion

The current capabilities of EUV metrology are meeting the needs of today's source developers. The results are a variety of tools that provide the necessary means to determine a source's performance and allow source cross-comparison despite differences in source design and geometry. There are still questions, however. With cw calibrations being applied to pulsed measurements, there is a need to fully address the relationship between pulsed and cw detector calibrations. This will become even more important as the source parameters approach the levels required by EUVL. The peak intensity in the intermediate plane will approach 1 MW/cm^2 , and diagnostics must be developed for linear operation in this high-intensity environment. Furthermore, high repetition rates will require faster diagnostics to reduce the effects of pulse-stacking. In addition, with the implementation of EUVL, tools will be required for more specialized metrology for monitors within the system at various locations such as the wafer plane, and EUV metrology tool developers will have to improve and adapt existing systems or develop new ones to meet these needs. The calibration facilities and techniques described here will help provide the basis for those upcoming needs and aid with the development of new techniques and instrumentation.

NIST is working to expand its program as well. An LPP source and instrumentation are in place, and calibration of an assembled EUV metrology tool is underway in order to determine the effects of the pulsed nature of an EUV source on a cw-calibrated instrument. The NIST/DARPA reflectometer has been modified to accept other assembled EUV metrology tools, and there are plans to modify the monochromator to meet the needs for reflectometry of the projection optics within an EUVL tool. Finally, the detector calibration program at NIST will also be upgraded. The EUV detector calibration facility at SURF III will be modified to improve the rejection of the second and third grating orders to decrease the uncertainty of the photodiode calibrations. Also, additional detectors will be directly calibrated with an ACR over a broader wavelength range than shown here to expand the ACR-covered range of the EUV detector calibration facility.

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Thomas Lucatorto received his Ph.D. from Columbia University for work on atomic structure. He is a fellow of the American Physical Society and is the recipient of the Department of Commerce Silver Medal. He has been the leader of the Photon Physics Group at NIST for the last two decades. That group initiated a program in EUV metrology in 1989 to aid in characterizing the EUV optics for astronomy, fusion plasma diagnostics, laser development, and the original AT&T program to explore EUVL as a possible next-generation lithography.

Chapter 30

Calibration of Detectors and Tools for EUV-Source Metrology

Frank Scholze and Gerhard Ulm

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30.1 Introduction

The routine availability of high-accuracy soft-x-ray radiometry is a prerequisite for the development of EUVL as the next-generation lithography (NGL).^{1,2} A main issue for EUVL is the ability to produce sufficient levels of EUV radiant power.^{3,4} Therefore, well-characterized radiation detectors that work reliably

over long periods of time at high irradiation levels are needed. This development has caused an increasing need for radiometric standards and quantitative radiometric measurements.⁵ In order to meet these demands, the Physikalisch-Technische Bundesanstalt (PTB) radiometry laboratory at the BESSY II electron storage ring pursues the characterization and calibration of radiation detectors and tools in the VUV and soft-x-ray spectral regions as a major task.⁶

The PTB has been providing EUV calibration services for many years within the European EUCLIDES⁷ and MEDEA⁸ projects at a dedicated radiometry beamline at the BESSY I^{9–11} electron storage ring and, from the year 2000, at the BESSY II electron storage ring,¹² exploiting the benefits offered by this third-generation facility. A large reflectometer enables the PTB to characterize EUVL optics up to 550 mm in diameter and 50 kg in mass,^{13,14} meeting the demands for the present designs of projection optics.¹⁵ For the spectral reflectance of a mirror in the EUV spectral region, a relative uncertainty of $u = 0.14\%$ is achieved.¹⁶

The radiometric approach made at PTB to the calibration of detectors in the EUV spectral range is the comparison with a primary detector standard, a cryogenic electrical substitution radiometer (ESR) operated at liquid-He temperature¹⁷ using monochromatized synchrotron radiation. The operating principle of an ESR is that an absorber transforms the incident radiant power into a heat flow directed through a heat link to a heat sink kept at constant temperature. The radiant power equals the change in the electrical heater power required for keeping the absorber temperature at a constant value when the radiation shutter is opened. Photodiodes are calibrated as transfer detector standards with a relative uncertainty of $u = 0.26\%$ by direct comparison with the radiometer.¹⁶ The calibration of tools for source characterization is thus directly traced to the SI system of units.^{18,19}

The calibrations at PTB use monochromatized synchrotron radiation, a quasi-dc radiation with a rather low radiant power of about 1 μW . For EUV source characterization, strongly pulsed radiation and very different radiant powers must be measured. High-accuracy calibrations for EUVL therefore require further investigations of the detector performance. Therefore, high-power beamlines for investigations of the linearity of the response and stability under irradiation with EUV were installed by PTB.

This chapter gives an overview of the measurement capabilities of PTB at the BESSY II storage ring and presents the status of the calibration of detectors and tools for EUV source metrology achieved at PTB.

30.2 Synchrotron Radiation Beamlines for EUV Metrology

30.2.1 Soft-x-ray radiometry beamline

The PTB soft-x-ray radiometry beamline at BESSY II²⁰ uses a plane-grating monochromator that allows the deflection angle and the incidence angle at the grating to be set independently.²¹ It covers the spectral range from 0.7 to 35 nm and is

characterized with respect to the available radiant power, spectral purity of the radiation, energy resolution, and stability.^{16,20} At 13.5 nm, the radiant power available is about 1 μW (see Fig. 30.1). The radiant power is shown with and without the transmission filters for higher-order suppression. For most spectral ranges, a contribution of higher-order radiation of about 1% is achieved by proper setting of the angles of incidence for the plane mirror and grating without additional filters. The steps in the radiant power without filter correspond to these changes of the so-called fixed-focus parameter.²¹ Above about 15 nm, the angle of the plane mirror is limited to 12-deg grazing by the mechanical drive, and the contribution of higher-order radiation strongly increases without a filter. Fortunately, this radiation can be efficiently suppressed using silicon and aluminum foils. Due to the gold coating of the mirror and grating as well as the properly set blaze angle of the grating, a high radiant power and at the same time high spectral purity is achieved in the EUV spectral region. The relative higher-order contributions to the radiant power are below 1% for all wavelengths between 0.65 and 35 nm, and below 0.05% in the EUV spectral region.²²

Resonance lines of the rare gases Kr, Ar, and Ne, which cover the working range of the monochromator, were used to determine the wavelength scale and the monochromator resolution (see Table 30.1). At each wavelength, different deflection angles at the grating were used to test the accuracy of the mechanical drives. The uncertainties of the monochromator wavelengths as given in Table 30.1 reflect the deviation between these measurements. Data for the monochromator resolution were derived from the measured linewidths. In the EUV spectral range around 13 nm, a resolving power of 2800 is available.

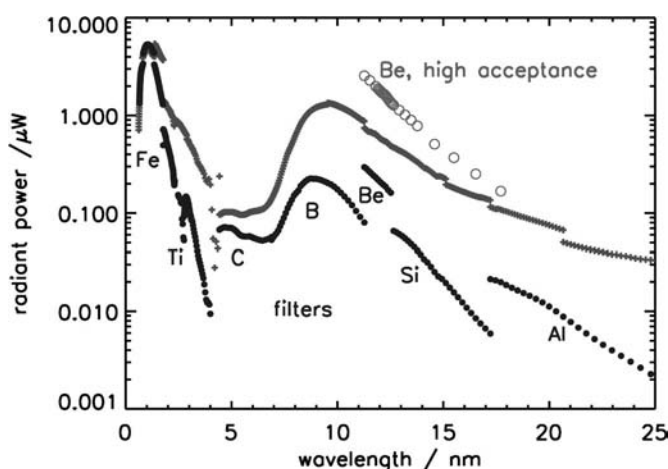


Figure 30.1 Radiant power at the soft-x-ray radiometry beamline at a stored electron current of 200 mA. The conditions are optimized for a small and parallel beam as used for reflectometry. The upper curve without labels shows the radiant power without transmission filters for higher-order suppression; the lower curve (closed circles) is with the filters in the beam. For detector calibration, the radiant power can be increased by a factor of 10 by using a higher angular acceptance of the beamline and increased bandwidth (open circles).

If, e.g., the responsivity of a photodiode is measured, we measure the ratio of the photocurrent at the diode, normalized to the stored electron current at that time, to the radiant power measured afterward with a reference detector, normalized to the stored electron current at that later time. Thus, the temporal stability of the normalized radiant power is an essential prerequisite for an accurate measurement. The usual duration of measurements at several wavelengths is about 30 min. For the normalized radiant power, a stability of 0.03% over 30 min is achieved.¹⁶

Similar demands are made on the stability of the wavelength scale of the monochromator. For a daily test, we measure the K edge of the Be filter foil. If the deviation from our reference value (11.0801 nm, which we derived by comparing the Be K-edge wavelength with the rare-gas resonances) exceeds 2.2 pm, the beamline is readjusted. In Fig. 30.2, the measured center wavelength of a Mo/Si multilayer mirror (MLM) is shown over a period of two years. The variation is well within the claimed reproducibility of 1.4×10^{-4} ($\sqrt{3}\sigma$, relative). The mirror was always

Table 30.1 Compilation of wavelength adjustment data for the PTB soft-x-ray radiometry beamline using rare-gas absorption resonances.

	Reference	Soft x-ray radiometry beamline	
	Wavelength	Wavelength	Resolution FWHM
	(nm)	(nm)	(pm)
Kr 3d _{5/2} -5p	13.5947(15) ⁵²	13.5935(5)	5.2
Ar 2p _{2/3} -4s	5.0732(2) ⁵²	5.0736(4)	1.3
Ne 1s-3p	1.42982(8) ⁵³	1.42967(28)	0.6

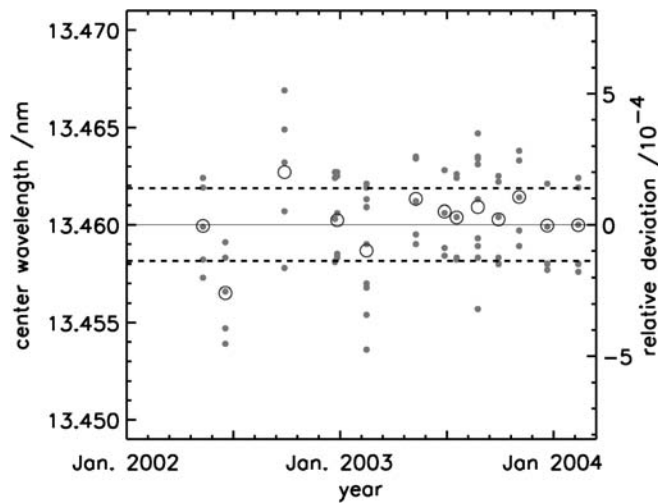


Figure 30.2 Reproducibility of the measured center wavelength of an EUV Mo/Si MLM for a time period of two years. The dots show measurements at five positions on the mirror (center, and 5 mm from center in the x , y , $-x$, $-y$ directions). The circles are the means of those five measurements. They coincide with the wavelengths measured at the center. The dashed lines indicate the interval of the claimed reproducibility of 1.4×10^{-4} ($\sqrt{3}\sigma$, relative).

measured at the same positions. What is also seen in Fig. 30.2 from the relative deviations of the wavelengths measured at five positions of the mirror is that the repeatability of the measurement results within short time scales, where no drifts in the monochromator alignment occur, is much better. The wavelength measured at the center always coincides with the mean of all measured wavelengths within about 5×10^{-6} .

30.2.2 EUV irradiation beamline

EUV lifetime studies for detectors and optics are performed at a bending-magnet beamline. The irradiation beamline²³ supplies broadband radiation with a total power of 900 mW (in the wavelength range from 5 to 100 nm) for a typical ring current of 200 mA. Synchrotron radiation from a bending magnet is focused with a grazing-incidence mirror into a contamination test chamber at the end of the beamline. The reflection at the mirror at 10-deg grazing incidence results in a cut-off wavelength of about 6 nm. The spectral distribution can be further narrowed using filters. The spectral radiant power is shown in Fig. 30.3 for different settings.

The spectrum of the EUV radiation behind the filters ranges roughly from 12 to 20 nm with about 10% inband EUV radiation, dependent on the filter(s) used, as shown in Table 30.2. The total power and the spectral components of the radiation are given for operation without a filter and with filters having 60% and 1% transmittance at 13.5 nm, respectively. The last line of Table 30.2 gives the conditions for the second position in the two-position sample holder if a mirror with

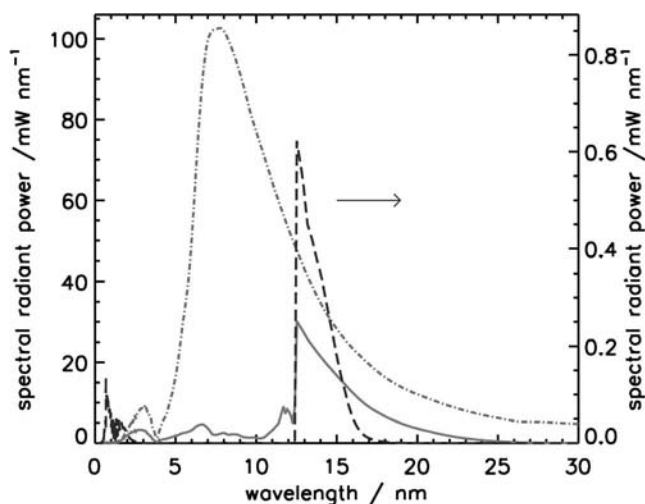


Figure 30.3 Spectral radiant power at the irradiation beamline for a stored electron current of 200 mA. Shown are the spectra of the radiation deflected by the mirror at 10-deg grazing incidence (dash-dot, left scale), with an additional Si/Zr filter having 60% transmittance at 13.5 nm (solid line, left scale), and with a thick filter having about 1% transmittance at 13.5 nm (dashes, right scale). The spectra are calculated from the known spectrum of the synchrotron radiation and the measured reflectance of the mirror and transmittance of the filters.

Table 30.2 Compilation of the basic parameters of the irradiation beamline.

	Total power		Short wavelengths (<12 nm)		Broadband EUV (12–16 nm)		Inband EUV (2% at 13.5 nm)		Long wavelengths (>16 nm)	
	Power (mW)	Power density (W cm ⁻²)	Power (mW)	Relative contrib.	Power (mW)	Relative contrib.	Power (mW)	Relative contrib.	Power (mW)	Relative contrib.
No filter	922	22	537	58%	151	17%	17	1.9%	233	25%
Thin filter	142	3.4	26	18%	77	55%	11	7.5%	39	27%
Thick filter	1.2	0.03	0.066	5.3%	1.1	92%	0.19	16%	0.032	2.7%
Thin filter + mirror	12	0.14	0.020	0.2%	12	97%	6.3	52%	0.3	2.5%

70% peak reflectance and 13.5-nm center wavelength is placed in the first position of the holder. Radiation of longer wavelength (DUV, UV, visible, and IR) as well as shorter wavelength is suppressed by the filters. It is therefore expected that the contamination processes are purely governed by the broadband EUV radiation. This broadband EUV radiation represents to some extent the conditions close to the EUV source.²

The irradiation test chamber can accommodate up to 10^{-2} mbar of gas pressure.²⁴ It is separated from the beamline through a differential pumping section. The base pressure of the test chamber is in the high 10^{-8} -mbar range, dominated by water vapor because the system cannot be baked with samples mounted. The integrated pressure for molecular masses >44 u (hydrocarbons) is below 3×10^{-11} mbar.²⁵ The irradiation chamber is connected to a gas supply system that can supply water, cleaning agents (e.g., oxygen), and hydrocarbons independently. The overall pressure is measured using a Granville-Phillips Stabil-Ion gauge, whereas the partial pressures of the different gases are determined using a quadrupole residual gas analyzer. Three different sample holders can be accommodated in the system, viz., a single sample, a stack of two samples, and a stack of eight samples. In order to minimize the occasions on which the vacuum of the chamber needs to be broken, the single and two-sample sample holders can be loaded through a dedicated UHV load lock system.²⁴ The first sample in each holder is placed about 350 mm behind the focal point of the mirror to achieve a sufficiently large irradiation spot for further investigations by, e.g., reflectometry. At this position, the beam has a wedge-shaped structure with a high-intensity region of about 2 by 1 mm adjacent to a region of about 3 times lower intensity, about 4 by 2 mm in size. About 40% of the power is focused onto the hot-spot region at the tip of the wedge. The intensity profile at the irradiation position was measured using a calibrated CCD (for a detailed picture see Refs. 26,27).

30.2.3 EUV direct undulator beamline

Because an undulator delivers horizontally and vertically collimated radiation, no focusing mirror needs to be used to achieve a high-intensity spot. Furthermore, it is advantageous to use only the central part of the beam to achieve higher spectral purity. The red-shifted part of the spectrum appears at higher off-axis angles, and only the uneven harmonics of the undulator have significant on-axis intensity. The data shown in Fig. 30.4 are for a 1- by 1-mm aperture at 30-m distance from the undulator U49. Either the direct undulator beam with no further optical element at all in between the source and the sample can be used, or a beam deflected by 13 deg at a grazing-incidence plane mirror.

There is nearly no continuous background radiation at all—in particular, no longer-wavelength contribution. There is a clean first order of the undulator at 13.5 nm, and discrete, small-bandwidth higher harmonics at shorter wavelength. These are significant contributions to the radiant power for the U49 undulator installed now at the beamline. The radiant power at 13.5 nm, however, is also higher

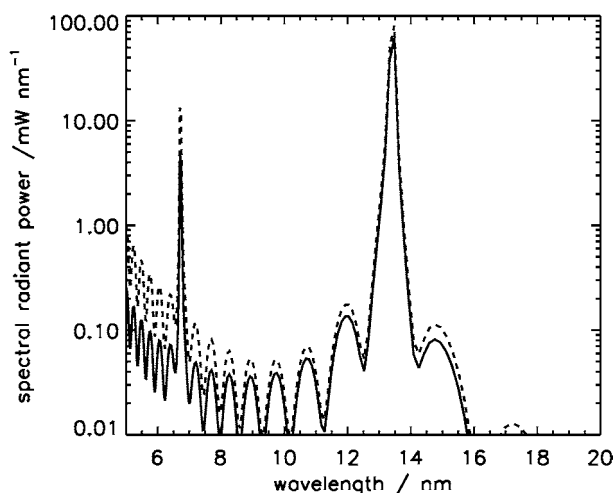


Figure 30.4 Spectral radiant power into a 1- by 1-mm aperture at 30-m distance at the direct undulator beamline for a stored electron current of 200 mA with the U49 undulator. Shown are the spectra of the direct undulator radiation (dashed), and the spectrum deflected by the mirror at 6.5-deg grazing incidence (solid line). The spectra are calculated from the known spectrum of the undulator radiation and the measured reflectance of the mirror.

than for the previously used U180 undulator (see Ref. 23). The higher harmonics contribute about 90% to the total radiant power in the direct beam (see Table 30.3). In Table 30.3, the total power and the spectral components of the radiation are given for operation at the direct undulator beam and a 13-deg-deflected beam, respectively. The last line gives the conditions for the second position in the two-position sample holder if a mirror with 70% peak reflectance and 13.5-nm center wavelength is placed in the first position of the holder. Because most of the radiant power is in the fifth and higher harmonics, the suppression by the 13-deg mirror reflection reduces its contribution to 60%. A further reduction using transmission filters would not be effective, for the transmittance of any filter for the third and higher orders is of the same order as the transmittance of the first order. An almost ideal spectrum is achieved by a further reflection at a Mo/Si MLM (see last row in Table 30.3). Note that the power given in Table 30.3 refers to an aperture of 1 by 1 mm. Using, e.g., a 6-mm-diameter aperture, about 30 times higher total power can be collected.

30.3 Instrumentation for Detector Calibration and Optics Characterization

30.3.1 EUV reflectometer

For the investigation of large optical components for EUVL tools, PTB is operating an EUV reflectometer for samples with up to 550-mm diameter and a mass of 50 kg, operated at the soft-x-ray radiometry beamline.^{13,14} It consists of a cylin-

Table 30.3 Compilation of the basic parameters of the undulator beamline.

Component	Total power		Short wavelengths (<12 nm)		Broadband EUV (12–16 nm)		Inband EUV (2% at 13.5 nm)		Long wavelengths (>16 nm)	
	Power (mW)	Power density (W cm ⁻²)	Power (mW)	Relative contrib.	Power (mW)	Relative contrib.	Power (mW)	Relative contrib.	Power (mW)	Relative contrib.
Undulator U49	218	21.8	197	90.2%	21.5	9.8%	19.9	9.1%	0.03	0.01%
Grazing mirror	40	4	23.5	59%	16.3	41%	15.1	38%	0.02	0.04%
Grazing mirror + thin filter	19	1.9	8.5	46%	10.1	54%	9.4	50%	6 × 10 ⁻³	0.03%
Grazing + Mo/Si mirror	10.5	1.05	8 × 10 ⁻⁴	8 × 10 ⁻⁵	10.5	100%	10.0	96%	1.5 × 10 ⁻⁴	1 × 10 ⁻⁵

drical vacuum chamber with a diameter of 1.9 m and a length of 2.1 m. Inside this chamber the sample stage is mounted. Figure 30.5 shows the reflectometer sample stage in front of the vacuum chamber. The ranges of travel and positioning uncertainties for the different axes are summarized in Table 30.4. The complete sample stage is motorized in vacuum. The photon beam size at the sample position is of the order of 0.5 by 0.5 mm with a flat top.¹⁴ The divergence is about 0.5 mrad in both directions. Optical components used for source calibration tools (e.g., filters, gratings, and mirrors) can be characterized in detail using the EUV reflectometer. The uncertainty contributions for the measurement of the peak reflectance of a Mo/Si mirror at 13.5 nm are given in Table 30.5. For the peak reflectance, the dominant

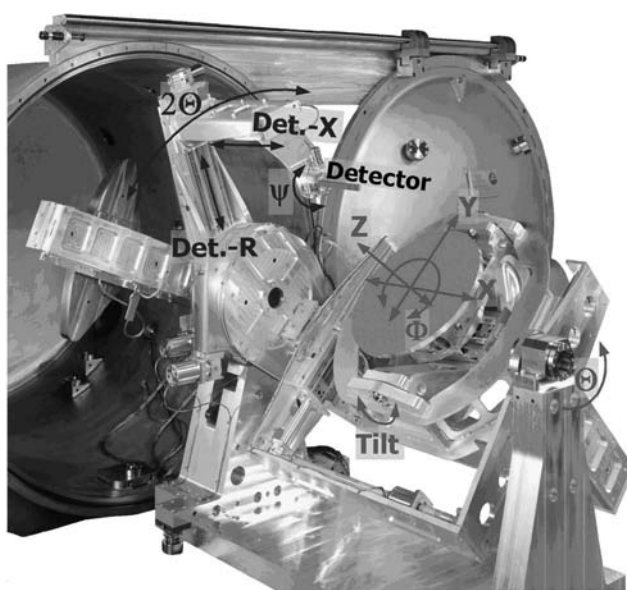


Figure 30.5 Mechanics of the EUV reflectometer.^{13,14} The in-vacuum detector and sample stages are shown in front of the vacuum vessel. The degrees of freedom are indicated for detector and sample. The baseplate of the sample holder is 550 mm in diameter.

Table 30.4 Compilation of the sample and detector movements of the EUV reflectometer with maximum travel range and positioning uncertainty.

	Axis	Range	Positioning uncertainty
Sample	X	180 mm	10 μm
	Y	310 mm	10 μm
	Z	155 mm	10 μm
	Θ	125 deg	0.01 deg
	Φ	360 deg	0.01 deg
	Tilt	20 deg	0.01 deg
Detector	2Θ	195 deg	0.01 deg
	x	120 mm	10 μm
	R	400 mm	100 μm
	Ψ	180 deg	0.01 deg

Table 30.5 Compilation of the uncertainty contributions for the measurement of reflectance at a wavelength of around 13 nm.

Quantity	Relative uncertainty contribution u
Peak reflectance	
Stability of normalized intensity	3×10^{-4}
Inhomogeneity of the detector	6×10^{-4}
Higher diffraction orders	3×10^{-4}
Diffuse scattered radiation	1.2×10^{-3}
Total relative uncertainty of peak reflectance	1.4×10^{-3}
Peak wavelength	
Kr resonance wavelength	1.2×10^{-4}
Repeatability of wavelength	8×10^{-5}
Total relative uncertainty of peak wavelength	1.4×10^{-4}

contribution is diffusely scattered radiation outside the mirror bandwidth that is incident on the diode in the direct beam and not reflected. The main uncertainty for the wavelength is the uncertainty of the reference wavelength.

In addition to the 2 Θ movement, the detector can be moved in the x direction for the measurement of bidirectional scattering. Furthermore, the distance between the sample surface and the detector can be varied to allow for the different beam divergence when reflected from a curved surface. A clean room of class 1000 in the front of the reflectometer chamber prevents the contamination of the samples with dust particles during mounting.

30.3.2 Cryogenic electrical substitution radiometer as a primary detector standard

In the past, radiometry in the VUV and soft-x-ray spectral regions was mainly based on rare-gas double ionization chambers, which allowed the determination of the spectral responsivity of photodiodes with a 6% to 9% relative uncertainty.^{28,29} During the last two decades, electrical substitution radiometers (ESRs) with an absorber cavity that is operated at liquid-helium temperature, so-called cryogenic radiometers, have been established in optical radiometry at several national metrology institutes as accurate radiometric standards. At PTB cryogenic radiometers have also been successfully employed for radiant power measurement of spectrally dispersed synchrotron radiation in the spectral range from UV to x rays.^{6,11,16,17,30,31}

The equivalence of radiant and electrical heating that makes a cryogenic radiometer a primary standard is not ensured by a physical equation of state. Therefore, the possibility of radiant energy being deposited in the absorber cavity without being transformed into heat must be excluded. Many possible loss effects, such as backscattering of radiation and fluorescence, can be directly addressed by measurements. The main concern is that radiant energy could be consumed in processes of

radiation damage, such as lattice displacements or the creation of electronic traps. For physical reasons, such effects should be absent for a cavity absorber made of metal.¹⁷ This expectation was experimentally justified by a direct comparison of the cryogenic radiometer with BESSY I, the primary radiometric source standard, by measuring the integral radiant power of synchrotron radiation.³²

In Fig. 30.6, the relation between total heating power and temperature of the absorber cavity in the ESR is shown. Setting an appropriate electrical heating power thus allows measurement at different radiant power levels. The sensitivity of the radiometer varies only slowly with the temperature.

A comprehensive description of the design and performance features of the ESR has been given in Ref. 17. The cavity absorber has a cylindrical shape with a copper wall of thickness about 100 μm and is coated with a thin gold layer for passivation. In the dynamic substitution mode, the temperature of the cavity absorber is controlled by a feedback loop assuring a constant temperature difference to the heat sink, whose temperature is also actively controlled. Thus a constant heat flow, $\dot{Q}$, from the cavity absorber through the heat link to the heat sink is realized, which is given by $\dot{Q} = P_{\text{el}} + (1 - \delta_{\text{ne}}) \cdot \alpha_{\lambda} \cdot (1 - \delta_{\text{loss}}) \cdot \Phi_{\lambda}$, where δ_{ne} is a correction of magnitude 2×10^{-4} for the nonequivalence of the heat-flow paths in electrical and radiant heating,¹⁷ α_{λ} is the fraction of incident radiant energy of the synchrotron radiation absorbed in the cavity, and δ_{loss} summarizes the corrections for radiant energy absorbed in the cavity but not transformed into heat. For the latter two corrections, values for the wavelength range down to 0.7 nm are reported in Ref. 17, the resulting value of $\alpha_{\lambda}(1 - \delta_{\text{loss}})$ being 0.9990(6). In a radiant-power measurement, the change in electrical power corresponding to a change in inci-

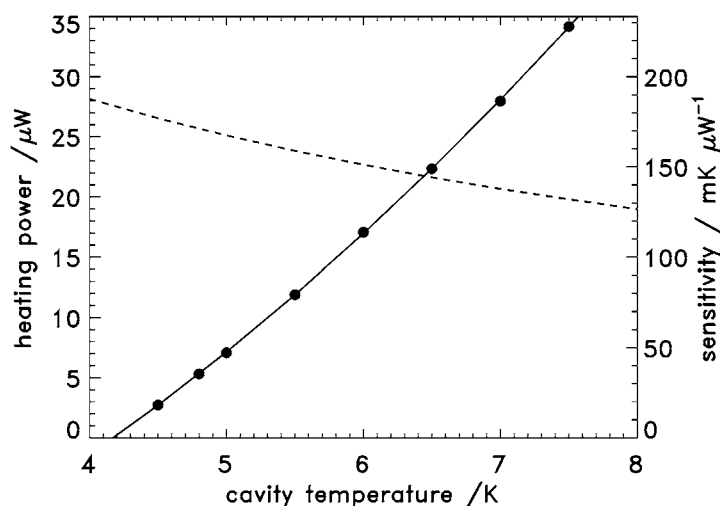


Figure 30.6 Relation between total heating power and temperature of the absorber cavity in the ESR (solid circles). The solid line is an interpolating polynomial fit. Since the thermal conductance of the heat link depends on the temperature, the curve is not linear. The sensitivity of the radiometer, shown as a dashed line with respect to the right scale, therefore also depends on temperature.

Table 30.6 Compilation of the uncertainty contributions for the measurement of a radiant power of about 0.2 μW by the cryogenic ESR.

Quantity	Relative uncertainty contribution u
Measured normalized heating power difference	1×10^{-3}
Radiant-energy conversion efficiency of the absorber ¹⁷	3×10^{-4}
Thermal nonequivalence between radiant and electrical heating ¹⁷	1.2×10^{-4}
Temperature correction for standard resistor ¹⁷	1.2×10^{-6}
Calibration of standard resistor ¹⁷	1×10^{-5}
Calibration of voltmeters ¹⁷	2×10^{-5}
Normalized radiant power	1.1×10^{-3}

dent radiant power is measured. In Table 30.6, the uncertainty contributions to the radiant-power measurement using the ESR at a radiant power of 0.2 μW are compiled. The dominant contribution is the statistical uncertainty in the determination of the heating-power difference with and without radiation.

30.4 Semiconductor Photodiodes as Reference Detector Standards

30.4.1 Calibration

Photodiodes are calibrated by comparing the photocurrent of the diode with the radiant power of monochromatized radiation at the soft-x-ray radiometry beamline as measured with the ESR. The diodes are aligned behind a cooled aperture 3 mm in diameter. The ESR with its 6-mm cooled aperture in front of the absorber is placed about 1 m behind the diodes to provide sufficient space for a cooled baffle system needed for infrared suppression.³³ The ESR is aligned and kept fixed during the measurements, whereas the diodes are mounted on a linear feedthrough. Since the photon beam does not cover either detector completely, for an ideal homogeneous detector, uncertainties of position need not be taken into account. The corresponding uncertainty depends on the individual detector and is therefore not included in the compilation given in Table 30.7. The photocurrent induced in the diode is measured with a Keithley 6517 electrometer.

30.4.2 Spectral responsivity of different types

The high absorption of EUV radiation in any material is a major problem for the use of semiconductor photodiodes as detectors, because the radiation must penetrate through the passivation layer and the front region (either p - or n -doped) into the pn junction region. Therefore, silicon photodiodes with a thick oxide passivation are not useful for EUV radiation. An alternative is to use Schottky diodes. Here, the depletion region starts directly at the metal-semiconductor interface. This

Table 30.7 Uncertainty contributions for the measurement of the spectral responsivity of a photodiode at a wavelength of 13 nm.

Quantity	Relative uncertainty contribution u
Radiant power (see Table 30.6)	1.1×10^{-3}
Measured diode photocurrent	1×10^{-3}
Electrometer calibration factor	6×10^{-4}
Diode temperature deviations, $(20 \pm 2)^\circ\text{C}$	1×10^{-4}
Wavelength uncertainty	1×10^{-4}
Spectral bandwidth of monochromator	1×10^{-5}
Higher diffraction orders	3×10^{-4}
Diffuse scattered radiation	2×10^{-3}
Angle of incidence at diode (normal ± 5 deg)	5×10^{-5}
Spectral responsivity	2.6×10^{-3}

type of diode, especially with a high-gap semiconductor, is still a good choice for measurement at low irradiation levels, because the dark signal of these devices is extremely low. A typical curve for the spectral responsivity of a GaAsP/Au Schottky diode is given in Fig. 30.7. Also shown is a model calculation (see Ref. 34) using a gold layer of a thickness of 7 nm, a charge collection efficiency at the GaAsP-gold interface of 35%, a relaxation depth for the recombination losses of 22 nm, a 100%-sensitive thickness of 180 nm, and a total sensitive thickness of $2.6 \mu\text{m}$ with zero collection efficiency at the bottom of the sensitive layer. The spectral dependence of the responsivity is dominated by the transmittance of the gold contact layer, which is only about 50% at 13.5 nm, as illustrated by the dashed line in Fig. 30.7, which allows only for the absorption of the gold layer. Thus, even minor variations in the thickness of the contact layer have a significant influence on the responsivity. For radiometric application, the diodes must be selected for spatial homogeneity.

The development of silicon photodiodes for the VUV and EUV spectral range was initiated by needs of the second-generation synchrotron radiation sources as well as the applications in x-ray astronomy, x-ray microscopy, and plasma diagnostics and the first investigations for EUVL in the late 1980s.³⁵ These diodes (called AXUV) were soon improved regarding their radiation stability³⁶ and used for radiometric applications.^{11,37,38}

AXUV diodes have a shallow n -conducting front region, passivated with a nitrided oxide,³⁶ on top of a p -type epitaxial layer a few tens of microns in thickness on a $200\text{-}\mu\text{m}$ -thick p^+ substrate (see Fig. 30.8). A special property of these AXUV diodes is their nearly ideal quantum efficiency.³⁶ The spectral responsivity varies only by about 10% over the whole EUV and soft-x-ray spectral range (see Fig. 30.7). The model calculation (see Ref. 33) uses an oxide layer with a total thickness of 4.2 nm, a collection efficiency at the silicon-oxide interface of 93%, a relaxation depth for the recombination losses of 110 nm, a 100%-sensitive thickness of $1 \mu\text{m}$, and a total sensitive thickness of $26.5 \mu\text{m}$ with a collection efficiency of 97% at the bottom of the sensitive layer.

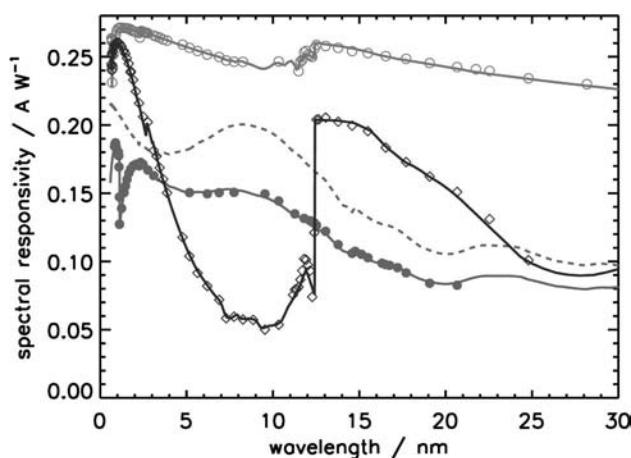


Figure 30.7 Spectral responsivity of three photodiodes measured using the ESR. The upper curve (open circles) is an AXUV-type diode. Data for an SXUV-type diode are shown with diamonds, and for a GaAsP/Au Schottky diode with solid circles. The lines represent model calculations with the parameters for each diode given in the text. For the Schottky diode, the dashed line represents the responsivity that would result if the charge collection efficiency were ideal and only the Au-contact-layer absorption were taken into account.

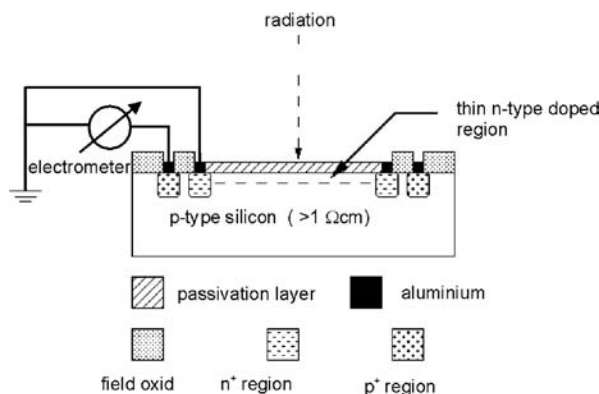


Figure 30.8 Scheme of the diode geometry and electrical connections for *n-on-p* silicon photodiodes (see Ref. 36).

Although these diodes have a nearly ideal performance regarding their responsivity, it turned out that the nitrated oxide is not sufficiently stable over time (see next subsection). For 157-nm F₂ laser radiation, PtSi Schottky-barrier diodes have been shown to be most stable.^{39,40} Regarding their homogeneity, these diodes suffer from the same problem of the highly absorbing front layer as discussed above for GaAsP-Au diodes. For applications in high-power EUV radiation, *n-on-p* diodes with improved passivation were developed. Because the damage of the oxide is most likely related to the creation of long-living electronic excitations in the insulating oxide, the new diodes (called SXUV) were passivated with metal silicides.⁴¹ They show good stability for EUV irradiation and good homogeneity.²⁷

The disadvantage of the metal silicide passivation is that the charge collection in the front region of these diodes is significantly lower than for the nitrided oxide devices. A typical responsivity of such a diode is also shown in Fig. 30.7. It shows a sharp cutoff at the silicon L edge at 12.4 nm. Diodes from different lots have a rather similar spectral responsivity at 13.5 nm, between 0.20 and 0.23 A/W; the responsivity at 10 nm, however, depends strongly on the individual device, varying between 0.05 and 0.15 A/W. The model calculation uses a passivation layer composed of 3.0 $\mu\text{g}/\text{cm}^2$ Ti, 1.0 $\mu\text{g}/\text{cm}^2$ Si, and 0.5 $\mu\text{g}/\text{cm}^2$ N, corresponding to a thickness of 15 nm for a density of 3 g/cm^3 , zero collection efficiency at the silicon-silicide interface, a relaxation depth for the recombination losses of 125 nm, a 100%-sensitive thickness of 3 μm , and a total sensitive thickness of 60 μm with a collection efficiency of 65% at the bottom of the sensitive layer.

30.4.3 Self-calibration

The AXUV-type photodiodes with nearly ideal responsivity have in the past been proposed as absolute detectors⁴² for EUV.³⁶ The basic idea is that the spectral responsivity $s(h\nu)$ of a photodiode for photons of energy $h\nu$ in the soft-x-ray region can be expressed as $s(h\nu) = (e/w)s_r(h\nu)$ with e the elementary charge, w the mean electron-hole pair creation energy, and $s_r(h\nu)$ a relative responsivity taking account of all loss processes, including reflection and absorption in the front layer. Reflection at normal incidence is negligible in the EUV spectral range. Thus for an ideal detector with 100% internal charge collection, only the absorption in the front layer needs to be known. This is the basis for an alternative approach to the determination of the spectral responsivity of photodiodes used earlier at PTB in the soft-x-ray spectral range,⁴³ the so-called self-calibration.⁴⁴ The absorptance of the front layers can be determined from the ratio $s_\Theta(h\nu)$ of the responsivity for 60-deg-to-normal incidence to that for normal incidence of the radiation. The relative uncertainties were estimated to be about 4% for n -on- p silicon diodes, and about 6% for GaAsP Schottky diodes.⁴³ Later on, this approach was improved to allow for a thin layer beneath the diode front contact where the charge generated is only partially collected.³³ This approach was successfully used to derive the mean energy for the production of electron-hole pairs in semiconductors from the absolutely measured responsivity of photodiodes using the ESR.³³ Measurements in the soft-x-ray range at PTB revealed a quantum efficiency proportional to the photon energy, i.e., a constant value of $w = 3.66(3)$ eV for the generation of an electron-hole pair in silicon in the wavelength range from 0.5 to 20 nm. In the wavelength range above 330 nm, exactly one electron-hole pair per absorbed photon is created, and for wavelengths shorter than 150 nm, the mean energy per electron-hole pair converges to the constant value for shorter wavelengths.^{34,39} For GaAsP, a value of $w = 4.58(7)$ eV was measured in the EUV and soft-x-ray spectral range.³⁴

The relative uncertainty achievable by the self-calibration method, however, is limited by the quality of the optical data used for the calculation of $s_r(h\nu)$ from the measured ratio $s_\Theta(h\nu)$. For the above-mentioned determination of w for silicon,

the optical data on the nitrided oxide had to be deduced from reflection measurements. The situation becomes even worse for highly absorbing front layers such as gold or silicides. The uncertainty is proportional to $1 - s_r(h\nu)$. For AXUV diodes with nearly ideal responsivity [$s_r(h\nu)$ close to 1], reasonable results might be obtained, while for Schottky diodes and SXUV-type diodes the uncertainty is about 10%.

30.4.4 Long-term stability

PTB has now had experience with the use of AXUV100G-type diodes as reference detectors for almost 10 years. The first high-accuracy calibrations^{11,31} were carried out in 1995. AXUV diodes were shown to be stable up to a fluence of 2×10^{16} photons/cm² at a wavelength of 9.6 nm, where the oxide is strongly absorbing.³¹ This corresponds to an irradiation of about 0.5 J/cm². The typical radiant power used in the calibration measurements is about 1 μ W, and the measurements take only a few minutes of total irradiation time for a broad wavelength range. Therefore the diodes were expected to be stable enough for use as reference detectors for measurements at about 1- μ W radiant power. It was, however, soon discovered that temporary changes in the responsivity occur close to the illuminated spot. This was explained by negative charging of the oxide by photoelectrons originating at the irradiated spot and deflected back to the diode by the positive charge remaining in the oxide.³⁸ Consequently, the responsivity could be restored by short illumination with only a few μ J/cm² to neutralize the oxide charge. If a potential of -100 V is applied to repel the photoelectrons during irradiation, no decrease of the responsivity in the adjacent areas is observed.³⁸

Some of the diodes first calibrated in 1995 were subsequently used as references for further calibrations, and some others were stored in dry air or in vacuum. Recalibrations of different subsets of the diodes were carried out later in 1995, and also in 1996, 1997, and 2001 (see Ref. 6). After about three years, most of the diodes became inhomogeneous and showed an unstable signal. As an example, the calibration history of one of the diodes is shown in Fig. 30.9. During a first interval, the diode was stored in dry air and used only occasionally in ultrahigh vacuum at a radiant power of 1 μ W or less. The spectral responsivity measured in 1995 and 1997 is nearly identical. A closer view, however, reveals systematic differences at longer wavelengths. These can only be explained by an additional absorbing layer, most probably oxygen that reacted with the initially oxygen-deficient³³ oxide. Later on, that diode was used for radiant-power measurements at a higher radiant power, of the order of 10 μ W. It was observed during these measurements that the diode became unstable and inhomogeneous. The result of a final calibration in 2001 is also shown in Fig. 30.9. The responsivity dropped by about 50% for wavelengths above 5 nm. A rather significant oxidation (about 22 nm of oxide) could be inferred from the spectral slope.

From these observations it can be concluded that the stability of AXUV-type diodes as reference detectors is strongly influenced by oxidation, which most probably occurs when—after using the diode for radiation measurements—the charged

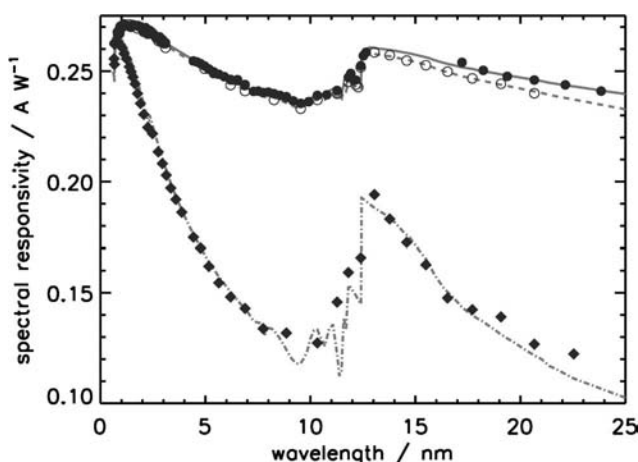


Figure 30.9 Spectral responsivity of an AXUV diode measured in 1995 using the ESR (solid circles). The line represents a model calculation (see Ref. 33) using an oxide layer with a total thickness of 5 nm and a charge collection efficiency at the silicon-oxide interface of 91%. The diode was recalibrated in 1997 (open circles). The dashed line represents a calculation with an additional amount $0.11 \mu\text{g}/\text{cm}^2$ of oxygen. Finally, after using the diode in intense EUV radiation, it was calibrated in 2001 (diamonds). The dash-dotted line represents a calculation with an additional 22-nm layer of SiO_2 . Furthermore, the collection efficiency at the silicon-oxide interface decreased to 60%.

oxide is exposed to ambient atmosphere during specimen change. Although we do not have a comparably long experience with SXUV-type diodes, a first comparison with recalibrations after six months for AXUV- and SXUV-type diodes strongly suggests that this problem is absent for the silicide passivation layers (see Fig. 30.10). After six months, no change in responsivity is observed in the whole wavelength range from 1 to 25 nm for the SXUV-type diode, while the AXUV-type diode significantly dropped in responsivity for wavelengths above 10 nm. Again the change is best fitted by the absorption of an additional amount of oxygen. It should be noted that the AXUV diode was stored in dry air during the six months, while the SXUV diode was used as a reference detector for customer calibrations and thus suffered several cycles of pumpdown, irradiation, and subsequent exposure to ambient atmosphere.

30.4.5 Irradiation stability

In the previous subsection, the long-term stability of only occasionally used photodiodes was discussed. For EUV source radiometry, however, the diodes are exposed to high radiation doses during the measurements; therefore the stability under high irradiation also must be investigated. A detailed study of SXUV-type diodes with different passivation layers has recently been published.²⁷

The diodes investigated had passivation layers of diamondlike carbon (DLC), PtSi, and TiSiN. The irradiation was performed at the EUV irradiation beamline (see Sec. 30.2.2), in a base vacuum of approximately 10^{-8} mbar, predominately

made up of water. The diodes were irradiated with an increasing dose and tested until a significant degradation was measured or a significantly higher exposure would have taken an unreasonably long time. A first and sensitive test for degradation is carried out by scanning the surface of a TiSiN-coated diode after radiant exposure with 143 kJ/cm^2 (see Fig. 30.11). At 11 nm the responsivity directly in

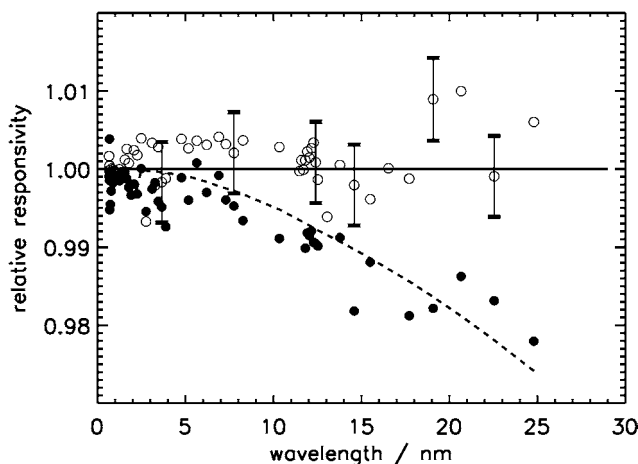


Figure 30.10 Ratio of spectral responsivity of an AXUV diode, measured using the ESR six months after the initial calibration, to the responsivity measured initially (closed circles), and the same for an SXUV100 diode with TiSiN passivation, measured at the same times (open circles). The error bars represent the uncertainty of a single measurement with the extension factor $k = 2$; see Table 30.7. The dashed line represents the transmittance of $0.11 \mu\text{g/cm}^2$ of oxygen.

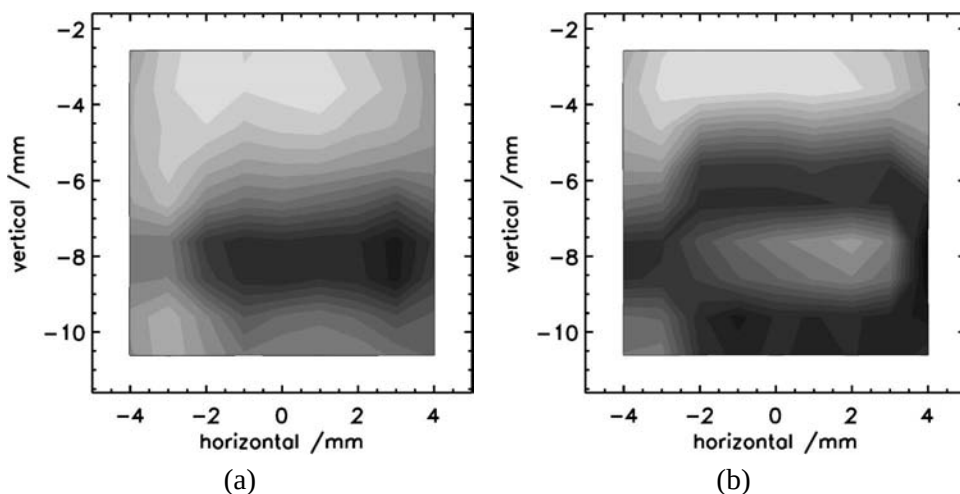


Figure 30.11 Homogeneity of the responsivity of a TiSiN SXUV diode after irradiation with 143 kJ/cm^2 , measured at 13 nm (a) and 11 nm (b) with a spot size of about 0.5 by 0.5 mm. The irradiation spot clearly appears as a region of reduced responsivity. The shading is in steps of 0.1% from 98% (dark) to 100% (white).

the illuminated area remained constant, while the area surrounding the spot was damaged. All but the diode with the PtSi passivation were stable up to a radiant exposure of about 100 kJ/cm^2 .

The spectral dependence of the irradiation-induced change in responsivity for the DLC- and TiSiN-coated diodes is shown in Fig. 30.12. The data for the TiSiN diode confirm the finding from the measurement of the homogeneity. Carbon contamination is clearly confirmed by the occurrence of the K absorption edge at 4.4 nm . A pure absorption layer, however, does not explain the measured spectral shape. There is no change in responsivity at all in the wavelength range from 5 to 11 nm . This behavior was simulated with the model³³ used to describe the efficiency of the diodes as shown in Figs. 30.7 and 30.9, assuming that the collection efficiency for charge carriers generated directly at the silicide-silicon interface has increased by 0.5% . For the DLC-coated diode no contamination is detected: the responsivity, also at long wavelengths, is constant. There is, however, the same slight increase in responsivity in the range from 5 to 11 nm .

It can be concluded that SXUV-type diodes with DLC as well as TiSiN proved to be stable up to a radiant exposure of about 100 kJ/cm^2 . If the carbon contamination in the case of the TiSiN device had been avoided, the responsivity would have remained unchanged within 1% over the complete spectral range from 2 to 25 nm . Using a model for the spectral responsivity of the diodes, the observed changes in the responsivity can be explained as the result of carbon contamination of the surface, yielding a decrease in responsivity, and changes in the charge collection efficiency at the silicon-silicide interface. It seems that a minor, but de-

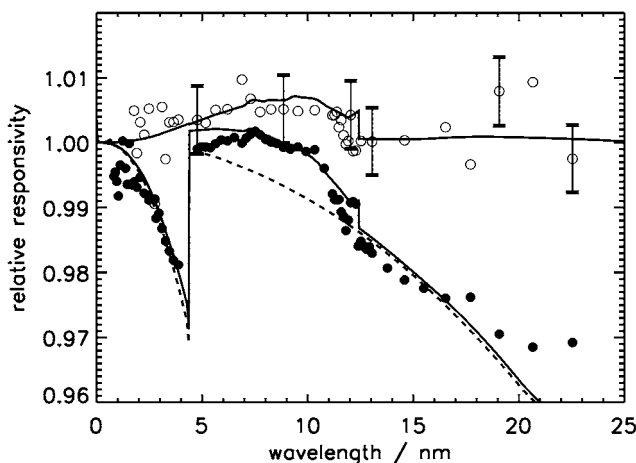


Figure 30.12 Irradiation-induced relative change in responsivity for two SXUV-type diodes. The diode coated with DLC (open circles) was exposed to 69 kJ/cm^2 , and the diode with TiSiN (closed circles) to 143 kJ/cm^2 . The dashed line shows the absorbance of $0.57 \mu\text{g/cm}^2$ of carbon. The solid lines show the change in responsivity due to an increase in the charge collection efficiency at the top silicon interface by 0.5 percentage point. The error bars represent the uncertainty of a single measurement with the extension factor $k = 2$ (see Table 30.7).

tectable, irradiation-induced increase in the charge collection efficiency at the top layer to the silicon interface might occur for SXUV diodes. For the AXUV-type diodes with nitrided oxide, these changes in the collection efficiency were always destructive (see Fig. 30.9). For the SXUV-type diodes, no additional oxygen is detected, although the irradiation was done in a water-vapor-dominated vacuum. This indicates that these passivation layers are oxidation-resistant.

30.4.6 Linearity

Detector calibrations at PTB are based on the comparison of the photodiodes with a cryogenic radiometer as primary detector standard, using monochromatized synchrotron radiation, a quasi-dc radiation with a rather low radiant power of about $1 \mu\text{W}$. At the customer's, these diodes may be used for strongly pulsed radiation and very different radiant powers. High-accuracy calibrations for EUVL therefore require investigations of the linearity of the response. Until recently, linearity investigations were reported only for laser radiation in the visible,⁴⁵ UV,⁴¹ and DUV⁴⁶ spectral ranges. A first investigation using EUV was done at the EUV direct undulator beamline.⁴⁷

The basic concept for the description of a photodiode for our measurement conditions is summarized in the following.

For dc operation using an electrometer, capacitance effects need not be considered, and the voltage in the outer circuit of the diode, or the load resistance, is zero. The equivalent circuit can thus be reduced to the form shown in Fig. 30.13. It is directly seen that the photogenerated current at the pn junction, I_L , is $I_L = I_D + I_{sh} + I$. The voltage U_D at the pn junction of the diode is $U_D = IR_s$. Using the basic expression for the current in the pn junction, we get $I_L = I_s \cdot [\exp(e/kTIR_s) - 1] + I \cdot R_s/R_{sh} + I$, with the reverse saturation current I_s , the elementary charge e , the Boltzmann constant k , and the temperature T . For high-quality diodes, the ratio R_s/R_{sh} is of the order of 10^{-6} and the term $I \cdot R_s/R_{sh}$ can be neglected: $I = I_L - I_s \cdot [\exp(e/kTIR_s) - 1]$. This equation can be used to model measured photocurrent curves.

We measured the photocurrent of an SXUV diode using a set of apertures having diameters from 0.125 to 6 mm at the EUV direct undulator beamline (see Sec. 30.2.3). At the diode position, 30 m from the undulator, the undulator beam

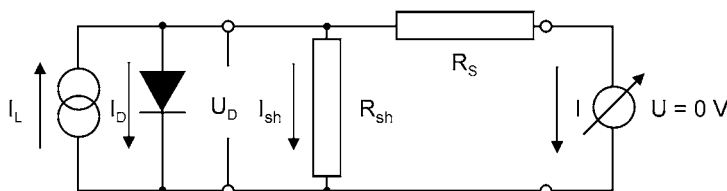


Figure 30.13 Equivalent electrical circuit for photocurrent measurement with an electrometer. In this circuit, the photodiode is characterized by its equivalent shunt resistance R_{sh} and series resistance R_s only.

is 4 mm in diameter (FWHM). In the spot, an irradiation level of about 2 W/cm^2 is achieved (see Table 30.3). We measured the photodiode current as a function of the stored electron current. The photon flux of the undulator scales linearly with the stored electron current. The photocurrent I_L generated in the pn junction is proportional to the incident power, which in turn is proportional to the stored electron current. Therefore, the ratio of measured photocurrent to stored electron current is a measure of diode linearity. The irradiance of 2 W/cm^2 was sufficient to saturate the diode with all but the smallest aperture (0.125 mm). The maximum radiant power incident on the diode for the 6-mm aperture and a stored electron current of 140 mA was about 500 mW. Although the spectral distribution of the radiation changes slightly with aperture size toward longer wavelengths, no effect is expected, for the spectral responsivity shows a flat behavior and the radiation is still in the broadband EUV range (shorter than 16 nm).

The series resistance obtained from these measurements⁴⁷ depends on the size of the photon beam (see Fig. 30.14). A simple model for the series resistance is as follows:⁴⁷ the photocurrent generated at the center of the diode must be carried in the thin front n -doped layer from the center to the n^+ contact ring. This layer is very thin and almost completely depleted, because no insensitive layer is observed in the photodiode's spectral responsivity. Thus, it forms a thin conducting layer with a certain square resistance. The current generated within a circular area as defined by the aperture diameter must flow through that thin layer to the outer electrode. If the diode were of circular geometry, the equations could be solved analytically and yield a logarithmic dependence of series resistance on aperture size.⁴⁷ For larger apertures deviations from this ideal behavior occur. The relation is, however, useful for the estimation of the saturation behavior for smaller aperture

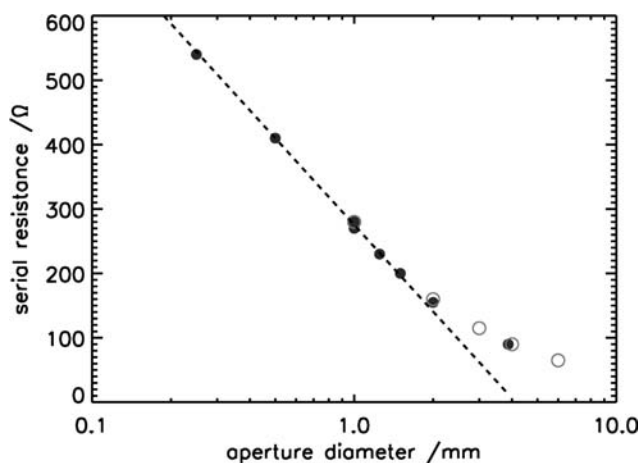


Figure 30.14 Presentation of the series resistance obtained from the saturation curves as a function of aperture size. The ordinate is scaled logarithmically in aperture size. Note the almost ideal logarithmic dependence up to an aperture size of about 2 mm. For larger aperture sizes, the slope decreases and the values appear to converge to a finite value for full diode illumination.

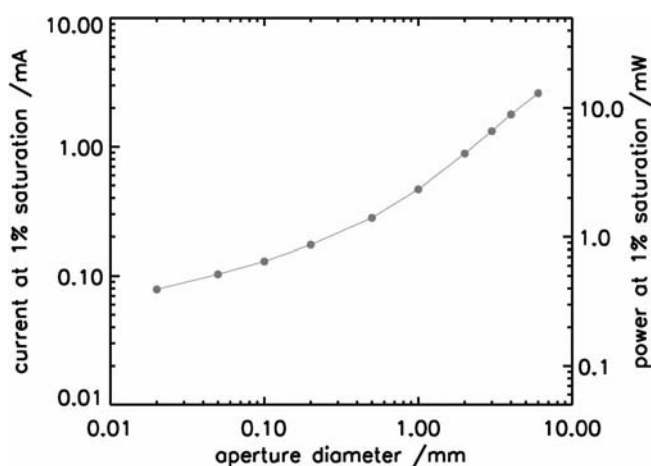


Figure 30.15 Relation between aperture diameter and current at 1% saturation as obtained from the relation between aperture size and series resistance.

sizes. This situation is, e.g., representative for source calibration tools of the Flying Circus (FC) type.⁴⁸ Here, a focusing mirror is used to image the source onto the detector diode. Therefore, dependence of the linear operation range of the tool on the source size should be expected. If we define the highest current for linear operation by, e.g., 1% relative saturation loss, it can be determined as a function of the series resistance. Expressing the series resistance as a function of aperture size, a relation between photon beam size and maximum current for linear operation is obtained as shown in Fig. 30.15. With decreasing aperture size, the maximum power that can be measured in the linear range of the diode decreases from about 10 mW for a 6-mm aperture to 2 mW at 1 mm and 0.5 mW at 0.1 mm. Therefore, it is important to specify the size of the photon beam if a limit for linear operation is specified. It must also be noted that the series resistance is an individual property of the diode and must therefore be checked for each individual device.

If, instead of the total radiant power, the diode is used to measure irradiance using an aperture of known size, the situation becomes quite different. The lower total-power limit for linear operation at small spot sizes is overcompensated by the influence of the aperture size, and the maximum irradiance increases from 30 mW/cm² for the 6-mm aperture to 6 W/cm² for the 0.125-mm aperture and about 100 W/cm² for a 20- μ m aperture.

30.5 Spectrally Filtered Tools and Spectrographs

For the optimization of radiation sources for EUVL and for the determination of the parameters needed for the system design and the system integration, these sources must be characterized in terms of the absolute inband power, the spectral distribution in the EUV spectral region and the out-of-band (OOB) spectral regions, the spatial distribution of the emitting volume, and the angular distribution of the emis-

sion. Also, the source debris has to be investigated. We present here some examples for the calibration of such tools at PTB.

30.5.1 Inband power meter

At present, two main types of inband power meters are in use, the FC tool⁴⁸ from the FOM Institute (see Sec. 5.1), which uses only one focusing MLM for spectral filtering, and the Jenoptik E-MON[®], using two flat MLMs^{5,49} (see Fig. 30.16). From the metrology point of view, the essential difference between the two concepts is the use of either one or two multilayer reflections. Further means of spectral filtering (e.g., transmission filters) are used in both tools in similar ways.

At PTB, a two-mirror power meter similar to the E-MON[®] was optimized for low calibration uncertainties for the characterization of the EUV emission of an Au-LPP⁵⁰ developed for a laboratory reflectometer.⁵¹ The mirrors are mounted at an angle of incidence of only 5 deg to the normal, the steepest angle possible. This reduces the sensitivity of the center wavelength to the angle of incidence to a 0.02-nm shift for 1-deg misalignment. Furthermore, the difference in responsivity for S- and P-polarized radiation is reduced. We chose this concept because it works with no focusing, so the source can be placed at any distance. This was particularly important in that we use collimated radiation at the soft-x-ray radiometry beamline for the calibration. The parallel synchrotron radiation beam underfills the

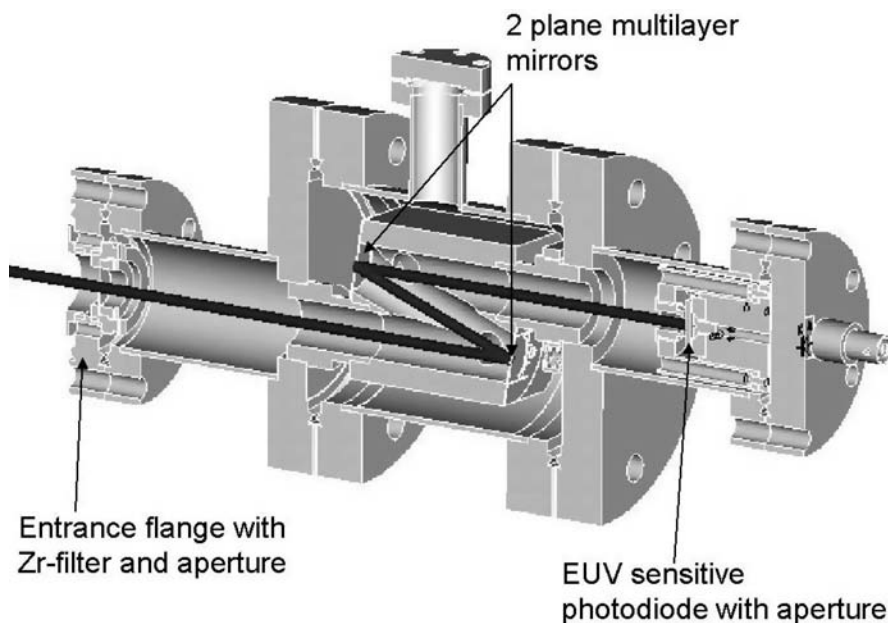


Figure 30.16 Schematic of a two-mirror inband EUV power meter, E-MON[®] from Jenoptik Mikrotechnik, courtesy of M. Schührmann, JOMT. The two flat MLMs serve as the bandpass filter. The solid angle of detection is defined by the aperture in front of the diode. Filters can be additionally used to suppress OOB radiation.

tool aperture. The calibration is therefore in units of diode photocurrent per unit incident radiant power (A/W, or C/J), as shown in Fig. 30.17. The results for the PTB tool⁵⁰ (no. 1) are shown together with those for tools using different angles of incidence at the mirrors. Tools 2 and 3 were first attempts toward an inband power meter within a German project for the benchmarking of EUV source concepts.¹⁹ The calibration results for the three tools are summarized in Table 30.8. The differences in responsivity and bandwidth for S- and P-polarized radiation strongly increase with increasing angle of incidence at the mirrors. So, there is a trade-off between the requirements for a compact design, which requires larger angles of incidence so that the beam can pass the mirrors (see Fig. 30.16), and the robustness of the tool calibration. An important feature besides bandwidth and responsivity is the stability of the bandpass wavelength with respect to the alignment of the tool axis relative to the direction of the source. From the point of view of calibration it is therefore desirable to have an angle of incidence as close to normal as possible.

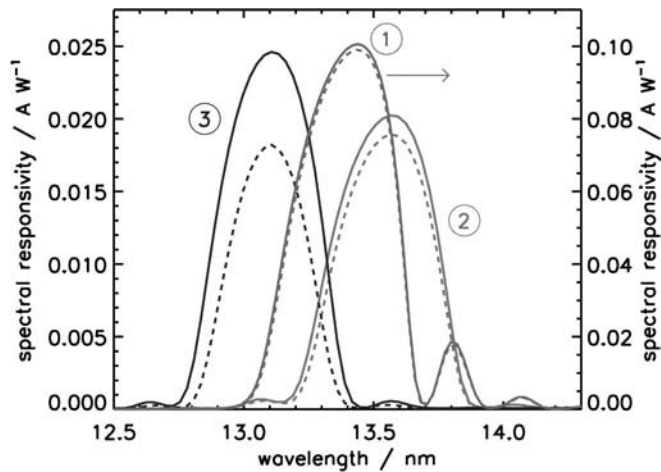


Figure 30.17 Spectral responsivity of different double-multilayer inband power meters. Shown are curves for s-polarized (line) and p-polarized (dashes) radiation. The responsivity for the PTB tool (tool 1) with 5-deg angle of incidence⁵⁰ and an AXUV diode as detector is shown on the right scale. Tools 2 and 3 use incidence angles of 10 and 18 deg to normal,¹⁹ respectively. The detector for these tools was a GaAsP/Au Schottky diode.

Table 30.8 Compilation of the calibration data for three different inband power meters using different angles of incidence at the mirrors.

Tool no.	Angle of incidence to normal	Bandwidth, FWHM (nm)		Bandwidth-integrated responsivity over 0.1 nm (C J ⁻¹)		Wavelength shift (nm deg ⁻¹)
		S-pol.	P-pol.	S-pol.	P-pol.	
1	5 deg	0.436	0.430	0.451	0.438	0.021
2	10 deg	0.444	0.422	0.0900	0.0815	0.042
3	18 deg	0.420	0.350	0.1034	0.0655	0.077

The Jenoptik E-MON[®], working at a 10-deg angle of incidence, is therefore a compromise between compactness and easy use on the one side and measurement accuracy on the other. With properly designed mirrors, a good spectral selectivity for inband EUV with very low side wiggles is achieved (see Fig. 30.18).

As discussed above, calibration at PTB is done using a small collimated beam. Therefore, additional uncertainties must be taken into account for measurements at a radiation source. For an isotropic emitting source (e.g., direct observation of a plasma source), the size of the aperture in the power meter and the distance of this aperture from the source point must be known. In practice, these might be the dominating uncertainties for measurements at the source, as illustrated in Table 30.9, which is taken from Ref. 50.

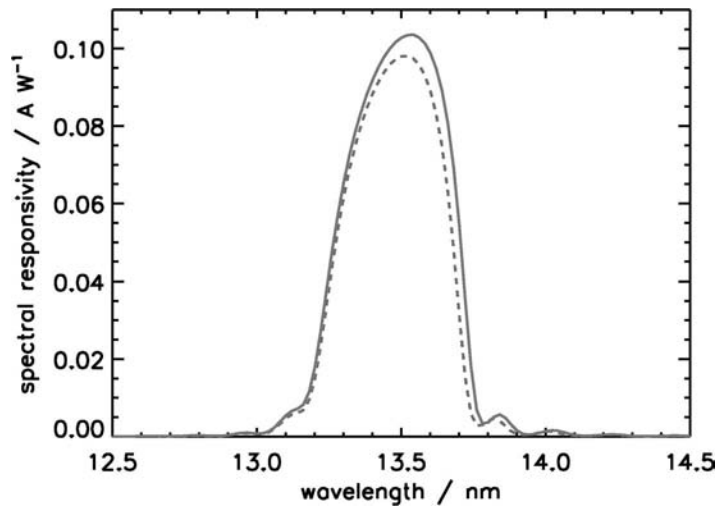


Figure 30.18 Spectral responsivity of an E-MON[®] power meter. Shown are curves for s-polarized (line) and p-polarized (dashes) radiation. The OOB wiggles in the responsivity are well suppressed by the multilayer coating design as compared to, e.g., tool 1 in 0. (See also Fig. 30.17.)

Table 30.9 Compilation of the uncertainty contributions for the inband power-meter calibration.

Quantity	Relative uncertainty contribution u (%)
Radiant power (reference detector)	0.5
Higher diffraction orders	0.03
Diffuse scattered light	0.2
Aperture area (diameter 2.8 ± 0.01 mm)	0.7
Distance between source and aperture of the power meter* (1465 ± 10 mm)	1.4
Power-meter responsivity	1.7

*Included here because it is a significant contribution to the uncertainty for measurements at a source.

30.5.2 Imaging spectrometer

An imaging spectrometer measures the spectral and spatial distribution of the radiation. There are several options for obtaining an image of an EUV source. The easiest way is to use a pinhole camera, which can be easily combined with a transmission grating to make a pinhole spectrometer. The disadvantage is that the spatial resolution is limited by the pinhole size, which also limits the spectral resolution, because only a few lines of a grating can be used. Diffractive imaging utilizes zone plates that are capable of very high spatial resolution, but due to its principle, it cannot focus broadband radiation. A more versatile design uses a grazing-incidence mirror for focusing. The scheme of the spectrograph⁵⁰ is shown in Fig. 30.19. The first optical element is a filter for visible and IR suppression, followed by an aperture, which defines the solid angle. Because the mirror is operated at grazing incidence, there is practically no dependence of the reflectance on the wavelength for the EUV spectral range. For use as a spectrograph, a dispersing grating is placed between the mirror and a CCD as the image sensor. The grating is a freestanding gold transmission grating with 5000 lines/mm (strengthened by a support grid) with an area of 5 by 10 mm. If the distance between the grating and the CCD is chosen such that the zero-order diffraction is detected by the CCD, an unambiguous wavelength calibration is possible without knowing the distance between the grating and the CCD or the grating line density, using only the position of the zero order and the L absorption edge of silicon. The L edge occurs in the spectra due to absorption in the front oxide of the CCD chip (see Figs. 30.20 and 30.21). The larger collection angle than with a pinhole spectrometer allows measurement in single-shot mode, using the full dynamic range of the CCD. So, shot-to-shot variations of source size, position, and spectrum could be investigated.

Since the calibration of the whole imaging system is not possible using the collimated beam, we carried out a component calibration. The mirror reflectance and the efficiency of the grating plus the CCD were measured independently. Figure 30.20 shows the efficiency as counts at the CCD with respect to the total energy of the photons incident on the grating. In the range from 10 to 15 nm, the spectrometer efficiency varies by about a factor of 2. At 13.5 nm, one count at the CCD corresponds to three photons incident at the grating. For calibration, the grating and the CCD sensor were mounted at their working distance at the end of

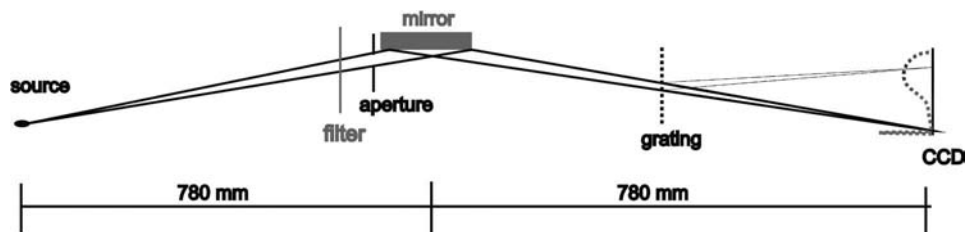


Figure 30.19 Scheme of an imaging spectrometer used to characterize the spectral distribution of EUV radiation and the spatial distribution of the emitting volume.

the soft-x-ray radiometry beamline. A reference detector was placed in front of the spectrometer for photon flux measurement, and a mechanical shutter for the CCD. For each wavelength, the grating was aligned relative to the CCD so that the diffracted radiation was incident at the same position as for the spectrometer operation. This is essential to allow for possible inhomogeneity of the response across the CCD area. The contributions to the uncertainty are summarized in Table 30.10.

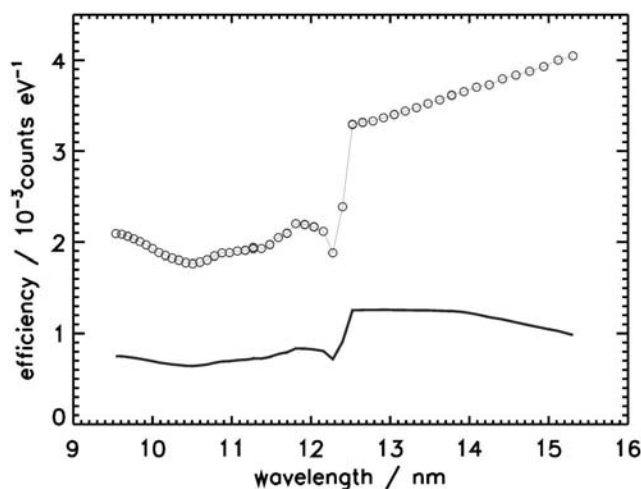


Figure 30.20 Spectral detection efficiency of grating plus CCD, measured by direct comparison with a photodiode using monochromatized radiation at the soft-x-ray radiometry beamline. Measured points are shown as open circles; the line is intended only to guide the eye. The lower line shows the efficiency including a 300-nm freestanding Zr-filter. Besides the sudden step by about a factor of 2 at the Si L edge, there is no significant spectral structure. The increasing efficiency toward longer wavelength due to the grating is roughly compensated by the filter.

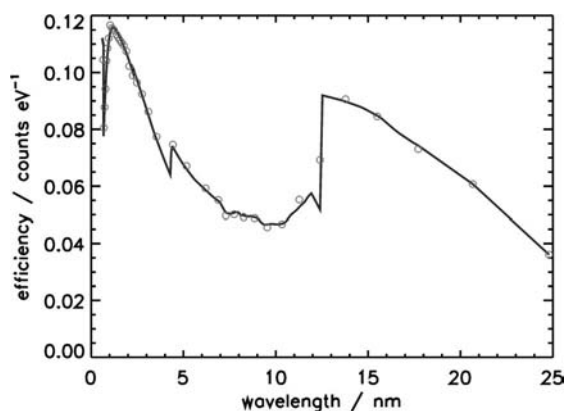


Figure 30.21 Detection efficiency of a back-illuminated CCD, measured by comparison with a photodiode using monochromatized radiation at the soft-x-ray radiometry beamline. Measured points are shown as open circles; the line is an interpolation using a responsivity model developed for photodiodes.³³

Table 30.10 Compilation of the uncertainty contributions for the spectrometer calibration.

Quantity	Relative uncertainty contribution u (%)
Radiant power (reference detector)	0.5
Higher diffraction orders	0.03
Diffuse scattered light	0.2
Integration time for CCD	5
Aperture area* (2.00 ± 0.01 by 6.00 ± 0.05 mm)	0.5
Distance between source and aperture of the spectrometer* (750 ± 10 mm)	2.6
Spectrometer efficiency	5.7

*Included here because it is a significant contribution to the uncertainty for measurements at a source.

Working with an integration time of a few seconds for the CCD, an overlap of the dynamical ranges of the photodiode, which needs sufficient radiant power for a good signal-to-noise ratio, and the CCD, which saturates at a too high photon flux, was achieved. Therefore, a significant uncertainty contribution resulted from the timing jitter of the mechanical shutter, which was about 0.1 s.

Additional investigation of the individual components reveals the reason for the rather strong spectral dependence of the efficiency: it is the efficiency of the CCD chip as shown in Fig. 30.21. Thus, the main source of the spectral dependence is the CCD, which clearly shows the need for absolute detector calibration for the characterization of spectrometers.

Another concept for a spectrograph is realized by the E-spec[®] of Jenoptik Mikrotechnik. It uses a grazing-incidence reflection grating by imaging an entrance slit onto a CCD sensor (see Fig. 30.22). Calibration at PTB can be provided with reference to the radiation passing the entrance slit. The monochromatized photon flux from the soft-x-ray radiometry beamline is measured with a calibrated photodiode placed on a linear feedthrough behind the entrance slit of the E-spec[®]. For each wavelength, the signal measured at the CCD (see Fig. 30.23) is normalized to this photon flux (see Fig. 30.24). Thus a calibration of all optical components is directly achieved. For measurements at a source, the size and distance of the entrance slit must be known precisely, as discussed for the PTB transmission grating spectrograph.

30.6 Conclusions and Future Needs

PTB has set up versatile instrumentation for the calibration and characterization of optical components and detectors in the EUV spectral range. High-accuracy detector calibration using a primary standard and reflectometry provide the basis for long-term reproducibility of the radiometric measurements. Further work will be dedicated to the reduction of the uncertainties of these measurements to keep up with the increasing needs of the industry as expressed in the lithography roadmap. To better serve the customers' need for calibration measurements, PTB will extend

its measurement capabilities toward the measurement of pulsed radiation at higher peak power and will further investigate the stability and reliability of detectors and optical components for EUV.

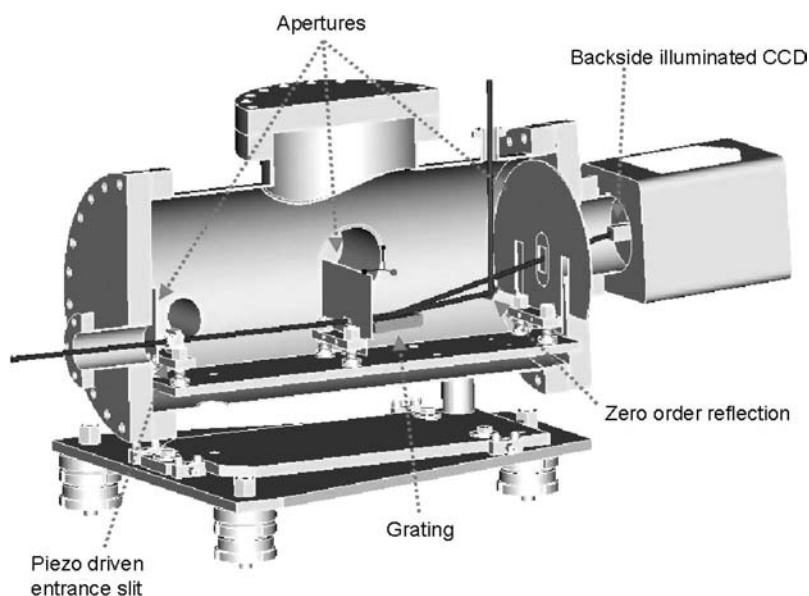


Figure 30.22 Schematic of the spectrograph E-spec® from Jenoptik Mikrotechnik, courtesy of M. Schührmann, JOMT. The radiation passing the entrance slit is dispersed in first order onto a CCD sensor by a grazing-incidence reflection grating.

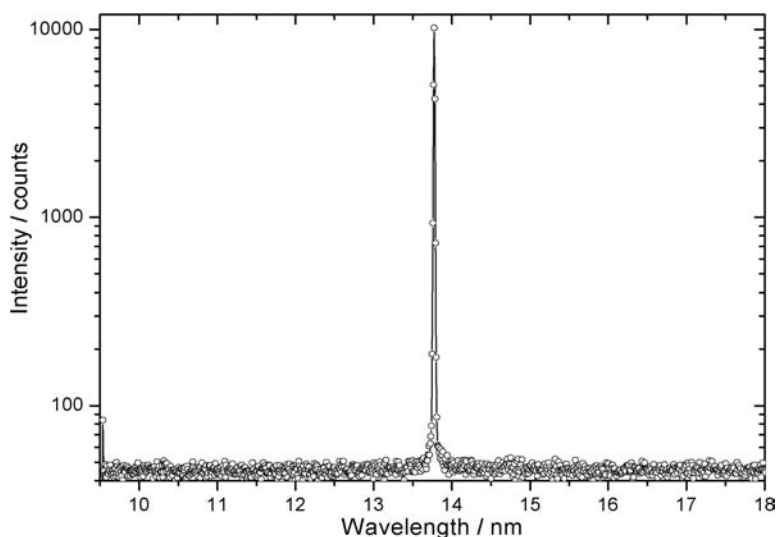


Figure 30.23 Response of the E-spec® to monochromatized radiation at the soft-x-ray radiometry beamline.

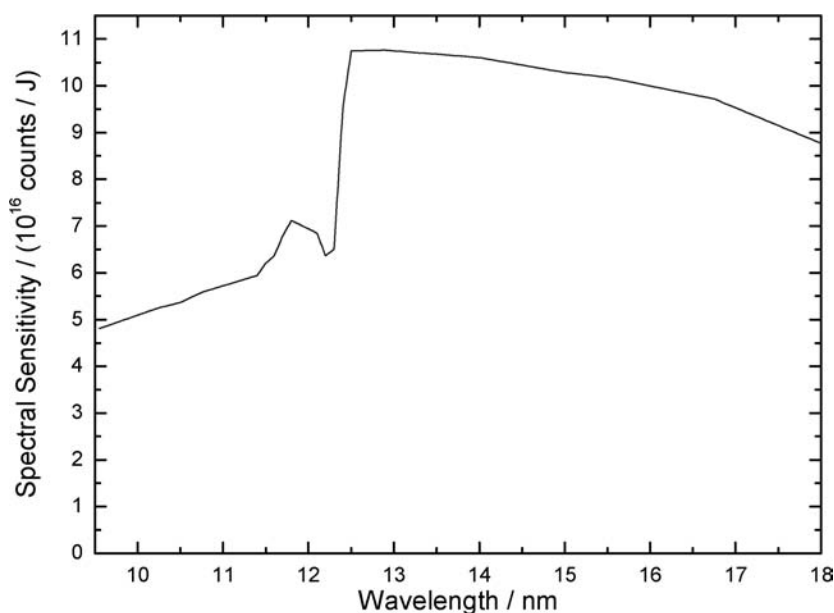


Figure 30.24 Detection efficiency of an E-spec[®] measured by comparing the signal at the CCD with the monochromatized photon flux passing the entrance slit and measured with a calibrated photodiode.

Acknowledgments

The authors acknowledge the valuable contributions of their colleagues from the radiometry laboratory, which greatly contributed to the results presented here. Particularly, we acknowledge the work of Roman Klein regarding the PTB undulator, of Roman Klein and Reiner Thornagel in installing and operating the irradiation beamline, and of Ralph Müller in investigating the diode linearity. Most of the measurements were done by our colleagues Thomas Bock, Christian Buchholz, Andreas Fischer, Christian Laubis, Bernd Meyer, Sven Plöger, David Rost, Frank Scholz, Uwe Schwarz, Johannes Tümmeler, Katrin Vogel, and Heike Wagner.

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A biography was not available for Gerhard Ulm.

Chapter 31

Electron-based EUV Sources for At-Wavelength Metrology

André Egbert and Boris N. Chichkov

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31.1 The EUV Tube—an Old Solution for New Applications

During the past few years, significant progress has been achieved in the development of multilayer-coated optical components for the EUV spectral range. At present, the characterization of EUV optics is carried out at synchrotron radiation facilities. Synchrotrons are high-quality sources that are ideal for scientific research, but they are very complex and expensive for applications. Therefore, compact, cheap, and easy-to-operate tools and systems are badly required for at-wavelength control and inspection, directly at the mirror fabrication labs and companies. Several attempts to develop laboratory EUV sources for metrology, based on laser- or discharge-produced plasmas,¹ are currently being made. Unfortunately, these sources have rather complex setups and high running costs. They operate at a relatively low repetition rate, exhibit considerable temporal and spatial fluctuations, and always require special efforts for debris mitigation.

Usually it is overlooked that one can produce EUV radiation directly from solid targets, avoiding all these plasma-related drawbacks.² This can be done by using electron-induced characteristic emission from solids. The electron-based EUV source can be considered as an analog to a conventional x-ray tube. Electrons are generated by a tungsten filament, accelerated in a high-voltage electric field toward an anode, and focused onto a solid target, which allows the generation of characteristic emission in the EUV spectral range. This radiation is produced by electron-impact ionization (excitation) of atomic inner shells, which is followed by radiative decay. In Fig. 31.1(a), dependences of the wavelengths of the characteristic K- and L-shell emission on the atomic number Z are shown. The $K\alpha$ line of beryllium ($Z = 4$) and the L-shell radiation of silicon ($Z = 14$) are located at 11.4 and 13.5 nm, respectively. Therefore, electron-induced emission from these materials (especially from silicon) is potentially of high practical importance for EUV-related applications. An EUV source operating via this mechanism (*EUV tube*) fulfills practically all requirements for a metrology source: stable, long-term, and debris-free operation; compact, low-cost, and user-friendly setup; and well-defined, easy-to-calibrate, and controllable output.

For several decades soft-x-ray sources based on the electron bombardment of solid targets have been studied³ and applied to the calibration of soft-x-ray spectrographs and detectors. However, the possibility of using this technique for the generation of EUV radiation has fallen into oblivion. Now, due to the rapid technological developments in EUVL, this technique has been rediscovered as a promising tool for EUV metrology.² An interesting but more complicated version of an EUV source based on narrowband Si L-edge Cherenkov emission induced by relativistic electrons also has been suggested.⁴

For radiation sources based on the electron bombardment of solid targets, it is well known that the fluorescence yield is less for lighter elements due to the competition between the radiative and Auger decays. As an example, in Fig. 31.1(b) the

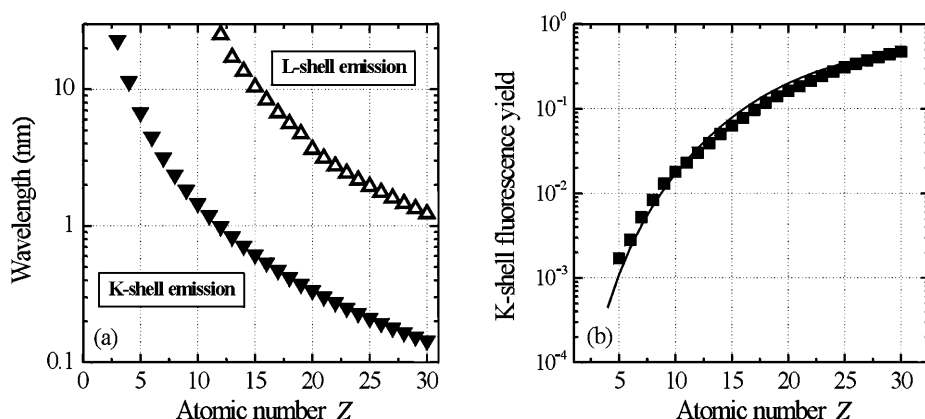


Figure 31.1 Dependences of (a) characteristic K- and L-shell emission wavelengths, and (b) K-shell fluorescence yield on the atomic number Z . The solid line in (b) represents a fit corresponding to $Z^4/(Z^4 + \text{const})$.

K-shell fluorescence yield as a function of the atomic number Z is shown.⁵ The solid line represents a fit corresponding to $A/(A + W) \sim Z^4/(Z^4 + \text{const})$, where A and W are the radiative and Auger decay probabilities. For the generation of high-power characteristic emission with beryllium and silicon targets, this behavior can be considered as a serious drawback. Nevertheless, the EUV tube can play an important role for various *at-wavelength* metrology applications: EUV reflectometry of multilayer mirrors (MLMs) and masks, calibration of EUV instruments, characterization of EUV optics, etc.

In Sec. 31.2, the spectral, spatial, and temporal properties of the EUV tube are presented in detail. The long-term stability and the debris-free operation of the source are demonstrated, and prospects for further power scaling are outlined. In Sec. 31.3, different applications of the source in the field of at-wavelength metrology are provided.

31.2 Characteristics of the EUV Tube

31.2.1 Target materials, spectral properties, and conversion rate

In the investigations presented here, a modified microfocus x-ray tube (phoenix|x-ray Systems+ Services GmbH) is used for the generation of electron-induced EUV radiation. The *sem|20* EUV tube is equipped with an electromagnetic focusing unit that allows computer-controlled variation of the electron spot size at the target surface. The accelerating voltage can be adjusted in the range of 5 to 20 kV. The maximum electrical power that can be applied to the target is 50 W. The tube is evacuated to a pressure below 10^{-4} mbar by a turbomolecular pump. A photograph of the *sem|20* EUV tube is shown in Fig. 31.2.

For the spectral characterization of the generated radiation, an EUV spectrograph developed and fabricated by JENOPTIK Mikrotechnik GmbH was used. This spectrograph is equipped with a piezo-controlled entrance slit, a spherical reflection grating, and a 1024×1024 pixel back-illuminated CCD camera (with a pixel size of 13 μm). Figure 31.3 illustrates a typical silicon EUV spectrum, which was recorded at an accelerating voltage of 10 kV using a silicon wafer target. The Si level scheme is shown in Fig. 31.4.⁶ The $L_{2,3}$ -shell emission band, radiating around 13.5 nm, shows a characteristic spectral shape corresponding to the Si valence-band structure.³ The radiation bandwidth is approximately 1.5 nm with a high-energy radiation edge starting at 12.4 nm. For applications related to EUVL, it is important that the radiation maximum of the silicon EUV emission occur exactly at 13.5 nm.

The absolute conversion rates from electrons into EUV radiation are measured for silicon wafer targets using a calibrated EUV spectrograph at JENOPTIK Mikrotechnik GmbH. This rate is defined as the emitted EUV power at 13.5 nm (in 2% bandwidth and a solid angle of 2π sr) per unit applied target current. The corresponding dependence of the conversion rate on the accelerating voltage is illustrated in Fig. 31.5. The value of the conversion rate is given in microwatts per



Figure 31.2 Photograph of the electron-based EUV tube (*sem|20*).

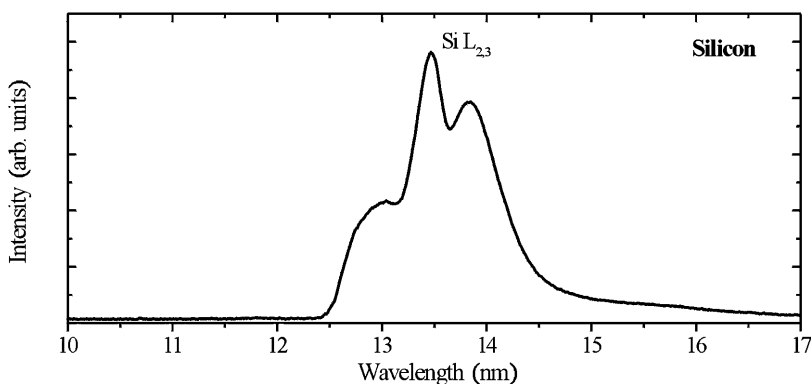


Figure 31.3 Silicon EUV spectrum.

milliampere. The measurements are performed at an emission angle of 70 deg with respect to the target normal. As can be seen, this curve exhibits a maximum in the range of 7 to 10 keV and reaches a value of approximately 16 $\mu\text{W}/\text{mA}$. Therefore, a total EUV power of more than 30 μW at 13.5 nm (2π sr, 2% bandwidth) can be obtained with the *sem|20* EUV tube at the maximum target current. This corresponds to an inband EUV flux of 2×10^{12} photons/s. The total EUV power emitted from the tube in a spectral range from 12.4 to 15 nm is larger than 100 μW in 2π sr.

In addition to EUV radiation, x rays at 1.74 keV ($K\alpha$ radiation) and some amount of bremsstrahlung are also generated upon electron impact on the silicon target. The total amount of these x rays is measured to be about 20 times higher than the EUV power between 12.4 and 15 nm. Nevertheless, these x rays are not

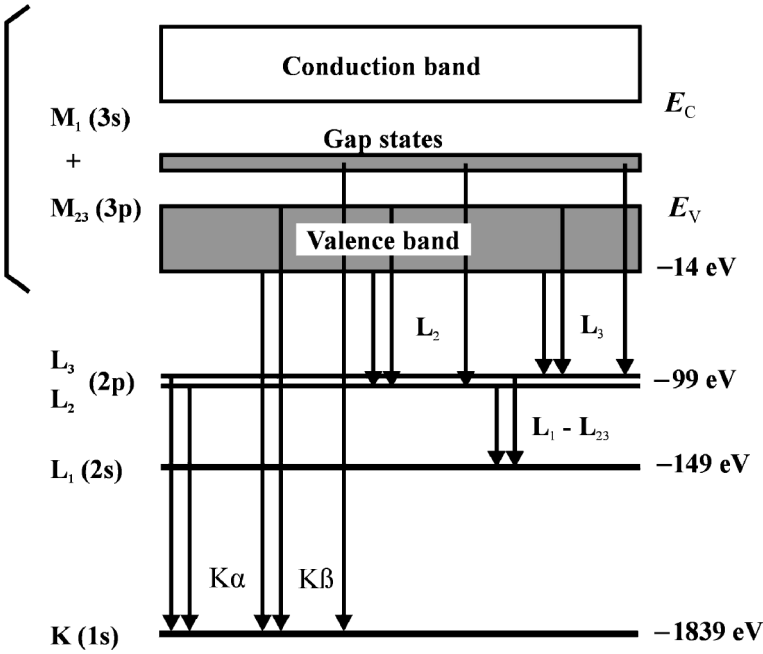


Figure 31.4 Silicon energy-level scheme.

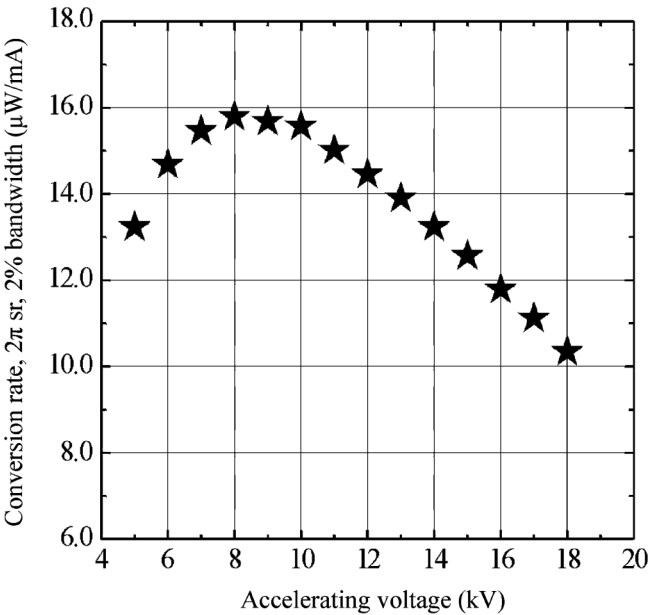


Figure 31.5 Conversion rate (inband EUV power at 13.5 nm per unit applied target current) versus accelerating voltage for a silicon wafer target and an emission angle of 70 deg.

of great importance and can be removed by a single reflection from a multilayer-coated EUV mirror.

Apart from silicon wafers, a number of different other target materials are being investigated using the EUV tube. As examples, the corresponding EUV and soft-x-ray spectra obtained from beryllium, silicon carbide, molybdenum, and copper targets are illustrated in Fig. 31.6. The Be K α emission [see Fig. 31.6(a)] consists

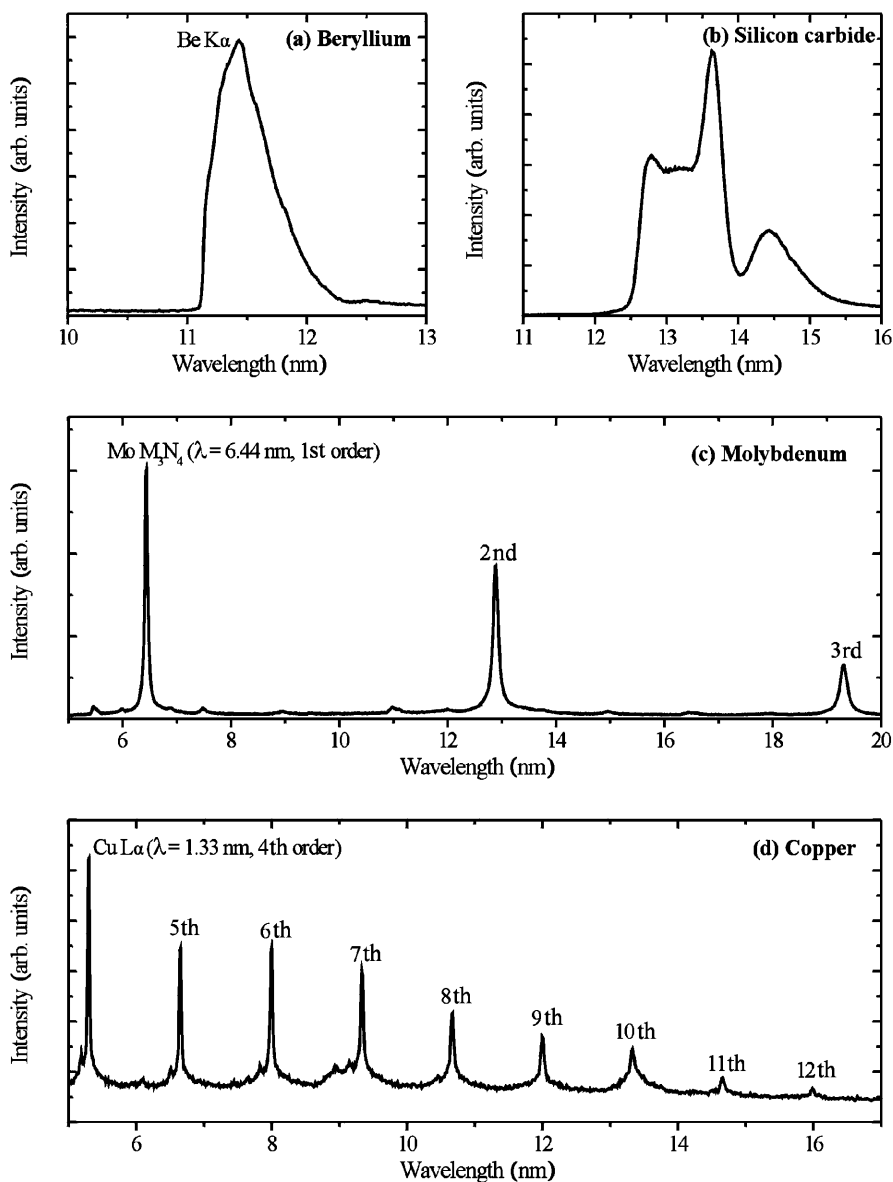


Figure 31.6 EUV and soft-x-ray spectra obtained with different target materials: (a) beryllium, (b) silicon carbide, (c) molybdenum, and (d) copper.

of a relatively broad wavelength band that spans from approximately 11.1 nm, corresponding to the Be $K\alpha$ high-energy radiation edge, up to 12.8 nm. The spectral shape and the maximum of the emission, which is located at 11.4 nm, are in agreement with previous spectroscopic investigations.³ Therefore, the electron-induced emission from beryllium is suitable for the characterization of Mo/Be MLMs.

Figure 31.6(b) shows the emission band from silicon carbide (SiC), which is slightly different from the spectrum obtained with a pure silicon wafer (see Fig. 31.3). The SiC spectrum is recorded after reflection from a gold-coated toroidal grazing-incidence mirror, which is used to collect and focus a part of the generated EUV radiation onto the entrance slit of the spectrograph. The generated carbon $K\alpha$ emission at 4.5 nm is not reflected by the toroidal mirror. Therefore, the spectrum from SiC is free from higher grating orders of the C $K\alpha$ line. The measured inband conversion rate for SiC is approximately 2 times smaller than that for Si wafers.

Figure 31.6(c) and (d) illustrate the spectra obtained with molybdenum and copper targets, respectively. These spectra are recorded directly without a gold-coated toroidal mirror. The observed molybdenum emission can be attributed to the Mo $M\xi$ ($M_5\ 3d_{5/2}-N_3\ 4p_{3/2}$) radiative transition at 6.44 nm, which appears in first, second, and third grating diffraction orders. Copper shows a bremsstrahlung continuum superimposed by the 4th to 12th grating orders of the Cu $L\alpha$ emission at 1.33 nm. Due to their small linewidth, the emission spectra from molybdenum and copper targets can be applied for a precise wavelength calibration of EUV spectrographs.

Since silicon with an EUV emission at 13.5 nm is the most important target material for the at-wavelength characterization of EUV mirrors and masks, all other characteristics of the EUV tube are presented for silicon targets.

31.2.2 Source size and angular distribution

The source size of the microfocus *sem|20* EUV tube is determined using a pinhole camera setup. In our experiments a pinhole with a diameter of 5 μm and a magnification of 25 is used for imaging the source size onto a CCD camera. Figure 31.7 illustrates pinhole images for an accelerating voltage of 10 kV and different values of the tube current. The pinhole images have been recorded at an angle of 70 deg with respect to the target normal. The electron optics used in the *sem|20* EUV tube allows one to achieve source sizes well below 20 μm in diameter. Therefore, the

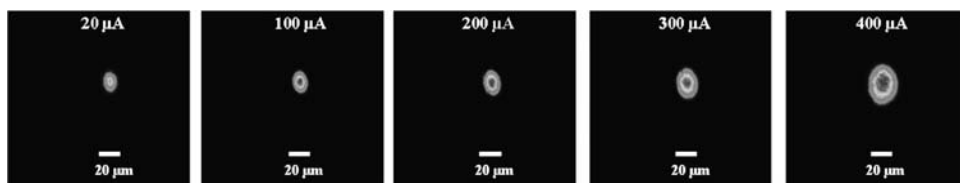


Figure 31.7 Pinhole-camera images of the source for different values of the tube current and at an accelerating voltage of 10 kV.

brightness (power per unit area) obtained with the electron-based EUV tube can be higher than that of plasma-based EUV metrology sources.

Another advantage of the EUV tube is the possibility of continuously varying the source size while keeping the total emitted EUV power constant. This can be done by a computer-controlled adjustment of the electron optics at a fixed value of the tube current and the accelerating voltage. Corresponding pinhole images are shown in Fig. 31.8 for 10 kV and 500 μA .

The EUV power emitted from the silicon target depends on the emission angle, due to reabsorption of the generated EUV photons inside the target. This angular dependence is measured using the setup illustrated in the left part of Fig. 31.9. As a detector an EUV power monitor consisting of a 45-deg MLM and an EUV diode (AXUV-100, IRD Inc.) is used. The measured conversion rate (in microwatts per milliampere, emitted into 2π sr and 2% bandwidth at 13.5 nm) is shown in Fig. 31.9 (right-hand graph, open triangles) for some angle values around the central emission angle of $\alpha = 70$ deg. The solid line represents a fit of the experimental data

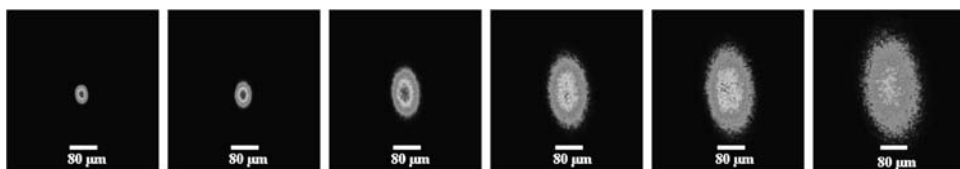


Figure 31.8 Pinhole-camera images for an accelerating voltage of 10 kV and a target current of 500 μA . Variation of the source size is achieved by adjusting the electron optics in the *sem/20* EUV tube.

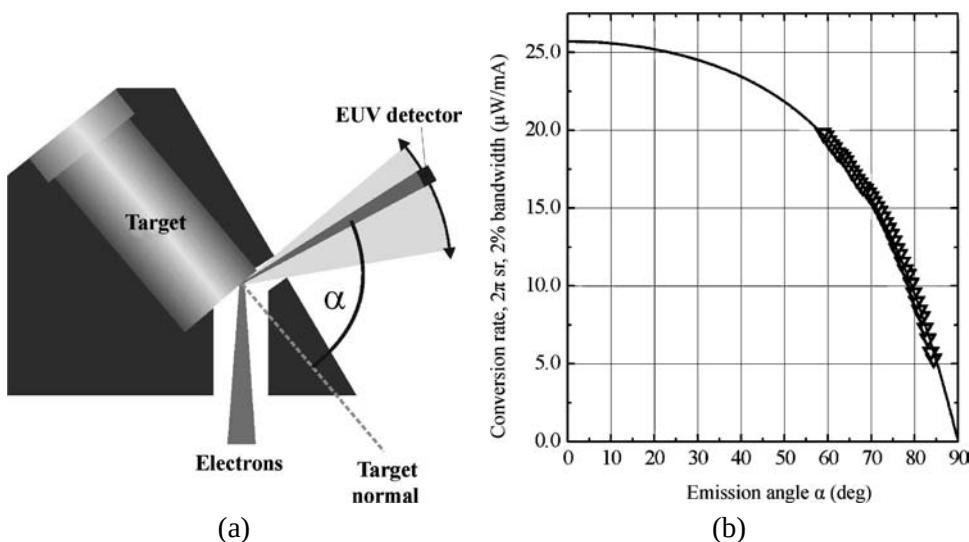


Figure 31.9 (a) Scheme of the experimental setup to investigate the angular dependence of the EUV emission. (b) Measured conversion rate at 13.5 nm as a function of the emission angle (open triangles) and fitted curve (solid line) corresponding to Eq. (31.1).

taking into account the distribution of generated EUV photons inside of the silicon target as well as their reabsorption during propagation out of the target. The fitted curve is given by the expression

$$I_{\text{EUV}}(\alpha) = A \int_0^a \exp\left(-\frac{x}{d \cos \alpha}\right) \left(1 - \frac{x}{a}\right) dx, \quad (31.1)$$

where a is the radiating-layer thickness ($a = 0.65 \mu\text{m}$), which is determined by the electron penetration depth; d is the EUV attenuation length in Si ($d = 0.58 \mu\text{m}$); x is the depth in the silicon target; and α is the emission angle with respect to the target normal. According to Eq. (31.1), a reduction of the emission angle would increase the conversion rate up to a value of $\approx 25 \mu\text{W}/\text{mA}$ (2π sr, 2% bandwidth at 13.5 nm) at an emission angle $\alpha = 0$ (parallel to the target normal).

31.2.3 Long-term stability and debris-free operation

A great benefit of the electron-based EUV tube compared to plasma-based sources is the excellent temporal long-term stability of the EUV emission. To record this stability, the radiation emitted from the *sem|20* EUV tube is reflected by a 45-deg Mo/Si MLM and detected using an EUV photodiode (IRD Inc., model AXUV-100) coated with a Ti/Zr/C layer to block visible radiation. The diode current is measured with a picoammeter. The distances from the mirror to the EUV source and from the mirror to the diode are 10 and 15 cm, respectively.

In Fig. 31.10, the stability of the source operation with a total running time of nearly 70 h is illustrated. In this case an accelerating voltage of 7 kV and a target current of 700 μA were used. The small apparent fluctuations of the signal are probably due to the inaccuracy of the photodiode current measurements and are below $\pm 0.5\%$. Since no additional filters between the source and the mirror are used and the recorded signal does not show any decrease, this measurement also demonstrates that the EUV tube is a completely debris-free source. No degradation of the MLM can be observed.

Both aspects, the high stability and the debris-free operation, make the electron-based EUV tube an ideal source for metrological applications.

31.2.4 EUV brightness and power scaling

To define a maximum electron current density that can be applied for the generation of EUV radiation from a stationary silicon wafer (without cooling and/or rotating the target), the electron-induced damage threshold is estimated using the following method: At different values of the accelerating voltage and tube current, the electron spot size at the target is varied in order to control the applied target load. For each set of parameters the target is irradiated for several minutes. The silicon wafer is inspected for damaged areas afterward, using a scanning electron microscope. Depending on the total electrical power, a damage threshold for the

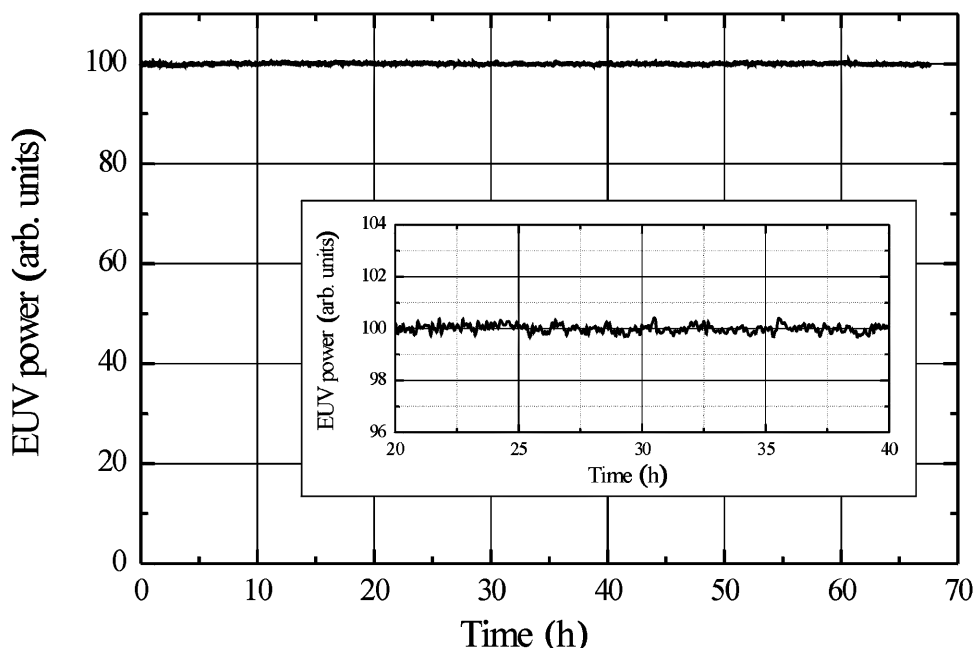


Figure 31.10 EUV power measured over a period of nearly 70 h. An enlarged part of the curve is shown in the insert.

silicon wafer in the range of 1 to 5 kW/mm² is determined from these measurements.

The measured damage threshold determines the maximum EUV power that can be extracted from a given source size (brightness). In the present version of the *sem|20* EUV source with a stationary silicon wafer target, a maximum of about 30 μW at 13.5 nm (2π sr, 2% bandwidth) of EUV radiation can be emitted from a minimum spot size with a diameter of ~100 μm. This corresponds to an EUV source brightness of approximately 10³ W/m² sr. In recent investigations, a 10× higher brightness is achieved by optimizing the target design.

Since the EUV power that can be extracted from a given source size is limited by target damage due to thermal melting, the target can be rotated (or cooled) to further increase the EUV brightness and power. This technique is already well established for medical and industrial applications of x-ray tubes. In the following the power gain that can be achieved by target rotation compared to a stationary target is estimated. The temperatures in a nonstationary, nonequilibrium regime of operation (T_{nst}) and in a stationary, equilibrium regime (T_{st}) are given by

$$T_{\text{nst}} = \frac{P_{\text{nst}}}{S} \sqrt{\frac{t}{\rho c k}}, \quad (31.2)$$

$$T_{\text{st}} = \frac{P_{\text{st}} r}{S k}, \quad (31.3)$$

where P_{nst} , P_{st} are the absorbed (electric) power, S is the irradiated area at the target, t is the irradiation time, ρ is the target density, c is the specific heat, k is the thermal conductivity of silicon, and r is the electron spot radius at the target. Here we assume that r also defines the characteristic scale length of the temperature gradient. For a rotating target, the irradiation time of a single spot at the target surface can be expressed by

$$t = \frac{r}{\pi f R}, \quad (31.4)$$

where R is the radius of the rotating target and f is the rotation frequency. Therefore, assuming $T_{\text{nst}} = T_{\text{st}}$, the power (and brightness) gain G that can be achieved by target rotation is given by

$$G = \frac{P_{\text{nst}}}{P_{\text{st}}} = \sqrt{\frac{\pi f R r \rho c}{k}}. \quad (31.5)$$

For typical parameters $R = 5$ cm, $r = 50$ μm , and $f = 150$ s^{-1} a power (brightness) gain by a factor of $G \approx 5$ is possible.

31.3 Applications of the EUV Tube

31.3.1 Calibration of EUV instruments

A set of different EUV tools and instruments (e.g., spectrometers or energy monitors) is already available for the characterization of high-power EUV sources in terms of spectral properties and output power. For absolute measurements a proper calibration of these metrology tools is necessary. Typically these instruments are calibrated at synchrotron facilities. However, time-consuming procedures and high related costs are a major drawback for industrial users. Therefore, devices for the on-site calibration of the EUV tools and instruments are required. Since the accuracy of the calibration procedures is mainly limited by the stability of the EUV emission, the EUV tube is an ideal source for these purposes.

As mentioned before, some target materials provide narrowband emission lines in the EUV and soft-x-ray spectral range, e.g., the Mo M_5N_3 emission at 6.44 nm. These lines can also be used for the precise wavelength calibration of EUV and soft-x-ray spectrometers, by taking advantage of higher grating orders [see Figs. 31.6(c) and (d)]. Besides molybdenum, a variety of other materials can be used to generate emission lines in the wavelength range from 5 to 20 nm, e.g., the M_5N_3 emission lines of rhodium at 4.77 nm, of niobium at 7.23 nm, of zirconium at 8.18 nm, of yttrium at 9.36 nm, of strontium at 10.86 nm, or the N_5O_3 emission line of barium at 16.44 nm. Using an EUV tube equipped with a multi-element target allows one to perform simple multiwavelength calibration of EUV spectrometers.

In a different application, the transmission of a double-MLM device (multilayer tool) developed and fabricated by JENOPTIK Mikrotechnik GmbH is measured using the *sem|20* EUV tube. This device reflects and filters the incoming EUV radiation and is used (in combination with an EUV diode) as an energy monitor for the characterization of EUVL sources. A detailed description of this tool can be found elsewhere.⁷

In our experiments the reflectivity of this multilayer tool as a function of radiation wavelength is determined. Figure 31.11 illustrates the silicon EUV spectrum as it is emitted from the *sem|20* EUV tube (light gray spectrum) and the spectrum after reflection from the two mirrors of the multilayer tool (dark gray spectrum). These two spectra are recorded using identical EUV tube parameters and are obtained after a 4-min illumination of the spectrograph CCD camera. The spectral response of the device is determined by division of the reflected spectrum by the original source spectrum. This reflectivity curve is illustrated in Fig. 31.12. The solid line represents the multilayer tool reflectivity measured with the *sem|20* EUV tube. As a reference, in Fig. 31.12 also the corresponding data from the Physikalisch Technische Bundesanstalt (PTB) are presented, which have been extracted from an earlier measurement of the spectral response of the multilayer tool equipped with an EUV diode (E-Mon[®]). It can be seen that the two reflection curves are in excellent agreement. The observed high accuracy originates from the very smooth shape of the silicon EUV spectrum. Note that no such high precision can be achieved by EUV plasma sources with emission lines in the relevant wavelength range. In their case a noiselike structure appears at the center of the measured curve.⁷

The determination of the transmission of thin foils, which can be used as EUV filters, is also an important issue in EUV metrology. The EUV emission from silicon is not suitable for this purpose, since the filter transmission can be determined

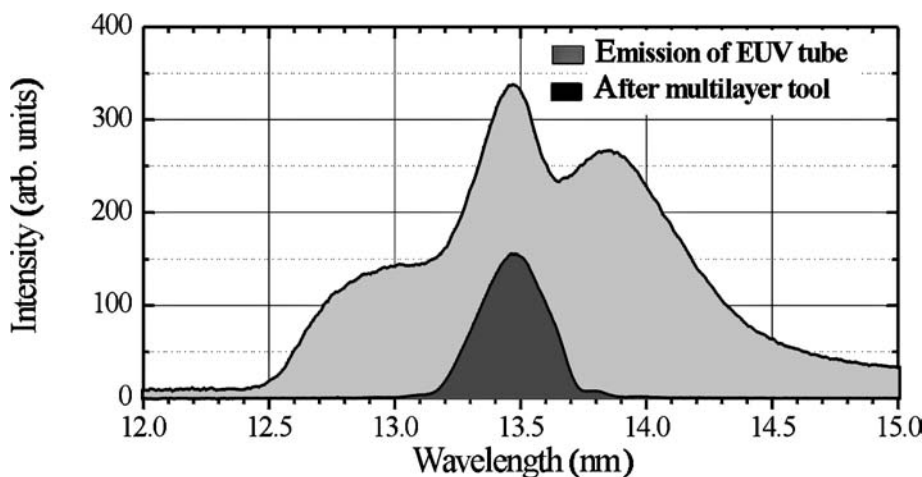


Figure 31.11 EUV spectra as emitted from the *sem|20* EUV tube (light gray spectrum) and after reflection from the two mirrors of the multilayer tool.

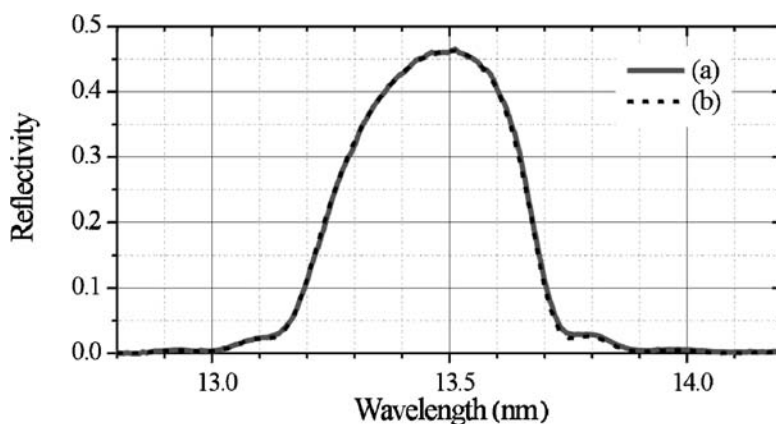


Figure 31.12 Reflectivity curve of the double-MLM tool measured with the *sem/20* EUV tube (a), and the corresponding data from a PTB measurement (b).

only in a small wavelength band from approximately 12.5 to 14.5 nm. Therefore, these applications require a broadband emitter. Tungsten as a target material provides the necessary emission spectrum, which consists of a broad bremsstrahlung continuum.

In our experiment a part of the emitted radiation from tungsten is collected by a gold-coated grazing-incidence toroidal mirror (see Sec. 31.3.2 and Fig. 31.15) and imaged onto the entrance slit of the EUV spectrograph. On one hand, the usable EUV flux is significantly enhanced by this imaging technique, which results in better accuracy of the transmission measurements. On the other hand, one can get rid of higher grating orders because the gold-coated toroidal mirror efficiently reflects radiation only above 10 nm. A tungsten spectrum recorded after reflection from the toroidal mirror is shown in Fig. 31.13 (black line). The shape of the measured spectrum demonstrates the spectral sensitivity of the used EUV spectrograph from JENOPTIK Mikrotechnik GmbH.⁷ The dip around 12.4 nm is due to the silicon absorption edge of the CCD camera used in this spectrograph. The thin foil filters to be examined are positioned in front of the spectrograph entrance slit. The gray line in Fig. 31.13 represents a tungsten spectrum after introducing a zirconium filter with thickness of 300 nm (Luxel Corp.) into the beam path. From these two spectra the wavelength-dependent filter transmission can be determined. The corresponding curve is illustrated in Fig. 31.14. The solid black line represents the measured zirconium filter transmission, whereas the dashed line is a calculated curve.⁸ In the wavelength range from 11 to 20 nm the two curves are in reasonable agreement. The difference between the measured and the calculated transmission for shorter wavelengths can be explained by the low reflectivity of the gold-coated toroidal mirror. In this spectral range the signal is too low to provide reliable measurements. The gray curve in Fig. 31.14 illustrates the measured transmission of a 200-nm-thick silicon nitride (Si_3N_4) filter (Silson Ltd.).

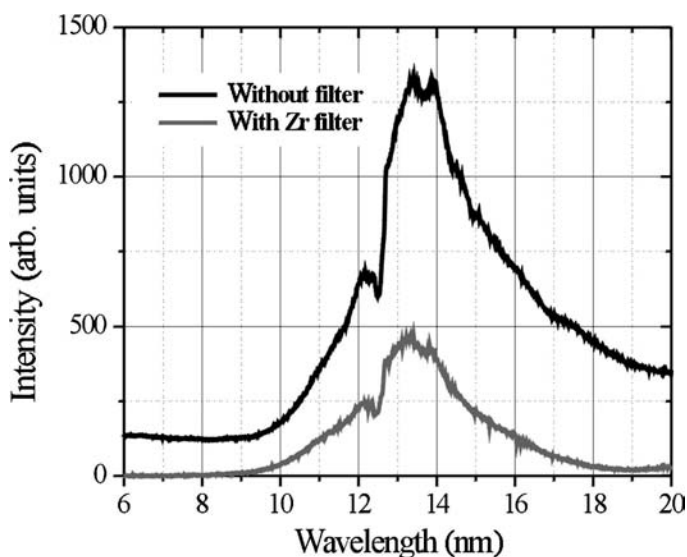


Figure 31.13 Tungsten spectrum after reflection from the gold-coated toroidal mirror (black line) and after an additional 300-nm-thick zirconium filter (gray line).

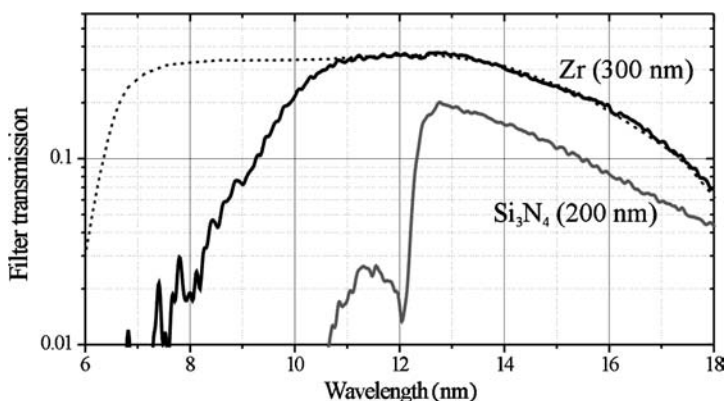


Figure 31.14 Measured transmission curves of 300-nm zirconium (black line) and a 200-nm silicon nitride (gray line) filters. The dotted line represents the calculated transmission⁸ of a zirconium filter.

31.3.2 Characterization of EUV optics and reflectometry

As a demonstrative example for the characterization of EUV optics, a toroidal grazing-incidence mirror [Zeiss; see Fig. 31.15(a)] is used to image our EUV source onto a back-illuminated soft-x-ray CCD camera. The mirror provides sagittal and tangential radii of 108 and 1000 mm, respectively, corresponding to an effective focal length of 164 mm. The mirror is operated at an angle of incidence of about 19 deg. The gold-coated mirror has an rms surface roughness of 1 nm.

The calculated reflectivity as a function of wavelength⁸ is shown in the right-hand graph in Fig. 31.15.

In Fig. 31.16, CCD images of the focal spot are illustrated for different EUV source diameters of 550, 350, 200, and 50 μm (from left to right), which are obtained for a constant EUV power using a silicon target. Whereas the horizontal (tangential) size of the imaged source spot is practically the same in all cases (~ 1000 μm FWHM) due to aberrations, the vertical (sagittal) size decreases with

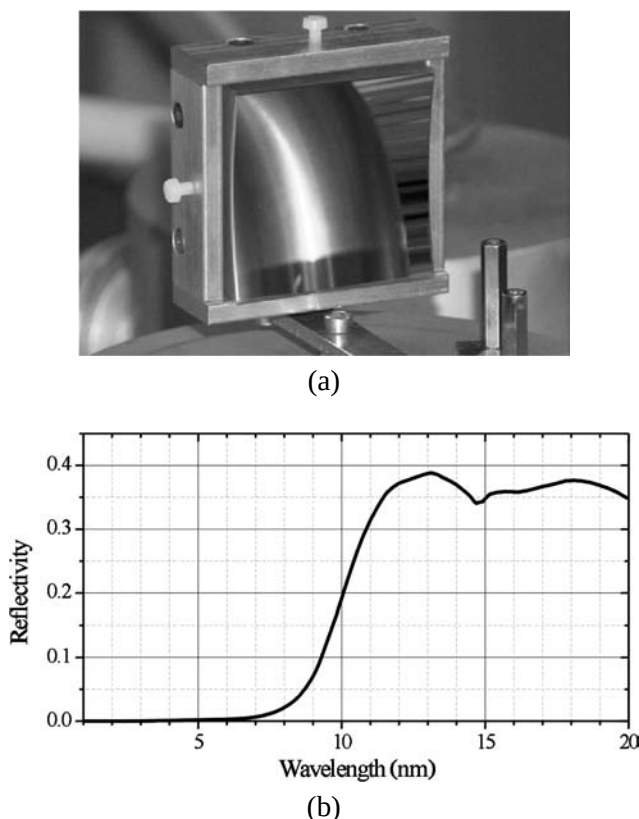


Figure 31.15 (a) Photograph of the toroidal mirror used. (b) Calculated reflectivity⁸ for a grazing-incidence gold mirror (rms roughness of 1 nm, unpolarized light, angle of incidence relative to the mirror surface 19 deg).

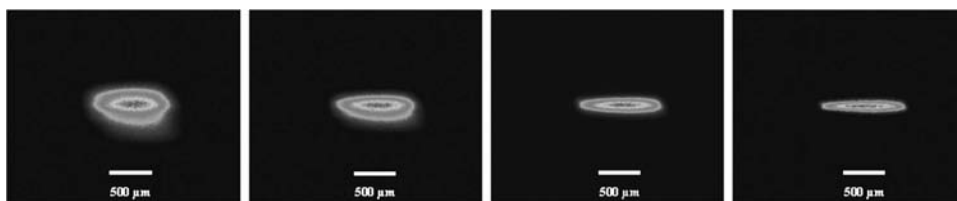


Figure 31.16 CCD images of the focal spot for different EUV source sizes (left to right: 550, 350, 200, 50 μm) after a gold-coated toroidal grazing incidence mirror.

decreasing source diameter. The minimum vertical size is determined to be about $120\text{ }\mu\text{m}$, which is more than 2 times larger than the original source diameter of $50\text{ }\mu\text{m}$. Again this effect can be explained by aberrations. Therefore, the extremely small source size of the *sem*/20 EUV tube allows one to investigate the focusing and imaging properties of EUV–soft-x-ray mirrors and optics and their limits.

In a joint proof-of-principle experiment with AIXUV GmbH, the EUV tube was combined with AIXUV's test-stand reflectometer. A photograph of the experimental setup is shown in Fig. 31.17. In this experiment the reflectivity of a sample MLM and of a broadband reference mirror, which has been previously calibrated by the PTB, are measured simultaneously. This procedure allows the determination of the absolute reflectivity of the sample mirror. The solid line in Fig. 31.18 illustrates the result of this measurement. The open circles show the corresponding

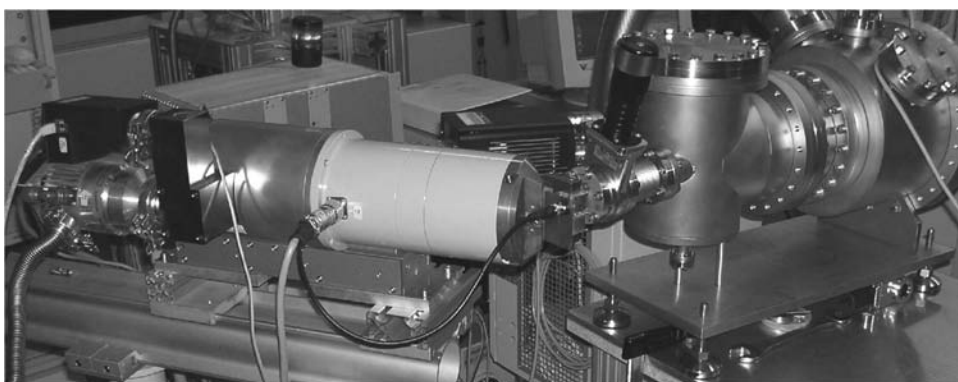


Figure 31.17 Photograph of the *sem*/20 EUV tube (left) connected to the AIXUV test-stand reflectometer (right).

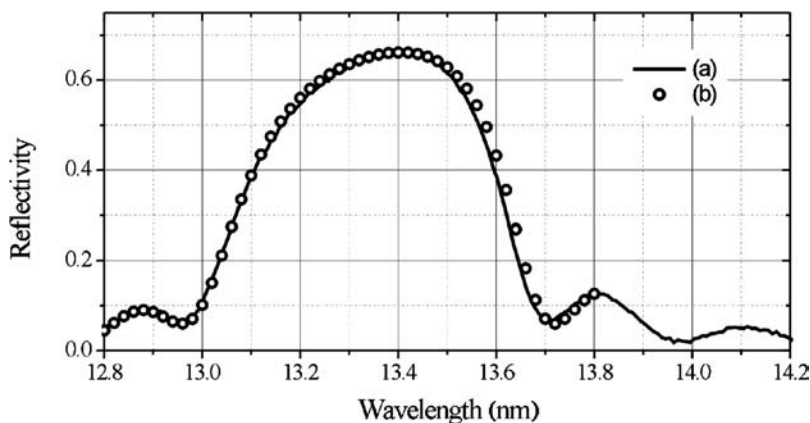


Figure 31.18 (a) The reflectivity curve of a sample MLM tool measured with the *sem*/20 EUV tube in combination with the AIXUV reflectometer, and (b) the corresponding data from a PTB measurement.

calibration of the PTB, which was obtained later. Again, both measurements are in excellent agreement.

31.3.3 Further applications

Further applications of the electron-based EUV source that have not been demonstrated so far may lie in EUV microscopy, the development of photosensitive materials, EUV-mask inspection tools, etc. Due to the excellent stability of the EUV tube regarding spectral properties and power, the source also can be applied for absolute radiometry.

31.4 Summary and Outlook

A compact, stable, debris-free, low-cost, computer-controlled continuous-wave EUV radiation source for off-synchrotron, on-site, at-wavelength metrology has been described. Different target materials allow one to easily access a broad EUV–soft-x-ray wavelength range for various applications. The EUV radiation power can be absolutely calibrated and varied by controlling the electron current and the accelerating voltage. Since no debris is produced, this source, called an EUV tube, promises to become a very important tool for EUV optics characterization and metrology. First application examples of this source have been presented.

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Chapter 32

Synchrotron Radiation Sources for EUVL Applications

Obert R. Wood, II and Alastair A. MacDowell

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32.1 Electron Storage Rings and Synchrotron Radiation

It is well known that when charged particles are accelerated they emit electromagnetic radiation. For example, when electrons traveling at nearly the speed of light are forced to move along a curved path by the magnetic fields of a storage ring, they emit photons into a narrow cone. Depending on the electron energy, this so-called synchrotron radiation can be extremely intense over a broad wavelength range extending all the way from the microwave to the x-ray spectral region. Because this radiation also tends to be vertically collimated and polarized, it has been used as a powerful research and development tool in chemistry, physics, material science, biology and medicine, and, in the last decade or so, has played a key role in the development of EUVL.

A drawing of a typical synchrotron radiation source built around a storage ring is shown in Fig. 32.1. The storage ring, a many-sided doughnut-shaped tube, enables a current of electrons to circulate at essentially the speed of light in a closed orbit for many hours, all the while emitting synchrotron radiation. The electron

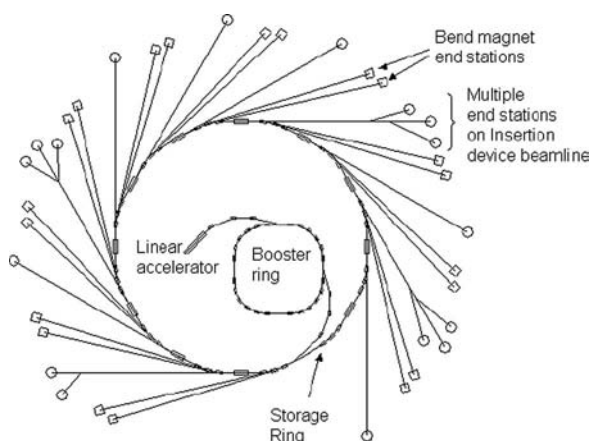


Figure 32.1 Schematic of a small synchrotron-radiation source.

beam decays slowly because of electron momentum loss during collisions with residual gas molecules, electron-electron collisions, and photoemission. If the momentum loss is too high, the electron is lost from within the storage-ring acceptance. To reduce electron-molecule collisions, the inside of a storage ring is maintained at extremely low pressure (in the range 10^{-9} to 10^{-10} Torr). Changing the electron beam's size can change the electron-electron collision rate, but the photoemission process is inherent in the quantum nature of photoemission. A system of magnetic lenses, bending magnets (dipoles), focusing magnets (quadrupoles), and steering magnets (sextupoles), strategically located around the ring, guides and focuses the electron beam. This so-called *lattice* determines the basic features of the circulating beam, such as its emittance and its transverse dimensions, and also determines the number, length, and location of any straight sections in the ring available for *insertion magnets*: devices that provide radiation with enhanced flux, brightness, and spectral range. The energy lost by the circulating electrons to synchrotron radiation is replenished by longitudinal electrical kicks imparted to the beam as it transverses one or more radio frequency (rf) cavities incorporated in the ring. The rf power in these cavities chops the circulating electron beam into bunches and hence determines the duration of the synchrotron radiation pulses; its frequency determines the minimum bunch spacing. The storage ring is filled with electrons from a source called an *injector*, e.g., a linear accelerator fed from an electron gun, a microtron, or a small booster ring fed by a linac or a microtron. Some of the synchrotron radiation from the bending magnets and most of the radiation from the insertion magnets (wigglers and undulators) escapes the storage ring through tangential ports, called *beamlines*, that allow the radiation to pass to experimental end stations located at convenient distances from the ring.

Some of the more important characteristics of the three different types of radiation available from a synchrotron light source¹ are illustrated in Fig. 32.2. *Bending-magnet* (or *dipole*) radiation is produced when relativistic electrons (with energy γmc^2 , where γ is the Lorentz contraction factor, m is the electron mass, and c is

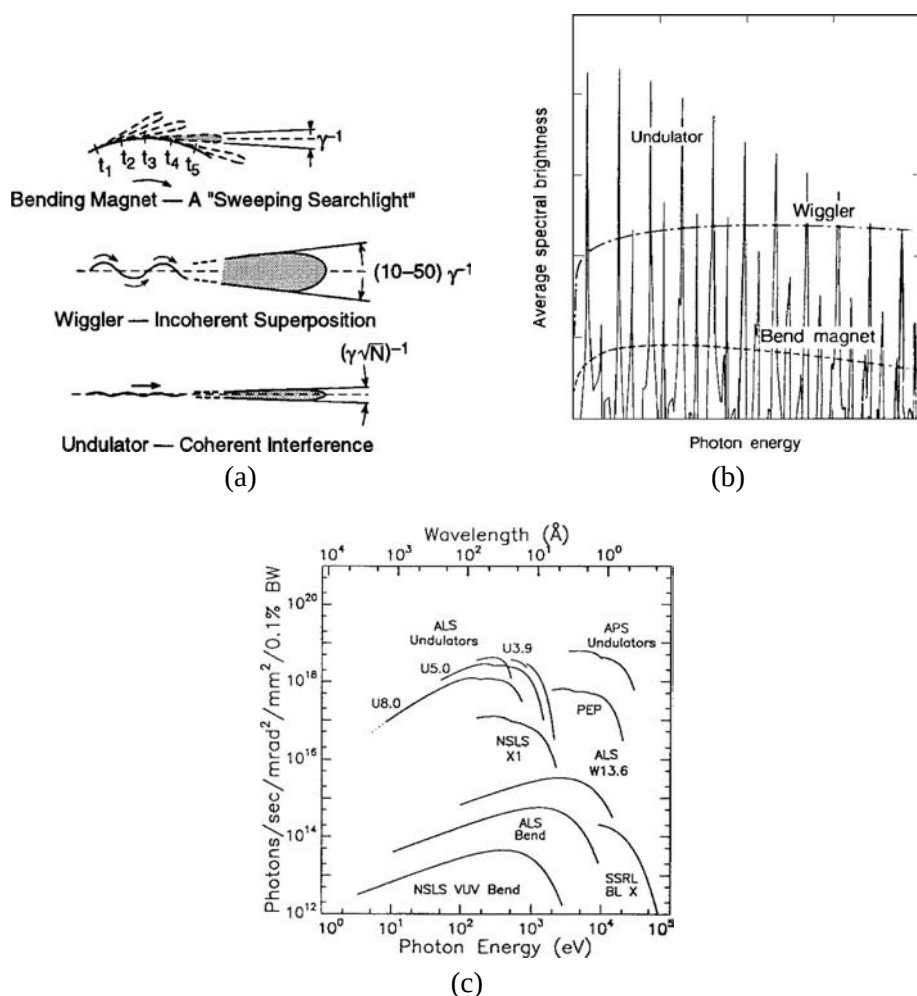


Figure 32.2 (a) Radiation emission pattern from a bending magnet, a wiggler, and an undulator (reprinted from Ref. 1 with permission from World Scientific Publishing); (b) typical emission spectra from a bending magnet, a wiggler, and an undulator; (c) spectral brightness from some representative insertion devices (reprinted from Ref. 2 with permission from World Scientific Publishing).

the speed of light in vacuum) travel in a uniform magnetic field. In this case the emission is confined to a sharp cone (with cone angle γ^{-1}) that sweeps around like the headlight on a toy train, producing a continuous swath of radiation in the plane of the bend, as shown in Fig. 32.2(a) (top). Synchrotron radiation with additional useful properties is produced when relativistic electrons traverse an insertion device with a spatially periodic magnetic field. The periodic magnetic field causes the electrons to wiggle, or undulate, from side to side as they pass through the device. The magnet period, field strength, and other geometric properties of the insertion device can be chosen to optimize one or more properties of the radiation: photon flux, wavelength selectability, spatial resolution, etc. For example, *undulator* radi-

ation is produced when a relativistic electron beam traverses an insertion device with a sufficiently weak periodic magnetic field. The characteristic emission angle from an undulator is narrowed by constructive interference of radiation from the array of magnets, resulting in a pencil-shaped beam of photons [with cone angle $(\gamma\sqrt{N})^{-1}$, where N is the number of magnet periods] that in many ways resembles the output from a laser, as shown in Fig. 32.2(a) (bottom). *Wiggler* radiation is produced when relativistic electrons transverse an insertion device with a strong periodic magnet field. Due to the stronger transverse fields, the oscillation amplitude is larger and the radiation cone angle is broader [with cone angle $K(\gamma)^{-1}$, where K is the electron deflection parameter], as shown in Fig. 32.2(a) (middle).

Typical radiation spectra from a bending magnet, a wiggler, and an undulator² are shown in Fig. 32.2(b). For bending-magnet and wiggler sources, the spectrum is a smooth continuum. The spectral shape of wiggler radiation is similar to that of bending-magnet radiation but shifted to higher photon energies by the higher magnetic fields and increased photon flux. Due to constructive interference, the spectrum of undulator radiation consists of a series of sharp intense peaks at harmonics of the fundamental energy, as shown in Fig. 32.2(b). The spectral brightness of synchrotron radiation from some typical insertions devices at several representative synchrotron radiation facilities² is shown in Fig. 32.2(c). A more detailed description of the characteristics of synchrotron radiation is provided in Sec. 32.2.

By tradition, storage rings are generally classified according to generation. A first-generation storage ring is one that was originally built for use in high-energy physics research and that has subsequently been outfitted with one or more parasitic beam ports to utilize the otherwise lost synchrotron radiation. Somewhat later, a second generation of storage rings, specifically designed as dedicated light sources, was constructed. In general, these second-generation rings have a larger number of bending-magnet beamlines and serve a large user community. The latest synchrotron-radiation facilities, so-called third-generation storage rings, are characterized by much lower electron-beam emittance and contain many straight sections specifically designed for insertion devices. Third-generation rings generally provide synchrotron radiation with much higher brightness. A fairly comprehensive survey of synchrotron-radiation facilities presently available around the world is presented in Sec. 32.3.

In this chapter, we review the fundamentals of synchrotron radiation, especially as they relate to EUVL.³⁻⁵ We begin by briefly reviewing the important characteristics of bending-magnet, undulator, and wiggler radiation in the EUV spectral region. We then list some of the important characteristics of the various synchrotron radiation facilities worldwide. Next, we discuss four applications of synchrotron radiation to EUVL that illustrate why synchrotron EUV sources have played such an important role in the development of this technology. Finally, we comment on the applications that are likely to continue to play an important role in this technologically important field.

32.2 Characteristics of Synchrotron Radiation

As discussed earlier, an electron undergoing acceleration, e.g., one forced to move along a curved path, will emit radiation tangentially in a forward-directed narrow cone, as shown in Fig. 32.2(a). Some of the more important properties of this radiation for the cases of circular motion (bending magnets) and sinusoidal motion (insertion devices with periodic magnetic fields) are described in greater detail in this section.

32.2.1 Bending-magnet radiation

The angular distribution of radiation emitted by electrons moving along a circular trajectory in the horizontal plane of a bending magnet can be calculated exactly if the electron energy, bending radius, electron current, angle relative to the orbital plane, distance to the target point, and vertical and horizontal acceptance angles are known. In practical units, the on-axis photon flux is given by⁶

$$F[\text{photons} \cdot \text{s}^{-1} \cdot \text{mrad}^{-2} \cdot (0.1\% \text{ bandwidth})^{-1}] = 1.327 \times 10^{13} E_e^2 [\text{GeV}] I [\text{A}] H_2 \left(\frac{E}{E_c} \right), \quad (32.1)$$

where E_e is the electron beam energy, I is the average beam current, and $H_2(y) = y^2 K_{2/3}^2(y/2)$, where $K_{2/3}$ is a modified Bessel function of the second kind. A plot of $H_2(y)$, as a function of photon energy E (keV), normalized to the critical photon energy E_c (keV), where E_c is defined as⁶

$$E_c [\text{keV}] = 0.6650 E_e^2 [\text{GeV}] B [\text{T}], \quad (32.2)$$

and B is the magnetic field, is shown in Fig. 32.3. The energy spectrum for bending-magnet radiation is seen to be smooth and broadband, peaking near the critical energy and falling off exponentially at higher energies.² Half the radiated power is in photons with energy greater than E_c , and half is in photons with energy less than E_c . Note that for a photon energy of $4E_c$, the photon flux is reduced by a factor of about 10 from its value at E_c . The emission wavelength corresponding to the critical photon energy, λ_c , is given by²

$$\lambda_c [\text{nm}] = 1.864 \left\{ E_e^2 [\text{GeV}] B [\text{T}] \right\}^{-1}. \quad (32.3)$$

The critical photon energy is the parameter traditionally used to characterize bending-magnet radiation.

Incidentally, since the acceleration of the electrons in the bending-magnet field is confined to the horizontal plane (for vertical bending-magnet fields), the electric field of bending-magnet radiation is polarized in that plane.

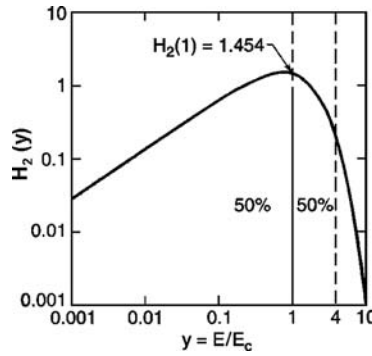


Figure 32.3 Plot of the function $H_2(y)$, where y is the ratio of photon energy to critical photon energy. (Adapted from Ref. 6.)

32.2.2 Undulator radiation

In an undulator and in a wiggler, electrons travel through a periodic magnetic structure such as the one shown in Fig. 32.4(a). In the case where the magnetic field B varies sinusoidally and is in the vertical direction, as shown in Fig. 32.4(a), the electron motion is also sinusoidal and lies in the horizontal plane. An important measure of the electron motion is the deflection parameter K , given by⁶

$$K = 0.934\lambda_u[\text{cm}]B_0[\text{T}], \quad (32.4)$$

where λ_u is the magnet period and B_0 is the peak magnetic field. If the electron's angular excursions are small compared to the natural radiation cone angle γ^{-1} , i.e., $K \leq 1$, the device is referred to as an undulator. In an undulator, the fact that the angular excursions are within the natural radiation cone leads to several interesting interference effects: cone narrowing, higher spectral brightness, and in some cases partial coherence. In addition, radiation from the different periods of the undulator can interfere coherently, producing sharp peaks of emission at the harmonics of the fundamental. The wavelength of the fundamental of an undulator, on axis, is given by⁶

$$\lambda_1[\text{\AA}] = \frac{13.056\lambda_u[\text{cm}]}{E_e^2[\text{GeV}]} \left(1 + \frac{K^2}{2}\right). \quad (32.5)$$

The relative bandwidth at the n th harmonic is $(\Delta\lambda/\lambda)_n = 1/nN$ ($n = 1, 2, 3, \dots$), where N is the number of magnet periods. Equation (32.5) implies that the emission wavelength on axis can be tuned by varying the value of K by changing B_0 , something that is done in practice by changing the size of the undulator-magnet gap. As an example, the tuning curve for power in the central radiation cone for an 8-cm-period undulator at the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory (LBNL)⁷ is shown in Fig. 32.4(b).

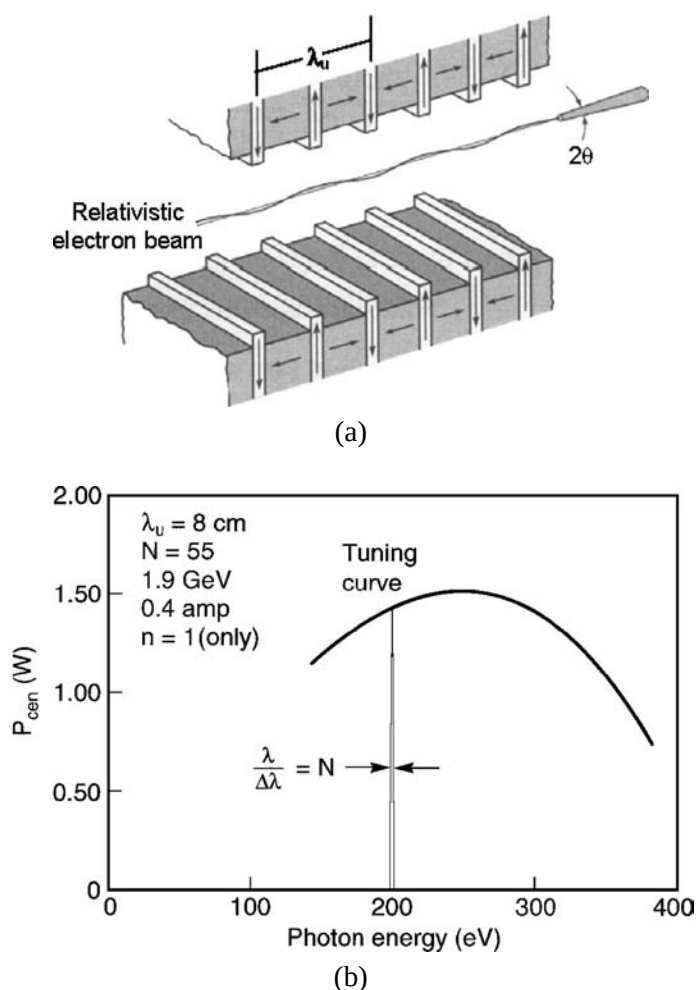


Figure 32.4 (a) Sketch showing how a narrow cone of synchrotron radiation is generated when relativistic electrons traverse an undulator magnet; and (b) plot of power in the central radiation cone from an 8-cm period undulator at the ALS in Berkeley, CA. (Adapted from Ref. 7 with permission from Cambridge University Press.)

The on-axis peak intensity of the n th harmonic from an undulator, P_n , is given by⁶

$$P_n [\text{photons} \cdot \text{s}^{-1} \cdot \text{mrad}^{-2} \cdot (0.1\% \text{ bandwidth})^{-1}] \\ = 1.744 \times 10^{14} N^2 E_e^2 [\text{GeV}] I [\text{A}] F_n(K),$$

where

$$F_n(K) = \frac{K^2 n^2}{(1 + K^2/2)^2} \left\{ \frac{J_{n-1}}{2} \left[\frac{nK^2}{4(1 + K^2/2)} \right] - \frac{J_{n+1}}{2} \left[\frac{nK^2}{4(1 + K^2/2)} \right] \right\}^2 \quad (32.6)$$

and where the J 's are ordinary Bessel functions. The angular distribution of the n th harmonic from an undulator is concentrated in a narrow cone, whose half angle θ is given by⁶

$$\theta = \frac{1}{\gamma^* \sqrt{N}}, \quad \text{where } \gamma^* = \frac{\gamma}{\sqrt{1 + K^2/2}}. \quad (32.7)$$

32.2.3 Wiggler radiation

In a wiggler, the deflection parameter K is large (typically ≥ 10), and radiation from different parts of the electron trajectory no longer adds coherently, because the radiation from various segments of an oscillation are widely separated in angle and therefore do not overlap in space after propagating a short distance. However, a wiggler does provide an increase in radiated power by a factor $2N$ (where N is the number of magnet periods) and a broad shift to higher photon energies. The flux distribution in a wiggler is given by $2N$ times the appropriate formula for a bending magnet. As the value of K increases, the insertion device passes from the undulator to the wiggler regime, and the sharp emission peaks begin to merge and are eventually submerged in the continuum.

For wiggler radiation with $K \gg 1$, the electron motion becomes significantly more complex and the acceleration becomes very high at the points of the maximum excursion. This causes a shift to higher photon energies and thus shorter wavelengths. Because the accelerations are greater, there is also a substantial increase in radiated power. The angular width, however, is increased in the horizontal plane to a value $K\gamma^{-1}$, and the apparent source size is increased. Expressions for the photon flux from a wiggler, in the limits $K \gg 1$ and $n \gg 1$, are similar to those for bending-magnet radiation but increased by a factor of $2N$ due to the strong acceleration that occurs twice each period at the peaks of magnetic field. The on-axis peak intensity from a wiggler in practical units is given by⁷

$$P_T [\text{photons} \cdot \text{s}^{-1} \cdot \text{mrad}^{-2} \cdot (0.1\% \text{ bandwidth})^{-1}] \\ = 2.65 \times 10^{13} N E_e^2 [\text{GeV}] I [\text{A}] H_2 \left(\frac{E}{E_c} \right), \quad (32.8)$$

where $H_2(y)$ is defined as before and is shown in Fig. 32.3. Relative spectra for both a bending magnet and a wiggler⁷ are shown in Fig. 32.5. Note the $2N$ -times-larger photon flux for the wiggler, and the shift to higher photon energies E_c .

32.3 Survey of Current Synchrotron Radiation Facilities

More than 60 storage rings that provide synchrotron radiation for research and development applications are in operation or under construction around the world at the present time. Synchrotron radiation facilities are not restricted to the most technologically developed countries. For the convenience of those readers who are

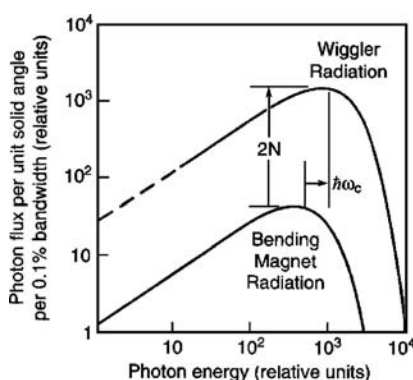


Figure 32.5 Comparison of the on-axis photon flux from a bending magnet and a wiggler magnet in the same storage ring. (Reprinted from Ref. 7 with permission from Cambridge University Press.)

interested in exploring the possibility of engaging in research in this area, a listing of synchrotron light source facilities, reprinted with permission from the Web page⁸ for SLAC at Stanford University, is provided in Table 32.1. The table lists the name of the storage ring, its location, its maximum electron energy, and its status as of February 2005. Readers are referred to www.lighthouse.org for current information.

32.4 Selected Applications of Synchrotron Radiation in EUVL

A list of all reported circumstances in which synchrotron radiation has been applied in EUVL would require a bibliography the size of this chapter. Instead, this section briefly describes three specific applications—EUV reflectometry, EUV interferometry, and EUV imaging—chosen because they illustrate how the unique properties of synchrotron radiation have been used to accelerate the development of EUVL.

32.4.1 EUV reflectometry

At normal incidence, no naturally occurring material provides more than about 1% reflectance in the EUV spectral region at wavelengths below 30 nm, because the index of refraction of all materials in this region is approaching unity. This fact is illustrated in the plots of normal-incidence reflectance of Al and Ir versus wavelength⁹ shown in Fig. 32.6(a). In fact, Al and Ir are two of the most widely used reflective coatings for mirrors and gratings at wavelengths between 30 and 80 nm. Historically, the way around the lack of adequate normal-incidence reflectance in the EUV spectral region has been to work near grazing incidence. Unfortunately, grazing-incidence optics tend to have small collection angles and result in highly aberrated images. In 1972, Eberhard Spiller showed that multilayer

Table 32.1 Synchrotron light sources of the world.

Location	Ring (institution)	Energy (GeV)	Status
Armenia			
Yerevan	CANDLE	3.2	Design/dedicated
Australia			
Melbourne	Australian Synchrotron	3	Dedicated*
Brazil			
Campinas	LNLS	1.35	Dedicated
Canada			
Saskatoon	CLS (Canadian Light Source)	2.9	Dedicated
China			
Beijing	BSRF (Inst. High En. Phys.)	1.5–2.8	Partly dedicated
	BLS (Inst. High En. Phys.)	2.2–2.5	Design/dedicated
Hefei	NSRL (Univ. Sci. & Tech. of China)	0.8	Dedicated
Shanghai	SSRF (Inst. Nucl. Res.)	3.5	Dedicated*
Denmark			
Aarhus	ASTRID (ISA)	0.6	Partly dedicated
	ASTRID II (ISA)	1.4	Design/dedicated
France			
Grenoble	ESRF	6	Dedicated
Orsay	SOLEIL (LURE)	2.5–2.75	Dedicated*
Germany			
Berlin	BESSY II	1.7–1.9	Dedicated
Bonn	ELSA (Bonn Univ.)	1.5–3.5	Partly dedicated
Dortmund	DELTA (Dortmund Univ.)	1.5	Dedicated/FEL Use
Hamburg	DORIS III (HASYLAB/DESY)	4.5	Dedicated
	PETRA II (HASYLAB/DESY)	7–14	Partly dedicated
Karlsruhe	ANKA (Res. Center Karlsruhe FZK)	2.5	Dedicated
India			
Indore	INDUS-I (Ctr. Adv. Tech.)	0.45	Dedicated
	INDUS-II (Ctr. Adv. Tech.)	2	Dedicated*
Italy			
Frascati	DAFNE (Frascati Nat. Lab.)	0.51	Parasitic
Trieste	ELETTRA (Synch. Trieste)	2–2.4	Dedicated
Japan			
Hiroshima	HISOR (Hiroshima Univ.)	0.7	Dedicated
Ichihara	NANO-HANA (Japan SOR Inc.)	1.5–2	Design/dedicated
Kashiwa	VSX (Univ. of Tokyo-ISSP)	1–1.6	Design/dedicated
Kusatsu	Rits SR (Ritsumeikan Univ.)	0.575	Dedicated
Kyoto	KSR (Kyoto University)	0.3	Dedicated
Nishi Harima	SPring-8 (JASRI)	8	Dedicated
	NewSUBARU (Himeji Inst. Tech.)	1–1.5	Dedicated
	NIJI III (Sumitomo Electric)	0.6	Dedicated
Okasaki	UVSOR (Inst. Mol. Science)	0.75	Dedicated
	UVSOR-II (Inst. Mol. Science)	1	Design/dedicated
Rokkasho	MOSLA	2	Design/dedicated
Sendai	TLS (Tohoku Univ.)	1.5	Design/dedicated
Tosu	Saga-LS (Saga Prefectural Government)	1.4	Dedicated*
Tsukuba	TERAS (ElectroTech. Lab.)	0.8	Dedicated
	NIJI II (ElectroTech. Lab.)	0.6	Dedicated
	NIJI IV (ElectroTech. Lab.)	0.5	Dedicated/FEL Use
	Photon Factory (KEK)	2.5	Dedicated
	Accumulator Ring (KEK)	6.5	Planned rebuilding

Table 32.1 (Continued).

Location	Ring (institution)	Energy (GeV)	Status
Jordan			
Allaan	SESAME	2.5	Dedicated*
Korea			
Pohang	Pohang Light Source	2	Dedicated
Russia			
Dubna	DELSY	1.2	Dedicated*
Moscow	Siberia I (Kurchatov Inst.)	0.45	Dedicated
	Siberia II (Kurchatov Inst.)	2.5	Dedicated
Novosibirsk	VEPP-2M (BINP)	0.7	Partly dedicated
	VEPP-3 (BINP)	2.2	Partly dedicated
	VEPP-4M (BINP)	5–7	Partly dedicated
	Siberia-SM (BINP)	0.8	Dedicated*
Singapore			
Singapore	SSLS (National Univ. Singapore)	0.7	Dedicated
Spain			
Barcelona	AURORA	2.5	Dedicated*
Sweden			
Lund	MAX I (Univ. of Lund)	0.55	Dedicated
	MAX II (Univ. of Lund)	1.5	Dedicated
	MAX III (Univ. of Lund)	0.7	Dedicated*
	MAX IV (Univ. of Lund)	1.5/3	Design/dedicated
Switzerland			
Villigen	SLS (Paul Scherrer Inst.)	2.4	Dedicated
Taiwan			
Hsinchu	SRRC (Synchrotron Rad. Res. Cntr.)	1.3–1.5	Dedicated
Thailand			
Nakhon Ratchasima	SIAM PHOTON (NSRC)	1	Dedicated
U.K.			
Daresbury	SRS (Daresbury)	2	Dedicated
Oxfordshire	DIAMOND (Rutherford Acc. Lab.)	3	Dedicated*
Ukraine			
Kharkov	Pulse Stretcher/Synch. Rad.	0.75–2	Partly dedicated
Kiev	ISI-800 (UNSC)	0.7–1.0	Design/dedicated
U.S.A.			
Argonne, IL	APS (Argonne Nat. Lab.)	7	Dedicated
Baton Rouge, LA	CAMD (Louisiana State Univ.)	1.3–1.5	Dedicated
Berkeley, CA	ALS (Lawrence Berkeley Lab.)	1.5–1.9	Dedicated
Durham, NC	DFELL (Duke University)	1–1.3	Dedicated/ FEL Use
Gaithersburg, MD	SURF III (NIST)	0.386	Dedicated
Ithaca, NY	CESR (CHESS/Cornell Univ.)	5.5	Partly dedicated
Stanford, CA	SPEAR (SSRL/SLAC)	3	Dedicated
Stoughton, WI	Aladdin (Synch. Rad. Center)	0.8–1	Dedicated
Upton, NY	NSLS I (Brookhaven Nat. Lab.)	0.8	Dedicated
	NSLS II (Brookhaven Nat. Lab.)	2.5–2.8	Dedicated

*In construction as of February 2005.

(ML) structures composed of thin layers of materials that have widely different values for EUV absorption can lead to constructive interference and hence enhanced reflection.¹⁰ In 1981, Underwood and Barbee demonstrated normal-incidence soft-x-ray imaging at a wavelength of 4.46 nm, and in 1985 the first solar x-ray image

was obtained using such mirrors.¹¹ This was the turning point for EUV optics—the point where it became clear that normal-incidence ML-coated optics offered clear advantages over the severe aberrations, small field of view, and difficulty of manufacture of grazing-incidence optics. A further key development occurred in 1985, when Barbee et al.¹² demonstrated that the ML combination of molybdenum and

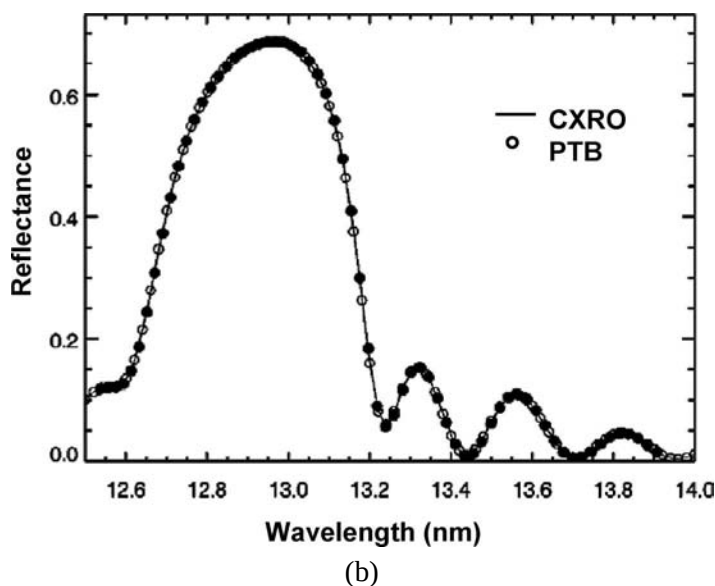
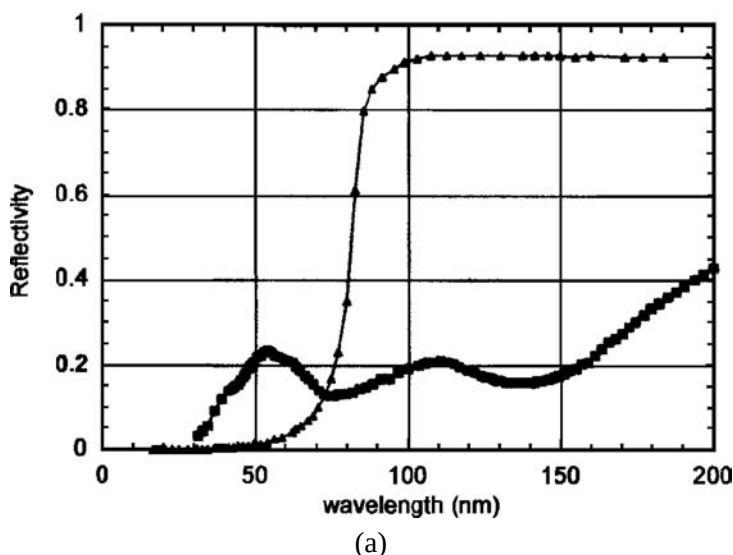


Figure 32.6 (a) Normal-incidence reflectances of clean Al (triangles) and Ir (squares) surfaces (from Tarrío et al.,⁹ reproduced by permission from SPIE), and (b) normal-incidence reflectance of a Mo/Si ML with 40 bilayers measured at CXRO and at PTB. (Reprinted from Ref. 13.)

silicon had an exceptionally high normal-incidence reflectivity at wavelengths just longer than the Si L absorption edge at 12.4 nm. The normal-incidence reflectance of the best modern Mo/Si MLs now approaches 70% in a narrow band of wavelengths near 13 nm,¹³ as shown in Fig. 32.6(b).

ML coatings have now been shown to be effective reflectors for normal incidence in the EUV spectral region at wavelengths from 4.5 to 30 nm.¹⁴ The ML structures consist of alternating layers of high-Z and low-Z materials with individual layer thicknesses in the range ≈ 1 –10 nm. The operation of such a coating is analogous to that of a quarter-wave stack; enhanced reflectivity occurs over a narrow spectral band peaked at the Bragg wavelength $\lambda = 2\Lambda \sin \theta$, where Λ is the ML period (bilayer thickness), and θ is the angle of incidence, as shown in Fig. 32.7(a). ML EUV mirrors are fabricated by depositing ML coatings on superpolished optical substrates using vapor-deposition techniques such as magnetron sputtering and electron-beam evaporation. In general, the reflectivity of a ML coating can be optimized by choosing materials and deposition conditions that maximize the contrast in the index of refraction and minimize the absorption (unavoidable in the EUV spectral region), and by depositing continuous layers with compositionally abrupt and smooth interfaces. A cross-sectional TEM micrograph of a Mo/Si ML coating, optimized for use at normal incidence of 13.4-nm wavelength (i.e., with $\Lambda = 6.9$ nm) and showing minimal evidence of interfacial roughness or interlayer diffusion, is shown in Fig. 32.7(b).

Currently the most demanding application for EUV optics is in EUV lithography. Each of the mirrors in an EUVL exposure tool must have the highest attainable reflectivity at 13 nm (to maximize tool throughput), and more importantly, the central wavelength of the reflectivity must be controlled to better than 0.01 nm (to maximize imaging performance). In order to provide diffraction-limited printing resolution, the mirror surfaces must have surface figure errors of order 0.1 nm rms, and the deposition of the ML coatings must not account for more than about one-quarter of this total error, a requirement that leads to strict requirements on deposition thickness control over the entire optical surface. The primary method used to determine the added figure errors due to the ML coating is to measure the reflectivity at several points across the surface of the mirror. Because of this, it is now necessary to have both high precision and high accuracy in all aspects of the reflectivity measurement, including sample positioning, wavelength control, and the measurement itself. The measurement requirements for the optics to be used in an EUVL exposure tool¹⁵ are: wavelength precision, 0.01%; wavelength accuracy, 0.03%; positional accuracy, 0.01 deg in angle and 0.5 mm in linear displacement; peak reflectance precision, 0.12%; and accuracy, 0.5%. These requirements have made it necessary to develop EUV reflectometry facilities with capabilities far beyond those needed in the past.

In order to satisfy the metrology requirement for the ML coatings on EUVL optics and masks, improvements have been made to reflectometry beamlines at a number of synchrotron-radiation facilities around the globe: at the National Institute of Standards and Technology (NIST)^{16–18} and at the Advanced Light

Source^{19–21} in the United States, at PTB's synchrotron-radiation laboratory^{22–24} at BESSY in Germany, and at NTT's Super-ALIS ring in Japan. The optical layout and critical specification of the Reflectometry and Scattering Beamline (6.3.2) at the ALS in Berkeley¹⁵ is shown in Fig. 32.8. Using this instrument, the peak reflectance of a typical Mo/Si ML can now be measured with a precision of 0.08%

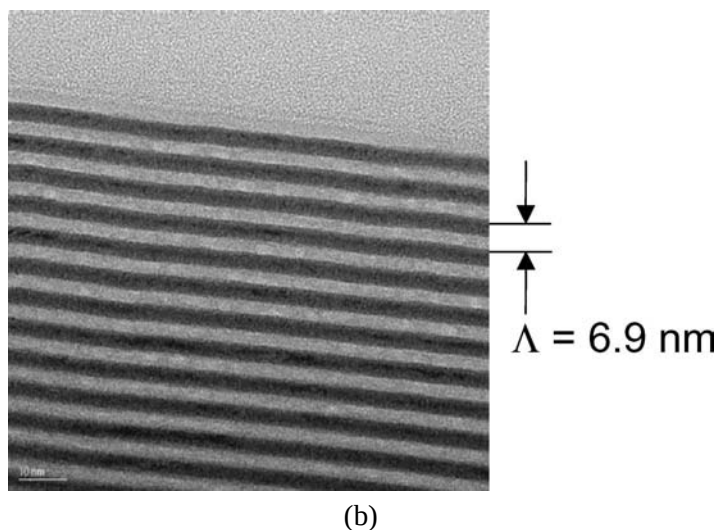
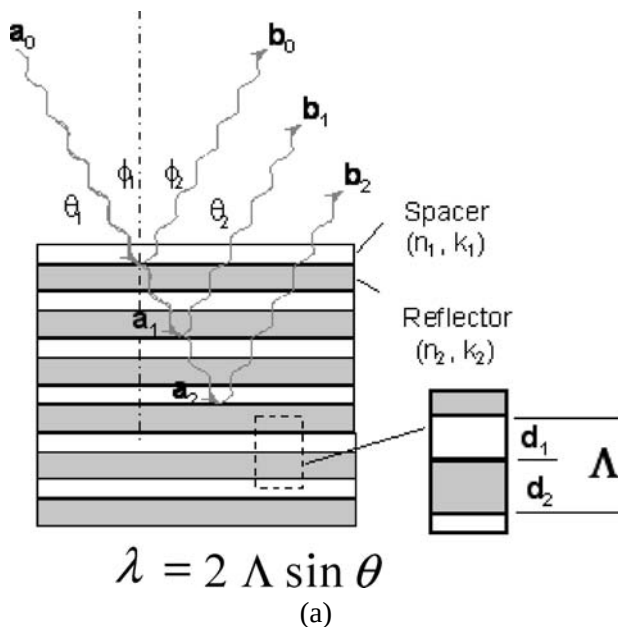


Figure 32.7 (a) Sketch of synthetic ML, showing how normal-incidence reflectance in the EUV spectral region can be enhanced by constructive interference at the Bragg condition; (b) TEM micrograph of a Mo/Si ML with a 6.9-nm bilayer period. (Photo courtesy of Saša Bajt, Lawrence Livermore National Laboratory.)

(relative), and the centroid wavelength with a precision of 0.007% rms. The absolute accuracy of the reflectivity measurement is determined by systematic errors and hence is more difficult to establish. A comparison with independent measurements at other facilities is a good test of such systematic errors. Such a comparison was done in 1998 with the reflectometer operated by the PTB at BESSY.²⁴ The results of that comparison are shown in Fig. 32.6(b), where the peak reflectance measured at both facilities on the same ML sample is seen to agree to better than 1%.¹³

32.4.2 EUV interferometry

Diffraction-limited imaging systems operating at 13.5 nm in the EUV spectral region are required to have a total system wavefront error in the $\lambda/50$ (≈ 0.25 nm rms) range, at least for the lower-spatial-frequency, or *figure*, aberrations.²⁵ An EUVL exposure tool is likely to require an imaging system composed of up to six ML-coated reflective optical elements. The total system wavefront error at each point in the image field will depend on the surface profile and alignment of each of these elements and on the spatially varying properties of their ML reflective coatings. Functional testing at the operational wavelength, i.e., EUV interferometry, is required when the optical elements are coated, aligned, and installed in the EUV imaging system. This is because the EUV coatings behave completely differently at their design wavelength than they do in visible light, for which they act as broadband reflectors. In particular, phase errors arising from nonuniformities in the layer compositions or thicknesses, departures from the designed period variations, stresses in the layers, or modification of the top surface of the coatings by oxidation or contamination will not be correctly evaluated by visible interferometry.

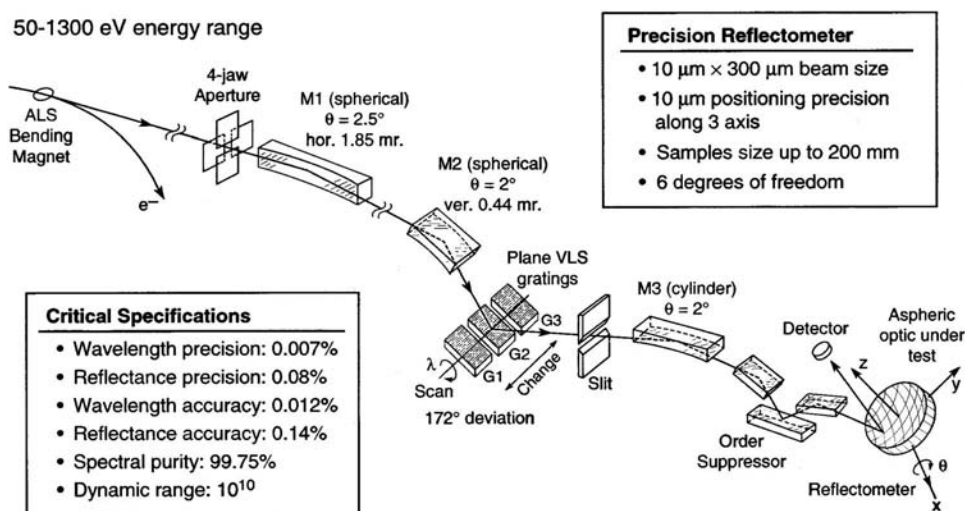


Figure 32.8 Optical layout and performance specifications for the Reflectometry and Scattering Beamline (6.3.2) at the ALS in Berkeley. (Reprinted from Ref. 15.)

Very early on it was recognized that undulator radiation, with its narrow divergence and partial coherence, would be an ideal source for EUV interferometry.²⁶

Several different EUV interferometers have been developed over the past decade.^{27,28} Foucault and Ronchi testing of the alignment of EUV optics has been demonstrated using both synchrotron and laser-plasma light sources.^{29,30} Other significant developments in this area have included refinement of the lateral shearing interferometer²⁸ and the point-diffraction interferometer.^{31,32} The most successful EUV interferometer to date has been the phase-shifting point-diffraction interferometer (PSPDI), first proposed by Medeck et al.³³ With a demonstrated reference-wavefront accuracy of better than $\lambda_{\text{EUV}}/350$ (≈ 0.04 nm at $\lambda_{\text{EUV}} = 13.5$ nm), the PSPDI is, to the best of our knowledge, the highest-accuracy EUV interferometer currently available.^{34–43}

A sketch of the experimental arrangement used to record the wavefront and align a two-mirror ML-coated Schwarzschild optic designed to operate near normal incidence with 13.4-nm-wavelength radiation, at a numerical aperture (NA) of 0.088 and providing $10\times$ demagnification, is shown in Fig. 32.9(a).³⁶ The PSPDI has only a few critical components, all of which are maintained in a vacuum chamber with a base pressure of 10^{-6} Torr. Inside the vacuum chamber, a synchrotron beam from an undulator is focused onto the object (reticle) plane of the Schwarzschild optic under test. A Kirkpatrick-Baez glancing-incidence optical system focuses EUV radiation from an undulator source onto a fixed spot nominally $5\text{ }\mu\text{m}$ wide. In the object plane, diffraction from a small pinhole (the object pinhole) produces spatially coherent spherical-wave illumination of the Schwarzschild optic, filling the pupil of the system with a divergence angle significantly larger than the NA on its input side. A grating beamsplitter placed between the object pinhole and the test optic creates a series of overlapping coherent beams that are focused to laterally displaced positions in the image (wafer) plane. By propagating through the Schwarzschild optic, each of these overlapping beams acquires the characteristic aberrations of the optic.³² In the image plane an open stencil mask selects two adjacent beams and blocks all others. One of the two beams, the test beam, passes through a relatively large window in the mask, thereby preserving the aberrations imparted by the Schwarzschild optic. The second unblocked beam is focused onto a pinhole (the reference pinhole), smaller than the diffraction-limited resolution of the test optic, thereby producing a perfectly spherical reference beam. The two beams (reference and test) propagate to a charge coupled device (CCD) detector, where they overlap, creating an interference pattern that records the deviation of the test beam from an ideal sphere,³² as shown in Fig. 32.9(b).

The results of diffraction-based visible and EUV interferometric measurement of a $10\times$ demagnification 0.083-NA Schwarzschild optic, provided with molybdenum/silicon ML coatings designed for peak reflectivity near 13.4-nm wavelength,³⁵ are shown in Fig. 32.10. The visible-light data were recorded with a Sommargren phase-shifting diffraction interferometer³¹ at Lawrence Livermore National Laboratory (LLNL). EUV and visible light interact with the ML coatings in different ways. While visible light accurately records the position of the surface,

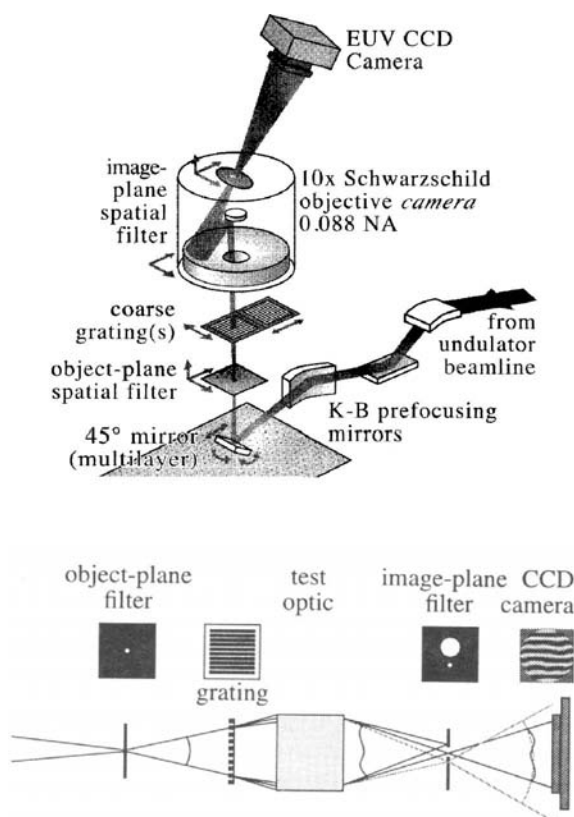


Figure 32.9 (a) 3D schematic of the EUV PSPDI configured to measure a 10 $\times$ Schwarzschild objective camera in a vertical configuration (reprinted from Ref. 36 with permission from the American Vacuum Society); and (b) 2D schematic of the PSPDI interferometer (reprinted from Ref. 32 with permission from OSA).

the location of the resonant EUV reflection depends sensitively on wavelength, incidence angle, and local layer thickness. Yet even in the presence of the spatially graded ML coatings, the visible and EUV wavefronts are seen to differ by only a few thousandths of a wavelength. The wavefront statistics shown in Fig. 32.10 are based on a 37-term Zernike polynomial fit. Remarkably, the difference between the visible and EUV wavefronts is less than 0.5 nm rms, or 3.7 nm peak to valley (PV). At-wavelength interferometric alignment of an EUV Schwarzschild objective has produced the smallest wavefront error observed to date in an EUV optical system³⁵—0.045 waves (≈ 0.60 nm rms, or $\lambda/72$) within the 0.083 NA. Using these same techniques, a group at Lawrence Berkeley National Laboratory has demonstrated EUV interferometry accuracy levels of $\lambda_{\text{EUV}}/330$ (≈ 41 pm rms) for 0.08-NA measurements,⁴² and below $\lambda_{\text{EUV}}/200$ (67 pm rms) for 0.1-NA measurements. Experience has shown that for testing 0.1-NA optics the optimal pinhole size is in the 80–130-nm range. Extrapolating to 0.3 NA, i.e., to the NA values that will be required in a production EUVL exposure tool, the optimal pinhole size will

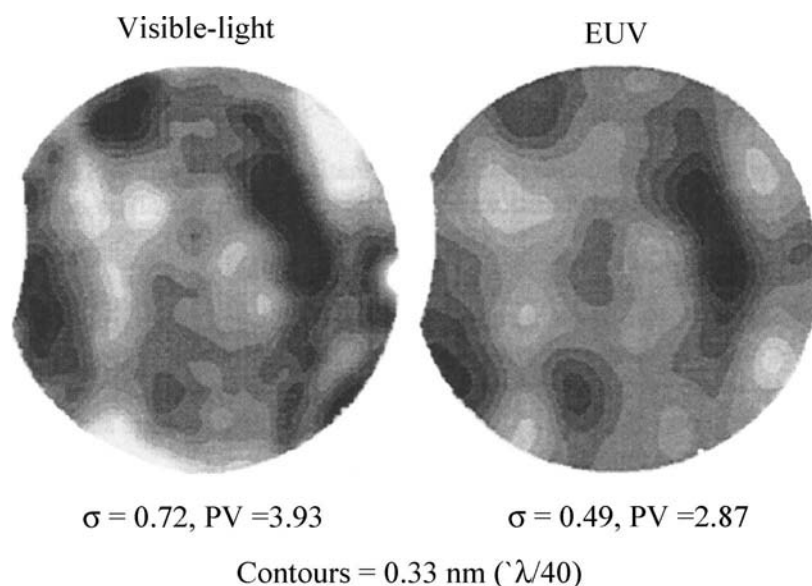


Figure 32.10 EUV and visible-light wavefront phase-map measurement data from a Mo/Si-ML-coated 10× Schwarzschild optic. (Reprinted from Ref. 35.)

be in the 30–40-nm range.⁴² These smaller pinholes will not only be challenging to fabricate and maintain carbon-free, but will necessitate the use of an undulator radiation source with small angular divergence and beam size so that the image capture time can be maintained at a reasonable value.

32.4.3 EUV imaging

EUV imaging experiments using synchrotron radiation sources have been taking place off and on^{44–64} since the first demonstrations of EUVL were carried out in Japan³ and in the United States⁴ in 1989. For example, synchrotron radiation was used in 1998 to test the imaging capabilities of the high-quality 0.1-NA Set-2 optic for the EUV Engineering Test Stand (ETS) developed by the Virtual National Laboratory (VNL) for the EUV LLC. Synchrotron radiation at PTB (BESSY) was used in 2003 to carry out the first printing experiments with a 0.3-NA EUV optic developed by Carl Zeiss SMT AG. Synchrotron radiation sources were utilized for these imaging demonstrations because they are the most versatile sources of EUV radiation. Three other important EUV imaging experiments made possible by the versatility of synchrotron radiation sources were as follows: (1) the ability to tune the central emission wavelength from an undulator source to the bandpass of an EUV coating was used a decade or so ago to study the effect of resist absorption on resist sidewall angle over the wavelength range from 7 to 40 nm;⁵¹ (2) an undulator source was used to provide programmable illumination for an EUV imaging system so that the effects of a wide variety of pupil fills⁶¹ could be evaluated; and (3) the small divergence angle and high partial coherence of an undulator source

were utilized recently to create extremely high-resolution resist images,^{55,56,58,60,63} allowing the limits of resist resolution to be experimentally evaluated. Because of their importance to the future development of EUVL, these three experiments are now described in somewhat greater detail.

It is well known that all resist materials absorb strongly in the EUV. As an example, the absorption coefficient of poly(methyl methacrylate) (PMMA) versus wavelength is shown in Fig. 32.11. The effect of absorption in PMMA and in the negative chemically amplified resist AZ PN114 has been studied experimentally at exposure wavelengths of 37.5, 13.9, and 6.8 nm.⁵¹ These three wavelengths were chosen for the following reasons: 37.5 nm is the shortest wavelength that can be used without having to resort to ML technology; 13.9 nm is near the reflectance maximum of Mo/Si MLs; and 6.8 nm is the shortest EUV wavelength that can be used in a ML-coated imaging system before the narrowness of the reflectance bandwidth begins to degrade the imagery by a process called chromatic vignetting.

The experiments used to produce the resist patterns employed EUV radiation from an undulator beamline at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory and three separate 20 $\times$ demagnification Schwarzschild optics. The exposures at 37.5-nm wavelength were produced with an Ir-coated optic, the exposures at 13.9 nm were produced with a Mo/Si-coated optic, and the exposures at 6.8 nm were produced with a Ru/B₄C-coated optic. Figure 32.12(a) shows a single-line scan from a scanning tunneling microscope

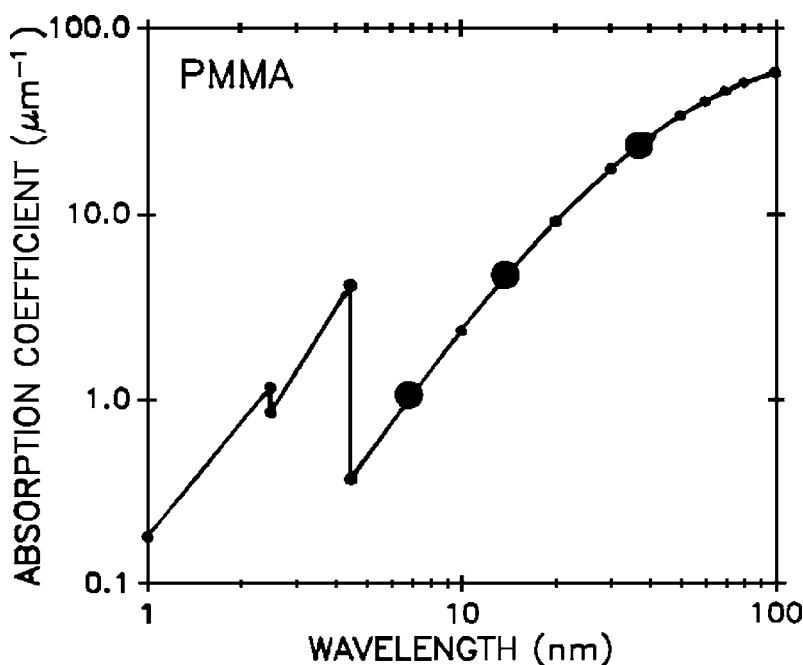
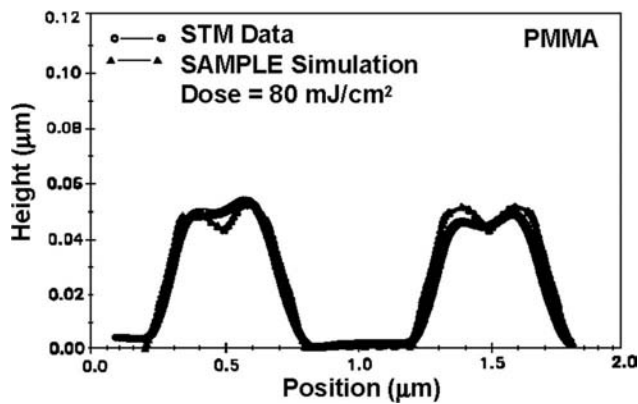
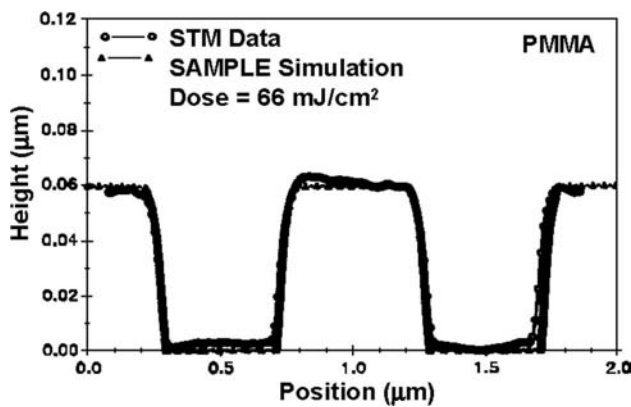


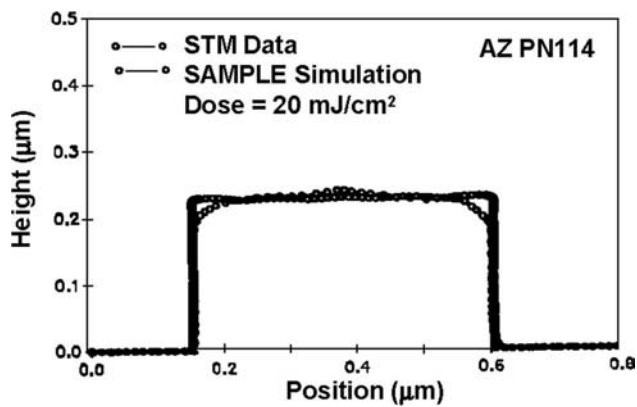
Figure 32.11 Absorption coefficient of PMMA versus wavelength in the EUV spectral region. (Reprinted from Ref. 51 with permission from OSA.)



(a)



(b)



(c)

Figure 32.12 (a) STM scan of 0.5- μm features in 0.06 μm of PMMA printed at 37.5 nm, together with a simulation, (b) STM scan of 0.5- μm features in 0.06 μm of PMMA printed at 13.9 nm, together with a simulation, and (c) SEM profile of isolated 0.5- μm feature in 0.25 μm of AZ PN114 printed at 6.8 nm, together with a simulation. (Reprinted from Ref. 51 with permission from OSA.)

(STM) image of 0.5- μm lines and spaces in a 0.06-nm-thick film of PMMA produced with an Ir-coated optic illuminated at 37.5 nm together with a resist profile calculated using Berkeley's SAMPLE simulation program. Figure 32.12(b) shows a single line scan from an STM image of 0.5- μm lines and spaces in a 0.06-nm-thick film of PMMA produced with a Mo/Si-coated optic illuminated at 13.9 nm together with a SAMPLE simulation. Figure 32.12(c) shows an SEM micrograph of an isolated 0.5- μm -wide feature in a 0.25-nm-thick film of AZ PN114 produced with a Ru/B₄C-coated optic illuminated at 6.8 nm. The resist images show that the sidewall angle is best (steepest) at 6.8-nm wavelength, due to the greater penetration depth of the short-wavelength radiation.

Unfortunately, ML technology does not yet provide sufficient reflectance at 6.8 nm to permit the construction of a practical lithography system at this wavelength; hence the interest in developing surface imaging resists for EUVL.⁵¹

The lithographic quality images needed for the development of an EUVL production tool require that EUV imaging systems be provided with partially coherent illumination ($\sigma \approx 0.7$). This value of partial coherence is very different from the coherence properties naturally provided by an undulator source ($\sigma < 0.05$). To overcome this problem, the novel illumination system shown in Fig. 32.13 has recently been developed.⁶¹ In this illuminator, a scanning mirror serves as an effective source that is re-imaged to the reticle by way of a spherical mirror. By controlling the angle of the scanning mirror, the source spatial-frequency content can be arbitrarily chosen. Figure 32.14 shows a series of EUV pupil fills generated by the scanning system described above and recorded through the ETS Set-2 optic with a back-thinned back-illuminated EUV CCD camera.⁵⁹ The dashed lines represent the full 0.1 NA of the ETS optics pupil. These images demonstrate the wide variety of pupil fills that can be generated, including resolution-enhancing pupil fills. Another very important benefit of this illuminator is the ability to simulate the pupil fills used in other imaging systems. For example, a pupil fill similar to the one provided by the six-channel illuminator employed in the ETS is shown on the lower right-hand side of Fig. 32.14.

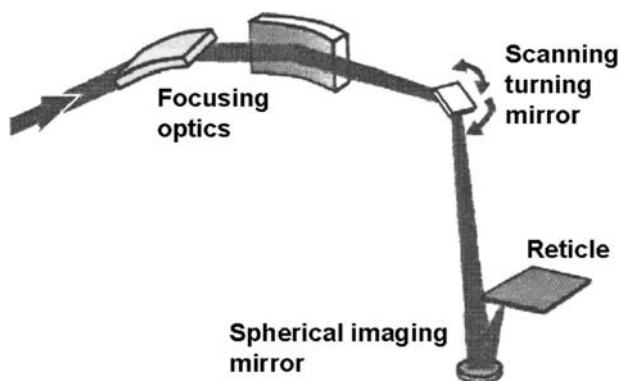


Figure 32.13 Schematic of scanning-mirror illuminator for the Static Exposure System at the ALS in Berkeley. (Reprinted from Ref. 61.)

A spatial-frequency-doubling technique has been used recently to print equal line and space patterns with linewidths as small as 30 nm. The experimental arrangement for this technique⁶⁰ is shown in Fig. 32.15. Spatially coherent, monochromatic EUV radiation provided by an undulator beamline (Beamline 12.0.1 at the Advanced Light Source, Lawrence Berkeley National Laboratory) was used to provide uniform and coherent illumination of a transmission grating, which was imaged with a 10 $\times$ demagnification Schwarzschild optic. A specially designed aperture stop that passes the +1 and -1 diffraction orders from the transmission grating but blocks the 0 order resulted in a spatial-period doubling of the image. A SEM micrograph of a 40-nm line-and-space pattern in a 250-nm thickness of PMMA printed with this system⁶⁰ is shown in Fig. 32.16. Simulations show that, at the fully extended NA of the 10 $\times$ Schwarzschild optic, the system should be capable of printing features with linewidths as small as 12 nm. This new technique shows great potential for use in evaluating the ultimate performance and extendibility of resist materials for EUV lithography.

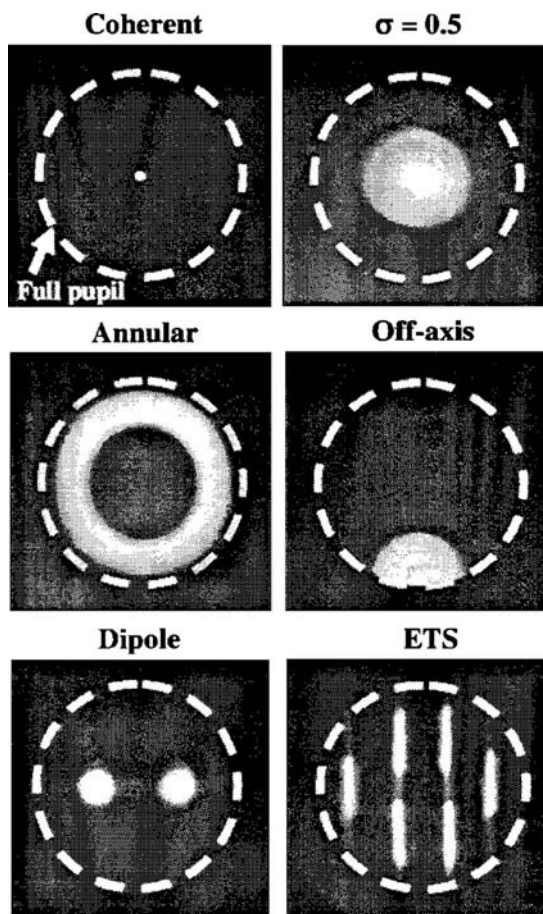


Figure 32.14 Back-thinned back-illuminated EUV CCD images of pupil fills generated using the scanning illuminator system shown in Fig. 32.15. (Reprinted from Ref. 59.)

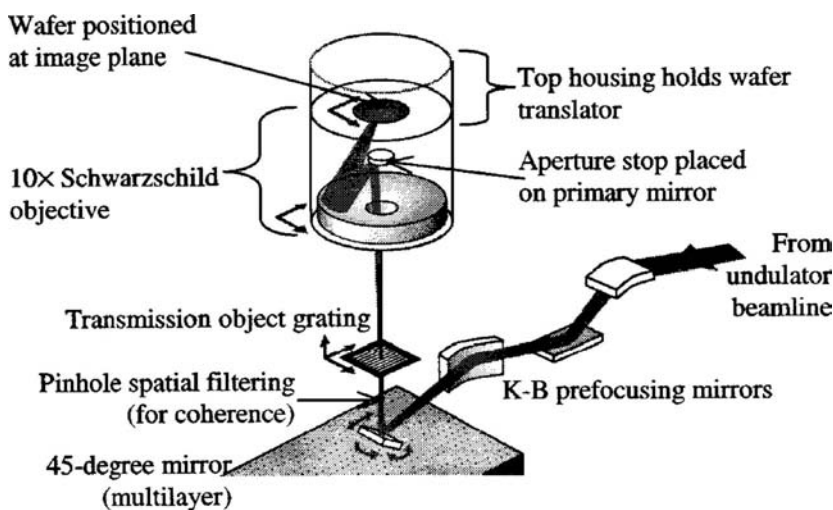


Figure 32.15 Sketch of experimental arrangement for extremely fine-pitch printing with a 10× Schwarzschild optics at EUV wavelengths. (Reprinted from Ref. 60.)

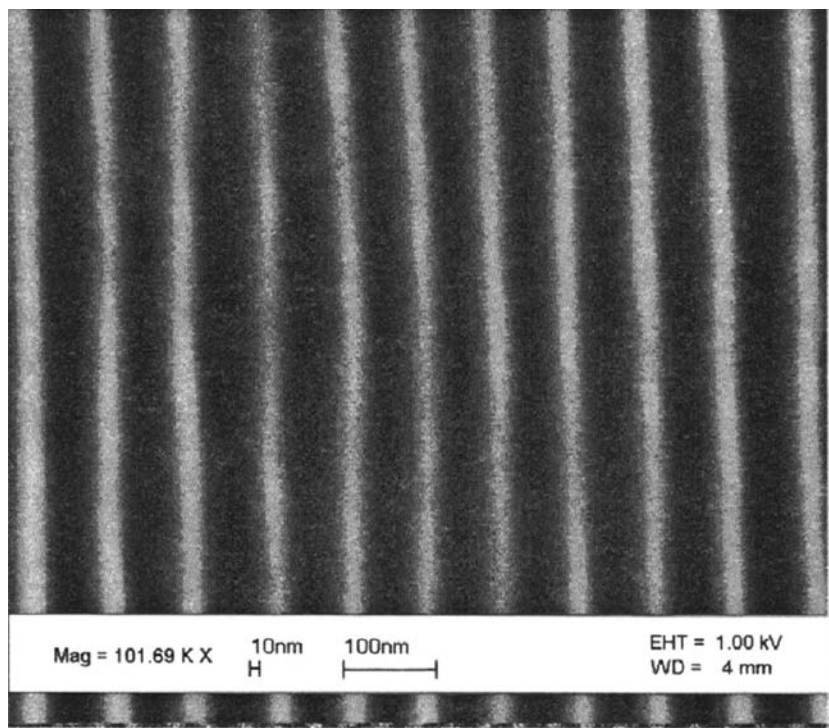


Figure 32.16 SEM images of 40-nm lines and spaces in 250 nm of PMMA printed with a spatial-frequency-doubling technique. (Reprinted from Ref. 60.)

32.5 Conclusions and Suggestions for Future Work

More than 15 years have elapsed since the first experimental demonstrations of EUV imaging were given with synchrotron light sources in Japan and in the United States, yet EUVL has still not reached the level of development that will be required for the manufacture of advanced computer chips.⁶⁵ It is now generally agreed that a synchrotron light source is not likely to be utilized in a commercial EUVL exposure tool, because the required levels of average power are not available;^{66,67} but synchrotron light sources will continue to play an important role in the development of EUVL, for actinic defect inspection of EUV reticle blanks, actinic wavefront metrology of EUV imaging systems, advanced EUV resist development, and accelerated life testing of oxidation-resistant coatings for EUV optics.

As one final example, the lifetime of Mo/Si ML-coated optics is known to pose a significant risk to the commercialization of EUVL. The development roadmap for reflective EUV coatings, showing the improvements required, is given in Table 32.2. Current estimates of coating lifetime based on accelerated EUV exposures suggest that the reflectivity of EUV reflective coatings will drop by more than 1% in a few days in the environment of a commercial EUVL scanner (see Fig. 32.17).⁶⁵ For Si-terminated Mo/Si-coated projection optics the primary risk is oxidation. When such a coating is exposed to EUV radiation, the large number of low-energy secondary electrons generated near the surface can dissociate adsorbed water molecules, creating reactive oxygen that can oxidize Si to SiO₂. To prevent oxidation of the coating, a protective (capping) layer that is oxidation-resistant (e.g., ruthenium) must be applied⁶⁸ (see Fig. 32.17). The best way to ensure that robust ML coatings will be available for the projection optics in EUVL exposure tools when they are needed for production is to carry out both accelerated and long-term environmental tests of candidate coating at synchrotron-radiation facilities. In fact, the testing of such coatings is currently underway at synchrotron-radiation facilities in Europe, Japan, and the United States and is likely to continue into the foreseeable future.

Table 32.2 Roadmap for improvement of EUV ML coating optics.

Issue	2003 Status	Beta-tool (2004)	Commercial tool (2007)
Peak Reflectance	65%	68%	70%
Lifetime (Imaging Optics)	1.6% [#] /week	1.6%/3 years	1.6%/5 years
Lifetime (1 st Condenser Optic)	Unknown	10%/year	10%/year

[#] Assumes standard Si-capped Mo/Si multilayer.

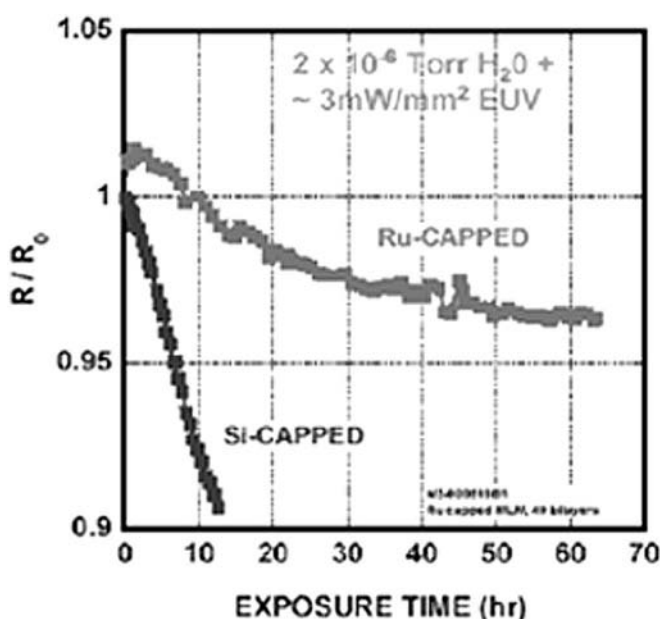


Figure 32.17 Change in EUV reflectance of ruthenium- and silicon-capped MLs coatings with time during EUV exposure in an oxidative environment. (Reprinted from Ref. 65 with permission from Henley Media Group Ltd.)

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Chapter 33

Grazing-Incidence EUV Collectors

Piotr Marczuk and Wilhelm Egle

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33.1 Introduction

Optical lithography has been successfully used since the 1960s for integrated-circuit production at linewidths of several microns. At present, volume production tools operating at 193-nm wavelength deal with linewidths about 100 nm. Intel's cofounder Gordon E. Moore predicted this downscaling trend in 1965,¹ and the leading chip manufacturers have followed "Moore's Law" during the past and plan to follow it for the coming decade with resolutions below 35 nm. According to

Rayleigh's criterion, the resolution of lithography systems is directly proportional to the wavelength λ used and inversely proportional to the numerical aperture (NA) of the system. Consequently, one strategy for next-generation lithography (NGL) toward higher resolution is to decrease wavelength.

Most likely, NGL optics will be based on extremely short wavelength UV light, also called soft-x-ray or EUV light, at a preferred wavelength of 13.5 nm. Other NGL options such as electron projection lithography, maskless lithography, and imprint lithography are still subjects of major research programs, but an insurmountable obstacle for these technologies is their low throughput prospects.

In the case of EUVL, the very low EUV transparency of common materials implies a technology migration from transparent lenses (all-refractive optics) to mirrors (all-reflective optics). Accordingly, any EUV chip manufacturing tool (wafer scanner) will need a powerful light source and efficient reflective optical components in order to supply a sufficient number of photons for a stable resist exposure process.

The main optical components of an EUVL scanner are shown schematically in Fig. 33.1. EUV light emitted from a suitable source is collected by the source optics and projected into an aperture (intermediate focus or IF), where it enters the illumination system. A uniformly illuminated field of the reticle (mask) is then imaged by the projection optics onto the resist-coated wafer. In the region of the IF an enlarged image of the source itself is created by the collector optics.

High EUV reflectivity of optical surfaces, as required for such an application, can be achieved either by suitable multilayer coatings at or close to normal incidence, or by very smooth metal reflectors at grazing incidence.

Several technological approaches, including plasma emission and synchrotron radiation, have been taken toward the development of a high-power EUV light source for lithography applications. Currently, the most promising EUV source types are the electrical-gas DPP and the LPP. Among other wavelengths, both types of sources emit light at around 13.5 nm into solid angles of around 2π sr or even more. For details about DPP and LPP sources, see Chapters 3 and 4, respectively. Information on some alternative sources other than DPP or LPP can be found in Chapter 6.

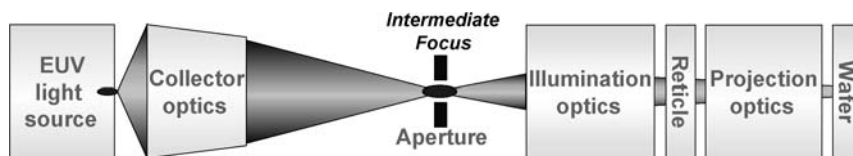


Figure 33.1 Schematic representation of the optical components of a wafer scanner for EUVL.

33.2 EUV Collectors: General Considerations

The two major tasks for the source optics module within the EUVL tool are to collect as much light as possible from the source, which at first approximation can be assumed pointlike, and to reflect these photons and transfer them into the next module of the lithography tool, viz., the illumination system at a given aperture angle.

Due to thermal considerations within the illumination system, it may also be desirable to prevent non-EUV photons from entering the illumination system. In this case a spectral filtering component (e.g., a transmissive or diffractive filter) must be included in the source optics design.

Depending on the EUV source's emission characteristics, the concept of the collecting optics must be chosen. In Fig. 33.2, the geometrical environment and possible collector design examples are shown for a DPP and an LPP source.

Due to a special electrode shape and the proximity of the light-emitting plasma to the electrodes, DPP sources typically emit usable light in the forward direction, which means that the emitting solid angle is typically smaller than 2π sr. In this case grazing-incidence reflectors can ideally be positioned in the free space in front of the light-emitting plasma pinch, and the collected EUV beam is directed away from the source electrodes and the rather bulky electrical power supply system.

In LPP sources, EUV light is generated by pulsed laser excitation of injected target particles (e.g., liquid Xe droplets). Both the laser and the injection apparatus are located at relatively large distances from the pinch, which in this case emits collectable light into 4π sr. As shown in Fig. 33.2, a possible collector design taking advantage of this pinch accessibility is an ellipsoidal mirror surface similar to the design used in automobile headlights. Only cut-out areas for the laser beam and the target material jet are required. The challenge in this case is at least twofold: (1) sophisticated technology is required to manufacture surfaces with such curvatures; and (2) highly reflective (multilayer or metal) coatings that allow for a wide incidence angle distribution and withstand expected thermal loads must be applied to the optical surface.

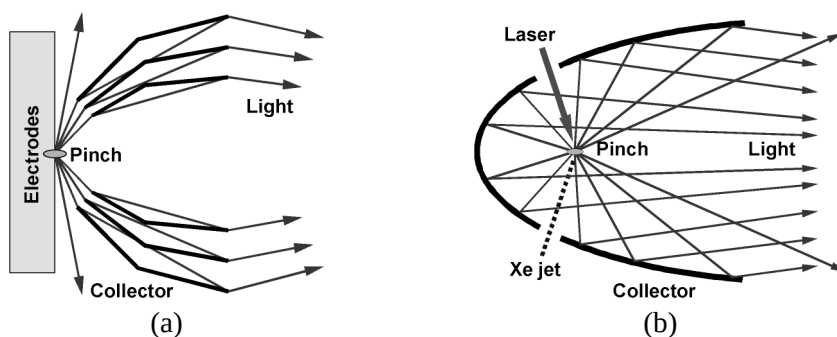


Figure 33.2 Due to geometrical shielding by the electrodes, a DPP source emits into 2π sr (a), while the pinch of an LPP source in principle is freely accessible (b).

This chapter is based on our previous paper² and reports on the design, development, fabrication, and testing of grazing-incidence collectors. Though this design is optimized for DPP sources, it also can be used to collect light from an LPP source.

33.3 Grazing-Incidence EUV Collectors

A variety of additional system and interface requirements drive the feasibility of design concepts for EUV collectors besides collection efficiency and reflectivity. Some of these requirements result from the source properties, whereas the illumination-system design restricts the output characteristics of the collector.

33.3.1 Requirements

33.3.1.1 Requirements at the collector entrance (source side)

The requirements described in this section are imposed by pure efficiency considerations and by the EUV source properties:

- For collection efficiency reasons, the solid angle must be maximized and obstruction by other hardware such as mounting elements must be minimized.
- For throughput efficiency reasons, the collector optical surfaces must have maximum reflectivity at EUV wavelengths. This can be achieved by keeping the grazing angles small at the mirror surfaces and by selecting the appropriate mirror coating material. Smooth noble metals are common high-reflectivity materials for EUV and x-ray radiation.
- EUV sources not only emit radiation at desired EUV wavelengths (namely, 13.5 nm with a bandwidth of 2%) but also significant portions of deep UV (DUV), visible, and even IR light. This additional out-of-band (OOB) radiation might get absorbed and cause thermal problems. Therefore a collector must either withstand elevated temperatures up to hundreds of degrees Celsius or have the means to dissipate absorbed power.
- In addition to radiation, EUV sources threaten optical components in their direct line of sight with debris expelled from the plasma. A collector optic directly exposed to the plasma pinch might quickly suffer from reflectivity loss either due to contamination or due to the abrasive nature of such a bombardment. Hence, the distance between the plasma pinch and the collector entrance must be large enough to allow for the accommodation of an efficient debris mitigation tool.

33.3.1.2 Requirements at the collector exit (IF side)

These requirements are mainly determined by the given input characteristics of the EUV illumination system. The collector has the task of imaging the EUV source into the illumination system at a specified location with well-defined optical parameters:

- The collector optics must provide an image of the source in a well-defined position at a certain distance. This so-called intermediate focus (IF) mainly enables the separation of the source and the illuminator module within the vacuum system by means of differential pumping.
- At the IF position the light cone from the collector must be restricted to a maximum NA ($NA_{\max}$).
- The maximum magnification of the collector is defined by the collection angle $NA_{\max}$, and it is desirable to achieve a specific NA dependence of the magnification in order to provide homogeneous far-field illumination.
- Usually the illumination system also requires a certain intensity distribution behind the IF aperture (in the far field), which needs to be considered in the optical design of the collector optics.

33.3.1.3 General requirements on the collector optics

The collector optics must fulfill the following general requirements:

Chip manufacturers must contend with limited installation space for lithography tools. This requirement puts limitations on the distance between the EUV source and the IF.

Because EUV light is strongly absorbed by most media, including air and inert gases, the light path is kept in vacuum. The whole EUV collector assembly must therefore comply with ultrahigh-vacuum requirements, including outgassing specifications.

In order to provide a reasonable lifetime, all materials used within the collector assembly must be stable against EUV and other short-wavelength radiation. Most organic materials, such as glues or rubber gaskets, decompose if irradiated by DUV or shorter-wavelength light. Most porous materials accumulate water or other volatile substances, and continuous outgassing of these substances over long time periods causes vacuum problems.

33.3.2 Design

This subsection describes the optical design of a grazing-incidence collector where all above requirements were taken into account. Early in the development program we discussed several design concepts, as shown in Fig. 33.3:

- Ellipsoidal mirrors, as depicted in Fig. 33.3(a), are characterized by a single reflection where the source is located at one focus and the image of the source is found at the other focus of the ellipse. As far as throughput is concerned, this design has the advantage of a single reflection, but the price one pays for this benefit is a NA-dependent magnification of the optics and strong off-axis aberrations.
- Parabolic mirrors, as used in astronomical telescopes, also work with a single reflection. Here again the source is located at the focus, but in contrast to the first concept, the corresponding source image does not exist due to

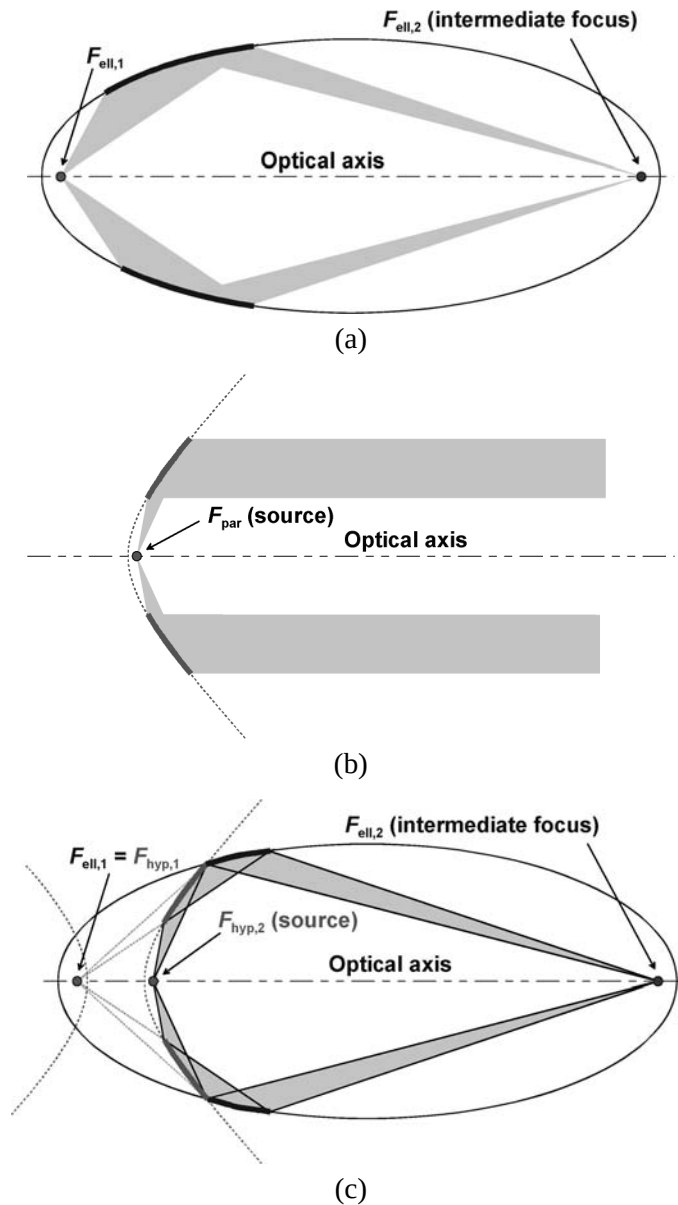


Figure 33.3 Potential optical designs for EUV collector optics: (a) ellipsoidal, (b) paraboloidal, and (c) combined hyperboloidal-ellipsoidal (Wolter type 1) design.

the infinite focal distance of this optical design. Clearly, this violates many requirements on the IF side, and this design was rejected. [See Fig. 33.3(b).]

- A combined hyperboloidal-ellipsoidal design, also known as the Wolter type 1 design, was evaluated. In this concept all rays of light are reflected once from the hyperboloidal surface and once from the ellipsoidal surface at quite shallow grazing angles, as shown in Fig. 33.3(c). In this case, the source

is located at the hyperbola's second focus ($F_{\text{hyp},2}$), and the source image is created in the ellipse's second focus ($F_{\text{ell},2}$). The first focus of the ellipse ($F_{\text{ell},1}$) coincides with the first focus of the hyperbola ($F_{\text{hyp},1}$) and acts as a virtual source.

Several optimization runs were necessary to fulfill the given requirements satisfactorily and to achieve a suitable optical design for our EUV collector system. We decided to select the Wolter type 1 concept due to its advantageous off-axis imaging properties for extended objects as compared to single reflection mirrors. This is a rather strong requirement, because the ellipsoidally shaped pinch of available high-power DPP sources extends up to sizes of more than 1 mm. Another outcome was the decision to use nested optical surfaces for increased efficiency at reasonable imaging performance.

Finally, we ended up with an optical design for a Wolter type 1 collector having the following main characteristics, which might vary within given ranges depending on the special customer requirements:

- Monolithic reflector design, consisting of one optical surface having a kink between the hyperboloidal and ellipsoidal parts.
- Two to ten nested mirror surfaces.
- Collection angles up to 45 deg, corresponding to solid angles of approximately 1.8 sr.
- Magnification of $6\times$ to $8\times$.
- Distance between the source and the IF position below 2000 mm.
- Optical surface dimension perpendicular to optical axis (diameter) up to 500 mm.
- Optical surface dimension along optical axis (length) up to 400 mm.
- All grazing angles below 20 deg.

Depending on the application and the customer's special requirements, the optical surfaces must be covered by reflective coatings made of gold (Au), palladium (Pd), ruthenium (Ru), or rhodium (Rh). Optical surface microroughness of better than 1 nm must be achieved to keep scattering and specular-reflectivity losses below a few percent. In our design, such a coating covers the inner surface of mirror shells made of nickel or copper. The mirror-shell wall thickness was designed to be up to 2 mm for larger (outer) shells and below 1 mm for smaller (inner) shells.

The optical surfaces of high-efficiency EUV collectors should have smooth reflecting surfaces and a high reflectivity at EUV wavelengths. Our EUV mirror shells are fabricated by applying the proven nickel electroforming process.^{3–5} This process was successfully deployed for fabrication of mirror shells for x-ray satellites. But in contrast to most astronomical x-ray mirrors,^{6–8} which are operated at much shorter wavelengths (higher photon energies) and at very low grazing angles (typically less than 2 deg) and which have a thin gold layer as reflecting material, EUV mirrors require metal coatings optimized for wavelengths around 13.5 nm

and for grazing angles up to 20 deg. The reflectivity of exemplary, ideally smooth metals is shown in Fig. 33.4.

The reflectivity decreases almost linearly with increasing grazing angle up to approximately 15 deg for the metals as plotted in Fig. 33.4. From this representation molybdenum (Mo) appears to be the best candidate, but unfortunately, it needs a capping layer, because it is also known for its high oxidation susceptibility.⁹ On the other side, Au has been known for decades to work well in x-ray telescopes, but its EUV reflectivity at high grazing angles is quite poor. The right coating material must be chosen with respect to high efficiency, reasonable lifetime, and manufacturability.

With regard to efficiency, the mirror surface roughness σ is an important factor: In Fig. 33.5 the dependence of EUV reflectivity on mirror roughness is plotted for Ru. From these simulated data the requirement of surface roughness below 1 nm becomes obvious.

For good mechanical integrity the mirror reflectors had to be mounted in a rigid and stable supporting structure (holding fixture or mounting). This mechanical requirement is achieved by a rigid stainless steel ring with quite massive spokelike stiffeners; we call it a *spider wheel*. The spokes can be used for shell fixation, and they can act as support structures for cooling and electronics interfaces. All mirror shells are fixed to the spokes either by bonding them into appropriate slits with a glue or by mechanical clamping. Several types of ceramic cements can be used for this purpose, because they combine an outstanding high-temperature resistance and low outgassing rates.

For thermomechanical reasons the coefficient of thermal expansion (CTE) of the mirror shells, the spider wheel, and the bonding cement have to match well to minimize thermally induced stresses in the system.

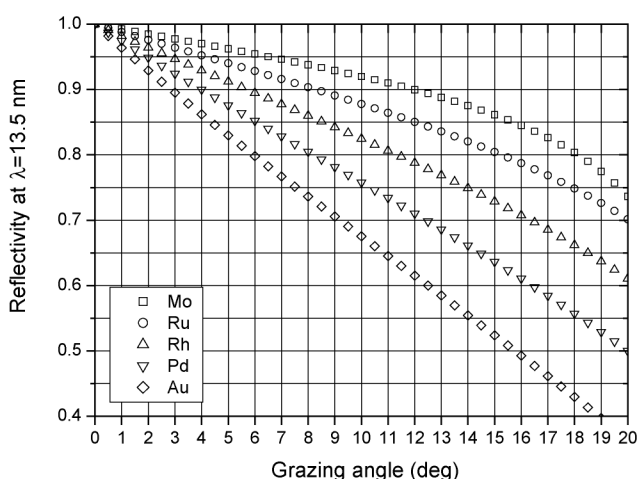


Figure 33.4 Reflectivities of five typical mirror materials at a wavelength $\lambda = 13.5$ nm—Mo: molybdenum; Ru: ruthenium; Rh: rhodium; Pd: palladium; and Au: gold. The surface of these materials was assumed as ideally smooth.

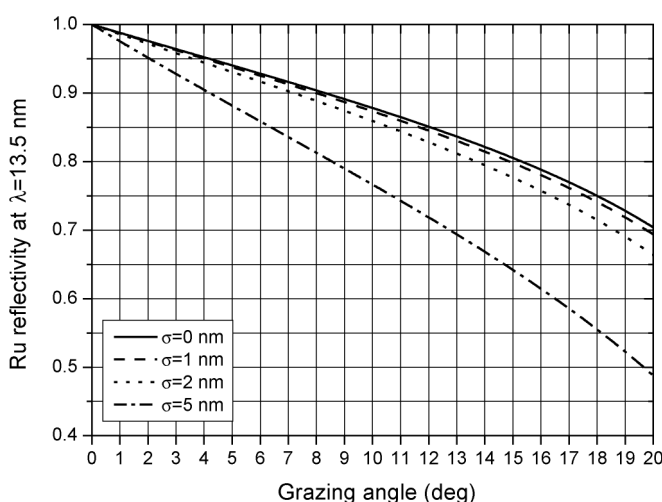


Figure 33.5 Dependence of Ru reflectivity on roughness that is included in the approximation given by the Nevot–Croce factor.¹⁰

The spider wheel's design includes corresponding mechanical interfaces for installation in the EUVL tool. These interfaces provide the means for required setup position accuracy and setup tilt accuracy.

33.3.3 Fabrication

33.3.3.1 Mirror-shell production

For our first collectors, we have chosen the approved nickel electroforming process, which has already been described in detail elsewhere;¹¹ therefore, here we only briefly describe the individual steps. Electroforming is a highly specialized process for fabricating a metal part by electrodeposition in a plating bath over a base form (mandrel), which is subsequently removed and can be reused. Some advantages of this process are: very good reproduction of the mandrel's form (figure*) and roughness, high metal purity, and low stress.

33.3.3.2 Mandrel fabrication

High-precision mandrels, having exactly the negative of the shape of the required mirror shells, are needed for the fabrication of high-efficiency EUV mirror reflectors. Not only the exact surface figure, but also a very smooth, superpolished surface is an absolute must for good mandrels.

A set of mandrels for all mirror shells has been manufactured at Carl Zeiss. All mandrels contain a rigid core of an aluminum alloy and are plated with a thin layer of high-quality electroless nickel. By application of state-of-the-art lapping, metrology, and superpolishing processes,⁸ high-quality replication mandrels with very smooth surfaces (microroughness below 0.5 nm rms; see Fig. 33.7) have been

*The term "figure" describes the surface topography on a centimeter-to-meter scale.

manufactured. Figure 33.6 shows the mandrel figure metrology setup before the superpolishing process, and Fig. 33.7 shows an example *ProMap* (phase-shift optical interferometric measurement) result for the superpolished mandrel surface.

33.3.3.3 Mandrel coating

A thin metal layer is deposited in high vacuum (PVD coating process) on the superpolished and cleaned mandrel surface, which later is transferred—by a replication



Figure 33.6 An EUV collector mandrel during figure metrology.

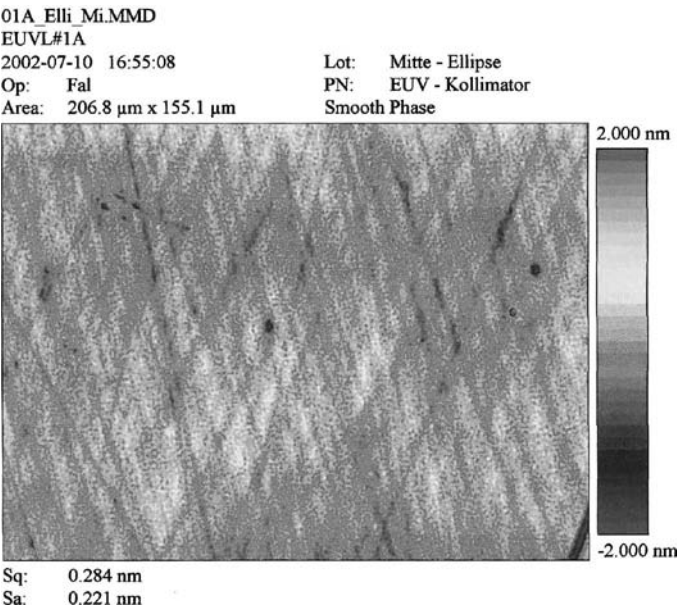


Figure 33.7 An exemplary microroughness measurement result as obtained by ProMap. (Result: $\sigma = 0.284$ nm rms.)

process—to the electroformed mirror shell substrate. This metal layer must provide good properties for EUV photon reflection and also act as a suitable release agent for a soft replication process. It is the delicate balance between the adhesive forces of the reflective coating on adjacent surfaces that decides a successful release and replication process.

33.3.3.4 Nickel deposition

Coated mandrels are mounted in suitable holding fixtures and immersed in a nickel electrolyte bath. They serve as the cathode during the electroforming process. Nickel is deposited on the mandrel surface by application of an electric field between the electrodes. The current density on the mandrel surface is controlled to keep internal stress low during nickel deposition. After having achieved the required thickness of the nickel layer (i.e., mirror-shell thickness), the electrodeposition process is stopped. The mandrel is extracted from the galvanic bath, cleaned, dried, and finally prepared for the next production step.

33.3.3.5 Separation of the mirror shell

By cooling down the mandrel–mirror-shell unit, the mirror shell can be smoothly released from the mandrel. Here we are taking advantage of the fact that the CTE of the nickel mirror shell differs substantially from that of the mandrel. On cooling down the mandrel–mirror-shell unit, the mandrel shrinkage is greater than the mirror-shell shrinkage. Finally, as the differential shrinking forces exceed the adhesion forces of the metallic coating layer on the mandrel surface, the mirror shell separates from the mandrel. If the process parameters were well controlled during the previous steps, then the mandrel's figure, surface roughness, and reflecting layer are transferred onto the nickel substrate, and the result is a freestanding EUV reflector.

The free mandrel is cleaned and can be reused for multiple mirror-shell production loops. Ten to fifteen mirror replications can be performed without significant degradation of the mandrel's performance. If more replications are planned, an intermediate repolishing must be performed.

33.3.3.6 Mirror-shell optical testing

The optical performance of a freestanding mirror shell, especially its figure (axial and circumferential profile deviations), is tested on a dedicated optical test stand. Equivalent metrology equipment been already designed and successfully used in the ABRIXAS mirror-shell fabrication program and has been described in previous papers.^{11,12}

For the EUV mirror shell and collector production program some adaptations of the original ABRIXAS test stands were necessary:

- A new light source had to be designed and built to simulate the illumination conditions of an EUV source. For that reason, a collimated beam of a commercial laser diode ($\lambda = 670$ nm) was expanded and spread uniformly

into a high-angle conical illumination. This setup allows us to produce a very small (pointlike) light source and to achieve uniform mirror-shell illumination with half angles up to ± 50 deg. (Currently, ± 45 deg is needed for our largest EUV collector mirror shell.)

- At the design focal distance from the light source we mounted a CCD camera that can acquire images of the light source at the IF position. The camera is mounted on a slide, which allows a travel of approximately ± 100 mm around the IF position along the optical axis.
- The mirror-shell support and alignment during optical testing had to be adapted to the special shape and design of the EUV mirror shells. For optical performance measurements of the individual mirror shells and for later collector integration purposes, it was necessary to provide lateral movement and tilting within the alignment mechanism (see Fig. 33.8).

Mirror-shell performance testing is carried out by moving the CCD camera into extra- and intra-focal positions, taking and storing pictures of the defocused source images, and processing the ring images by software for optical performance evaluation. With such dedicated analysis software, we can derive from the ring images all necessary information needed to judge whether a mirror shell under test fulfills our primary acceptance criteria:

- Diameter of 50% encircled energy (on axis): half energy width (HEW).
- Diameter of 90% encircled energy (on axis): W90.



Figure 33.8 An EUV collector mirror shell on the optical test stand.

- Optimum focus position: Z_{opt} (interpolated fit).
- Mirror-shell roundness deviations (Fourier analysis).

Due to the high magnification factor of our collector optics ($7\text{--}8\times$), the test on EUV mirror shells is much more sensitive than on astronomical x-ray mirrors (e.g., ABRIXAS mirrors), which focus the image of an infinitely distant source in the focal plane.

33.3.3.7 Mirror-shell integration

Integration of EUV mirror shells into their holding fixture (spider wheel) is carried out in a similar way as for the ABRIXAS telescope modules.^{11,12} The major difference from ABRIXAS is that the EUV mirrors are inserted into the spider wheel from the bottom and the EUV mirror shells are suspended at appropriate support rings.

The EUV collector integration stand is more or less a 1:1 copy of the EUV mirror shell test stand. However, an additional support structure and an alignment stage had to be developed and built for the massive EUV spider wheel. The spider wheel must be moved in the axial direction (vertically) in order to allow for insertion of the next mirror shell. Both support systems are adjustable in the lateral directions (with an $x\text{--}y$ stage), can be tilted, and allow very fine movement in the axial direction (along the z axis). Mirror-shell assembly is started with the innermost (smallest) shell and is continued step by step with the next larger shell until all reflectors have been inserted in the collector.

All mirror shells are coaligned with respect to a reference optic, and the correct focus position of each individual mirror shell is achieved through active alignment along the optical axis. All adjustment and alignment tasks on the reflectors are carried out under real-time optical control. Aligned mirror shells are fixed to the spokes by bonding with an appropriate cement. During bonding and curing of the cement, the mirror shell's optical performance can be checked online by optical means. After curing of the cement, the next mirror shell is inserted, aligned, and finally bonded to the collector spider wheel. Figure 33.9 shows a spider wheel with four integrated mirror shells.

33.3.4 Testing

33.3.4.1 Collector testing with visible light

With special annular apertures, each integrated mirror shell can be tested on the integration stand, individually or in a package of several shells. It is also possible to test optically and analyze the complete assembly of a collector with all mirror shells integrated. Figure 33.10 shows an example of the output of a test on an experimental collector with four integrated mirror shells. The top portion of Fig. 33.10 shows the reconstructed HEWs and 90% encircled energy widths (W_{90}) at different positions around the best focus position. The HEW_{min} value and the $W_{90\text{min}}$

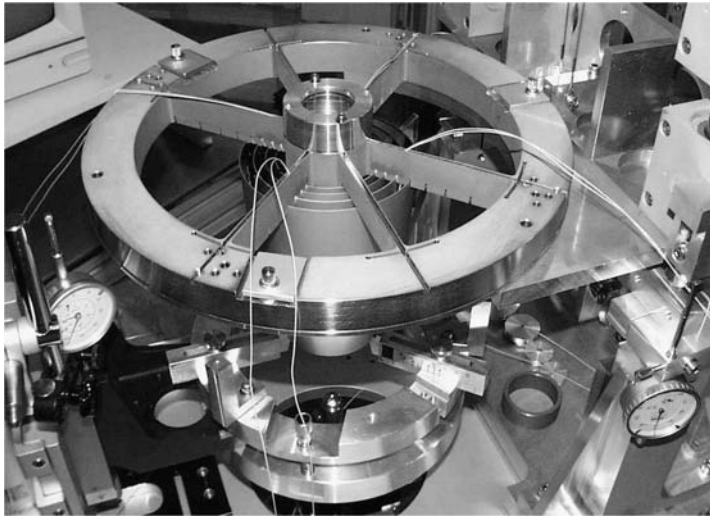


Figure 33.9 A collector on the integration stand. Four mirror shells are integrated.

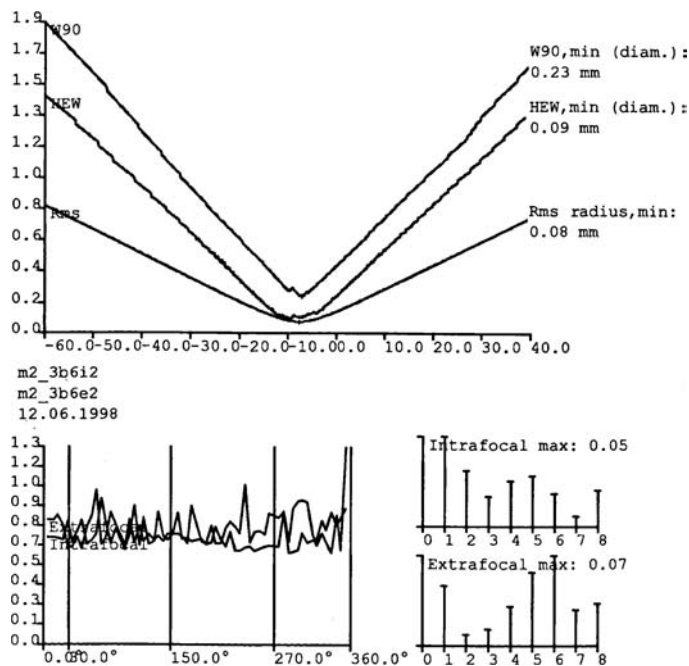


Figure 33.10 Example result of collector optical test and analyses.

value correspond to the HEW diameter and W90 diameter at the best focus position, respectively. The bottom part shows unfolded ring image intensity distributions of the extrafocal and intrafocal images and the corresponding powers of the first eight Fourier components. These data can be used to rate mirror-shell roundness.

33.3.4.2 Collector testing with EUV light

Reflectivity Measurements on Mirror Samples

Reflectivity tests have been carried out on representative samples of real EUV mirror shells at the German Synchrotron Radiation Laboratory BESSY II in Berlin. For that purpose small striplike samples (approximately 15 by 60 mm; see Fig. 33.11) have been prepared by cutting out segments from the ellipsoidal or hyperboloidal section of a real Pd-coated EUV mirror shell. In order to preserve the original figure of the flexible mirror samples, they have been supported on the rear side by a stable metal plate.

Several mirror samples have been tested, and example data are shown as follows for two measurement modes:

- at $\lambda = 13.5$ nm wavelength and with grazing angles varying from 5 to 15 deg (see Fig. 33.12);

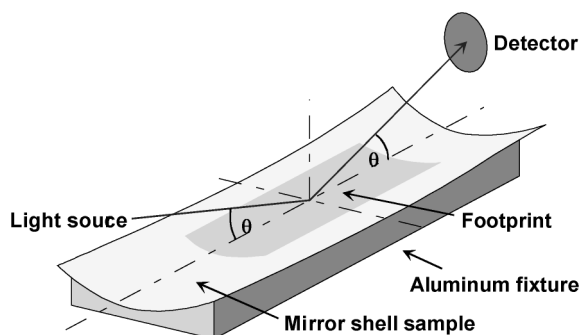


Figure 33.11 Mirror-shell sample and reflectivity measurement setup.

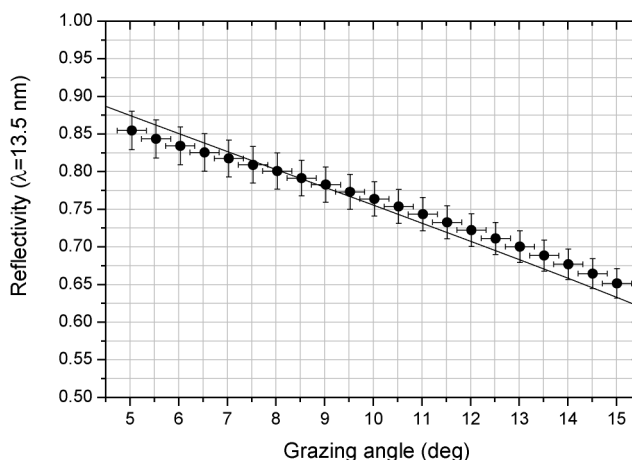


Figure 33.12 Measured reflectivity data from a mirror-shell sample at $\lambda = 13.5$ nm (circles) versus theoretical data on a thick Pd mirror (solid line).

- at constant grazing angles (5, 10, and 12 deg) with wavelengths varying from 12 to 33 nm (see Fig. 33.13).

Figure 33.12 shows the measured reflectivity data and theoretical data¹³ from a simulation of a thick plane Pd mirror with a surface roughness of 0.5 nm. The experimental reflectivity data reproduce the theoretical data to within $\pm 2\%$. The reflectivity is systematically too low for small grazing angles ($\theta < 8$ deg) and too high for larger grazing angles ($\theta > 8$ deg). To some extent this inconsistency can be explained by bent sample geometry (i.e., smearing effects and alignment inaccuracies), but the reason for a general slope deviation of the measured data is unclear.

Figure 33.13 depicts the measurement results of a mirror-shell sample together with simulated reflectivity data from a thick plane Pd mirror¹³ for varying wavelength at three constant grazing angles θ . The experimental data reproduce the theoretical result and deviate at most by approximately 5% from the simulation values up to a wavelength of 26 nm. For these results, we suspect the limited accuracy of the theoretical values (the data from Ref. 13 are results from theoretical calculations where inner-shell interactions have been neglected) to be responsible for the theory-experiment discrepancies.

Reflectivity Measurements on Collectors

Several experimental EUV collectors have been fabricated for different customers. Depending on the customer's requirements and specifications and the planned application, the ordered collectors were equipped with a prescribed number of mirror shells.

Three different types of EUV collectors have been fabricated by Carl Zeiss Laser Optics GmbH:

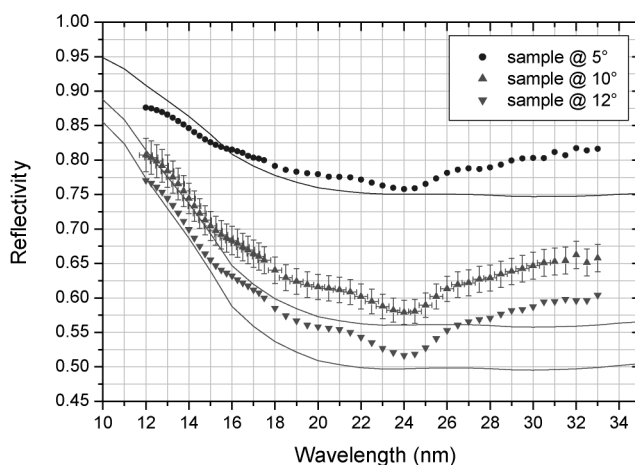


Figure 33.13 Results from reflectivity measurements at fixed grazing angles ($\theta = 5, 10$, and 12 deg) from a mirror-shell sample (symbols) versus theoretical data on a thick Pd mirror (lines).

- Collector type A: four medium-size mirror shells (see Fig. 33.14).
- Collector type B: two large mirror shells.
- Collector type C: eight mirror shells.

A type B collector has been selected for EUV reflectivity measurements at PTB at BESSY II in Berlin. The optical assembly was aligned in the reverse direction, i.e., the EUV pencil beam came from the IF position, and the twice reflected (first from the ellipsoidal and then from the hyperboloidal surface) photons were recorded at the designated source position. Two points were measured on every shell of the collector, and the results are presented in Fig. 33.15. The two-bounce



Figure 33.14 Experimental collector with four mirror shells.

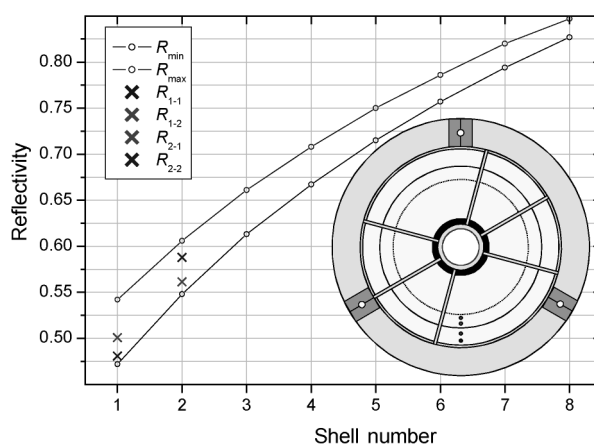


Figure 33.15 EUV reflectivity measurement results from a two-mirror-shell collector assembly. Here $R_{\min}$ and $R_{\max}$ correspond to the maximum and minimum expected (calculated) two-bounce reflectivities, and R_{1-x} and R_{2-y} are the reflectivities from shells 1 and 2, respectively.

reflectivities match expected values as calculated for two thick mirror reflections very well.

33.4 Summary, Trends, and Challenges

In this chapter we have reported on requirements of EUV collectors. We have described in depth the design, fabrication, and testing of grazing-incidence EUV collectors as they can be used for DPP and LPP sources. Wolter type-1 collectors with different configurations have been manufactured and successfully tested with visible light for optical performance, and with EUV light for efficiency (see also Refs. 14, 15). Results from the application of our EUV collectors at DPP or LPP EUV sources can be found elsewhere in this volume.

The EUV collector program is now at the first of three steps that, from today's perspective, will lead the technology into high-volume production. The first tools will have an anticipated EUV inband light power of approximately 15 W, which will allow an exposure of several wafers per hour (wph). The second step is a tool where 20–30 wph should be achieved; and finally, more than 100 wph will be needed for high-volume production. A major challenge is that future collectors for high-volume production will have to deal with light powers increased by a factor of 10 to 100 over present EUV source powers.

Light radiation that, if too high or spectrally unfavorable, can cause thermal degradation of collector materials is not the only challenge. Today, source manufacturers are in the process of studying and controlling side effects such as debris ejected by and electromagnetic fields generated around the source pinch. These effects definitely have an effect on EUV collector performance and lifetime. Depending on their production cost and long-term stability, collectors are planned either as consumables to be swapped after reasonable periods of time or as long-lasting optical components with lifetimes of at least a few years.

For high-throughput tools, collectors having larger collection angles and higher efficiencies will probably be needed, which, however, can be designed and fabricated by our elaborated manufacturing processes.

DPP and LPP sources seem to be in a neck-and-neck race to become the optimum and ultimate source for EUVL, and today nobody can foresee which will win or, indeed, if either of these two will make it to the finish. In any case, as the manufacturer of optical components situated next to the source, we should be prepared to adapt the development program.

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Chapter 34

Collection Efficiency of EUV Sources

Günther Derra and Wolfgang Singer

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34.1 Introduction

One of the most important characteristics of an EUV light source for microlithography is the available inband EUV power. A power of at least 80 W, measured at the second focus of the collector, will be needed for a production tool, taking into account the optical requirements—expressed by the system etendue—of the whole imaging system. The available power at the second focus is given by the electrical

input power P_{el} , the conversion efficiency (CE) of electrical input to EUV radiation, the system transmission, T_{sys} , taking into account collector reflectivity and possible gas transmission, and—to be considered here—the collection efficiency, η_{col} :

$$P_{\text{EUV}} = P_{\text{el}} \cdot \text{CE} \cdot T_{\text{sys}} \cdot \eta_{\text{col}}. \quad (34.1)$$

The collection efficiency is one of the most important characteristics of a radiation source in an EUVL system. It is a geometrical quantity defined as the fraction of the total inband EUV radiation power that can actually be picked up and used in the subsequent total optical path of an EUV projection system down to the wafer. It is not a property of the source alone, but is determined both by the details of the optical system and by the geometrical intensity distribution of the source plasma.

The collection efficiency of an extended source in an optical system can be analyzed with the etendue formalism. Under the assumption of an ellipsoidal source intensity distribution, an analytical expression for the source etendue is derived. This can be used to analyze the collection efficiency for various source geometries as a function of collection angle.

The design of efficient illumination systems and detailed simulation analysis of the collectible source power is complex and time-consuming. The goal of this chapter is therefore to provide an estimate of the collectible source power by a simplified analysis. In a first step, the etendue of an idealized source in its dependence on the collection aperture is evaluated. This leads to a collectible source volume, from which in a second step the collected power of a real source can be estimated by projecting and integrating the collected radiance of the source.

34.2 Etendue of Illumination Systems

34.2.1 The geometrical flux of extended volume sources of elliptical shape

In 1941 G. Hansen introduced the term *Lichtleitwert* for the geometrical flux G of an optical system when he investigated the imaging of volume sources.¹ It was shown later that the geometrical flux G corresponds to the *Helmholtz–Lagrange invariant* (HLI) of optical systems, also called the *etendue* or *phase-space volume* of conservative systems. Thus etendue, geometrical flux, HLI, and phase-space volume are synonymous terms. According to fundamental laws of physics, the geometrical flux is invariant in optical systems.² Therefore, once the geometrical flux is given, e.g., at the object plane of an optical system, the collectible power of a light source is also determined.

The geometrical flux G is in general defined by a four-dimensional volume integral over, e.g., the field size of the optical system and the aperture. The aperture is defined relative to the main propagation axis, e.g., the axis of symmetry of an optical system. The integration in the angular domain has thus to be taken over

optical direction cosines p_x and p_y , defined by the tangent vectors at a light ray multiplied by the refractive index n :

$$G = \int \int_{\text{area}} \int \int_{\text{direction cosine}} F(x, y; p_x, p_y) dx dy dp_x dp_y = \int \int_{A \Omega} dA \cos \alpha \cdot d\Omega, \quad (34.2)$$

where F is the aperture function of the optical system, limited, e.g., by the field and pupil stops. The geometrical flux G of imaging optical systems is given by the field area A and the numerical aperture (NA), here given by the solid angle Ω . As an example, the object field size of EUVL systems is typically in the range of $X = 104$ mm $\times$ $Y = 8$ mm, the NA at the wafer is, e.g., $\text{NA} = 0.25$, and the magnification $\beta = 0.25$. With a typical coherence parameter $\sigma = 0.5$, the geometrical flux G of the illumination distribution is given by

$$G = XY \cdot \pi(\sigma\beta \cdot \text{NA})^2 = 104 \times 8\pi(\sigma\beta \cdot \text{NA})^2 \text{ mm}^2 \approx 2.55 \text{ mm}^2. \quad (34.3)$$

Due to the limited geometrical flux G of optical systems, the collectible light from a given incoherent source of finite extension is also restricted. The efficiency of the illumination system is limited by the radiance of the source emitted into the phase-space volume and thus by the geometrical flux G of the optical system. For a given geometrical flux of an EUV system and a given collection aperture, an ideal source size can thus be derived for which all light can be collected.

For the evaluation of the geometrical flux of an incoherent extended volume source, it is convenient to apply the right-hand side of Eq. (34.2), where the area A is taken at a distance from the source and the solid angle Ω is given by the visible source size as a function of the coordinates over A (see Fig. 34.1). We further restrict the discussion to rotational symmetrical plasma sources. We derive from Eq. (34.2):

$$G = \int \int_{A \Omega} dA \cos \alpha \cdot d\Omega = \int \int \int_{\varphi r \Omega} r dr d\varphi \cos \alpha \cdot d\Omega = 2\pi \int \int_{r \Omega} r dr \cos \alpha \cdot d\Omega. \quad (34.4)$$

For a simplified analysis, the source is approximated by an ellipsoid of diameter $2b$ and length $2a$. For EUV plasma sources, the FWHM level of the source density distribution is used to determine the length and diameter of the ellipsoidal volume. The visible diameter $d(\alpha)$ of the source can be approximated for large z_0 by

$$d(\alpha) = 2\sqrt{a^2 \sin^2 \alpha + b^2 \cos^2 \alpha}. \quad (34.5)$$

The solid angle Ω is given for large z_0 by the ratio of the projected area of the source to the distance $R(\alpha)$:

$$\Omega(\alpha) = \frac{\pi b \cdot d(\alpha)}{R^2(\alpha)}. \quad (34.6)$$

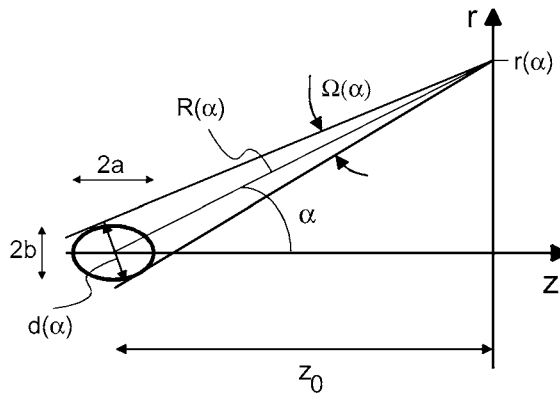


Figure 34.1 Illustration of the visible solid angle of an extended volume source at field height h .

Thus, insertion in Eq. (34.2) gives

$$G = 2\pi^2 \int_r r dr \cos \alpha \cdot \frac{b\sqrt{a^2 \sin^2 \alpha + b^2 \cos^2 \alpha}}{R^2(\alpha)}$$

$$= \frac{2\pi^2 b}{z_0^2} \int_r r dr \cos^4 \alpha \cdot \sqrt{a^2 \tan^2 \alpha + b^2}. \quad (34.7)$$

After substitution of $r = z_0 \tan \alpha$, it follows that

$$G = 2\pi^2 b^2 \int_{\alpha} \sin \alpha \cdot \sqrt{1 + \frac{a^2}{b^2} \tan^2 \alpha} d \sin \alpha. \quad (34.8)$$

For $\alpha_{\min} = 0$, the integral can be expanded to

$$G = \pi^2 b^2 NA^2 + \frac{\pi^2}{4} a^2 NA^4 + \frac{\pi^2}{24} \frac{a^2}{b^2} (4b^2 - a^2) NA^6$$

$$+ \frac{\pi^2}{64} \frac{a^2}{b^4} (8b^4 - 4a^2 b^2 + a^4) NA^8 + O(NA^{10}). \quad (34.9)$$

For large apertures, integration of Eq. (34.2) yields

$$G = \pi^2 b \left[\frac{a^2}{e} \arctan \left(\frac{\sqrt{b^2 + a^2 \tan^2 \alpha}}{e} \right) - \frac{\sqrt{b^2 + a^2 \tan^2 \alpha}}{1 + \tan^2 \alpha} \right]_{\alpha_{\min}}^{\alpha_{\max}} \quad (34.10)$$

with $e = \sqrt{a^2 - b^2}$.

Figure 34.2 shows the result for $a = 0.8$ mm, $b = 0.65$ mm, and $\alpha_{\min} = 0$ for different orders of the series expansion of the geometrical flux according to Eq. (34.2).

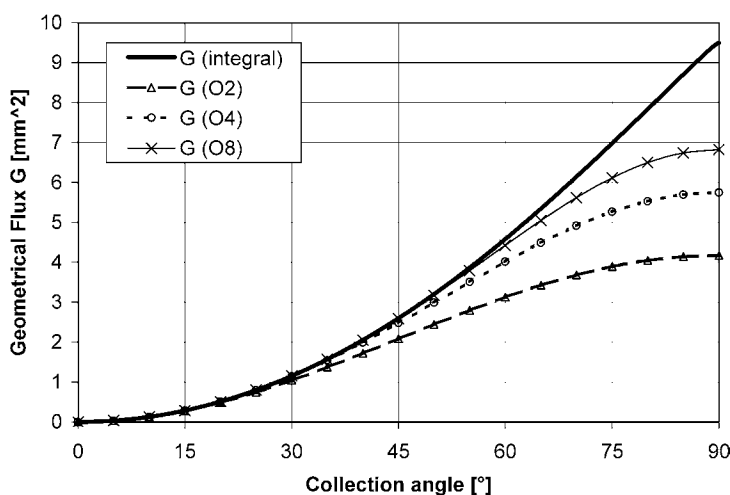


Figure 34.2 Geometrical flux of an elliptical source model with $a = 0.8$ mm, $b = 0.65$ mm in dependence on the collection angle. The series expansions of G up to second (O2), fourth (O4), and eighth (O8) order are given for comparison.

34.2.2 Collection angle of efficient illumination systems

From Fig. 34.2 the ideal collection angle for an efficient illumination system can be derived. The geometrical flux $G = 2.55$ mm² of the example above is reached at a collection angle of 45 deg, or a NA ≈ 0.7 . As soon as the collection aperture increases above that value, some of the collected light must be lost somewhere in the illumination optical system, e.g., at physical stops or lens or mirror boundaries. The evaluation of the collectible aperture of ≈ 45 deg according to Fig. 34.2 shows that for a source with a diameter $\varnothing = 1.3$ mm and a length $L = 1.6$ mm (FWHM), the collectible power is restricted to $\approx 29\%$ of the power emitted into 2π sr, if only the geometrical losses are considered. However, the radiance provided by the plasma source is in general not constant, and the collected geometrical flux or phase-space volume thus will not be filled homogeneously. This offers the capability to optimize the efficiency by selectively collecting the parts of the geometrical flux of the source with larger radiance.

The source volume of 1.3×1.6 mm limits the source region from which all rays emitted into the cone determined by the example collection aperture of the collector with NA = 0.7 can be collected. For larger sources, however, any ray in the direction of the collectible aperture that intersects the ideal source volume does not increase the geometrical flux and can thus also be collected. An example is given in Fig. 34.3, where the ideal source volume is shown in an arbitrary source distribution. The limited geometrical flux determines a collectible bundle of rays, and of course it does not limit the position on an individual ray of the source emitting this ray. However, the larger the distance of a source point P from the collectible source volume, the smaller is the collectible cone of rays C from this source point. Therefore the collection efficiency decreases rapidly with increasing

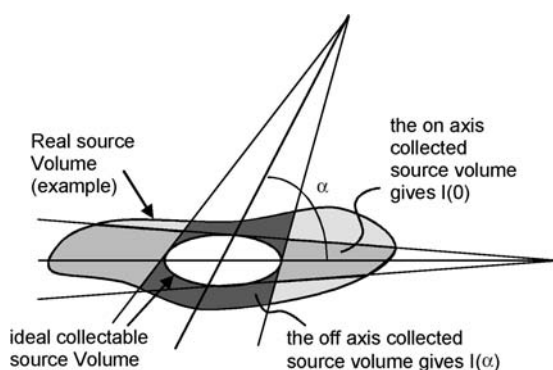


Figure 34.3 Collected radiation from a source larger than the ideal elliptical source volume; the collected radiant intensity depends on angle α .

source size, leading to large light loss in the illumination optical system, leading in turn, e.g., to unwanted heat load.

34.3 Determination of EUV Source Power

A quite accurate method of source evaluation for an EUVL system is optical ray tracing of the total illumination and imaging system. Accurate ray tracing requires considerable computing time, which limits its use as a quick diagnostic tool. In addition, ray tracing has to rely on a model of the source distribution, which must be extracted from pinhole-camera measurements and can thus not be free of errors. If the procedure is done carefully, however, the ray-tracing method is a good reference for evaluation of the source performance.

During source development and optimization, however, a quick evaluation of laboratory measurements is necessary, which can be done within the source development group. Following the discussion given above, it is possible to derive an *allowed* source volume of ellipsoidal shape, defining a region in space from which rays from the source can be collected through the optical system, taking into account all etendue limitations. This must be done only once for a given optical system.

Based on this, a simple and fast, but still reliable, method for evaluation of collection efficiency has been developed. The new method is based on taking pinhole images of the source plasma with a CCD camera, preferably under various observation angles. From these intensity maps, a three-dimensional model source intensity distribution can be estimated. This estimate is used as input to a subsequent projection algorithm to calculate projected images. By comparison with the measured pinhole images, the source-intensity-distribution model is refined iteratively.

Using this source intensity distribution with the projection model, angular radiation characteristics of the source can be calculated. Integration also yields the total radiation power within a certain collection angle.

Finally, the etendue limits of the optical system are included by performing the same projection calculations, but taking into account only radiation from the allowed source volume determined beforehand. This yields the actual collected power within etendue limits and the collection efficiency.

Comparison with detailed ray-tracing model calculations of the complete optical system indicates good accuracy of the method. It can be used in a simple way for source optimization and enables reliable evaluation and specification of source performance in EUV projection systems.

To summarize, the proposed method can be outlined as follows:

1. Absolute measurement of the source radiation power by a calibrated photodiode (equipped with a multilayer tool to limit the spectral response to the 13.5-nm band).
2. One or more pinhole-camera measurements of the source at various angles to the optical axis.
3. Determination of a model source distribution from the camera image(s).
4. Calculation of the *usable* radiation by a projection algorithm, including electrode obscuration effects and etendue limits by taking into account the pre-calculated source volume.
5. Calculation of the angular distribution.
6. Calculation of the collection efficiency and total usable radiation.

A more detailed discussion of the different steps will now follow.

34.3.1 Pinhole-camera measurement and fit of source distribution

First, pinhole-camera images are taken at an arbitrary angle of view θ with respect to the optical axis. For reasons of accuracy, the angle should be >10 deg, preferably >20 deg. Usually, a few measurements are sufficient and axial symmetry is assumed. From the measured images, parameters are extracted, which are later used for comparison with the model distribution results. The most important parameters in the case of a nearly ellipsoidal source image are z_0 (the z location of the source center), l_p (the on-axis FWHM length of the source), and r_p (the center radius of the source, FWHM).

In a second step, this measurement is used in a fitting procedure to generate a source distribution model of the EUV source. This is done as follows: a suitable function is assumed for the source distribution, having not too many free parameters, preferably three or four. Suitable starting values for the parameters are estimated. The source distribution function represents the radiant power per unit volume of the source, measured in watts per cubic meter. Any suitable function can be chosen here to match the measured pinhole-camera images so long as its total volume integral (equal to the total source power) is finite. As a simple and often sufficiently accurate model source distribution, one can use a Gaussian distribution

as follows, z_0 denoting the location of the source reference point:

$$S(z, r) = S_0 \exp \left[-\frac{(z - z_0)^2}{\lambda_0^2} - \frac{r^2}{\rho_0^2} \right]. \quad (34.11)$$

The projected view of this initial source distribution is computed for the projection angle θ , taking into account any obscuration, in the case of the hollow-cathode-triggered (HCT) pinch of the anode. The assumption of an optically thin source plasma is used here. Comparing the computed projection of the model source distribution with the pinhole-camera image, the free parameters of the source distribution model are adjusted iteratively until a good model source distribution is found.

Some steps of the procedure are now explained in more detail.

34.3.2 Projection of the model source distribution

The projection algorithm used is a simple parallel projection, which is nearly identical to the pinhole-camera imaging, because the long imaging distances used are very large compared to the CCD image size.

All points of the source distribution are viewed at an arbitrary angle θ . The points (z, x, y) of the source distribution are therefore first transformed into a tilted coordinate system (w, u, v) . Then a projection is performed along the w axis to the (u, v) plane, which is the projection plane; see Fig. 34.4 for reference.

Because the plasma is optically thin—an assumption that can be justified by comparison of photodiode signals under different observation angles—the intensity (measured in $\text{W/m}^2 \text{sr}$) of a source with emission coefficient ε (measured in $\text{W/m}^3 \text{sr}$) at a point (u, v) at an angle θ can be written as a projection integral. The intensities due to all source points lying on the line of sight can be summed to obtain the total intensity:

$$L(u, v, \theta) = \int_{-\infty}^{\infty} \varepsilon dw = \frac{1}{4\pi \text{sr}} \int_{-\infty}^{\infty} S[z'(u, w), r'(u, v, w)] \cdot dw, \quad (34.12)$$

where

$$\begin{aligned} z'(u, w) &= u \sin \theta + w \cos \theta + z_V, \\ r'(u, v, w) &= \sqrt{(u \cos \theta - w \sin \theta)^2 + v^2}. \end{aligned}$$

Here, $S(z, r)$ is a source distribution as defined as an example in Eq. (34.2), and z_V denotes the intersection of the w axis in the actually chosen view coordinate system with the z axis, i.e., the rotation center point. For the calculation of the collection efficiency of a collector system, it would be chosen to be the focal point of the collector.

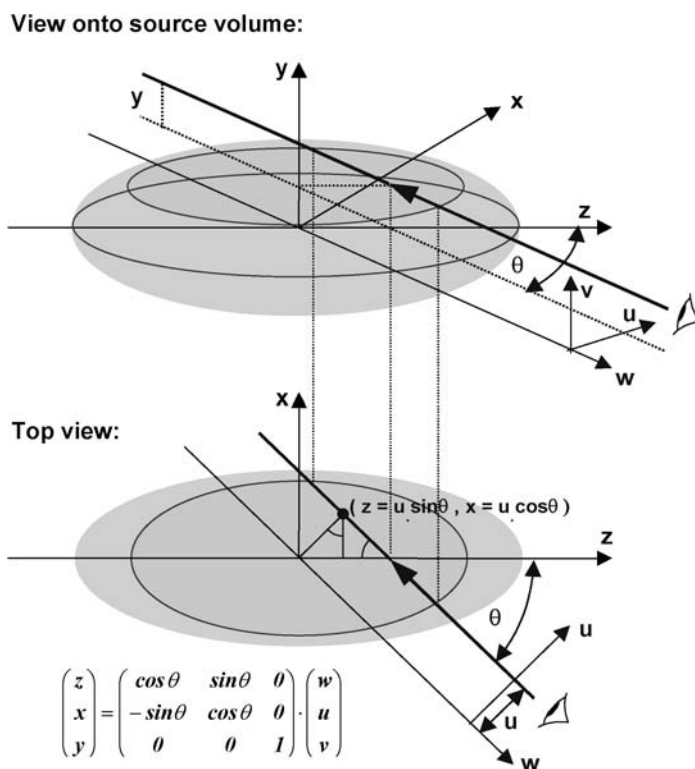


Figure 34.4 Projection geometry.

34.3.3 Projection of source volume

Analogously to the projection of the source, it is also useful to calculate the projection of the specified source volume already discussed above. This source volume is not a sharply defined volume, such that only radiation from it contributes to the usable radiation power. As discussed before (see Fig. 34.3), it is a “touching” volume, which all rays of radiation from the source to the collection optics must touch in order to contribute to the total usable power. In the following, the source volume shape is assumed ellipsoidal:

$$SV(z, r) = \begin{cases} 1 & \text{if } \frac{(z - z_V)^2}{l_V^2/4} + \frac{r^2}{r_V^2} \leq 1. \\ 0 & \text{otherwise.} \end{cases} \quad (34.13)$$

This is a function that is 1 within the source volume and 0 everywhere outside. Here, the center of the ellipsoidal is located at $z = z_V$, the rotation center of the projection. Whenever the line of sight defined by (u, v) is touching the specified source volume, the projection value defined above is 1; if the line of sight does not touch the source volume, it is 0.

For the projection algorithm, a weighting function is used, which delivers unity as the result only if the ray defined by (u, v, θ) is touching the source volume:

$$PV(u, v, \theta) = \begin{cases} 1 & \text{if } \int_{-\infty}^{\infty} SV[z'(w), r'(w)]dw > 0, \\ 0 & \text{otherwise.} \end{cases} \quad (34.14)$$

34.3.4 Obscuration by electrode system

Electrode obscuration can lead to partial obscuration of the source, especially for large observation angles, depending on the relative positions z_0 of the source and z_{el} of the electrode and on the electrode radius r_{el} (see Fig. 34.5).

A visibility function of the projected coordinates can be defined as follows:

$$VIS(u, v, \theta) = \begin{cases} 1 & \text{if } \frac{u}{\sin \theta} > (z_{el} - z_V) - \frac{\sqrt{r_{el}^2 - v^2}}{\tan \theta}, \\ 0 & \text{otherwise.} \end{cases} \quad (34.15)$$

Whenever the line of sight defined by (u, v) is touching the electrode borehole, the visibility value is 1; if the line of sight does touch the electrode, it is 0.

34.3.5 Iteration of source distribution function

Comparing the computed projection of the model source distribution as described above with the pinhole-camera image, the free parameters of the source distribution model are adjusted iteratively until a good model source distribution is found.

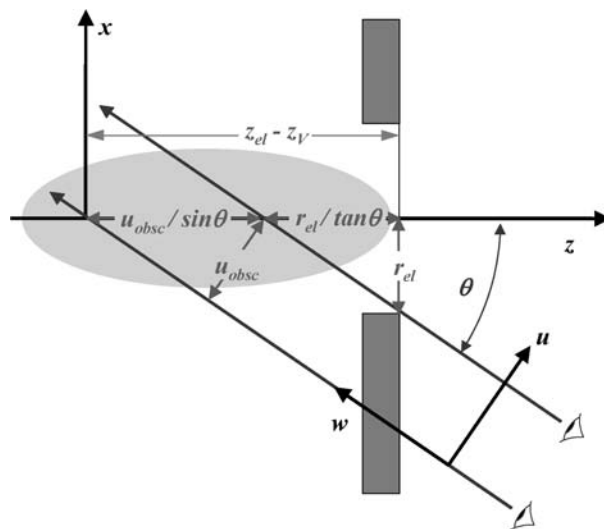


Figure 34.5 Geometry for electrode obscuration.

The most important quantities—the projected length and width of the source—are determined and compared with the corresponding pinhole-camera image results. In the case of the Gaussian distribution 0 used above, the adjustable parameters are just the source position z_0 , the length λ_0 , and the radius ρ_0 . After a few iteration steps, normally a good model source distribution is found, which can be used further for evaluation of the total source power.

34.3.6 Angular distribution

The next step is the computation of the source angular distribution. Here the model source distribution is projected for every observation angle, and the total intensity of the projected rays is integrated. Only the rays touching the specified source volume are included. In addition, obscuration by the electrode structure is considered. The angular distribution of radiated power for a given observation angle θ is calculated by integration of all projected intensity over the total projected image plane, taking into account the electrode obscuration Eq. (34.15):

$$P_{\text{VIS}}(\theta) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} L(u, v, \theta) \cdot \text{VIS}(u, v, \theta) dv du. \quad (34.16)$$

The normalized angular distribution is then simply

$$I(\theta) = \frac{P_{\text{VIS}}(\theta)}{P_0} \quad \text{with } P_0 = P_{\text{VIS}}(0 \text{ deg}), \quad (34.17)$$

where P_0 is the total observed power in an on-axis measurement.

The discussion of angular distribution of radiated power given so far has not included the etendue limitations of the optical collection and illumination system. This can be included by using the weighting function $PV(u, v, \theta)$ of the source volume defined above. Only rays touching the source volume are counted:

$$P_{\text{SV}}(\theta) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} L(u, v, \theta) \cdot \text{VIS}(u, v, \theta) \cdot PV(u, v, \theta) dv du. \quad (34.18)$$

The resulting angular distribution yields the radiated power at a certain observation angle, including electrode obscuration and taking into account the etendue-limited collection capabilities of the collection and imaging system. It will be called the angular distribution of *usable* radiation power.

34.3.7 Total usable radiation power

Finally, the total usable radiation power, including the etendue limitations of the optical collection and illumination system, is computed from the angular distribution of usable radiation. This can be done by simple integration over the acceptance

solid angle of the collection system:

$$P_{SV\text{ tot}} = 2\pi \int_{\theta_{\min}}^{\theta_{\max}} P_{SV}(\theta) \sin \theta d\theta. \quad (34.19)$$

If normalization by the total emitted power is included, the result is expressed as an effective solid angle, which can be considered as the collection efficiency of the actual source in the optical system:

$$\eta_{\text{col}} = P_{SV\text{ tot}}/P_0. \quad (34.20)$$

Determination of the total usable power in absolute numbers is done by calibration with an absolutely calibrated photodiode, equipped with a calibrated multilayer tool to limit the spectral response to the 13.5-nm band. The diode measurement must be done in such a way that all light emitted by the source into the measurement direction is captured without obscuration. The basic measurement can be done on axis. To control the influence of contributions from plasma parts that are located deep in the electrode system and cannot be seen at an angle to the optical axis, diode measurements at an angle are also advisable. The resulting absolute value can then be compared with the calculated total flux from the source model distribution to yield an absolute calibration of the source model.

34.4 Example Measurements at the HCT Pinch

In this section, three measurements of the HCT pinch EUV sources³⁻¹¹ are presented as examples to demonstrate the method. The measurements were done by O. Rosier and R. Apetz from Fraunhofer Institute für Lasertechnik and Philips Extreme UV GmbH, Aachen, respectively. It must be stated very clearly that the measurements and the source models presented here are related to particular configurations of the source and to particular settings of discharge parameters. Changes in the source geometry and operating parameters will lead to different source distributions and to considerable deviations from the results given here.

34.4.1 Pinhole-camera measurements

In the first example measurement, the electrode geometry was as follows: cathode diameter 5 mm, anode diameter 11 mm, anode thickness 4 mm, electrode gap 6.5 mm. The EUV radiation source center was about 6 mm above the cathode. The pinhole images under different observation angles are shown in Fig. 34.6. As can be seen from the pinhole-camera images, the source consists of an ellipsoidal main distribution plus a long, thin tail extending down to the cathode borehole.

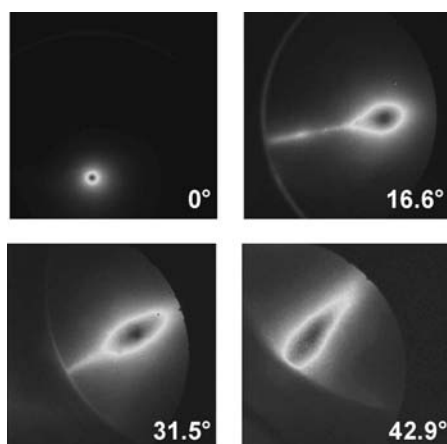


Figure 34.6 Pinhole-camera images for various observation angles.

34.4.2 Fit of source distribution

For the iterative calculation of the source distribution, a superposition of two Gaussian functions was used:

$$\begin{aligned}
 S(z, r) &= S_0(z, r) + S_1(z, r) \\
 &= S_0 \exp \left[-\frac{(z - z_0)^2}{\lambda_0^2} - \frac{r^2}{\rho_0^2} \right] + S_1 \exp \left[-\frac{(z - z_1)^2}{\lambda_1^2} - \frac{r^2}{\rho_1^2} \right].
 \end{aligned}
 \tag{34.21}$$

After the iteration, the resulting values of the parameters were:

$$\begin{aligned}
 S_0 &= 1, & z_0 &= 6 \text{ mm}, & \lambda_0 &= 2.2 \text{ mm}, & \rho_0 &= 0.65 \text{ mm}, \\
 S_1 &= 1.1, & z_1 &= -3 \text{ mm}, & \lambda_1 &= 9 \text{ mm}, & \rho_1 &= 0.23 \text{ mm}.
 \end{aligned}
 \tag{34.22}$$

A graph of the source distribution $S(z, r)$ is shown in Fig. 34.7.

By integration over volume, the relative powers in the two parts $S_1(z, r)$ and $S_2(z, r)$ of the source distribution can be calculated to be 64% and 36%, respectively. Roughly one-third of the radiant power is located in the tail of the distribution and can hardly contribute to the collectible power. Two-thirds of the total power is located in the ellipsoidal head. The length and diameter of the source distribution are 3.7 and 1.0 mm (FWHM), respectively.

Using this source distribution function, the projection algorithm above for various observation angles results in the projected images shown in Fig. 34.8. The images are directly comparable to the original pinhole-camera images shown in Fig. 34.6.

As can be seen, the source model can reproduce the measured pinhole-camera images quite well. In Fig. 34.9, the projected source distribution is shown for sev-

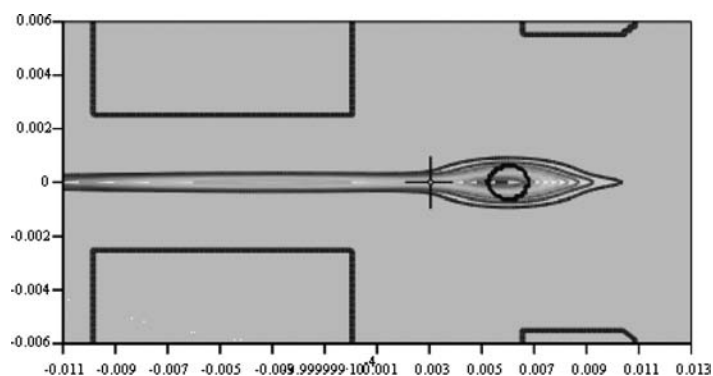


Figure 34.7 Source volume distribution. The black ellipse indicates the specified source volume; the cross is the center of rotation for the pinhole-camera measurements.

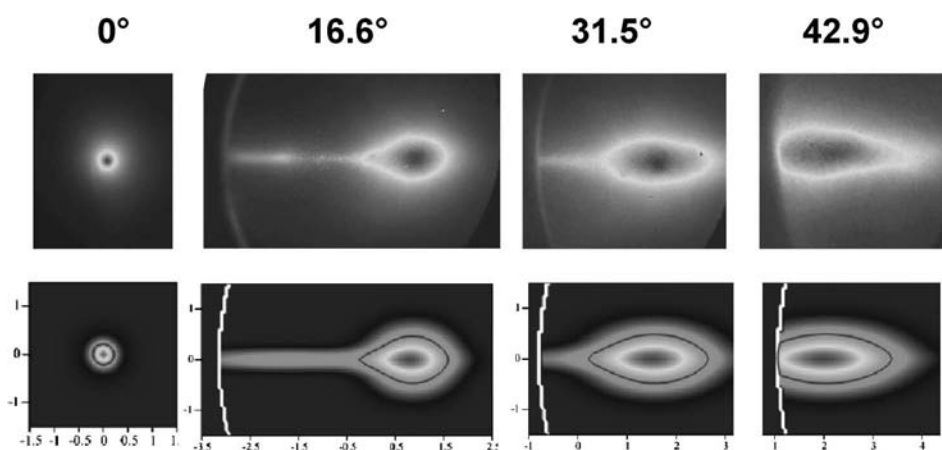


Figure 34.8 Measured pinhole images (top row) and projected images calculated from model source distribution (bottom row). Black line: 50% level of source distribution. White line: projected anode edge.

eral observation angles. The edge of the anode opening is shown as a white line. In addition, the elliptical source volume, as specified above, is indicated.

34.4.3 Angular distribution

Using the source distribution found above, the evaluation of the total usable power is possible. According to the procedure described above, the angular distributions of the total radiated power and of the power from rays touching the specified source volume were calculated (including electrode obscuration). The result is given in Fig. 34.10.

The dashed curve indicates the total radiation in a certain direction, that is, the integral of the intensity over the entire projection images as shown in Fig. 34.9. The decrease of intensity with increasing observation angle above 10 deg results

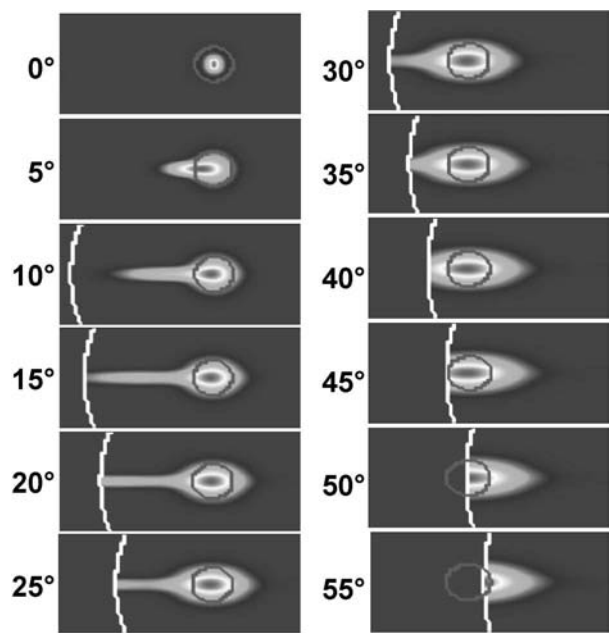


Figure 34.9 Calculated source projections for various projection angles. White line: anode edge; dark gray ellipses: source volume boundary.

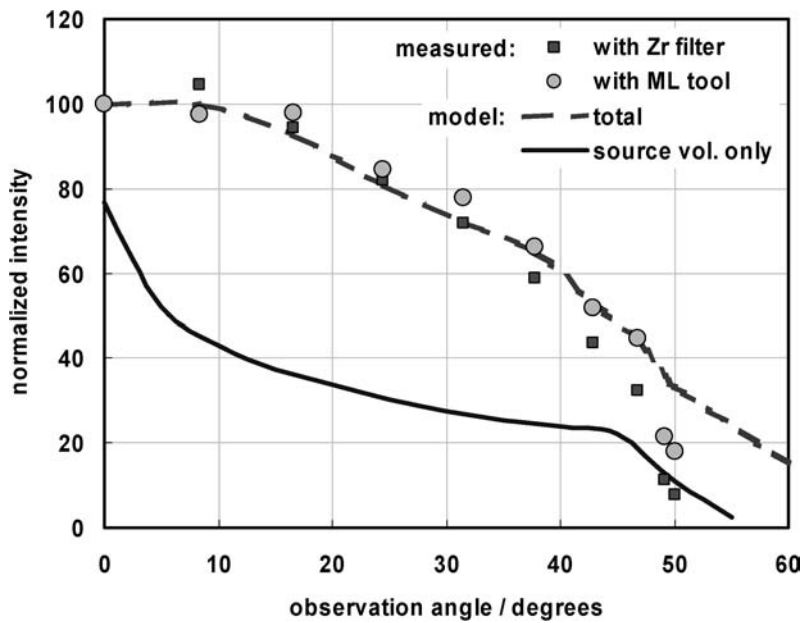


Figure 34.10 Normalized angular distribution of the total radiated power according to the model calculation and to photodiode measurements (with Zr filter and multilayer tool). The solid curve indicates the angular distribution of the radiation from the specified source volume only.

from the fact that more and more intensity from the tail of the distribution is cut off by anode obscuration. Obscuration of the main distribution sets in at some 40 deg.

The total angular distribution has been measured with a photodiode with two different methods for spectral filtering. First, a zirconium filter was used with a transmission between 12 and 20 nm. Secondly, a multilayer tool with two near-normal-incidence reflections was used to measure the inband EUV distribution. The comparison of the simulated angular distributions with the measured ones shows remarkably good agreement (except for 50 deg, where the discrepancy is due to a geometrical alignment error).

34.4.4 Total usable radiation power

For the example EUVL system of Sec. 34.2.2, the ellipsoidal source volume corresponding to the etendue limit 2.55 mm^2 of the lithographic system had a length of 1.6 mm and a width of 1.3 mm.

The solid curve in Fig. 34.10 is the angular distribution of the part of the projected images originating from the specified source volume only. It indicates the intensity at a certain angle, integrated over only the projected source volume, i.e., only the intensity inside the gray source-volume projections in Fig. 34.9. The values are lower than for the dashed line, because the source diameter is too big to be fully collectible within the limits of the source volume. For the actual source distribution, 78% of the total value P_0 is reached on the axis.

The total usable power can now be calculated by integration over the collector acceptance angle range up to 45 deg. First, the total acceptance solid angle of the collector is computed for reference:

$$\Omega_{\text{col}} = 2\pi \int_{0 \text{ deg}}^{45 \text{ deg}} \sin \theta d\theta = 1.84 = 29.3\% \times 2\pi. \quad (34.23)$$

The value 29.3% of 2π is the upper limit of collection efficiency, which would be reached for a point source with an ideally flat angular distribution within the collection range of up to 45 deg.

Finally, the collection efficiency for the given source distribution is calculated, including electrode obscuration and the system etendue limits:

$$\eta_{\text{col}} = \frac{2\pi}{P_0} \int_{0 \text{ deg}}^{45 \text{ deg}} P_{\text{SV}}(\theta) \sin \theta d\theta = \frac{P_{\text{SV tot}}}{P_0} = 0.52 = 8.3\% \times 2\pi. \quad (34.24)$$

For this example measurement, only 8.3% of the total power emitted into 2π can be collected.

34.4.5 Other examples

For other settings of the HCT pinch experimental parameters, higher collection efficiencies can be found. In Fig. 34.11, several examples of pinch sources in xenon and tin are given. In the first example shown, the measurement revealed a source of length 2.8 mm and diameter 0.6 mm (FWHM). The resulting collection efficiency is 15.2% for a 45-deg collection angle.

In the second example, also shown in Fig. 34.11, a small source can also be realized with length 1.8 mm and width 0.2 mm (FWHM), resulting in a collection efficiency of 23.5%, which is already rather close to the limit of 29.3% imposed by the assumed collection angle of 45 deg.

A final example of a pinch discharge in tin is given in Fig. 34.11. Here, an extremely small discharge with a length of 0.8 mm (FWHM) leads to a collection efficiency of 27.3%, nearly reaching the limit of 29.3%.

34.4.6 Variation of source size

Using the source model described above, the effect of pinch size was studied by calculating the effect of a variation of both length and width of the source distribution. For simplicity, the tail of the distribution was omitted here. The elliptical source volume dimensions used before (1.6×1.3 mm) were used for all calculations.

As can be seen in Fig. 34.12, the collection efficiency increases with decreasing source length up to the maximum theoretical limit defined by the collection-angle range of 45 deg. The source diameter has a smaller influence. Obviously, a decrease in pinch size can result in a significant improvement of the collection efficiency.

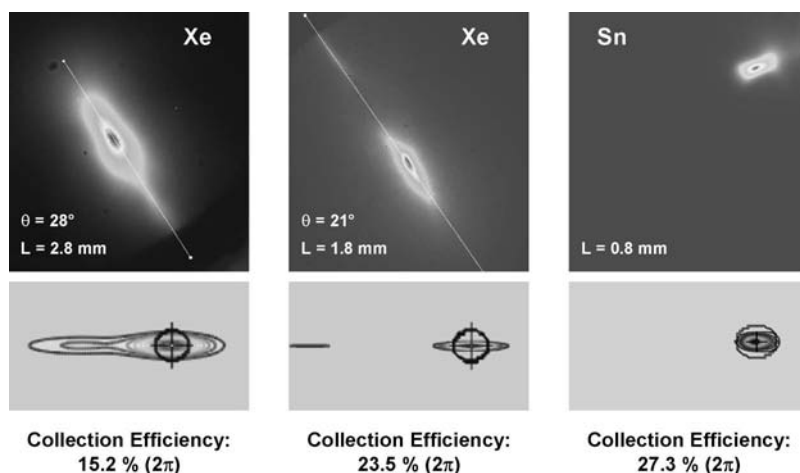


Figure 34.11 Other examples: pinhole-camera images and corresponding source distributions.

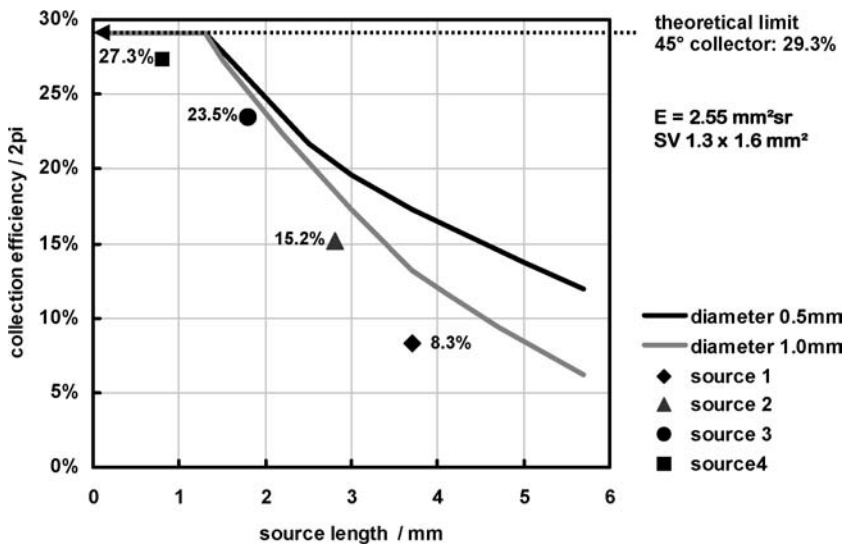


Figure 34.12 Effect of change of the source size on the collection efficiency (source distributions without tail are assumed) and calculated example source distributions.

The example source distributions presented before fit well into the overall picture. Generally, the measurements show somewhat lower values than expected from an ideal source distribution. For example, for source 1 (diameter 1 mm), the collection efficiency is $\approx 30\%$ lower than expected from the corresponding gray line. Source distribution 3 closely approaches the limit, however.

Based on a source distribution of 0.5-mm diameter, the effect of increasing the system collection angle and etendue has been calculated. As shown in Fig. 34.13, the increase of the collection angle to 55 deg and of the system etendue to 7 mm^2 can increase the collection efficiency substantially. For example, at a source length of 3 mm, the collected flux can nearly double.

The results of the simplified collection model using the specified source volume to account for the system etendue limits has been cross-checked with full ray-tracing calculations. A good match between the results of the new procedure presented here and the rigorous ray-tracing calculation was found; the deviations were below 10%.

34.5 Conclusions

The collection efficiency of an extended source in an optical system can be analyzed with the etendue formalism. Under the assumption of an ellipsoidal source intensity distribution, an analytical expression for the source etendue is derived. This can be used to analyze the collection efficiency for various source geometries as a function of collection angle. Given a lithographic imaging system with NA 0.25 and coherence parameter 0.5, the etendue limit is 2.55 mm^2 . For a source of

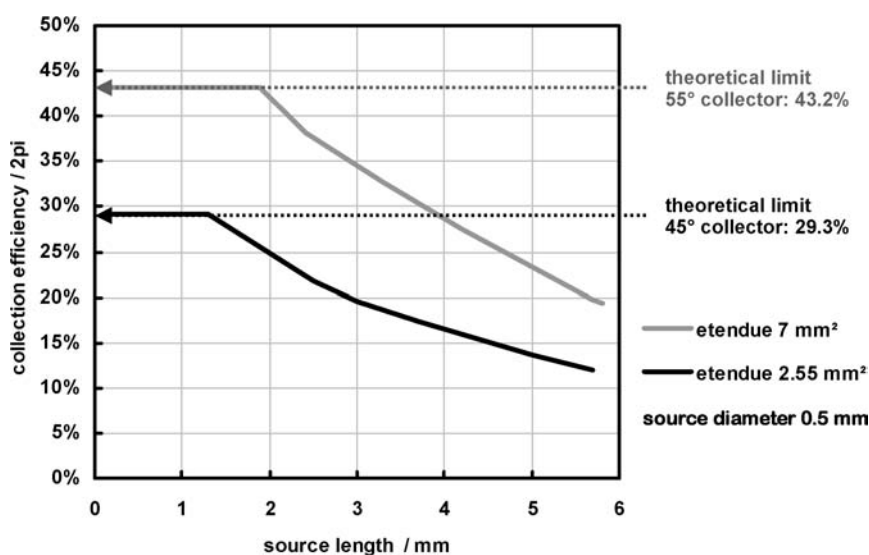


Figure 34.13 Effect of change of the source size on the collection efficiency for system etendues of 2.55 and 7 mm².

1.6-mm length and 1.3-mm diameter, a maximum collection angle of 45 deg is possible under these conditions.

From the rigorous ray-tracing models, however, it is also possible to derive an allowed source volume of ellipsoidal shape, defining a region in space from which rays from the source can be collected through the optical system, taking into account all etendue limitations. Based on this, a simple and fast, but still reliable method for evaluation of collection efficiency has been developed. The new method is based on taking pinhole images of the source plasma with a CCD camera, preferably under various observation angles. From these intensity maps, a three-dimensional model source intensity distribution can be estimated. The estimate of the source intensity distribution is used as input to a subsequent simple projection algorithm to calculate projected images. By comparison with the measured pinhole images, the source intensity distribution model is refined iteratively.

Using this source intensity distribution with the projection model, angular radiation characteristics of the source can be calculated. Integration yields also the total radiation power within a certain collection angle. Finally, the etendue limits of the optical system are included by performing the same projection calculations, but taking into account only radiation from the allowed source volume determined beforehand. This yields the actual collected power within the etendue limits and the collection efficiency.

Comparison with detailed ray-tracing model calculations of the complete optical system indicate the good accuracy of the method. It can be used in a simple way for source optimization and enables reliable evaluation and specification of source performance in EUV projection systems.

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Chapter 35

Electrode and Condenser Materials for Plasma Pinch Sources

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35.1 Introduction

This chapter presents a summary of plasma-surface interactions in electrode and condenser-optic materials in plasma pinch sources for EUV light generation, with special emphasis on DPPs. In DPP EUV devices, electrodes at the source are exposed to short (10–20-ns) high-intensity plasmas, leading to a variety of erosion mechanisms. Erosion of the electrodes is dictated by the dynamics of the plasma pinch for configurations such as the dense plasma focus (DPF), Z pinch, and capillary. The transient discharge deposits 1–2 J/cm² per pulse on electrode surfaces. Large heat flux is deposited at corners and edges, leading to enhanced erosion. Understanding of how particular materials respond to these conditions is part of the rigorous design of DPP electrode systems. Erosion mechanisms can include physical sputtering, current-induced macroscopic erosion, melt formation, and droplet and particulate ejection. Erosion at the surface is also governed by the dynamics of how a plasma can generate a vapor cloud, leading to a self-shielding effect, which results in ultimate protection of the surface bombarded. Determining which will dominate—either microscopic erosion mechanisms such as physical sputtering, or macroscopic mechanisms such as melt formation and droplet ejection—remains an open question in DPP electrode design. This is because such mechanisms are inherently dependent on the pinch dynamics and operation of the source.

In addition to plasma-surface interactions in electrodes, for condenser optics, especially collector optics, erosion is due to fast ions and neutrals born in the plasma pinch, leading mainly to physical sputtering and other bombardment-induced mechanisms. If the surface is composed of more than one species, which is mostly the case, then radiation-induced and thermally activated effects govern the behavior of the surface and govern lifetime levels of the exposed material. Exposure includes debris from electrodes, high-energy ions and neutrals, highly charged ions (HCIs), background impurities, photon radiation [13.5-nm and out-of-band (OOB)], and redeposited eroded mirror material. Figure 35.1 presents an overview of DPP plasma-surface interaction modeling that can be complemented by materials testing. It shows the transient plasma region (region 1) to the left and the quiescent expanding plasma region (region 3) to the right where the collector optics is located. Region 2 comprises a number of debris mitigation schemes that can also be modeled and experimentally tested. A number of modeling simulators can couple regions 1–3 in a self-consistent manner. This can be useful in designing mirrors that are compatible with the debris mitigation schemes selected as well as the EUV fuel used at the source. This is especially important if alternative EUV radiator fuels are selected, such as Sn or Li. Designs at the source with alternative radiator fuels can be studied and their effect on mirrors assessed.

The goal of this chapter is to provide an overview of current modeling and testing utilized to evaluate and test candidate materials for electrode and condenser-optics applications in EUV plasma-pinch DPP sources. A summary of electrode thermal response is followed by a section on materials selection for DPP electrodes and insulators. Then a section on materials testing in a high-intensity plasma pinch

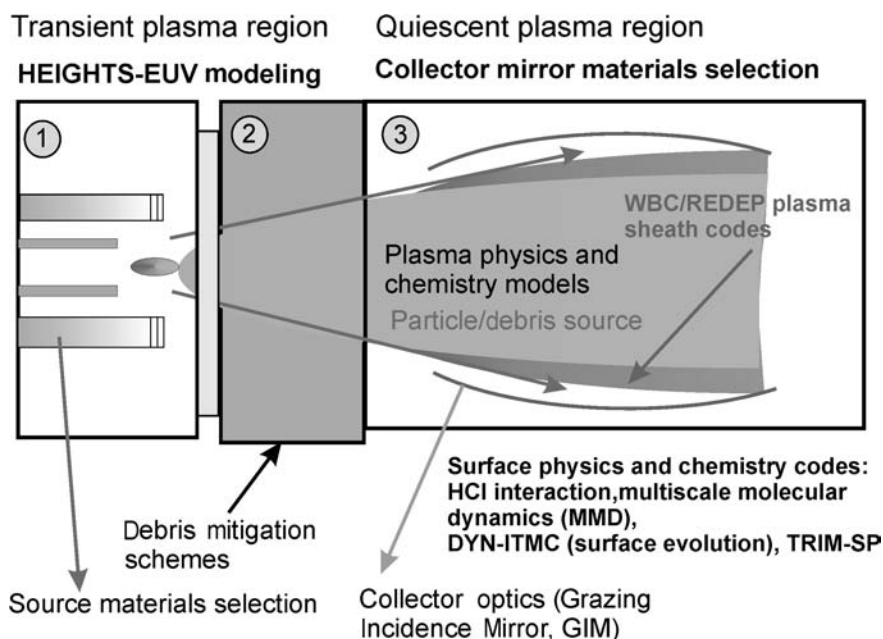


Figure 35.1 Modeling of plasma-surface interactions in DPP configuration.

device is presented, describing the testing of copper and tungsten materials. That section is followed by a section on materials selected as electrodes and tested in a DPP EUV device. The chapter ends with summaries on condenser-optics modeling and testing.

35.2 Electrode Thermal Response

The rapid heating of the electrodes due to radiation and ion energy deposition may lead to melting and subsequently to surface evaporation. The HEIGHTS-EUV modeling package includes comprehensive models to describe the behavior of conductive flow in the magnetic field due to current displacement triggered by the discharge. In modeling functioning DPP devices, such as the Z pinch and DPP, the organization of the correct energy exchange is important for proper simulation. The energy exchange is determined by a set of energy transport processes, including magnetic diffusion, thermal conduction, and radiation energy loss. The result of the magnetohydrodynamics (MHD), radiation transport, and thermal conduction core HEIGHTS-EUV package is the hydrodynamic, radiative, and magnetic state of the source environment at each time step of the discharge, which gives a full description of the energy loads on the electrodes. Details of these calculations and results of numerical experiments can be found elsewhere.^{1,2}

The major mechanisms of electrode heating include radiation absorption (the energy that reaches the electrode surface due to photon transport), plasma particle bombardment (the energy of moving plasma ions and electrons), and electric

current dissipation in the skin layer, which results in heating of the wires due to current flow. As a result, the electrodes are exposed to photon radiation and particle fluxes with a wide range of energies. Soft x-rays deposit their energy within a micron of the surface, very rapidly heating a thin layer on the electrodes. Electric current dissipation may additionally input heat on the skin layer near the surface. Harder energy spectra penetrate longer distances into the material, therefore heating a larger mass to a lower temperature. Additionally, due to the heating, the loads may cause various kinds of secondary damage due to other erosion mechanisms, such as change of phase (melting, evaporation, sublimation), debris-surface interactions due to physical/chemical sputtering or radiation-enhanced sublimation, ablation due to macroscopic metal droplets from splashing, hydrodynamic instabilities, and other erosion mechanisms, which will lead to severe erosion of the electrodes.

The primary interactions of photons with materials include the photoelectric effect, coherent and incoherent scattering, and pair production. Cross sections for each of these reactions have been tabulated in various forms and are available for numerical calculation. The wall thermal response to photon deposition can be determined if the photon spectrum is specified.³

HEIGHTS-EUV is a computer simulation package designed to model the hydrodynamic and optical processes that occur in DPP devices. The developed model will eventually address three main subjects: plasma evolution and MHD processes, detailed photon radiation transport, and interaction between plasma/radiation and material. The total variation diminishing (TVD) scheme in the Lax-Friedrich formulation for the description of magnetic compression and diffusion in a cylindrical multidimensional geometry is the most suitable and is used in our model. Depending on the complexity of the problem and the availability of computer time, a combination of various atomic and plasma models is being developed and implemented in the package for calculating populations of atomic levels, ion concentrations, plasma properties, and opacity, such as a collisional radiation equilibrium (CRE) plasma model, a Hartree-Fock (HF) self-consistent-field atomic model, and a Hartree-Fock-Slater (HFS) method with splitting of atomic levels. Due to its importance and its influence on the whole dynamics of the discharge, radiation transport for both continuum and lines, with detailed spectral profiles, is calculated using two alternative approaches, viz., discrete-ordinate and Monte Carlo methods. The features of the package allow the study of the hydrodynamics and radiation of two-gas mixtures in DPP devices in the presence of impurities and erosion products that can affect radiation output. If not otherwise stated, all results below correspond to the modeling of a Xe-based EUV source.

The output of the HEIGHTS-EUV package includes the hydrodynamic state of the modeled device, its radiation both over a wide range of energies and in the specified EUV range, and magnetic field and current profiles at each time step of the simulation. These data are used later in evaluating the radiation flux, heat flux, and electron and ion fluxes, i.e., the mechanisms that contribute to the electrodes' thermal response.

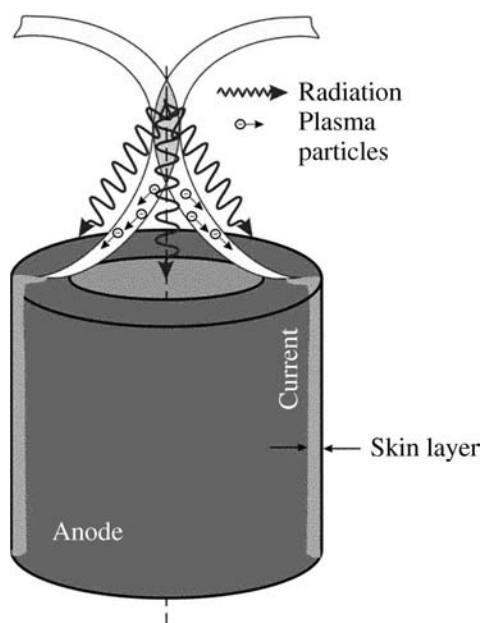


Figure 35.2 Mechanisms of electrode heating induced by a hot, dense plasma.

Various mechanisms contribute to the electrode heating in DPP devices, as mentioned above. Some of them are schematically shown in Fig. 35.2. There is one more source of energy coming from the plasma to the electrode, which is heat conduction. Additionally, the DPP device works repetitively at some frequency (repetition rate), which defines the duration of cooling of the source between two discharges. An increase of the repetition rate linearly increases the energy load on the electrodes, which leads to a higher temperature on the electrode and more damage.

Consider a typical DPF device. Figure 35.3 presents results of numerical simulation of the radiation load on the anode at chosen time steps (top), and at chosen representative anode points (bottom). As one may expect, the highest energy load corresponds to the time of maximal radiation output of the source (which is near the moment of the pinch) at the point closest to the pinch. In one simulation, the internal wall of the electrode near the top is found to receive its highest load between 500 and 700 ns of the discharge. The top of the electrode is also found to be exposed to a high radiation load, but due to the longer distance and sharp angle, the load is slightly less. Other places are relatively safe from radiation damage.

35.2.1 Thermal response

HEIGHTS-EUV includes comprehensive models for calculating the electrode thermal hydraulic response by solving the thermal conduction equation, which takes account for the energy coming from the radiation flux, the electron flux, and the

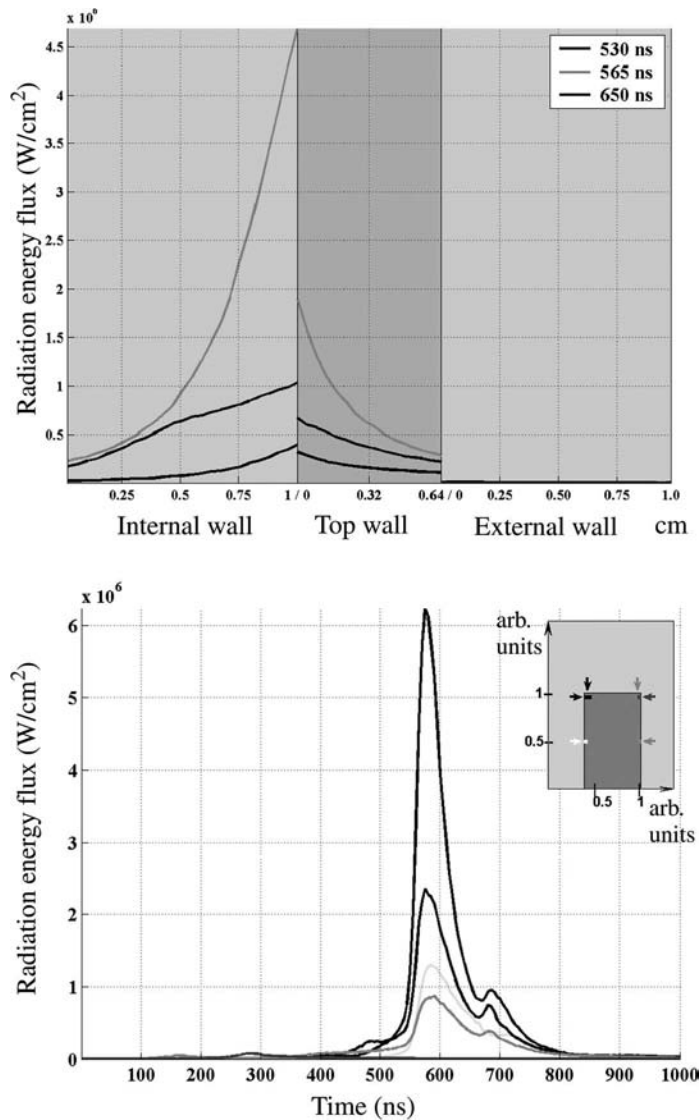


Figure 35.3 HEIGHTS simulation of spatial distribution of various energy loads.

current flowing through the skin layer of the electrode:

$$\frac{\partial \varepsilon}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} \left(r \chi \frac{\partial T}{\partial r} \right) - \frac{\partial}{\partial z} \left(\chi \frac{\partial T}{\partial z} \right) = \Omega, \quad (35.1)$$

$$\Omega = \Omega_{\text{rad}} + \Omega_{\text{p}} + \Omega_{\text{cur}},$$

where ε is the internal energy density, χ is the thermal conductivity coefficient, T is the temperature, and Ω is the source of the heat, which includes Ω_{rad} (radiation heating), Ω_{p} (plasma particle heating), and Ω_{cur} (heating from the electric current

in the skin layer of the electrode). This simple model may be extended to include the effect of variable thermal properties and the coolant heat transfer coefficient, so as to reliably compare different electrode materials for a specific source geometry such as Cymer's DPF or Philips Extreme's hollow-cathode triggered (HCT) pinch plasma source.

An additional parameter of our simulation is the repetition rate, which determines the frequency of pinching and the time when the plasma source needs to be restored into its initial condition.

Figure 35.4 presents results of HEIGHTS-EUV calculations of the temperature of a tungsten anode for typical discharges with 1- and 5-kHz repetition rates. We assume that the ground surface of the electrode is constantly cooled to room temperature. At the 1-kHz rate the electrode is heated but not destroyed; at 5 kHz, however, its surface is evaporated and the anode is partly destroyed. Unfortunately, the problem of optimizing a particular EUV source is a very complex one with multiparameter tasks, which include not only increasing the output EUV by creating a brighter, more powerful EUV pinch by changing the initial design of the source and the temperature and/or pressure in the source chamber, but also improving the collection efficiency of the source by generating a smaller pinch, and increasing the lifetime of the source components, especially the electrodes.

Figure 35.5 displays a combination of various simulations, including the calculation of the scaling laws by changing initial parameters of the EUV source (shown on the abscissa scales), the EUV output of the device (shown by the contours labeled with the relative values of the collectible EUV output), and the highest temperature of the tungsten-made electrode at a given repetition rate (given by the gray scale in kelvins). Figure 35.5(a) corresponds to simulating a DPF device with fixed input energy into the discharge and fixed initial parameters of a Xe plasma. As shown, increasing the width of the anode would decrease the anode temperature, but as seen from the contours that present the corresponding collectible EUV, the optimal EUV output appears at intermediate values of the width. By carefully choosing the initial parameters of the discharge, it is possible to increase the output of the source and at the same time keep the temperature of the electrodes low enough. The circle and the triangle in Fig. 35.5(a) show the experimentally measured values reported by EUV source suppliers. A similar situation to the DPF appears in modeling a HCT pinch plasma source, shown in Fig. 35.5(b). In this case, the input energy load can be selected so that the output is optimized at lower energy input, where the electrode temperature is not high. Another limiting case is shown analytically for a tungsten electrode in Fig. 35.6. Here a 5-kHz repetition rate with a power density of 5 kW/cm^2 is shown. The figure shows the time dependence of the temperature on a tungsten surface. Note that during the pulse ($\approx 20 \text{ ns}$, oscillations too close to see in the figure) the temperature can increase to levels above melting.

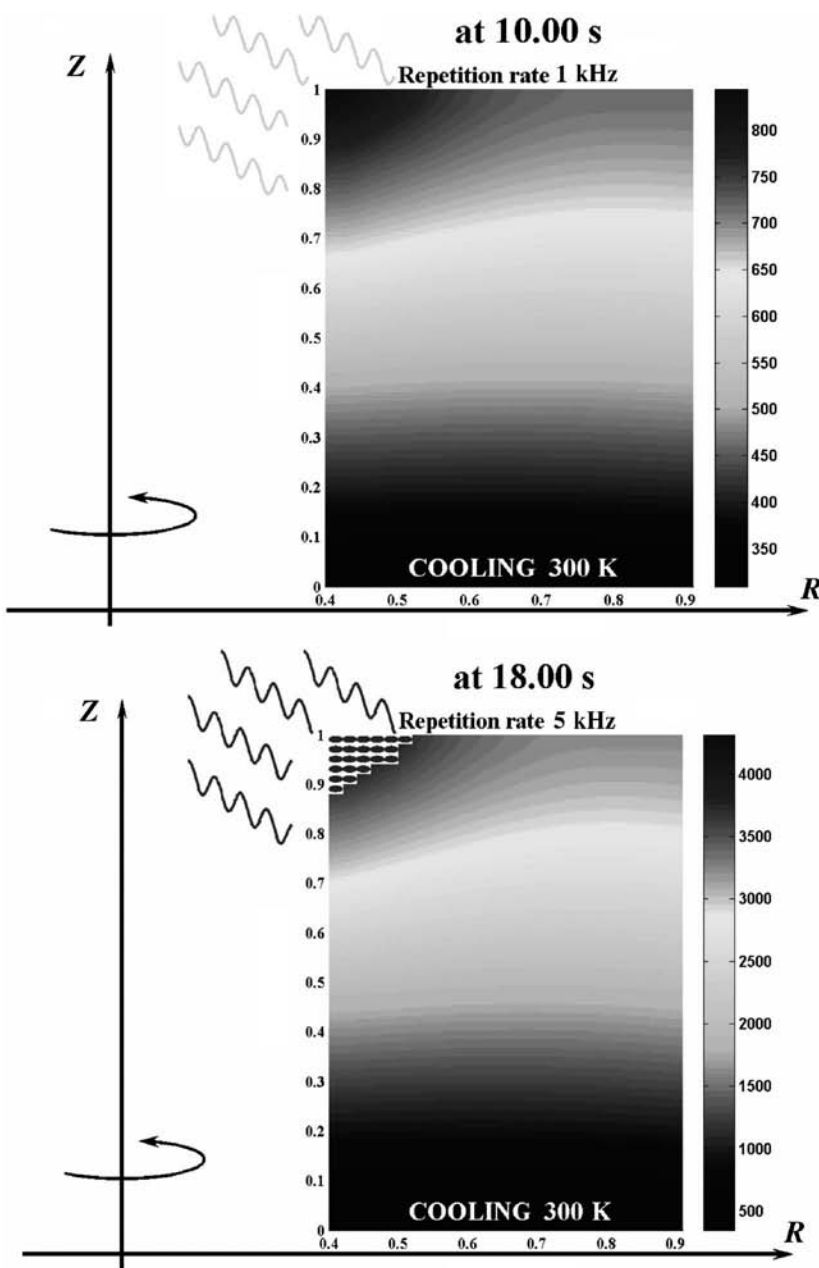


Figure 35.4 HEIGHTS-EUV simulation of the electrode thermal response.

35.2.2 Erosion mechanisms

The erosion mechanisms of debris-surface interaction include physical sputtering, chemical sputtering, and radiation-enhanced sublimation (RES). High-Z materials, such as tungsten, show low sputtering yield at low ion energies and therefore

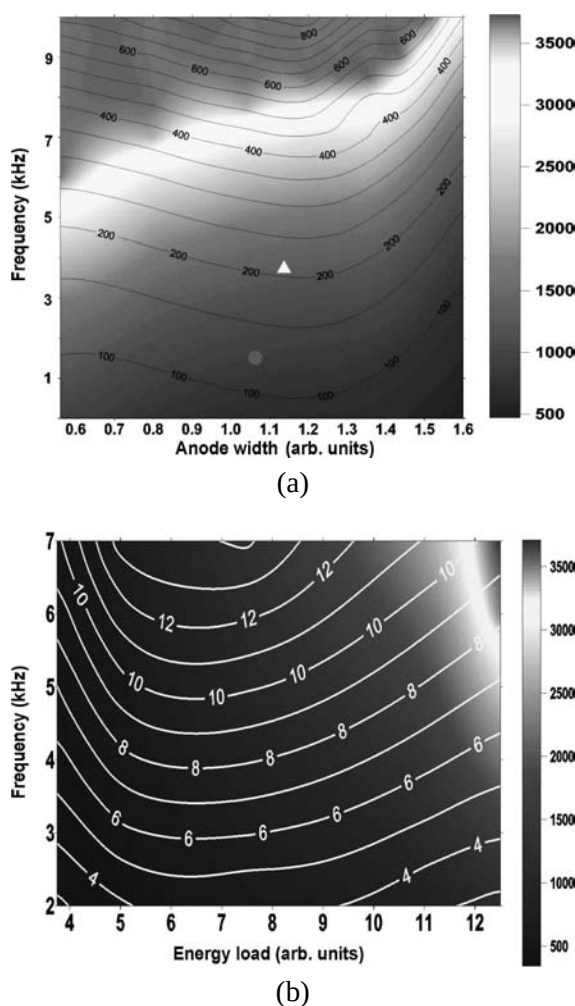


Figure 35.5 (a) Electrode surface temperature in a DPF, and (b) in a HCT pinch plasma source.

may be the preferred choice. The relatively high incident particle energies in the discharge condition will likely cause lower sputtering yields. However, if a working gas is employed without sufficient density to stop these energetic ions, it may result in higher sputtering erosion.

Chemical erosion of carbon-based materials (CBMs) strongly depends on the electrode surface temperature and reaches its maximum around 800 K. For graphite, besides erosion by chemical sputtering, RES yields were calculated for ion bombardment at target temperatures above 1200 K. Chemical sputtering and RES remain major erosion mechanisms, compared to the erosion by physical sputtering. Although the tungsten wall lacks both chemical sputtering and RES, its physical-sputtering erosion is still significant and can play a very important role in the total erosion yield.³

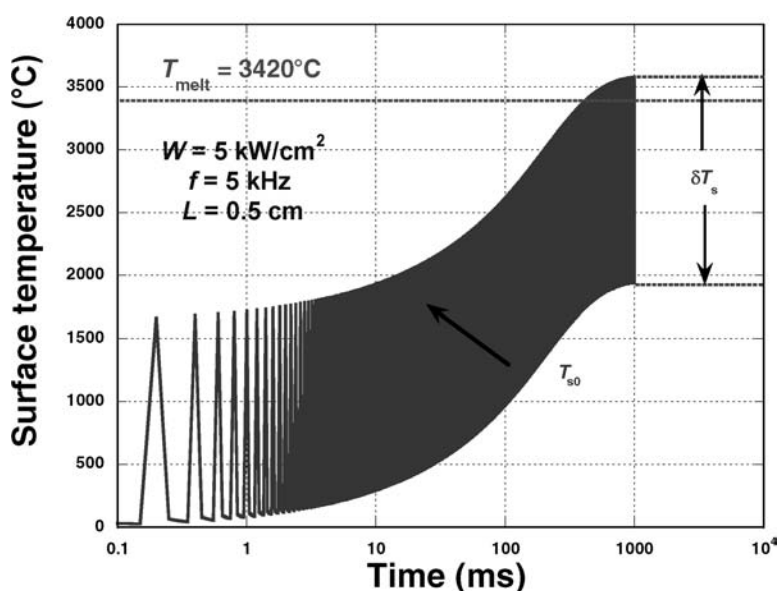


Figure 35.6 Time dependence of an electrode tungsten surface irradiated by a pulsed pinch plasma.

The surface vaporization losses of various materials can be lowered by different protection methods. However, ablation due to macroscopic metal droplets from splashing and to hydrodynamic instabilities is a concern.⁷ The ejected macroscopic particles will form an aerosol cloud near the target surface. An alternative to gas protection is the use of thick liquid walls or jets, but fragmentation models have shown that the strong shock waves initiated in the thick liquid wall as a result of neutron-deposited energy will lead to severe damage to the wall. The produced fragments with very high velocity will seriously aggravate the chamber clearing required prior to next target injection, as well as shortening the wall lifetime.

35.2.3 Conclusions on electrode thermal response

Models have been developed and implemented in the comprehensive HEIGHTS-EUV package to study the dynamic behavior of DPP devices. The hydrodynamic response of the electrodes, photon radiation transport, plasma particle bombardment, and dissipation of the current heat are calculated in detail as a function of the deposited energy.

Several erosion-causing mechanisms are modeled and evaluated for assessing electrode lifetime, such as vaporization, chemical and physical sputtering, RES, melt-liquid splashing, and macroscopic erosion. Depending on the discharge energy yield and EUV-source gas pressure, most of these erosion mechanisms could be important factors in determining the best choice of material and the overall lifetime of the electrodes in DPP devices. No obvious choice of chamber protection mechanism is identified. More detailed analysis is needed to determine if a

DPP source of EUV energy will be economically feasible and meet both the Intel Lithography Roadmap goals for high-volume manufacturing (HVM) in the future. One challenge to DPP source devices, as discussed, is the lifetime of electrodes and other plasma-facing components. The next section will discuss the selection of materials for such application.

35.3 Materials Selection for Plasma Pinch Sources

Materials selection and lifetime issues for EUVL are of critical importance to the success of this technology for commercial applications. This section reviews current trends in production and use of plasma-facing electrodes, insulators, and wall materials for EUV sources. Ideal candidate materials should be able to withstand high thermal shock from the short-pulsed plasma, withstand high thermal loads without structural failure, reduce debris generation during discharge, and be machined accurately. We reviewed the literature on current and proposed fusion plasma-facing materials as well as current experience with plasma guns and other simulation devices. Both fusion and EUV source materials presented problems of surface erosion by particle sputtering and heat-induced evaporation/melting. These materials are either bare structural materials or surface coatings.

EUV materials can be divided into four categories: wall, electrode, optical, and insulator materials. For electric discharge sources, all four types are required, whereas LPP EUV sources do not require electrode and insulator materials. Several types of candidate alloy and other materials and methods of manufacture are recommended for each component of EUVL light sources.

The DPP (e.g., Cymer Inc., San Diego), the Z pinch (e.g., XTREME technologies GmbH), the LPP (e.g., Sandia National Laboratory, Livermore), the capillary discharge (e.g., EUVA, Sandia National Laboratory), and the HCT (e.g., Philips Extreme) are techniques being developed as light sources for EUVL. Materials selection and lifetime issues are of critical importance to the success of these techniques for commercial applications. The ideal candidate materials should be able to withstand high thermal shock from the short-pulsed plasma; be resistant to ion bombardment, including that by HCIs; withstand high thermal loads without structural failure (requiring a high melting point, high thermal conductivity, thermal shock resistance, etc.); minimize debris generation during discharge; and be able to be machined accurately to the required geometry. The focus of this section is on thermal and related issues; plasma particle erosion issues are being studied in detail and will be reported on in the future.

Good sources of information about candidate plasma-facing materials for EUV source components are the national and international fusion programs. General issues for both fusion and EUV applications are thermomechanical, electrical, and vacuum properties. Both fusion and EUV source materials involve surface erosion by particle sputtering and heat-induced evaporation/melting. (Fusion additionally involves neutron damage, which is of course not present in EUV applications, thus

permitting more materials options.) In the context of the International Thermonuclear Experimental Reactor (ITER), the development of new plasma-facing materials has generated a unique base of experimental data on material response to powerful heat and plasma fluxes.

Numerous scientific studies for the high-tension spark-gap and heavy-current electrode technologies also provide essential data for review and analysis to select the best candidate plasma-facing components materials for EUV sources based on current laboratory devices.

The study of damage, structural changes, and property alterations of the materials exposed to intense ion and thermal pulses is very important for developing candidate plasma-facing materials for EUV sources and predicting the materials' behavior in different modes of source exploitation.^{8,9}

The problem of modeling the effect of powerful plasma pulses is particularly interesting. As with fusion, evaluations of candidate materials are greatly aided by simulation facilities for plasma-material interaction. Facilities operating with intensive plasma beams,^{10–14} electron accelerators,^{15–18} and laser beams^{19,20} generally present the possibility of implementing such a model experimentally.

35.3.1 Selection of electrode candidate materials

The choice of an electrode material (both anode and cathode) for powerful plasma sources must take into account diverse and sometimes conflicting requirements. For the usual metals, required physical properties are refractoriness and high hardness in combination with high thermal and electrical conductivity, high resistance to ionic and thermal erosion, absence of discharge-induced welding, and exceptional material transfer properties.

Except for the material structure, the electrophysical and high-temperature strength and vacuum properties are all influenced by the size of the material grains, the texture, and the presence of impurities. The reproducibility of properties of the manufactured electrode products is important to consider when choosing the material. This condition must be satisfied for materials with high erosion resistance and durability under various modes of working loads, in diverse gas environments, and at different operating temperatures.

The use of traditional metallurgical technologies may not allow achieving the diverse and complicated set of characteristics necessary for the material of an electrode in one homogeneous material. For this reason, most modern electrode materials are composites. The so-called *pseudo-alloys* are manufactured from components that do not dissolve each other either in solid or in liquid phases, such as W-Cu, Mo-Cu, Mo-Ag, Ag-C, Ag-Ni, and Ag-CdO. These materials have a heterogeneous structure consisting of a matrix with implanted dispersed phases joined to the matrix by a strong adhesive connection, but do not react to form solid solutions or chemical compounds.

The same effect may also be achieved by reinforcing spatial grids of fibers and crystals or materials with threadlike crystals implanted into the matrix. Both in the

matrix and in the dispersive phase, the materials may be either metallic or non-metallic. The additive combination of the required properties in cathode materials is obtained from the corresponding phase constituents.

Extended operation of the electrodes in powerful plasma sources leads to irreversible changes of both working surfaces and bulk properties. The type of changes, as well as the area and the depth of affected material, is determined by the magnitude and type of energy deposited in the volume or at the working surface. In turn, the amount of energy deposited depends upon the value, density, and transit time of the electric current, as well as the specific and intermediate resistance of the electrode material. The heat generated can result in recrystallization and weakening of the material, and, depending upon design, its plastic deformation. When an electric arc is initiated, the temperature of the electrodes and vicinity may be increased by thousands of degrees. This can melt and vaporize the electrode material around the contact surface. In the course of electrode use, the factors mentioned above can lead to the appearance of craters, cracks, and debris as a result of thermal and fatigue stresses.

For the development and manufacture of materials in the energy-intensive region of the cathode and anode, electrodes are generally made of pseudo-alloy. One component of the alloy is a refractory, solid, heat-resistant, arc-suppressing material forming a spatial skeleton matrix. The second component is a fusible, electrically and thermally conductive filler uniformly permeating all pores and discontinuities. To ensure reliability, the pseudo-alloy material must maintain its integrity, requiring low porosity and high strength of the interphase adhesive bond. The recourse in manufacture is to add dopants to decrease the contact angle of wetting and to increase the capillary pressure and the strength of the adhesive bond. Fine dispersible inert fills limit sintering of the surface layers of the porous refractory framework and improve infiltration of ingrained melt and its uniform spread by porous channels in the bulk. For the refractory components, the following materials are usually used: metals such as W, Mo, Pd, Ni, Ta, and Cr; some nonmetals such as C and B; oxides such as CdO, WO₅, MoO₃, Ta₂O₅, and CuO; carbides such as WC and Mg₂C; and borides, silicides, and nitrides. The refractory components of the composite electrode materials are selected so that they have arc-suppressing properties.

The occurrence of small electric arcs in the course of operating the plasma source with these materials results in the formation of tiny amounts of molten metal in the regions of fusible microphases. Generally, the composite material keeps its integrity, and the probability of forming macro-melt areas at the surface is significantly reduced.

Copper, silver, and their alloys are usually used as fusible components. Refractory components are used not only as a pseudo-alloy framework but also as dopants in the fusible component, providing high-temperature strengthening by means of solidification or hardening of the dispersibles. Titanium and zirconium are dispersible strengthening dopants for copper. The intermetallic compounds Cu₃Zr and Cu₄Ti result from their reaction with the copper. Different oxides and refractory

materials used as dispersible strengthening dopants play an essential role in increasing electrode endurance and erosion resistance. These heat-absorbing materials provide arc suppression through thermal dissociation. The main heat-absorbing component in a pseudo-alloy is the fusible phase, ablating under melting and vaporization. It is partly held in a liquid state in pores and channels of the refractory framework by means of capillary pressure.

Other important electrode materials are pyrolytic graphite and carbon-fiber composites (CFCs). These materials do not melt and have high resistance to erosion from vaporization. In addition, CFCs can be manufactured with very high thermal conductivity. These materials are not recommended for fusion applications because they are susceptible to neutron damage, but that does not exist in the EUV environment. Chemical erosion and RES may be of some concern, however. Endothermic phase changes and phase transformations, as well as additives to the electrode material with low ionization potential, provide active heat removal from the contact points of the arc to the electrode surface. Adding impurities with low work functions allows us to control the formation and movement of cathode spots at the surface of the electrode.

The technologies of powder metallurgy allow us to develop and implement electrodes with a complex design that can consist of several parts (main part, inserts with greater ionic- and thermal-erosion resistance, arc-suppressing inserts, etc.) having different functions.²¹ A supplemental benefit of adding impurities is increased durability as a result of dispersive solidification. The same outcome may also be achieved by forming a pseudo-alloy that adds a strengthening component. However, the requirement that the material maintain a sufficiently high plasticity, allowing as high as 20%–90% compression, restricts the amount of such impurities. The fine structure of the material influences the durability and reliability of the electrode in many respects. Despite having higher-dispersion structure, the electrode materials exhibit lower plasticity, but they show essential advantages in erosion resistance in contrast with coarse-grained electrodes.

The advantages of tungsten electrodes become particularly apparent if a dispersible and fibrous structure is applied, ensuring the production of fibers normal to the working surface of an electrode. Such electrodes are not only more durable and erosion-resistant, but also firmer and easily manufactured.

From the facts mentioned above, one may conclude that to manufacture the electrodes of EUV sources, the candidate materials near the energy-intensive parts should likely be a frame-structured pseudo-alloy based on tungsten, molybdenum, or tungsten carbide with silver or copper. These pseudo-alloys were developed by various American and other companies.^{22–26}

The refractory component in a pseudo-alloy can be up to 70–80 wt%. To improve the heat removal from the most energy-intensive surfaces of the electrode, the main component can be made of copper, while the working surfaces can be made from arc-resistant pseudo-alloy film of the required depth. Such a combined electrode is expected to survive longer than traditionally manufactured electrodes. At the same time, the new-design electrode should have higher resistance to the

erosion caused by both ion sputtering from the gas environment and the impact of the electric arc.

The electrode material should not, however, contain any adsorbed or dissolved gases. For this purpose, it is desired to employ iron-copper-, tungsten-copper-, or molybdenum-copper-based materials with volatile metallic dopants. These metals could also be fused to the areas of working surfaces that are in the most energy-intensive working parts. The saturation of liquid copper in a pre-sintered refractory skeleton is an attractive process for manufacturing this grade of electrode. Electrode inserts made of tungsten, molybdenum, or tungsten carbide pseudo-alloys, which provide the welding or brazing of the electrode to the main frame, can be supported by a copper or silver sublayer.

35.3.2 Selection of high-temperature insulator ceramics for EUV sources

The choice of an insulator material for plasma-facing components of EUV sources is determined by the physicochemical and electrophysical properties of the material, its vacuum-sorption properties, the operating temperature of the EUV source, and the operating parameters of the plasma-forming gas. Currently, most insulators are made of high-temperature ceramics based on the sufficiently studied oxides and carbides or on the less-studied nitrides.

The thermophysical and electrophysical properties of oxides are widely presented in the literature. In contrast, little is known about the electrophysical properties of nitrides, even at low voltages. The reason is that powdered boron nitride and aluminum nitride isolators are not manufactured by large commercial or industrial organizations. Therefore, their properties are substantially determined by the powder impurities and the technology of powder generation and sintering. Thus, precise measurements are especially needed for the high-voltage electrophysical characteristics of anisotropic polycrystalline materials—for example, pyrolytic boron nitride.

Among a number of candidate high-temperature dielectrics, the best insulator properties are believed to be those of corundum (α - Al_2O_3), zirconium dioxide (ZrO_2), beryllium oxide (BeO), and nitrides of aluminum (AlN) and boron (BN); Al_2O_3 , BeO , BN , and AlN are manufactured in the form of powder, and the isolators are made by hot pressing.

The method of gas-phase sedimentation for manufacturing products out of boron nitride was developed in the last few years. The material obtained is called pyrolytic boron nitride (PBN). The advantage of such powder materials is the opportunity of pressing the insulators to the desired size and thickness. The peculiar feature of BN and PBN is the anisotropy of their properties in mutually perpendicular directions, explained by their graphitelike hexagonal crystal structure. Taking into account the complexity of desired physicochemical properties, especially the dependence of thermophysical and mechanical parameters of the materials on temperature, BN and PBN are considered to be the most appropriate dielectric materials capable of effectively working in the high-temperature and plasma-loading

conditions typical of EUV sources. Their high melting point, low evaporation rate, high mechanical resistance to thermal erosion at high temperature, and other properties allow us to successfully use these two materials as insulators for the energy-intensive parts of powerful plasma sources.

PBN possesses a high thermal conductivity in a direction parallel, and a low one in the direction perpendicular to the sedimentation surface. Also, because of its high-temperature conductivity, PBN has excellent thermal resistance, not being prone to cracks or segregation. The best oxide ceramic, BeO, performs worse than PBN. In contrast to the other ceramics, PBN is very stable under thermal shock tests. Under stretching, bending, and compression, the mechanical durability of PBN at low temperatures is lower than that of other ceramics, but at higher temperatures (> 1000 K), it becomes comparable to or even considerably exceeds the others.

For BN and PBN, the approximate density is 2 g/cm^3 (the theoretical density is 2.28 g/cm^3). This density is optimal from the standpoint of both manufacture of the insulators and required material properties. Decreasing the density of PBN to $1.8\text{--}1.7 \text{ g/cm}^3$ would lead to decreasing its mechanical durability by a factor of approximately two; its chemical stability would also go down, and the probability of product segregation would be increased. PBN is easily processed by mechanical methods and possesses good enough vacuum properties. Soldering PBN by the contact-jet method with Ti-based solders forms vacuum-dense joints of titanium and copper.

The following conclusions were reached about candidates for insulator ceramics for EUV sources:

- The material properties of pyrolytic boron nitride allow us to unequivocally recommend it as capable of working in the conditions of high temperature, intense pulsed plasma loading, and arcing.
- Thick-wall insulators or insulators of complicated geometry may also be produced out of hot-pressed boron nitride, beryllium oxide, or aluminum nitride.
- To make a final choice of an insulator material capable of working in a multipulse mode, we need additional experimental measurements of their high-voltage electrophysical properties, as well as their lifetime in conditions similar to the working conditions of EUV sources.

35.3.3 Conclusions on materials selection for plasma pinch sources

35.3.3.1 Electrode materials

Suitable choices are apparent for electrode materials for low-frequency, low-power devices. However, for higher-power and -frequency commercial EUV sources, it is very difficult to decide which material is the best for electrodes. This depends on the specific tasks of the device and on the given experimental conditions. The best design may well depend not only on the choice of material but also on the shape and size of the electrodes. Copper is the most common material in standard

plasma guns as well as in standard plasma focus devices. Here a “standard” device means one that works with a single shot (one shot in a few minutes) and with a moderate discharge current (systems with an electrical energies of 100 kJ to 1 MJ and electrode sizes of tens of centimeters up to 1 m).

In recently manufactured powerful plasma devices with a large current density and dense plasma at a high pressure, erosion of the electrodes was the main observed problem. Several electrode materials were tested that were produced in the former Soviet Union, such as Cu (oxygen-free high-conductivity copper), Cu-Al₂O₃ alloy (containing 1% of micron-size Al₂O₃ particles), Cu/Mo (thin layers of Cu and Mo, produced by implosion), W-Cu sintered alloy (produced using powder technology), Mo, Ti, Ta, and W.

In high-power devices, a Cu electrode suffers the most erosion and damage, while W suffers the least. However, the best plasma properties of the discharge were obtained with Cu electrodes. Recently, composite materials such as W-Cu alloys, though anticipated to have better performance as electrode materials, have been disappointing. Copper is eroded from the electrode surface, and the surface layer becomes porous and flakes away. This is a typical problem for most composite materials. Another possibility is to use electrodes made of sintered copper-tungsten composites at different locations on the electrode.

35.3.3.2 Insulator materials

Properties of insulators are particularly critical for plasma-focus devices. In plasma focuses, various ceramics based on Al₂O₃ are usually used. It is well known among experimentalists that ceramics are good insulators; however, such insulators must be treated with hundreds of preliminary discharges before the device works well. Sometimes a laser is used for treating the insulator surface before operation. As an alternative, BeO and BN can be used to reduce debris formation and improve operating conditions.

Insulator materials in DPF devices should also withstand damage and redeposition caused by the erosion products that are emitted from the electrodes and then travel to the insulator surface. This may not be a common problem for plasma guns and DPF devices if the insulator in these devices is placed in a special protective gap. For a final choice of electrode, wall, and insulator materials, a number of experiments are necessary to determine their resistance to high thermal shocks from shot-pulsed-plasma impingement and intensive ion bombardment, including that of HCIs.

The materials shown in Table 35.1 are proposed to initiate the overall comparative analysis. Note that the properties of materials, especially ion and thermal erosion, will depend importantly not only on their chemical composition, but also on the technology of their manufacture. For example, for a material such as boron nitride or tungsten-copper pseudo-alloy, it is recommended that samples be obtained from several manufacturers. This approach will permit unequivocal evaluation and choice of electrode and insulator materials for EUV-source plasma-facing components.

Table 35.1 The major candidate materials for EUV source plasma-facing components.

Material	EUV-source plasma-facing component
Pseudo-alloy, 75% W, 25% Cu	Electrodes or the inserts for energy-intensive parts
Pseudo-alloy, 80% Mo, 20% Cu	Electrodes or the inserts for energy-intensive parts
Pseudo-alloy 75% W, 20% Cu, 4% Ni, 1% La ₂ O ₃	Electrodes or the inserts for energy-intensive parts
Single-crystal W with 2% Re	Inserts for energy-intensive parts
Copper	Electrode
Sintered tungsten	Electrode
Pyrolytic graphite and carbon-fiber composites (CFCs)	Electrode
Stainless steel	Wall of vacuum chamber
Corundum (α -Al ₂ O ₃)	Insulator
Beryllium oxide (BeO)	Insulator
Pyrolytic boron nitride (PBN)	Insulator
Thin-film Ru, Pd, or W	Condenser optics (grazing-incidence mirror)*

*Mirror materials are discussed in a later section of this chapter.

This section has pointed to candidate materials for plasma-facing DPP electrodes and insulators. The next section will cover testing of candidate materials under dense-plasma-relevant conditions. This is done in *simulated* experiments in high-intensity plasma facilities briefly discussed in this section.

35.4 Testing of Materials in Plasma-Gun Facilities

Small plasma pinch devices operating with frequencies of 5–10 kHz, pulse energies on the order of 1–100 J, and gas mixtures of Xe and He are very promising as sources of EUVL radiation ($\lambda = 13.5$ nm). A serious problem in the design of such EUV sources concerns erosion of the pinch components under the action of electric currents, hot plasma particles, and photon radiation.²⁷ Material erosion limits the lifetime of plasma-facing components, thereby reducing the practical feasibility of DPP EUV sources. Investigation of erosion mechanisms and their dependences on the operational parameters is quite important for successful development of commercial DPP EUV devices.

Experiments described in this section investigate material erosion caused by hot, dense Xe and H plasmas on copper and tungsten sample targets. The experiments were carried out at the plasma-gun facility MK-200, at TRINITI, Russia. A pulsed plasma gun is used as the source of Xe or H plasma. The gun accelerates low-temperature Xe plasma to a high velocity. Then the plasma stream collides with the structural material to be investigated. Due to collision of the supersonic plasma stream with the solid target, a shock front arises in the plasma stream, and a cloud of hot, dense Xe plasma is formed near the target surface. Thus the target surface is exposed to the interaction of energetic particles and photon radiation from the hot Xe plasma, as in DPP EUV devices.

A cloud of Xe plasma is formed at a temperature $T = 30\text{--}50$ eV, similar to those found in EUV plasma pinch devices. This magnitude of temperature is needed for the tenfold ionization of Xe to produce Xe^{+10} ions emitting spectral lines at the wavelength $\lambda = 13.5$ nm. Theoretical analysis shows that the required temperature can be obtained in the shock wave if the plasma stream moves with a velocity of the order of 10^7 cm/s. Therefore, the first task of the experiment was to produce Xe plasma streams with sufficiently high velocity. Besides a high velocity, the plasma stream must have a rather large energy and pulse duration. In this manner, material testing and lifetime assessment could be realized during a short time.

The experiments performed are a first step toward understanding the problem of material damage induced by hot Xe plasma. They were focused mainly on the development of appropriate experimental techniques relevant to conditions in high-heat-flux regions on electrodes in DPP EUV devices. Initial results indicate various mechanisms of material erosion (such as vaporization, sputtering, and melt splashing) and surface modification (bubble and blister growth and cavity formation) that can all exist in regions of high heat flux in DPP EUV device electrodes.^{7,8}

35.4.1 Plasma-gun-device setup

As stated earlier, the experiment was performed at the MK-200 facility, consisting of two plasma gun devices: MK-200UG and MK-200CUSP.²⁸ The basic scheme of MK-200UG is shown in Fig. 35.7. The facility consists of a pulsed plasma gun, a long drift tube, and a target chamber with attached diagnostic tools. The plasma gun is fed from a 1152- μF capacitor bank. As a rule, the gun operating voltage is 20–25 kV. This voltage range corresponds to 230–360 kJ of energy stored in the capacitor bank.

The plasma gun injects a H or Xe plasma stream into the drift tube, consisting of a 6.5-m cylindrical section and a conical section with a length of 3.0 m. The diameter of the cylindrical tube is 30 cm. In the conical section, the tube diameter reduces towards its exit from 30 cm to 15 cm.

The drift tube is filled with a longitudinal magnetic field. The magnetic field induces thermal isolation of the plasma stream from the tube wall. For this reason, the plasma stream is transported over large distances (10 m) with negligible energy loss. The magnetic field is used also to control the plasma stream's properties. In

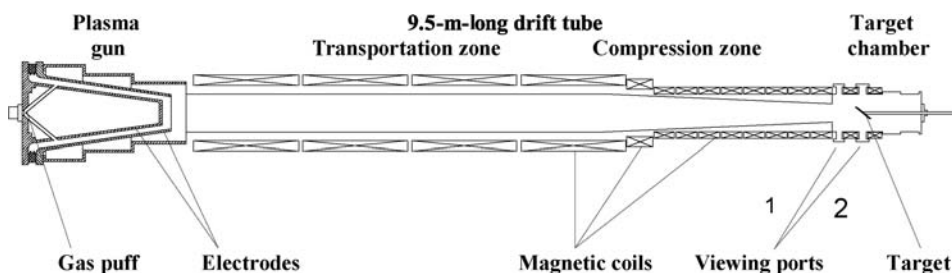


Figure 35.7 Basic scheme of the MK-200UG high-intensity plasma gun.

the conical section, where the magnetic field increases, the plasma stream is compressed radially, leading to an increase in plasma density. It should be noted that plasma-stream parameters in the target chamber depend strongly on the magnetic field profile in the drift tube. By changing the magnetic field profile the plasma stream's properties (density, pulse duration, velocity, and others) might be varied widely. The cylindrical tube is filled with a uniform magnetic field of 0.7 T. In the conical section the magnetic field rises from 0.7 to 2.0 T. Samples to be studied are placed in the target chamber. The diameter of the chamber is 30 cm, and its length 50 cm. The magnetic field is 2.0 T in the target chamber.

Table 35.2 shows parameters of the plasma stream measured in the target chamber. The values are very close to those that are required for testing of materials in Xe plasma. However, the parameters listed in Table 35.2 were obtained for a H plasma stream and not for Xe.

The MK-200CUSP machine is schematically shown in Fig. 35.8. The plasma gun is fed from a 1152-μF capacitor bank. The gun injects the plasma stream into the cylindrical tube ($L = 50$ cm, $D = 30$ cm) with a longitudinal magnetic field of 1 T. Then the plasma stream comes into the conical section ($L = 50$ cm), where the diameter of the tube reduces towards its exit from 30 to 14 cm while the magnetic field strength rises from 1 to 2.6 T. The low-energy tail of the stream cannot traverse the steep magnetic gradient, and it stops in the magnetic cone. The high-energy leading part of the stream passes through the increasing magnetic field, and it is radially compressed.

Table 35.2 Parameters of H plasma stream at MK-200UG.

Total energy	$Q = 30\text{--}50$ kJ
Energy density	$q = 1\text{--}1.5$ kJ/cm ²
Pulse duration	$\tau = 30\text{--}50$ μs
Velocity	$V = (4\text{--}6) \times 10^7$ cm/s
Plasma density	$n = (2\text{--}6) \times 10^{15}$ cm ⁻³
Plasma stream diameter	$D = 5\text{--}7$ cm

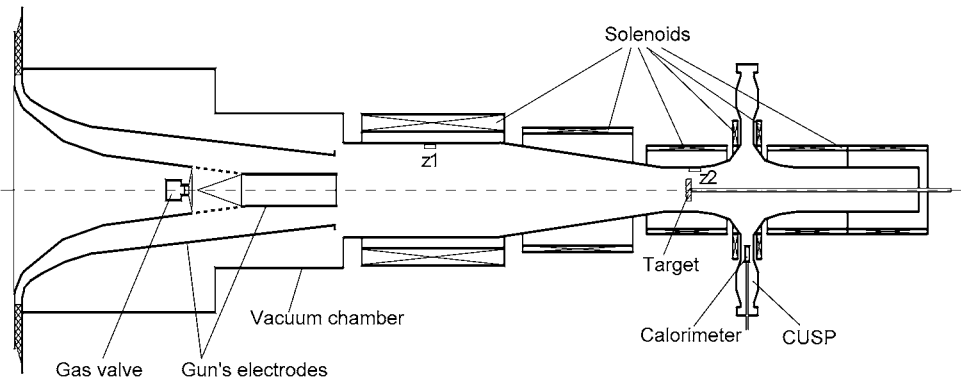


Figure 35.8 Basic scheme of the MK-200CUSP high-intensity plasma gun.

Table 35.3 Parameters of H plasma stream at MK-200CUSP.

Total energy	$Q = 20\text{--}30 \text{ kJ}$
Energy density	$q = 1\text{--}1.5 \text{ kJ/cm}^2$
Pulse duration	$\tau = 7\text{--}15 \text{ }\mu\text{s}$
Velocity	$V = (3\text{--}5) \times 10^7 \text{ cm/s}$
Plasma density	$n > 10^{16} \text{ cm}^{-3}$
Plasma-stream diameter	$D = 5 \text{ cm}$

The scheme of MK-200CUSP is very similar to that of MK-200UG. The main difference is the shorter length ($l = 1.2 \text{ m}$) of the drift tube in the MK-200CUSP. In the short drift tube the plasma-stream density is greater than in a long drift tube. Table 35.3 shows the plasma-stream parameters measured at the target position in MK-200CUSP.

35.4.2 Diagnostics of plasma stream

The first objective of the present experiment was to obtain a Xe plasma stream having a velocity of the order of 10^7 cm/s and total energy 20–50 kJ. Diagnostic tools that are suitable for the measurements of plasma velocity and energy were applied.

The plasma stream energy was measured by using large and small calorimeters. Large calorimeters (trapping the whole plasma stream) were applied for the measurement of the total plasma stream energy, and small calorimeters (1.5–2 cm in diameter) for the measurement of radial distribution in the plasma stream energy. All the calorimeters have a cylindrical form; their lengths are 3–5 times larger than their diameters. The growth of the calorimeter temperature (which is proportional to the absorbed plasma energy) was measured by thermocouples.

The velocity of the plasma stream was measured by a time-of-flight method using magnetic probes, which are distributed along the whole length of the magnetic drift tube at various distances from the gun. The probes are placed in the vicinity of the tube wall; they do not contact the plasma, and thus they do not affect the plasma-stream properties. When the plasma stream moves in the drift tube, the magnetic field increases near the wall because of the diamagnetic effect (the plasma pushes away the magnetic field).

35.4.3 Irradiation of target materials by hot Xe plasma

Tungsten and copper are typically used as structural materials for DPP electrodes. These materials were exposed to Xe plasma streams in the MK-200CUSP. The targets were irradiated by Xe plasma with energy density 100–200 J/cm². Since a hot Xe plasma cloud is formed in front of the exposed target, the target surface is exposed to the interaction of Xe plasma particles and photon radiation.

Besides Xe plasma, the targets were also tested with hydrogen plasma streams having practically the same energy density as Xe plasma streams. The experiment

focused on investigation and comparison of surface damage caused by Xe and H plasmas. This type of experimental data is quite important for understanding whether the numerical models used in HEIGHTS-EUV, for example, which are being developed for simulation of material damage caused by H plasmas, can also be applied and benchmarked for modeling of material damage induced by Xe plasmas with applications to numerical modeling of DPP high-intensity-plasma–material interactions.

35.4.4 Target design

Four targets were tested: two identical tungsten targets and two identical copper targets. The targets were produced in the form of rectangular plates fully overlapping the plasma stream. The plates were manufactured absolutely flat, and their face surfaces were prepolished, which is required for profilometry measurement of the exposed surface after irradiation.

Each target was equipped with a diaphragm having a 3-cm hole [Fig. 35.9(a)]. The diaphragm was placed in front of the target face at a distance of 1–2 mm. A gap between the target surface and the diaphragm was produced by using an intermediate plate as shown in Fig. 35.9(b).

The target was equipped with a diaphragm for the following reasons. The diaphragm reduces the size of the plasma-irradiated area to a diameter of 3 cm. This allows the surface profile to be analyzed using a standard mechanical profilometer. The scanning length of the profilometer is limited to 5 cm. When the target is exposed to the whole plasma stream, the diameter of the eroded area is larger than 5 cm.

The melt, which is splashed from the plasma-irradiated region, falls outside the region protected by the diaphragm from plasma irradiation. Therefore the splashed metal melts again in subsequent plasma shots, and it retains its original properties. This clarifies whether the melt is splashed in the form of droplets and jets or moves as a whole.

35.4.5 Surface and material loss diagnostics

The profile of the exposed target surface was measured by using a mechanical profilometer. Because of deep surface cracks and open surface cavities, the diamond pin that is typically used in the mechanical profilometer could not be applied in the present experiment for analysis of the exposed surface profile. Instead, a small ball was used as the sensing element. The ball sensor is well suited for the measurement of the averaged surface profile, but it is not good for analysis of the surface cracks and small surface cavities. Surface damage and surface microstructure were studied by the use of an optical microscope and a scanning electron microscope (SEM). The mass of the eroded material was measured by weighing the targets before and after the plasma test. The targets were exposed to 15 plasma shots, and then the mass loss ΔM was measured. Afterward, the mass loss per shot, $\Delta m = \Delta M/15$, was evaluated. The thickness of the eroded material, d , was evaluated from the

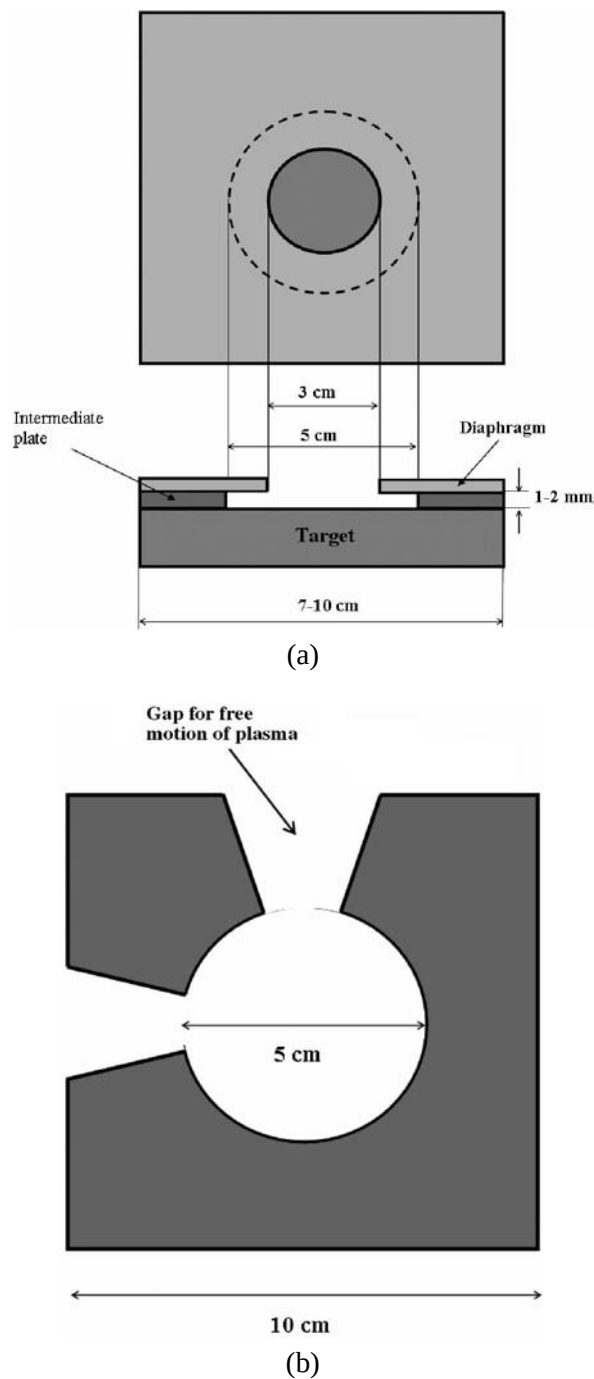


Figure 35.9 (a) Target equipped with diaphragm. (b) Intermediate plate placed between target and diaphragm.

measured mass loss as $d = \Delta m / \rho S$, where ρ is the specific gravity of the target material, and S is the plasma-irradiated area determined by the diaphragm hole of 3-cm diameter.

35.4.6 Irradiation by Xe and H plasmas

Copper and tungsten targets were exposed to 15 shots of Xe and H plasma at practically identical heat loads: 150–250 J/cm². The material erosion evaluated from the measured mass loss was found to be about 0.1 μm per shot for both copper and tungsten, under Xe and H plasma exposure. In principle, H plasma should cause lower mass loss, by about 30%, but the mass loss measured was nearly the same as for Xe. Thus the performed mass loss measurements have shown that copper and tungsten erosion caused by material evaporation, sputtering, and droplet ejection is limited to 0.1 μm per shot of Xe and only slightly less for H.

35.4.7 Copper surface damage

Figure 35.10(a) shows a photograph of the copper target after being exposed to 15 shots of H plasma. This photograph was taken when the diaphragm had been removed but the intermediate plate, which was placed between the target surface and diaphragm, remained in place. Examining the exposed target surface, one can see that the copper melt is partly splashed from the area exposed to the H plasma stream to the outside area protected by the diaphragm from plasma action. Melt splashing occurs in the form of droplets and jets moving in the radial direction. The displacement of the melt is limited to 1–2 mm. It is important to note that a leading part of the splashed melt is detached from the target surface and there is a small gap between the splashed melt and the target surface. In other words, the splashed melt is not well bonded to the target surface. The central zone of the exposed target area looks rather rough. The rough surface is formed due to boiling of the melt and to excitation of surface waves in the liquid metal under plasma action.

Figure 35.10(b) shows the surface of a copper target after 15 exposures to Xe plasma. In contrast to the experiment with hydrogen plasma [Fig. 35.10(a)], melt splashing does not occur under exposure to Xe plasma. Only a few traces of splashed droplets are seen outside the exposed area [Fig. 35.10(b)]. The macrostructure of the exposed surface looks very similar to that obtained in H plasma experiments.

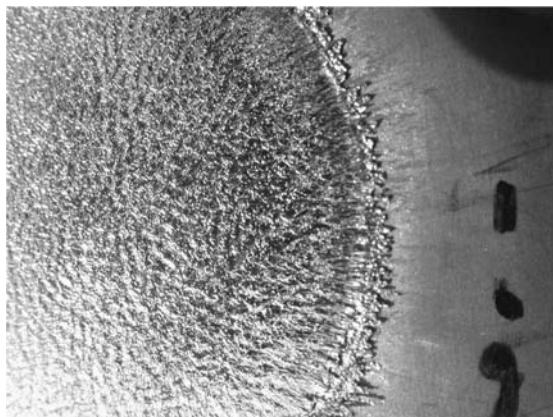
The copper targets exposed to H and Xe plasmas were analyzed using a mechanical profilometer. The target regions protected by the diaphragm from the plasma action remain at the original (zero) surface level, and they are used as a reference in the profilometry measurements. The measured surface profiles are shown in Fig. 35.11(a) (H plasma) and Fig. 35.11(b) (Xe plasma).

The surface profile induced by the H plasma stream consists of an erosion crater and meltlike mountains at its edge. The crater is located in the plasma-irradiated region; the mountains, in regions protected by the diaphragm from the plasma. The

measured surface profile indicates that the H plasma stream stimulates melt motion in the radial direction from the plasma-irradiated area to the periphery. The measured mountain heights are rather large, up to 150 μm , but this value is erroneous and cannot be used for evaluation of the melt volume accumulated in the mountains. This is because the splashed melt is detached from the target surface, thus leading to an overestimation of the mountain's height measured by the profilometer.

The depth of the erosion crater is 10–15 μm (i.e., the erosion rate is about 1 μm per shot). This means that the erosion caused by copper melt movement along the target surface is 10 times larger than the erosion caused by copper evaporation, sputtering, and droplet emission (the erosion mechanisms leading to mass loss).

In the case of Xe plasma [Fig. 35.11(b)], melt motion may also take place in principle. From the data, shorter melt mountains are in fact formed around the exposed target area. However, the melt motion is not as intense as in the H plasma



(a)



(b)

Figure 35.10 Copper target after 15 exposures to (a) H plasma, and (b) Xe plasma.

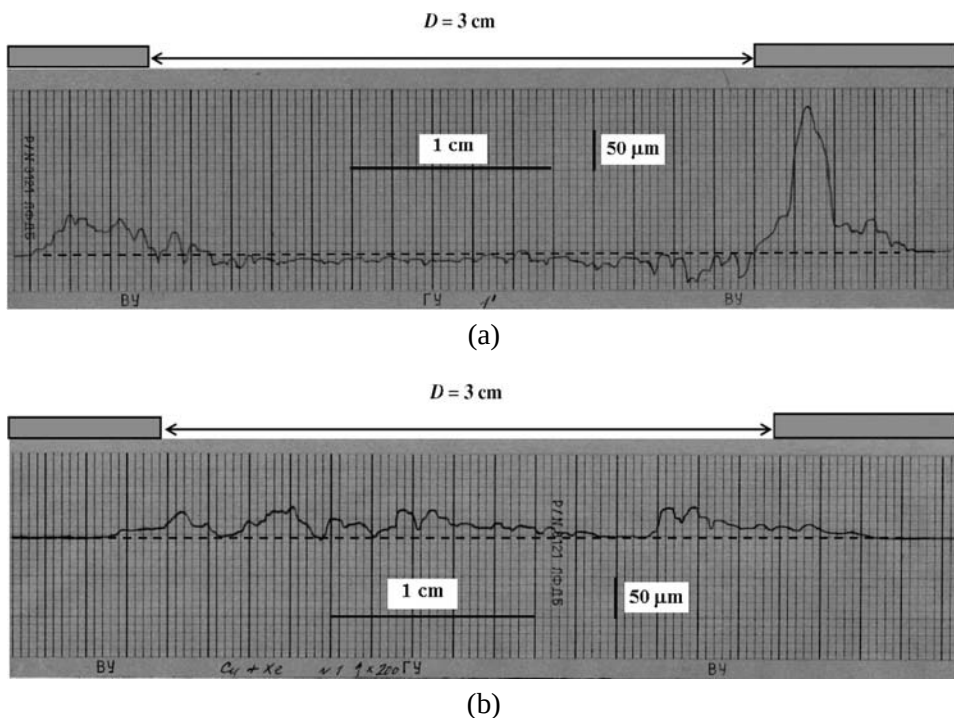


Figure 35.11 Surface profile of copper target after 15 plasma exposures to (a) H plasma, and (b) Xe plasma.

case, and therefore, the melt displacement does not produce a significant erosion crater.

The above experimental results show that a H plasma stream causes melt movement along the target surface, while a Xe plasma does not produce any notable melt displacement. Evidently the melt motion occurs because of the pressure gradient that forms at the target surface due to the action of the plasma stream. One could assume that the Xe plasma stream has a lower impact pressure than the H stream and that is why the melt movement is practically absent in the former case. However, this assumption does not agree with available experimental data. Xe and H plasma streams have very similar energy densities $Q = 150\text{--}250$ J/cm² and plasma pulse durations $t = 5\text{--}10$ μ s. The plasma stream energy density is equal to

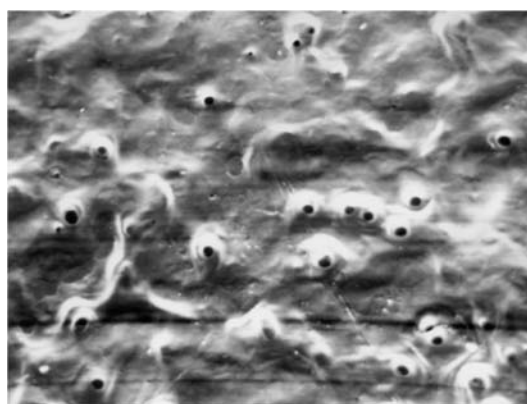
$$Q = \rho V^3 t = (\rho V^2) V t = P V t, \quad (35.2)$$

where ρ is the mass density of the plasma stream, V is the velocity of the stream, and P is the impact plasma pressure. In the present experiment, the velocity of the Xe plasma, $V_{\text{Xe}} = (1\text{--}2) \times 10^7$ cm/s, is slightly less than the velocity of the H plasma. Therefore, the impact pressure for Xe plasma must be larger than for H plasma, and the Xe plasma should also induce melt motion.

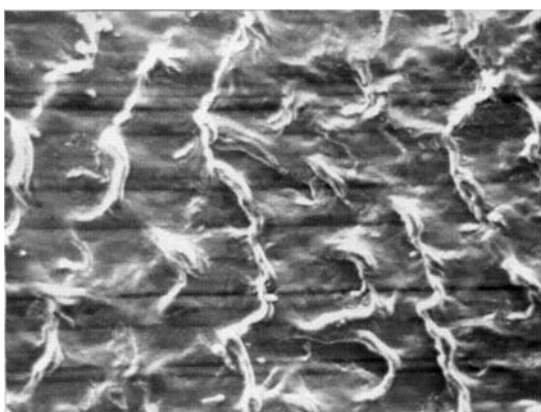
The experimental results might be explained by the following argument. Xe plasma emits much more intense radiation than H plasma. Therefore, after collision

of the Xe plasma with the target surface, a significant part of the plasma energy is lost from the plasma cloud into photon radiation. As a result, the Xe plasma stream produces weaker thermal action on the target surface than the H plasma stream, in spite of the fact that the plasma streams have identical energy densities. So, in the case of a Xe plasma we may predict a self-shielding effect, which leads to reduced action on the target surface.

It was mentioned above that the macrostructures of the target surfaces exposed to Xe and H plasmas look very similar. However, the details of the microstructures (e.g., surface morphology) are very different. Figure 35.12(a) shows SEM images of the copper surface exposed to H plasma. The surface is covered by open cavities, which form due to copper melt boiling. A typical size of the cavities is 10–30 μm .

300 μm

(a)

300 μm

(b)

Figure 35.12 SEM image of copper surface after 15 exposures to (a) H plasma stream, and (b) Xe plasma stream.

In the Xe plasma case [Fig. 35.12(b)], melt boiling does not occur. In contrast to H plasma, Xe plasma produces a regular wavy structure on the target surface. The nature of the observed differences is not clear.

35.4.8 Tungsten surface damage

Two identical tungsten targets were also exposed to 15 shots of H and Xe plasma streams. Figures 35.13(a) and (b) show tungsten targets after their irradiation by H and Xe plasma, respectively.

At the right side of the target surface shown in Fig. 35.13(a) (at a distance of 5–6 mm from the boundary the exposed target area), one can see the splashed droplets and jets. These droplets and jets were splashed from the diaphragm but not from the exposed tungsten area. Splashing of tungsten melt is practically absent. The central part of the target area is damaged by surface cracking. The cracks are parallel, and a typical distance between them is about 1 mm.

The action of Xe plasma also produces surface cracks. However, the cracking is not as intense as in the case of H plasma, and therefore the target surface exposed to Xe plasma looks smoother.

Figure 35.14(a) shows a measured profile of the tungsten surface exposed to the H plasma stream. The amplitude of the surface roughness is 20–30 μm . The observed surface roughness is caused by surface cracks. Surface cracks are formed not only in the target area directly exposed to the plasma stream, but also in the adjacent areas protected by the diaphragm from plasma action. No erosion crater or meltlike mountains are evident. Even if the melted tungsten moves under the action of H plasma (as in the experiment with the copper target), there is no accurate way to measure the erosion crater and the melt mountains against the background of large surface roughness caused by tungsten cracking.

Figure 35.14(b) shows the surface profile of the tungsten target irradiated by Xe plasma. The surface roughness is considerably less than in the case of H plasma,

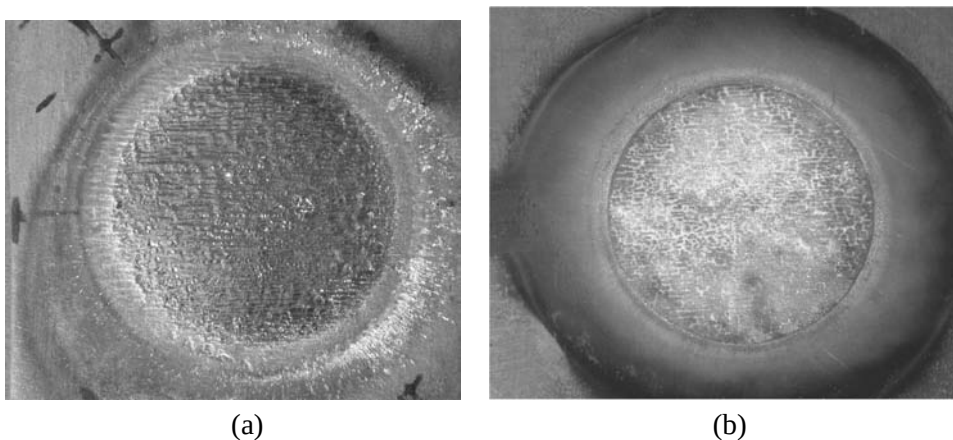


Figure 35.13 Tungsten target after 15 exposures to (a) H plasma, and (b) Xe plasma.

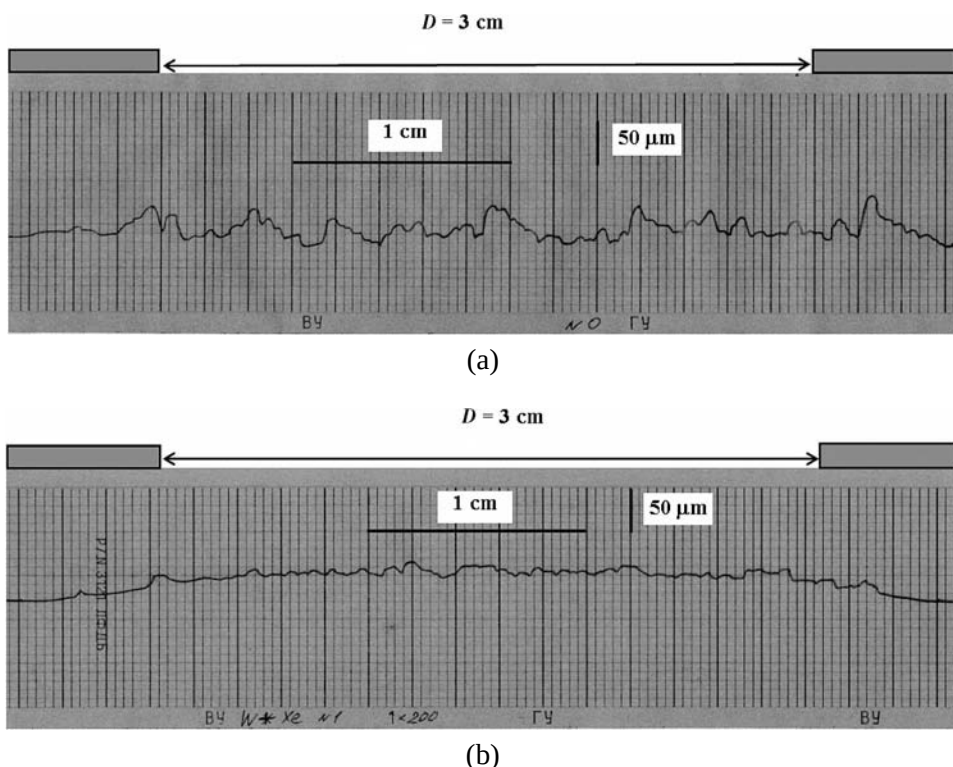


Figure 35.14 Surface profile of tungsten target after 15 exposures to (a) H plasma, and (b) Xe plasma.

being no more than 10 μm . The exposed target region is shown to swell up with respect to the unexposed region. No such effect has ever been observed in experiments with hydrogen plasma.

Figure 35.15(a) shows SEM images of the tungsten surface after its irradiation by Xe plasma. One can see that the surface is covered entirely with bubbles (or blisters). Their size is 20–30 μm , and they are separated by small distances. As mentioned earlier, a small ball was used in the present experiment as the sensing element of the mechanical profilometer. The ball is not able to follow exactly the profile of a single bubble. Rather, it goes along the tops of the bubbles. For this reason, the measured profile shows swelling of the whole target surface. In reality, general surface swelling seems to be absent.

As shown in Fig. 35.15(a), the bubbles produce a regular wavy structure on the tungsten target surface. This fact indicates that the bubbles may be related to the surface waves that arise in the liquid metal under action of the plasma stream. At the melt cooling and solidification stage, the surface waves may fall into separate parts because of melt surface tension, and this process may produce small melt mountains, which resemble surface bubbles.

The microstructure of the tungsten surface induced by action of H plasma is shown in Fig. 35.15(b). The surface structure is very different from that obtained

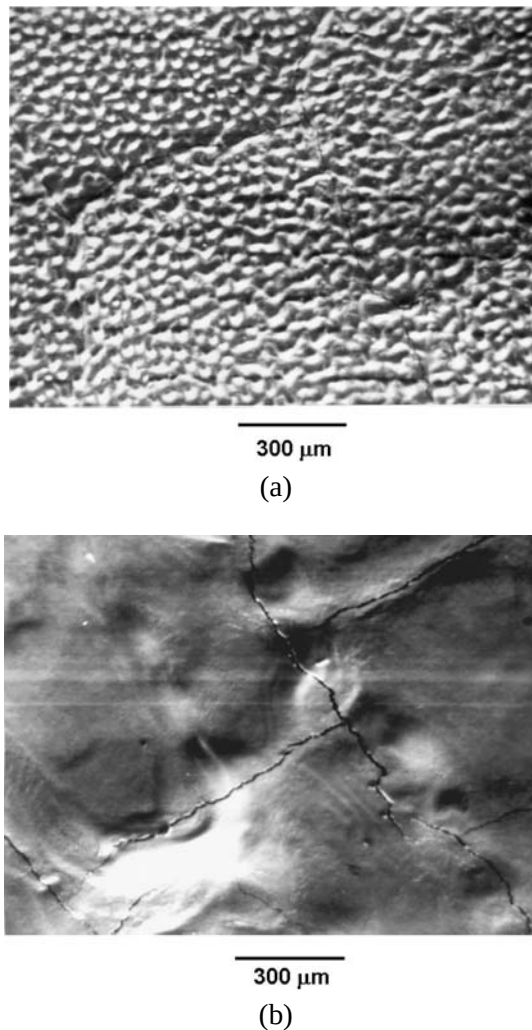


Figure 35.15 SEM image of tungsten surface after 15 exposures to (a) Xe plasma stream, and (b) H plasma stream.

in the case of Xe plasma. H plasma causes severe surface cracking. The cracks divide the surface into separate plates. There is no any evidence of melt motion or melt bubbles. The exposed tungsten surface consists of small flakes. The last fact shows that H plasma may cause the well-known brittle destruction of the tungsten surface in the form of flakes.

35.4.9 Conclusions on testing materials in plasma-gun facilities

Tungsten and copper targets have been tested with hot Xe plasma ($T = 30\text{--}50$ eV) formed near the target surface due to collision of a supersonic Xe plasma stream with the solid target. The same materials have been tested also with a H plasma

stream having similar energy density to the Xe one. Plasma-induced erosion and surface damage were studied.

The experimental results can be summarized briefly as follows:

- Copper and tungsten erosion caused by material evaporation, sputtering, and droplet injection (the erosion mechanisms leading to target mass loss) is about $0.1\text{ }\mu\text{m}$ per shot of Xe or H plasma.
- Hot Xe or H plasma produces a melt layer at the exposed target surface.
- Under the action of a plasma stream, copper melt is splashed from the exposed target area. Erosion of copper due to melt movement is about $1\text{ }\mu\text{m}$ per shot of H plasma. Xe plasma causes much less splashing of copper melt.
- Splashing of tungsten melt is practically absent.
- The microstructures of target surfaces exposed to Xe and H plasmas are quite different.

For *copper*, a H plasma causes melt boiling, producing open cavities at the exposed target surface. A copper target irradiated with a Xe plasma is entirely covered with surface waves. For *tungsten*, a H plasma causes severe cracking of the surface. A Xe plasma causes considerably milder cracking. A H plasma produces small flakes at the tungsten surface, causing brittle destruction of the tungsten. A Xe plasma produces a wavy structure on the tungsten surface, consisting of bubbles. These results show that surface damage induced by Xe plasma differs from that induced by H plasma.

One important observation is the variety of erosion mechanisms under high-intensity plasma exposure for materials such as copper and tungsten. The erosion is not only due to normal physical sputtering. It also depends on the effectiveness of the vapor shielding, which, in the case of Xe bombardment and the conditions in these experiments, is quite effective. Thus normal sputtering is not the only erosion mechanism, though the overall mass losses from Xe and from H are measured to be of the same order of magnitude.

Concerning implications of these results for DPP EUV devices, the following points are concluded. Xe damage at the surface is quite distinct from that due to other gases such as H. The details of surface damage are relevant, since the experiments presented here produce the same net energy deposition as that found in DPP devices. A Xe self-shielding effect should be expected during operation of DPP devices, and thus melt motion can be expected in certain regions on DPP electrode surfaces. The net energy deposited into the materials tested in the MK-200 plasma guns is between 1.5 and 2.5 J/cm^2 , resembling conditions in DPP electrode regions exposed to high heat flux. More importantly, the experiments conducted with the MK-200 system studied the interaction of the He plasma over a long time (≈ 10 – $20\text{ }\mu\text{s}$) compared to the characteristic time (≈ 20 – 50 ns) of the plasma pinch in a DPP device, in which melting occurs, providing for accelerated testing equivalent to 1000 shots in a DPP device.

The next section will extend the simulated experiments discussed above to experiments testing candidate materials in an actual DPP device. The DPP device was chosen for the tests, and a summary of the results is given in the next section.

35.5 Modeling and Testing Condenser-Optic Response

Critical to the performance of future EUV source systems is how operation of the source affects the region near and around the condenser 1 (C1) optic, that is, the collector optics. Degradation of the condenser optics is presently one key challenge for existing and future EUV source systems that will need to perform at frequencies greater than 5 kHz to reach powers near and above 100 W at intermediate focus (IF), meeting HVM demands. Operation under these conditions will lead to heavy electrode erosion and surface contamination, and even with debris mitigation schemes, condenser optics will face nontrivial degradation problems. Degradation of collector optics includes EUV-induced processes (e.g., oxidation, carbonization), and erosion and deposition of debris from various components in EUVL devices. Materials solutions will not likely lead to a factor 10–100 improvement in EUVL source performance. However, understanding of the C1 optic's response to the operation of the source and debris mitigation schemes can lead to a window of opportunity for integrated solutions with respect to C1 optics that will ultimately result in significant improvements in EUVL source performance.

In order to address these issues one must complement debris mitigation efforts with a thorough, directed, fundamental, and pragmatic study of the behavior of condenser-optic material surfaces under high-power EUV source conditions. This can only be done by careful diagnosis of the condenser-optic region (COR) in existing EUV source devices. Fundamental understanding of the effects EUV radiation and additional particle interactions have on plasma-facing condenser mirrors can lead to the design of advanced collector-optic materials that possess unique surface properties extending the condenser optic (CO) lifetime and enhancing EUV source performance. In DPP devices, generation of EUV light is collected by grazing-incidence mirrors (GIMs), as stated earlier. Synergy in environmental conditions can have significant effects on GIM performance. For example, how singly charged fast ions and neutrals created at the source induce surface damage of candidate optical materials interacts with OOB radiation heating of the GIM surface. Such synergistic effects can be studied and candidate materials tested with experimental facilities such as IMPACT at the Argonne National Laboratory (ANL). Other facilities conducting condenser-optics erosion studies include the University of Illinois at Urbana-Champaign and the ETS source at Sandia National Laboratory at Livermore. Figure 35.16 shows a schematic of characteristic debris GIMs are exposed to.

One of the outstanding issues with DPP source devices for EUVL is the lifetime of the C1 optics. The lifetime is currently defined as the loss of EUV reflectivity of about 10% after operation with about 10^{11} shots. The fabrication characteristics and component properties of Mo/Si multilayer mirrors (MLMs) are determining

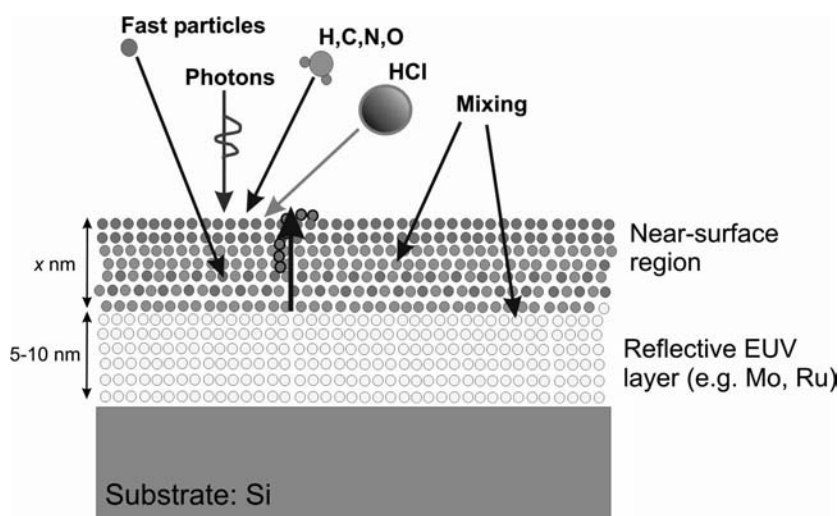


Figure 35.16 Schematic of various debris that interacts with a GIM surface in a DPP device. A typical GIM consist of a single thin-film layer with high EUV reflective properties.

factors for the reflective intensities of the C1 mirrors in LPP systems. The design of MLMs includes the choice of the optimum layer period as well as control of compressive versus tensile stresses. Optimization of these parameters as well as maintaining low surface roughness and using interface engineering²⁹ results in increased C1 optic lifetime and greater mean reflective intensities for lithography. Additional issues include interlayer mixing.

In DPP EUV-source devices, GIMs are applied. These can consist of thin films of high-EUV-reflectivity materials (e.g., Ru, Mo, Pd). Understanding erosion mechanisms as well as additional thermodynamic and radiation-induced mechanisms is critical in the design of GIM materials for HVM operation. In addition, diagnosis of the environmental conditions that mirror surfaces are exposed to is critical to the advancement of GIM design. However, any materials improvement will have to be coupled with debris mitigation schemes near the source, due to the high heat load that electrodes at the source will be exposed to under HVM operation. In addition, understanding and diagnosis of the COR will be important for determining which erosion mechanisms will dominate at the surface. For example, OOB radiation can lead to local heating of the GIM surface. Therefore, the effect of fast ions and neutrals at the GIM surface must be taken into account under these conditions. This chapter summarizes key particle-surface interactions important for the design of GIM surfaces for HVM DPP EUV devices.

Near-surface composition modifications in multicomponent systems (MCSs) from ion bombardment have been observed from many alloy systems, both in the solid and in the liquid state.^{30–37} A number of nonthermal and thermally activated mechanisms can exist when a MCS is irradiated. All of these mechanisms work synergistically, leading to changes in the near-surface region—a region important

in determining the lifetime of condenser-optic materials under EUV-source system conditions.

Conceptually, the phenomenon of bombardment-induced compositional changes is simplest when only nonthermal processes exist, such as preferential sputtering (PS) and collisional mixing (CM). PS occurs in most MCSs due to differences in binding energy and kinetic energy transfer to component atoms near the surface. CM of elements in MCSs is induced by displacement cascades generated in the MCS by bombarding particles/clusters and is described by a diffusion model.

Irradiation can accelerate thermodynamic mechanisms such as Gibbsian adsorption (GA), or segregation, leading to substantial changes near the surface with spatial scales of the order of the sputter depth (a few monolayers). GA results from thermally activated segregation of alloying elements to surfaces and interfaces, reducing the free energy of the alloy system. Typically, GA will compete with PS, and thus, in the absence of other mechanisms, the surface reaches a steady-state concentration approaching that of the bulk. However, when other mechanisms are active, synergistic effects can once again alter the near-surface layer, and complex compositions can result.^{38,39}

These additional mechanisms include radiation-enhanced diffusion (RED) due to the thermal motion of nonequilibrium point defects produced by bombarding particles near the surface; and radiation-induced segregation (RIS), a result of point-defect fluxes, which at sufficiently high temperatures couples defects with a particular alloying element, leading to compositional redistribution in irradiated alloys in both the bulk and near-surface regions. Additional mechanisms include ion-induced mixing and preferential recoil implantation. All of these mechanisms must be taken into account in the design of proposed advanced materials, in addition to considering other bombardment-induced conditions (clusters, HClIs, neutrals, redeposited particles, debris, etc.).³⁹

35.5.1 Erosion and redeposition at condenser-optic material surfaces

Optic material surfaces will be eroded via sputtering by slow and fast ions from the expanding postdischarge EUV source plasma. For a He-Xe discharge, for example, sputtering will occur due to physical sputtering by He and Xe ions.

The source design should seek to minimize erosion by choice of geometry and optic materials, and possibly by optimizing the plasma constituents (e.g., He/Xe ratios). The *net* sputter erosion rate of any surface depends critically on the balance between gross erosion and redeposition. *Gross* physical-sputter fluxes depend on the incident particle fluxes and energy, the latter primarily determined by sheath acceleration. Redeposition occurs due to ionization of sputtered atoms by the plasma electrons and subsequent transport of those ions back to the surface via collisions with the incoming plasma. Net erosion rates approaching zero are possible under some plasma and material conditions.

Sputtering erosion and redeposition have been extensively studied in fusion-power research. The ANL REDEP code¹⁰ package is the world's leading code for predictive simulations of plasma-surface interactions including erosion and redeposition, and will be used for EUV source studies. This code package contains hundreds of models for the relevant erosion and redeposition processes and has been extensively validated with experimental data. As stated earlier, the conditions near collector optics are believed to be characterized by a relatively warm plasma ($T_e \approx 20\text{--}30$ eV) and low to moderate electron density ($\sim 100\text{--}1000$ times less than the source density). Such plasma conditions at the optical surfaces are actually similar to fusion edge conditions with regard to ion and electron temperatures and density ranges. Because of ANL's extensive experience in this area, we have access to and can readily implement any additional process models relevant to EUV optical-surface sputtering and transport. One additional task is the characterization of an admixture plasma (viz., He and Xe) expanding toward the GIM surfaces. The expertise at ANL and contacts with other experts in the field facilitate our ability to effectively and efficiently implement plasma edge models.

35.5.2 Condenser-optics materials testing

Experimental facilities such as IMPACT at ANL, shown schematically in Fig. 35.17, can test candidate mirror materials under intense charged-particle irradiation. IMPACT consists of a well-collimated ion source with an energy range between 50 and 5000 eV, fluxes of $10^{11}\text{--}10^{17}$ ions/cm² s, and incident angles from normal incidence to about 60–70 deg with respect to normal. Base pressures are attainable down to 10^{-10} Torr with gas inlets for controlled impurity desorption/adsorption experiments. In addition, an *in situ* heating design can vary the sam-

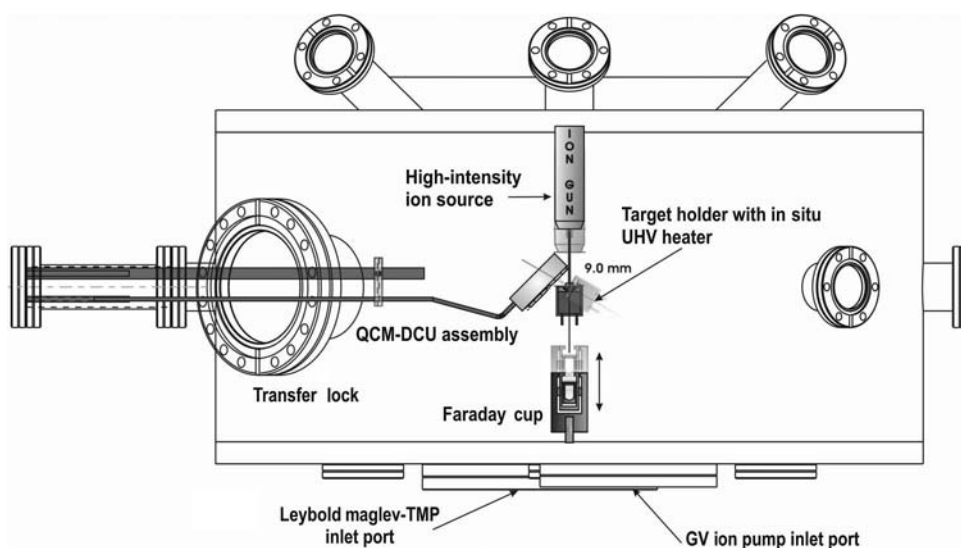


Figure 35.17 The QCM-DCU system in the IMPACT experiment at ANL.

ple temperature from ambient conditions to about 1000°C. IMPACT currently has a quartz-crystal-microbalance–dual-crystal-unit (QCM-DCU) diagnostic system for *in situ* real-time total-erosion measurements and has additional *in situ* metrology, including low-energy ion scattering spectroscopy (LEISS), Auger analysis, and x-ray photoelectron spectroscopy (XPS), for multicomponent erosion measurements. The sample is fixed on a rotatable manipulator, whose rotation axis lies in the plane of the sample surface. This allows for angle-of-incidence measurements on the irradiated surface. In addition, the sample holder includes an *in situ* ultrahigh vacuum (UHV) heater system with a thermocouple located underneath the sample for temperature-variation tests. The heater is equipped with a set-point controller with the capability of also setting the heating rate (K/s). This is important because various microstructures and surface morphologies depend on the local surface condition. The sample sits in a stainless steel cup, allowing for exchange of samples *in vacuo* with a manipulator and transfer lock system. When the sample is removed from the ion beam, the beam is collected by a Faraday cup for beam profile analysis. The Faraday cup consists of four small pinholes about 0.125 mm in diameter and 2 mm apart.

In situ diagnosis is important for several reasons. A surface under ion irradiation is actively changing during the exposure dose. For example, RIS will drive certain target components to the surface, while RED will drive them away from the surface. Adsorbates will be active on a given surface according to the surface kinetics and thermodynamics, and their role in mechanisms such as sputtering and reflection can be assessed only by actively interrogating the surface irradiated.

Accelerated testing of candidate GIMs or MLMs can be done with ion sources affording a large range of ion-bombardment fluxes and long-term electron-gun exposures. IMPACT also is equipped with an *in situ* UHV heater providing for thermal annealing tests while the sample's surface is diagnosed and for simulating OOB radiation heating effects. This chapter presents initial experiments in IMPACT on total single-component erosion by use of the QCM-DCU diagnostic system.

Figures 35.18(a) and (b) show results of total-sputtering measurements for Ar^+ and Xe^+ bombardment at normal incidence for energies ranging from 200 to 5000 eV. The results are compared with well-known experimental data, thus serving as good calibration references for the setup in IMPACT. The QCM-DCU technique works by depositing a quantity of eroded material on a gold-covered quartz crystal oscillator. The oscillator vibrates at a fundamental frequency of about 6 MHz. As mass is deposited on the surface of the oscillator, its frequency decreases. The measurement of total physical sputtering is very sensitive; therefore, a dual-crystal unit is applied. The unit works by one oscillator monitoring the eroded material and the other the background frequency. The frequency difference is then utilized in the calculation of the sputtering yield. Attention is paid to several important factors: the sticking coefficient of known species to the collector surface of known surface composition, the collecting solid angle, and the resputtering of collected material by fast reflected ions or neutrals. Surface compositions are taken from previous surface analysis results.

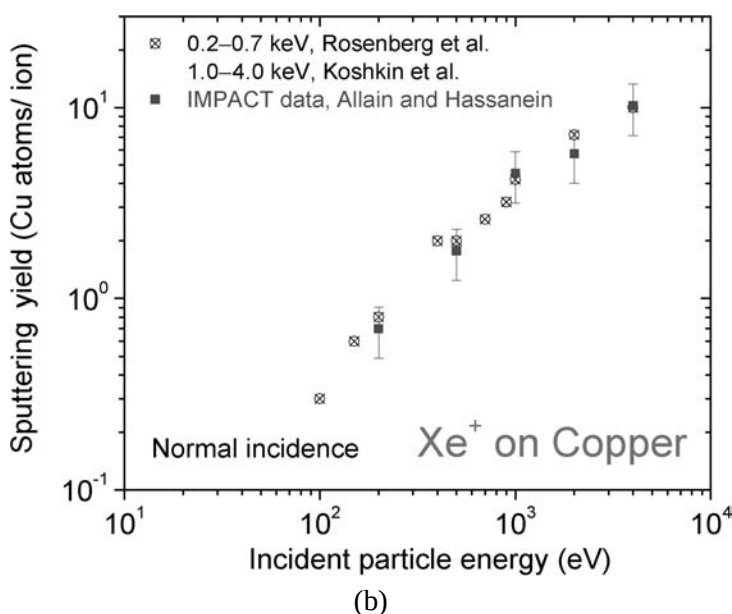
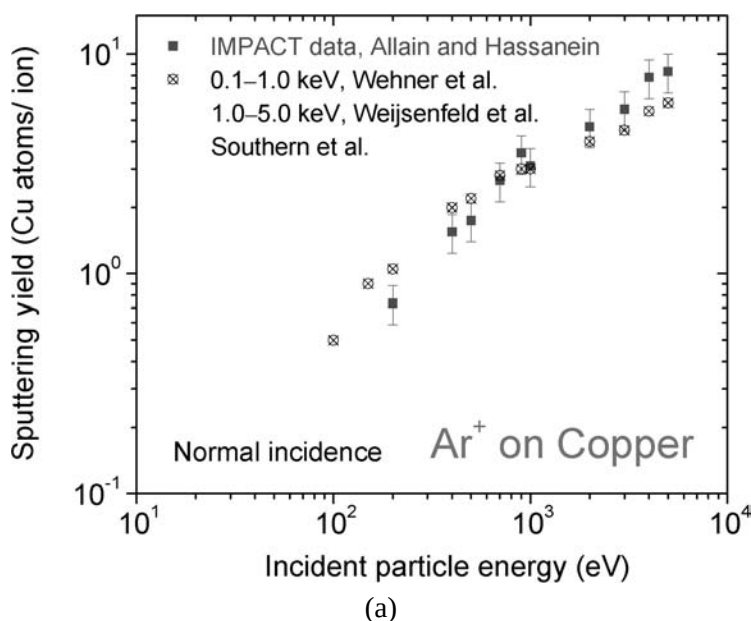
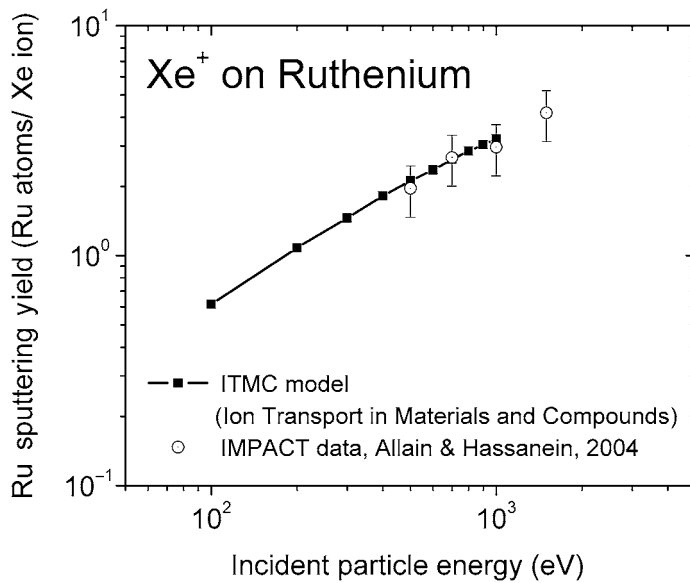


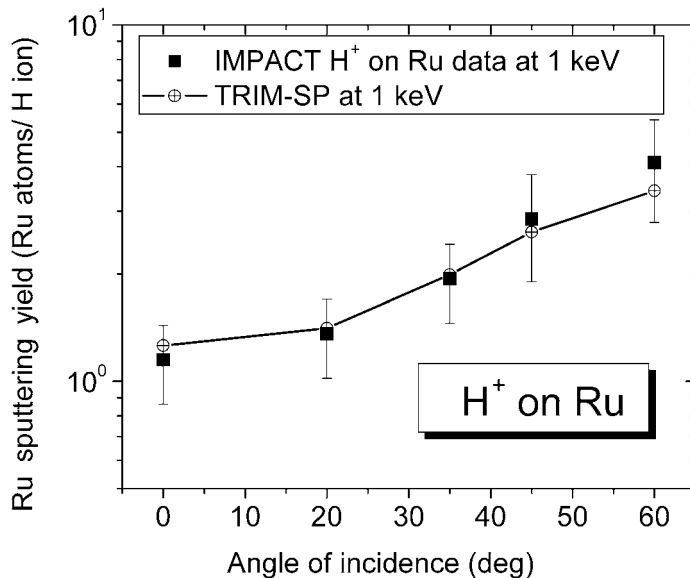
Figure 35.18 Sputtering yield of copper bombarded by singly charged (a) Ar, and (b) Xe, at normal incidence in the IMPACT experiment at ANL.

35.5.3 Oblique-incidence erosion of Ru bombarded by Xe^+

The physical sputtering yield of Xe^+ bombardment of ruthenium at 45 deg was measured in IMPACT. The incident particle energy ranged from 500 to 1000 eV, and the results are shown in Fig. 35.19(a). The sputtering yield rises from about



(a)



(b)

Figure 35.19 Sputtering yield of Ru bombarded by (a) Xe plasma stream, and (b) H plasma stream.

0.1 Ru atom/ion at 500 eV to about 0.4 Ru atom/ion at 1500 eV. Xe⁺ bombardment shows no indication of nonlinear erosion. This is because the binary collision approximation (BCA) based code ITMC is used to model the system for a number of incident particle energies. The model implemented in the ITMC code is con-

sistent with the linear sputtering model. There is very good agreement between the model and experimental data, and thus we do not expect the Ru yield to rise nonlinearly with temperature. For a GIM, the measurements of oblique incidence of fast ions (e.g., Xe^+) are of interest due to the solid angle collecting EUV light, which provides for very oblique angles in incidence for fast, singly charged ions, as shown in Fig. 35.19(b). In these measurements a Ru oxide layer was assumed to deposit on the collecting crystal of the QCM-DCU diagnostic. This assumption needs further investigation using postexposure surface analysis.

35.6 Conclusions

Plasma-facing EUV-source device materials will need to be carefully designed to stand up to the harsh environment they will be exposed to. Electrode materials must be designed to provide erosion resistance and good thermal conductivity. High-density plasmas in DPP devices will lead to serious erosion challenges as HVM conditions are attained. However, with proper electrode design and robust debris mitigation schemes, some opportunity exists for operation in HVM. Condenser-mirror optics face the same challenge. The mirror surface will have to be designed to contend with incident debris, highly energetic singly charged and multicharged particles, and fast neutrals. More importantly, the synergy of such fluxes combined with background impurities and OOB radiation will ultimately decide the fate of plasma-facing mirrors. This is mainly dictated by the specification of the condenser-optic lifetime for the collector optics. This specification requires that only a 10% loss in EUV reflectivity occurs over 30,000 operating hours.

Proper design coupled with debris mitigation schemes will enable emerging lithography technologies to operate under HVM conditions. This goal can be attained in timely fashion by designing well-diagnosed, controlled off-line experiments, such as the IMPACT experiment, to understand synergistic erosion mechanisms that can lead to advanced mirror designs.

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For a biography of author V. Bakshi, see Chapter 1. Biographies for the other authors of this chapter were not available.

Chapter 36

Origin of Debris in EUV Sources and Its Mitigation

David N. Ruzic

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36.1 Introduction

Particle emission is an unavoidable consequence of using a plasma to generate photons. These particles will interfere with the collection mirrors for the EUV radiation. Low-energy atoms from sputtered material or condensable fuels such as Sn or Li can deposit on the mirrors. Higher-energy ions and charge-exchanged neutral atoms can sputter, implant, and roughen the mirrors. Both of these effects reduce the reflectivity. This chapter describes the sources of the energetic and condensable particles, analyzes mitigation schemes aimed at reducing their flux to the mirrors, and offers two new ideas to mitigate their effect on the mirror's surface. While this chapter deals most directly with DPPs, many aspects are relevant for LPP systems as well.

36.2 Source Terms

36.2.1 Theoretical considerations

Consider the plasma source shown in Fig. 36.1. Though a dense plasmas focus (DPF) is drawn, this section applies equally to any DPP, such as a Z pinch or vacuum arc. A dense pinch plasma is produced close to the inner electrode of the source. During the pinch, energetic fuel ions are created in the dense hot plasma and then move outward in all directions as the plasma expands. A fraction q_1 of

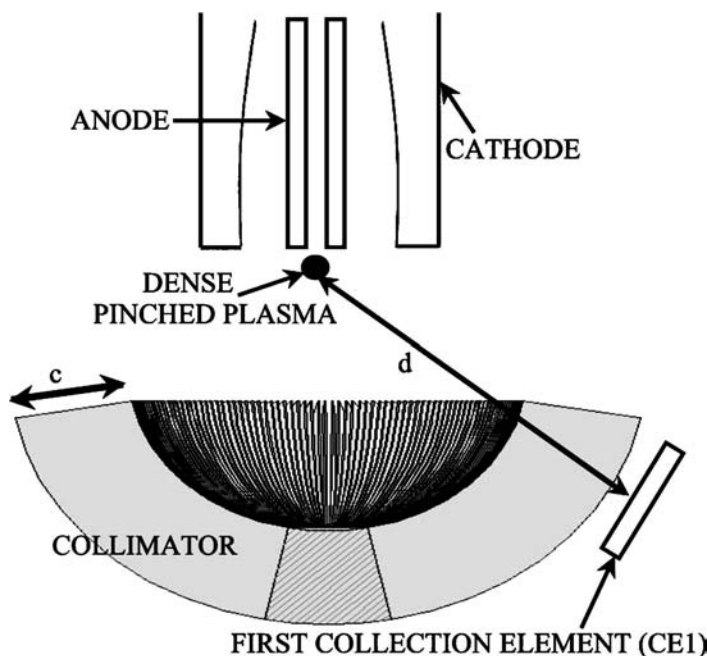


Figure 36.1 Schematic of a DPP and a foil trap collimator. The first collection element (CE) in this case would be a grazing-incidence EUV mirror.

these ions strike the inner electrode, and an independent fraction q_2 strike the outer electrode, producing low-energy sputtered atoms from each electrode. In addition, some of the ions incident on the electrodes reflect from the surfaces as neutral atoms, creating a source of medium-energy fuel atoms. Another fraction, q_3 , of the highly energetic ions produced in the pinch travel the same path as the collected photons that are produced, and head straight toward the first collection element (CE1). This is not an exhaustive list of debris sources. Sudden heating of the electrodes can lead to atomic vaporization, ablation of molten material, or other effects.

Let J equal the number of energetic fuel ions produced in one pulse. Then

$$G = \text{number of sputtered atoms produced} = q_1 J Y_a + q_2 J Y_c,$$

where Y_a is the sputtering yield of the anode, and Y_c is the sputtering yield of the cathode. Note that a DPF works independently of the bias on the electrodes. The inner electrode can be the anode or the cathode. Other DPP sources, such as a Z pinch, only have one electrode closer to the pinch plasma, but still have multiple surfaces that can be sputtered. In either case, G sputtered atoms will be produced.

Let R_a and R_c equal the reflection coefficients for energetic particles striking the anode and cathode, respectively. Then

$$F = \text{number of fast reflected gas atoms} = q_1 J R_a + q_2 J R_c.$$

The number of energetic ions proceeding directly to CE1 is

$$I = q_3 J.$$

The magnitudes of these quantities can be estimated for a DPF similar to that made by Cymer Inc.¹ or in laboratory experiments at the University of Illinois, with the geometry shown in Fig. 36.1—though other sources would be similar. In fact, the same estimates apply to the XTS 13-35,² manufactured by XTREME technologies and installed at the University of Illinois.

36.2.1.1 Estimation of J

There are two methods to estimate a maximum value for J . The first is through energy conservation. Say 5 J of energy goes into the pulse. This number is quite reasonable for the XTS 13-35, where similar numbers have been measured. Experience with plasma guns in general has shown that the energy taken away by the electrode coolant system approximately equals the energy going into the device. This implies that almost all of the energy from the pulse turns into ohmic heating or into photons or energetic particles that lose their energy to the electrodes. Obviously some fraction of the energy is not returned to the electrodes, or there would be no energetic debris to worry about mitigating! Say the maximum amount that could be unaccounted for is 25%. That would imply that at most 25% of the energy could have turned into energetic particles and photons that could travel away from

the pinch region, or 50% turned into energetic particles and photons traveling all directions, since the solid angle the electrodes intercept is at best 2π (50%).

To be able to produce approximately 100-eV photons, the electron temperatures, T_e , must be on the order of 30 eV. Since these plasma are very dense and self-compress quickly, high ionization states of the fuel occur. The desired EUV light comes from Xe^{9+} through Xe^{11+} or Sn^{6+} through Sn^{13+} . A given radiating ion may be reexcited many times during the brief pinch duration. Finally, the plasma begins to expand and cool—reducing the charge state through recombination. In this process a certain number of fast electrons are expelled, causing a charge imbalance. This results in a Coulomb explosion, which then accelerates the ions away from the pinch region.³ Instabilities can also cause ion emission.

Measurements⁴ and modeling⁵ have shown that the average energy from our XTS 13-35 source is 8 keV (Xe^+). For the Illinois Debris-Mitigation for EUV Applications Laboratory (IDEAL) DPF, the energy was a bit less (3 to 5 keV). Using 8 keV, we can make an estimate for J with the assumption that the total energy going into energetic particles is 2.5 J. Note that $2.5 \text{ J} = 4.0 \times 10^{19} \text{ eV}$. Thus

$$J = 5 \times 10^{15} \text{ ions at 8 keV.}$$

An alternate method to calculate the maximum possible value of J is to consider the total volume of gas swept up by the pinch. A 1-cm-diameter cylinder 5 cm deep has an approximate volume of 4 cm^3 . At a pressure of 35 mTorr, which is the gas feed pressure, the total number of gas molecules in that volume that could all be part of the pinched plasma is another estimate of J . Using the relation number density (in cm^{-3}) $= 3.3 \times 10^{16} \times P$ (in Torr), we have

$$J = 4.6 \times 10^{15} \text{ ions.}$$

This estimate is for a temperature of 300 K. Different geometries, temperatures, and pressures would change this number, but it is of the same magnitude as given by the energy estimate.

I will use an average value of 5.0×10^{15} energetic ions for J . Note that the actual value of J may be lower. Less of the input energy may be conveyed to the particles, more energy may go to radiation, there may be much lower ion energies produced, and/or all the input fuel atoms may not get ionized or trapped. All estimates of the debris source will be made in terms of J , so the remaining calculations can be scaled as needed.

36.2.1.2 Estimation of G , F , and I

At this point we must assign actual materials to the electrodes and fuel. To match the IDEAL experiment, I will assume the working fuel gas is Ar and the electrodes are Cu. Data also will be provided for W electrodes and Xe, Sn, and Li fuels.

The ions that are produced in the pinch will show a large distribution of charge states. In fact, the temperature and density of the pinches are optimized to produce

the maximum amount of inband (13.5 nm) radiation. For Xe, this is Xe^{9+} through X^{11+} ; for Sn it is a broader range centered around Sn^{10+} . For Li the line required is from Li^{2+} . The high charge state of the pinch ions is what is largely responsible for the high energies. They are accelerated away from the pinch plasma during its aftermath by the faster electron exodus. This is why both the cathode and the anode of such devices show sputtering. The typical plasma sheaths produced have a potential drop equal to approximately 3.5 times the electron temperature, on top of any potential still left on the electrodes. The potential of the plasma will rise to be the highest potential in the system, so these effects are additive. If the pinch is produced with maximum efficiency, the current will be at a peak and therefore the voltage on the electrode will be near zero.

It is important to note that the instantaneous potential drop between the hot plasma and nearby material surfaces such as the electrodes or mirrors can be much higher than $3.5T_e$. In LPPs, the initial interaction of the laser beam with the target causes an energetic electron pulse whose magnitude depends on the pulses' shape, energy density, and power density. These electrons will elevate the potential of the target and cause ions to be accelerated from the target during the aftermath of the plasma. A similar phenomenon happens in a DPP, causing fast electrons to leave, which effectively accelerate ions to higher energies.

In our IDEAL facility we used an Ar-fueled DPF with Cu electrodes to simulate an EUV plasma. In the most benign case, where there is no left-over potential on the cathode and some superthermal initial electron ejection, we may expect an approximate 100-eV potential difference between the plasma and the electrode. The sputtering yield for 100-eV Ar on Cu is approximately 0.3.² However, the more likely case is where the Ar ions will be multiply charged and accelerated by Coulomb repulsion. Those that head toward the electrodes could impact them with 1 keV. The sputtering yield for 1000-eV Ar on Cu is approximately 3.0. The reflection coefficient for 1000-eV Ar is roughly 0.05. The energy reflection coefficient happens to also be approximately 0.05.⁷ Estimating the solid-angle fractions $q_1 + q_2 = 0.5$ and $q_3 = 0.5$, then to a rough first approximation the condensable and energetic particles produced in one pulse on a Cu-electrode DPF powered with Ar can be characterized as

$$\begin{aligned} G &= 7.5 \times 10^{15} \text{ Cu atoms at 3 eV,} \\ F &= 0.125 \times 10^{15} \text{ Ar atoms at 50 eV,} \\ I &= 2.5 \times 10^{15} \text{ Ar}^+ \text{ ions at 8000 eV.} \end{aligned}$$

The sputtered atoms (G) and the reflected atoms (F) are emitted from the surface of the electrodes with a cosine distribution. The energetic ions (I) are emitted directly toward the collector optics. They have a larger energy because there is a larger distance between the pinch and a physical boundary, which allows for more acceleration by the Coulomb-explosion repulsive electric field.

Note that the loss of G Cu atoms from the electrodes per pulse comes both from the anode and from the cathode in a DPF. If we assume that half of the atoms are sputtered from the anode and that the area of the anode that is eroded is a

ring 1.5 cm in diameter and 0.5 cm wide, the erosion rate of the electrode can be estimated. Using $G = 7.5 \times 10^{15}$ gives an erosion rate of 0.2 nm (about half a monolayer) per pulse. Assuming that net erosion is half of gross erosion, and that the useful lifetime of the anode is reached when approximately 2 mm is eroded, the lifetime of the anode is on the order of 40,000,000 pulses. Other mechanisms such as microarcing may also be responsible for electrode wear, but sputtering alone is also significant.

It is instructive to look at other gas and target materials and energies as well. Cu is much too easy to sputter. Relevant sputtering yields gleaned from the collected experimental literature⁶ are given in Tables 36.1 and 36.2.

Note that a Xe-fueled system with a W electrode using the same energy parameters would last approximately 3.6/1.1 times longer due to the sputtering yields. In a Z pinch, where one electrode is intercepted primarily by the ion flux, the expected lifetime would be cut by some fraction. (One-half is used in the following example.) Therefore, the expected lifetime of a W electrode in a Xe-fueled Z-pinch plasma, based on these assumptions, is

$$40,000,000 \times (3.6/1.1) \times 0.5 = 65,000,000 \text{ shots.}$$

Indeed, the lifetimes of the XTS 13-35 electrodes at the University of Illinois were on this order. The first set of electrodes was replaced after approximately 70,000,000 shots and showed a few millimeters of erosion.

36.2.2 Experimental evidence

Over the last two years, the IDEAL DPF has been operated at the University of Illinois. More detail on the IDEAL DPF, including an expansion of the results described in this section, can be found in Refs. 8 and 9. The IDEAL DPF is operated between 1 and 50 Hz at a voltage of 3 to 4 kV applied across the switch and plasma load during firing of the device. Figure 36.2 shows a typical I – V waveform trace. Voltage is applied across the coaxial electrodes, leading to surface breakdown and plasma formation across the insulator in phase II. Liftoff and rundown

Table 36.1 Sputtering yields for 100-eV ions at normal incidence.

	He	Ar	Xe
Cu	0.06	0.3	0.12
W	0	0.06	0.015

Table 36.2 Sputtering yields for 1000-eV ions at normal incidence.

	He	Ar	Xe
Cu	0.35	3.0	3.6
W	0.023	0.8	1.1

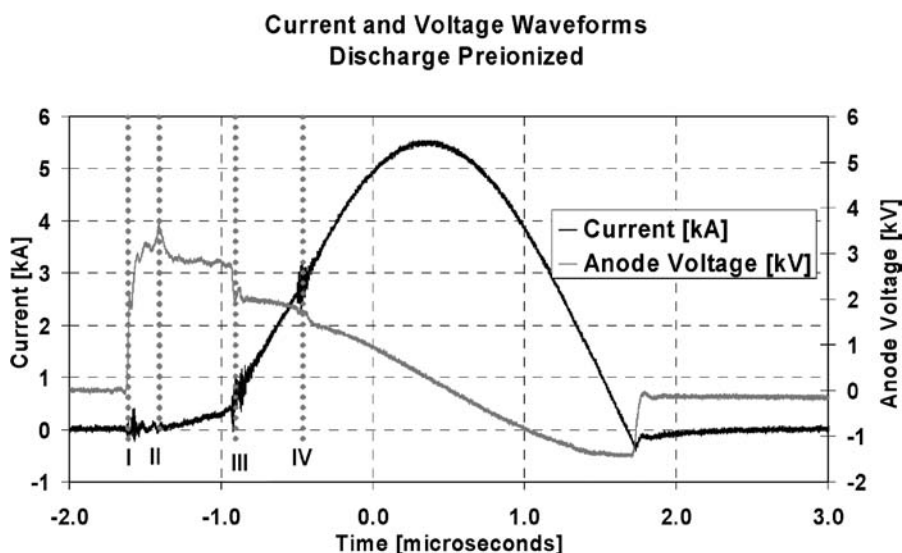


Figure 36.2 DPF waveform current and voltage, illustrating stages of discharge evolution from (I) switch closure, (II) surface breakdown, (III) plasma liftoff and rundown, (IV) pinch phase, and expansion at later times.

of the plasma sheath occurs during phase III, characterized by a large increase in current. The plasma reaches the end of the anode tip and pinches in phase IV, followed by expansion of the plasma into the main chamber.

From Fig. 36.2, it is apparent from the I – V trace that the pinch phase occurs early in the current pulse, not achieving maximum compression, which is proportional to I^2 . This is due to the inherent large system inductance limiting the current rise time in conjunction with a modest electrode length. Compared to commercial EUV systems, the IDEAL pulse length is a factor of 5 times longer.¹⁰ Shorter pulse lengths are achieved in commercial sources through magnetic pulse compression and insulated gate bipolar transistor (IGBT) switching to arrive at large amplitudes and small pulse widths. However, for generating representative debris the IDEAL system was found to be comparable to reports from industry showing multi-charge-stage fast ions and sputtered electrode material.

Figure 36.3 shows a representative signal from a gridded energy analyzer (GEA) operating as an ion detector placed just above a quartz-crystal microbalance (QCM). The ion detector can be used as a time-of-flight detector to determine ion energies. Operation at 3 kV shows a peak in the fast-ion signal corresponding to the arrival of 5.5-keV ions. Why this energy? According to the theory section, the ions will be accelerated away from the pinch by the potential difference. While the IDEAL pinch plasmas are not very hot (due to their occurrence well before the current maxima is reached), they do experience acceleration from the potential drop between the central electrode and the grounded detector. At the time of the pinch, the voltage on the center electrode for this discharge was 1870 V. This would imply that the predominant charge state reached in the plasma for Ar was 3+. Certainly

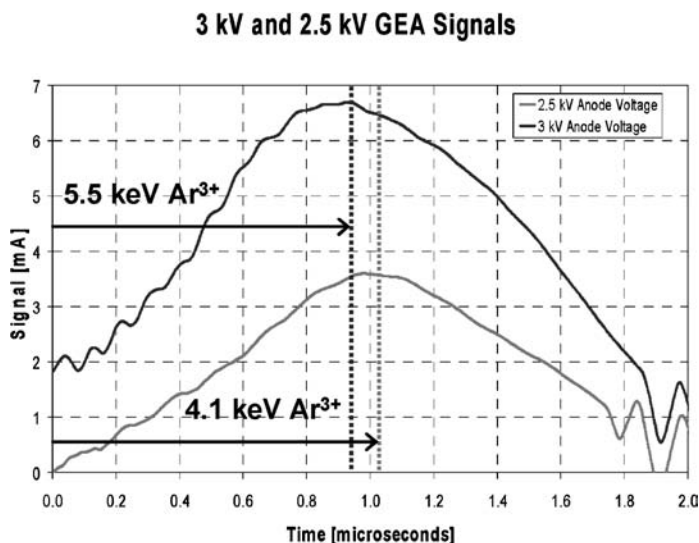


Figure 36.3 Operation at 3 and 2.5 kV shows delay in peak of detector signal and magnitude. Time-of-flight correlation with applied pinch voltage yields estimates of 3+ charge-state Ar ions arriving at the detector position.

a cooler plasma is expected, given the reduced current. To test this hypothesis the experiment was repeated at 2.5 kV. At that voltage, the ion signal peak is shifted to lower energies, indicating the arrival of 4.1-keV ions. During this experiment, the voltage was at 1400 V at the time of the pinch. The ratio of these voltages leads us to conclude that indeed the dominant ion species expelled from the pinch was Ar^{3+} . This low charge state does not produce the same magnitude of Coulomb explosion that is experienced by commercial devices, and thus the ion energy is primarily due to the existing potential difference in the plasma.

There is an additional fast-ion signal from IDEAL that may be present in many DPP systems. The rundown phase of the DPF, or any formation phase for other DPPs, may expel fast ions. We find that the magnitude of these rundown or breakdown ions depends critically on the preionization conditions. With preionization, their magnitude is greatly reduced. Without preionization, their magnitude rivals the magnitude of the pinch ions, though they are only singly ionized and have energy corresponding to the voltage of the electrode during pinch formation. Unlike pinch ions, this component should be able to be controlled by judicious choice of whether to make the center electrode the anode or the cathode and also by geometrical considerations.

Evidence of this rundown component can be seen in the IDEAL data shown in Fig. 36.4. Note the difference in signals when preionization is present and when it is not. The second peak represents rundown ions at approximately 3.3 keV. This is close to the potential of the DPF during the rundown phase—little voltage drop has occurred at that point.

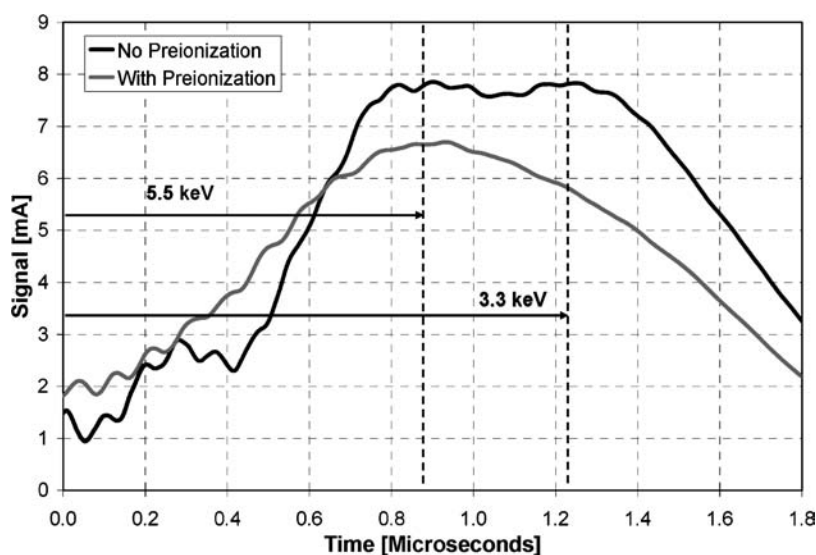


Figure 36.4 Time-of-flight ion signals from the GEA, showing a 5.5-keV ion energy peak from the pinch plasma and a 3.3-keV ion energy peak from the rundown phase. With preionization, the peak from the rundown phase is greatly reduced.

Additional evidence for the existence and mitigation of rundown ions through preionization comes from QCM data.¹¹ The oscillator frequency changes as material is added or removed from the crystal surface. A dual-crystal unit is used, where one crystal is always covered and acts as a reference. The frequency difference between them is proportional to the erosion or deposition rate. With no preionization at all, the erosive flux measured by the QCM is larger than it is with preionization present.

Further experimental evidence comes from operation of an XTS 13-35 at Illinois. The Xtreme Commercial EUV Exposure Diagnostic (XCEED) experiment began operation in the summer of 2004. The XCEED experimental test chamber is a custom design built to mate to the XTS 13-35 source for diagnostic access. A schematic of the chamber with spherical-sector electrostatic energy analyzer (ESA) access is shown in Fig. 36.5. A more complete description is given in Refs. 4, 8, and 9. The source flows Xe gas into a small chamber, where preionization occurs, initiating a discharge resulting in a Z-pinch plasma column. The self-compression of this column results in heating sufficient to generate Xe^{8+} to Xe^{12+} ions capable of emitting EUV light at 13.5 nm. Photons must pass through the debris mitigation tool before exiting the source for collection. A debris mitigation tool is commercially provided by XTREME technologies GmbH. The location of the mitigation region is shown in Fig. 36.5 at the junction between the test chamber and the EUV source adapter.

The EUV source emission is monitored using an International Radiation Detectors, Inc. (IRD) Ti/Zr/Si 6/480/50-nm photodiode capable of measuring 13.5 nm. This photodiode is positioned at the 35-deg port. It is used in a single reflection

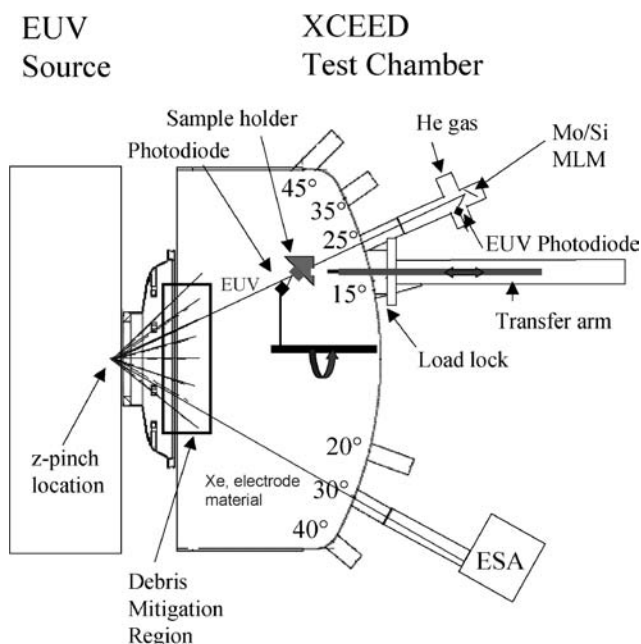


Figure 36.5 The XCEED test chamber allows diagnostic access at 5-deg increments from 15 to 45 deg off the Z-pinch axis.

system from a 40-bilayer Mo/Si mirror with a 4-nm Si capping layer. The reflectivity is 70%. The mirror is housed behind a 1-mm orifice and backfilled with He gas. This is intended to minimize ion damage to the mirror.

The primary diagnostic on XCEED is an ESA¹² capable of measuring ion energy and discriminating by charge state. These experiments use a Comstock¹³ model AC-902B™ with dual microchannel plate (MCP) detectors from Burle Corporation (model CP-618C™).^{14,15} The analyzer has line-of-sight access to the source through 2¾-in. ConFlat (CF) ports positioned at angular intervals of 5 deg from 15 to 45 deg from the centerline of the pinch. Access at 0 deg is impeded by the beam stop of the debris tool. Current experiments are performed at 20- and 30-deg angles. Data acquisition for the ESA is triggered by the rising light signal from the photodiode. The ESA is mounted on a bellows connection to the chamber for 3D pointing control. A 1-mm orifice located proximal to the ESA limits flow to the diagnostic. It is 97 cm from the pinch. The entrance orifice to the ESA deflector section is 3 mm in diameter, and the total distance traversed by the ions from the source to the MCPs is 150 cm. The layout for the diagnostic is shown in Fig. 36.6.

Ions that successfully traverse the distance from the plasma source to the entrance orifice of the ESA are discriminated against based on energy-to-charge ratio. The spherical sectors of the energy analyzer are charged to equal voltages of opposite sign. The inner sector is negatively charged and the outer is positively charged for proper ion deflection. This creates an electric field inside the device, which turns ions through 160 deg of curvature, where they impact MCP detectors. Ions

that are too fast are not turned sufficiently and extinguish against the outer sector wall. Similarly, ions that are too slow are overdeflected and extinguish against the inner sector wall.

A sample of the results from this diagnostic is shown in Fig. 36.7. At minimal buffer gas flow (10% of maximum) the primary ion seen is Xe^+ . The average energy is 8 keV.

The ion emission from the Z pinch is quite forward peaked. Figure 36.8 shows a comparison of the ion flux at 20 and 30 deg. From these data a rough estimate of the forward peaking factor can be made. Approximately twice as many ions come out at 20 deg than expected from an isotropic distribution. Therefore the predicted

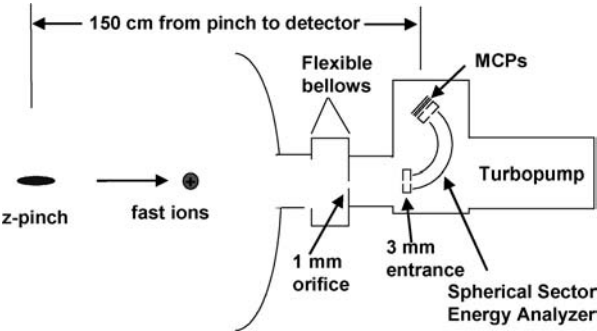


Figure 36.6 The ESA is mounted on a flexible bellows with a 1-mm orifice that limits flow and allows differential pumping.

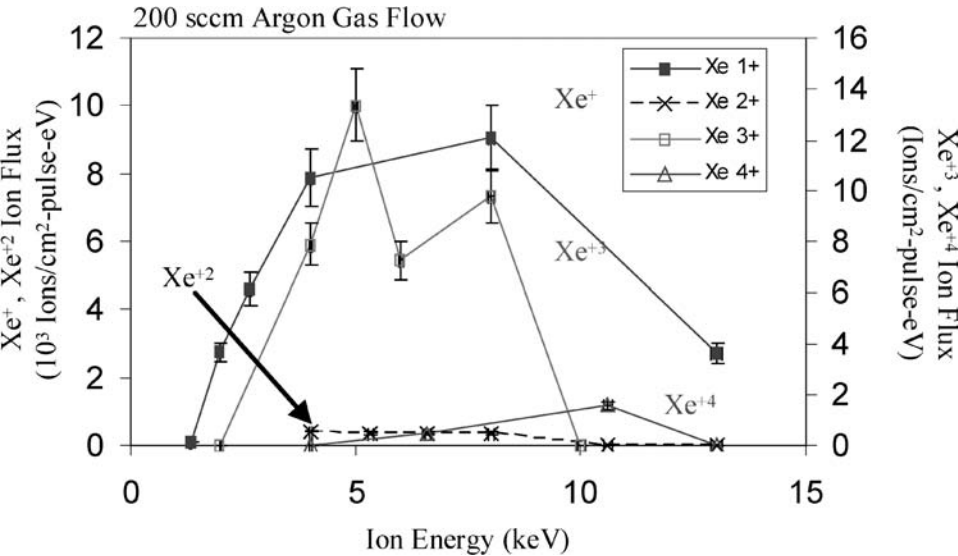


Figure 36.7 Ion energy spectra for 10% of maximum buffer gas flow at 20 deg from center-line at a distance of 97 cm from the pinch.

flux of ions 97 cm away from the pinch is

$$\frac{J}{4\pi(97)^2} \times 2 = 8.4 \times 10^{10} \text{ ions/cm}^2.$$

The XTS 13-35 was operated in Xe in our laboratory with the following conditions: The voltage drop over the pulse was 4.3 kV. The current through all the capacitors was 10 kA, and the pulse lasted about 0.25 μs . Therefore, these discharges were indeed on the order of 5 J per pulse, and the predictions should be valid.

The flux measured is shown in Fig. 36.7. To understand the scale of the figure, the dE energy bins are 1 eV. In other words, there are 9×10^3 Xe^+ ions between the energies of 7999.5 and 8000.5 eV. Integrating the energy distribution as half an ellipse and using a peak at 8 keV gives an integrated flux (over all energies) of 8.8×10^7 ions/cm² at 97 cm from the pinch. The reason the two numbers do not agree is the gas scattering over the path length. The ESA only detects an *uncollided* flux. During these experiments, the gauge pressure of the gas in the tank was 2 mTorr, which is about 1.4 mTorr of Xe. Using a measured cross section of $1.5 \times 10^{-15} \text{ cm}^2$ for Xe^+ in Xe, and the conversion ratio 1 mTorr = $3.3 \times 10^{13} \text{ cm}^{-3}$, we get uncollided flux = (predicted flux) $\times \exp(-1.4 \times 3.3 \times 10^{13} \times 1.5 \times 10^{-15} \times 97) = (8.4 \times 10^{10}) \times \exp(-6.72) = (8.4 \times 10^{10}) \times 0.0012 = 10 \times 10^7$ ions/mm² at the measurement orifice.

The agreement of these two numbers is fortuitous. Small errors in the scattering gas pressure could change the number substantially. However, the order-of-

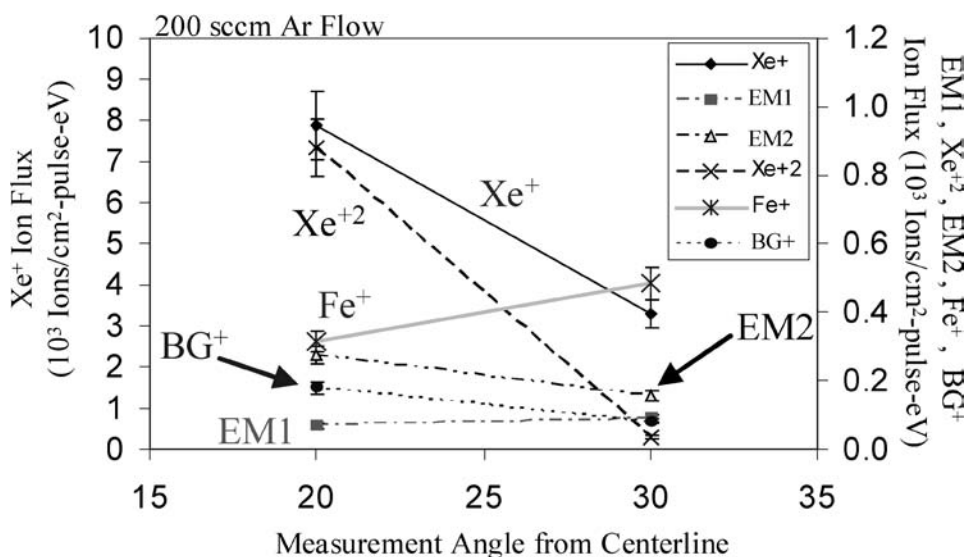


Figure 36.8 Angular dependence of measured 4-keV ion species measured from the Z-pinch centerline, taken at 10% of maximum buffer gas flow rate.

magnitude agreement lends credence to the arguments presented on the origin of the fast-ion signal.

36.3 Standard Mitigation Techniques

There are two primary mitigation techniques currently in use. The first is the use of a collimator, often called a *foil trap*. Though there are a variety of geometries proposed (see Ref. 16, for example), we will consider a foil trap whose thin plates are arranged like the spokes of a wheel from a central hub. The average spacing between spokes is s , the depth of the foil trap plates is c , and the geometrical transmission of the foil trap is t . See Fig. 36.9.

The other mitigation technique is simply to have a gas present between the source and CE1. Of course, the techniques can also be combined (see Ref. 17, for example), and usually will be if a foil trap is used, since gas must flow into the chamber to create the source in the first place. However, to analyze the effect of each of these techniques, we will examine each phenomenon independently and then combine the effects.

36.3.1 No mitigation

Even though the sputtered neutral atoms and reflected atoms are emitted in a cosine distribution, a large number of those atoms will still make it to some portion of CE1 if no foil trap and no scattering gas are present, since the collection elements are designed to intercept a large solid angle. That fraction should be similar to the collection solid angle for photons, q_3 . Therefore the total number of sputtered atoms to arrive at CE1 from one pulse, G_0 , is Gq_3 , and the total number of fast reflected atoms, F_0 , is Fq_3 . The number of fast ions to arrive, I_0 , is still I , since the factor

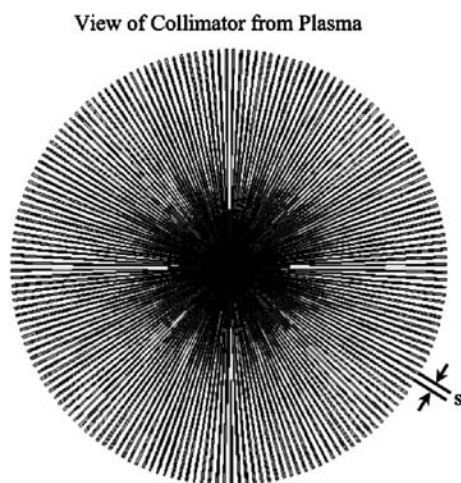


Figure 36.9 View of the foil-trap collimator from the EUV source.

q_3 was already taken into account in the definition of I . If one wished to allow for the peaking factor of ions, an additional factor of 2 or so should multiply I . To review:

$$G_0 = Gq_3,$$

$$F_0 = Fq_3,$$

$$I_0 = I.$$

The effectiveness of a given mitigation scheme will be given as a *protection factor*, which, for example, is the ratio of the number of fast ions that make it through a given mitigation scheme to I_0 .

36.3.2 Addition of a foil trap only

If a foil trap with transparency t is added to the system, but there is still negligible scattering between the source and CE1, the arrival species change as follows: The sputtered and reflected components drop dramatically, assuming that $c \gg s$. Let d be the distance between the pinch and CE1, as shown in Fig. 36.1. Then the total number of sputtered atoms to arrive at CE1, G_c , is approximately given by

$$G_c = G_0 t \frac{s}{c}.$$

The geometrical factor s/c comes from calculating the acceptance angle of the foil trap, since for small angles $\tan \theta = \sin \theta = \theta$. This angle is independent of d , since if d is increased and c and s stay constant, the numbers of slots in the foil trap must increase.

The total number of fast reflected atoms to arrive, F_c , is approximately

$$F_c = F_0 t \frac{s}{c}.$$

The total number of energetic ions (which follow the same trajectory as the photons) to arrive, I_c , is approximately

$$I_c = I_0 t.$$

Typical s/c ratios are likely to be 40:1, while t can be as high as 80%. This gives protection factors of 50 for the sputtered atoms and reflected atoms, but only 1.25 for fast ions.

36.3.3 Presence of a background gas only

A background gas fundamentally changes the problem from a geometrical calculation to a diffusion calculation, as long as the pressure is large enough that the mean free path for a sputtered neutral atom is much less than the dimensions of the

device. The mean free path for sputtered atoms in a background gas has been the subject of numerous works.^{18,19} Those calculations show that the mean free path λ for Cu in Ar can be given by

$$\lambda[\text{cm}] = \frac{9.2}{P[\text{mTorr}]}.$$

So, at $P = 35$ mTorr—a typical pressure very near the source—the mean free path is sufficiently small for the diffusion approximation to be valid. Other mean free paths have been calculated as well, and the resulting constant in the formula above is shown in the shaded boxes in Table 36.3. The other mean free paths in the table are merely approximations and should not be trusted unless no other data are available.

These are not the same mean free paths as the energetic Xe or Ar ions have. As shown earlier, an 8-keV Xe^+ has a mean free path of approximately 20 cm at 1 mTorr.

Assume there is a constant pressure P in the space between the source and CE1. A single pulse produces G sputtered atoms. These diffuse into a total volume of roughly $2d^3$. There are f pulses per second. Therefore the volumetric source rate is

$$\text{source rate} \left[\frac{\text{no.}}{\text{cm}^{-3} \cdot \text{s}} \right] = G \frac{f}{2d^3}.$$

The volumetric loss rate is

$$\text{loss rate} \left[\frac{\text{no.}}{\text{cm}^{-3} \cdot \text{s}} \right] = D \frac{n}{\Lambda^2},$$

where D is the diffusion coefficient and Λ is the diffusion length. The diffusion length and coefficient for the sputtered electrode atoms are approximately given by

$$D = \frac{\pi}{8} \lambda \overline{v_0},$$

Table 36.3 Mean free paths (in mTorr·cm) for low-energy sputtered atoms at 1-mTorr pressure.

(in mTorr·cm)	Al	Ti	Cu	W
He	32.6	37.2	38.8	42.1
Ne	6.6	15.5	24.1	35.3
Ar	4.4	6.9	9.2	28.2
Kr	4.3	4.1	5.5	16.4
Xe	4.1	4.0	4.5	7.0

$$\Lambda = \frac{d}{\pi},$$

where $\overline{v_0}$ is the average thermal velocity given²⁰ by

$$\overline{v_0} \left[\frac{\text{cm}}{\text{s}} \right] = 1.56 \times 10^6 \sqrt{\frac{T(\text{eV})}{\mu(\text{amu})}}.$$

Setting the source rate equal to the loss rate, we can calculate the average density n of sputtered metal atoms in the intervening space:

$$n = \frac{4Gf}{d\pi^3\lambda\overline{v_0}}.$$

The flux to the walls, Γ , is approximately given by $\Gamma = Dn/\Lambda$, so

$$\Gamma = \frac{Gf}{2\pi d^2}.$$

Using $d = 15$ cm, $f = 1$ kHz, $P = 35$ mTorr of Ar, and a Cu temperature equal to several times the background gas temperature of, say, 0.1 eV, then

$$n \text{ (cm}^{-3}\text{)} = 5.3 \times 10^{-4} G,$$

$$\Gamma \text{ (cm}^{-2} \cdot \text{s}^{-1}\text{)} = 0.7 G.$$

Note that the flux of atoms depositing per pulse is *independent of the background gas pressure* as long as (1) the pressure is high enough to allow the diffusion treatment to be valid, and (2) the gas does not flow. (Use of a flowing gas will be treated in the next section.) Using the G from earlier and assuming all the Cu atoms stick, the growth rate of a Cu layer on CE1 is about 40 nm/s. A layer of Cu (or W) thicker than about 10 nm will have a significant detrimental effect on the reflectivity. Clearly some mitigation scheme is called for.

The calculation of the flux of fast reflected fuel-gas neutrals arriving at CE1 is not necessary, since they will be thermalized due to the collisions with the background gas and therefore become indistinguishable from it.

If the only mitigation scheme employed were truly a static gas, all the energetic ions (and energetic neutrals through charge exchange) would still arrive at CE1. They would not be going in their original direction, but since they would primarily undergo forward-peaked scattering, they would still hit the mirror surface somewhere. With an eye toward combining gas pressure with the presence of a foil trap, we can calculate the uncollided flux after traveling a distance x . It is given by

$$I(x) = I(0) \exp\left(\frac{-x}{\lambda_{\text{in}}}\right),$$

where $I(0) = I$, and λ_{in} is the mean free path for ion-neutral collisions. Charge exchange has a higher probability, but it does not change the direction of the particle or its energy. The ion-neutral mean free path is given by

$$\lambda_{\text{in}} = \frac{1}{n_{\text{g}} \sigma_{\text{in}}},$$

where σ_{in} is the ion-neutral elastic scattering cross section, and n_{g} is the gas density. The ion-neutral elastic scattering cross section has a value of about $3 \times 10^{-16} \text{ cm}^2$ at 1 keV for Ar^+ in Ar ,^{21,22} and maybe $5 \times 10^{-16} \text{ cm}^2$ at 100 eV.

Therefore, for $P = 35 \text{ mTorr}$ we have $\lambda_{\text{in}} = 3.0 \text{ cm}$. For $x = d = 15 \text{ cm}$, we have $I(\text{CE1}) = 0.0067I = 1.68 \times 10^{13}$ energetic ions or neutrals per pulse that are uncollided. The flux of energetic ions or neutrals, Γ_{i} , at CE1 is given by

$$\Gamma_{\text{i}} = \frac{I(\text{CE1})f}{2\pi d^2} = 0.7I(\text{CE1}).$$

Thus $\Gamma_{\text{i}} = 1.2 \times 10^{13} \text{ cm}^{-2} \cdot \text{s}^{-1}$ for uncollided energetic Ar at 8000 eV and a source operating at 1 kHz.

Note that this number of uncollided ions at 15-cm distance from the pinch in a background pressure of 35 mTorr compares favorably with the observed currents in the IDEAL GEA. Only the uncollided flux will make it through the collimator to be detected. From Fig. 36.4 the current on the grid was around 6 mA over a microsecond from a single pulse. Dividing by the outer grid transparencies and taking into account the solid angle subtended, the measured current corresponds to roughly 1.0×10^{10} energetic ions per pulse, almost exactly the predicted number accounting for the repetition rate.

So, the protection factor of a background gas without the aid of flow or of a collimator is just 1 for the sputtered material, due to the diffusive nature of the sputtered atoms. It is also 1 for the energetic ion flux, since the gas will merely deflect the ions onto a different region of the collector. Only the reflected fuel atoms will be affected, and they will be thermalized completely, given any reasonable pressure and working distance.

36.3.4 A flowing background gas

If the background gas were moving, the bulk flow speed would have to be on par with the diffusive speed of the particles being mitigated to have an effect. Equivalently, the average resident time of the flowing gas would have to be comparable to the diffusion time. The diffusion time constant τ for a sputtered atom to cross a distance d is given by

$$\tau = \left(\frac{d}{\pi}\right)^2 \frac{1}{D}.$$

For Cu traversing a d of 15 cm, we have $\tau = 3.5 \text{ ms}$.

A flow of S sccm through a chamber of volume V at pressure P has an average resident time τ_{gas} of

$$\tau_{\text{gas}} = \frac{P[\text{Torr}]V}{760S}.$$

For a volume of $25 \times 25 \times 25$ cm, a pressure of 35 mTorr, and a flow rate of 200 sccm, τ_{gas} is 3.6 ms. The flux of any species arriving at CE1 is reduced approximately by the factor

$$\exp\left(-\frac{\tau}{\tau_{\text{gas}}}\right),$$

where τ is the diffusion time constant for that species. For the sputtered material in our example, the flux Γ of sputtered Cu atoms in a case where there is 200 sccm of Ar at 35 mTorr is now reduced by the exponential to

$$\Gamma(\text{cm}^{-2} \cdot \text{s}^{-1}) = 0.7 \exp(-0.97)G = 0.26G.$$

This is approximately a factor of 3. At 2000 sccm the sputtered atom flux is reduced to $6.1 \times 10^{-5}G$. The effect of the gas flowing on the energetic components is negligible because their resident time in the chamber is so short.

If the pressure were higher, say 1 Torr, and the flow kept at 200 sccm, then for the case of 0.1-eV Cu atoms diffusing through 1 Torr of Ar over a 15-cm path length, the diffusion time constant τ would be longer (100 ms). However, the resident time τ_{gas} would also be longer by the same factor (it too equals about 100 ms), so the effect on the mitigation would be the same and is independent of pressure. Gas flow is the most effective for droplets or other high-mass, slow components. Even for those components, though, the flow rate, not the pressure, is the important variable.

36.3.5 A foil trap and a background gas

When both a foil trap and a background gas are present, the diffusion calculation for the sputtered atoms is essentially unchanged. However, there are now many more surfaces on which to impinge, and therefore any deflection caused by the gas prior to the foil trap will have a marked effect. As long as the smallest dimension of the foil trap, s , is less than the mean free path, the combination of foil trap and gas pressure will prove more effective by far than either system by itself. That is the case for the example included in this work.

Diffusion through the foil trap is similar to a conductance problem in the molecular flow regime. For slits of varying width-to-depth ratios, the conductance a is given in the literature.²³ For $c/s = 10$, the conductance is reduced by a factor of 0.2. If the diffusing species did not stick to the surfaces, this factor would be the reduction in the flux. However, in this problem our diffusing species is Cu, which

has a sticking coefficient S of about 0.5. Therefore each bounce through the channel loses a factor of S from the flux. For a channel with aspect ratio c/s , there are approximately c/s bounces. All told, the flux to CE1 of sputtered atoms, taking into account a stationary background gas and a slotted foil trap Γ_c , is

$$\Gamma_c = \Gamma_a S^{c/s} = 2 \times 10^{-4} \Gamma \quad \text{for } S = 0.5 \text{ and } c/s = 10.$$

This factor can even be larger if c/s is larger, or if the sticking coefficient S is larger.

Only the portion of the energetic particle flux (fast ions and fast charge-exchange neutrals) that is uncollided will make it through. It was calculated previously and is only reduced from the previous calculation by the transmission of the foil trap. Therefore the energetic particle flux, Γ_{ic} , is

$$\Gamma_{ic} = t \Gamma_i = 0.8 \Gamma_i.$$

If the background gas were flowing, the flux of sputtered atoms would be further reduced by the exponential factor from the previous section. However, the flux of energetic particles would remain unchanged.

Therefore the total flux of sputtered atoms from the source (or condensable fuel gas atoms) for a flowing buffer gas and a foil trap is given by

$$\Gamma_c = \frac{f}{2\pi d^2} \exp\left(-\frac{\tau}{\tau_{\text{gas}}}\right) a S^{c/s} G.$$

The protection factor for the sputtered atom or condensable fuel gas is just the reciprocal of

$$\frac{1}{q_3} \exp\left(-\frac{\tau}{\tau_{\text{gas}}}\right) a S^{c/s}.$$

For a 200-sccm flowing background Ar gas at 35 mTorr, a foil trap with 80% transmittance and $c/s = 10$, a distance of 15 cm, and a sticking coefficient $S = 0.5$, the protection factor is about 30,000. This number can be greatly increased by improving the geometrical ratio, having a higher S , or increasing the flow rate. The residence time of the gas atoms in a region where they can affect the sputtered flux can also be lowered by flowing gas through the foil trap itself.

The fast-ion flux at the collector, Γ_{ic} , for the combination of a flowing gas and foil trap is given by

$$\Gamma_{ic} = \frac{f}{2\pi d^2} \exp\left(-\frac{d}{\lambda_{\text{in}}}\right) t I.$$

The protection factor for the fast ion (and charge-exchanged neutral) is just the reciprocal of

$$\exp\left(-\frac{d}{\lambda_{\text{in}}}\right)t.$$

For the same conditions listed above, this is approximately 185. It can be greatly increased by increasing the pressure and thereby reducing λ_{in} . For instance, doubling the pressure increases the protection factor to approximately 30,000. The flow rate has little to no effect on this component.

36.4 Mitigation through Plasma-based Secondary Ionization

Consider Fig. 36.10, which shows a secondary plasma generated in the space between the source and the foil trap. Previous experience^{18,24} leads us to believe that at 35 mTorr of Ar we will be able to sustain a $T_e = 2.5\text{-eV}$ plasma with an electron density of $3 \times 10^{11} \text{ cm}^{-3}$. This will lead to an ionization fraction of 90% for the sputtered neutral flux.¹⁹ That figure comes from running the SATIS code, which is a hybrid Monte Carlo and fluid code using a complete set of elastic and inelastic collisions, as well as past experience.

At higher pressure, say 300 mTorr, the electron temperature would be similar, but the density less by approximately an order of magnitude.²⁵ At these pressures

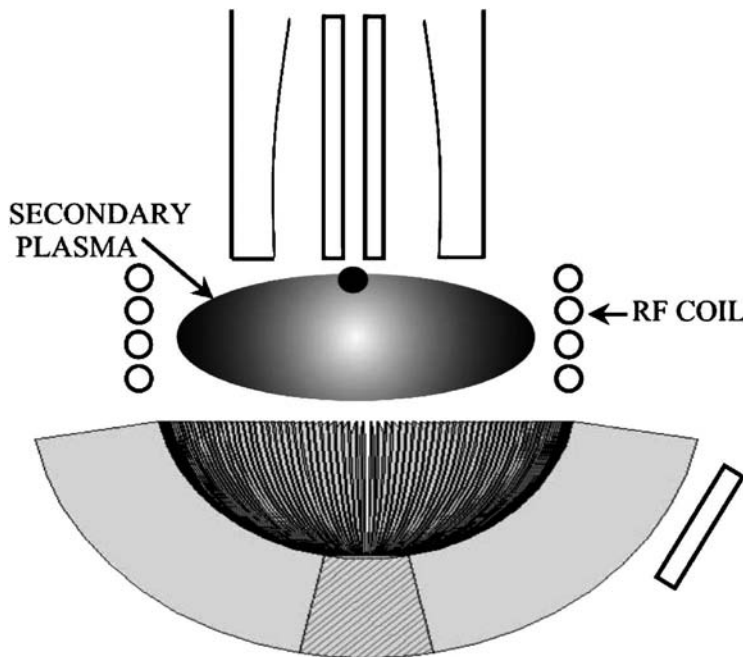


Figure 36.10 Schematic view of a DPF with a foil trap collimator and a secondary rf plasma.

the power to the plasma would be capacitively coupled, which is much less efficient. On the other hand, the residence time of a sputtered atom in the plasma is increased proportionally to the pressure, so it is not unreasonable to expect a similar degree of ionization, since the density times the residence time is about the same for both cases.

The pressure can be optimized for the degree of ionization. Guided by the commercial tools sold for ionized physical vapor deposition (PVD), where the key consideration is the degree of ionization of the sputtered species, pressures in the 60–75-mTorr range may be optimal. Ionized PVD tools also claim even higher degrees of ionization and sputtered material, approaching 100%.

36.4.1 Experimental ionization fraction

An experiment was conducted in IDEAL to determine the ionization fraction. This can be done by making a matrix of four measurements: the QCM can be placed directly under the pinch, or slightly to the side, where it primarily views the run-down portion of the ion signal; and the foil trap can be inserted or not at each of these locations. The complete results of those experiments are published in Ref. 9, but they are summarized below.

Consider Table 36.4. The presence or absence of each component is marked. For example, rundown ions *cannot* be seen when the QCM is on axis, independent of whether or not the foil trap is in place.

This experimental data set had to be taken with a relatively low rf power. In the present configuration of IDEAL, care must be taken to keep the coil’s floating potential low enough prevent sputtering of the antenna. If higher rf power were used, sputtering from the coil would be added to the debris components and invalidate the experiment.

Experimental values for *A*, *B*, *C*, and *D* correspond to the slope of QCM data at that setting. The system of equations ($X + 0 + Z = A$, etc.) can be solved for each debris component, and the ionization fraction is determined from here as well. The factor α is the optical transmission of the foil trap for a diffusive source. The factor γ is a geometrical reduction factor that accounts for the pinch region ions at oblique incidence to the QCM surface. Both α and γ are calculated geometrically.

Table 36.4 Matrix of expected signals for each of the experimental measurements. *A*, *B*, *C*, and *D* are measured quantities. The values of *X*, *Y*, *Z*, and *I* can then be determined. FT = foil trap.

	On axis		Off axis	
	No FT	FT	No FT	FT
Sputtered Cu	<i>X</i>	$(1 - i)\alpha X$	<i>X</i>	$(1 - i)\alpha X$
Rundown ions	0	0	<i>Y</i>	<i>Y</i>
Pinch-region ions	<i>Z</i>	<i>Z</i>	γZ	0
Total	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>

The ionization fraction of the sputtered Cu is i . In our case, α is calculated to be ≈ 0.828 , and γ is ≈ 0.928 .

Solving the system of equations yields the following formula for I :

$$i = 1 - \frac{1}{\alpha} + \frac{\gamma}{\alpha} \left[\frac{A - B}{(1 + \gamma)A - B - C + D} \right].$$

The other values can be solved for as well. The end results are:

Sputtered Cu flux, $X = 4.48$ (relative units)

Rundown ions, $Y = -2.26$

Pinch-region ions, $Z = -2.82$

Ionization fraction, $i = 0.61 \pm 0.03$

Note that the Cu flux is the largest contribution to the debris. However, on using a foil trap that intercepts 2π sr, this flux would significantly decrease due to the transmittance. This is consistent with observations in commercial devices that energetic ions are the main sources of mirror degradation.²⁶ The 61% ionization fraction is low due to the small amount of rf power that could be added without sputtering the rf coil. With Faraday shields surrounding the rf coil, higher rf power fractions can be tolerated, achieving a higher ionization fraction while not adding another source of debris.

36.4.2 Effect of the plasma on debris

If there is no foil trap present, ions will diffuse in a similar manner to the neutrals. There will be no difference in the deposition rate compared to the gas-only case. What will change is the charge state of the flux arriving at CE1. As described above, 90% (or more) of the sputtered Cu atoms would become ions. This means that they could be intercepted by the foil trap or other structures. The fast reflected neutral component will vanish due to the ionization, and even the fast ions will show some additional attenuation due to scattering interactions with the plasma.

Evidence for this last point comes from mounting an ion collector grid in the chamber below the DPF. The grid shows that as the rf input power is increased, the ion signal goes down and the ions slow down as well. Figure 36.11 shows this phenomenon. The top case is the one shown before, where a low-density plasma was present and the pinch ions are clearly seen with 5.5 keV of energy. The second case involves a much denser plasma more confined in the region between the foil trap and the pinch. High rf power is input into the device with the addition of 90 A of dc current through the helicon antenna itself to act as a magnetic shield. These operating conditions yield a plasma with $n_e = 10^{11}$ and a temperature of a few electron volts. Time-of-flight analysis of the measurements shows a reduced ion signal amplitude as well as reduced mean energy. This indicates that some screening of fast ions is occurring merely on account of having a secondary rf plasma in the chamber. This comes about through increased Coulomb scattering. The mean

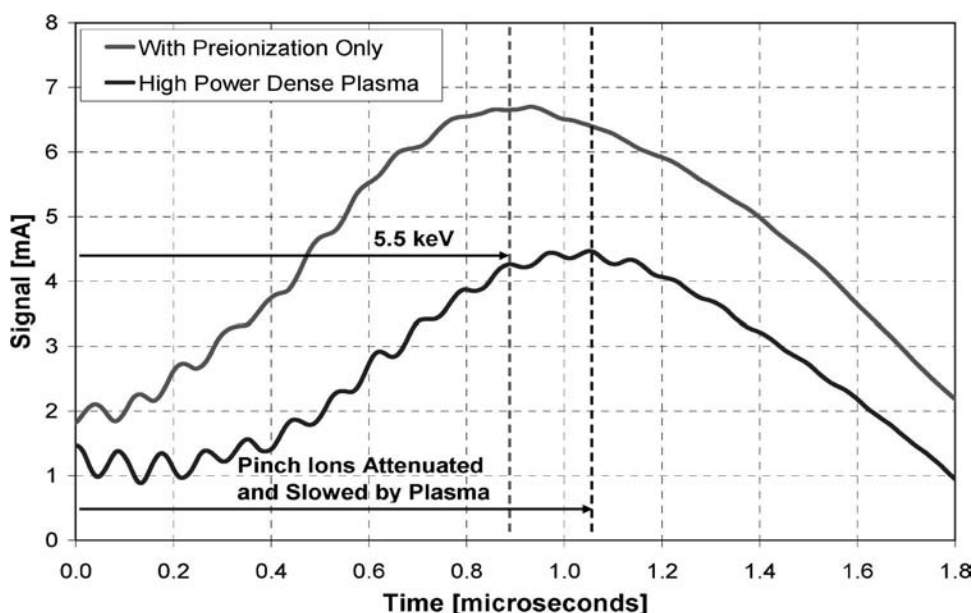


Figure 36.11 GEA time-of-flight signal showing how the plasma attenuates and slows the ion signal.

free path decreases with increasing number density. In addition to this, the bulk of the high-energy ions are of the same species as the secondary rf source plasma is, resulting in the largest possible energy transfer during collision events. Both of these effects account for the reduced ion signal measured on the ion collector grid.

Additional evidence for the plasma's effect on the fast ions comes from looking at the QCM signal. Separate data points were taken with virtually no rf power—only enough to provide a minimal preionization signal. The purpose was to still provide the preionization for the breakdown to occur, while not having any plasma in the region where it could ionize the sputtered Cu debris or affect the ion transit. Figure 36.12 shows that turning on the rf plasma *decreases* the erosion to the QCM. Some fast ions are attenuated by the plasma.

36.4.3 Plasma and biased collimation

The most efficient debris barrier, once a secondary ionization source is present, is the use of biased collimation. Figure 36.13 shows two adjacent planes of the radial foil trap. If every other plate is biased positively with respect to the plate between them, an electric field is produced that alternates in sign. This electric field deflects ions that traverse the foil trap. To stop an energetic ion with energy E_0 , a relation can be derived among the potential difference V between the plates, the length of the plates (c), and the separation of the plates (s) such that the incident ion shown

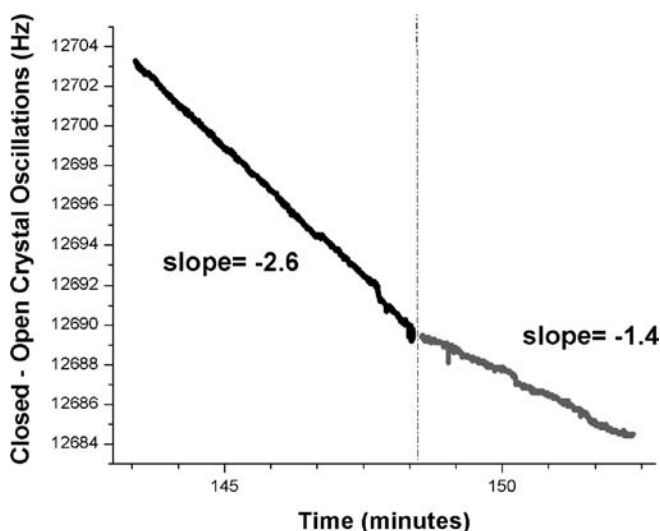


Figure 36.12 Pulsing with preionization only and then turning the rf plasma on results in less erosion to the QCM. Increased Coulomb scattering is responsible for a decrease in the number of high-energy ions incident on the surface. In the work presented here, a negative change in slope indicates erosion.

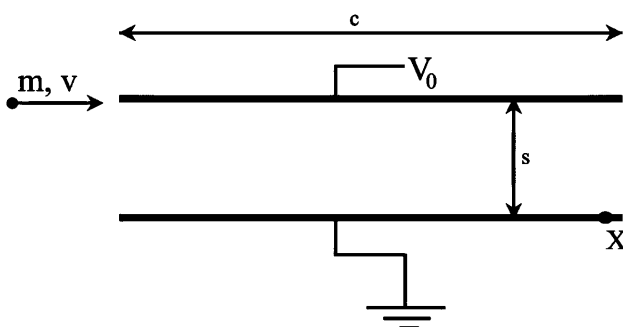


Figure 36.13 A blowup of one slot in a foil-trap collimator where every other foil has an alternate bias.

in Fig. 36.13 will strike the point marked X. The relation is

$$s = \frac{1}{2}c \sqrt{\frac{qV(\text{volts})}{E_0(\text{eV})}},$$

where q is in unit charges and will normally equal 1.

One problem with this approach is the pulsed nature of the EUV-generating process. During each pulse a fast-electron component is generated, which instantaneously biases the foil trap and masks the alternating electric fields. Likewise, the presence of a plasma may shield out any bias placed on the plates. To actu-

ally have an electric field present between the plates during the ion transit requires sophisticated timing of a pulse voltage signal to the plates.

Nonetheless, application of a secondary plasma between the DPF pinch location and the QCM produced measurable effects on debris deposition at the QCM monitor. Figure 36.14 provides data for the variable-aspect collimator in the 3:1 position for application of low-power rf secondary plasma. The debris deposition rate decreases by 30%. Both of these signals also have an accompanying erosive ion flux present, but are the same for each. The apparent ionization fraction is low due to the very low power and the 3:1 collimator. Placing alternating biasing (+100 V) on the collimator plates produced no measurable effect on deposition or erosion in this experiment, suggesting that the fast ion trajectories were not appreciably altered; this is consistent with the time-of-flight measurements of >4-keV ion energies and the discussion above.

At 200-W rf power a significant decrease in deposition is observed when the 5:1 foil trap is inserted as shown in Fig. 36.15. At this higher rf power, the discharge contains more sputtered neutral atoms and becomes deposition-dominated as opposed to erosion-dominated, due to sputtering of the helical resonator coil. However, the effect of the ionizing ability of the plasma in conjunction with the foil trap can clearly be seen.

If the timing of the biasing is handled correctly, a 100-V potential difference will deflect even 1-keV ions with an aspect ratio c/s as small as 6.4. Almost any field or spacing is sufficient to deflect the low-energy sputtered atoms, which have now become ions, as shown in Fig. 36.15.

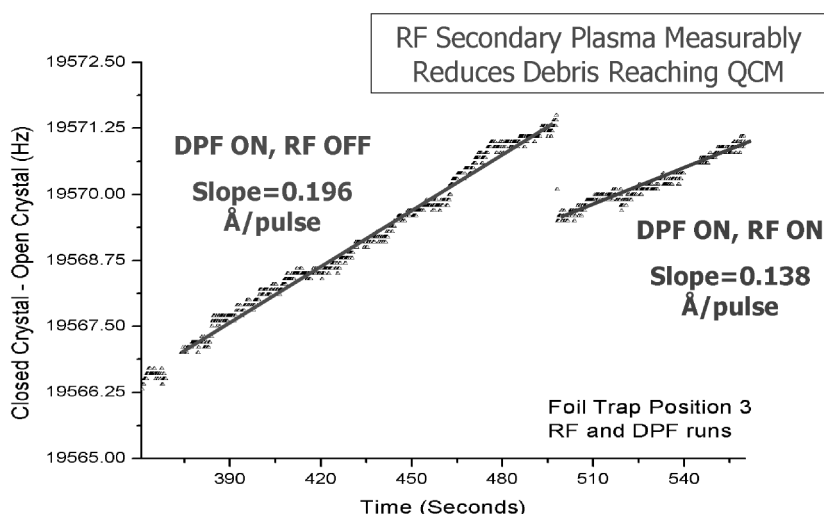


Figure 36.14 The QCM shows measurable reduction in debris during the application of low-power rf secondary plasma with a variable-aspect collimator in 3:1 position.

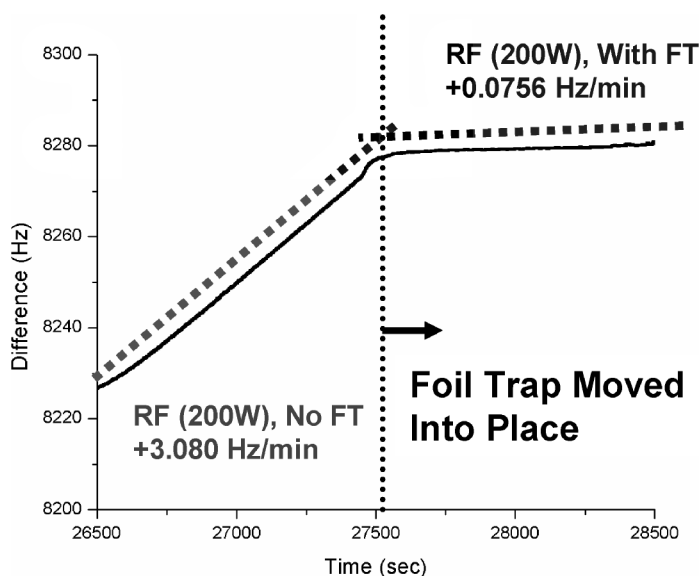


Figure 36.15 QCM signal, showing the effect of grounded 5:1 foil trap and rf ionization on debris and indicating >97.5% debris removal rate at very high-power rf.

The flux of sputtered electrode atoms reaching CE1 after high-powered plasma and biased collimation, Γ_p , is

$$\Gamma_p = 0.025\Gamma_c.$$

The factor of 0.025 comes from the 97.5% degree of ionization of the sputtered flux anticipated. As seen in Fig. 36.15, anything that is turned into an ion is blocked by the biased foil trap. This increases the sputtered electrode protection factor by a factor of 40.

The flux of energetic particles will depend on the ratio of the uncollided charge-exchange neutrals to the uncollided ions at the foil trap entrance. Any ion beam that transits a volume containing its own species will strike a balance between electron stripping (or ionization by a plasma) and electron capture (charge exchange).²⁷ For a beam that starts at 100% ions, the ratio of energetic ions to energetic neutrals, R_+ , after a distance x through a gas with number density n is given by

$$R_+ = \frac{\sigma_{\text{strip}} + \sigma_{\text{CX}} \exp[-(\sigma_{\text{strip}} + \sigma_{\text{CX}})nx]}{\sigma_{\text{CX}}\{1 - \exp[-(\sigma_{\text{strip}} + \sigma_{\text{CX}})nx]\}}.$$

In this case the integrated path length, nx , is large, and the ionization cross section outweighs the stripping cross section. Therefore the ratio of energetic ions to energetic neutrals, R_+ , reduces to

$$R_+ = \frac{n_e \langle \sigma v \rangle_{\text{ionization}}}{n_o \langle \sigma v \rangle_{\text{CX}}},$$

since n_0 is much greater than n_e , and the mean free path for charge exchange is so small (0.54 cm for these conditions)²⁸ that virtually all the uncollided flux charge-exchanges into neutrals. Whatever is left over will be attracted to the biased foil trap. The advantage of the plasma is that the uncollided flux is significantly smaller than if the energetic ions merely passed through a gas. This is due to the Coulomb collisions with the ions in the plasma in addition to the elastic scattering with the neutral atoms. Values from the literature²⁹ suggest that the ion-ion collision rate is on the order of 10^6 Hz for a plasma with $n_i = 3 \times 10^{11} \text{ cm}^{-3}$. The ion-fast-neutral collision rate would be a bit less. This leads to an ion-energetic-species mean free path λ_{ii} of approximately 5 cm. The combined mean free path λ_{total} is now less than that predicted before and equals 1.9 cm, from

$$\frac{1}{\lambda_{\text{total}}} = \frac{1}{\lambda_{ii}} + \frac{1}{\lambda_{in}}.$$

For a distance of 15 cm, the uncollided flux at CE1 with a plasma present, $I_p(\text{CE1})$, is

$$I_p(\text{CE1}) = t \exp\left(\frac{-15}{1.9}\right) I = 3.0 \times 10^{-4} I,$$

where t is the transmission of the foil trap (80%). This is an increase in the protection factor of 18 over not having a plasma present.

The flux of the charge-exchanged fast neutrals with a plasma present may be significant. The ionization cross section of very fast charge-exchange neutrals in the plasma is small, due to their short transit times. The uncollided flux that is charge-exchanged due to the presence of the background gas of the same species will travel directly to the mirrors. However, it is still just the uncollided flux that will make such a transit.

36.4.4 Pulsed plasma operation

How long does the plasma need to be sustained to have the effects calculated above? The transit time for a 1000-eV Ar across 15 cm is very small—only 0.6 μs . The diffusion time of the ionized sputtered neutrals is much longer. It can be computed from the confinement time τ :

$$\tau = \left(\frac{d}{\pi}\right)^2 \frac{1}{D_a},$$

where D_a is the ambipolar diffusion coefficient

$$D_a = D \left(1 + \frac{T_e}{T_i}\right),$$

where D was given earlier. Using an ion temperature after thermalization of 0.05 eV, an electron temperature of 2.5 eV, and a pressure of 35 mTorr, we have

$$\tau = 150 \mu\text{s}.$$

The time between pulses at 1 kHz is 1000 μs , so the ions that are created can easily diffuse during this time, even if the plasma is terminated early. Early termination may be beneficial for other reasons.

At higher frequencies, even a pulsed plasma will take on continuous characteristics; however, as long as there is a plasma present during some significant portion of the 150 μs following an EUV-producing pulse, mitigation should occur. This leads to the possibility of having the frequency of the secondary-plasma-producing circuit coupled to the EUV-producing plasma. Such a coupling may also mitigate the pulsed-voltage screening effect if the timing can be precise enough.

36.4.5 Magnetic field

The addition of a magnetic field confines the plasma, thus raising the electron density. This effect will increase ionization and ion scattering of the energetic species born in the pinch. There could also be an effect on the generation of the sputtered material. In addition, the magnetic field may physically confine the plasma nearer the source and thus reduce the current drawn by the biased foil trap. The effect on the etendue of the source may be prohibitive. Earlier DPF papers³⁰ show that adding a magnetic field to the pinch elongates the luminous region by stabilizing the kink instability.

36.4.6 Other effects

The addition of an inductively coupled secondary plasma source would introduce other components into the EUV source chamber and therefore potential sources of impurities. By use of a helical resonator coil with Faraday shields, sputtering of the coil can be reduced significantly. Even without that reduction, the impurities generated from the EUV source itself would dwarf any sputtering from the coil or feedthroughs in a commercial system. It is the proximity of the electrodes to the dense plasma source that causes their erosion. The coil and other structures necessary for the secondary plasma would be much further away from the pinch plasma.

The presence of the secondary plasma could influence the breakdown characteristic of the pinch plasma. This could be a beneficial effect and make the preionization step of some DPP schemes unnecessary. On the other hand, it could preclude operation in some breakdown regimes. The timing and voltage characteristics of the secondary plasma will have to be carefully matched to the particular pulsed primary plasma circuit.

The effect of the secondary plasma on the EUV light generated by the pinch plasma is expected to be minimal. The plasma will not be hot or dense enough for

reabsorption of the radiation. The light generated by the plasma will be diffuse and not be of the appropriate wavelengths to be reflected by the optics.

36.4.7 Plasma-mitigation conclusions

Debris mitigation by the addition of a dense plasma, a flowing background gas, and a pulse-biased foil trap will reduce the number of particles reaching CE1 significantly. Comparing the final results with the particle load expected with no mitigation (G_0 , F_0 , and I_0) for the specific parameters listed in this chapter (including a doubling of pressure in the trap to help attenuate fast ions) gives protection factors for each species of

1,200,000 for sputtered atoms,
 ∞ for reflected gas atoms,
540,000 for fast ions and charge-exchanged fast gas atoms.

The effect for other materials, pressures, gases, and geometries can be calculated given the equations already described. Higher flow rates, for instance, will dramatically reduce the flux of sputtered atoms.

36.5 Mitigation through Manipulating the Optical Elements

Another way to “mitigate” debris is to lessen its effect on reaching the optical elements. This can be done by offering a continually replenished sacrificial layer if the flux to the mirrors is primarily erosive, or by continual removal of the deposited material if the flux to the mirrors is primarily depositive.

36.5.1 Gibbsian segregation

There is an observed tendency of certain solutes in solid solutions to migrate from a bulk intermixed state and accumulate at imperfections, grain boundaries, and interfaces. This phenomenon is called Gibbsian segregation. Since the sputter depth—the characteristic length sputtered atoms are sputtered from—is only a few monolayers (0.2–1 nm) of material (whereas the EUV reflection properties are associated with depths of 1–2 wavelengths into the material, that is, 13.5–27 nm), there is an opportunity for Gibbsian segregation to result in enhanced surface properties. For example, high-reflection Ru could be alloyed with a sputter-resistant material, such as tungsten (W, ~2%), or a massive segregating material, such as gold (Au, ~2%), to form a shallow, high-surface-energy layer to protect the reflection layer (Ru). Or highly segregating Cu could be added in a small percentage to be sputtered preferentially. Alloy and segregation-layer combinations even could be selected for self-healing diffusion and migration processes to repair surface damage and protect from debris impact. In a reference case, W-capped Ru, EUV rays are able to penetrate this shallow surface layer due to their high energy and are subject to reflectivity from the bulk ruthenium material.³¹

The primary mechanism of surface enrichment is diffusion of one species through the bulk lattice medium. In addition, there are crystal imperfections (point defects, line defects, and 2D defects) and grain boundaries, which serve as solute conduits for delivering material to the surface of a material. The driving force for segregation is the difference in chemical potential between the surface and the bulk for a given component. Equilibrium is achieved when the total free energy (including contributions from the bulk and surface regions) is minimized at a given temperature; thus the optimal surface segregation depends on the thermodynamics (temperature) and the crystal structure (closed-packed orientation). Figure 36.16 illustrates the concept.

The selvedge and near-surface characteristics are important for estimating the EUV reflectivity for total external reflection, which must be satisfied for reflection with minimal attenuation in the bulk material. There are binary, ternary, and quaternary alloy configurations to maximize the surface binding energy, to provide sacrificial material (to be lost due to preferential sputtering), and/or to enhance thermodynamic transport properties for regenerative healing. The surface mole fractions will depend on the free-energy minimization between the host and solute elements.

Initial code investigations of a hypothetical 100%-segregated material indicate that there is a slight reduction in reflectivity due to the presence of the surface layer. For the reference cases of Ru-W and Mo-W, the reduction is 2–5%, depending on the angle of incidence. These results are shown in Fig. 36.17.

Initial estimates of the effect of segregated layers on lifetime for an ideal segregated surface are impressive. For the case of a pure Ru collector with EUV incident at 20 deg (relative to the surface plane), 100–1000-eV He^+ and Xe^+ ions (emitted from the Z pinch during maximum compression) will sputter approximately 0.3 Ru atoms per incident ion. The presence of a 0.5-nm W segregation layer on top of the Ru reduces the Ru sputtering yield to zero, effectively shielding the mirror surface from ion damage. Figures 36.18 and 36.19 show the sputtering yields of W and Ru for such a surface as a function of Xe and He impact energy, respectively. A bare Ru surface is shown for comparison in both figures. Some segregated surface W atoms are sputtered, while displaced Ru atoms from the bulk lattice are trapped inside the bulk due to the segregated capping layer. This process occurs even at 1000-eV Xe impact energies and is illustrated in Fig. 36.20.

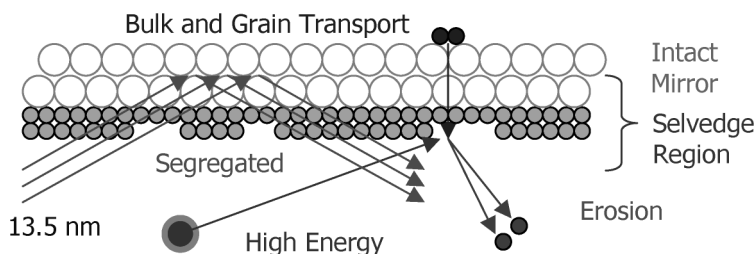


Figure 36.16 Illustration of an erosion-resistant, self-healing Gibbsian-segregated collector alloy. The selvedge surface region is marked by deviations from the bulk lattice spacing.

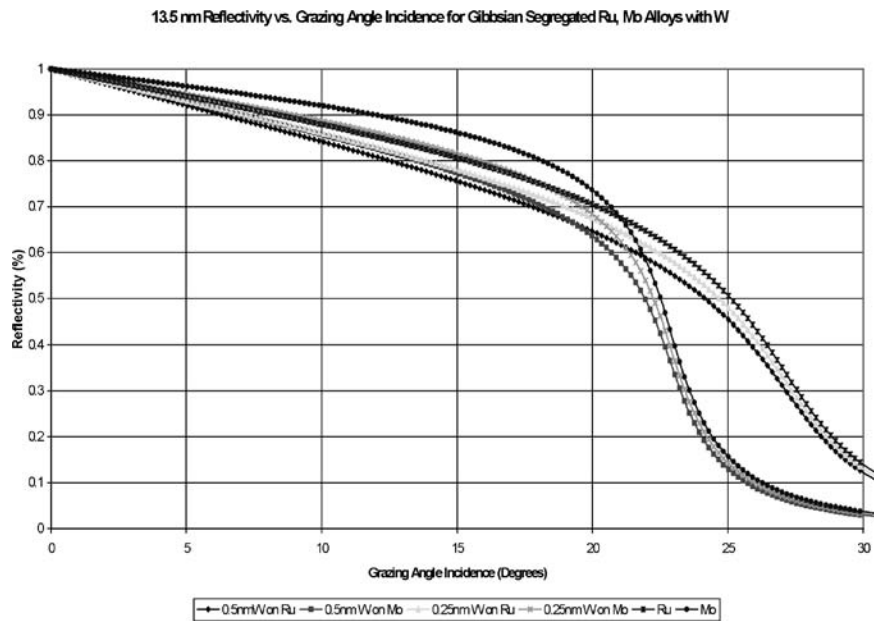


Figure 36.17 Reflectivity versus grazing angle for segregated Ru- and Mo-W alloys at 0.5 nm.

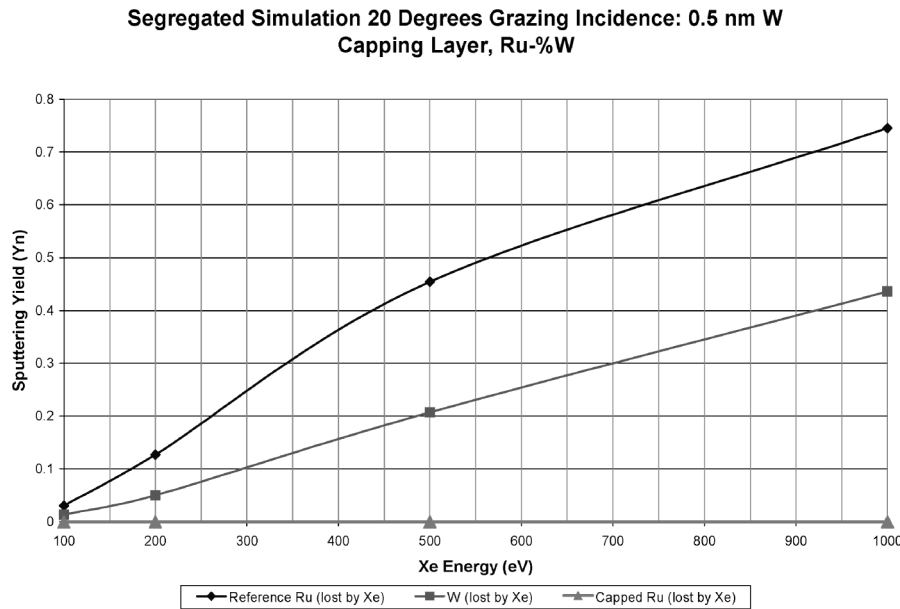


Figure 36.18 Code simulations for sputtering yield at 20-deg Xe grazing incidence for pure Ru and for Ru with a segregated 0.5-nm W capping layer. Note zero Ru sputtering with W layer.

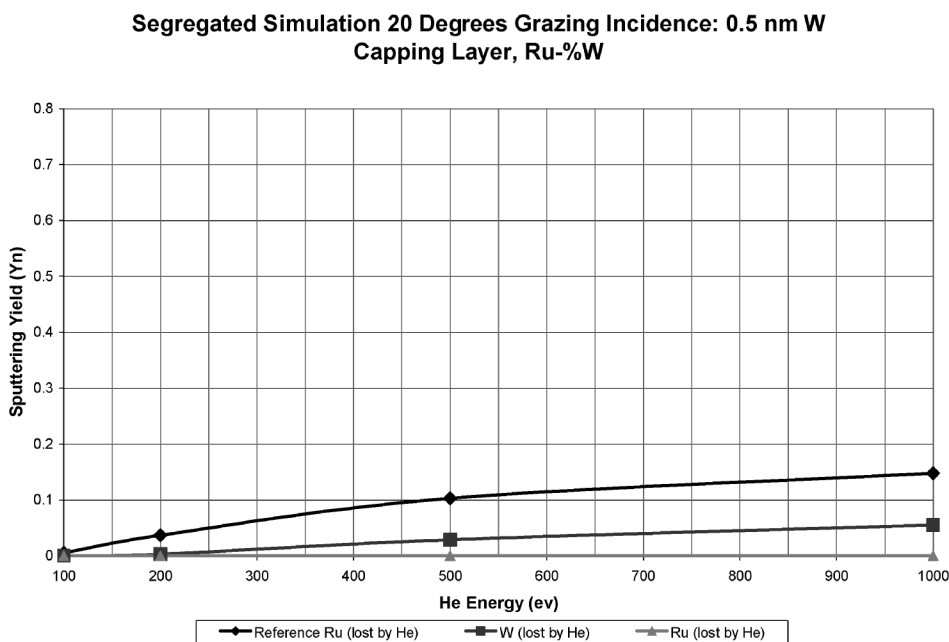


Figure 36.19 Code simulations for sputtering yield at 20-deg He grazing incidence for pure Ru and for Ru with a segregated 0.5-nm W capping layer. Note zero Ru sputtering with W layer.

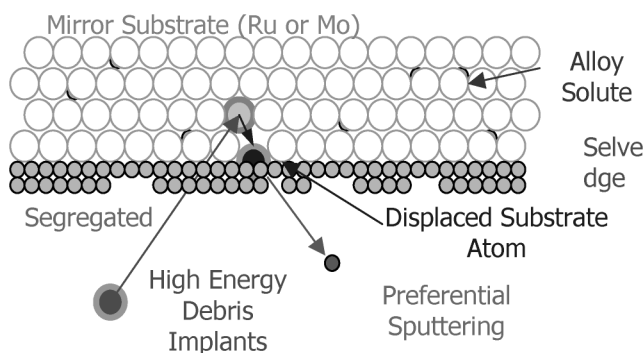


Figure 36.20 Illustration of trapping phenomena, where a substrate Ru or Mo atom is displaced by high-energy debris, but cannot tunnel the surface segregation layer.

These results indicate that if the regenerative transport processes (bulk, grain, crack diffusion) and surface renormalization are faster than the erosion time scale (i.e., the average time between large energy sputtering events), then the collector optic could be self-repairing. Estimates of these quantities depend greatly on the activation energy for segregation along a grain boundary, E_a . For $E_a = 0.6$ eV, the flux rate of atoms to the surface is $10^{20} \text{ cm}^{-2} \text{ s}^{-1}$. This is orders of magnitude above any loss rate from a sputtering flux. However, there are still many unanswered questions, such as the effect of surface roughness, the ability of ma-

material to segregate through impurities, and whether an easily diffusible sacrificial alloy material that is only one or two atoms thick would indeed offer superior lifetime. Experiments at the University of Illinois are underway to test this concept.

In addition, such segregation properties will enhance the collector mirror surface's resistance to active cleaning techniques to remove passive carbon and oxygen layers (even Sn and Li vapor deposition).

36.5.2 Active plasma cleaning

If condensable fuels are used in an EUV-producing device such as Sn or Li, the protection factor required against their diffusion to the mirror surface will be enormous. Most likely there will still be a significant flux of Sn or Li vapor ultimately reaching the grazing-angle mirror surface. Therefore a mechanism to remove the Sn or Li atoms is needed. Low-energy discharge plasma etching could be used to preserve the collector mirror's integrity by actively removing the deposited material. Sn vapor contaminant deposits with thermal energies, has a low heat of sublimation, and binds only weakly to collector surfaces. There are various halide etchants that could etch Sn selectively. Li vapor also deposits with thermal energies but has a strong affinity to form compounds. However, Li also has a high vapor pressure and could be removed thermally or allowed to diffuse toward sacrificial trapping sites. In either case, low-temperature plasma can be used to continuously knock off weakly bound, deposited atoms with low-energy ions and neutrals. Since this active cleaning is a statistical process, involving surface binding energies, plasma energy, broadband light illumination, and the mirror substrate temperature, the rate coefficients for Sn or Li removal can be adjusted for an optimal condition. If a low-mass particle, such as H or He, is used for the cleaning process, then damage to the underlying mirror substrate can be minimized.

The presence of a very thin Sn or Li layer on the mirror surface could be beneficial to mitigate mirror substrate erosion from high-energy debris impacts. A few monolayers of fuel vapor left on the mirror substrate surface will have a small EUV attenuation effect, since the distance (0.2–1.0 nm) is less than the wavelength. The small attenuation loss due to this layer could be surpassed by the gain in collector erosion resistance, since the Sn layer will act as an erosion shield and sputter guard or the Li will act as a sacrificial layer to be sputtered. Therefore, continuously bombarding the collector surface with the weak plasma could control the fuel vapor layer to a manageable level without harming the substrate beneath, and extend the lifetime of the collector optic. Such a system is illustrated schematically in Fig. 36.21.

Experiments are underway at the University of Illinois in a new facility called SCOPE (Surface Cleaning of Optics by Plasma Exposure) to test the effects of active plasma cleaning to remove Sn and Li deposition from collector optics.³² A theoretical treatment of the problem is given in the next section.

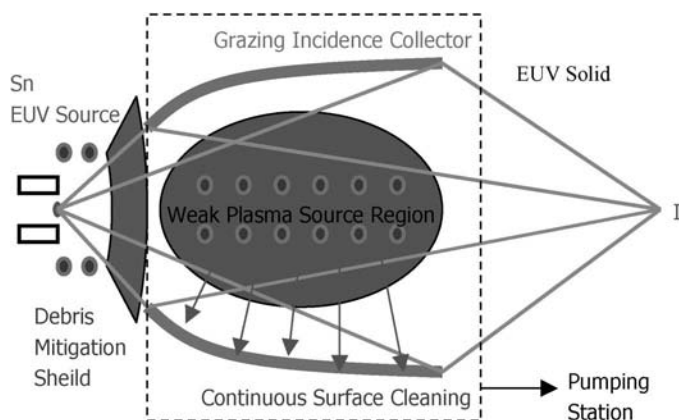


Figure 36.21 Illustration of continuous collector Sn management system. A weak plasma source is driven in the intramirror space to drive low-energy H or He onto the surface.

36.5.3 Theoretical analysis

A system where thermal Li deposits on a temperature- and voltage-controlled mirror surface while simultaneously being bombarded by Li ions and by a He cleaning plasma has been simulated. Full details for both Sn and Li can be found in Ref. 33. The energy and, to a good extent, the density of the secondary He plasma are the only controllable parameters in this analysis. The evaporative and energetic Li flux will be determined by the particular EUV system being analyzed.

A He plasma can be generated with a density of around 10^{12} cm^{-3} , with the energy of He ions striking the surface controlled by the biasing of the mirror. The directed ion flux is given by $\Gamma = n v$. Figure 36.22 shows that the secondary He plasma allows complete control over the net erosion or deposition of the Li layer. With no plasma, or at the very low end of the energy or density range, Li builds up on the surface at or near a rate of 4 monolayers every second. However, with a slight increase in He plasma density or incident ion energy, we can achieve steady-state conditions or even remove Li at relatively high rates.

Figure 36.22 shows that a low He plasma density of 10^{10} cm^{-3} would require a mirror bias between 200 and 300 eV. At 10^{11} cm^{-3} , the energy required is between 25 and 50 eV. At higher densities the He^+ energy can be 25 eV or even less. It should be noted that at such low energies the sputtering data used in the model become less reliable, because the binary-collision approximation becomes less accurate at lower energies. From a practical standpoint, it may also be easier to control the Li layer thickness with a lower density due to the steep nature of the 10^{12}-cm^{-3} curve in Ref. 22.

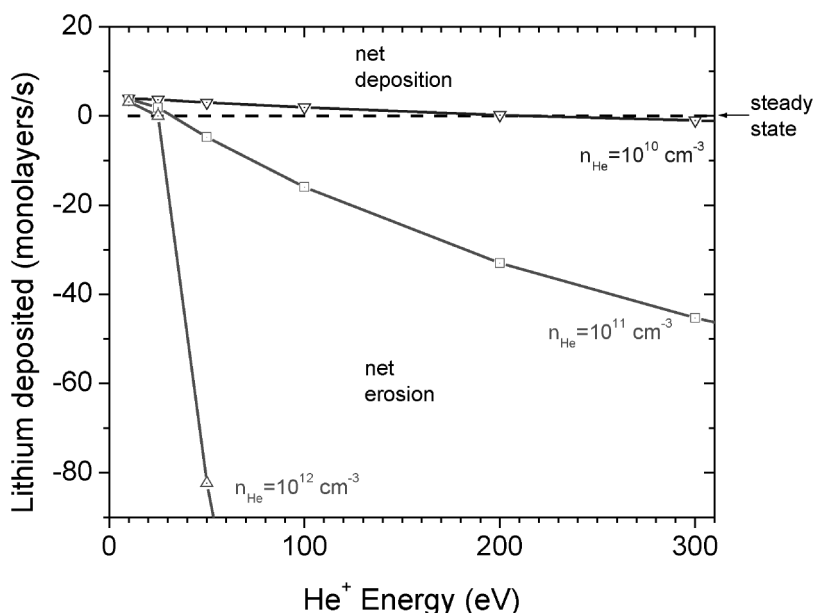


Figure 36.22 The requirements for He plasma density and incident He ion energy to maintain a steady-state thickness of Li on the surface.

Acknowledgments

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Chapter 37

Erosion of Condenser Optics Exposed to EUV Sources

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Neal R. Fornaciari, and Hiroshi Komori

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37.1 Introduction

EUVL is a leading candidate for integrated circuit (IC) chip manufacturing below the 45-nm node.¹ The technical basis for the approach is the use of a much smaller wavelength, 13.5 nm (92.5 eV), than is used in current manufacturing (193–248 nm). The very small radiation wavelength allows for much higher imaging resolution at relatively small numerical aperture (NA), all with an acceptable depth of field. Since the initial development of EUVL in the early 1990s, followed by the much more intensive development effort conducted by the Virtual

National Laboratory (VNL) in collaboration with the EUV Limited Liability Company (LLC), an important challenge to the technology has been the development of a commercially viable EUV light source. The source of 13.5-nm radiation must provide sufficient EUV flux to enable high-volume manufacturing (HVM): the production of one hundred 300-mm-diameter wafers per hour while being highly reliable. Other contributors have discussed the types of EUV sources (all based on localized plasmas) that have been developed, including their spectral output, stability, size, and other operating characteristics. In this chapter, the focus will be on the degradative effects on optics directly exposed to plasma sources of EUV radiation. In particular, the tendency of the plasma to physically remove optical coatings, a process we call erosion, will be discussed.

There are two distinct types of commercially viable EUV sources: laser-produced plasmas (LPPs) and discharge sources.² In an LPP source, an intense laser beam (typically Nd-YAG, 1064 nm) is directed onto a target. The target can be solid, liquid, or gas. Under intense laser radiation, the target is dissociated and vaporized into a highly ionized plasma. Electron acceleration within the plasma (producing continuum radiation) as well as fluorescence from ionized atomic species leads to radiative emission over a broad range of wavelengths from the IR to the soft-x-ray. Of particular interest for EUVL is that the emission can also take place near 13.5 nm. Much work³ in the 1980s and early 1990s was performed on solid targets such as gold, tungsten, and tin, although it was very quickly realized that in addition to creating large numbers of EUV photons, the sources produced a large amount of debris consisting of vapor and particles from the solid target. This debris produced undesirable deposition on collecting optics and plasma diagnostic equipment. This debris-induced deposition is a serious limitation to the use of solid targets as a reliable source of EUV radiation.

In an effort to circumvent the problem of debris-induced deposition, a great deal of work⁴ has focused on laser plasma sources using targets composed of liquid or frozen Xe, the idea being that once the Xe was volatilized by the laser beam, the gaseous Xe could not deposit on the collecting optics. This expectation was in fact realized, and Xe LPP sources have since been the focus of a great deal of work. However, experience has shown that it is still possible to generate condensable debris from a Xe LPP source if the nozzle producing the condensed Xe flow is degraded by exposure to the plasma.

A second type of source is generally termed a discharge-produced plasma (DPP). In a DPP source, an electrical discharge is struck in the target medium, producing a plasma that emits EUV radiation. DPP sources include those based on a capillary electric discharge, as well as those based on a Z pinch.² If a condensable target material is used in these discharge sources, large amounts of target material can be deposited on collector optics, degrading reflectivity. Even if a non-condensable target material is used (such as Xe), degradation of the electrodes by plasma operation can also lead to deposition at the collector optics.

As EUV sources have developed, in some cases it has been possible to completely eliminate the deposition of foreign materials onto optics collecting the EUV

radiation. In the case of an LPP source, this debris elimination has been achieved by using a filament-jet Xe source in which the Xe target is produced as a solid frozen rod (filament) of Xe. The rod can be made stable at large distances (5 to 10 cm) from the source nozzle, allowing the plasma to be created by the laser beam well away from the nozzle hardware. This arrangement eliminates debris coming from plasma-induced degradation of the nozzle.

However, it has been found⁵ that there is another damage mechanism that becomes predominant when deposition of debris is completely eliminated. That damage mechanism is erosion of the multilayer coatings on the collector optic. By necessity, the first collector optic must directly face the plasma in order to collect as much EUV light as possible. This plasma-facing optic, typically the only optic in the lithographic system that directly views the plasma, can suffer rapid loss of coating when exposed to it. This chapter will focus exclusively on the problem of the erosion of EUV multilayer coatings on plasma-facing condenser optics. Other authors have discussed the history and progress of minimizing the deposition of foreign materials (debris) onto the condenser. A third mechanism for condenser-optic degradation—namely, the EUV-induced degradation of the condenser by the interaction of EUV photons with trace amounts of water vapor or hydrocarbons in the system,⁵ leading to oxidation or carbonization – will not be discussed.

One type of condenser optic consists of alternating layers of Mo (~ 28 Å) and Si (~ 40 Å) deposited on a water-cooled substrate. The erosion of these layers leads to loss in reflectivity. Figure 37.1 shows a calculated plot of the EUV reflectivity of a multilayer-coated optic as a function of the number of layer pairs deposited on the substrate. For zero added pairs, the reflectivity is negligible, because the normal-incidence EUV reflectance for all materials is essentially zero. As layer pairs are added to the substrate, the reflectivity increases until approximately 40 pairs are added, at which point the reflectivity does not increase further. Erosion results in the removal of layers from the optic. From Fig. 37.1, it can be seen

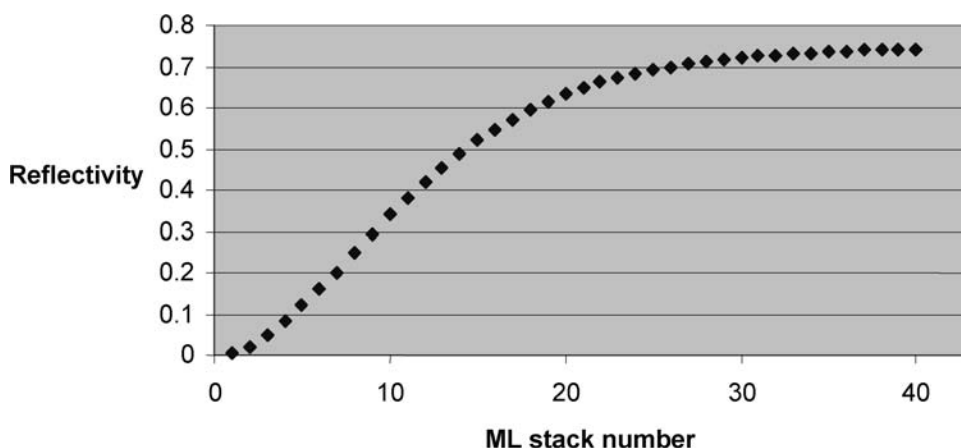


Figure 37.1 Theoretical plot of reflectance of a Mo/Si-coated mirror as a function of the number of bilayer pairs (reprinted from Ref. 5).

that while the optic is tolerant of the removal of approximately 10 bilayers, with further removal the reflectivity drops dramatically. This loss in reflectivity is the primary degradation caused by the erosion process. An additional difficulty for an EUVL tool occurs if this erosion produces nonuniform losses in the condenser reflectivity. Such nonuniformities will degrade the quality of the exposure at the wafer plane. This problem will be discussed later in examining the influence of condenser erosion on the operation of the Engineering Test Stand (ETS).

The remainder of this chapter is organized as follows. In Sec. 37.2, we review early observations of the erosive effects of plasma exposure. In Sec. 37.3, the observations of condenser erosion during the operation of the ETS will be reviewed. The erosive phenomenon observed in the ETS motivated a research project, sponsored by International SEMATECH, into the causes of this erosion. This project examines the species emanating from a high-power Xe LPP and the nature of the erosive process. The studies will be reviewed in Sec. 37.4. There has also been work through the EUVA consortium on the problem of condenser erosion. This other work will be reviewed in Sec. 37.5. Section 37.6 briefly touches on work in other laboratories.

37.2 Early Work on Condenser Erosion

Of the potential sources that have been studied, the electric capillary discharge source⁶ was one of the smallest and simplest. Previous work on the EUV electric capillary discharge source showed a consistent increase in power generation and a reduction in debris generation over several years of development.⁶⁻⁸ However, there remained a significant problem of erosion for optics directly viewing the discharge plasma.

37.2.1 Debris studies from the electric capillary discharge source

Studies of debris from the electric capillary discharge source and its mitigation using a *gas curtain* are now summarized.

The intent of the gas curtain was to alter the trajectory of the electrode debris enough to prevent it from depositing on or sputtering plasma-facing condenser optics (see Fig. 37.2). To do this, a jet of gas flowing perpendicular to the axis of the lamp imparted transverse momentum to the debris, deflecting it enough to miss the condenser. For these experiments, the gas curtain was a round supersonic jet formed by flowing He through a diverging nozzle. Helium was used because it was determined to be the best compromise between deflection efficiency and EUV absorption losses.

A laboratory dedicated to the development of the gas-curtain debris mitigation system was constructed at Sandia National Laboratories. This lab features robust pumping and gas-flow capabilities. The experimental chamber is shown in Fig. 37.3. The witness plate was located 14 cm from the source, which was the approximate distance of the condenser optics in the ETS. The ratio of the output of

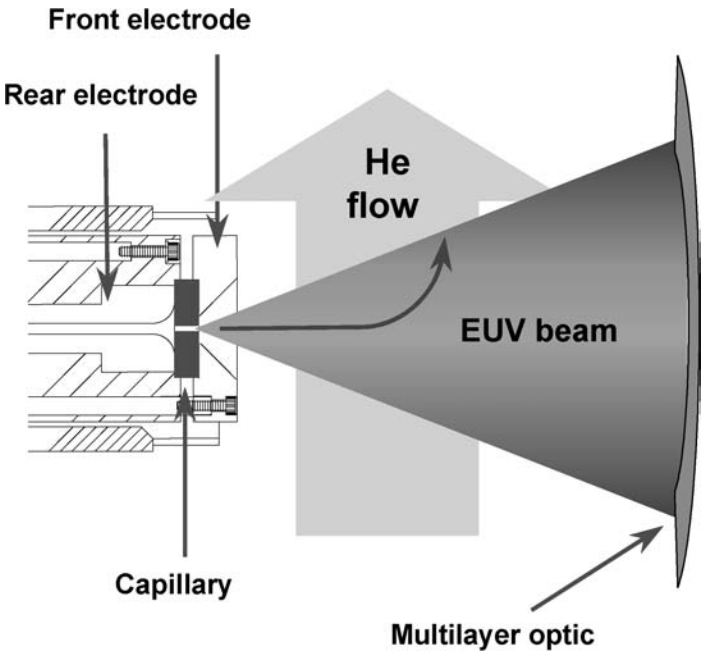


Figure 37.2 Schematic showing the gas-curtain concept.

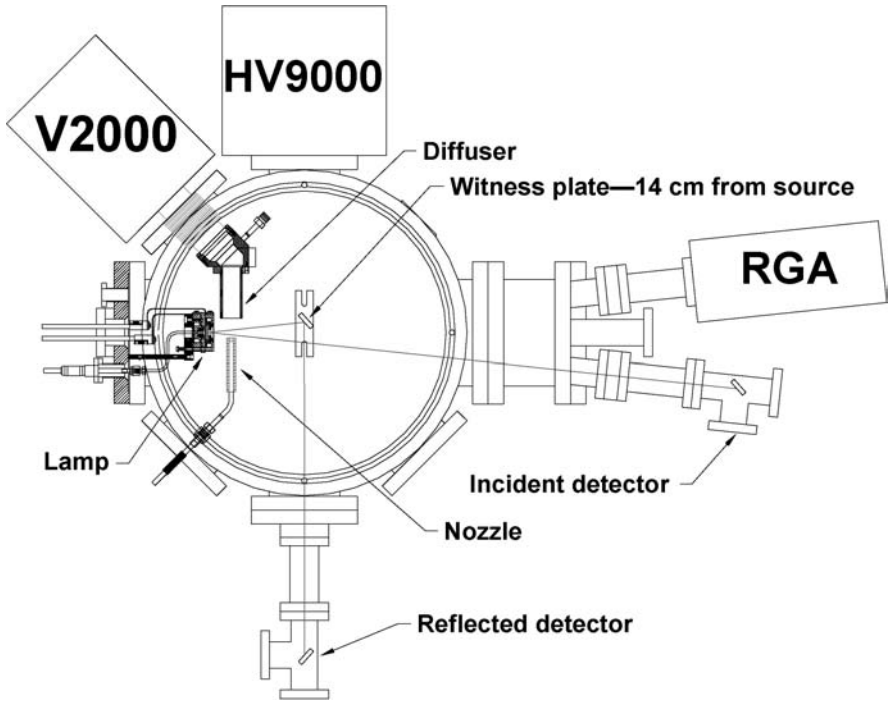


Figure 37.3 Experimental chamber for gas-curtain studies.

the two EUV detectors indicated in Fig. 37.3 measures the reflectivity of the multilayer condenser optic as a function of time, independent of changes in the lamp output. The 1-in.-diameter diffuser was located 1 in. from, and was coaxial with, the nozzle. Two large pumps were incorporated into the system. An Aerzon V2000 two-stage Roots-based pump was used on the diffuser, and an Aerzon HV9000 three-stage Roots-based pump was used on the chamber. The He gas throughput was 760 Torr·l/s; the ambient He pressure was approximately 22 mTorr.

The mitigation efficiency of the gas curtain was determined by analysis of witness plates exposed to 1 million pulses both with and without the gas curtain operating. The witness plates were 1-cm-square Si substrates coated with 20 Mo/Si layer pairs. The source was operated at 500 Hz, 1500 V, and ~ 5 -Torr Xe pressure with a 1- μ s pulse width, yielding a peak current of about 3.5 kA. The lamp was outfitted with 80%/20% W/Cu electrodes.

37.2.2 Erosion mitigation

An analysis of the witness plates using Auger depth profiling typically reveals the amount of vapor debris deposited during an exposure run. For these erosion Auger analyses, the multilayer was sputtered through to the Si substrate to determine if any erosion had occurred during the test. Figure 37.4 is a plot of the depth profile for the case without the gas curtain. The analysis reveals that only 3 of the original 20 layer pairs remained after 1 million pulses. Because of the significant amount

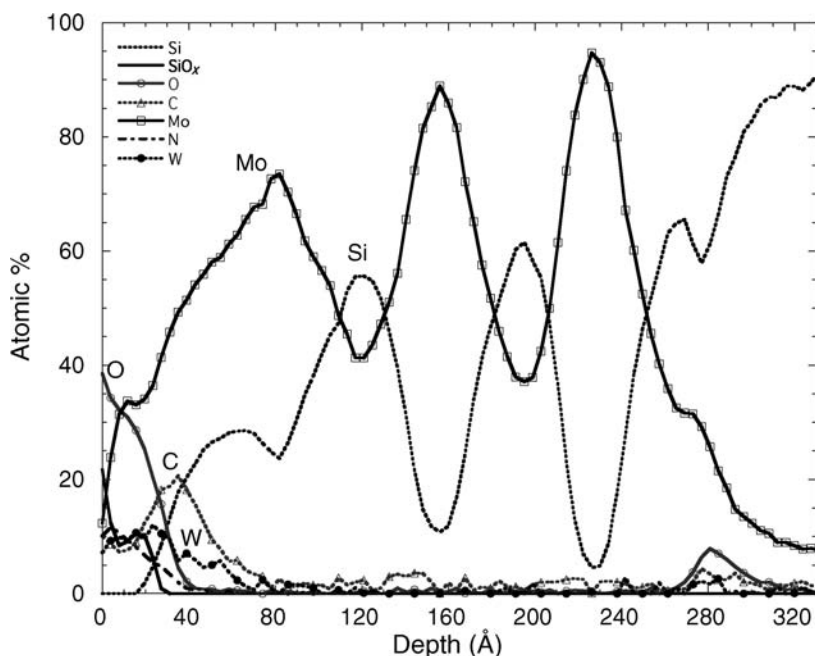


Figure 37.4 Auger sputtering results for the witness plate exposed without the gas curtain operating.

of erosion that took place, no conclusion could be drawn regarding the rate of deposition on the witness plate without the gas curtain. By contrast, Fig. 37.5 reveals that only the Si capping layer and perhaps part of the first Mo layer were eroded with the gas curtain operating. The mechanism for erosion mitigation using the gas curtain was not elucidated in these experiments, as debris mitigation was the primary aim. In particular, the relative contributions of He gas flow and the 22-mTorr He background were not determined.

Figure 37.6 shows the near surface of the witness plate from Fig. 37.5. This plot shows a moderate amount of both tungsten and copper deposited on the surface of the witness plate with the gas curtain running. While at first glance this would seem to imply that the gas curtain is not working to deflect the vapor debris, a look at the geometry of the experimental setup reveals a more plausible explanation. Figure 37.7 is a side view of the gas-curtain geometry. Figure 37.7(a) shows the exclusion zone where debris generated by the lamp heading toward the witness plate would be intercepted by the gas-curtain jet. Most debris generated and traveling within this exclusion zone would be deflected away from the witness plate. Figure 37.7(b) highlights a zone where debris generated from the front electrode could circumvent the jet and be deposited on the witness plate. The tungsten and copper seen in Fig. 37.6 are believed to be deposited via this mechanism.

Near the end of this work, Langmuir-probe measurements were made at the same position as the witness-plate samples that showed erosion. These plasma measurements were made as an initial attempt to determine if sputtering by the Xe

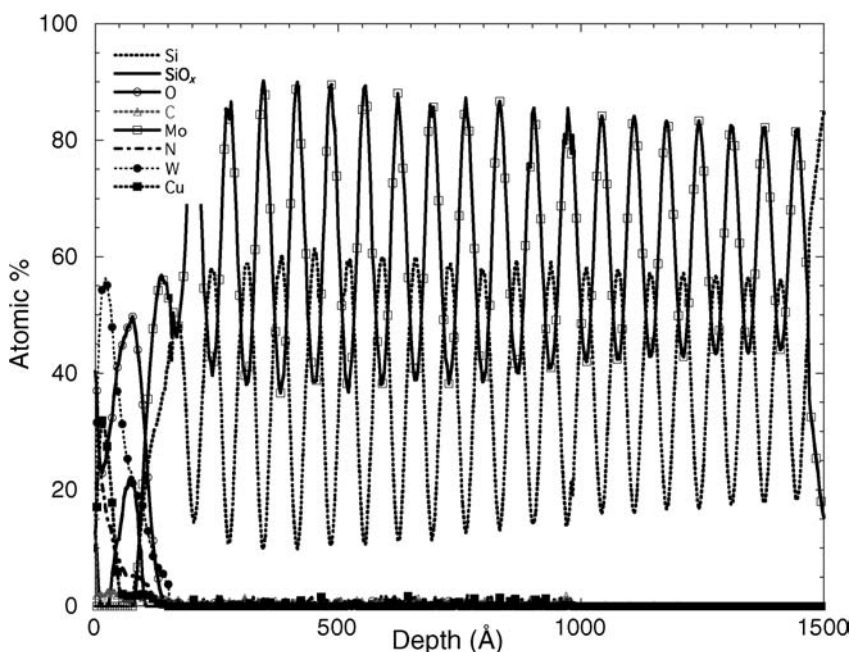


Figure 37.5 Auger sputtering results for the witness plate exposed with the gas curtain operating.

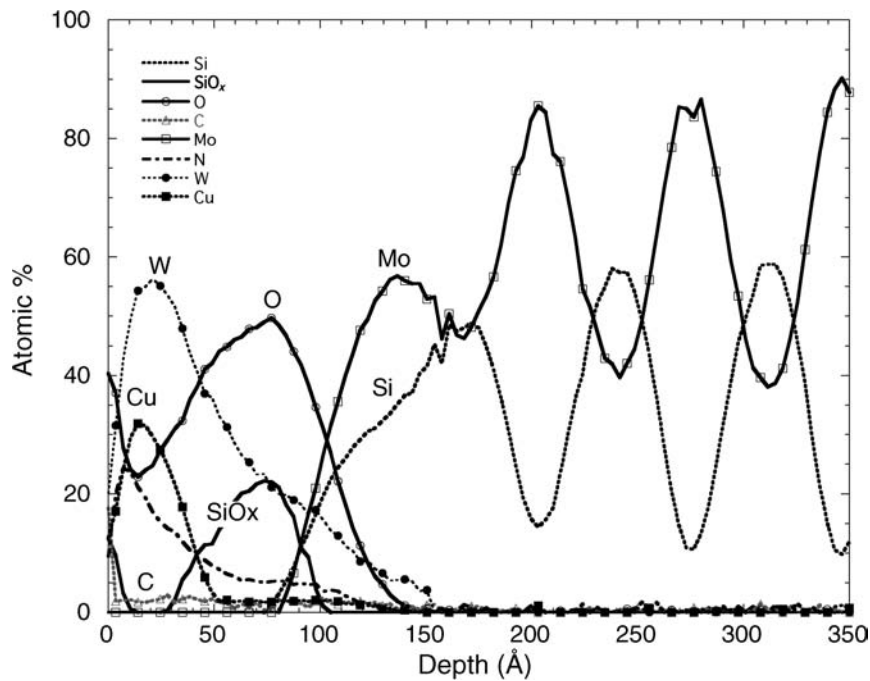


Figure 37.6 Near-surface composition for witness plate exposed with gas curtain operating.

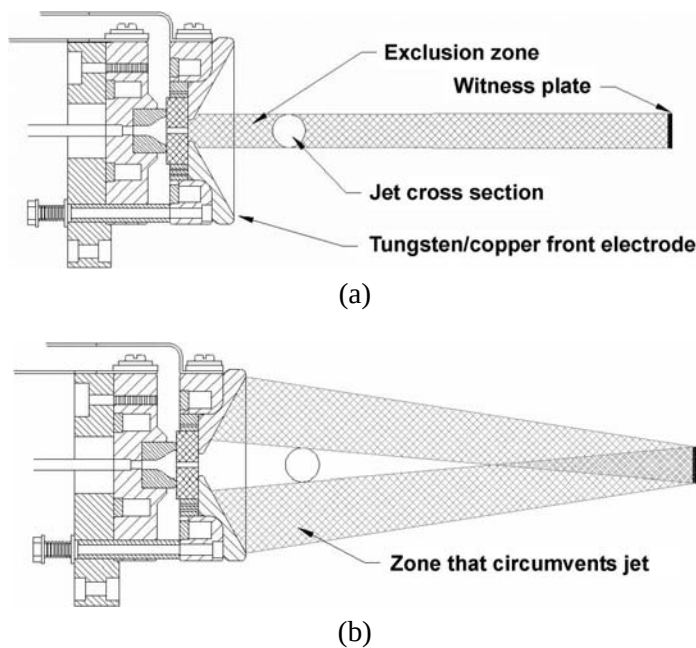


Figure 37.7 (a) Exclusion zone where the gas curtain jet intercepts debris generated at the lamp heading toward the witness plate. (b) Zone where debris generated at the front electrode can circumvent the jet and deposit on the witness plate.

could account for the observed erosion. Although further work would be needed to make the findings more quantitative, the measured plasma temperature of approximately 25 eV at this position could support a sheath voltage drop of 150 V (due to the high mass of Xe ions). Ions from the plasma would be accelerated across this sheath and impact the substrate with sufficient energy to cause sputtering. The probe measurements were also used to infer a Xe-ion fluence of approximately 4×10^{17} ions/cm² during the 1 million plasma shots. Combined with calculated values for Xe sputtering yields, to within an order of magnitude, such a Xe flux could account for the observed erosion rate via physical sputtering. The mitigation of the erosion through the use of a He gas curtain may arise because of the lower sputtering yields and lower sheath voltage drop for a He plasma.

37.3 Condenser Erosion Observations in the ETS

The ETS⁹ is a prototype EUV exposure tool that was constructed at Sandia National Laboratories in Livermore, California, through the EUV LLC program. The purpose of the ETS was system learning in the areas of source, stage, sensors, optics, and environment.

The optical layout of the ETS is shown in Fig. 37.8. The source of EUV was a spray-jet Xe LPP source excited by a high-power [three chains, 500 W (time-averaged) per chain] Nd-YAG laser built by Northrup Grumman. The conversion efficiency (CE) of the spray-jet Xe LPP was typically $\approx 0.2\%$. The first optical element was C1, a water-cooled Si substrate with 40 Mo/Si bilayers deposited on

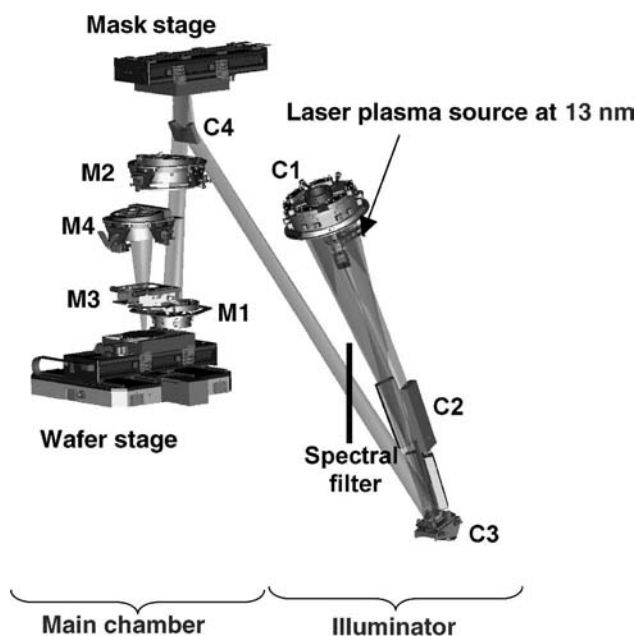


Figure 37.8 Optical layout of the ETS.

them. The plasma-C1 radial distance was typically ~ 10 cm, although this distance varied azimuthally. The solid angle subtended by the C1 optic was approximately 2.1 sr. The C1 optic was the only optic that directly viewed the plasma.

The C1 optical array is shown in more detail in Fig. 37.9. It contained six individual Mo/Si optics called *petals*. The petals could be individually shuttered to shield them from unnecessary EUV exposure during setup and testing, and to understand how each optical channel propagated through the ETS lithographic system. Amongst the C1 petals was a Mo/Si witness sample. The sample was water-cooled and exposed to the plasma directly during EUV imaging tests, as well as during ETS condenser erosion experiments. The sample would be removed, as desired, and analyzed with sputter Auger depth profiling to count the Mo/Si layers remaining on the witness sample. A limitation of the witness sample was that, while of reasonable physical extent in the radial dimension, it provided only limited lateral resolution. Hence, the witness sample was a poor indicator of the uniformity of erosion.

Figure 37.10 shows results of experiments collected with the witness sample over the course of many months of ETS operation. The data are plotted as bilayers removed versus plasma shot count. Although there is considerable scatter in the data, due in part to source instabilities, it is clear that erosion was observed, at a bilayer removal rate of ~ 1 bilayer removed per 15 million shots.

To provide context for the interpretation of this result, under ETS exposure conditions it would require ~ 45 million shots to expose a single 300-mm-diameter

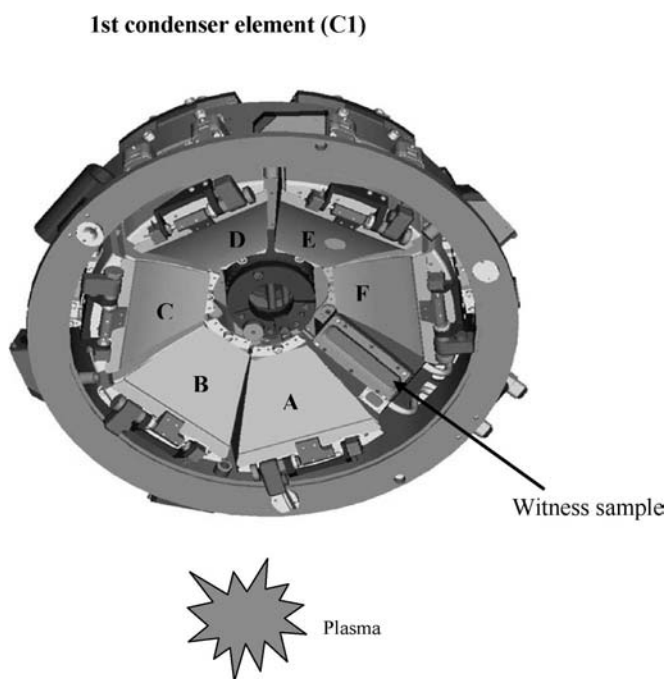


Figure 37.9 C1 condenser optic assembly with Mo/Si witness sample.

wafer, assuming an EUV dose per shot such as exists in the ETS, and assuming a 5-mJ/cm^2 resist.¹⁰ This fact, combined with the reduced reflectivity predicted in Fig. 37.1 as bilayers are removed, points to a serious lifetime problem for the C1 optic. It is important to note that there was no effort made in the ETS to mitigate such erosion. Therefore, the result of Fig. 37.10 is a worst-case scenario for the spray-jet Xe LPP source. Nonetheless, erosion degradation at the C1 optic was the greatest maintenance problem experienced with ETS operation. During one day of setup and testing, the source was operated as a filament target. During that time, the erosion rate measured at the witness sample increased to 0.82 bilayers removed per million shots. The ETS source was not operated again as a filament jet to minimize damage to the condenser.

In anticipation of lifetime problems with the C1 condenser element, four identical C1 assemblies were made. One of the petals from the first set was removed after 300 million shots, and an EUV reflectance characterization was made. The EUV reflectance at one point on the mirror is shown in Fig. 37.11. The relative reflectivity $\Delta R/R_0$ had dropped by $\sim 20\%$. Furthermore, the period of the reflectivity wiggles in the wings of the envelope had changed, indicating reduced thickness of the multilayer stack (i.e., erosion). The data of Fig. 37.11 are generally consistent with an erosion rate of ~ 1 bilayer per 15 million shots, as reported in Fig. 37.10.

During the operation of the ETS, it became clear that there was a degradation of exposure uniformity at the wafer plane. Figure 37.12 shows a plot of the dose uniformity across the field at the wafer plane for each of the six individual petals A–F. Ideally, the wafer-plane dose should be flat (no variation) to within $\sim 2\%$. However, large nonuniformities in dose delivered to the wafer ($\sim 10\%$ – 30%) were observed. Some channels, in particular, were severely affected, whereas others were only mildly affected. Initially, it was unclear where in the optical train C1–M4 the problem lay. However, a series of tests suggested that the problem lay in a nonuniformity with which the C1 optic reflected EUV radiation. In a definitive test, the actual C1 petals A and E were switched and reinstalled in the ETS, and the dose uniformity data collected again. The nonuniformity problem tracked the

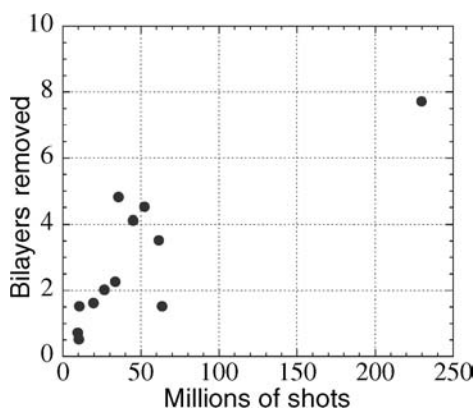


Figure 37.10 Bilayers of Mo/Si removed plotted versus number of plasma shots.

physical switching of the petals, thereby exonerating the rest of the optical system.

A photograph of the C1 assembly set 2, after 150 million shots, is shown in Fig. 37.13. It is clear that there are large variations in erosion. The lighter areas roughly correlate with Si left as the outer layer, whereas the darker areas roughly correlate with Mo. In some areas, for example on petal A, the multilayers have been completely removed. It remains unknown what the origins are of the striking nonuniformities in Figs. 37.12 and 37.13. However, the data in Figs. 37.11 and 37.12 indicate that well before the reflectivity of the C1 element dips below unacceptable levels ($\sim 10\%$ or so), the exposure nonuniformity, caused by nonuniform erosion, becomes intolerable.

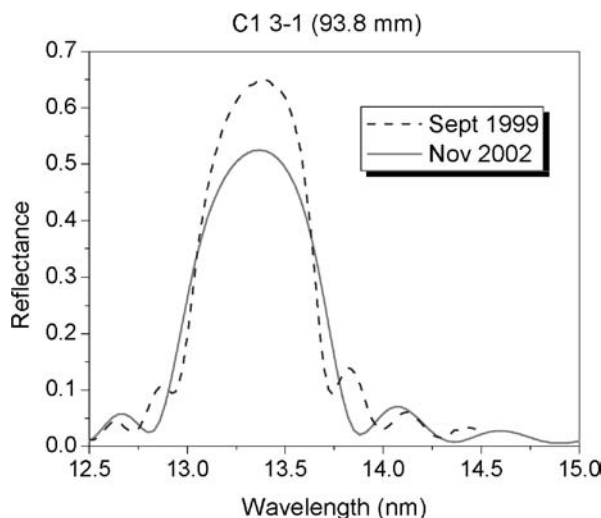


Figure 37.11 Reflectance of the C1 condenser optic before and after exposure to Xe LPP.

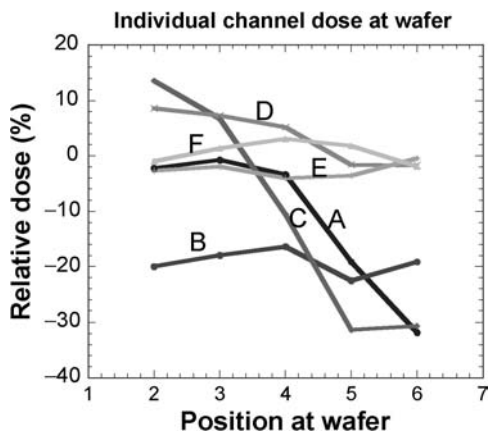


Figure 37.12 Plot of illumination uniformity at the wafer plane for the six individual C1 petals.

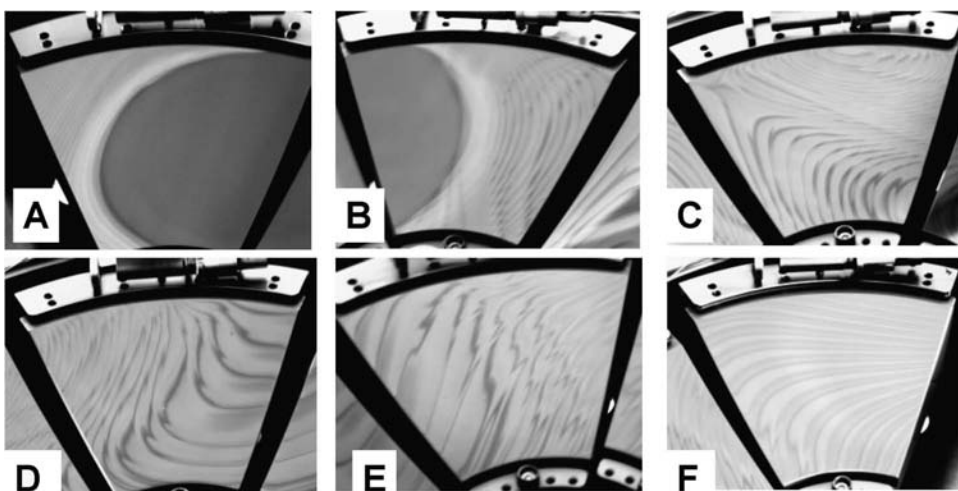


Figure 37.13 Optical photograph of the C1 set 3 mirrors after exposure to ≈ 150 million plasma shots.

37.4 Condenser Erosion Study Systems After the ETS

As described above, during operation of the ETS, the Si/Mo multilayer mirrors (MLMs) used in the condenser optic were eroded by extended exposure to the LPP source. For all lithographic printing, the source target was the spray jet, a directed aerosol of liquid Xe. The average rate of condenser material loss was 0.07 layer pairs (4.0 nm Si and 2.8 nm Mo) per million source pulses.

The ETS illuminator chamber was designed to provide EUV light for lithography and was not optimal for systematic investigation of condenser erosion. *In situ* diagnostics were largely limited to an array of photodiodes used to monitor the intensity and symmetry of the source, and a multilayer witness plate located between segments A and F on the condenser. The witness plate could only be retrieved and replaced when printing was inactive, and was analyzed by sputter Auger depth profiling to count the remaining layer pairs. Substituting diagnostics for condenser segments would have reduced the EUV flux going to the projection optics assembly, and the ETS chamber itself had only a limited number of ports that might have been dedicated to diagnostic access.

Under a research program sponsored by International SEMATECH, a test chamber was constructed at Sandia to systematically investigate the erosion of materials exposed to a Xe LPP source. The inside of this chamber is shown in Fig. 37.14. The view faces what would have been the condenser in the ETS, showing that the reflector assembly has been replaced with diagnostics to measure materials erosion in real time while monitoring the EUV intensity of the source and measuring its plasma characteristics. We have used this chamber and its capabilities to measure the erosion rates of gold, Mo, and Si when exposed to an LPP source using a liquid Xe filament jet as its target. The filament-target source produced a promising 0.6% CE.¹¹

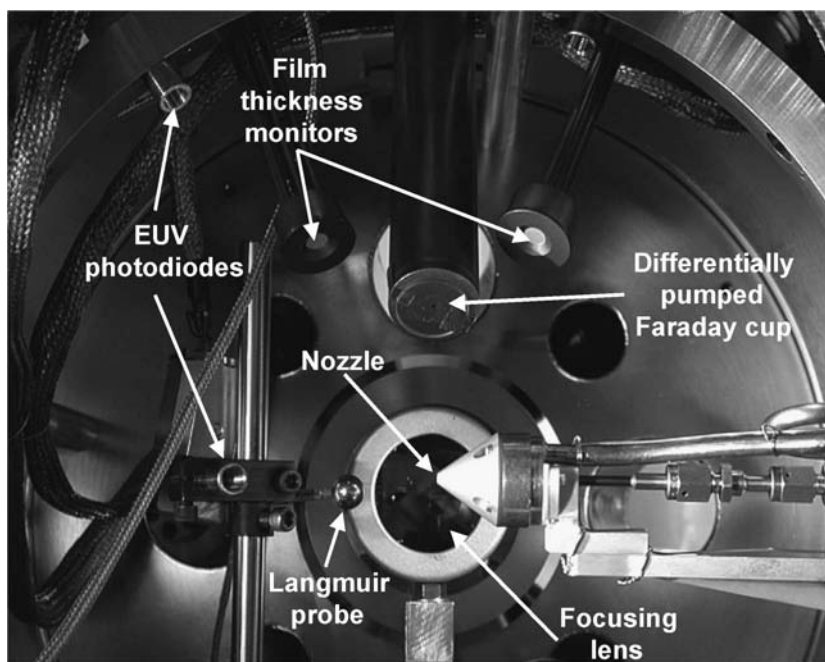


Figure 37.14 Photograph of the condenser erosion chamber interior with source and diagnostics.

37.4.1 Experimental methods for condenser erosion studies

The source target in the condenser erosion test chamber was formed using a nozzle assembly identical to that used in the ETS. Xe at nearly 30-bar absolute pressure was liquefied in a temperature-controlled reservoir cooled by liquid nitrogen and was forced out a 30- μm -diameter orifice, the jet then passing into the vacuum chamber through a 0.2-mm-diameter duct 2 mm long in a conical graphite heat shield cooled to -70°C . This assembly is visible in Fig. 37.14. The nozzle can be operated to produce either a spray jet, shown in Fig. 37.15, or a filament jet, shown in Fig. 37.16. However, since only the CE of the filament jet target approaches that needed for production purposes, only the filament jet target was used for these experiments. The chamber was evacuated by two 3200-l/s turbomolecular pumps to maintain 4.6-mbar chamber pressure at a Xe flow rate of 1.05 slm. The chamber had never been baked, so its base pressure after a few hours of operation was about 10^{-7} mbar.

The laser used for these experiments was a Coherent* Infinity Nd:YAG laser used at its fundamental wavelength, 1.06 μm . This variable-output laser produces 4-ns pulses at up to 400 mJ per pulse at 100 pulses per second (pps), and up to 500 mJ per pulse at 50 pps. The laser focusing optics were the same as those used with the spray jet, forming a beam waist at the target about 60 μm in diameter

*Names of commercial products are mentioned for experimental clarity and completeness. Mention of products by name does not constitute endorsement by the researchers or their institution.

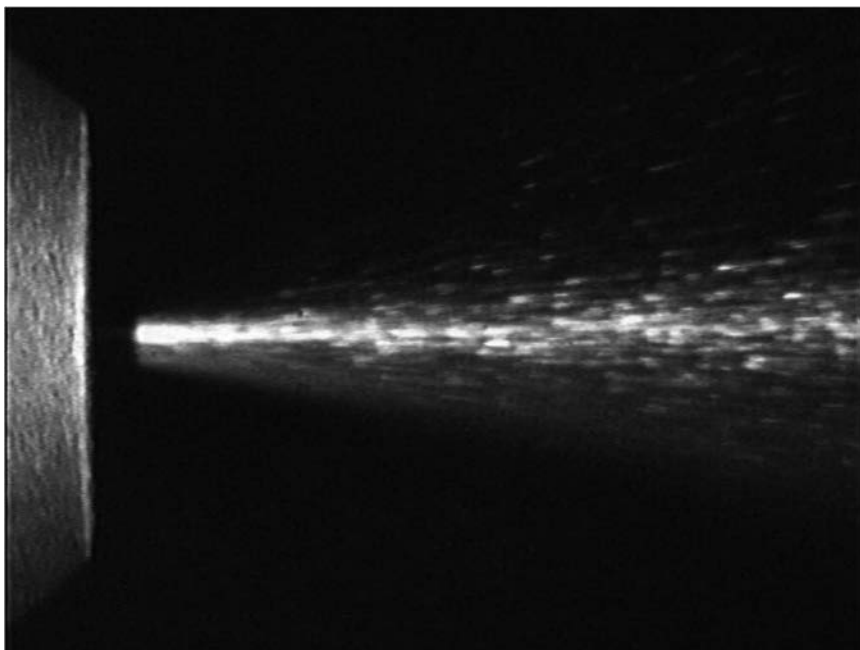


Figure 37.15 Optical photograph of the spray jet.

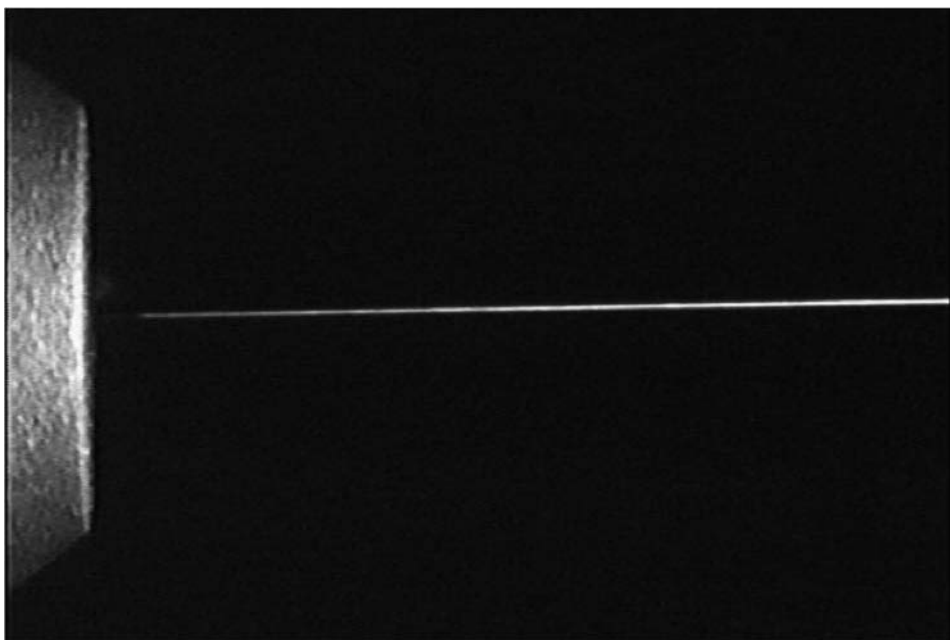


Figure 37.16 Optical photograph of the filament jet.

and thus not optimum for coupling to the 30- μm -diameter target. The CE was thus only 0.30%, but this source was deemed suitable for these materials erosion experiments.

Materials erosion rates were measured using quartz crystal thickness monitors whose quartz crystals were coated with the materials in question. The monitor was a Sigma* model SQM 160 instrument, used with two probes in the chamber as shown in Fig. 37.14. The UHV-compatible probes were cooled by ambient-temperature water. They were positioned 110 mm from the source at an angle of 51 deg from the laser illumination axis, which placed them near the condenser position within the solid angle subtended by the condenser assembly in the ETS. For these experiments, the following samples were provided by the vendor according to our specifications: 50 nm of gold deposited on the quartz crystal, 50 nm of Mo over 50 nm of gold on the quartz crystal, and 200 nm of Si over 50 nm of gold on the quartz crystal. The rated thickness-change sensitivity of this device is 0.0027 nm for a material density of 2.7 g/cm³.

The plasma environment created by the source was investigated using a Langmuir probe and a Faraday cup to measure the fast ion current. The Langmuir probe measures current flow in the plasma through a surface defined by the biased tip of the probe. The current can be ion flow or electron flow, depending on the sign of the applied bias. The distance of the probe from the source could be varied from 100 to 300 mm. A schematic of the Faraday cup is shown in Fig. 37.17. The defining entrance aperture (1-mm diameter) into a differentially pumped chamber was placed at a distance typical of the condenser surface (in this case, 170 mm from the source). An additional drift length of 930 mm separated the aperture from the Faraday cup itself, which is biased at a negative potential to repel electrons co-propagating with the ions. The 110-cm source-to-charge collector distance allowed discrimination of ion current from photoelectrons driven from the collector surface by EUV emission and recombination luminescence, and detection of well-resolved ion pulses. The pressure in the drift region was maintained at about 0.2 mbar, allowing the mean free path of the ions to be substantially greater than the travel distance in the drift tube.

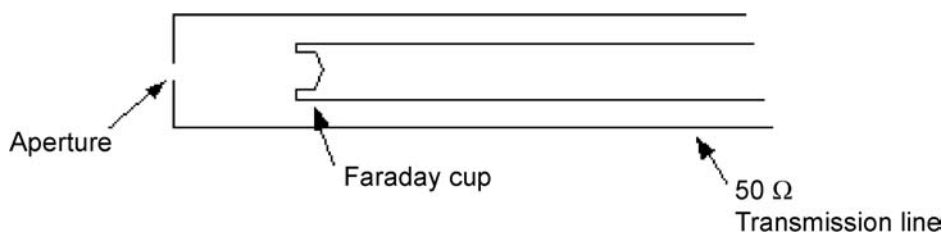


Figure 37.17 Schematic design of the time-of-flight (TOF) Faraday cup.

37.4.2 Results and discussion

The results derived from this dedicated condenser erosion facility are now summarized. Quartz crystals coated with gold, Mo, and Si were exposed to the Xe-filament-jet LPP source driven by 300-mJ laser pulses (as in the ETS) for 3.6×10^5 pulses, for three experiments each. The change in thickness was monitored in real time, and the net change was also recorded after the source was extinguished. The average material erosion rates were:

Gold: 95 nm/ 10^6 pulses
 Mo: 18 nm/ 10^6 pulses
 Si: 9 nm/ 10^6 pulses

The experimental error associated with these measurements were all ± 1 nm/ 10^6 pulses. The relative rates of erosion (Au:Mo:Si) for the data above are approximately 11:2:1. Based on these measurements, we infer an equivalent Mo/Si erosion rate of approximately 1.7 layer pairs per million pulses for the Xe filament jet, a 25-fold increase over the ETS spray-jet erosion rate.

To facilitate discussion of these results and those below, we show in Fig. 37.18, for a number of materials, the calculated erosion rates based on sputtering by monoenergetic Xe ions. We have used a Monte Carlo simulation of the slowing down and scattering of energetic ions in materials (TRIM^{12,13} version TRVMC98). This code was developed jointly at Sandia National Laboratories and the Hahn-Meitner-Institut, Berlin, and is currently maintained by Wolfgang Eckstein at the Max-Planck-Institut für Plasmaphysik in Garching, Germany. The code simulates

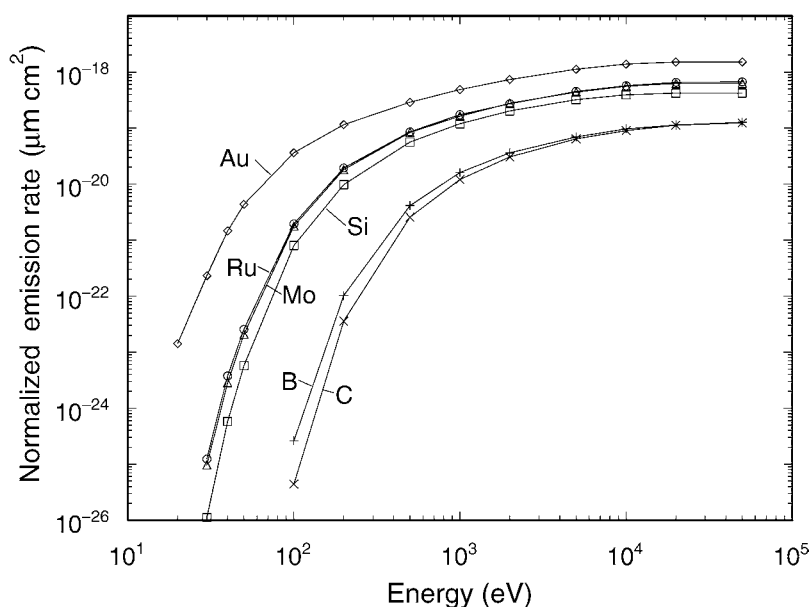


Figure 37.18 Flux-independent erosion rates calculated for Xe ion sputtering.

the flight paths of both the incident particles and the recoiled particles as a sequence of binary collisions, separated by straight free-flight paths. The energy is reduced as a result of nuclear and electronic (inelastic) energy losses, and particles are followed until their energy falls below a predetermined value (0.5 eV for this work). The target material is assumed to be amorphous and have theoretical density (although this can be varied if desired). Recoil atoms heading toward the surface are allowed to escape (and add to the sputter yield) if their approach energy exceeds the surface binding energy of the target material.

Although the TRIM code has been tested extensively against ion-beam experiments, care must be used in applying the results to specific situations. These calculations do not take into account the mixing that can occur at the end of range in multilayer structures. As the top layer is thinned and its thickness approaches the range of the incident Xe, mixing of the multilayer materials will occur, and this can influence the sputtering rate. In addition, these calculations neglect the effect of the implanted Xe on the sputtering rate. In a low- Z material such as silicon, carbon, or boron, the implants can cause backscattering of the incident Xe ions and intensify the collision cascade energy at the surface, thereby increasing the sputtering yield.

From Fig. 37.18, taking the asymptotic normalized erosion rates applicable at 20 keV, Fig. 37.18 predicts relative sputtering ratios Au:Mo:Si of $\approx 4:1.5:1$. These ratios are near those observed experimentally (11:2:1). The similarity of the experimentally measured relative erosion rates to those calculated for a Xe-ion sputtering model suggests that Xe-ion sputtering contributes significantly to erosion of materials exposed to the liquid-jet-target LPP source.

To investigate the erosion mechanism in more detail, we have measured the plasma environment that results from the use of the LPP source. Figure 37.19 shows the current measured by the Langmuir probe biased for ion current following a single source pulse. The first peak is a strong, prompt signal of photoelectrons driven from the probe by the plasma single light pulse. Following quickly is a pulse of positive current, which we ascribe to the arrival of fast ions emanating from the source. Finally, much later in time, the plasma from the source expands slowly through the background gas and arrives at the probe, where it persists for some time. By extending the time scale of the experiment to show the slowly expanding plasma, we have artificially attenuated the magnitude of the first two contributions to the current. Although the weak current flow suggests that the density of this long-lived thermal plasma is quite low, its persistence requires that we consider it as a possible erosion source. In the high-pulse-rate environment of a proposed production tool (greater than 2000 pps), this thermal plasma would continually exist adjacent to the surface of the condenser. Even at a low density of low-kinetic-energy ions, the constant bombardment could erode the surface.

A quantitative evaluation of the long-lived plasma must await more extensive analysis of current-versus-bias-voltage data, but a semiquantitative assessment of the contribution to erosion by the long-lived plasma can be made by comparing results for the LPP source using spray-jet and filament-jet targets. Figure 37.20 shows the Langmuir-probe response for each of these sources on a long time scale.

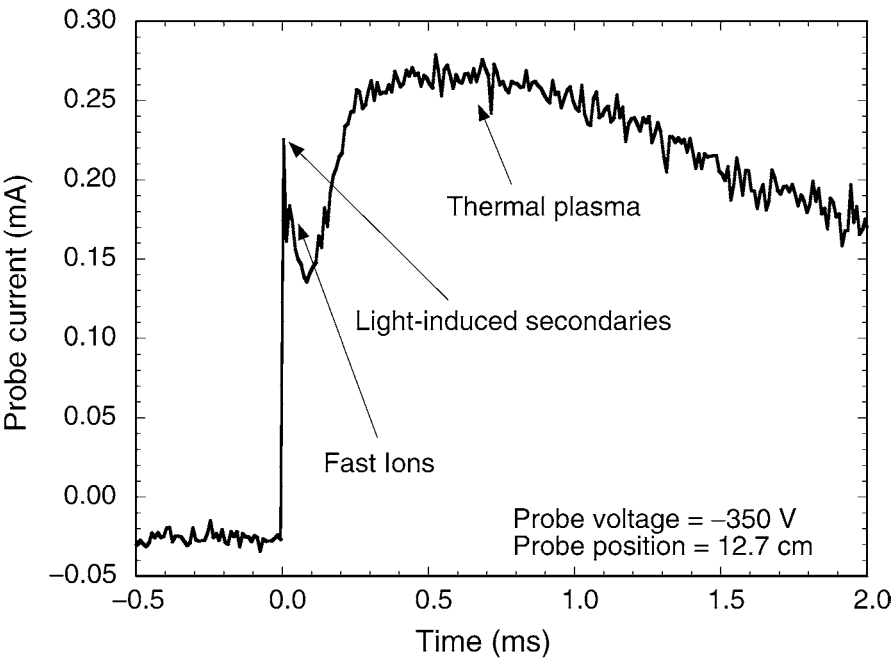


Figure 37.19 Langmuir-probe signal from a single plasma shot.

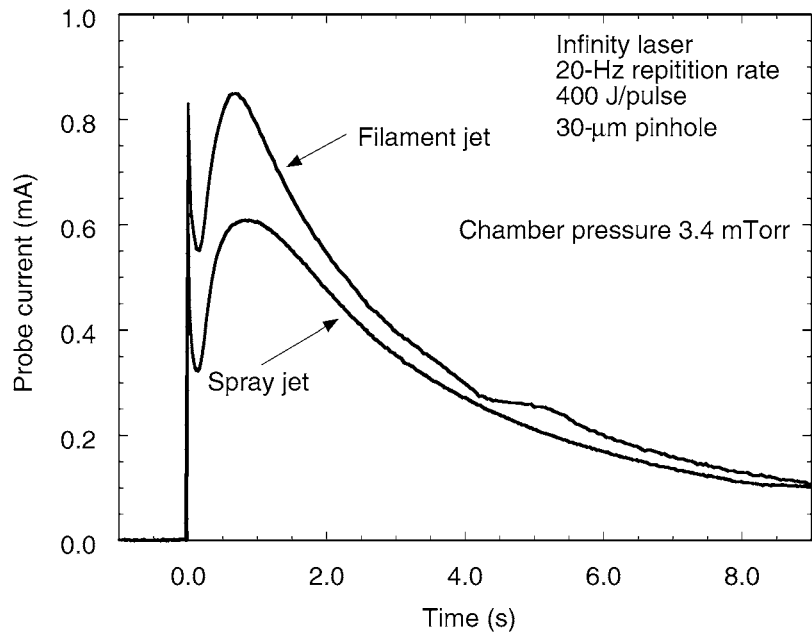


Figure 37.20 Comparison of Langmuir-probe signals for the spray-jet and filament-jet source targets.

Although the filament:spray erosion-rate ratio measured in the ETS is greater than 10 (and probably as great as 25), the long-lived plasma ion current caused by the filament source is less than 50% greater than that caused by the spray source. This suggests that the long-lived plasma is not the dominant erosive agent.

Figure 37.21 shows fast ion currents measured using the TOF Faraday cup with the filament-jet target at five pulse energies of the drive laser. Given the distance of the collector from the source, and assuming that the charge is carried as Xe ions, we may convert the charge arrival-time scale to a Xe kinetic energy scale, as shown in Fig. 37.22. This shows that most of the ions in the fast ion pulse have kinetic energies exceeding 10 keV. This charge-flux measurement carries no particle-flux information directly; if we assume that the ions are all singly charged, the integrated flux for a 300-mJ laser pulse is 1.7×10^{10} Xe⁺/cm². The calculated erosion-rate curves of Fig. 37.18 show that the flux-normalized erosion rate varies slowly for energies greater than 10 keV; using the erosion rate at 20 keV as an average, and the particle flux for singly charged ions, we calculate a Si erosion rate of 6.8 nm/10⁶ pulses, close to the measured experimental value 9 nm/10⁶ pulses.

The agreement of the Si erosion rate just calculated with that measured is instructive but possibly fortuitous. It is important to remember what the Faraday-cup signal measures. The background Xe gas in the chamber, at 4.6 mbar and room temperature, has a mean free path of 1.4 cm. The mean free path¹⁴ of much faster Xe particles moving through this background is greater by a factor of $\sqrt{2}$, and thus about 2 cm. The distance from the source to the acceptance

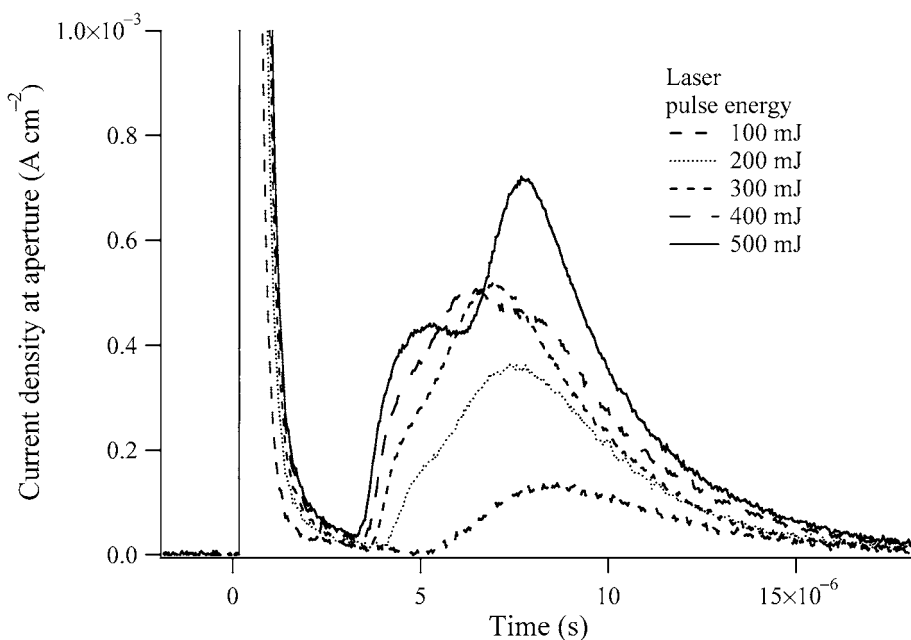


Figure 37.21 Ion currents measured in the Faraday cup as a function of time.

aperture is therefore about 8 mean free paths. The solid angle of the acceptance aperture is only 3×10^{-5} sr (1-mm diameter at 170 mm from the source). Since any hard-sphere collision with a body of similar mass will scatter a fast ion from the source–aperture–Faraday-cup trajectory characterized by this acceptance angle, the only ions contributing to the collector current are those reaching the aperture from the source without being scattered by the background gas. Since EUV light arises from transitions involving highly ionized Xe within the hot source plasma, these collected ions are likely to be highly charged, which reduces the particle flux inferred from the current density, and hence the calculated erosion rate. However, in 8 mean free paths, most of the fast ions will have undergone collisions altering their trajectories, but will still be traveling at much higher velocities than those of the background gas; slowing them down requires at least hundreds of collisions. Even if a fast ion born in the LPP source loses 90% of its kinetic energy as it propagates to the condenser, it will arrive with enough residual kinetic energy to erode the surface. Furthermore, many collisions with slowly moving background atoms may give rise to additional energetic erosive particles. Thus the observation of tens-of-keV ions is likely the tip of the erosion iceberg; they are likely too sparse to explain the entire erosion rate, but they are likely to be indicative of a greater number of erosive ions reaching the condenser surface with a considerable distribution of energies and angles that we have not yet measured.

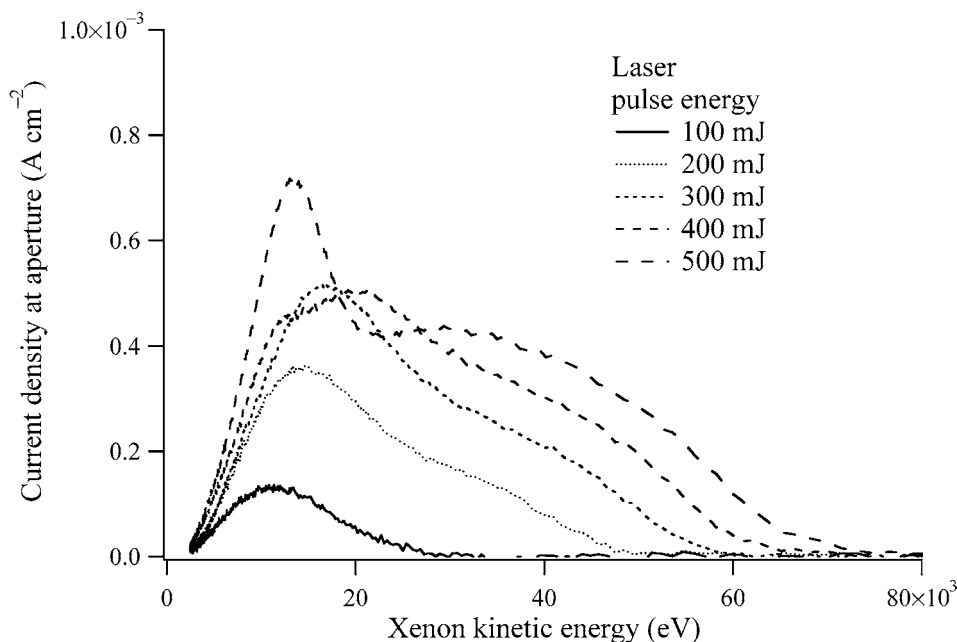


Figure 37.22 Ion currents in the Faraday cup on a Xe kinetic energy scale.

37.4.3 Conclusions from the Sandia condenser erosion studies

Experiments conducted with an electric capillary discharge source indicated significant erosion of Mo/Si multilayers. This erosion could be greatly reduced by using a He gas curtain. Operational experience with ETS revealed a significant problem of condenser-optic erosion with a Xe spray jet, and more so with a Xe filament jet. The erosion reduces condenser reflectance and causes nonuniformities in the EUV flux at the wafer plane.

Working in a chamber specifically instrumented to investigate materials erosion by an LPP EUV source, we have measured erosion rates for gold, Si, and Mo. The source utilized a liquid-Xe-jet target. The rates for Si and Mo can be combined to give an equivalent erosion rate for multilayer EUV mirrors of 1.7 layer pairs per million pulses, similar to the 0.82 layer pairs per million pulses measured in the ETS under similar conditions. The relative erosion rates measured for the three materials are similar to relative rates calculated using a Xe-ion sputtering model. At the position of the condenser there is evidence for fast-ion flux at a low duty factor and for slower-ion flux due to a longer-lived plasma. The latter we conclude to be an unlikely erosive agent. The fast ion flux, however, is sufficient to be a strongly erosive agent, removing multilayer coatings by sputtering.

To more firmly establish the likely mechanism, we will extend the measurement of erosion rates to materials lighter than Si. We must also measure the charge/mass ratios (and hence the identities) of the fast ions in the flux, and we will also measure off-axis fast ions to investigate the importance of scattered fast ions in the erosion mechanism. However, the data to date suggest that the principal erosion mechanism is sputtering of the substrate by high-energy (1–20-keV) ions of some charge.

37.5 Erosion Studies of EUVA

To improve the future foundation of the semiconductor industry in Japan, the Japanese government, academia, and semiconductor manufacturers are involved in EUV research and development. To manage and consolidate R&D activities, the Extreme Ultraviolet Lithography System Development Association (EUVA) was formed from 10 EUV-related companies, under the auspices of the Japanese Ministry of Economy, Trade and Industry (METI). Here, we summarize work on condenser erosion performed at EUVA.

The EUVA approach is that it is important to characterize the fast ions from the plasma and to understand their effect on the Mo/Si multilayer in order to mitigate condenser erosion. In this section, we summarize EUVA's progress in the characterization of fast ions, their effect on Mo/Si multilayers, and the effectiveness of a magnetic confinement scheme on their mitigation.

37.5.1 Fast-ion characterization

Expected damage mechanisms in LPP EUV sources include Xe-fragment impact, including Xe-ion sputtering.¹⁵ In addition to the Sandia work presented above,

high-energy Xe ions with up to 15-keV kinetic energy have recently been measured at several laboratories in EUV LPPs.^{16,17} Therefore, the characterization of fast ions, with regard to their atomic number and charge state, is required. A TOF measurement combined with an electrostatic energy analyzer (ESA) has been used in various applications to study LPPs.^{18–20} The same method has been applied to characterize the fast ions from the liquid-Xe-jet plasma. The experimental setup is shown in Fig. 37.23. A liquid Xe jet with 10- μm diameter and excited by a 8-ns or 150-ps Nd:YAG laser was used as the plasma source. The repetition rate is 20 Hz. An ESA (Comstock, AC-901)* equipped with a double microchannel plate (MCP) measured the TOF of the plasma ions. The ESA was placed inside a small vacuum chamber and connected via a TOF tube to the main vacuum chamber. The total TOF distance was about 845 mm. A pinhole of 0.75-mm diameter was used in the middle of the flight tube in order to differentially pump the analyzer section. The pressures inside the EUV chamber and the TOF chamber during plasma emission were about 1×10^{-3} and 6×10^{-5} mbar, respectively.

The relationship between the kinetic energy E_{kin} of an ion, its charge state Z , and the applied voltage δV between the inner and outer electrodes of the energy analyzer is given by¹⁹

$$\frac{E_{\text{kin}}}{Z} = ek\delta V, \quad (37.1)$$

where e is the elementary charge and k is the geometric factor of the ESA, which is 2.254 in the current case.

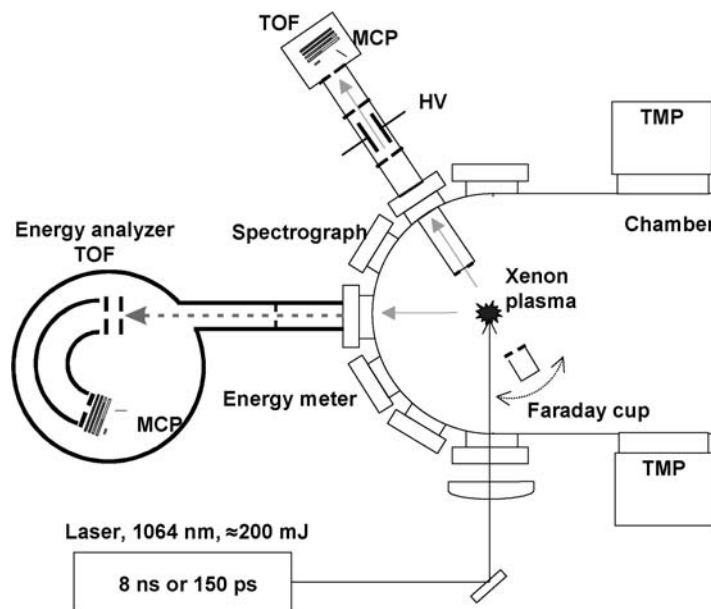


Figure 37.23 Experimental setup of the fast-ion measurements.

A typical signal measured by the ESA is shown in Fig. 37.24. The laser parameters were 160 mJ and 8 ns, and the analyzer voltage δV was set so that E_{kin}/Z equaled 1 keV. In the figure triangles indicate the calculated delay times of the Xe^+ to Xe^{6+} ions, which showed good agreement with the measured signals. The good agreement between experimental delay times and calculated delay times assuming Xe indicates that the measured ions are in fact Xe and not some other species. Though up to Xe^{6+} ions were observed, Xe^{2+} was the main observed charge state. The TOF signals measured with different applied voltages are shown in Fig. 37.25(a) with the 8-ns laser, and in Fig. 37.25(b) with the 150-ps laser. The laser energy was 100 mJ in both cases, and estimated laser intensities on the Xe-jet target were (a) $4 \times 10^{11} \text{ W/cm}^2$, and (b) $2 \times 10^{13} \text{ W/cm}^2$. Though Xe^{2+} was the main ion in both cases, higher-charge-state Xe ions were observed with the plasma produced by the 150-ps laser, e.g., at higher laser intensity. The results have not been corrected for the MCP gain dependence on ion energy²¹ and charge number,²² which would be necessary for a quantitative analysis.

Figure 37.26 shows the energy distribution of fast Xe ions measured by TOF without ESA for 8-ns and 150-ps laser pulses, displayed with a bold and a thin line, respectively. The laser energy was 200 mJ in both cases, and estimated laser intensities on the target were $8 \times 10^{11} \text{ W/cm}^2$ for 8-ns and $4 \times 10^{13} \text{ W/cm}^2$ for 150-ps irradiation. The TOF measurements of Fig. 37.26 were performed at an angle of 150 deg from laser incidence. At 150 deg, Xe ions of kinetic energy $\sim 2\text{--}5 \text{ keV}$ were observed, as shown in Fig. 37.26. Very recently, measurements

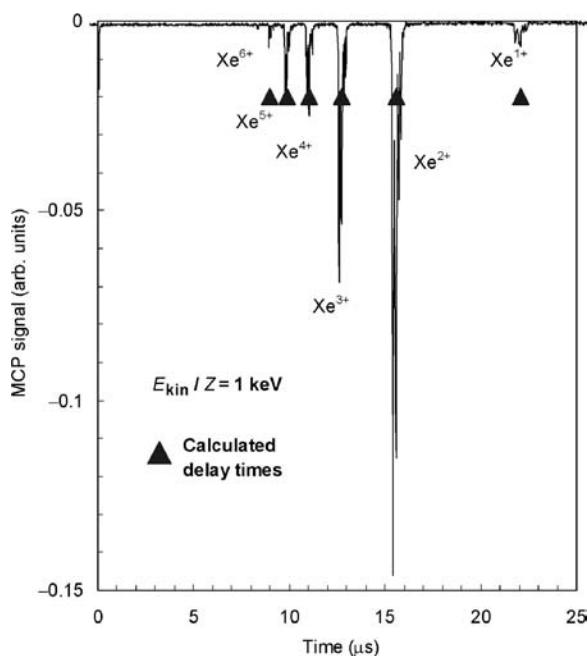


Figure 37.24 Typical energy-analyzer TOF signal. Triangles indicate calculated delay times of Xe ions.

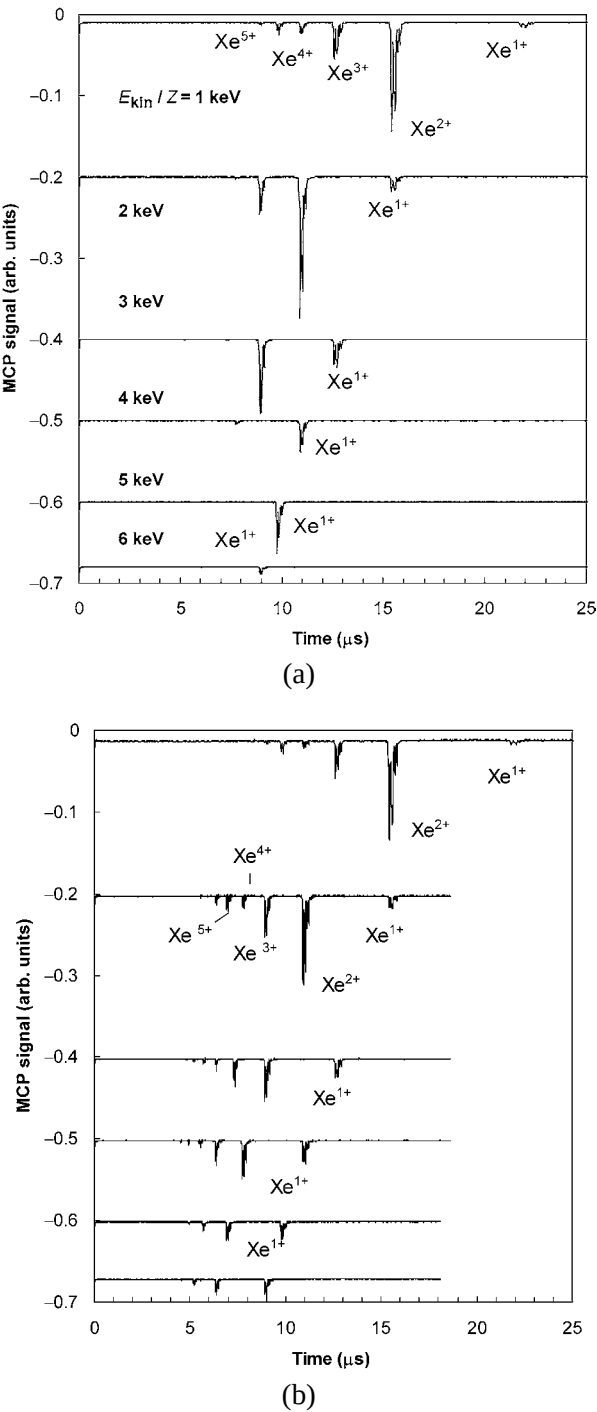


Figure 37.25 TOF signals (a) with an 8-ns, 100-mJ laser, and (b) with a 150-ps, 100-mJ laser.

have been made at an angle of 45 deg from the laser incidence direction. At that angle, Xe ion energies up to ~ 20 keV were observed.

In order to measure the neutral-particle ratio of the TOF signal, a pair of high-voltage electrodes were placed inside the TOF tube as shown in Fig. 37.23. A maximum voltage of 5 kV was applied between the electrodes to separate ions from neutrals, allowing only neutral species to strike the MCP detector. The result of the neutral-particle measurement is shown in Fig. 37.27. The TOF signals obtained for 160-mJ 150-ps laser pulse irradiation with and without a high voltage of 4 kV are plotted with a bold line and a thin line, respectively. The measured neutral-particle number is approximately 1/5 of the ion number if we assume that the MCP gain is the same for neutral particles and ions.²³

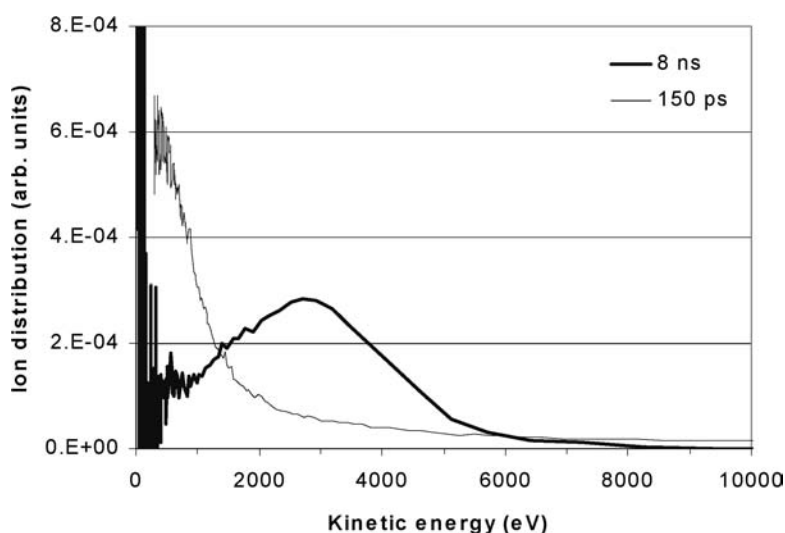


Figure 37.26 Overall behavior of fast ions with different laser pulse widths.

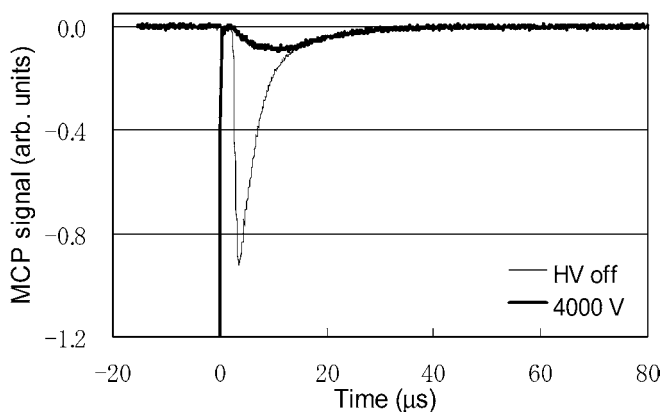


Figure 37.27 TOF measurement of ions and neutral particles.

37.5.2 Xe-ion exposure experiments

The energetic ions produced by the Xe filament-jet LPP of Fig. 37.23, as reported in Fig. 37.26, would be expected to considerably damage the multilayer of a future collector mirror. In order to investigate the damage mechanism of high-energy ions on Mo/Si MLMs, Xe-ion exposure experiments were therefore performed using an ion gun. The cold-cathode ion gun (VG Scientific, AG2*) generated a uniform Xe^+ ion beam with energy between 2 and 5 keV. The Xe^+ ions exposed the sample over an area of 12×12 mm at normal incidence. Energies of 2, 3, and 5 keV were used, with a total ion dose of $3.7 \times 10^{16} \text{ cm}^{-2}$ for the 2- and 3-keV and $2.8 \times 10^{16} \text{ cm}^{-2}$ for the 5-keV beam. MLMs with 10 Mo/Si bilayers on a Si substrate were used as witness samples. After exposure, the samples were analyzed for reflectivity, surface roughness [atomic force microscopy (AFM)], cross-sectional structure [transmission electron microscopy (TEM)], depth-profile [Auger electron spectroscopy (AES)], and Xe implantation [x-ray photoelectron spectroscopy (XPS)].

The reflectivity of the samples was measured with a reflectometer developed by Kandaka et al.²⁴ The measured and calculated reflectivities of the exposed Mo/Si multilayer samples are shown in Fig. 37.28. The peak reflectivity of the unexposed reference sample was 17%, and the reflectivity decreased with increasing ion dose. Note that the sample reflectance was low due to the limited number (10) of multilayers on the sample. The agreement between measured and calculated reflectivities is good for multilayer parameters as listed in the Table 37.1. As can

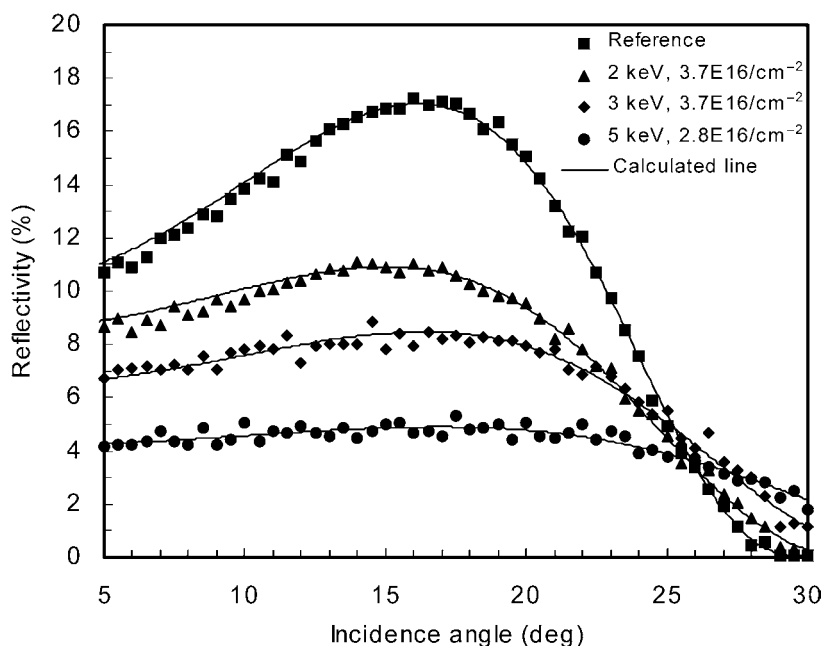


Figure 37.28 Measured and calculated reflectivities of exposed Mo/Si multilayer samples.

Table 37.1 Multilayer parameters used for reflectivity calculation.

Item	Reference	2 keV	3 keV	5 keV
Layer period (Å)	69.6	69.15	69.55	69.55
Number of layers	10	8	7	5
Thickness ratio	0.35	0.35	0.35	0.35
Interface layer thickness (Å)	17.9	17.9	17.9	17.9
Rms interface roughness (Å)	1.2	3.7	4.1	3.6

be seen in the table, the calculated number of Mo/Si bilayers decreases and the interface roughness increases with increasing ion dose. It is therefore expected that the multilayers are sputtered by the Xe ions and that the interface and/or surface roughness increases.

Figure 37.29 shows 3D AFM scans (area $1 \times 1 \mu\text{m}$) and TEM cross-sectional images of the Mo/Si multilayer (a) reference sample, and (b) sample with $2.8 \times 10^{16}\text{-cm}^{-2}$ (5-keV) ion dose exposure. The rms surface roughness increased from 0.20 to 0.41 nm, and 3.5 Mo/Si bilayers were removed by the Xe ion exposure. The increase in surface roughness and especially the decrease in bilayer pairs indicate that the Xe ions sputter the Mo/Si multilayer structure. It can also be seen from the TEM image that the boundary region between the Mo and Si layers closest to the multilayer surface was less pronounced after exposure. This indicates that the Xe ions mix the Mo/Si boundary layer near the surface. The same tendency can be seen in the AES depth profiles of the exposed samples.

Xe implanted inside the Mo/Si multilayer has been analyzed by XPS. Figure 37.30 shows the result for a multilayer sample exposed with the $2.8 \times 10^{16}\text{-cm}^{-2}$ (5-keV) ion dose. The Xe is implanted over a total depth of 10 nm with a maximum concentration of 0.7%. As is well known, neutral and low-ionized Xe strongly absorbs at 13.5 nm, but the absorption due to the implanted Xe is less than 0.5% and therefore negligible. In a next step, an exposure measurement with an LPP will be important in order to compare the results with ion gun exposure.

37.5.3 Fast-ion mitigation in the EUVA experiments

As just described, the charge state and the kinetic energy of high-energy ions from a Xe filament-jet LPP were measured. The EUVA group then sought the best mitigation technology based on the measured fast-ion characteristics. Magnetic field confinement was thought to be effective to prevent fast ions from damaging the coatings of the collector mirror, which is located 10 to 20 cm from the plasma. Figure 37.31 shows the relationship between the ion energy and the required magnetic field to keep the Larmor radius at 50 mm for Xe^{1+} to Xe^{4+} ions. This graph shows that a magnetic field of about 0.9 T is required for Xe^{2+} ions with kinetic energy 3 keV.

The effectiveness of the fast-ion mitigation by magnetic field confinement was examined with the experimental setup shown in Fig. 37.32. A coil pair produced a

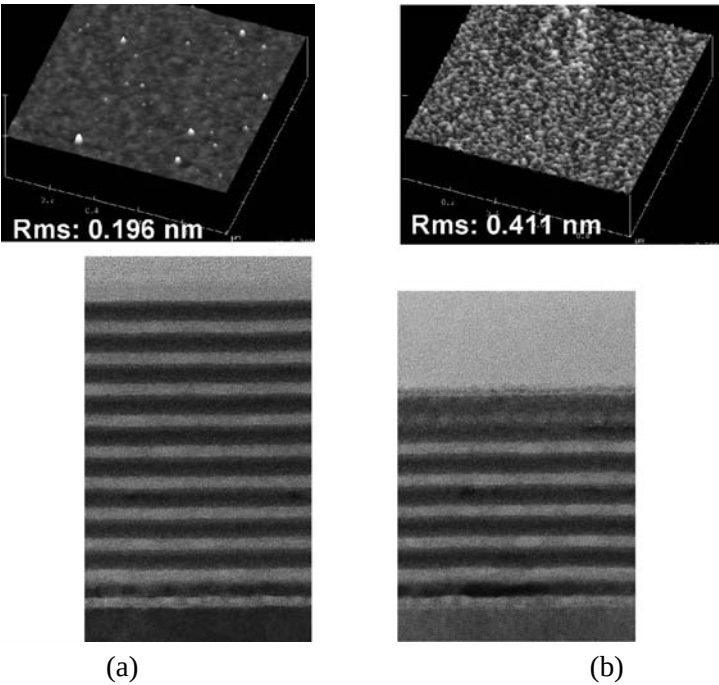


Figure 37.29 AFM scans and TEM cross-sectional images of the Mo/Si multilayer: (a) reference sample; (b) sample after $2.8 \times 10^{16}\text{-cm}^{-2}$ 5-keV-ion dose exposure, showing erosion and layer mixing.

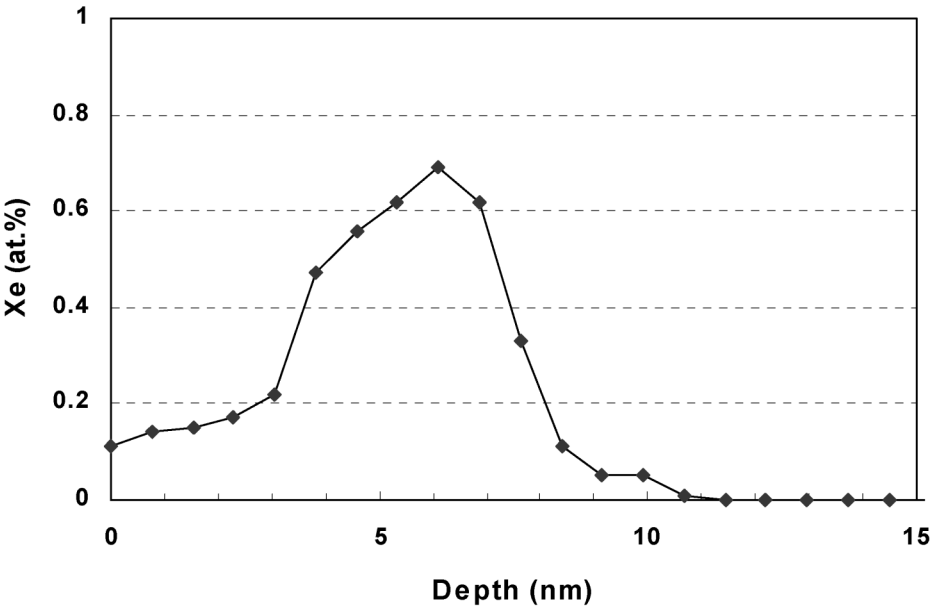


Figure 37.30 XPS analysis of Xe inside the Mo/Si multilayer with a $2.8 \times 10^{16}\text{-cm}^{-2}$ 5-keV-ion dose exposure.

maximum static magnetic field of 0.3 T on the coil axis. A perfluoropolyether jet that has an emission line at approximately 13 nm was used as a target. The laser plasma was produced at the center of the magnetic field by an Nd:YAG laser with 200-mJ, 7-ns pulses at a repetition rate of 10 Hz. The result of fast-ion measurements performed with a Faraday cup located horizontally at 23 deg to the laser-beam axis (see Fig. 37.32) is shown in Fig. 37.33. The thin line shows the signal without applying a magnetic field, and the bold line shows the signal with a magnetic field of approximately 0.17 T. The drastic decrease of the fast-ion signal (presumably due to carbon and fluorine ions) with increasing applied magnetic field indicates the effectiveness of the fast-ion mitigation by the magnetic field confinement. Since

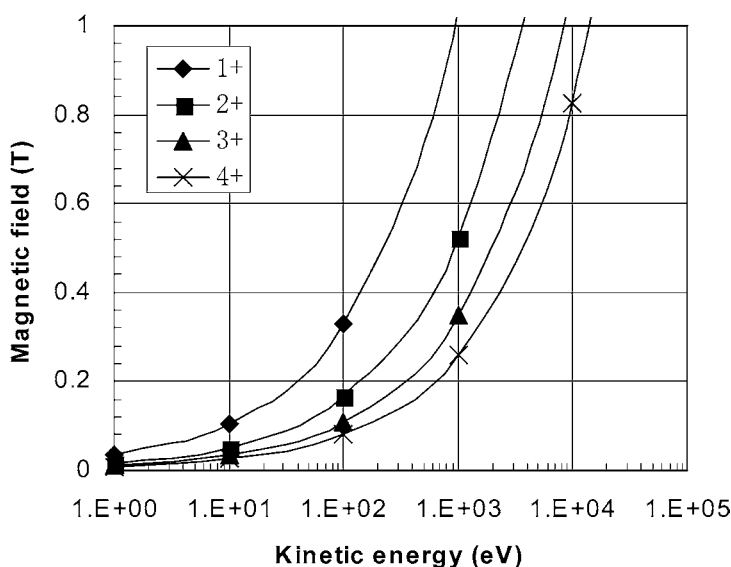


Figure 37.31 Relationship between ion energy and required magnetic field to keep the Larmor radius at 50 mm for Xe¹⁺ to Xe⁴⁺ ions.

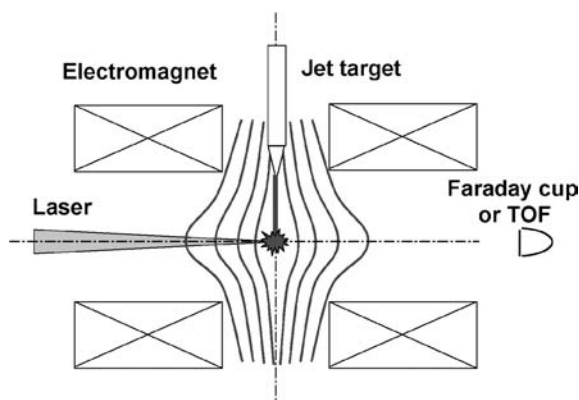


Figure 37.32 Fast-ion mitigation by magnetic field confinement.

the distance between the coil pair is currently only 3 cm, it will have to be increased to allow for an efficient collection angle of EUV emission.

The horizontal angular dependence of the fast plasma ions was measured inside the EUV vacuum chamber by integrating the current signal of the Faraday cup at different angles. Figure 37.34 shows the result of the measurement (a) without, and (b) with a magnetic field of approximately 0.17 T. The magnetic field direction is perpendicular to the figure plane. The angular dependence was measured (a) between 23 and 158 deg, and (b) between 203 and 338 deg in the horizontal plane including the laser-beam axis and at a distance of 14 cm from the plasma source. The Faraday cup was (a) directly facing the plasma source, and (b) rotated 60 deg from the plasma direction.

Without a magnetic field, the number of emitted ions peaked at the smallest measured angle, i.e., near the incident laser beam [see Fig. 37.34(a)]. The tilted Faraday cup shows a more isotropic distribution around 293 deg with applied magnetic field. This can be expected, since the magnetic field redistributes the ions as shown in Fig. 37.35. The figure shows the visible plasma emission taken by a CCD camera at an angle of 225 deg (see Fig. 37.34) (a) without, and (b) with a magnetic field of approximately 0.17 T. When the magnetic field is applied, bright plasma emission is observed due to increased collisions between the magnetically confined particles. The bright blue emission is shifted toward the left side (incident laser) as observed with the Faraday cup in case of a magnetic field [Fig. 37.34(b)]. The measured distribution is slightly asymmetric with respect to 225 deg, viz., shifted to the left side in Fig. 37.35, because initially (i.e., without the B field), most ions are emitted toward the incident laser beam.

To measure the ions emitted axially, i.e., along the magnetic field lines, a Faraday cup was placed on the magnetic coil symmetry axis at about 170 mm from the plasma. The nozzle was placed horizontally and perpendicular to the incident laser

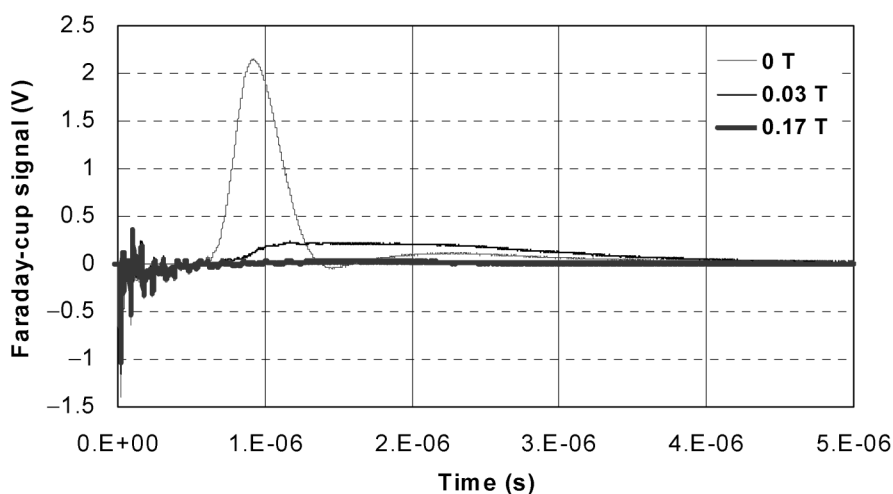


Figure 37.33 Fast-ion measurement with magnetic field.

beam for this measurement. Results are shown in Fig. 37.36. The measured ion current increases with increasing B because the ions travel along the field lines, and the number of ions inside the loss cone increases due to collisions. The observed signal is negative because of the high electronegativity of fluorine; probably F^- ions are generated during the relatively long TOF.

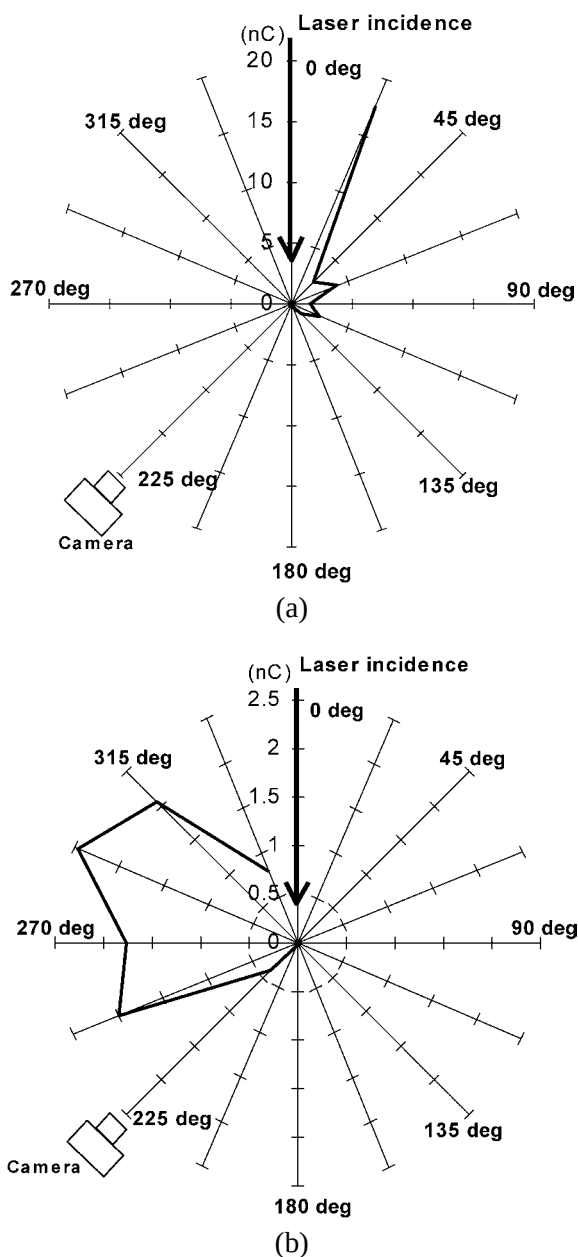


Figure 37.34 Result of Faraday-cup measurement (a) without, and (b) with a 0.17-T magnetic field.

37.5.4 Conclusions from EUVA work

Kinetic energies of fast Xe ions from the LPP have been measured with the TOF method. Though Xe^+ to Xe^{6+} ions are observed with a 150-ps and a 8-ns pulse

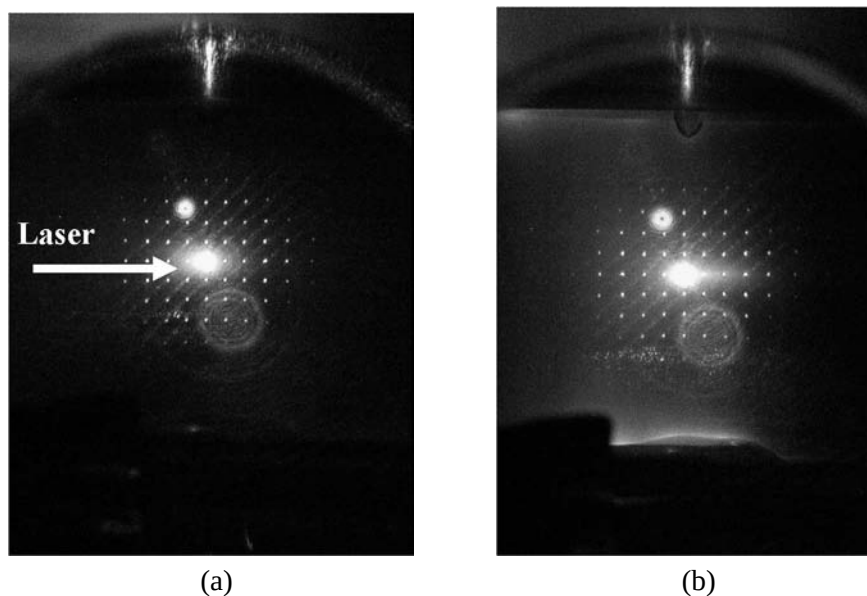


Figure 37.35 Plasma-source image in a visible range (a) without, and (b) with 0.17-T magnetic field.

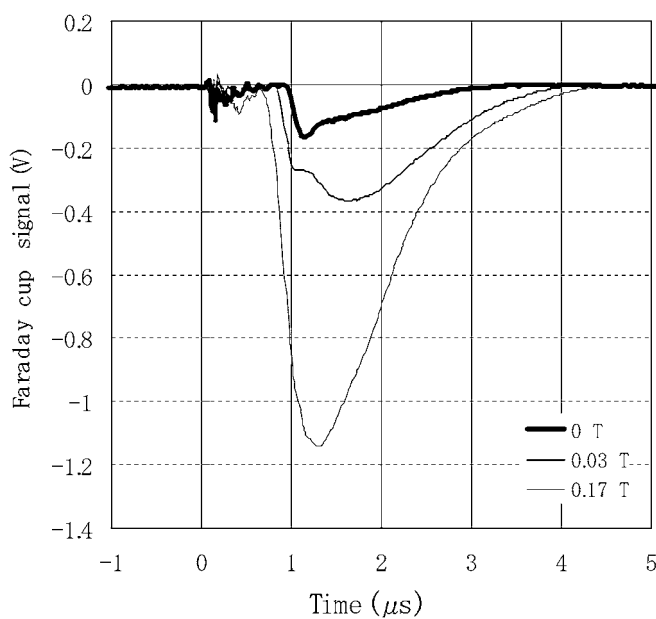


Figure 37.36 Results of collected-ion measurements by a Faraday cup placed on the magnet.

width, and 100-mJ pulse energy from Nd:YAG lasers, Xe^{2+} is the main charge state. Damage mechanisms involving fast ions on Mo/Si MLMs have also been studied using an ion gun. Ion sputtering is the main damage mechanism, but multilayer boundary mixing and increased surface roughness are also observed. A first test of a magnetic confinement scheme has demonstrated its feasibility.

37.6 Work in Other Laboratories

The condenser erosion work described in this chapter has stimulated interest in other laboratories. Significant condenser erosion research and development is being conducted by XTREME technologies, a German-based company developing EUV sources. That work is reported in Chapters 14 and 19.

In addition, work has been initiated at the National Institute of Standards and Technology (NIST) in the area of condenser erosion phenomena. Several of the C1 condenser elements exposed during ETS operations are undergoing state-of-the-art surface analysis by NIST scientists. The purpose of the studies is to gain information on the condenser erosion mechanism by an analysis of the damage to exposed multilayer optics. In addition, prior work at NIST has shown that highly charged ions (HCIs) can produce catastrophic sputtering when encountering a substrate surface. By a Coulombic explosion process, HCIs can produce much greater sputtering of substrate material than is produced by an equal number of singly charged ions. The possibility that this mechanism is contributing to condenser erosion phenomena is being investigated by NIST scientists, as reported by Pomeroy et al. in Chapter 38.

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Chapter 38

Potential Energy Sputtering of EUVL Materials

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38.1 Introduction

Of the many explanations suggested for the erosion of critical EUVL components, potential energy (PE) damage remains relatively uninvestigated. Unlike the familiar kinetic energy sputtering, which is a consequence of the momentum transferred by an ion to atoms in the target, PE sputtering occurs when an ion rapidly collects charge from the target as it neutralizes. Since the neutralization energy of a singly charged ion is typically on the order of 10 eV, PE effects are generally neglected for low-charge-state ions, and hence in the bulk of the sputtering literature. As an ion's charge state is increased, the PE increases rapidly; e.g., $\text{PE}(\text{Xe}^{1+}) = 11 \text{ eV}$, $\text{PE}(\text{Xe}^{10+}) = 810 \text{ eV}$, $\text{PE}(\text{Xe}^{20+}) = 4.6 \text{ keV}$.¹ By comparison, the binding energy of a single atom on a surface is typically about 5 eV, so even inefficient energy transfer mechanisms can lead to large quantities of material being removed; e.g., 25% efficiency for Xe^{10+} corresponds to ≈ 40 atoms/ion. By comparison, singly charged Xe ions with $\approx 20 \text{ keV}$ of kinetic energy sputter only about 5 atoms/ion at normal incidence, and less than 1 atom/ion at typical EUV source energies (as determined using TRIM and sputter-yield data tables²).

EUV light sources are optimized for producing approximately 10^{16} Xe ions per shot with an average charge state of $q = 10$ in the core plasma.³ At operational rates of $\approx 10 \text{ kHz}$, the number of ions produced per second becomes a whopping

10^{20} . Even if only one in a billion ions reaches the collector,* erosion rates could exceed $\approx 10^{12}$ atoms per second, severely reducing the collector lifetime (for an average yield of 10 atoms/ion). In addition, efforts to reduce contamination effects may contribute to reduced neutralization and even larger PE damage rates. In order to provide accurate estimates for collector lifetimes and to develop mitigation schemes, National Institute of Standards and Technology (NIST) is working to understand and quantify potential energy damage mechanisms on materials relevant to EUVL. Accurate PE damage rates can then be used for projecting component lifetimes as source plasma conditions are modified and characterized.

This chapter will serve to provide an introduction and some background to the physics of highly charged ions (HCIs) and some of the relevant experimental work in the literature. It will first provide a brief background and an overview of the interaction of HCIs with solids as it is currently understood. Secondly, it will present current data from screen test measurements performed to isolate and evaluate the effects of PE damage on critical EUVL materials. It will then speculate on the implications of work to date and the outlook for EUVL development, and finally summarize.

38.2 Interactions of HCIs with Solids

When singly charged ions interact with solids, the transfer of the ions' forward momentum is the dominant damage-forming mechanism, creating lattice dislocation and sputtered atoms. Kinetic energy sputtering is a thoroughly studied and well-understood process for most elements and kinetic energies. Extensive experimental work has generated data on sputter rates as a function of kinetic energy for nearly every known combination of elements in the periodic table.² The compilation of these data has resulted in the accumulation of accurate parameters for use in analytical fits such as Yamamura's semiempirical model (based on Sigmund's theory of sputtering⁴). With increased interest in technologies that employ ion energies nearer to sputtering thresholds and at nonnormal incidences, the models have been refined to increase their accuracy in the low-energy and light-ion regimes.⁵ In addition to semiempirical fits to actual data, the Monte Carlo simulation SRIM (TRIM) has been widely tested and accepted as an accurate benchmark for quantitatively describing ion-solid interactions, particularly stopping ranges and sputter yields.⁶ In recent history, SRIM has been used to generate accurate predictions at arbitrary energies and incidence conditions for even further refinement of semiempirical formulas that more accurately model the low-energy (threshold) regime and the low-mass-ratio regime.⁷ This vast compilation of knowledge, fit functions, and simulations makes estimation of kinetic energy damage relatively easy and accurate, but such simulations neglect charge and PE effects entirely.

*Efforts are underway to measure the actual flux at the collector. Estimates using the source gas pressure and electron-capture cross sections indicate that the source-collector distance is approximately the mean free path for Xe¹⁰⁺, so that half the ions escaping the plasma sheath would neutralize on the collector.

The effects of kinetic energy, which are the leading-order effects for singly charged ions, are still present during interactions of HCIs with surfaces, but are not necessarily the most significant effect. As many electrons are removed from an atom, the charge imbalance leads to enormous electric fields; e.g., the 1s electron on an Ar^{17+} ion will experience an $\approx 5 \times 10^{13}$ V/cm electric field. The ion's enormous electric field interacts with the surface from many Bohr radii away, tearing electrons from the surface well before the ion interacts kinematically with the surface.⁸ These extracted electrons are captured by the ion into atomic energy levels similar to the energy level the electron occupied in the solid, i.e., at energies similar to the work function. These atomic energy levels tend to be very high-lying Rydberg states;⁹ e.g., Xe^{25+} on Au will capture electrons into levels where the principal quantum number $n > 20$. Electrons captured into highly excited states with potentially high angular momentum numbers will relax by cascading to lower- n levels, but the transition rates are highest when momentum is conserved by ejecting another electron. For example, in the process of one electron moving from the $n = 20$ down to an $n = 15$ level, five other electrons may be ejected from the ion, which will subsequently be replaced by five more electrons from the surface. Measurements of secondary-electron yields from HCI-surface interactions have shown that a HCI can “pump” hundreds of electrons per ion, many times the HCI's initial charge state.¹⁰ Electronic extraction of this magnitude corresponds to an enormous macroscopic quantity; for example, if a Xe^{20+} ion requires ≈ 100 electrons from a surface to become completely neutralized, and the entire charge transfer occurs in a 1-nm^2 area and in ≈ 0.1 ps,[†] this corresponds to a current density of $\approx 1 \times 10^{10}$ A/cm². With current densities of this magnitude, it is easy to see how the charge transfer is one way an HCI can destabilize a surface (depending on the material, bulk vaporization will occur between 10^5 and 10^8 A/cm²).¹¹

The process of neutralizing HCIs on surfaces is known to dramatically destabilize some surfaces, as has been demonstrated by large secondary-electron yields, extremely high sputter yields (in diverse classes of materials, including SiO_2 , LiF, GaAs, and UO_2),⁸ similarly large secondary-ion yields,¹² and x-ray emission from target materials during HCI exposure.¹³ A unified theory that explains all these results has not yet been presented, but a few theories that have captured significant attention are worth summarizing.

Perhaps the most intuitive model for target damage due to HCIs simply suggests that the rapid charge transfer from the surface can locally deplete electrons in the solid. The residual positive charge expands due to the repulsive Coulomb forces, resulting in a potentially massive explosion that removes many more atoms than the initial charge state.¹⁴ This *Coulomb explosion* model has persisted in part because of its ability to explain the large number of neutral atoms removed due to the HCI's neutralization, as was shown in a molecular dynamics simulation where charge was pinned on a predetermined geometry of surface atoms.¹⁵ The principal weakness

[†]The exact neutralization time will depend on experimental conditions and the properties of the neutralizing surface. This estimate is based on a relatively slow ion's drift time from the distance of first electron capture (classical over-the-barrier method)⁹ to penetration into the solid.

of the Coulomb explosion model is its reliance on hole lifetimes long enough to develop a shock wave.¹⁶ Nevertheless, the model captures the key idea that the HCI, through some mechanism, can introduce a shock into the target that results in significantly elevated damage rates in comparison with kinetic energy effects.

Depending on the target material of interest, mechanisms other than Coulomb repulsion can be identified that could generate a shock wave resulting in massive surface damage. In covalent solids such as III-V materials, Si, and SiO₂, HCIs can induce a structural instability leading to a shock wave electronically by *ultrafast electronic excitation*.¹⁷ These materials are stable solids due to the binding nature of the valence bands, but the conduction bands are strongly antibonding. If enough carriers (approximately 1 per surface atom in the region of interest) are promoted from the valence to the conduction band, the equilibrium lattice spacing can grow significantly, introducing a severe internal stress.¹⁸ This stress can provide enough internal energy to significantly increase sputter yields, which may explain the large yields seen in materials such as GaAs.¹⁹

The most dramatic potential sputtering effects have been reported in the alkali halides, particularly LiF, where sputter yields increased by a factor of ≈ 30 when the charge state was increased from Ar¹⁺ to Ar¹¹⁺ at 1 keV of kinetic energy, with total sputter yields exceeding 80,000 u/ion for Xe²⁷⁺ at 1 keV of kinetic energy.^{20,21} A *defect-mediated desorption* (DMD) model has been employed to explain these data,²¹ leveraging earlier work indicating that self-trapped excitons (STEs) in these systems could decay into lattice defects.²² If the HCI's intense electronic interaction with the LiF target produces high densities of electron-hole pairs, these can decay into subsurface F₂ molecules and STEs. Each of these can then decay so that a fluorine atom escapes into the vacuum and a neutral Li atom remains on the surface. Subsequent ion-surface interactions (kinetic energy and PE) stimulate desorption of the Li, preventing the growth of a segregated overlayer.

The defect-mediated desorption model provides a plausible explanation for materials with strong electron-phonon coupling, but further extension is required to incorporate dramatic PE effects observed in materials such as MgO, which do not have strong electron-phonon coupling. The principal proponents of DMD argue that the lattice defects created by the kinetic energy of the incident ion allow electronic energy to become localized in the target, thereby providing a mechanism for large yields due to PE.²³ The proponents argue that this explains the apparent absence of potential sputtering in the limit of zero kinetic energy, and the strong dependence of the sputtering yields on both kinetic energy and charge state.

While each of the potential sputtering models summarized here has directly dealt with only the PE, much of the experimental data suggest a synergy of kinetic and potential energies.²⁴ Though the ion's interaction time with the surface prior to collision is determined by the kinetic energy and charge, it seems that the deposition of PE into the surface prior to the collision cascade presoftens the surface, resulting in much higher yields of ejected material; i.e., PE transfer enhances kinetic energy sputtering. It has also been suggested that the collision process may produce lattice defects that allow electronic energy to be localized (STEs),

resulting in an enhanced DMD process,²⁵ i.e., kinetic energy enhances potential sputtering.

It is clear that at higher charge states, the interaction of the ion with target materials becomes more intense and complicated, involving many more mechanisms at nonnegligible rates. Of all the materials classes studied, the noble metals are the only ones that have not shown clear and convincing evidence of PE-related damage,²⁶ and even for them, PE effects are not conclusively excluded.[‡] Essentially all low-conductivity materials studied have shown some sort of susceptibility to PE damage, including metal oxides²⁷ and semimetals.²⁸

Selection of appropriate materials for use in a plasma environment requires balancing the relative significance of many different mechanisms; e.g., materials least susceptible to PE damage may be most susceptible to kinetic energy damage, and attempts to screen critical components with gas curtains, etc., may actually increase component oxidation rates and therefore increase PE damage rates. Further studies on actual devices to quantify relative rates of damage are critical for accurate projection of component lifetimes and development of schemes for mitigating expected damage.

38.3 Experimental Studies of PE Damage to EUVL Devices

The electron beam ion trap (EBIT) at NIST is capable of producing very highly charged ions (e.g., Bi⁷³⁺, Xe⁵²⁺, Sn⁴⁸⁺) and delivering monoenergetic beams of a particular charge state onto target samples. HCIs can be created from a wide range of elements, over a broad range of charge states, and delivered onto samples via a complex ultrahigh-vacuum (UHV) ion-beam line (described in detail elsewhere^{29,30}). The NIST EBIT is being used in support of EUVL to isolate PE damage effects by exposing candidate materials and actual EUVL optics³¹ to controlled doses of HCIs and then characterizing the effects with *in situ* scanning tunneling microscopy (STM) and *ex situ* EUV reflectometry.

An example of an EUV reflectance map is shown in Fig. 38.1 of a prototype piece of EUVL optic after exposure to a very low dose of Xe⁴⁴⁺ (≈ 1 ion per 250 nm²). The reflectivity of the optic is changed by $\approx 0.8\%$ in the lower part of the figure, corresponding to the region where the optic was exposed to the Xe ions.[§] A similar optic exposed to ≈ 1 Xe¹⁰⁺ ion per 10 nm² (a $25\times$ higher dose) showed a 0.3% (a $2.5\times$ lower) change in the EUV reflectivity (not shown). Data of this type suggest that the reflectivity of an EUV optic is initially changed 1% for every ≈ 250 eV/nm² of PE delivered to the optical surface.[¶] Using the bulk densities for

[‡]The reader should note that several other materials reported in Ref. 26 to have “no effect” have since been found to have significant effects at higher charge states, e.g., GaAs, MgO, and Si.

[§]For these measurements, the EUV reflectivity initially increases while the thickness of the capping layer, which inhibits reflectivity, is reduced. Continued erosion would result in a maximum of reflectivity and a subsequent reduction to values much less than the initial reflectivity. This nonfunctional (double-valued) dependence introduces an ambiguity in the analysis. The solution of least damage is assumed; the actual damage may be ≈ 2 times worse.

[¶]The change of reflectivity is calculated from the known beam spot size, total dose, and measured reflectivity maps, assuming a spatially homogeneous ion beam.

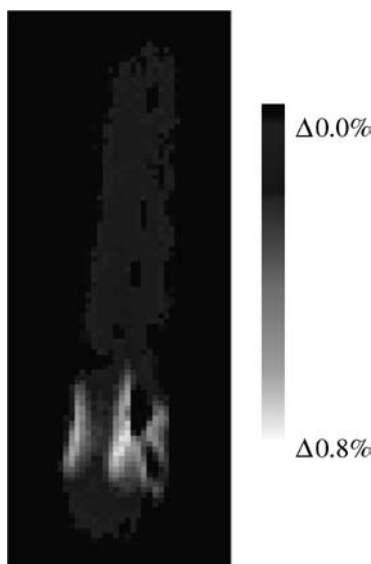


Figure 38.1 The 13.4-nm reflectivity of an EUVL mirror after exposure to a very low dose of HCl ions (≈ 1 ion/ 250 nm^2) shows evidence of damage. The yellow lobes at the bottom of the image correspond to the regions of HCl exposure. We believe this increase in the reflectivity is due to an ablation of the capping layer in those regions, which has removed some of the oxide, effectively thinning the ruthenium capping layer.

the ruthenium oxides, this implies that ≈ 20 eV of PE is required for the removal of each molecule. Using an estimated bulk binding energy of ≈ 5 eV, we can infer that $\approx 25\%$ of an ion's PE is converted to sputtered material. Efficiencies of this magnitude are similar to computational results on damage due to PE effects.¹⁵

The reflectivity data were taken on samples that are part of a series of EUV optics exposed to the same number of HCl ions per unit area and studied by STM and tunneling spectroscopy. For that series, the optics were exposed to $\approx 5 \times 10^9$ ions/ mm^2 , or 1 ion per $\approx 200 \text{ nm}^2$. A $200 \text{ nm} \times 200\text{-nm}$ sample image of another EUV optic's surface after exposure to a higher density (1 ion per $\approx 10 \text{ nm}^2$) of Xe^{10+} ions is shown in Fig. 38.2(a). Extensive analysis of the surface topography does not reveal any characteristic feature(s) that can be correlated with an individual ion's impact. This can be understood after comparing the time scale of the ion exposure with the time scale for intrinsic surface smoothing. The ion exposure took place over the course of an hour, and the subsequent imaging in the STM takes place over several hours. While this is not long enough for the surface to react with any contaminants present in the UHV environment, it is long enough for the surface kinetics to wash out any characteristic feature, so the signature is lost in the intrinsic roughness.

While individual topographic features due to HCl impacts are not evident in the topographic images, spatially localized spectral features in the surface conductivity maps at moderate bias (-0.63 V) are consistent in density with the ion dose and consistent in size with analysis of the EUV reflectivity data. A representative $20\text{-nm} \times 20\text{-nm}$ spectral map is shown in Fig. 38.2(b). This image represents the

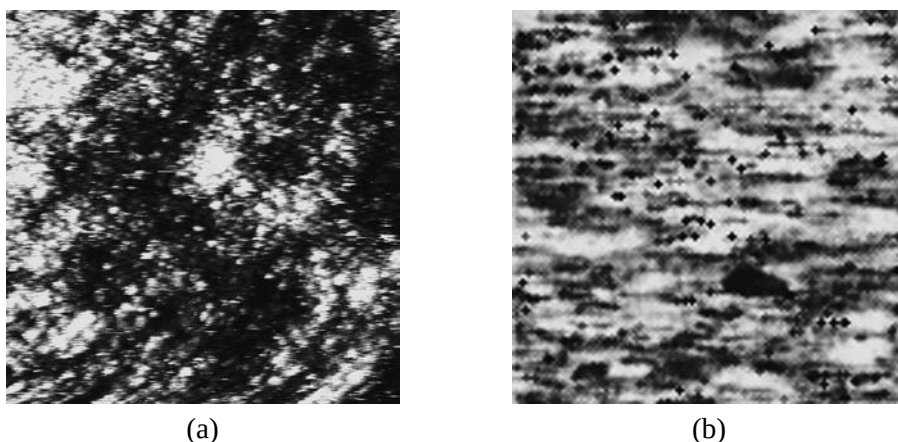


Figure 38.2 (a) A 200-nm $\times$ 200-nm STM image of an EUVL mirror after exposure to Xe^{10+} ions. The rich surface morphology and rapid kinetics mask morphological damage. (b) A spatial slice of spectroscopic data taken at -0.63 V of bias; the image is a current map as a function of position, 20 nm $\times$ 20 nm. The dark, high-conductivity dots may be due to single ion impacts creating a low-resistance pathway through the surface oxide. (The dots look like crosses due to nearest-neighbor filtering used to reduce pixel noise.)

current at a -0.63 -V bias as a function of position. Since the bias is negative, bright areas represent poor conduction and vice versa. The dark cross-shaped features^{||} are patches of the surface with significantly higher conductivity than the surrounding region, which may be due to single ion impacts. These individual features collectively represent a measurable change in the surface, which we have statistically analyzed.

While we have not seen quantifiable PE damage in the surface topography on the EUV optics, statistical analysis of the tunneling spectroscopy reveals an increase in the surface conductivity with increasing PE, shown in Fig. 38.3. The optic's surface relative conductivity (normalized to the unexposed optic) systematically increases with the PE deposited per ion.^{**} This is likely due to PE ablation of oxide on the surface. The higher PE density corresponds to a larger fraction of the surface's oxide being removed. Since the oxide is not deliberately grown, but is a consequence of exposure to the atmosphere, the surface is rough on the nanometer scale prior to HCI exposure [nominally the same as Fig. 38.2(a)]. This roughness has an ≈ 5 -nm characteristic lateral feature size, which may be indicative of oxide clusters (root-mean-square roughness < 1 nm). An incident HCI may remove some oxide clusters whole, particularly if they are weakly bonded to the underlying capping layer.³² This cluster dissociation idea is one possible model for the removal of large amounts of material per incident ion.

^{||}The crosslike shape is due to nearest-neighbor filtering used to reduce pixel noise.

^{**}The error bars represent the propagated rms values of the distribution of conductivities for mean-value conductivity analysis. We are currently pursuing more advanced analysis that is expected to be more sensitive to the conductivity change, thereby reducing the relative errors.

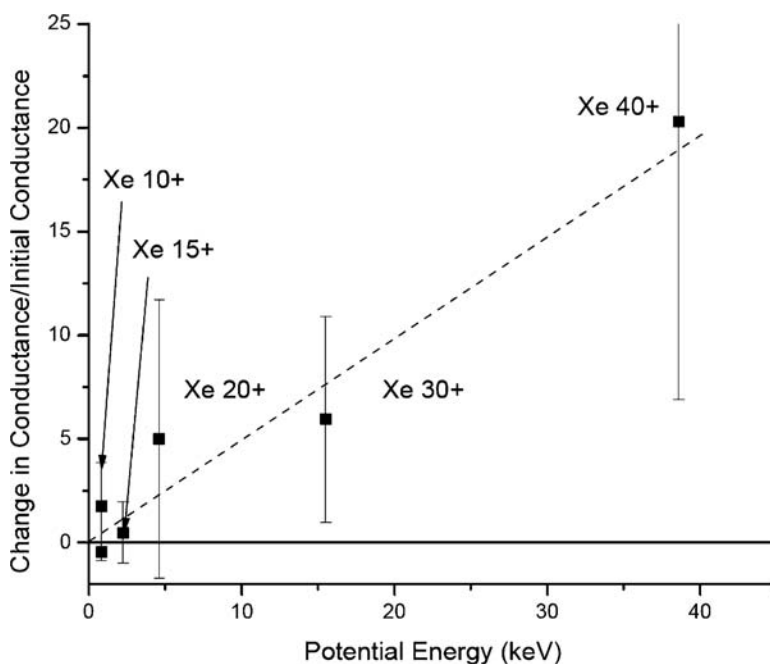


Figure 38.3 EUVL optics exposed to HCIs show an increase in the surface's relative conductivity (normalized to the unexposed optic) that increases systematically with PE density, i.e., with the amount of neutralization energy deposited per unit surface area. The increasing surface conductivity is likely due to increased removal of the surface oxide. It is not believed that these data suggest any kind of charge or energy threshold. Error bars represent the propagated standard deviations of the surface-conductivity data, and are not uncertainties of the mean.

The HCI dose used in this study (Fig. 38.3) was selected to avoid saturation effects at high-charge states; higher doses of low-charge states are expected to lead to damage that scales with the PE. We do not believe that the suggestion of any threshold is an accurate interpretation of the data. Initial data from much higher doses of Xe^{10+} on EUV optics suggest that damage scales with total PE dose, rather than strictly with charge state (or PE per ion). Calculations made with TRIM of the sputter and dislocation rates due to kinetic energy effects alone in the materials studied indicate that the same dose of singly charged ions would not yield a measurable change in either the EUV reflectivity or the surface conductivity. The PE dependence is further illustrated by the factor-of-50 increase in the number of Xe^{10+} ions required to damage the optic as much as Xe^{40+} . Estimates (based on TRIM calculations) suggest that Xe^{10+} ions damage the optics ≈ 15 times more than singly charged ions.

Observed changes in EUV reflectivity indicate that the EUV optic materials are susceptible to potential sputtering as they are currently deployed. Whether optic lifetimes will ultimately be limited by effects of PE erosion will largely be determined by the source's operational characteristics. Since EUV sources do not yet meet the industrially required power output, demanding potentially dramatic

changes in design and operation, proper consideration of PE and the associated damage when minimizing risk to critical components is prudent.

38.4 Implications and Outlook

Evidence of HCI damage on EUV optics, taken in concert with data listed in the references presented in this chapter, clearly indicates the existence of PE damage effects. EUV devices, as currently optimized for use in production tools, are susceptible to PE damage. It is possible to minimize or mitigate damage to the components by seeking to harden the components by utilizing materials with lower damage rates, or by minimizing the flux of HCIs from plasma sources so that PE damage is negligible compared with the kinetic energy effects. In either case, accurate quantitative data for damage rates of various materials are highly desirable, since accurate modeling of component lifetimes relies on accurate rate estimates.

Efforts to determine if sources currently in testing are emitting substantial fluxes of HCIs, or ions with substantial energies, are not conclusive. Some source suppliers indicate ion emission with kinetic energies as high as 20 keV, while others are adamant that their source is not emitting ions above 500 eV. As sources are ramped up to production power levels and repetition rates, substantial ion emission may become more likely. Whether or not PE damage will be a limiting factor in production tools will ultimately depend on the source's ion emission rates, but prudent assessment of materials properties can allow for last-minute corrections that might mitigate a show-stopping oversight.

38.5 Summary

In summary, NIST's work indicates that EUVL optics are susceptible to PE damage due to the neutralization of HCIs. Initial estimates for damage yields from experiments suggest that ≈ 20 atoms may be removed for each Xe^{10+} ion, about an order of magnitude more than due to kinetic energy alone. The removal of optical material results in an EUV reflectivity change of about 1% for $\approx 250 \text{ eV/nm}^2$ deposited on the surface. This change is correlated with an increase in the surface conductivity measured by tunneling spectroscopy and appears to be a very sensitive measure of the change of the surface state, which can be employed for studying a broader class of critical materials. Further efforts are expected to provide more quantitative guidance for mitigating PE damage effects.

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