2015 International Workshop on EUV and Soft X-Ray Sources
November 9-11, 2015
Dublin ▪ Ireland

Workshop Proceedings
2015 International Workshop on EUV and Soft X-ray Sources

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2015 International Workshop on EUV and Soft X-Ray Sources

November 9-11, 2015, Dublin, Ireland

Monday, November 9, 2015 (Newman House)

6:00 PM – 7:00 PM Registration, Reception and Speaker Prep

Tuesday, November 10, 2015 (George Moore Auditorium)

9:15 AM Announcements and Introductions

Welcome, Announcements and Introduction (Intro-1)

Joe Carthy, UCD, Dublin

Vivek Bakshi, EUV Litho, Inc., USA

9:35 AM Session 1: Keynote Session -1

Session Chair: Padraig Dunne (UCD)

EUVL Advancements Toward HVM Readiness (S1)

Britt Turkot
Intel Corporation

Performance Overview and Outlook of EUV Lithography Systems (S2)

Wim van der Zande
ASML
Break 10:55 AM (20 Minutes)

11:15 AM  Session 2: HVM EUV Sources

Session Co-Chairs: Wim van der Zande (ASML) and Hakaru Mizoguchi (Gigaphoton)

**Performance of One Hundred Watt Source and Construction of 250Watt HVM LPP-EUV Source (S12) (Invited)**

Hakaru Mizoguchi, Hiroaki Nakarai, Tamotsu Abe, Krzysztof M Nowak, Yasufumi Kawasuji, Hiroshi Tanaka, Yukio Watanabe, Tsukasa Hori, Takeshi Kodama, Yutaka Shiraishi, Tatsuya Yanagida, Georg Soumagne, Tsuyoshi Yamada, Taku Yamazaki, Shinji Okazaki and Takashi Saitou
Gigaphoton Inc. Hiratsuka facility, Hiratsuka Kanagawa, JAPAN

**Studies of Laser-produced Tin plasmas for EUV Light Sources using Collective Thomson Scattering (S13) (Invited)**

Kentaro Tomita¹, Yuta Sato¹, Toshiaki Eguchi¹, Shoichi Tsukiyama¹, Kiichiro Uchino¹, Tatsuya Yanagida², Hiroaki Tomuro², Yasunori Wada², Masahito Kunishima², Takeshi Kodama², Hakaru Mizoguchi²
¹ Interdisciplinary Graduate School of Engineering and Sciences, Kyushu University, 6-1, Kasugakoen, Kasuga, Fukuoka 816-8580, JAPAN
² Gigaphoton Inc., 400 Yokokurashinden Oyama, Tochigi, 323-8558, JAPAN

**Experimental and Theoretical Studies of Tin Droplets Shaping by Picosecond Laser pre-pulses (S24) (Invited)**

Slava Medvedev et al
Institute for Spectroscopy, Russian Academy of sciences

**Correlation between Laser Absorption Process and Energy Conversion to Extreme Ultraviolet Radiation in Laser Produced Tin Plasma (S16)**

Hiraku Matsukuma¹, Atsushi Sunahara², Tatsuya Yanagida³, Hiroaki Tomuro³, Kouichiro Kouge³, Takeshi Kodama³, Tatsuya Hosoda¹, Shinsuke Fujioka¹, and Hiroaki Nishimura¹
¹ Institute of Laser Engineering, Osaka University, Suita, 565-0871, Japan
² Institute of Laser Technology, Suita, 565-0871, Japan
³ Gigaphoton, Inc., 3-25-1, Shinomiya, Hiratsuka 254-8555, Japan

Lunch 12:35 PM
2:00 PM Session 3: Modeling Session Dedicated to the Memory of Vladimir G. Novikov

Session Chair: Gerry O’Sullivan (UCD) and A. Sunahara (Osaka University)

In the Memory of Prof. Vladimir G. Novikov (S38)

Slava Medvedev
Institute for Spectroscopy, Russian Academy of sciences

Hydrodynamics Modeling of the Dynamics of Sn droplet Target for the EUV Source (S17)

Akira Sasaki
Kansai Photon Science Institute, Japan Atomic Energy Agency, Kyoto, Japan

Radiation Hydrodynamic Simulation of Laser-produced Tin Plasmas (S20) (Invited)

A. Sunahara¹, H. Matsukuma², K. Nishihara², and A. Sasaki³
¹Institute for Laser Technology
²Institute of Laser Engineering
³Japan Atomic Energy Agency

Experimentally Validated Neutral Cluster Debris Mean Velocity and Trajectory Model for Droplet-Based Laser Produced Plasma Sources (S34)

Duane Hudgins, Nadia Gambino, Bob Rollinger and Reza S. Abhari
Laboratory for Energy Conversion, Swiss Federal Institute of Technology Zurich (ETHZ), Switzerland
Adlyte AG, Zug, Switzerland

3:10 PM Break and Group Photograph (20 Minutes)
3:30 PM  Session 4: EUV Sources for Metrology

Session Co-Chairs: Klaus Bergmann (Fraunhofer-ILT) and Reza Abhari (ETH)

**Bright and Reliable Xe-based EUV Source for Metrology and Inspection Applications (S31) (Invited)**

Oleg Khodykin  
*RAPID, KLA-Tencor Inc., USA*

**Discharge based EUV Source for Metrology and Inspection (S32) (Invited)**

Klaus Bergmann, Alexander von Wezyk and Jochen Vieker  
*Fraunhofer Institute for Laser Technology – ILT, Aachen, Germany*

**High-radiance LDP Source: clean, Reliable and Stable EUV Source for Mask Inspection (S35) (Invited)**

Yusuke Teramoto, Bárbara Santos, Guido Mertens, Ralf Kops, Margarete Kops, Hironobu Yabuta, Akihisa Nagano, Noritaka Ashizawa, Takahiro Shirai, Kunihiko Kasama, Alexander von Wezyk$^1$ and Klaus Bergmann$^1$  
*USHIO Inc.*  
$^1$Fraunhofer ILT

**Light Sources for High Volume Metrology and Inspection Applications (S37) (Invited)**

Reza S. Abhari  
*ETH Zurich, Switzerland*

**Break 4:50 PM (20 Minutes)**

Adjourn for the day – Time off for Networking

**5:10 PM  Source TWG meeting (Closed) –Location TBA**

**End of Day 2**
Wednesday, November 11, 2015

9:15 AM Announcements

Introduction and Announcements (Intro-2)
Vivek Bakshi, EUV Litho, Inc.

9:25 AM Session 5: Keynote Session - 2

Session Chair: Padraig Dunne (UCD)

Laser Plasma Sources of Soft X-rays and Extreme ultraviolet (EUV) for Application in Technology and Science (S3)

Henryk Fiedorowicz
Institute of Optoelectronics, Military University of Technology, Warsaw, Poland

10:05 AM Session 6: Optics

Session Co-chairs: Joost W.M. Frenken (ARCNL) and Eric Louis (University of Twente)

The Advanced Research Center for Nanolithography (S41) (Invited)

Joost W.M. Frenken
Advanced Research Center for Nanolithography (ARCNL), Science Park 110, 1098 XG, Amsterdam, The Netherlands

Studies of Thermal Transport in Mo/Si Multilayer Structures (S42)

Slava Medvedev
Institute for Spectroscopy, Russian Academy of sciences
EUV and Beyond EUV Optics Research at the University of Twente (S43) (Invited)

Eric Louis, Robbert van de Kruijjs, Andrey Yakshin, Johan Reinink, Dmitry Kuznetsov, Ben Wylie van Eerd, Chris Lee and Fred Bijkerk, \textsuperscript{1}Hartmut Enkisch and \textsuperscript{1}Stephan Müllender
MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE, Enschede, The Netherlands
\textsuperscript{1}Carl Zeiss SMT GmbH, Rudolf-Eber-Straße 2, 73447 Oberkochen, Germany

11:05 AM Break (20 minutes)

11:25 AM Session 7: XUV Sources

Session Co-chairs: Rainer Lebert (Research Instruments) and Ladislav Pina (CTU)

Identification of Plasma Sources for Water Window Imaging: Recent Spectroscopic Studies (S58) (Invited)

G. O’Sullivan\textsuperscript{*}, P. Dunne\textsuperscript{*}, T. Higashiguchi\textsuperscript{†}, B. W. Li\textsuperscript{§}, R. Lokasani\textsuperscript{*}, E. Long\textsuperscript{*}, H. Ohashi\textsuperscript{#}, F. O’Reilly\textsuperscript{*}, P. Sheridan\textsuperscript{*}, J. Sheil\textsuperscript{*}, E. Sokell\textsuperscript{*}, C. Suzuki\textsuperscript{+}, and T. Wu\textsuperscript{*}
\textsuperscript{*}School of Physics, University College Dublin Belfield, Dublin 4, Ireland
\textsuperscript{†}Department of Advanced Interdisciplinary Science and Center for Optical Research (CORE), Utsunomiya University, Utsunomiya, Tochigi 321-8585 Japan,
\textsuperscript{§}School of Nuclear Science and Technology, Lanzhou University, Lanzhou, China
\textsuperscript{#}Graduate School of Science and Engineering for Research, University of Toyama, Toyama, Japan
\textsuperscript{+}National Institute for Fusion Science, Toki, Gifu 509-5292, Japan

UCD Physics Overview (S70)

Gerry O’Sullivan / Padraig Dunne (UCD)

Effects of Optical Thickness on Soft X-ray Spectral Feature Observed in Gd and Tb Plasmas (S54)

Chihiro Suzuki\textsuperscript{1}, Takeshi Higashiguchi\textsuperscript{2}, Atsushi Sasanuma\textsuperscript{2}, Goki Arai\textsuperscript{2}, Yusuke Fuji\textsuperscript{2}, Thanh Ding Hung\textsuperscript{3}, Fumihiro Koike\textsuperscript{3}, Izumi Murakami\textsuperscript{1}, Naoki Tamura\textsuperscript{1}, Shigeru Sudo\textsuperscript{4}
\textsuperscript{1}National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan
\textsuperscript{2}Utsunomiya University, 7-1-2 Yoto, Utsunomiya 321-8585, Japan
\textsuperscript{3}Sophia University, 7-1 Kioi-cho, Chiyoda-ku, Tokyo 102-8554, Japan
\textsuperscript{4}Chubu University, 1200 Matsumoto-cho, Kasugai 487-8501, Japan
Laser-Produced Plasma Spectroscopy of Medium to High-Z Elements in the 2 to 9-nm Spectral Region (S55)

Elaine Long¹, Chihiro Suzuki², John Sheil³, Elgiva White³, Ragava Lokasani¹, Bowen Li¹, Paul Sheridan¹, Patrick Hayden⁴, Emma Sokell¹, Padraig Dunne¹, Fergal O’Reilly¹ & Gerry O’Sullivan¹

¹ UCD School of Physics, University College Dublin, Belfield, Dublin 4, Ireland
² National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan
³ Summer Intern at UCD School of Physics
⁴ National Centre for Plasma Science & Technology and School of Physical Sciences, Dublin City, Dublin, Ireland

12:35 PM Lunch

1:40 PM Session 8: Applications of XUV Sources

Session Co-chairs: Torsten Feigl (optiX fab) and Larissa Juschkin (RWTH)

Multilayer Collector Optics for Water Window Microscopy (S65) (Invited)

Torsten Feigl
optiX fab, Germany

Application of Lens-less Imaging Techniques for Nano-scale Microscopy Employing Plasma-based EUV Source (S64) (Invited)

Larissa Juschkin¹,², Jan Bußmann¹,², Michal Odstrcil³, Raoul Bresenitz¹,², Denis Rudolf²

¹ RWTH Aachen University and JARA—Fundamentals of Future Information Technology, Chair for the Experimental Physics of EUV, Aachen, Germany
² Peter Grünberg Institute 9 and JARA—Fundamentals of Future Information Technology, Research Centre Jülich, 52425 Jülich, Germany
³ Optoelectronics Research Center, University of Southampton, United Kingdom
Laboratory-based Photoemission Spectro-microscopy at 71.7 eV for Studies of Complex Materials (S61)

Daniel Wilson 1,2,4,5, Christoph Schmitz 1,5, Denis Rudolf 2,3,5, Sally Rieß 3,5, Martin Schuck 3,5, Carsten Wiemann 1,5, Astrid Besmehn 6, Hilde Hardtdegen 3,5, Detlev Grützmacher 3,5, Claus M. Schneider 1,5, F. Stefan Tautz 4,5, and Larissa Juschkin 2,3,5
1 Forschungszentrum Jülich, Peter Grünberg Institut (PGI-6), Germany
2 RWTH Aachen University, Experimental Physics of EUV, Aachen, Germany
3 Forschungszentrum Jülich, Peter Grünberg Institut (PGI-9), Germany
4 Forschungszentrum Jülich, Peter Grünberg Institut (PGI-3), Germany
5 Jülich-Aachen Research Alliance (JARA), Fundamentals of Future Information Technology, Germany
6 Forschungszentrum Jülich, Central Institute for Engineering, Electronics and Analytics (ZEA-3), Germany

Water-Window Microscope Based on Nitrogen Plasma Capillary Discharge Source (S63)

T. Parkman1, M. F. Nawaz2, M. Nevrkla2, M. Vrbova1, A. Jancarek2
1Czech Technical University in Prague, Faculty of Biomedical Engineering, 272 01 Kladno, Czech Republic
2Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, 180 00 Prague 8, Czech Republic

3:00 PM Survey (ALL) (10 Minutes)

3:10 PM Break (20 Minutes)

3:30 PM Session 9: FEL Sources for EUVL

Session Co-Chairs: Akira Endo (HiLase) and Alexander Chao (SLAC)

Picosecond, kW Thin-disc Laser Technology for LPP and FEL EUV Sources (S21) (Invited)

A. Endo1,2, M. Smrz1, O. Novak1, H. Turcicova1, J. Muzik1, J. Huynh1, T. Mocek1, K. Sakaue2 and M. Washio2
1) HiLASE Centre, Institute of Physics AS CR, Dolní Břežany, Czech Republic
2) RISE, Waseda University, Tokyo, Japan
Current Progress on Design Work of High Power EUV-FEL based on ERL (S22) (Invited)

Kensei Umemori
High Energy Research Organization (KEK), Tsukuba, Ibaraki, Japan, 305-0801

A Kilowatt Storage Ring EUV Source Based on Steady State Microbunching (S23) (Invited)

Alexander Chao, Daniel Ratner
SLAC National Accelerator Laboratory, Menlo Park, CA, USA

4:30 PM Workshop Summary and Announcements

Workshop Summary and Announcements (Summary)
Vivek Bakshi, EUV Litho, Inc.

4:50 PM Break (20 Minutes)

5:20 PM Session 10: Poster Session (90 Minutes)
(Poster Paper Listing on Following Pages)

7:00 PM Depart for Dinner
5:20 PM  Session 10: Poster Session

Session Chair: Padraig Dunne (UCD)

**Topic: EUV Sources for HVM**

**Research of the Tin Droplet Generator and Plume Expansion of Laser Produced Tin Droplet Plasma (S11)**

Chen Ziqi, Wang Xinbing and Zuo Duluo  
*Wuhan National Laboratory for Optoelectronics, Huazhong University of Science & Technology, Wuhan 430074, China*

**Research of CO₂ Laser Produced Sn and SnO₂ plasma (S14)**

Lan Hui ¹,³, Wang Xinbing ², Zuo Duluo ², Zhen Guang³  
¹School of Optical and electronic information, Huazhong University of Science and Technology, Wuhan 430074, China  
²Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China  
³School of Physics and information engineering, Jianghan University, Wuhan 430056, China

**Droplet Generator for High Brightness LPP EUV Source (S15)**

Alexander Vinokhodov¹, Vladimir Krivtsun¹,², Mikhail Krivokorytov¹, Yury Sidelnikov¹,², Viacheslav Medvedev¹,², Konstantin Koshelev¹,²  
¹EUV Labs/RnD ISAN, Moscow, Russia  
²Institute for Spectroscopy RAS, Moscow, Russia

**ARCNL’s Laser-produced Plasma EUV Source (S18)**

D. Kurilovich, F. Torretti, W. Ubachs, R.A. Hoekstra, O.O. Versolato  
*Advanced Research Center for Nanolithography, Science Park, Amsterdam*

**A Study of Colliding Plasma Processes for Elements of Different Mass (S19)**

D.Kos¹, O. Maguire², P. Oudayer², P. Dunne¹, F. O'Reilly¹, and E. Sokell¹  
¹School of Physics, University College Dublin, Belfield, Dublin 4, Ireland  
²University of Paris-Sud, 15 Street Georges Clemenceau, 91400 Orsay, France
Topic: EUV Sources for Metrology

**Combination of Discharge and Laser-produced Plasmas for High Brightness Extreme ultraviolet (EUV) Light Sources (S33)**

Florian Melsheimer\(^1,2,3\); Richard Lensing\(^1,2,3\), Girum Beyene\(^1,2,3,4\), Xiaoduo Wang\(^1,2,5\), Larissa Juschkin\(^1,2,3\)

\(^1\)Experimental Physics of EUV, RWTH Aachen University;  
\(^2\)Peter Grünberg Institut (PGI-9), Research Centre Jülich GmbH  
\(^3\)Jara – Fundamentals of Future Information Technology  
\(^4\)School of Physics, University College Dublin  
\(^5\)Changchun Institute of Optics, Fine Mechanics and Physiks, University of Chinese Academy of Sciences

**Plasma Design of the EQ-10 EUV Source (S39)**

Stephen F. Horne, Matthew J. Partlow, Deborah S. Gustafson, Matthew M. Besen, Donald K. Smith, Paul A. Blackborow  
Energetiq Technology Inc., 7 Constitution Way, Woburn MA 01801 USA

Topic: XUV Sources

**Feature of Unresolved Transition Array Emission in Water Window Soft X-ray Spectral Region from a Dual-pulse Laser-produced Bismuth Plasma (S51)**

Hiroyuki Hara, Goki Arai, Thanh-Hung Dinh, and Takeshi Higashiguchi  
Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), Utsunomiya University, Utsunomiya, Tochigi 321-8585 Japan

**Laser-produced Multiply Charged Ion Plasma Sources for a Compact Water Window Soft X-ray Microscope (S52)**

Yoshiki Kondo\(^1\), Thanh-Hung Dinh\(^1\), Goki Arai\(^1\), Takeo Eijima\(^2\), and Takeshi Higashiguchi\(^1\)

\(^1\)Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), Utsunomiya University, Utsunomiya, Tochigi 321-8585 Japan  
\(^2\)Institute of Multidisciplinary Research for Advanced Materials (IMRAM), Tohoku University, 2-1-1, Katahira, Aoba-ku, Sendai, 980-8577 JAPAN
**Absorption Spectral Structure in Highly-charged Zirconium Plasmas in Water window Soft X-ray Spectral Region (S53)**

Takanori Miyazaki\textsuperscript{1,2}, Goki Arai\textsuperscript{2}, Hiroyuki Hara\textsuperscript{2}, Thanh-Hung Dinh\textsuperscript{2}, Takeshi Higashiguchi\textsuperscript{2}, Akinobu Irie\textsuperscript{2}, Chihiro Suzuki\textsuperscript{3}, Daiji Kato\textsuperscript{3}, Akira Sasaki\textsuperscript{4}, Padraig Dunne\textsuperscript{1}, and Gerry O’Sullivan\textsuperscript{1}

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\textsuperscript{3}National Institute for Fusion Science (NIFS), Toki, Gifu 509-5292, Japan

\textsuperscript{4}Quantum Beam Science Center, Japan Atomic Energy Agency, 8-1-7 Umemidai, Kizugawa, Kyoto 619-0215, Japan

**Experimental Study of the Interaction of Sub-nanosecond and Nanosecond Duration Laser Pulses with Solid Targets at Different Laser Energies (S56)**

Ragava Lokasani\textsuperscript{1,2}, Elaine Long\textsuperscript{2}, Oisin Maguire\textsuperscript{2}, Domagoj Kos\textsuperscript{2}, Paul Sheridan\textsuperscript{2}, Patrick Hayden\textsuperscript{2}, Fergal O'Reilly\textsuperscript{2}, Padraig Dunne\textsuperscript{2}, Emma Sokell\textsuperscript{2}, Akira Endo\textsuperscript{3}, Jiri Limpouch\textsuperscript{1} and Gerry O’Sullivan\textsuperscript{2}

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\textsuperscript{2}UCD School of Physics, University College Dublin, Belfield, Dublin 4, Ireland.

\textsuperscript{3}Institute of Physics of Academy of Sciences of the Czech Republic, HiLase Center, Za Radnici 828, 252 4, Dolni Brezany, Czech Republic

**Colliding Laser - produced Plasma Experiments on Carbon Group Elements (S57)**

O. Maguire\textsuperscript{1}, D. Kos\textsuperscript{1}, P. Oudayer\textsuperscript{2}, P. Dunne\textsuperscript{1}, F. O'Reilly\textsuperscript{1}, T. McCormack\textsuperscript{1} and E. Sokell\textsuperscript{1}

\textsuperscript{1}UCD School of Physics, University College Dublin, Dublin 4, Ireland

\textsuperscript{2}University of Paris-Sud, Orsay, France

**Efficient EUV Sources by Short CO\textsubscript{2} Laser-produced Plasmas (S59)**

Atsushi Sasanuma\textsuperscript{1}, Reiho Amano\textsuperscript{1}, Thanh-Hung Dinh\textsuperscript{1}, Goki Arai\textsuperscript{1}, Takeshi Higashiguchi\textsuperscript{1} and Taisuke Miura\textsuperscript{2}

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\textsuperscript{2}HiLASE Centre, Institute of Physics ASCR, v.v.i., Dolni Brezany, Czech Republic
**X-ray Generation Enhancement from a Nano-structured Targets Irradiated by Long Laser Pulses (S62)**

Ragava Lokasani<sup>1, 2</sup>, Ellie Barte<sup>1</sup>, Jan Proska<sup>1</sup>, Lucie Stolcova<sup>1</sup>, Oisin Maguire<sup>2</sup>, Domagoj Kos<sup>2</sup>, Paul Sheridan<sup>2</sup>, Fergal O'Reilly<sup>2</sup>, Padraig Dunne<sup>2</sup>, Emma Sokell<sup>2</sup>, Tom McCormack<sup>2</sup>, Jiri Limpouch<sup>1</sup>, and Gerry O'Sullivan<sup>2</sup>

<sup>1</sup>Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Brehova 7, 11519 Praha 1, Czech Republic

<sup>2</sup>UCD School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

**ABSORPTION OF EUV RADIATION IN MATTER AND RELATED PROCESSES (S66)**

Chiara Liberatore<sup>1</sup>, Klaus Mann<sup>5</sup>, Matthias Müller<sup>5</sup>, Andrzej Bartnik<sup>6</sup>, Inam Ul Ahad<sup>6</sup>, Ladislav Pina<sup>3</sup>, Libor Juha<sup>4</sup>, Ludek Vyšín<sup>4</sup>, Jorge J. Rocca<sup>7</sup>, Akira Endo<sup>2</sup> and Tomas Mocek<sup>2</sup>

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