Towards solid-state-laser-driven plasma sources of EUV light: An update on ARCNL’s Source Research program

Groups:
- EUV Plasma Processes (Versolato, Ubachs, Hoekstra)
- EUV Generation & Imaging (Witte, Eikema)
- Ion interactions – Groningen (Hoekstra)
- EUV Plasma Theory & Modelling – NN

EUVL Workshop - online June 10th, 2020
Oscar Versolato
Head of ARCNL Source Department
ARCNL Source Research: physics challenges

1. Understand exploding tin microdroplets
   - What determines deformation and fragmentation?

2. Key insights to enable source predictive modeling
   - What emits that EUV light?

3. Push the fundamental limits of the conversion efficiency
   - What sets the fundamental limit?

4. Control expansion dynamics of laser-produced plasma
   - What is the cause of the ion energy distribution?

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References:

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S. Rai, et al., NIMB 143 (2020); D. Hemminga et al., in preparation
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B. Liu and R. Meijer, et al., JAP **129**, 053302 (2021);
R. Meijer et al., under review; J. Hernandez-Rueda, in preparation
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J. Scheers, et al., PRE 102, 012304 (2020); J. Scheers, et al., PRA 101, 062511 (2020);
F. Torretti, J. Sheil, et al., Nature Communications 11, 2334 (2020);
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O. O. Versolato, Plasma Sources Sci. Technol. **28**, 083001 (2019);
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See talk Javier Hernandez-Rueda P46

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F. Torretti, J. Sheil, et al., Nature Communications 11, 2334 (2020);
What emits that EUV light?

Busquet’s method: approximate non-LTE level populations using LTE -- for CO$_2$-laser-driven plasma

CO$_2$ conditions:
\[ n_e \approx 10^{19} \text{ cm}^{-3} \]
\[ T_z = 26 \text{ eV} \]

Majority (CO$_2$ case: 66%) of 2%BW opacity from transitions between multiply-excited states

F. Torretti, J. Sheil, et al., Nature Communications 11, 2334 (2020);
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Push the fundamental limits of CE

Research at ARCNL: “Contribute to >500 Watt EUV LPP source beyond 2020; pushing the fundamental limits of the conversion of solid-state drive laser light into EUV light”

Up to now: max CE for YAG (1 micron, MP only) at ~3% at ARCNL* – limited by its large optical depth

Key question: what laser operating at what wavelength should best be used to drive plasma for next-generation’s EUV light sources?

For this 2019 EUV Source Workshop, we have taken the first steps in this system-level EUV source trade study

1D HYDRA ensemble modeling agrees with our earlier on-par CE for 2 vs 10 μm, and shows a potential 1% gain (20% relative)

HYDRA simulations of Tm:Sn vapor ensembles depicting conversion efficiency (“absorbed energy CE”) as a function of laser wavelength and intensity. Figure taken from Craig Siders’ talk at the 2019 Source workshop.

Push the limits of CE

Characterization of angularly resolved EUV emission from 2-µm-wavelength laser-driven Sn plasmas using preformed liquid disk targets

Enhanced capabilities and performance of 2-µm-driven plasmas produced from disk targets when compared to 1-µm driven plasmas

Push the limits of CE

- CE and EUV emission geometrically increase with target diameter, while SP decreases
- CE, SP independent on 2 micron laser pulse intensity – EUV emission increases with input power
- CE, SP independent on 2 micron laser pulse length – EUV emission increases with input power
- CE, SP strongly increase with drive laser wavelength 1->2 micron

R. Schupp and L. Behnke et al, under review;
L. Behnke and R. Schupp, et al., Opt. Express 29, 4475 (2021);
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D. Hemminga and L. Poirier, et al., in preparation
What is the cause of the ion energy distribution?

Hydro approach valid when the local Debye length \( \lambda_D \ll L \) (flow scale variation).

High pressure in hot, dense plasma drives expansion. For an ideal gas with moderate ionization degrees:

\[
P \approx n_e kT_e = Z n_{\text{ion}} kT_e
\]

Ion energy peak attributed to high-velocity, dense shell formed early; subsequent higher velocity plasma (from intense part of pulse) shocks into this shell.

D. Hemminga and L. Poirier, et al., in preparation
Step 1: prepulse

Step 2: main pulse

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ARCNL Source Research: team

ARCNL EUV PP team:
Ruben Schupp (PhD defense March 2021)
Zoi Bouza (TKI PhD)
James Byers (TKI PD @ UT)
Bo Liu (VIDI PhD)
Lars Behnke (VIDI PhD)
Lucas Poirier (ERC PhD)
Yahia Mostafa (ERC PhD)
N.N. (PhD)
Adam Lassise (PD)
Javier Hernandez-Rueda (ERC PD)
Randy Meijer (PhD -> PD)
Laurens van Buuren (technician)
Ronnie Hoekstra (group leader)
Wim Ubachs (group leader)
Oscar Versolato (group leader)

ARCNL EUV G&I team:
Jan Mathijssen (PhD)
Zeudi Mazzotta (PD)
Stefan Witte (group leader)
Kjeld Eikema (group leader)

RUG-ARCNL team:
Subam Rai (PhD, RUG)
Klaas Bijlsma (PhD, RUG)
N.N. (PhD)
Mart Salverda (technician)
Ronnie Hoekstra (group leader)

SOURCE Plasma modeling team + N.N (Tenure-track group lead)
John Sheil (PD)
Diko Hemminga (ERC PhD)

Academic collaborators:
James Colgan (LANL): plasma theory (opacity)
A. Ryabtsev (ISAN): spectroscopy
M. Basko (KIAM, ISAN): plasma
J.R. Crespo López-Urrutia (MPIK): spectroscopy
H. Gelderblom (TU/e): fluids
A. Borschevsky (U. of Groningen): atomic theory
J. Berengut (UNSW Australia): atomic theory
Ahmed Diallo et al. (PPPL Princeton): thomson & PIC modeling
Mendez, Rabalan (UAM-Madrid): charge exchange
Muharrem Bayraktar, Fred Bijkerk, Marcelo Ackermann (U. Twente): spectroscopy

Total staff currently involved in Source:
4 PI's (~ 2 fte), 5- postdocs, 9 PhD students,
2 technicians; (3 vacancies)
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