2018 Source Workshop

Meeting Summary

November 6 -7, 2018

Vivek Bakshi
EUV Litho, Inc.

2018 Source Workshop, Agenda Day 1 – November 6, 2018

- **10:00 AM Session 1: Keynote Session -1**
- **Laser Produced Plasma Light Sources for Short Wavelength Applications (S3)** Gerry O'Sullivan, *University College Dublin*
- **Still more CE can be attained at 13.5 nm. Modelling needs more atomic data. Solid state mid-IR lasers could give better beam profiles (spatially and temporally)**
- Highest CE for $\Delta n = 0$ UTA in 2-3% BW around Ce or Pr. (8-8.8 nm)
- $\Delta n=1$ transitions in medium and high Z elements and $\Delta n=0$ in high Z elements can be used for water window sources.
- **$\Delta n=1$ transitions require less energy for excitation than $\Delta n=0$. Also some match existing MLMs.**
- **Ideal source ideally depends on mirror bandwidth. For very narrow bandwidth at low wavelength H-like 1s-2p line in low Z ions best. Water/ammonia/organic liquid droplet, dual ps pulse irradiation.**

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- **10:00 AM Session 1: Keynote Session -1**
- **Lifetime Achievement Award Presentation**
- **"In the mid-1980s, O'Sullivan et al. found that a strong narrowband emission is generated from a plasma of rare earth elements, that the peak wavelength scales with the atomic number of the element, and that a Sn plasma emits a strong band with the spectral peak at 13.5 nm." – Toshi Tomie, JM3 021109 (2012)**
- Soft x-ray, EUV, continua, UTA, Sources, atomic physics, chaos Molecular physics, EUVL, water window …………
- Educated countless science & engineering undergraduates, Supervised or co-supervised > 50 graduate students, >200 publications, >50 invited talks, >1700 citations, 2 patents, I company

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- **11:00 AM Session 2: Blue-X - I**
- **Blue-X – the New Frontier (S11)** Vivek Bakshi, *EUV Litho, Inc.*
- Next Steps for the community: Questions for us to answer
- ML Optics
  - Reflectivity and bandwidth in the 1-13.5 nm region
    - How we can get ~70% reflectivity?
  - New ML deposition technologies for reducing interface roughness for increased reflectivity at lower wavelengths
  - What innovations are possible?
- Source
  - Is UTA the option the best – which one? Lighter elements?
  - CE vs wavelength?
  - Drive lasers for 100- 300 kW – which technology offers best CoO?
  - FEL – can we deliver 500- 1000 W, while addressing current concerns about FEL
- Any other challenges?

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- **11:00 AM Session 2: Blue-X - I**
- **Liquid-jet laser-plasma sources for sub-5-nm emission (S17) (Invited Talk)**

  Hans M Hertz, *KTH/Albanova*
- **Liquid-jet laser plasmas w/ λ=2-11 nm emission are decently well understood.**
- **Power? – possibly**
- Stability? – possibly
- Mirrors? – see upcoming talk
- Will it happen?

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- **A Water Window Source for Soft X-Ray Microscopy and other Applications (S16) (Invited Talk)** Fergal O Reilly, *UCD*
- *Summary of water window source status*
- Photons at Sample Plane ~8E8 ph/sec
- Small high energy plasma
- Source at < 5 nm as a broadband source for experiments
- Results on CE scaling
- Spectra from 1.5 to 4.5 nm

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- **Recent Advances in Development and Application of Compact Laser-Plasma Soft X-ray Sources based on a Gas-Puff Target (S12) (Invited Talk)** Henryk Fiedorowicz, *Military University of Technology*
- compact laser plasma EUV and soft X-ray sources based on a **gas puff target** have been developed,
- the sources were used in metrology of EUV optics, EUV and soft X-ray microscopy, EUV and soft X-ray pulsed radiography, EUV processing materials, EUV photoionization studies, and soft X-ray radiobiology,
- application in **soft X-ray absorption spectroscopy** (**NEXAFS**), **soft X-ray optical coherence tomography** has been recently demonstrated,
- new techniques based on a laser plasma soft X-ray and EUV sources **are ready** for the use in ”real” research.

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- **Wavelength and Brilliance Scaling Potential of Discharge based XUV Sources (S13) (Invited Talk)** Klaus Bergmann, *Fraunhofer– ILT*
- **Proposed alternative emitters for 6.x nm (in addition to known Gd and Tb) – Line emitters e.g. Al . Gd Alloys with lower melting point**
- Results for quasi-braodband emission in water window region – Ar and Ar/S02
- Results on optimization of EUV emission from DPP

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- **Xe Laser-Plasma EUV Source – from 13.5 nm to 11 nm: Researches to Optimize the Xe LPP 11-nm Source (S14)**
  S Kalmykov, *Ioffe Institute*
- Compact laser plasma EUV and soft X-ray sources based on a **gas puff target** have been developed at 11.4 nm
- The sources were used in metrology of EUV optics, EUV and soft X-ray microscopy, EUV and soft X-ray pulsed radiography, EUV processing materials, EUV photoionization studies, and soft X-ray radiobiology,
- Application in **soft X-ray absorption spectroscopy** (**NEXAFS**), **soft X-ray optical coherence tomography** has been recently demonstrated,
- New techniques based on a laser plasma soft X-ray and EUV sources **are ready** for the use in ”real” research.

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- **2:00 PM Session 3: Blue-X – II**
- **Multilayer Optics for 1 nm to 13.5 nm: Can We Reduce the Lithography Wavelength Further? (S18) (Invited Talk)** Torsten Feigl *optiX fab*
-

λ, nm	1.4	2.4	2.7	4.4	6.7	9.0	12.0	13.5
R, %	0.02	18.1	26.2	16.8	61.0	36.0	49.2	70.1
FWHM, nm	0.002	0.005	0.008	0.02	0.05	0.11	0.32	0.52

- It's really hard to make high-reflective multilayers for wavelengths < 13.5 nm
- Challenges: low reflectance, narrow bandwidth
- Please match source emission with multilayer absorption edges…
- **Still a very long and steep way to go … but good to start now**

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- **2:00 PM Session 3: Blue-X – II**
- **Depth-modified Bragg Mirrors for sub-10-nm Wavelengths (S19)**

  R. Meisels, *Institute of Physics, Austria*
- **Simulations** using the MSM (multiple scattering method) allow prediction of reflection by arbitrary layer systems
- **13.5 nm** (Mo/Si system): Combined grading and superlattices enable all-angle reflection.
- **Sub 10 nm** (6.64 nm B4C/La and 3.12 nm Cr/Sc system) via superlattice and depth grading
  - No all-angle reflection due to lower index contrast and narrow reflectance peaks. SL peaks remain sharp at certain angles.
  - Grading allows to widen the spectral and angular ranges of reflection. A trade-off is reduced peak (normal incidence) reflectance.
  - The wider spectral ranges of reflection of graded mirrors allow to better exploit sources with broad spectral widths.
  - **Reflectance of Cr/Sc multilayers near 3.12 nm >60%**

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- **New Architectures for PW-Scale High Peak Power Lasers Scalable to Near-MW Average Powers and Their Application to EUV Generation (S15) (Invited Talk)**

  C. W. Siders, *Lawrence Livermore National Laboratory*

- **Scalable & efficient 2-mm BAT Laser is a strong candidate next-gen Blue-X driver lasers.**
- 3 J, 100 k Hz, 100 fs,

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- **3:10 PM Session 4: Lasers**
- **Beam Quality of Pulsed High-power CO_2-Lasers for EUV Lithography (S36) (Invited Talk)** Johannes Kaschke, *TRUMPF*
- Industrialized TRUMPF Amplifier including multi-stage amplification and seed isolation.
- Evolution of power and peak power has been enabler for 250 W EUV with Good beam quality shown systematically for all field systems
- **Roadmap towards higher EUV-power scaling and possible scaling options were presented. Combined with possible increases via repetition rate scaling, this could pave the road towards 500 W EUV.**

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- **3:10 PM Session 4: Lasers**

- **Progress on laser-driven soft x-ray lasers at LOA (S32) (Invited Talk)**
  S. Sebban, *Université Paris-Saclay*

- 32.8 nm diffraction-limited multi μJ 100’s fs laser operation
- Efficient guiding at $n_e=10^{20}cm^{-3}$
- Full control of the polarization from linear to circular
- Source adapted for single shot CDI experiments (narrow bandwidth, high coherence, Fourier limited)
- Prospect for 10’s fs multi 10’s μJ operation
- **Future challenges : improve the seeding extraction**
- **Measure the pulse duration with 100 fs time resolution**

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- **Technologies and Applications of High-average-power Lasers at HiLASE (S33) (Invited Talk)** Tomas Mocek, *HiLASE*
- **Laser Technology R&D Infrastructure**
- **Up & Running since 2016**
- **Branch of the Institute of Physics**
- **DPSSLs with breakthrough parameters**
- **Applications of DPSSL in hi-tech industry**
- Project of National Interest
- 84 FTE / 95 heads + 30 part-timers
- FY2017 budget: CZK 110M (USD 5M)
  - 11% (institutional)
  - 89% (projects & contracts)

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- **Ultrafast Thin-Disk Amplifiers (S35) (Invited Talk)**

  Thomas Metzger, *TRUMPF*

- Regen. amplifier: **200 mJ; 1kHz (standard)**
- **500W ; 6-100 kHz (standard)**
- **1kW; 5-100 kHz (standard – new goal 500fs)**
- Nonlin. Compression: **first ideas for 200mJ (project has started)**
- Multipass amplifier: **1 kHz; 1 J; ~2 ps (development - project towards multi-kW)**
- OPCPA: **µJ energies (standard)** and **mJ energies (custom design possible)**

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- **Quantum Technology and kW, ps thin disc lasers (S34) (Invited Talk)**

  Akira Endo, *HiLASE*

- *Proposed* **High brightness Attosecond EUV-XUV sources**
- **Quantum Technology** : leading the next decade
- **kW, picosecond Yb:YAG laser** : driver for the advanced light sources

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- **High-harmonic Generation for EUVL: Source Developments and Applications for Spectroscopy and Metrology (S31) (Invited Talk)**

  Peter Kraus, *ARCNL*
- Proposed HHG sources as **ultrafast, coherent, table-top XUV/soft x-ray source**
- **The OPCPA will drive a unique EUV/soft x-ray HHG source (<600 eV / 2 nm) which will serve many collaborations within and outside of ARCNL.**
- HHG lasers for study of spectroscopy of resists

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- **EUV Source for Lithography: Readiness for HVM and Outlook for Increase in Power and Availability (S1)** Igor Fomenkov, *ASML*
- 34 NXE:3XY0B systems operational at customers. Dose-controlled power of 250W on multiple tools at customers
- Progress in EUV power scaling for HVM. -Dose-controlled power of 250W on multiple tools at customers
- Collector lifetime ~ 150 Billion Pulses in the field
- CO_2 development supports EUV power scaling
- Clean (spatial and temporal) amplification of short CO2 laser pulse. -High power seed system enables CO2laser power scaling
- Droplet Generator with improved lifetime and reliability. >700 hour average runtime in the field. ->3X reduction of maintenance time
- Path towards 500W EUV demonstrated in research. CE is up to ~ 6 %. -In-burst EUV power is up to 450W

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- **High Power LPP-EUV Source with Long Collector Mirror Lifetime for Semiconductor High Volume Manufacturing (S2)** Hakaru Mizoguchi, *Gigaphoton*
- **Pilot#1 is up running and its demonstrates HVM capability;**
  - *High conversion efficiency 5% is realized with Pre-pulse technology.*
  - *High speed (>90m/s) & small (20micron) droplet is realized.*
  - ***Output power 250W in-burst power @50% duty (125W ave.) several min, 113W in-burst power @75% duty (85W ave.) 143hrs.***
  - *Pilot#1 system achieved potential of 89% Availability (2weeks average).*

- ***Recent achievement for most critical challenges mirror life***
  - *--0.2%/Gpls with 125W ave. was demonstrated at short term dummy mirror test*
  - ***-1.0%/Gpls with 125W ave. was demonstrated during 30Mpls with mirror test (preliminary)***

- ***Next Step***
  - *-0.2%/Gpls with 125W ave. more than 50Bpls with full size mirror.*
  - *Ce enhancement based on Tomson scattering measurement.*
  - ***>90% availability challenge with operation software enhancement.***
  - ***250W ave. with -0.2%/Gpls, >90% availability proof test in 2020 target***

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- **11:40 AM Session 7: Metrology Sources**
- **Characterization and Performance Improvement of Laser-assisted and Laser driven EUV sources for Metrology Applications (S56) (Invited Talk)** Yusuke Teramoto, *Ushio Inc.*

- ***Laser-assisted source***
- Brightness of Sn-LDP source is sufficiently high for enabling EUV actinic mask inspections (ABI, API and AIMS).
- Current development is focusing on stability, reliability and robustness through multiple long-term tests.
- Tests at higher pulse repetition rate has started. Plasma is tunable and can be optimized for power or brightness.

- ***Laser-driven source***
- Compact LPP source is being studied as EUV and X-ray sources.
- Highest brightness of 100 W/mm^2/sr was obtained at 20 kHz (laser power 160 W).
- Brightness efficiency was improved by a factor of 1.6 by introducing a short-pulse, high-intensity laser. 50 W/mm^2/sr was obtained at 15 kHz (laser power 50 W).

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- **High-brightness Light Source Based on a New Concept of LPP for Actinic EUV microscopy and Metrology Applications (S54) (Invited Talk)**

  Mikhail Krivokorytov, *RnD-ISAN/EUV Labs and ISAN*
- Ytterbium pulsed fiber laser, IPG Photonics, YLPP-1-150V-30 with Target of Sn/In eutectic alloy
- 30 W average power. 50 W/ mm2 sr, 0.5 % CE

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- **Mixed gas fueling experiments on the Energetiq EQ-10 (S52) (Invited Talk)**

  Stephen F. Horne, *Energetiq Technology, Inc.*
- We began by adding N2 to the beamline to mitigate any beamline plasma. Since N2 in the source causes the plasma to be unstable, we used He to purge N2 from the source.
- **The purge idea worked well. So well, it improved stability even with no N2.**
- The cause of the instability is plausibly identified as a unipolar arc;
- The results imply that we should investigate whether there is some simple mixture of Xe/He that we could provide to customers, if they wish to improve the pulse-to-pulse stability of their EQ-10 beyond its already stellar performance.

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- **Electron impact type laboratory EUV source for metrology and imaging (S55) (Invited Talk)**
  Ladislav Pina, *Rigaku and Czech Technical University*
- **3D X-ray source & 3D X-ray mirror combination for metrology and imaging. Descripton of following:**
    - Electron tube
    - Rotationally symmetric X-ray optic
    - CW or pulsed operation
    - mm X-ray focal spot size
    - Power
    - Compactness
    - Stability

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- **EUV/X-ray Sources driven by New-generation of Lasers for User-applications at ELI Beamlines (S51) (Invited Talk)** Jaroslav Nejdl, *ELI-BL*
- Brief overview of the ELI Beamlines facility
- Laser driven XUV/X-ray sources
  - HHG beamline
    - Correlation of HHG properties with IR laser spectral features
  - Plasma X-ray source
  - Betatron/inverse Compton beamline
  - Laser Undulator X-ray Source/ Laser-driven FEL (A. Molodozhentsev, S24)

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- **3:00 PM Session 8: FEL**
- **Upgrade plan of cERL for the POC as a First-Stage of the Development on EUV-FEL High-power Light Source (S21) (Invited Talk)** Hiroshi Kawata, *KEK*
- Upgrade plan of cERL for the POC as a first stage of the development on EUV-FEL high power light source has been studied.
- Present planning is a full version to demonstrate the FEL power and also the performance of the SRF accelerator.
- Wavelength of FEL is proportional to $1/E_{acc}^2$.
- Dr. R. Hajima has already presented as the next slide of "Possible upgrade to 6.5 nm" in the source workshop at 4/November/2014 at Dublin.
- Is it possible to obtain 6.6 to 1 nm wavelength from EUV-FEL? Absolutely Yes!
- If so what will be the challenges of this work?

There is no big challenge from the view point of accelerator technology. We just increase the accelerator energy up to ~1131 MeV from 800 MeV. The size reduction is always very important.

- It is necessary to examine whether the acceptance of the wavelength on the Multi-layer reflectivity curve at the 6.X nm is wide enough to accept the whole FEL light (Dl/l = 6 x 10^{-3}).

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- **3:00 PM Session 8: FEL**
- **Surface Ablation by Soft_X-ray Laser Pulse for EUV_nano-scale fabrication (S22) (Invited Talk)**

  Masaharu Nishikino, *Kansai Photon Science Institute, QST*
- **Nano-scale surface modifications**
- **·We show the surface ablation/modifications formed on Al induced by single SXFEL pulse irradiations.**
- **·Surface modification thresholds of SXFEL pulse for materials are essentially lower than those of optical lasers.**
- **·The MD simulation developed for soft x-ray ablation reveals the spallation process for surface modifications.**
- **EUV lithography components test**
- **·We started the EUV damage test on multi-layered mirrors and EUV lithography components.**
- **·The surface damage are occurred in essentially *lower* fluence than those of ns-plasma x-ray source.**
- **·There is a possibility that the exposure sensitivity is also lower than a ablation threshold.**
- **·We can exposure the resist material (PMMA, etc) under non-ablative condition with SXFEL.**

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- **Laser-cooled Electron Source (S23) (Invited Talk)**
  Jom Luiten, *Eindhoven University of Technology*
- **ColdLight**: Laser-cooled electron source for ICS EUV generation
- Narrowband, easily tunable over entire EUV range
- Full spatial and temporal coherence down to H_2O window
- Coherent amplification by micro-bunching

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- **Fs-laser driven free-electron laser development in ELI-BL (S24)**
  Alexander Molodozhentsev, *ELI-BL*
- **fs' laser-driven free-electron laser opens the way to the 5th generation of FEL**
- **'demo' laser-driven FEL is under development in ELI-beamlines in collaboration with University of Hamburg and DESY (CFEL)**
- **we are developing a tunable tool for applications**
- **We are eager to hear from the EUV community in order to play with the right knobs to develop a tailored FEL for lithography applications**

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- **4:40 PM Session 9: LPP Sources**
- **Nd:YAG-laser-driven Sn plasma: an ARCNL research update (S41) (Invited Talk)** O. O. Versolato, *ARCNL*
- Update on fundamental study of LPP plasma via study of transitions and charge state with goal to increase CE
- Ion charge / energy spectroscopy
- Detailed study of YAG-ns pre-pulse physics

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- **4:40 PM Session 9: LPP Sources**
- **Tin-ion Interactions (S42) (Invited Talk)**
  Ronnie Hoekstra, *ARCNL*

- Overview “ARCNL” tin ion interactions program
- Channeltron and MCP Sn-Ion detection efficiencies determined
- Excellent absolute agreement between ESA and FC ion traces
- **Charge eXchange in H_2 buffer gas determines ionic charge state distributions**
- CX modelling requires high-quality cross sectional data which by and large are still lacking
- ZERNIKELEIF facility for energy, mass, and charge state selected beams of Sn ions operational
- **First scattering experiments on Mo and Ru surfaces hint at issues with SRIM, the standard program for particle – matter interactions**

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- **Influence of Opacity in Nd:YAG Laser-produced Tin-Plasmas (S43)** R Schupp, ARCNL
- High SP for short-pulses and small droplets
- Radiative efficiency well described by simple geometric plasma expansion model
- State of the art opacity calculations
- **Emission spectra from Nd:YAG LPPs well approximated by calculations for single density, single temperature plasma**

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- **EUV & Soft X-ray Sources based on Medium-Z LPPs (S44) (Invited Talk)**

  P. Dunne, *University College Dublin*
- **To get below 3 nm: Δn = 0 (4-4 & 5-5) transitions in high-Z or Δn = 1 (3-4) transitions in medium-Z**
- Results of strontium EUV spectroscopy and Infulence of pulse shape and energy on plasma properties
- Nest step: $\lambda < 3$ nm spectroscopy & imaging

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- **Computer modeling of contamination and cleaning of EUV source optics (S47) (Invited Talk)**
  Dmitry Astakhov, *RnD- ISAN*
  - We have developed 3D transient model that couples energy and momentum input from tin plasma to the flow in the EUV source chamber
  - The model takes into account tin deposition and cleaning from surfaces. Main etch product is assumed to be chemically active SnHx
  - The model have ability to smoothly vary time step from pulse-to-pulse (~1e-6s) resolution to characteristic times (~100s) of cleaning processes
  - **The model can be used to optimize the chamber geometry, flow structure etc. for regime during source operation**

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