Physics aspects of solid-state-laser-driven plasma sources of EUV light: ARCNL’s Source Research program

EUV Source Workshop - online November 5th, 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?

See poster presentations Lucas Poirier S34; Subam Rai S35 and talk Ronnie Hoekstra S46.
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?

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?

See talk Bo Liu S48

ARCNL Source Research: highlights

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?

See talk James Colgan S47
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?

L. Behnke, submitted (2020); R. Schupp, submitted (2020)
Motivation and key question

**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?

Key learning: plasma parameters scale (inversely) proportionally with drive laser wavelength, and not quadratically.

\[ I, \rho \sim \frac{1}{\lambda} \]
Optical depth reduces with drive laser wavelength, also with droplet size – better spectral purity (SP)

\[ \tau_\lambda := \int \kappa_\lambda n_i dx \]

Opacity

Path length

Density

\[ L_\lambda = S_\lambda \left( 1 - e^{-\tau_\lambda} \right) \]

\[ \tau_\lambda = -\ln \left( 1 - \frac{L_\lambda}{B_\lambda} \right) \]

\[ \tau_{\lambda,i} = a_i \tau_{\lambda,0} \]

R. Schupp et al, APL 115, 124101 (2019)
Optical depth reduces with drive laser wavelength, also with droplet size – better spectral purity (SP)

![Graph showing intensity vs wavelength and droplet diameter vs peak optical depth]

1 micron (smaller droplet = smaller depth)

2 micron

\[
L_\lambda = S_\lambda \left( 1 - e^{-\tau_\lambda} \right)
\]

\[
\tau_\lambda = -\ln \left( 1 - \frac{L_\lambda}{B_\lambda} \right)
\]

\[
\frac{L_{\lambda,i}}{B_{\lambda,i}} = 1 - \left( 1 - \frac{L_{\lambda,0}}{B_{\lambda,0}} \right)^a
\]

R. Schupp, L. Behnke, et al, submitted
Optical depth reduces with drive laser wavelength, also with droplet size – better spectral purity (SP)

$$\tau_\lambda := \int \kappa_\lambda n_i dx$$

opacity, path length

density

$$L_\lambda = S_\lambda (1 - e^{-\tau_\lambda})$$

$$\tau_\lambda = -\ln \left(1 - \frac{L_\lambda}{S_\lambda}\right)$$

$$S_\lambda = B_\lambda$$

$$\tau_{\lambda,i} = a_i \tau_{\lambda,0}$$

$$\frac{L_{\lambda,i}}{B_{\lambda,i}} = 1 - \left(1 - \frac{L_{\lambda,0}}{B_{\lambda,0}}\right)^{a}$$

R. Schupp, L. Behnke, et al, submitted
Key learning: the optical depth of the plasma scales (slightly less than) inversely proportionally with drive laser wavelength, and not quadratically.

This brings wins for SP… and CE?
Doubling of CE and SP going from 1- to 2-µm-wavelength drive laser

1. Substantial increase in CE, SP going for MOPA
2. Strong absorption features from YAG-LPP absent in MOPA-LPP
3. Laser intensity needed to achieve plasma temperature 2x lower for MOPA

L. Behnke, R. Schupp, et al, submitted
ARCNL Source Research: highlights

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

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

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

4. Control expansion dynamics of laser-produced plasma
   o What is the cause of the ion energy distribution?
EUV spectroscopy of highly charged Sn$^{13+}$–Sn$^{15+}$ ions in an electron-beam ion trap
EUV spectroscopy of Sn$^{5+}$-Sn$^{10+}$ ions in an electron beam ion trap and laser-produced plasmas
Time- and space-resolved optical Stark spectroscopy in the afterglow of laser-produced tin-droplet plasma
ARCNL Source program: team

**ARCNL EUV PP team:**
- Dmitry Kurilovich (Phd 04-2019; - ASML)
- Francesco Torretti (Phd 12-2019; - ASML)
- Joris Scheers (PhD defense 10-11-2020)
- Ruben Schupp (PhD)
- Zoi Bouza (TKI PhD)
- Bo Liu (VIDI PhD)
- Lars Benhke (VIDI PhD)
- Lucas Poirier (ERC PhD)
- Yahia Mostafa (ERC PhD)
- Adam Lassise (PD, ex-ASML)
- Javier Hernandez-Rueda (ERC PD)
- Randy Meijer (PD)
- Laurens van Buuren (technician)
- Ronnie Hoekstra (group leader)
- Wim Ubachs (group leader)
- Oscar Versolato (group leader)

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

**RUG-ARCNL team:**
- Subam Rai (PhD, RUG)
- Klaas Bijlsma (PhD, RUG)
- Ronnie Hoekstra (group leader)

**SOURCE Plasma modeling team**
- 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
- Muharrem Bayraktar (U. Twente): spectroscopy
- Fred Bijkerk (University of Twente): spectroscopy

**Total staff involved in Source:**
- 4 PI’s (~ 2 fte), 5 postdocs, 10 PhD students, 1 technician (no current vacancies)
Physics aspects of solid-state-laser-driven plasma sources of EUV light: ARCNL’s Source Research program

EUV Source Workshop - online November 5th, 2020

Oscar Versolato
Head of ARCNL Source Department