2018 Source Workshop

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Workshop Abstracts

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Welcome

Dear Colleagues;

We have an excellent agenda this year for the 2018 Source Workshop and I am looking forward to welcoming you to Prague, Czech Republic.

Source workshop, now in its 9th year, is the largest annual gathering of EUV and XUV source experts! This year we are including the new topic of Blue- X (EUVL extension via short wavelength sources and optics). The workshop proceedings will be published online and made available to all.

This year, the EUV Source Workshop is organized by HiLASE and EUV Litho, Inc. and the workshop has been made possible by the financial support of workshop sponsors: Greateyes, Gigaphoton, ETHZ and Energetiq. I will also like to thank Source workshop's technical working group (TWG), workshop support staff, session chairs and presenters for their part in making the workshop a success. I look forward to your participation in the workshop.

Best Regards

Vivek Bakshi
Chair, 2018 Source Workshop

Source Technical Working Group (TWG)

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ABSTRACTS

S1

EUV Source for Lithography: Readiness for HVM and Outlook for Increase in Power and Availability.

Igor Fomenkov

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EUV lithography is planned for high-volume manufacturing (HVM) production at 7nm node and beyond. Several of ASML's NXE:3400B EUV scanners are already installed at customers fabs, delivering throughput at the 125 wafer per hour level with the current generation of EUV sources. The paper describes the technologies incorporated into tin laser-produced-plasma (LPP) extreme-ultraviolet (EUV) sources and describes the improvements in the source architecture and subsystems which have led to improved stability and availability of EUV lithography sources at the EUV power levels required for HVM. The paper also describes performance improvements of the main subsystems, such as high-power CO_2 laser, tin droplet generator, collector protection and control system. The results of research activities for power scaling and a perspective for LPP EUV sources with power levels of ~ 500W will be shown.

Presenting Author

Igor Fomenkov is an ASML Fellow in Technology Development Group in San Diego, California. After completing a Ph.D. in Physics and Mathematics at Moscow Institute of Physics and Technology (MPTI) in 1986, he joined General Physics Institute as a senior scientist, where he worked in the field of interaction of high intensity laser radiation with matter and diagnostics of laser produced plasma. He joined Cymer in 1992 and worked on the development of high power, high reliability KrF and ArF Excimer lasers for DUV (at 248nm and 193nm) microlithography. Since 1997 he has been conducting research and development of sources for Extreme Ultraviolet Lithography at 13.5nm. He was appointed Cymer Fellow in 2003 and ASML Fellow in 2014. He has authored over 50 technical papers and holds over 100 patents in the areas of DUV and EUV light sources.

S2

High Power LPP-EUV Source with Long Collector Mirror Lifetime for Semiconductor High Volume Manufacturing

Hakaru Mizoguchi

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We have developed first practical source for HVM; "GL200E" [1] in 2014. We have proved high average power CO_2 laser more than 20kW at output power cooperate with Mitsubishi electric cooperation[2]. Pilot#1 is up running and its demonstrates HVM capability; EUV power recorded at111W average (117W in burst stabilized, 95% duty) with 5% conversion efficiency for 22hours operation in October 2016[3]. Availability is potentially achievable at 89% (2weeks average), also superior magnetic mitigation has demonstrated promising mirror degradation rate (= 0.5%/Gp) above 100W level operation with dummy mirror test.[4].

Recently we have demonstrated actual collector mirror reflectivity degradation rate is less than -0.4%/Gp by using real collector mirror around 100W (at I/F clean) in burst power during 30 Billion pulses operation. We will report latest data 125W average operation with actual collector mirror at the workshop.

1) Hakaru Mizoguchi, et. al., "Sub-hundred Watt operation demonstration of HVM LPP-EUV source", Proc. SPIE 9048, (2014)
2) Yoichi Tanino et.al.," A Driver CO2 Laser Using Transverse-flow CO2 Laser Amplifiers", EUV Symposium 2013 (Oct.6-10.2013, Toyama)
3) Hakaru Mizoguchi et al., "Performance of 250W High Power HVM LPP-EUV Source", Proc. SPIE 10143, Extreme Ultraviolet (EUV) Lithography VIII (2017)
4) Hakaru Mizoguchi, et al, "High Power HVM LPP-EUV Source with Long Collector Mirror Lifetime", EUVL Workshop 2017, (Berkley, 12-15, June, 2017)

Presenting Author

Hakaru Mizoguchi is Executive Vice President and CTO of Gigaphoton Inc. He is member of The International Society of Optical Engineering, The Laser Society of Japan and The Japan Society of Applied Physics. He received a diplomat degree in plasma diagnostics field from the Kyushu university, Fukuoka, Japan in 1982 and join Komatsu Ltd. He joined CO2 laser development program in Komatsu for 6 years. After that he was guest scientist of Max-Plank Institute Bio-Physikalish-Chemie in Goettingen in Germany 2 years, from 1988 to 1990. Since 1990 he concentrated on KrF, ArF excimer laser and F2 laser research and development for lithography application. He was general manager of research division in Komatsu Ltd. until 1999. He got Dr. degree in high power excimer laser field from Kyushu university in 1994. In 2000 Gigaphoton Inc. was founded. He was one of the founders of Gigaphoton Inc. From 2002 to 2010 he organized EUV research group in EUVA program. Now he is promoting EUV light source product development with present position.

S3

Laser Produced Plasma Light Sources for Short Wavelength Applications

Gerry O'Sullivan

University College Dublin, Belfield, Dublin 4, Ireland

Laser produced plasmas (LPPs) have been shown provide versatile sources of extreme ultraviolet radiations, Depending on the choice of target they can be used as sources of continuum or line radiation and indeed one of the first reported applications was their use as continuum sources for inner shell photoexcitation of atoms and ions. It was also observed that the short wavelength emission spectra of plasmas from some medium and high Z elements was dominated by intense bands of emission arising from unresolved transition arrays (UTAs) that resulted from resonance transitions in a range of ion stages that overlap within a narrow wavelength range and whose intensity and spectral profile was very sensitive to plasma opacity. Since the critical density of LPPs is approximately $10^{21}(\lambda_L^{-2})$ cm^3, where λ_L is the laser wavelength in μm, plasmas produced by solid state lasers with $\lambda_L \leq 1$ μm, are, in general, optically thick. However, the opacity can be reduced by using longer wavelength lasers, low density targets, dual pulse irradiation or by using sub nanosecond pulses since opacity also increases with laser pulse duration. These observations have been successfully exploited in EUV lithography sources where power outputs exceeding 200 W in a 1% bandwidth centered on 13.6 nm have been demonstrated. However the production of similar power levels at shorter wavelengths remains a major challenge since the conversion efficiency, which depends on the ion stage distribution in the plasma, decreases due to need to produce higher ion stages. Indeed, alternative sources such as compact FELs may ultimately provide a more viable solution for future lithography.

More recently there have been extensive studies of laser produced plasma for biomedical imaging applications in the water window (2.3-4.4 nm) following on the development of optical components that can be used in this spectral region. Traditionally such work has been performed at synchrotron sources and lab based 'table-top' alternatives are required in order to meet researcher requirements. Here microscope systems based resonance lines of nitrogen and carbon ions have been developed and research is ongoing on the potential use of UTA emission also. Since imaging requires a small plasma size, lasers with pulse durations of a few hundred picoseconds or less, sufficient to produce the ion stages required but short enough to limit plasma expansion, are required. Interestingly, a recent study has shown that water window emission has been obtained using 170 fs laser pulses which generated a plasma that contained ion stages up to 22+. However more work needs to be done to establish the optimum laser irradiation conditions for particular promising target materials which in turn depends on the availability of suitable optics. Moreover, such imaging systems are not without competition and alternative strategies based on the use of high harmonics with coherent diffractive imaging are also emerging.

Presenting Author

Gerry O'Sullivan obtained his B. Sc. in Experimental Physics in 1975 from University College Dublin where he subsequently completed his PhD in atomic spectroscopy under the supervision of Prof. Kevin Carroll in 1980. After a period in Dublin City University, he returned to UCD as a lecturer in 1986 and was Head of the School of Physics from 2002 to 2008. He is currently a Professor and director of the Atomic and Laser Physics Research (Spectroscopy) Group. His research interests include spectroscopy of laser produced plasmas, spectroscopy of ion gas collisions and the development of laser produced plasma based light sources for applications ranging from ionic photoabsorption studies to lithography and 'water window' microscopy. For the source development work his group have been involved in a number of very productive collaborations with both academic and industrial research groups in Ireland, the US, the Czech Republic, Germany, Italy , Poland China and Japan. For his contribution to research he was elected to Membership of the Royal Irish Academy in 2004.

S12

Recent Advances in Development and Application of Compact Laser-Plasma Soft X-ray Sources based on a Gas-Puff Target

Henryk Fiedorowicz, Andrzej Bartnik, Przemysław Wachulak, Karol Janulewicz, Roman Jarocki, Jerzy Kostecki, Tomasz Fok, Łukasz Węgrzyński

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Laser plasma sources of soft X-rays and extreme ultraviolet (EUV) have been developed for application in various areas of technology. The sources are based on a gas puff target irradiated with a nanosecond laser pulse. The targets are created using an electromagnetic valve system equipped with a double-nozzle. The valve system, which is supplied with two different gases, produces a double-stream gas puff target which consists of an elongated stream of high-Z gas surrounded by a stream of low-Z gas. The double-stream gas puff target approach secures high conversion efficiency of laser energy into soft X-ray and EUV energy without degradation of the nozzle. The targets are irradiated with laser pulses produced by commercial Nd:YAG lasers (EKSPLA) with a duration of 1 ns to 10 ns, energy in the pulse from 0.5 J to 10 J with a repetition of 10 Hz. The sources have been applied in various fields, including processing of materials, nanoimaging, radiography and tomography, photoionization of gases, radiobiology and others.
In this paper the recent results on application of the sources in X-ray absorption spectroscopy and optical coherence tomography (OCT) are presented. The use of the source in laboratory systems for the near-edge X-ray absorption fine structure (NEXAFS) spectroscopy is demonstrated. The NEXAFS system was applied for 2-D elemental mapping of EUV-modified polymer samples. A single-shot exposure NEXAFS spectroscopy is presented. Application of the source in X-ray optical coherence tomography (X-OCT) has been also demonstrated. The preliminary results on X-OCT imaging of Mo/Si multilayers with 2 nm axial resolution, using broad-band soft X-ray emission, are presented.

Presenting Author

Henryk Fiedorowicz received M.S. degree in technical physics in 1975, Ph.D. degree in material engineering in 1989, both from the Military University of Technology in Warsaw, habilitation in physics in 1998 from the Institute of Physics Polish Academy of Sciences in Warsaw and the title of professor of physical sciences in 2009. In the years 1975-1992 he worked at the Institute of Plasma Physics and Laser Microfusion in Warsaw and studied laser-produced plasmas using X-ray diagnostics. In 1992 he joined the Institute of Optoelectronics at the Military University of Technology in Warsaw, where he established the laser-matter interaction laboratory. He has proposed a new method of generation of X-rays and extreme ultraviolet (EUV) using a laser-irradiated gas puff target. His recent works focus on the development, integration, and application of laser-plasma X-ray and EUV sources, including X-ray lasers. He was director of the Institute of Optoelectronics in the years 2002- 2010. Author of about 250 scientific publications.

S13

Wavelength and Brilliance Scaling Potential of Discharge based XUV Sources

Klaus Bergmann, Lars Behnke, Alexander von Wezyk, Jochen Vieker

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Compact, discharge based XUV sources are in use for a variety of applications with main focus in the environment of EUVL development at a central wavelength of 13.5 nm. At Fraunhofer ILT the Xenon based hollow cathode triggered pinch plasma is under investigation with respect to power scaling and improvement of the long term stability. Currently, a continuous long-term emission of more than 40W/2□sr at 13.5 nm into 2% b.w. is achieved. Recent results on the long-term stability of the collectable EUV power will be presented. Furthermore, concepts and first results on the scaling potential to shorter wavelengths and increase of the brilliance for applications with small collection angle will be discussed.

Presenting Author

Klaus Bergmann is Group Manager for EUV Technology at the Fraunhofer Institute for Laser Technology - ILT in Aachen, Germany. The focus of work is on the scaling of plasma based EUV- and soft x-ray sources and their applications in future structuring and analysis methods. Klaus Bergmann received the M.S. degree in physics and the PhD degree from the University of Technology, RWTH Aachen, Germany, in 1992 and 1996, respectively. Since 1992, he has been with the Department for Plasma Technology at the Fraunhofer Institute for Laser Technology – ILT with main focus on XUV source development.

S14

Xe Laser-Plasma EUV Source – from 13.5 nm to 11 nm: Researches to Optimize the Xe LPP 11-nm Source.

S Kalmykov, M Sasin, et al

Ioffe Institute, St. Petersburg, Russia

Results of researches aimed at enhancement of the EUV radiation output from the Xe LPP 11-nm source are described. The goal of the study is to create a basis for a change of the working wavelength from 13.5nm to 11.2nm as it had been proposed in the Institute for Physics of Microstructures (Russia) in 2013.
A number of Xe LPP spectra has been obtained under a variety of experimental conditions using both an EUV spectrograph and turnable Mo/Be and Si/Mo interference mirrors. Combination of these two methods provided absolutely calibrated spectra with no scattered light pedestal. All the spectra obtained looked like wide continuous peaks within a λ≈9-14nm band, with their maxima demonstrating a regular displacement along the λ-axis subject to the target density and the laser pulse energy. In the spectra, a tenfold excess of the intensity at λ≈11.2nm over that at λ≈13.5nm has been found.
Irradiation of the Xe gas-jet target with a wider laser beam has been discovered to increase the observed EUV radiation intensity by an order of magnitude relative to the sharp focusing case. This is attributed to suppression of the photoionization absorption in peripheral layers of the target.
Absorption of the laser beam energy in the plasma has been measured. A value of ≈0.5 seems to be an upper limit of the absorption in plasmas with restricted dimensions because of its non-linear nature. An additional optical system returning the unabsorbed portion of the laser energy into the plasma is recommended to increase the conversion efficiency (CE).
Summary. Applying optimization methods above allows to expect, to date, that the 11-nm source CE≈1.5-5% is attainable.

Presenting Author

S15

New Architectures for PW-Scale High Peak Power Lasers Scalable to Near-MW Average Powers and Their Application to EUV Generation

C.W. Siders, S. Langer, A.J. Bayramian, A.C. Erlandson, T.C. Galvin, E.F. Sistrunk, T.M. Spinka, and C. L. Haefner

Advanced Photon Technologies, Lawrence Livermore National Laboratory, NIF & Photon Science Directorate, 7000 East Avenue, Livermore CA 94550

Laser architectures based upon multi-pulse extraction and continuous-wave laser diode pumping are scalable to near-MW peak power while maintaining application-enabling high peak power. These new high average power lasers are capable of producing up to 300kW average power and (for applications requiring ultrashort pulses) petawatt-class peak powers and emphasize efficiency through direct diode pumping of the amplifier medium. They use commercially-available, inexpensive, high-efficiency continuous-wave diodes to achieve optical-to-optical efficiencies of ~40%, electrical-to-optical efficiencies ~30%, and true wall-plug efficiencies of ~20%. We will discuss the Big Aperture Thulium (BAT) laser, a new class high-power 2-m lasers and their potential application as drivers for next-generation EUV sources.

Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344.

Presenting Author

Dr. Siders is a physicist at Lawrence Livermore National Laboratory's National Ignition Facility (NIF) & Photon Science Directorate. As Commercial Technology Development Leader he fosters the growth of commercial opportunities within the Advanced Photon Technologies (APT) Program, and as Senior Scientist he engages in the evaluation and development of technologies towards future advanced photon sources and their applications. APT investigates and develops cutting-edge laser technologies that enable scientific advancement, Inertial Fusion Energy (IFE) relevant technologies, and new commercial applications. A Senior Member of the Optical Society of America, Dr. Siders has over 30 years of experience in optics, photonics, and high-intensity & high-energy density physics, including experience at the sister National Laboratories of LLNL and Los Alamos (LANL) and his published work has garnered over 7000 citations. Before joining LLNL, he was an assistant professor of optics, photonics and physics at the College of Optics and Photonics/CREOL at the University of Central Florida (UCF) in Orlando. While there, he was a co-founder of a start-up fiber laser company. Craig's 1998-2000 work as a Research Faculty member in Kent Wilson's group at UCSD involved some of the earliest applications of femtosecond X-ray diffraction to the study of unique states of matter, with seminal publications in Science and Nature. His 1996 doctoral thesis work at UT Austin with Mike Downer and Toshi Tajima involved designing and building one of the earliest table-top Terawatt lasers and applying it to the first demonstration of a Laser Wakefield Accelerator. Craig graduated with Highest Honors and Distinction in Physics from Kenyon College in 1988.

S16

A Water Window Source for Soft X-Ray Microscopy and other Applications

Paul Sheridan[1], Alberto Manzoni[1], Aodh O Connor[1], Ciaran Rogers[1], David Rogers[1], Dunja Skoko[1], Fergal O Reilly[1,2], Gordon Murray[1], Isaac Tobin[1], James Costello[1], Jason Howard[1,2], Kenneth Fahy[1], Martina Donnellan[1], Stephen Brady[1], Tony Donnelly[1], Tony McEnroe[1], William Fyans[1]

[1]SiriusXT Ltd, Dublin, Ireland
[2]School of Physics, UCD Dublin, Ireland

Water-Window Microscopy is pushing the boundaries in understanding the internal structure of biological cells. This important work, which is delivering valuable new insights to the disease research and drug discovery community, has been pioneered by a small number of Soft X-Ray Microscope stations at synchrotron's around the world [1]. However, oversubscription is restricting access to these microscopes and is limiting the development of this research. The availability of a lab-scale Soft X-Ray Microscope is now of critical importance.

SiriusXT is developing a water-window microscope with resolution and image quality comparable to the synchrotron systems. SiriusXT's patented technology allows the use of a Laser Produced Plasma (LPP) as a very bright source of water window photons (lambda = 2.4 to 4.4 nm). The SXT100 microscope is capable of imaging a whole, cryogenicaly frozen, biological cell in 3 dimensions with a resolution of 40 nm Performance of the system will be presented, with a focus on the source and how it's performance may also be useful to the semi-conductor processing industry in it's quest for ever shortening wavelength sources.

[1] C.A. Larabell & K.A. Nugent, Current Opinion in Structural Biology **20** (2010), p623.

Presenting Author

Paul is the co-founder and CTO of SiriusXT where he leads a team developing and testing a lab scale Soft X-Ray microscope. He received his PhD in 2009 and MSc in 2005 from University College Dublin with the Spectroscopy Group in School of Physics. Here he also spent many years as a postdoctoral researcher with a primary focus on the development of novel, bright and short wavelength lab scale sources. Paul was also a co-founder and CTO of Newlambda Technologies whose primary focus was the development of a bright EUV source at 13.5 nm for the semiconductor metrology market.

S17

Liquid-jet laser-plasma sources for sub-5-nm emission

Hans M Hertz

Biomedical and X-Ray Physics, Dept of Applied Physics, KTH/Albanova, Stockholm, Sweden

We pioneered the liquid-droplet and liquid-jet laser-plasma soft-x-ray and EUV sources. The key feature is the regenerative stable high-speed target that allows uninterrupted laser-plasma operation at a distance from the nozzle with high repetition rates and high power. These sources now enable EUV lithography at λ =13 nm, while our focus has been on shorter wavelengths, for water-window x-ray microscopy (λ =2.3-4.4 nm). Here our present work horse is the liquid-nitrogen-jet target , using the λ =2.48 nm NVII line from a plasma produced by a 0.8 ns/2kHz/200 W Nd:YAG slab laser. This source now approaches early-bending-magnet brightness and is operated with great stability and reliability, allowing biological cryo-tomography.

In this paper we will review our early work in the λ =2-4 nm range, including a variety of target liquids and laser-pulse configurations . We will discuss laser and plasma properties and as well as the potential for scaling these sources to high-repetition rates for high-power operation.

Rymell & Hertz, Opt. Commun. 103, 105 (1993);
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E.g. Berglund et al, APL 69, 1683 (1996).

Presenting Author

S18

Multilayer Optics for 1 nm to 13.5 nm: Can We Reduce the Lithography Wavelength Further?

Torsten Feigl[a], Marco Perske[a], Hagen Pauer[a], Tobias Fiedler[a], Philipp Naujok
Christian Laubis[b], Frank Scholze[b]

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Most likely EUV Lithography using a wavelength of 13.5 nm will face high-volume production at major chip companies in the early years of next decade. While current EUV tools are printing wafers with a numerical aperture of 0.33, the next generation of EUV tools will operate at NA of 0.55. Since it's hard to believe that tool and optics suppliers can realize a further increase of the numerical aperture one could think about reducing the wavelength below 13.5 nm for future increase of resolution.

This paper critically assesses the opportunities, challenges and risks of multilayer development for wavelengths from 1 nm to 13.5 nm and their potential use in future EUV lithography tools. The optical performance of such multilayers will be presented and discussed.

Presenting Author

Torsten Feigl studied physics in Jena, Germany, and in Paris, France. He graduated with a PhD in physics from the University of Jena in 2000. Torsten Feigl joined Fraunhofer IOF in 1994 working on design, manufacturing and characterization of optics for the extreme ultraviolet spectral range and X-rays. For more than ten years he was leading the "EUV and soft X-ray optics" working group at the Fraunhofer IOF. In 2013 Torsten Feigl founded optiX fab, a Fraunhofer IOF spin-off company. Located in Jena, Germany, optiX fab is currently supplying chipmakers, EUV tool and source manufacturers as well as institutes, universities, synchrotron beamlines and EUV research consortia worldwide with customized multilayer and grazing incidence optics for EUV lithography applications at 13.5 nm and the entire XUV, soft and hard X-ray spectral range.

S19

Depth-modified Bragg Mirrors for sub-10-nm Wavelengths

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Standard Bragg mirrors for soft x-rays and the EUV consist of multilayers of two materials with “large” contrast of the refractive index. For 13.5 nm we have introduced the concept of superlattices which allows adding reflection peaks in the angular range between normal incidence and total reflection. The combination of different superlattices and depth grading leads to reflection - partly weak – in the whole angular range. Here, we report on numerical studies for wavelengths < 10 nm. Additionally to the effect of superlattices we investigate the effect of blocks of standard mirrors in series. The lattice period is varied between the blocks. With superlattices the additional reflection peaks are very narrow because of the reduced index contrasts at wavelengths < 10 nm. The number of these peaks increases with the superlattice period but their sharpness prevents all-angle reflection. With the “block concept” the angular width of the near-normal incidence peak can be increased. Using B_4C/La designed for 6.7 nm the half-width at half maximum (s polarization) is about 15° for the block structure compared to 7° for the standard mirror. Weak reflection extends up to 20° and 12°, respectively. This can be useful for optics with increased numerical aperture.

Presenting Author

Professor Meisels studied physics at the University of Vienna, Austria from 1974. From 1997 he worked on his dissertational thesis “Spectroscopy of III-V Compounds in the Far Infrared” and acquired his PhD in 1983. He worked as a post doc until 1993 with a research stay at the Imperial College in London in 1987 - 1988. Then he worked as a university assistant at the Montanuniversitaet in Leoben until 2002 when he completed his habilitation. Since then he is associate professor at the Montnuniversitaet.

S21

Upgrade plan of cERL for the POC as a First-Stage of the Development on EUV-FEL High-power Light Source

Hiroshi Kawata, Norio Nakamura, and Ryukou Kato

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It is important to develop the high power EUV light source up to 1 kW to realize the 3nm node to reduce stochastic variation and achieve a higher through put. To this end, we have proposed an energy recovery linac (ERL)-based free electron laser (FEL) ,which will produce more than 10 kW EUV light to provide the light into several scanners. We gave an idea to develop the POC of the ERL-FEL by using compact ERL (cERL) as a first stage of the EUV-FEL. In this paper, we present the upgrade plan of cERL for the POC.

Presenting Author

S22

Surface Ablation by Soft X-ray Laser Pulse for EUV nano-scale fabrication

Masaharu Nishikino

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We present an overview of our systematic studies of the surface modifications resulting from the interactions of a soft x-ray free electron laser (SXFEL) pulses with materials, such as gold (Au), copper (Cu), aluminum (Al), and silicon (Si) and EUV multi-layered optics were investigated. We show experimentally the possibility of the precise nanometer size structures (~10–40 nm) on metal surfaces by ultra-low (~10–30 mJ/cm^2) fluencies of single SXFEL pulse. Comparison experimental results with the atomistic model of ablation, which was developed for the single SXFEL interaction with dielectrics and metals, is provided. Theoretical description of surface nanostructures is considered and is shown that such structures are formed after laser illumination in a process of mechanical spallation of ultrathin surface layer of molten metal. Spallation is accompanied by a strong foaming of melt, breaking of foam, and freezing of foam remnants. Those remnants form chaotic nanostructures, which are observed in experiments. Our results demonstrate that tensile stress created in metals by SXFEL pulse can produce spallative ablation of target even for drastically small fluencies, which open new opportunities for material nano processing.

Presenting Author

Masaharu NIshikino is Group leader of X-ray Laser Group of Kansai Photon Science Institute, QST. After completing a Ph.D. in Engineering at Institute of Laser Engineering, Osaka university in 2001, he joined Japan Atomic Energy Research Institute (National Institutes for Quantum and Radiological Science and Technology; QST) as a post-doctoral fellow, where he worked in the field of laser plasma x-ray laser and its application. Since 2009 he has been conducting research for EUV laser ablation research.

S23

Laser-cooled Electron Source

Jom Luiten

Eindhoven University of Technology, The Netherlands

We are developing a pulsed, ultracold electron source based on near-threshold photoionization of a laser-cooled and trapped atomic gas. This new and exotic technique allows us to enter entirely new regimes of beam brightness.

The electrons are produced in pulsed mode using femtosecond photoionization resulting in picosecond bunches containing ~10^3 electrons with a high degree of coherence. The intricate dependence of the source properties on acceleration field strength, ionization laser wavelength, and laser polarization have been studied in detail both theoretically and experimentally. By a proper choice of these parameters it is possible to achieve source temperatures of ~10 K or ~1 meV, 2-3 orders lower than conventional field or photoemission sources. An important goal is to produce bunches with much more charge, preferably in excess of 10^6 electrons, while retaining a high degree of coherence. This would enable single-shot electron diffraction of macromolecules and thus dynamical studies of biomolecules at atomic length and timescales. Furthermore the source may enable single-shot, ultrafast electron microscopy and electron energy loss spectroscopy with ~1 meV resolution. In addition, the ultracold electron source may be an interesting source for driving compact, (soft) X-ray FELs.

Presenting Author

Jom Luiten is professor in the Department of Applied Physics at the Eindhoven University of Technology in The Netherlands, in charge of the group Coherence and Quantum Technology. He obtained his PhD from the University of Amsterdam in 1993 on spectroscopy and laser cooling of magnetically trapped atomic hydrogen. From 1993 until 1997 he worked as a postdoctoral fellow at the Space Research Organization Netherlands on superconducting tunnel junctions for X-ray detection. After spending a year in industry at the Dutch wafer stepper company ASML he moved onto the Eindhoven University of Technology in 1998. There he first worked on relativistic femtosecond electron accelerators for generation of X-rays and terahertz radiation. Gradually his interest shifted to the sub-relativistic domain of ultrafast electron diffraction and microscopy, where he introduced the use of radiofrequency accelerator technology and laser-cooled charged particle sources. His interests focus on coherent charged particle beams, ultra cold plasmas, ultrafast electron diffraction and microscopy, and coherent light-matter interaction.

S24

Fs-laser driven free-electron laser development in ELI-BL

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Free-electron lasers (FEL) are unique light source for different applications on the femto-second scale, including for instance the most basic reaction mechanisms in chemistry, structural biology and condensed matter physics. The laser wake field acceleration (LWFA) mechanism allows to produce extremely short electron bunches of a few fs length with energies up to a few GeV providing peak current of many kA in extremely compact geometries. This novel acceleration method therefore opens a new way to develop compact "laser-based" FELs. ELI beamlines (ELI-BL) is an international user facility for fundamental and applied research using ultra-intense lasers and ultra-short high-energy electron beams. In frame of this report we present the ELI-BL activity to develop a compact "LFWA" based soft X-ray FEL, which can deliver a photon peak brightness of 10^{30} photons/sec/mm^2/mrad^2/0.1%bw. A combination of this achievement with novel higher repetition rate laser technologies will open new perspectives for the development of extremely compact FELs with few or even sub-femtosecond photon bunches for a very wide user community.

Presenting Author

Dr. Alexander Molodozhenstev works in the area of Beam dynamics in charge particles accelerators (collective effects), Machine commissioning (compact proton synchrotrons for hadron therapy; large accelerator complex – JPARC, LHC) and fs-Laser driven X-ray Free-Electron Laser. Since 2015 he is a Senior Researcher of Institute of Physics, Czech Academy of Science.

S31

High-harmonic Generation for EUVL: Source Developments and Applications for Spectroscopy and Metrology

Peter Kraus

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High-harmonic generation (HHG) is the up-conversion of many infrared photons into one soft x-ray photon through a highly non-linear laser-matter interaction. The produced soft x-ray pulses have a high degree of spatial coherence, and pulse durations down to attoseconds. These unique properties make high-harmonic generation sources ideal candidates for table-top ultrafast soft x-ray spectroscopy, as well as x-ray imaging experiments.

This talk will describe current developments to improve the available flux from high-harmonic generation sources in order to enable them to become a valuable tool for extreme ultraviolet lithography (EUVL) applications. Current efforts to develop a high-power soft x-ray HHG source covering the water window (280-540 eV) based on a kilo-Watt level pump laser are ongoing and will be reported.

The most promising applications of HHG in the context of EUVL will be outlined. These are the application of HHG in semiconductor metrology for the on-line monitoring of device manufacturing, as well as extreme ultraviolet/soft x-ray spectroscopy of processes relevant to nanolithography. Such processes are, for example, the monitoring of the photochemistry of a photoresist. First experiments to measure the broadband extreme ultraviolet absorption of photoresists with HHG sources will be presented.

Presenting Author

Peter Kraus obtained his PhD at ETH Zurich (Switzerland) in 2015. He developed and advanced the techniques of high harmonic-spectroscopy for investigations of electronic and nuclear structure and dynamics of molecular systems. Peter subsequently worked at the University of California, Berkeley (USA) on the development of new experimental techniques for investigating attosecond phenomena in solid-state materials. He started as a tenure-track group leader/assistant professor at ARCNL in May 2018. Peter is leading a program to develop extreme ultraviolet (EUV) sources from high-harmonic generation and apply them for ultrafast spectroscopy and nanoscale metrology experiments with relevance to nanolithography.

S32

Progress on laser-driven soft x-ray lasers at LOA

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We report here recent work on an optical-field ionized (OFI), high-order harmonic-seeded EUV laser. The amplifying medium is a plasma of nickel-like krypton [1] obtained by optical field ionization focusing a 1 J, 30 fs, circularly- polarized, infrared pulse into a krypton-filled gas cell or krypton gas jet. The lasing transition is the $3d^94p$ (J=0) → $3d^94p$ (J=1) transition of Ni-like krypton ions at 32.8 nm and is pumped by collisions with hot electrons.

The gain lifetime of the EUV laser amplifier strongly depends on the depletion rate of the lasing ion population because of collisional ionization during the lasing process. When increasing the plasma density from 3×10^{18} cm^{-3} up to 1.2×10^{20} cm^{-3}, the gain duration monotonically decreased from 7 ps to an unprecedented shortness of 450 fs FWHM [2]. The integrated energy of the EUV laser pulse was also measured, and found to be up to 4 µJ per shot. It is to be noted that in the ASE mode, longer amplifiers were achieved (up to 3 cm), yielding EUV outputs up to 14 µJ.

We employed ptychographic coherent diffraction imaging [3] for characterizing the beam of the 32.8 nm SXRL in amplitude and phase with high fidelity. Backpropagation of the field allows determining source properties. We find that HHG seeding results in excellent spatial coherence properties, while a high degree of temporal coherence is maintained through the narrow-band amplification. Further, we find that the time delay dependence between the pump and seed pulses causes significant reshaping of the amplified laser beam hinting at a complex seed-plasma interaction.

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Presenting Author

S. Sebban is the Director of research at CNRS working on laser-driven x-ray sources. He received his Ph.D. in 1997 et University of Paris about x-ray laser studies and applications. Form 1997-1998 he was a Post doc at Institute of Laser Engineering (Osaka-Japan) working on Ni-like laser from 5 to 13 nm. Between 2010-2015 he was the Group leader of the RP2 group at ELI beamlines.

S33

Technologies and Applications of High-average-power Lasers at HiLASE

Tomas Mocek

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HiLASE is a new technological infrastructure in the field of application-oriented laser research and development, up and running since 2016. Under one roof we develop the next generation of high power Diode Pumped Solid State Lasers (DPSSL) with high pulse energy and high repetition rate, while at the same time, we exploit these unique light sources for a wide range of hi-tech industrial applications. PERLA is an in-house developed compact high average power thin-disk laser platform generating <2 ps pulses in the spectral range from DUV to mid-IR. Bivoj is the world's first DPSSL delivering 1 kW average power in 105 J, 10 ns pulses at 10 Hz, based on cryogenic gas-cooled, multi-slab ceramic Yb:YAG amplifier technology. Our mission is to build a strong relationship with industry and transform our advanced lasers from laboratory prototypes to customized products. DPSSL systems deployed at HiLASE facility are also available for external users for scientific experiments (Open Access) as well as for commercial research in the areas of laser induced damage, laser shock peening, laser microprocessing and functional materials.

Presenting Author

Tomas Mocek (born 1970) received his Ph.D. in Physics from the Korea Advanced Institute of Science and Technology (KAIST), South Korea in 2000, and in Applied Physics from the Czech Technical University in Prague, Czech Republic in 2001. Since 2011, he is the Head of HiLASE Centre at the Institute of Physics of the Czech Academy of Sciences. His research expertise includes development of high-average power diode-pumped solid state lasers for hi-tech applications, EUV generation, high-order harmonic generation, mid-IR generation, laser induced periodic surface structures, laser acceleration of particles, dense plasma diagnostics, optical-field ionization, X-ray lasers, and spectroscopy of laser plasma. His research activity is documented by 147 papers in international peer-reviewed journals with impact factor which acquired over 2400 citations, and H-index of 25. He was awarded by the "Prize of Josef Hlávka" for talented young researchers by the Foundation "Nadání Josefa, Marie a Zdeňky Hlávkových" in 2000, and by the "Otto Wichterle Award" for young scientists by the Czech Academy of Sciences in 2005. Since 2013, he serves as a member of the Editorial Board of High Power Laser Science and Engineering journal. He has been Principal Investigator or Coordinator of numerous research and development projects with total cumulative budget of about 80 mil. EUR.

S34

Quantum Technology and kW, ps thin disc lasers

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It is recently observed that quantum devices are maturing to be actual technical applications in broad areas like from high precision sensing to quantum computing. Fabrication of such devices are depending on the availability of advanced light sources with short wavelength and pulse width, and higher average power is critical for higher through put of the production.

Several research programs are just starting globally in the field of Quantum Technology to make happen the 2nd Quantum Revolution. The technical background of the light source for the quantum technology, is the recently developed kW class, high beam quality ps solid state laser. The ps laser is employed as the base of an intelligent micro machining setup of tailored pulse supported by machine learning. It is also employed as the HHG generator of EUV attosecond pulses for metrology applications, after compression to a few cycle and CEP stabilization.

The author reports on the recent progress of the thin disc based kW class, ps laser and the perspective of the further development for the quantum technology applications.

Presenting Author

S35

Ultrafast Thin-Disk Amplifiers

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With an inexorable demand for increased peak power, the management of heat deposition and the buildup of nonlinearities have become pressingly challenging for energetic ultrafast lasers. Due to its efficient one-dimensional heat removal and the small longitudinal extension of the gain medium, the thin-disk geometry offers exceptional scaling performance both in terms of energy and average power. As a regenerative amplifier, 200 mJ were in fact recently extracted at 5 kHz out of two Yb:YAG disks [1,2]. Likewise, multipass arrangements have led to >1 kW with good temporal and spatial performances [3], and in a following work 2.5 kW could be reached [4].
In this contribution, we present different commercial ultrafast solutions based on regenerative amplifiers with up to 200 mJ of pulse energies and more than 1 kW of average power. Their industrial-grade engineering ensures an outstanding power stability of <0.3% (rms). Further amplification experiments implementing a multipass cell were performed on a 20 ns laser and resulted in >3 kW of average power [5]. Thus Combining both technologies, the completion of a high-energy sub-picosecond laser with multi-kW output powers would be at our fingertips. We will present our efforts about a nonlinear compression scheme aiming for high-energy and kilowatt-class sub 50fs pulses. Such laser sources could give rise to a manifold of exciting applications such as inverse Compton scattering [6], pumping optical parametric amplifiers [7], laser based lightning rod [8], high harmonic [9] and X-ray [10] generation and laser wakefield accelerator-based light sources [11].

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Presenting Author

Thomas Metzger studied mechanical engineering at the Technical University in Stuttgart and received his Diploma in 2002. After his degree he worked in 2003 as an intern at Spectra-Physics. During his PhD and as Postdoc in the research group of Prof. Ferenc Krausz at the Technical University in Vienna and at the Max-Planck Institute of Quantum Optics in Garching, he developed ultrafast thin-disk amplifiers in close collaboration with TRUMPF Laser. Since 2012 Thomas Metzger is the CTO of TRUMPF Scientific Lasers GmbH + Co. KG.

S36

Beam Quality of Pulsed High-power CO_2-Lasers for EUV Lithography

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The TRUMPF Laser Amplifier is at the heart of industrial EUV generation via pulsed CO_2 laser systems. EUV systems incorporating these lasers have shown continuous progress [1] and are delivered to end customers in increasing numbers [2]. CO_2 laser beam quality is a decisive factor for high conversion efficiencies and EUV generation [3]. We present laser beam parameters for pulsed operation at 50 kHz. Important beam properties such as beam quality, temporal pulse shape, average power and peak power will be presented and influences of factors such as cooling, gas properties and pressure will be discussed. Typical mode properties for several serial systems will be shown. The talk will also briefly outline potential improvements for future generation systems.

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Presenting Author

Johannes Kaschke is a group leader at TRUMPF Lasersystems for Semiconductor Manufacturing GmbH (TLSM) where he is responsible for optical and systems development of the high-power amplification chain of TRUMPF high-power CO_2 systems for EUV generation. He previously had worked as an engineer in the TRUMPF Laser Amplifier optical development team at TRUMPF after having received his diploma and Ph.D. in Physics at the Karlsruhe Institute of Technology (KIT) in Germany where his work had focused on next-generation three-dimensional direct laser writing lithography approaches.

S37

High-Harmonic Generation for EUV Frequency-Comb Spectroscopy of He^+

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Precision spectroscopy of the hydrogen-like helium ion (He^+) allows for a test of bound-state quantum electrodynamics (QED). He^+ as a charged particle is trappable and coolable, allowing for smaller systematics, and the transition frequencies are more sensitive to higher-order corrections of the theory compared to the long-studied atomic hydrogen. We aim to excite the 1s-2s transition with an extreme-ultraviolet (EUV) frequency comb around 60.8 nm wavelength, which is generated as the 17^{th} harmonic of an infrared system via high-harmonic generation (HHG) in a gas target. In order to reach the output-coupled EUV power of >100 µW needed to drive the excitation, we use a high-power Yb:YAG amplifier, external pulse compression based on nonlinear spectral broadening in a multi-pass cell (MPCSB), and an enhancement resonator with efficient geometrical EUV output coupling.

Presenting Author

Johannes Weitenberg was born in Rhede, Germany in 1981. He studied physics at RWTH Aachen University, Germany and received the Diploma degree in 2007. From 2008 to 2015 he has been working at the Chair for Laser Technology of RWTH Aachen University and since then at Fraunhofer Institute for Laser Technology, Aachen. Since 2015 he has been working at the Max-Planck Institute of Quantum Optics, Garching, Germany. He received his PhD in physics in 2017. His current research interests include development of solid-state lasers, high-harmonic generation, enhancement resonators, nonlinear pulse compression and frequency comb spectroscopy.

S38

0.5-kW Picosecond Thin-disk Laser System for Pre-pulsing in High-power EUV Sources

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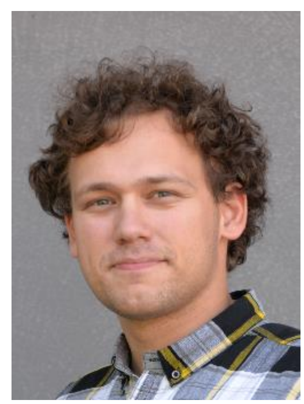
High-average-power picosecond solid-state lasers are an important part of the extreme ultraviolet (EUV) lithography technology using laser-produced plasma (LPP). They allow to increase the conversion efficiency from laser to 13.5-nm EUV emission multiple times by conditioning the droplet target with a picosecond pre-pulse into a uniform mist form before it is hit by the main CO_2 laser pulse. This poster will present a half-kilowatt high-repetition-rate picosecond laser system PERLA C developed at the HiLASE Center in Czechia and it has parameters relevant to LPP-EUV lithography.

The PERLA C laser system is based on an Yb:YAG thin-disk regenerative amplifier with single thin disk in ring cavity. The main amplifier is compact (footprint size of 1200×900 mm^2), highly efficient (43% extraction efficiency) and capable of a reliable long-term operation. The laser system can currently produce 5-mJ pulses at 100 kHz repetition rate (500 W average output power) or 9-mJ pulse energy at 50 kHz repetition rate. Further upgrade plans to 1 kW average power will be also shown.

Presenting Author



Jiří Mužík is a Junior Researcher at the HiLASE Centre in Dolní Břežany, Czech Republic, where he is involved in the development of high-average-power picosecond thin-disk laser systems. He received his master's degree from the Czech Technical University in Prague in 2014 and is currently working towards the PhD. degree in Physical Engineering. His research interests include high-power thin-disk lasers and mid-IR solid-state lasers.

S39

High-energy Burst-mode Thin-disk Multipass Amplifier for Laser Compton X-ray Source

Siva Sankar Nagisetty[1,2], Michal Chyla[1], Martin Smrž[1], Akira Endo[1] and Tomáš Mocek[1]

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Synchrotron X-ray sources are used for scientific research worldwide because of their high brightness, tunability and narrow photon-energy bandwidth. However, synchrotrons are typically large devices because of the size of their component electron accelerator and undulator. Thanks to the recent developments of high energy short pulse lasers. Compact Laser Compton X-ray source has been developing as an accelerator-laser hybrid technology. Laser based Compton sources are able to combine the compactness of the instrument with a beam of high intensity and high quality. To generate short duration pulses from Compton X-ray source, high-energy and high repetition rate ps-laser pulses with superior beam quality (M2<2) are required. PERLA B laser system at HiLASE Center is focused on development of high-energy, picosecond thin-disk laser amplifiers. Scaling towards higher pulse energies is often limited by the onset of thermal effects and ASE thus influencing the amplifier's extraction efficiency. The solution can be the burst pulse amplification. In this paper we report our recent development of PERLA B thin-disk laser system, modelling and results of thin-disk multipass amplifier operating in a burst mode.

Presenting Author

Siva Nagisetty is a Junior Researcher at HiLASE Center.

S40

Development of a High-energy, Cryogenically-cooled Yb:YAG Laser System

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We report on a compact, high energy, cryogenically-cooled laser system for EUV-X ray generation. The laser delivers energies >100 mJ at repetition rate of 100 Hz and spectrum supporting 5-ps pulses. The laser system consists of a seed mode-locked fiber laser, chirped fiber Bragg grating stretcher, room temperature thin-disk regenerative amplifier (RGA) and a cryogenically cooled four-pass booster amplifier. The RGA amplifier produces 4.5 mJ of energy with high energy stability (~0.6% rms) and beam quality (M2 <1.2). The booster amplifier based on a single Yb:YAG slab further amplifies the pulses to ~108 mJ with energy stability of ~0.75% rms. The performance of the laser system in terms of pulse energy and bandwidth under a variety of pump condition will be presented.

Presenting Author

S41

Nd:YAG-laser-driven Sn plasma: an ARCNL research update

O. O. Versolato

Advanced Research Center for Nanolithography (ARCNL), Science Park 110, 1098 XG Amsterdam, The Netherlands

In this talk the progress is presented in our studies on Nd:YAG-laser-produced (LPP) tin plasma for the production of extreme ultraviolet (EUV) light. New spectroscopies of the ARCNL LPP are presented and our interpretations are augmented by a recent measurement campaign at MPI-K in Heidelberg that focused on charge-state-resolved measurements of the in-band emission of the relevant tin ions using an electron beam ion trap. Further, we will present our progress on the measurements on our LPP of the tin ion kinetic energy distributions. There will also be a glimpse of our new analyses of the deformation and fragmentation of tin drops by laser pulse impact, relevant for prepulses studies.

Presenting Author

Oscar Versolato received his PhD in 2011 from the University of Groningen, The Netherlands, for work on laser spectroscopy on trapped, short-lived radium ions. He did postdoctoral work at the Max-Planck-Institute für Kernphysik in Heidelberg, Germany, on spectroscopy and sympathetic laser cooling of highly charged ions (with PTB Braunschweig, DE), and molecular ions (with Aarhus University, DK).

Since 2015 he is a tenure-track group leader in the EUV Plasma Processes group at the Advanced Research Center for Nanolithography (ARCNL) in Amsterdam. His present research interests include plasma sources of extreme ultraviolet radiation, droplet deformation and fragmentation after laser pulse impact, physics of highly charged ions, and spectroscopy. He was awarded the 2016 NWO Vidi research grant as well as the 2018 ERC Starting grant.

S42

Tin-ion Interactions

Ronnie Hoekstra

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In this talk the progress in our studies on tin ion interactions with stopping gas and plasma-facing materials surrounding a Sn Laser Produced Plasma (LPP) EUV source is presented. Tin ions in a wide variety of charge states are expelled from the LPP EUV source with the high-energy tail of the kinetic energy distribution of the ions reaching up to a few ten of keV. The two topics that will be addressed in detail are the charge exchange reactions of 1 keV Sn^{q+} ions traversing a molecular hydrogen gas and the scattering of 10 keV Sn^{q+} ions off a Mo surface.

The generic charge exchange experiments were done at the Sn LPP EUV source installed at ARCNL – Amsterdam. By changing the pressure of the molecular hydrogen surrounding the source the charge state distributions can be changed and cross sections estimated.
At the Zernike Institute for Advanced Materials at the University of Groningen we have recently taken ZERNIKELEIF facility for low-energy ion beams into operation. The 14 GHz supernanogan highly-charged ion source driving the facility is equipped with an oven system to generate ions from solid materials. At this facility we can produce charge state, energy and isotope selected beams of tin ions. In a first series of experiments we have studied the backscattering of tin ions from a Mo surface. The energy distributions of the scattered tin ions are compared to SRIM simulations and turn out to show characteristic differences.

Presenting Author

Prof. Ronnie Hoekstra is group leader of EUV Plasma Processes group at ARCNL.

S43

Influence of Opacity in Nd:YAG Laser-produced Tin-Plasmas

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Laser-produced plasmas (LPPs) from liquid tin micro-droplets are used as source of extreme-ultraviolet radiation in next-generation nanolithography. In order to optimize and predict the emission into the technologically relevant 2% bandwidth around 13.5nm, it is crucial to obtain full understanding of the atomic structure of the tin ions contributing to the plasma emission. Further, it is necessary to understand the opacity related spectral broadening causing emission outside the wavelength band of interest.

Using the Los Alamos suite of atomic codes the atomic structure of the tin ions was calculated. Assuming LTE conditions, the opacity of tin plasma was subsequently calculated for various temperatures and densities using the Los Alamos code ATOMIC. Comparing the calculation results with experimental spectra obtained from Nd:YAG LPPs of tin micro-droplets we find good agreement of theory and experiment. The influence of radiation transport onto the emission profile will be addressed.

Presenting Author

Ruben Schupp is a PhD applicant at the Advanced Research Center for Nanolithography (ARCNL) in Amsterdam, The Netherlands. His PhD research focusses on the atomic processes in and the optimization of laser-produced plasma light sources for 13.5nm. He obtained his bachelor's degree in physics at the University of Heidelberg (Germany) followed by a master's degree with specialization in atomic, molecular and optical physics.

S44

EUV & Soft X-ray Sources based on Medium-Z LPPs

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Laser Produced Plasmas (LPP) are a rich source of ions for spectroscopic studies and a range of applications. LPPS formed on the 5th row elements from strontium (Z = 38) to molybdenum (Z = 42) emit a range of transition arrays in the soft x-ray region of the spectrum (1 – 10 nm). These are composed of resonance transitions (3d – 4p, 3d – 4f and 3p – 4s) as well as satellite transitions of the type $3d^{n-1}4s$ – $3d^{n-2}4snl$ [1,2]. Analysis of these spectra is supported by calculations using the Cowan suite of atomic structure codes [3] and the Flexible Atomic Code (FAC) [4].

These emission arrays, based on $\Delta n = 1$ transitions, shift to shorter wavelengths with increasing ionization, unlike the case of the $\Delta n = 0$ arrays in tin for example, which overlap across a range of ions. They also shift to shorter wavelengths with increasing Z. This allows one to tune the wavelength of the emission peaks to suit a particular application, and to use the spectral evolution of an LPP with electron temperature as a diagnostic or a metric to benchmark a model or a simulation. It is possible to use the spectra for plasma diagnostics, in the context of a modified collisional-radiative (CR) model [5]. The modifications take into account the temporal distribution of the laser pulses, as the initial CR model is a steady state model. Comparisons are presented for a range of plasma temperatures. The LPPs were imaged using a pinhole camera setup, revealing a plasma diameter on the order of 5 – 15 microns when using filtered EUV light between 2 & 3 nm.

The plasmas were created by focusing 7-ns (Continuum Surelite), 170-ps (EKSPLA SL312P), 20-ps (EKSPLA PL2250) Nd:YAG lasers using 50 mm aspheric lenses. The radiation from the LPPs was observed at 45° to the incident laser axis, using a 0.25-m grazing incidence spectrometer equipped with a 1200-grooves/mm, variable spaced grating (SHIMADZU, 30-002). The spectrum is formed in a flat field and detected by a cooled CCD camera (ANDOR, DX436-BN). Wavelength calibration was based on the spectra of nitrogen and silicon from a reaction-bonded silicon nitride target (RBSN) and on known emission lines of carbon, oxygen and aluminium from an alumina (Al_2O_3) target.

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Presenting Author

S45

EUV-induced Plasma of Hydrogen with Nitrogen Admixture

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We report on the theoretical studies of plasma generated by extreme ultraviolet radiation (~ 10 nm) in low pressure atmosphere of hydrogen (P_{H2} ~ 1-10 Pa) with small admixture of nitrogen (P_{N2} ~ 0.0001-0.1 Pa). For that we consider a simplified model of a gas tube with radius 1 - 10 cm where plasma is generated by periodic pulses of EUV radiation. The evolution of plasma is described by the transient diffusion equation taking into account ion production through the photoionization, ion conversion reactions, ion volume recombination and plasma decay at the tube walls. By scanning the partial pressure of nitrogen, the tube radius and EUV beam radius to the tube radius ratio, we show how the ionic composition of the plasma changes. If in pure hydrogen plasma the dominant ion is H3+, then At P_{N2} ~ 0.001 - 0.01 Pa NH2+ becomes the dominant ion. We also use particle-in-cell simulations to predict the evolution of the ion energy distribution function with the changing partial pressure of nitrogen.

Presenting Author

S46

Validation of Radiation Hydrodynamic Model against Experiment with CO_2-laser-produced tin Plasma

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Optimization of laser produced plasma (LPP) sources of EUV radiation requires predictive theoretical modeling. Such models should include description of a lot interconnected physical processes ongoing in plasma, such as: material ablation, ionization, plasma dynamic, radiation energy transport in plasma etc. In order to include this complex physics in the model its comparison with experiments is required. In this work we present results of specially designed experiment on tin ablation by CO_2 laser. Laser pulse intensity varied from 10^8 to 10^{10} W/cm^2, which is relevant to EUV source conditions. In the experiment plasma radiation spectrum, EUV source size and plasma recoil momentum were measured simultaneously. We compare the experiment results with simulations of RHD model – RZLINE (developed at ISAN). Modelling results are consistent with experiment.

Presenting Author

S47

Computer modeling of contamination and cleaning of EUV source optics

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State-of-the-art EUV radiation sources for high-volume manufacturing lithography employ plasma of multiply charged tin (Sn) ions as an emitter of 13.5 nm photons. Such sources use hydrogen as a buffer gas protecting the source optics from contamination with Sn debris. First, the buffer gas slows down the plasma fluxes. Second, hydrogen radicals forms volatile compounds with tin. The latter results in etching of tin deposited onto the optical surfaces. Thus in-situ cleaning may be possible with appropriate engineering of the EUV source operation conditions. In this work, we present a integrated computer model that describes complex multicomponent flow in the EUV source chamber and surface/volume chemistry processes. We present simulations of laboratory experiments with tin cleaning in hot filament reactors. We analyze examples of modeling of long term (~hours) source operation with focus on the source optics contamination and cleaning.

Presenting Author

S51

EUV/X-ray Sources driven by New-generation of Lasers for User-applications at ELI Beamlines

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The laser-driven X-ray sources developed at the ELI-Beamlines facility will be driven by new generation of femtosecond lasers with higher repetition rate and higher peak power compared to the current laser systems. These sources have the capability, unlike large-scale facilities such as third-generation synchrotrons or X-ray free-electron lasers (XFELs), to offer a much broader accessibility. In addition to reducing size and costs, these X-ray sources provide intrinsic synchronization between the optical driver laser and the X-ray pulses that are generated, as well as the full spectrum of different VUV to X-ray sources that each deliver specific properties.

Three main paths have been developed within the ELI research area for transforming optical driver laser pulses into brilliant bursts of short wavelength radiation: High-order harmonic generation in gases, Plasma X-ray sources and sources based on relativistic electron beams accelerated in laser plasma. For each of these research areas, dedicated beamlines are built to provide a unique combination of X-ray sources to the user community. The application of these beamlines has a well-defined balance between fundamental science and applications in different fields of science and technology.

Presenting Author

Jaroslav Nejdl is a leader of the research program on Laser-driven X-ray sources within the ELI Beamlines project since 2016. He graduated from the Czech Technical University in Prague in 2006 and he obtained his PhD at the same university in 2012. He spent one year as an intern at Laboratoire d'Optique Appliquee, ENSTA, ParisTech, France and one year as a Fulbright research fellow at ERC for EUV science and technology at Colorado State University, USA. His research interests include coherent and incoherent laser-driven short wavelength sources, their metrology and applications, as well as laser-matter interaction and EUV/X-ray optics.

S52

Mixed gas fueling experiments on the Energetiq EQ-10

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Energetiq Technology, Inc.

A conventional Z-pinch relies on metal electrodes to source and sink the plasma current. In contrast, the EQ-10* design relies on continuous plasma loops, driven inductively, to produce the plasma current. The design requires a large (compared to a conventional design) plasma chamber to allow space for these loops; fueling is accomplished by simply injecting Xenon into this chamber.

As we have evolved the EQ-10 design from the original 5-10W source to the existing higher power system, we have not been able to significantly increase power and brightness beyond roughly 20W/2π and 8 W/mm^2-sr. This limit seems to be connected to fueling of the pinch – as the input power increases, the neutral gas temperature within the chamber increases – thus reducing the gas density and starving the pinch. Increasing chamber pressure helps only up to a point, as EUV absorption by the gas also increases.

We plan to investigate whether a dual-gas injection system will increase the EQ-10 source brightness and/or power. This idea relies on injecting Xenon directly into the bore, while supporting the plasma return loops (which in the EQ-10 play the role of the electrodes) with an argon plasma.

We will also summarize some related data relevant to operation with other mixed gasses.

* Horne, Stephen F., Matthew M. Besen, Paul Blackborow, Ron Collins, Deborah S. Gustafson, Matthew J. Partlow, and Donald K. Smith. "The EQ-10 Electrodeless Z-Pinch™ Metrology Source." (2018): 193-206. In "EUV Lithography, Second Edition" SPIE; Editor: Vivek Bakshi

Presenting Author

Stephen Horne has been the Senior Scientist at Energetiq Technology, Inc. since it was founded in 2004. He received his PhD in Plasma Physics from the University of Wisconsin.

S54

High-brightness Light Source Based on a New Concept of LPP for Actinic EUV microscopy and Metrology Applications

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In this work we present a new concept of LPP light source based on a liquid metal rotating target. This concept provides significant advantages such as higher EUV dose stability and longer optics lifetime. High speed rotation ensures protection of the optics from droplet debris generated in the plasma region. Protection from plasma debris (fast ions and neutrals) is implemented by the use of gas flows and magnetic field. The use of tin and its alloys as target material provides high values of conversion efficiency. Employing drive laser system with power density $2.4 \cdot 10^{10}$ W/cm^2 (27W of average power) and corresponding CE 1%/2π, we have demonstrated brightness of about 54 W/mm^{2}sr, with no noticeable contamination of optics during 0.2 giga shot. For the low rep rate laser system with power density $>10^{11}$ W/cm^2 we have achieved conversion efficiency of 2%/2π. We predict that for the laser with $M^2<=2$ and power density $>10^{11}$ W/cm^2 the brightness can be scaled up with the formula: $4P_{laser}\, W/mm^2 sr$, where P_{laser} – the average laser power. Hence, a 100 W laser easily provides source brightness of 200 – 400 W/(mm²sr). New experimental data will be presented.

Presenting Author

Mikhail Krivokorytov is a Researcher at RnD-ISAN/EUV Labs. After completing a Ph.D. in Physics and Mathematics at Moscow Institute of Physics and Technology (MPTI) in 2014, he joined the Institute of Spectroscopy as a Junior Scientist, where he worked in the field of interaction of high intensity laser radiation with matter and diagnostics of laser produced plasma.

S56

Characterization and Performance Improvement of Laser-assisted and Laser driven EUV sources for Metrology Applications

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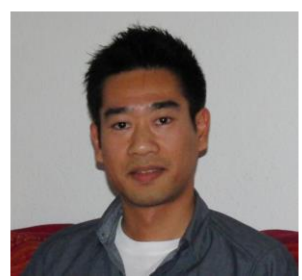
The Laser-assisted discharge-produced (LDP) plasma EUV source is developed as a light source for actinic mask inspections. Since the focused laser irradiation is used to ignite the discharge, the LDP plasma has a unique feature of high brightness and high power. A LDP source is currently used in the beam line facility of which rated power is 70 W/2□sr and maximum frequency is 10 kHz. The LDP source technology is further developed as a light source for actinic mask inspection tool. Multiple experiments were performed at the brightness level of 100 and 200 W/mm2/sr to study and improve short- and long-term brightness stability. The laser-driven source is being researched aiming at the compact high-brightness radiation source. A liquid Sn-covered disk is used as a target and the laser irradiation intensity is adjusted to emit radiation at 13.5 nm. Two types of laser were tested in order to compare conversion efficiencies and a very good agreement with the previous works was obtained. Pulse repetition rate was increased up to 24 kHz and the maximum brightness of 100 W/mm^2/sr was observed at 20 kHz. Both source technologies were characterized observing EUV power, brightness, plasma shape and stability.

Presenting Author



Yusuke Teramoto received Ph.D. degree in 2002 from Kumamoto University, Japan. He joined Ushio Inc., Japan in April 2002 and started research and development of Xe- and Sn-fueled discharge EUV sources. In 2008, he moved to Aachen, Germany to participate the co-development program between Ushio, XTREME, Philips and Fraunhofer ILT. He engaged in source development for NXE3100 scanner, especially in power scaling. Now he is working for BLV Licht- und Vakuumtechnik GmbH, an Ushio group company. He is currently the leader of R&D Unit 1 of EUV Business Project managed by Ushio Inc. and working on EUV and X-Ray metrology sources research and development.

S57

Xenon plus additives in the Energetiq EQ-10: Initial Results

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When the EQ-10* is used in an application requiring a relatively large source etendue, the nature of the electrode-less discharge causes a plasma plume to exit the source. This plume can carry substantial energy. To dissipate this energy, we rely on nitrogen injection in the beamline. Since nitrogen is molecular (hence radiates efficiently in the IR) and is also electronegative, it removes both energy and electrons from this plume and efficiently shields downstream structures. However, nitrogen diffusing upstream into the source discharge can cause the source plasma to become less stable, due to these same characteristics.

The high ionization energy of helium, and the low mass of the helium ion (both compared to xenon) imply that when mixed with the source xenon it should not participate (to zero order) in the z-pinch electrodynamics. Therefore by injecting helium into the source, the total flow rate might be increased (compared to pure xenon operation) to assist in flushing nitrogen from the source – thus improving source stability. We will present preliminary data that supports these ideas.

* Horne, Stephen F., Matthew M. Besen, Paul Blackborow, Ron Collins, Deborah S. Gustafson, Matthew J. Partlow, and Donald K. Smith. "The EQ-10 Electrodeless Z-Pinch™ Metrology Source." (2018): 193-206. In "EUV Lithography, Second Edition", SPIE. Editor: Vivek Bakshi

Presenting Author

S58

The Extendibility of the Maintenance- interval of a Discharge based EUV Source

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Gas discharge based EUV sources for 13.5 nm have been under development for about 20 years. While being compact and easy to use a major aspect to this technology is to increase the maintenance interval, which is mainly limited by the electrode erosion.

The influence of this erosion on the generation of EUV radiation from the hollow cathode triggered pinch plasma, which is under development at Fraunhofer-ILT, has been studied recently. The results highlight the effects on the total and spatial distribution of the 13.5 nm emission as well as the spectral distribution of the broadband emission from the Xenon pinch plasma, which allow for the design of electrode systems where the EUV emission is more tolerant against the electrode shape. Based on lifetime experiments an estimate of the extendibility of the maintenance interval regarding the 13.5 nm output and radiance will be presented. The effects of working gas (e.g. Ar or Kr) to yield different emission spectra on the maintenance interval will be discussed.

Presenting Author

Jochen Vieker received his Diplom (M.S.) in physics in 2011 from Bielefeld University, for his work on high harmonic generation. Since then he has been scientist in the EUV technology group at the Fraunhofer Institute for Laser Technology. He is manager of the projects related to the FS54 EUV sources. He also is a PhD student at the RWTH Aachen University. Fields of research include fundamental research on gas discharge systems as well as the development of EUV sources with attention towards brightness, output power and long term stability.

S59

Advances in Laser-heated Discharge-plasma Sources

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The approach of laser heated discharge plasma (LHDP) is based on the idea to combine the most common plasma-based methods for EUV generation. It utilizes an electrically generated compressed plasma pinch (DPP) as target for additional heating by intense laser radiation (LPP). Possible advantages are increased brilliance, stabilization of the pinch process, extension of spectral range and higher power at shorter wavelength.

We report on the current state and results of the experimental setup. It consists of a modified gas discharge source that produces a compressed plasma pinch [1], with which the pulse of a CO_2 TEA laser with 10.6 μm wavelength and up to 1 Joule pulse energy is synchronized. The laser beam is focused onto the pinch plasma. The implementation of a far infrared heating laser allows for more efficient laser-plasma interaction compared to prior experiments [2]. Reflected and scattered laser light is utilized to probe the plasma properties. Impact of laser radiation on pinch dynamics and EUV spectra (5-20 nm) of different gasses is discussed.

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[2] 2015 International Workshop on EUV and Soft X-Ray Sources, S33

Presenting Author

Florian Melsheimer is a PhD student at Rheinisch Westfälisch Technische Hocheschule, Aachen. He is working in the area of EUV Source development based on CO_2-laser heating of a z-pinch gas discharge. In 2016 he received Master of Science from Rheinisch Westfälisch Technische Hocheschule, Aachen. Title of his thesis was - Characterization and synchronization of z-pinch gas discharge and Nd:YAG laser for improved EUV light generation.

S60

EUV PLASMA SOURCE AT HILASE

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It is well known that EUV systems are very promising devices for use in nanolithography and the micro-/nanostructuring of materials in a variety of important applications (e.g. in fabrication of microchips, medical devices, etc.). For these objectives, monochromatic EUV beams are preferable.

The goal of this work is to build a laser-induced EUV plasma source at the HiLASE Centre targeting possible applications in industry, medicine and scientific research (e.g. investigation of mechanisms of EUV polymers ablation). The setup shall utilize a picosecond laser system (2 ps, 100 mJ, 1 kHz) and a solid laser target. Thus, in a first step, we will establish effective parameters for laser irradiation of metallic targets, to be used as a guideline for the construction of the plasma source. In this context, data from first experiments on radiation emitted from a laser-induced plasma using a pulsed gas jet will be reported.

In order to focus the EUV radiation, the experimental setup will then be expanded with a Schwarzschild (LLG) and an elliptical mirror (Rigaku).

Presenting Author

Chiara Liberatore received her PhD degree at the Czech Technical University in 2015. After working in Canada and in France, she is currently a senior researcher at the HiLASE Centre, in the group of Prof. Bulgakova, with IR and bio-applications as main topics.

S61

Free-standing Carbon Nanotube Membranes for Applications in Extreme -ultraviolet and Soft X-ray Optics

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Constant demand of increasing optical resolution motivates technologies like photolithography and microscopy to master the short-wavelength range with □ ~ 1-10 nm. High natural radiation absorptance of various materials in this range generates challenges for designing high-performance optical systems. Under these conditions, optical elements composed of freestanding ultra-thin films become crucially important. This paper examines the feasibility of application of single-walled carbon nanotube (SWCNT) thin films as constructing elements for the short-wavelength optics. Test samples were fabricated using an aerosol chemical vapor deposition method. Synchrotron radiation was used to record transmission spectra of the samples in the spectral range of interest. The measured transmission exceeds 75% for wavelengths below 20 nm for a 40-nm-thick film, at the operational wavelength of the extreme ultraviolet lithography the transmission coefficient is 88%. The measured stress-strain curve for the test samples shows that the SWCNT-based films have rather high ductility unlike fragile films made of conventional condensed-matter materials. The combination of high radiation transmittance and unique mechanical properties makes the SWCNT-films very promising for applications in the short-wavelength optics.

Presenting Author

S62

Design and Evaluation of a Focusing EUV Monochromator for Laboratory-based Photoemission-electron Microscopy beyond He II

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We present raytracing simulations, design, experimental characterization and evaluation of a compact tunable imaging monochromator (a combined collector and emission line selector) for 5 to 20 nm wavelength, based on a curved grating [S83, 2017 Source workshop] and a toroidal mirror. First results were obtained using a high power EUV gas discharge source and are compared to the raytracing simulations. The irradiance near the focus is of the same order of magnitude as for our successful proof of concept using Bragg multilayer mirrors, but with the possibility to select a desired wavelength and focus the light to 250 µm spot size diameter. An average fluence of (2448.8 $\pm$ 369.4) W/m² at full width half maximum FWHM = 135 µm for the 15 nm or 86.66 eV photon energy emission line was measured. Also, spectral resolution was investigated to separate the single emission lines of light elements, e.g. oxygen, to take advantage of the inherent small bandwidth of these emission lines.

Presenting Author

Daniel Wilson is a PhD. Student at Forschungszentrum Jülich. His research topic is Optimization of a compact plasma gas-discharge source with optics to select and focus spectral lines in the EUV for photo-emission spectroscopy and microscopy.

S63

Monitoring EUV and DUV spectral emission ratios of a high power EUVL source

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Extreme ultraviolet (EUV) lithography light source plasmas are effective emitters around 13.5 nm with inherent parasitic emission in other wavelengths. The deep ultraviolet (DUV) range of this parasitic emission can be strongly absorbed in pellicles contributing to the heat load on the pellicle. DUV load has also impact on the imaging performance through contrast loss at the scanner side. Additionally, the spectral characteristics in the DUV and visible wavelength bands can provide unique insights in the conditions of the plasma. So far, such a comprehensive characterization is proven to be difficult due to challenges in calibration of spectrometers and covering this broad wavelength range with a single spectrometer.

Using a novel transmission grating spectrometer developed at University of Twente, we have measured the spectral characteristics of an ASML proto EUV light source under various operating conditions. The UT spectrometer is proven to be able to monitor EUV and DUV spectral emission ratios and could potentially be used for EUV source broadband optimization.

Presenting Author

Muharrem Bayraktar earned his BSc degree from Bilkent University in 2007, MSc degree from Sabanci University in 2010 and PhD degree from University of Twente in 2015. His MSc research was on digital holography and interference techniques, and applications of these techniques in three dimensional imaging and metrology. His PhD research included development of spectral filters and novel adaptive optical components based on piezoelectric thin films for applications in Extreme Ultraviolet (EUV) wavelengths. His postdoctoral research at the University of Twente is on developing a broadband spectrometer for characterization of EUV light sources with a valorization grant awarded by the NanoNextNL Programme of the Netherlands.

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A Single-shot NEXAFS Spectroscopy using Laser Plasma Double Stream Gas Puff Target SXR Source

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Thin organic samples and silicon nitride membrane were measured by means of a single-shot near edge X-ray fine structure spectroscopy, using a laboratory laser produced plasma soft X-ray source. High power nanosecond laser pulse from an Nd:YAG laser is interacting with a double stream gas puff target, forming krypton/helium plasma. Efficient emission in the "water window" spectral region allows one to obtain simultaneously emission spectrum of the source and transmission spectrum of the investigated sample, using a specially designed grazing incidence SXR spectrometer. Calculated absorption spectrum is then independent of source energy fluctuations and mechanical instabilities. Fine structures near the carbon K-α edge of PET film and ascorbic acid sample, as well as features near nitrogen K-α edge of silicon nitride membrane are revealed and compared with a multi-shot NEXAFS experiment and numerical simulations. Spectral resolution is comparable with early synchrotron measurements.

Presenting Author

Martin Duda is a Ph.D. student at HiLASE Centre and Czech Technical University in Prague. He received his B.S. and M.S. degree in Laser Technology and Electronics from Czech Technical University in Prague in 2016 and 2018, respectively, working on DPP and LPP "water window" sources for NEXAFS and XUV microscopy. Currently, his main focus is pulse compression in Type II second-harmonic generation processes.

S65

Soft X-ray Spectroscopy and Microscopy using a Table-top Laser-induced Plasma Source

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The progress in development of laboratory-scale soft x-ray sources in recent years has enabled experimental techniques that could be performed before almost exclusively at synchrotrons. Here, we present two applications of a compact, long-term stable and nearly debris-free laser-induced plasma source based on a pulsed gas jet target: Broadband radiation is used for polychromatic absorption spectroscopy in the 'water window´ spectral region, investigating the fine-structure of absorption edges that reveals information e.g. about type of bonds, oxidation states and coordination. The performance of this NEXAFS spectrometer is demonstrated for a variety of different organic and inorganic samples probing the K- and L-edges of carbon, calcium, oxygen, manganese, and iron. On the other hand, monochromatic radiation at a wavelength of 2.88 nm produced from a nitrogen plasma is employed for soft x-ray transmission microscopy, accomplishing a spatial resolution of about 50 nm. In this context, we discuss possible methods to increase the brilliance of the compact plasma source.

Presenting Author

Matthias Müller is a PhD student at Laser-Laboratorium Göttingen e.V. in the department 'Optics / Short Wavelengths'. He received his Master degree in Physics at the Georg-August-Universität Göttingen in 2012. He mainly works on the development of laser-induced plasma sources for the generation of soft x-rays and the application of this radiation, e.g. in x-ray microscopy and absorption spectroscopy.

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Study of Light Sources in the Soft X-ray Region for the Development of a Tabletop Microscope

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Here we report a study of potential Laser-Produced Plasma(LPP) based light sources for the development of a tabletop soft x-ray microscope. The spectral region of interest is below 2 nm, where there is high elemental sensitivity due to the presence of K and L edges in the absorption spectra of many medium-Z elements [1], thus producing high contrast images. Spectroscopic studies and pinhole imaging of the LPPs were conducted in order to identify source materials that will produce radiation in this region, and also to produce plasmas with diameters below 10 microns. Minimizing the size of the plasma is a powerful method to optimise brilliance.

Presenting Author

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Adopting Crab Crossing to Laser-Compton Scattering X-ray

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Laser-Compton scattering (LCS) has been expected as a compact and intense X-ray source. Since the cross section is limited to a small value, it is clever to recycle the laser pulse again and again in a laser enhancement cavity. With a compact linac and a laser enhancement cavity, head-on collision which is advantageous for generating high energy, large number photons, is difficult to realize. Crab crossing of electron beam and laser pulse enables quasi-head-on collision at the interaction point. We are going to perform the proof-of-principle experiment of crab crossing LCS using a tilted electron beam so that quasi-head-on collision is realized though both pulses cross with an opening angle. Also for the colliding laser, we are developing a CPA laser system with Yb:YAG thin-disk regenerative amplifier. We will report our study of crab crossing LCS, our laser system dedicated for this study, and some future prospects.

Presenting Author

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