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

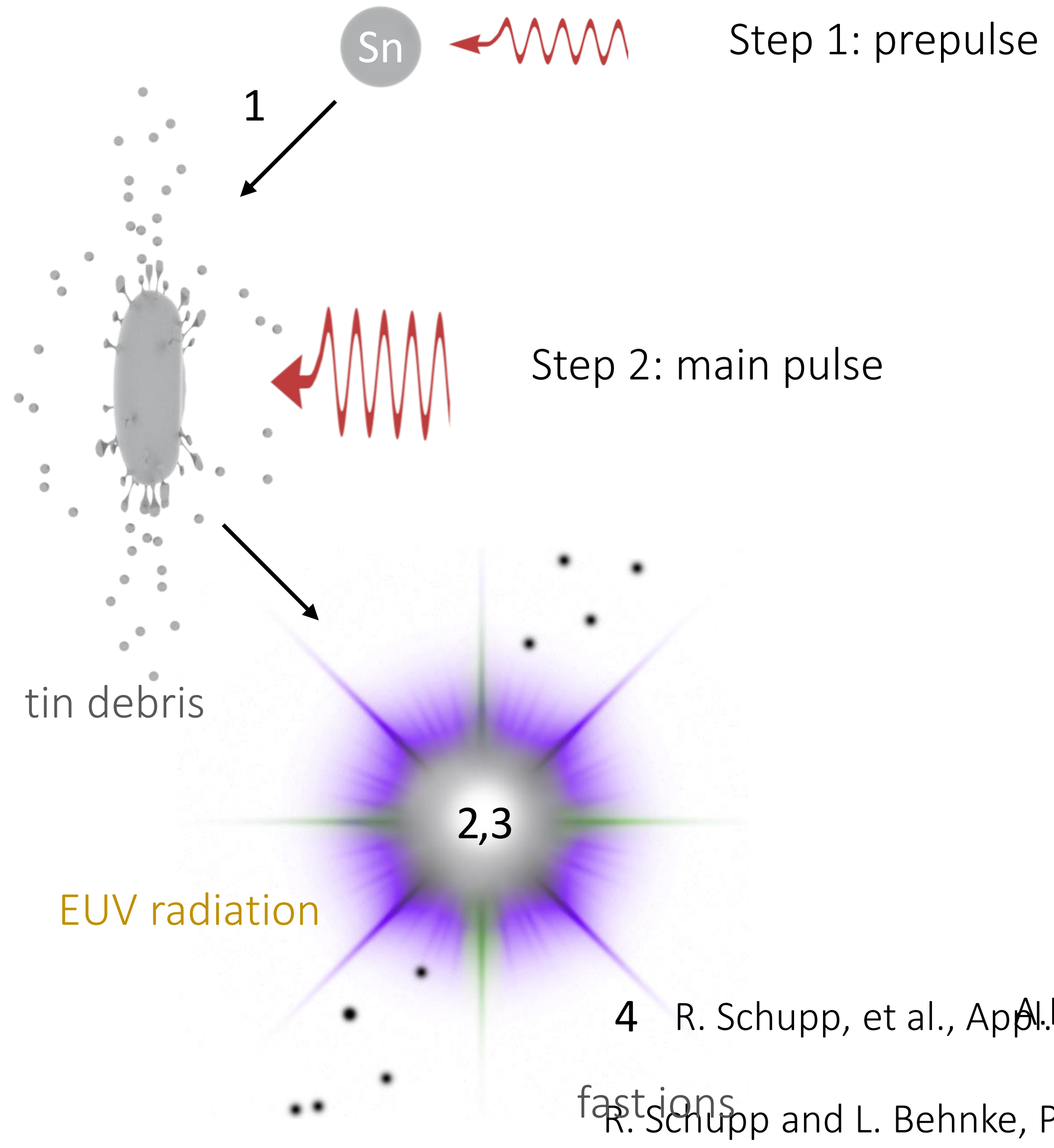
Groups:
EUV Plasma Processes (Versolato, Ubachs, Hoekstra)
EUV Generation & *Imaging* (Witte, Eikema)
Ion interactions – Groningen (Hoekstra)
EUV Plasma Theory & Modelling – NN

EUVL Workshop - online June 10th, 2020

Oscar Versolato
Head of ARCNL Source Department

ARCNL

ARCNL Source Research: physics challenges



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

J. Scheers, et al., PRE 102, 013204 (2020); J. Scheers et al., PRA 101, 062511 (2020);
R. Schupp, et al., Appl. Phys. Lett. 115, 124101 (2019); A. L. Klein, J. Fluid Mech. 893, A7 (2020); B. Liu, et al., Phys. Rev. Applied 13, 024035 (2020);
F. Torretti, J. Sheil, et al., Nature Communications 11, 2334 (2020);
R. Schupp and L. Behnke, Phys. Rev. Res. 3, 013294 (2021);

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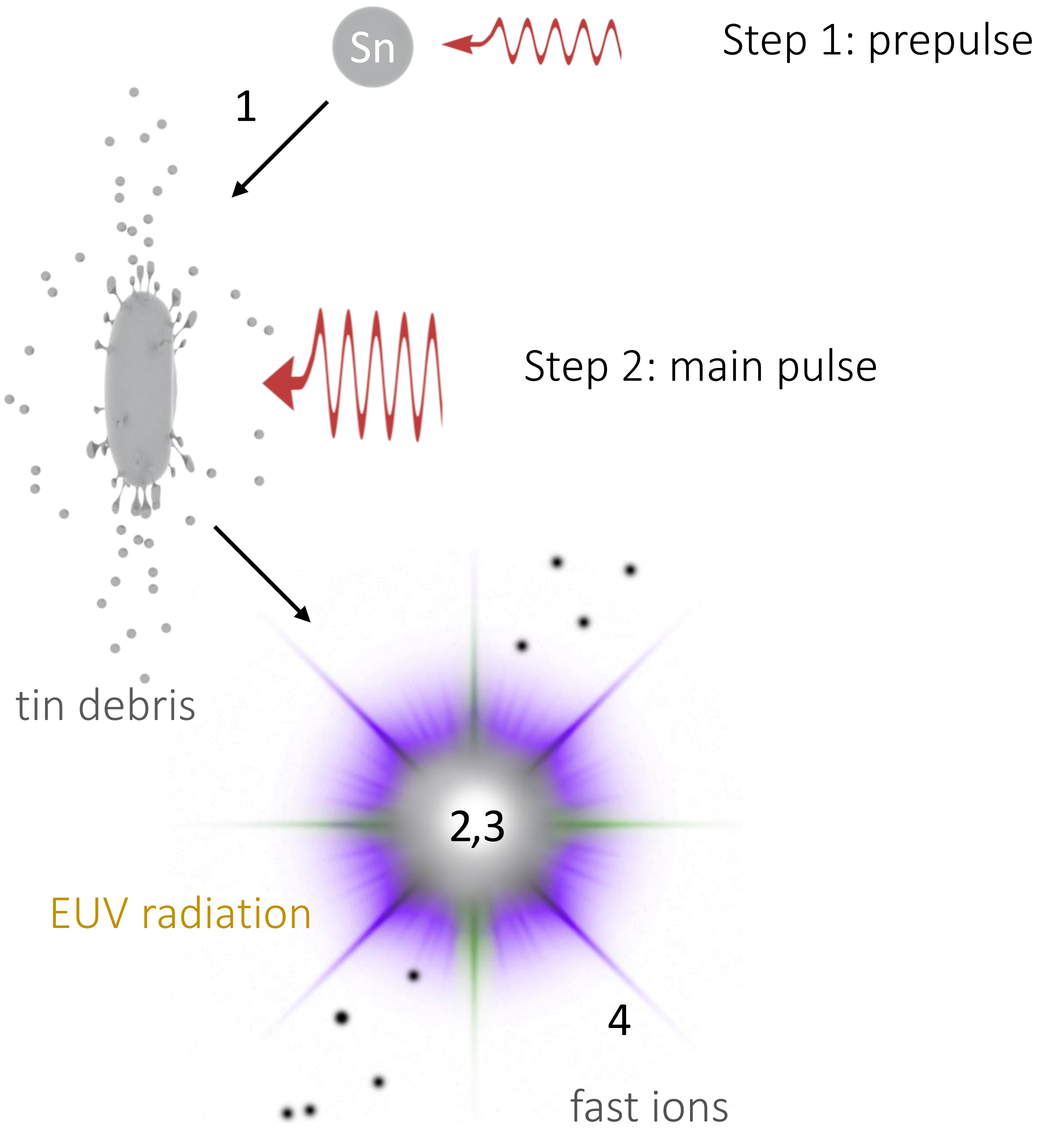

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S. Rai, et al., NIMB **143** (2020); D. Hemminga et al., in preparation

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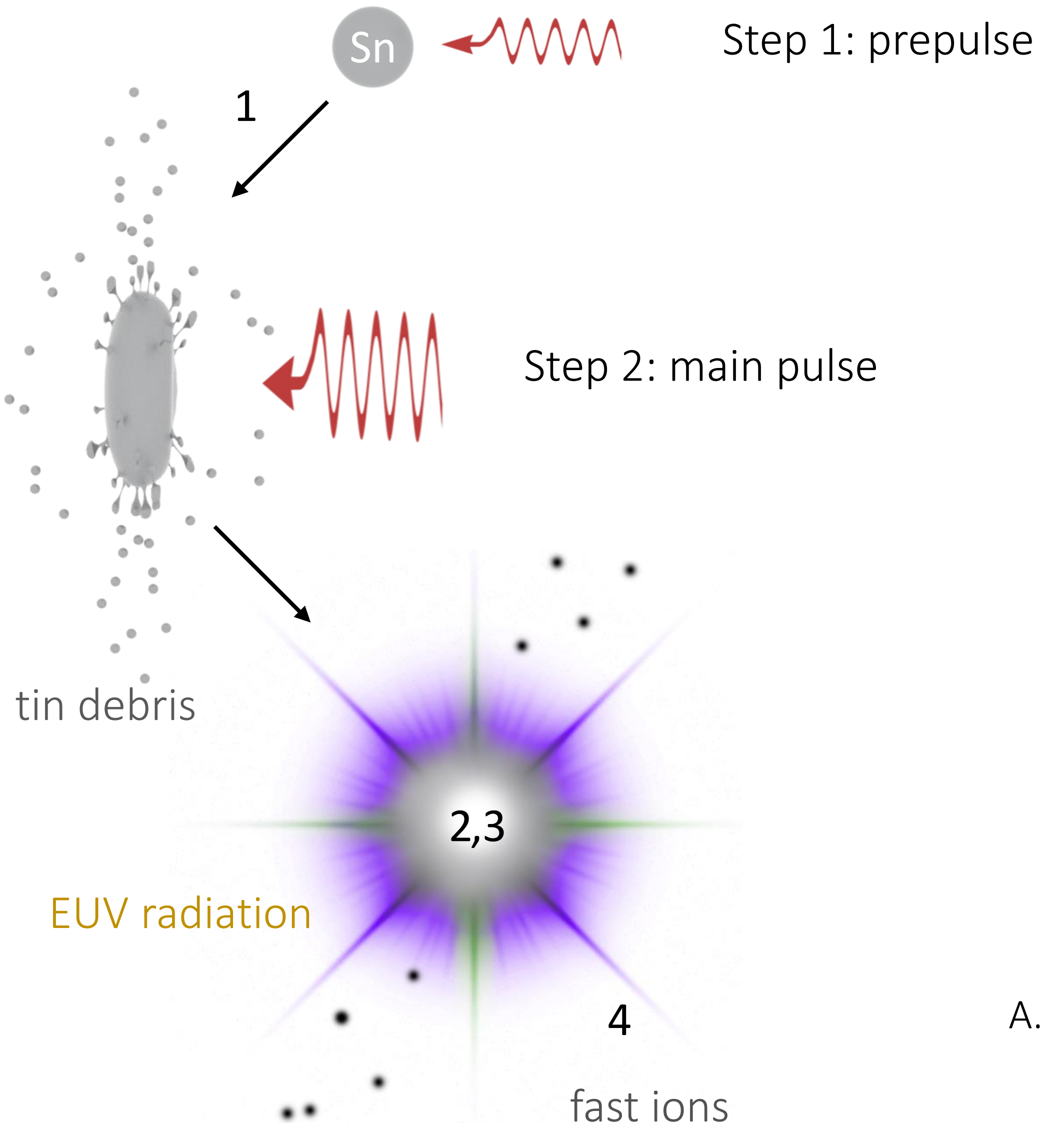

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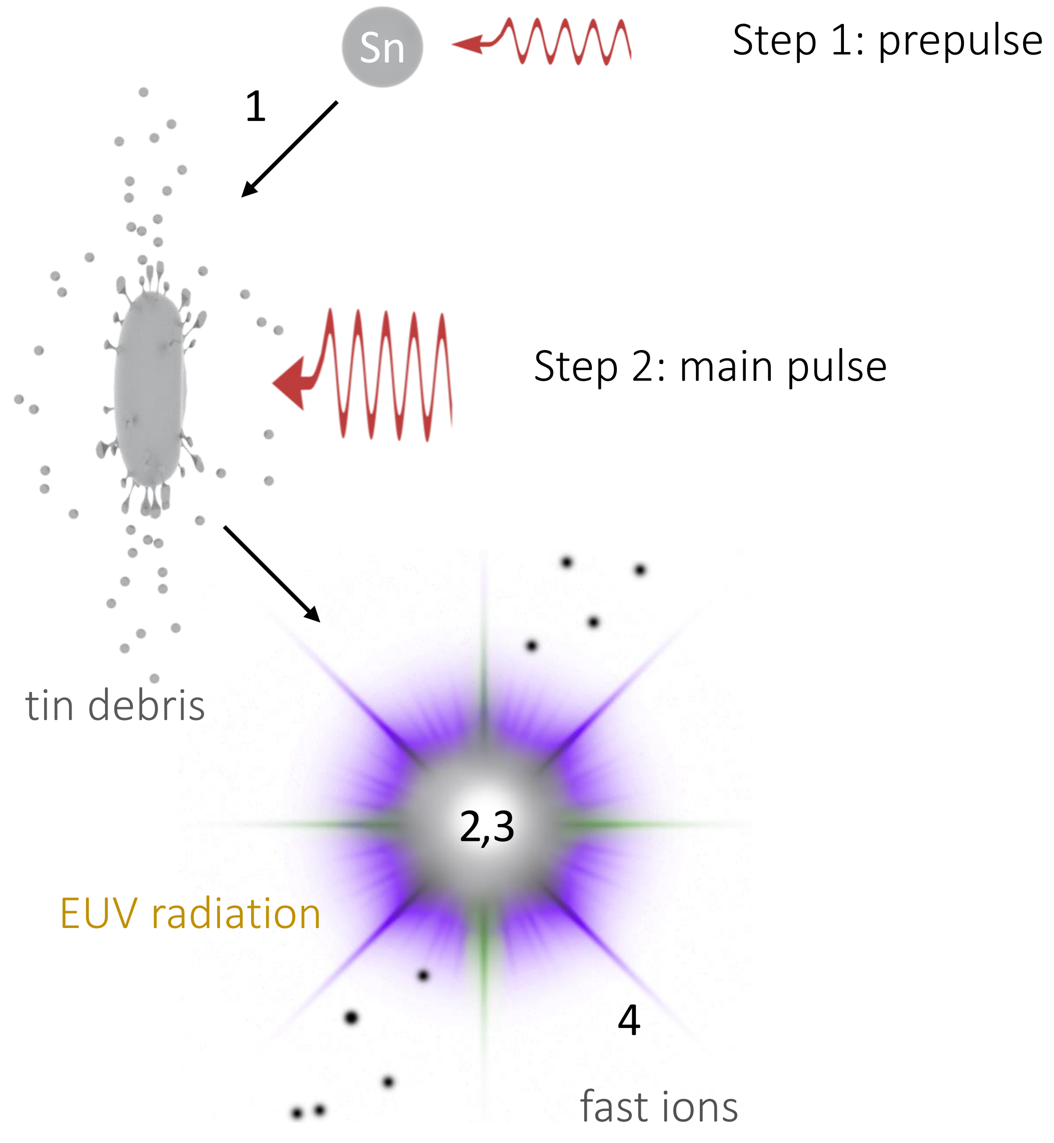

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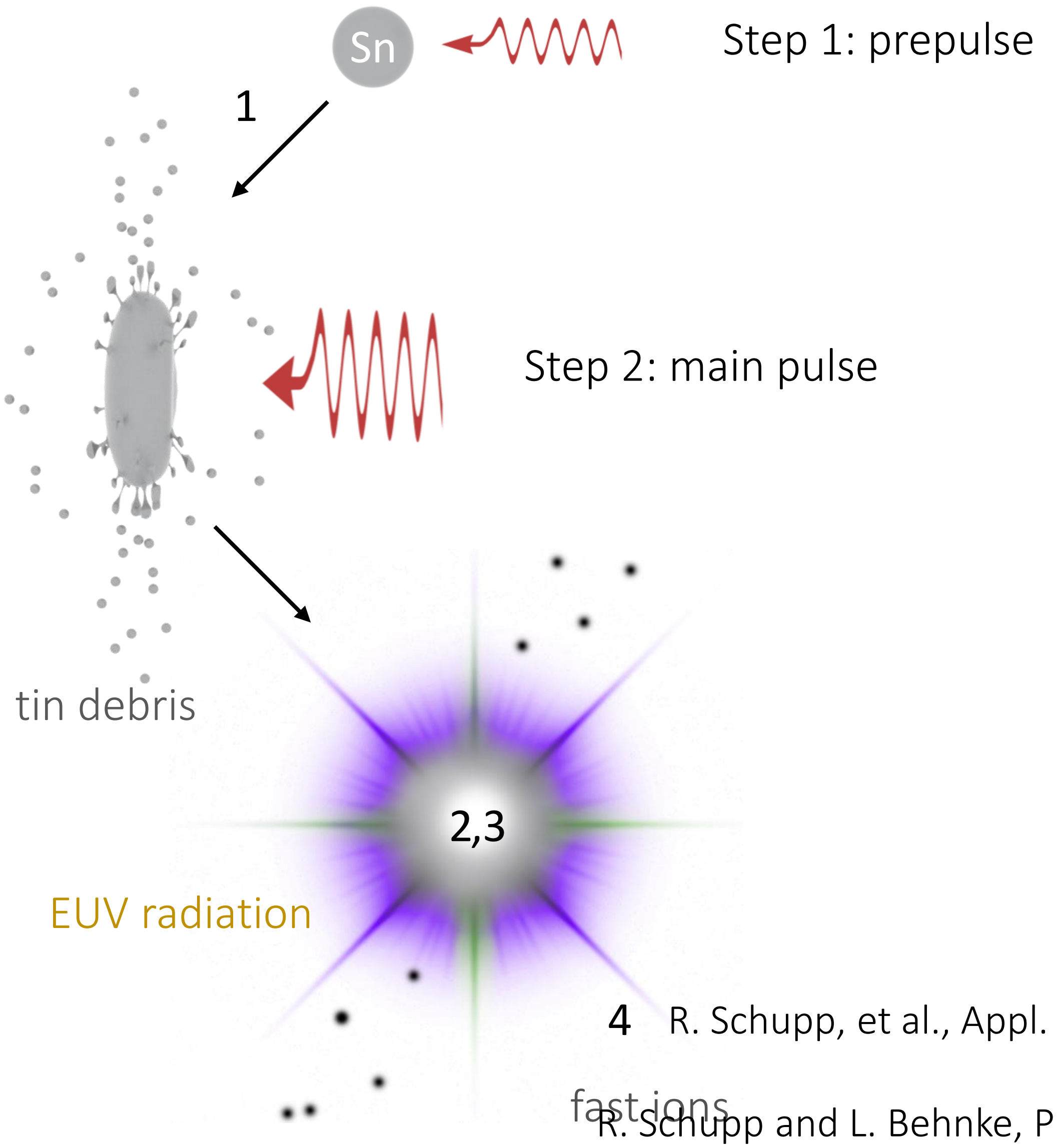

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O.O. Versolato, Plasma Sources Sci. Technol. **28**, 083001 (2019);
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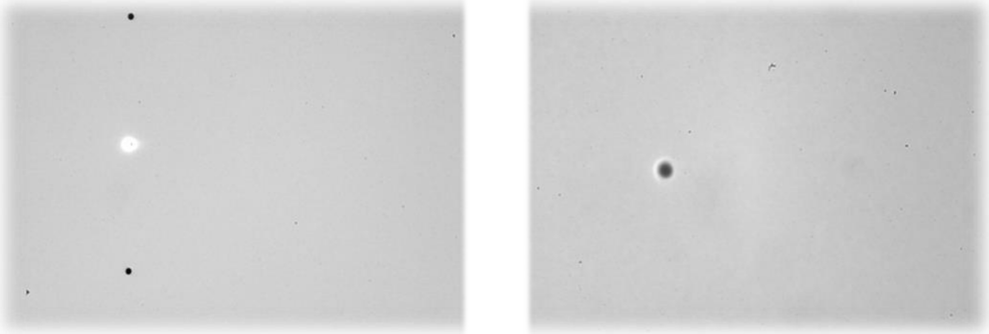
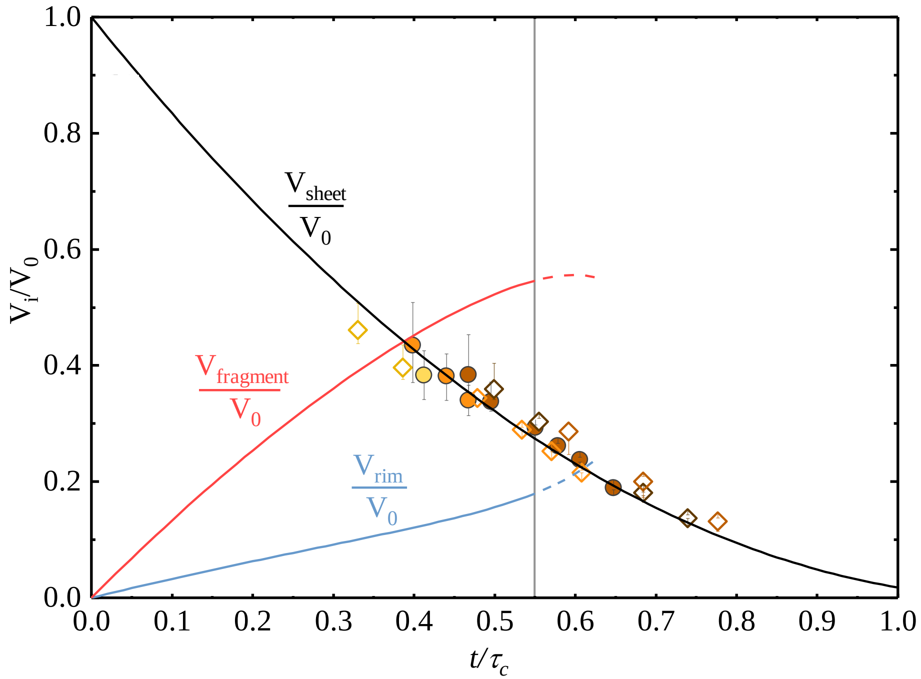
F. Torretti, et al., J. Phys. D. **53**, 055204 (2019);
R. Schupp and L. Behnke, Phys. Rev. Res. **3**, 013294 (2021), L. Behnke and R. Schupp, Opt. Express **29**, 4475 (2021)

ARCNL Source Research: highlights





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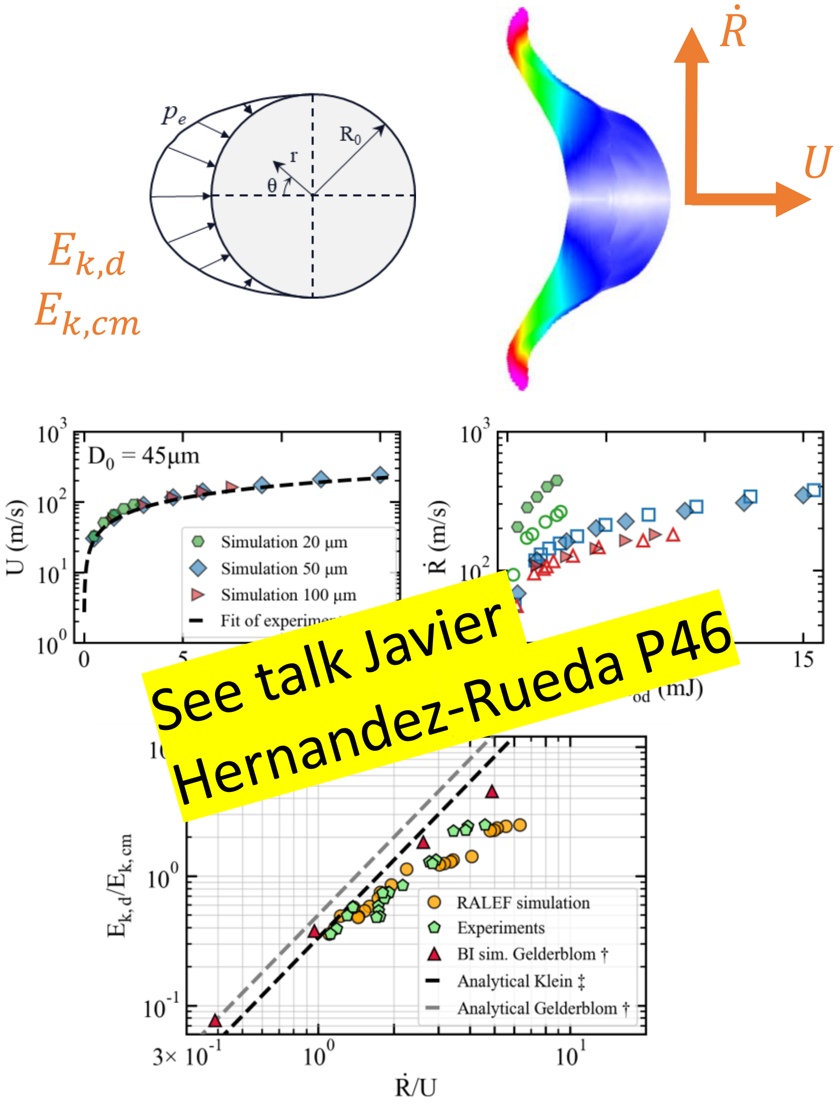

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J. Hernandez-Rueda, in preparation; H. Gelderblom, J. Fluid. Mech. **794**, 676 (2016)

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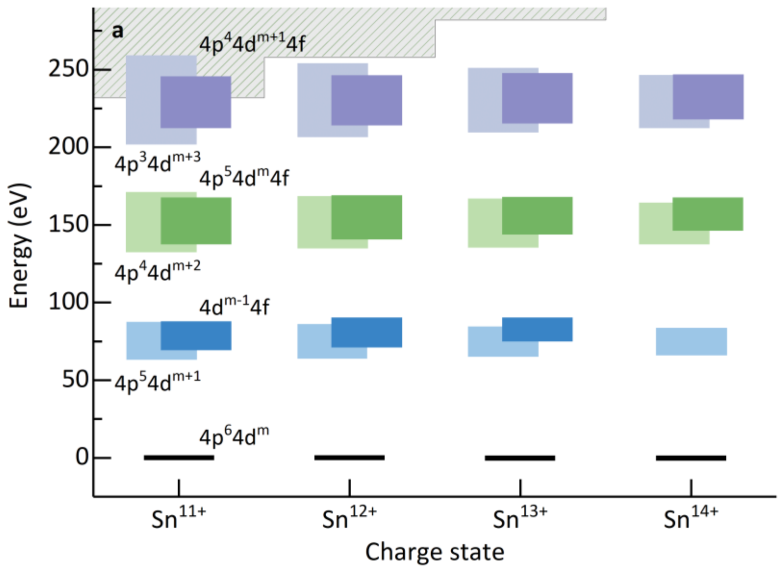

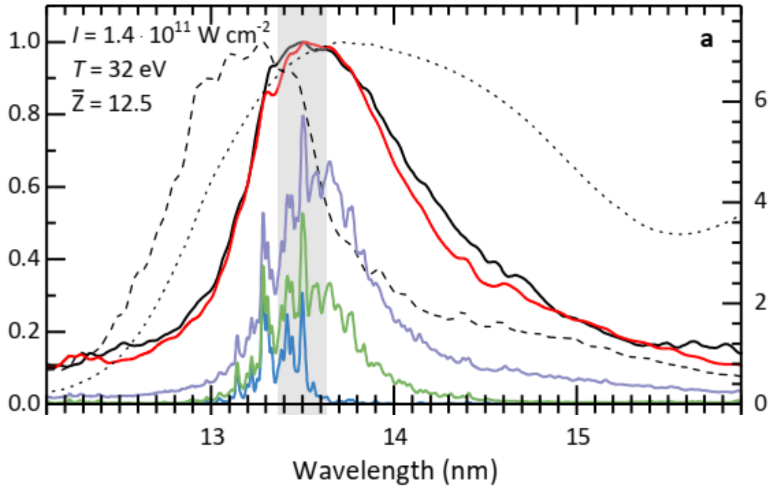

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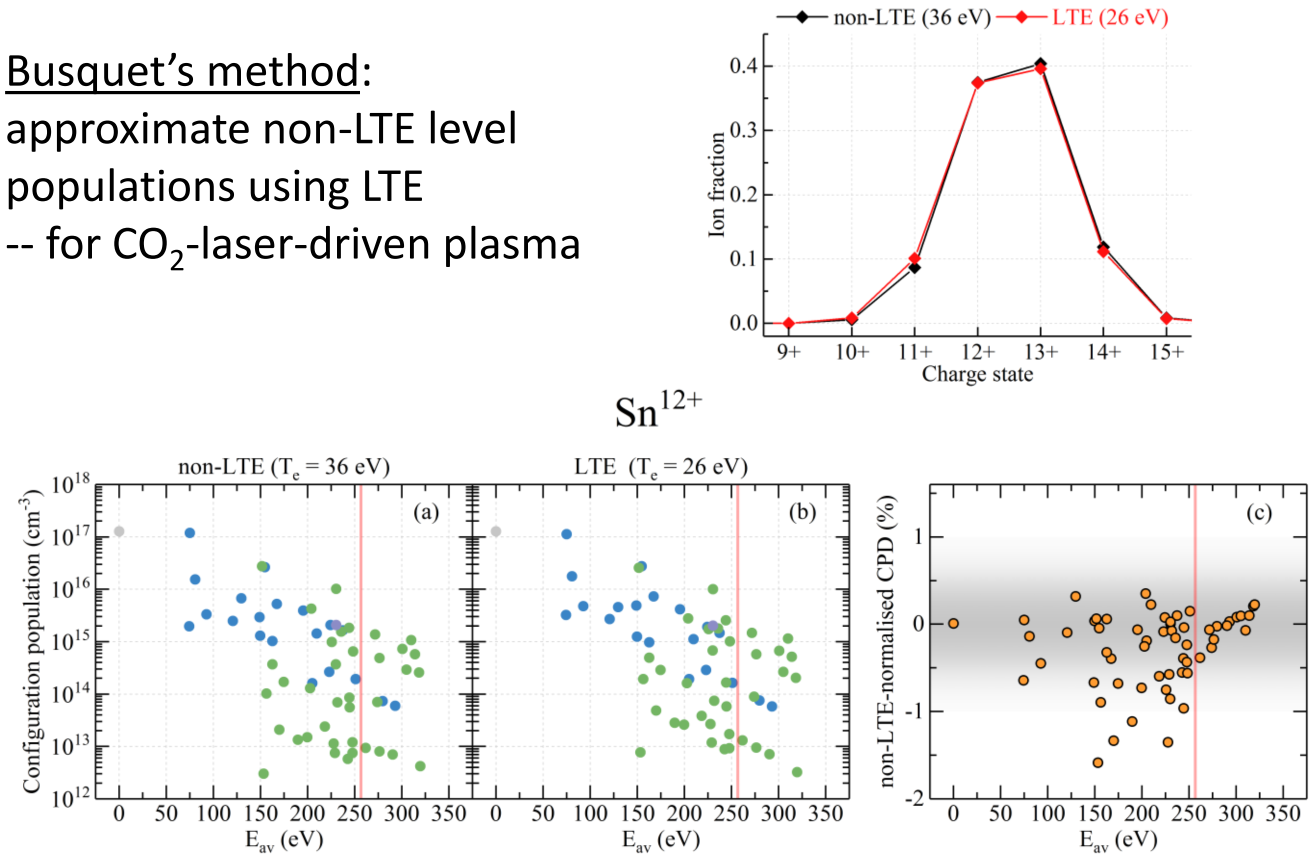
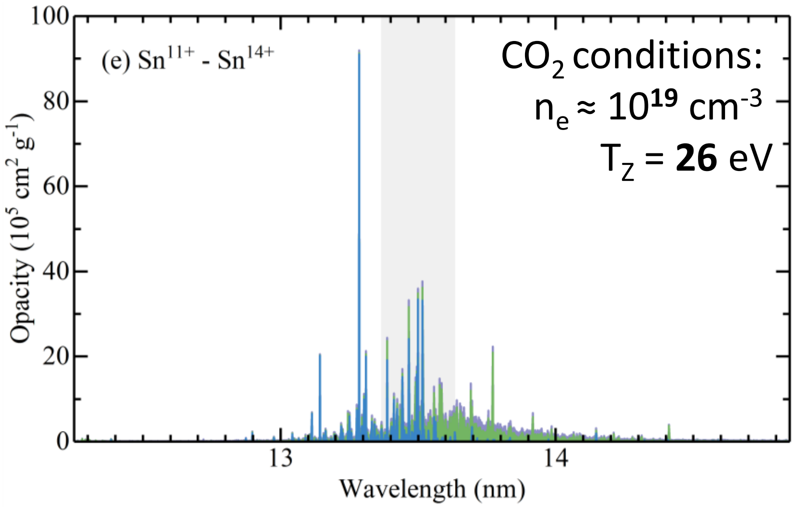
J. Sheil, et al., J. Phys. B. **54**, 035002 (2021)

What emits that EUV light?

<u>Busquet's method</u>:
approximate non-LTE level populations using LTE
-- for CO_2-laser-driven plasma





CO_2 conditions:
$n_e \approx 10^{19}$ cm^{-3}
T_Z = **26** 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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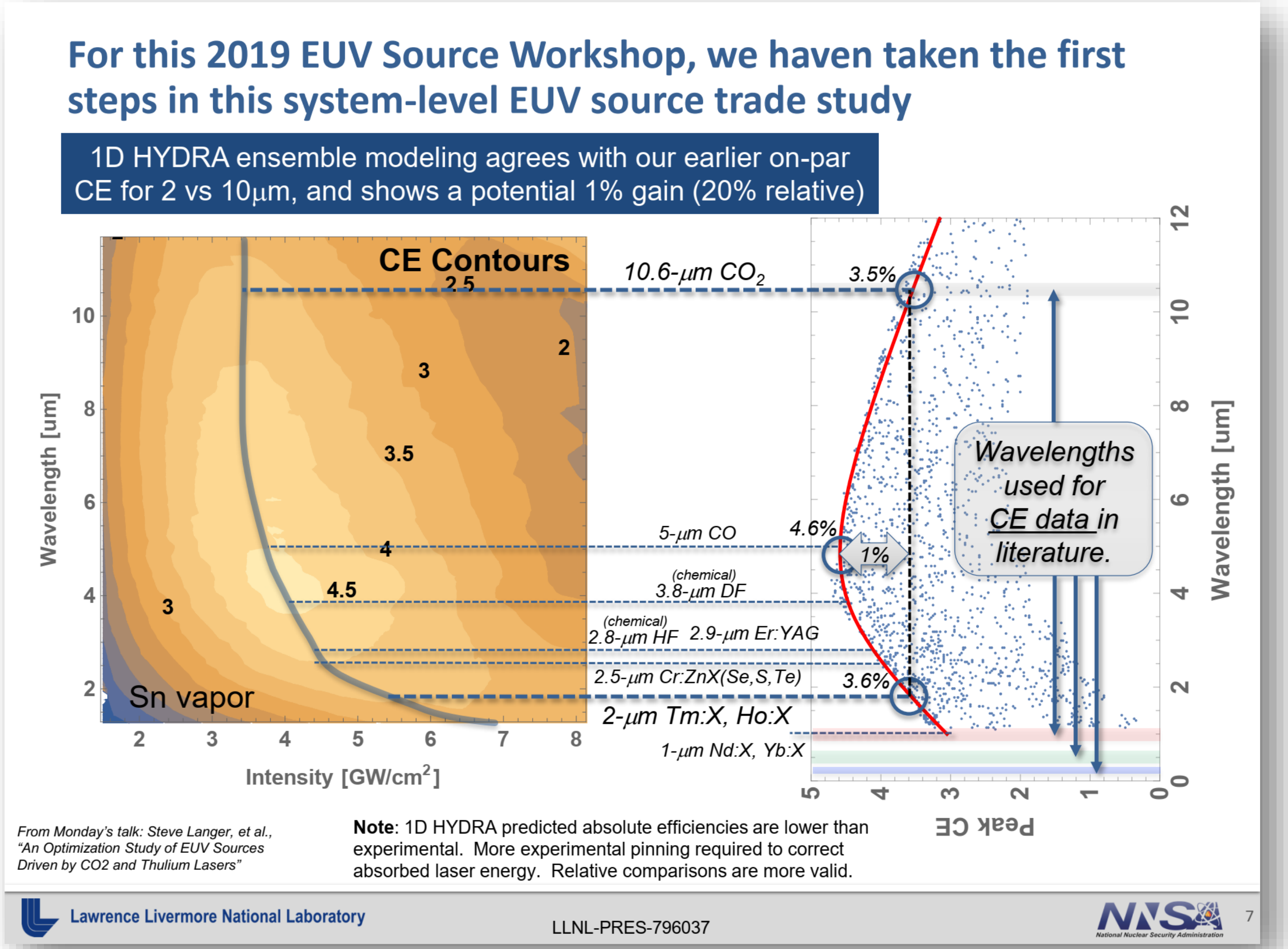
Push the fundamental limits of CE



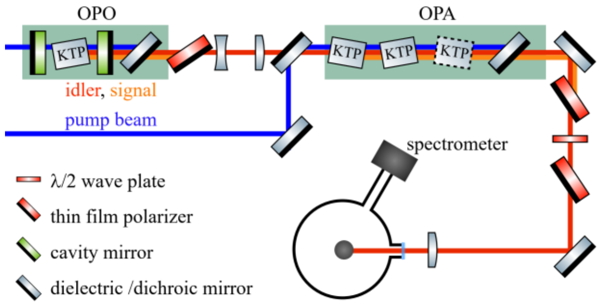
HYDRA simulations of Tm:Sn vapor ensembles depicting conversion efficiency ("absorbed energy CE") as a function of laser wavelength and intensity. Figure taken from Craig Siders' talk at the 2019 Source workshop.

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?

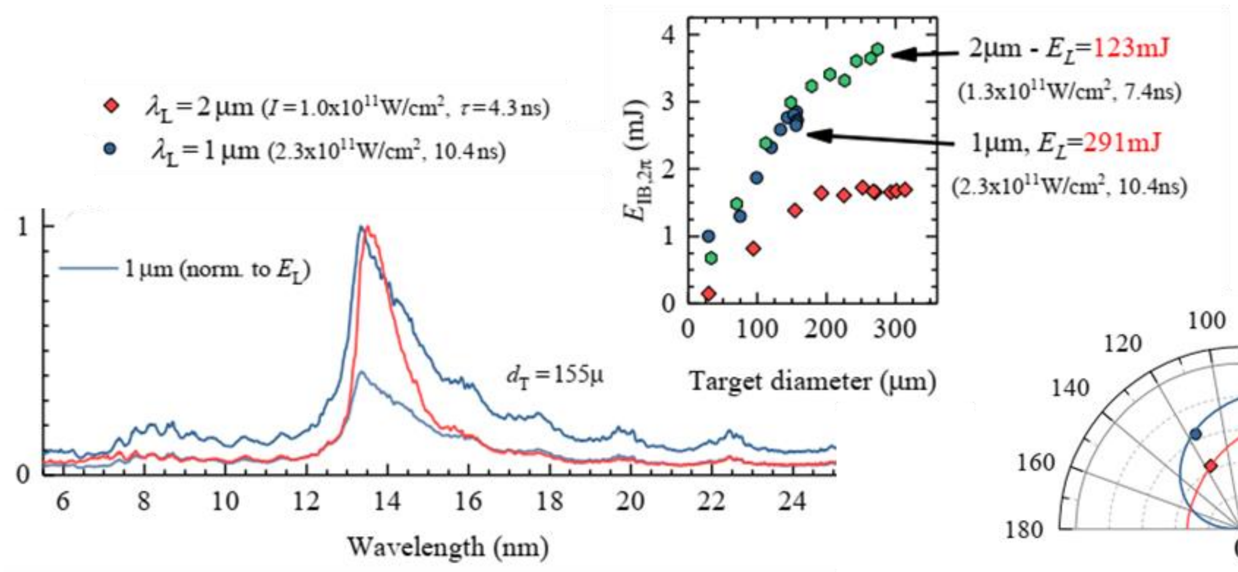
*R. Schupp, et al., Phys. Rev. Applied **12**, 014010 (2019)

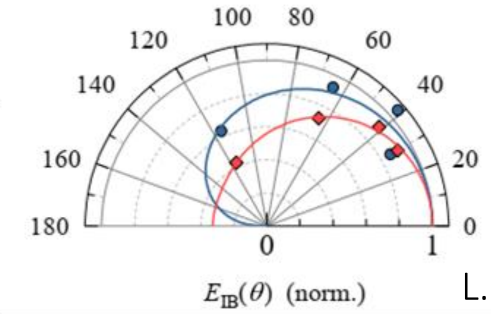


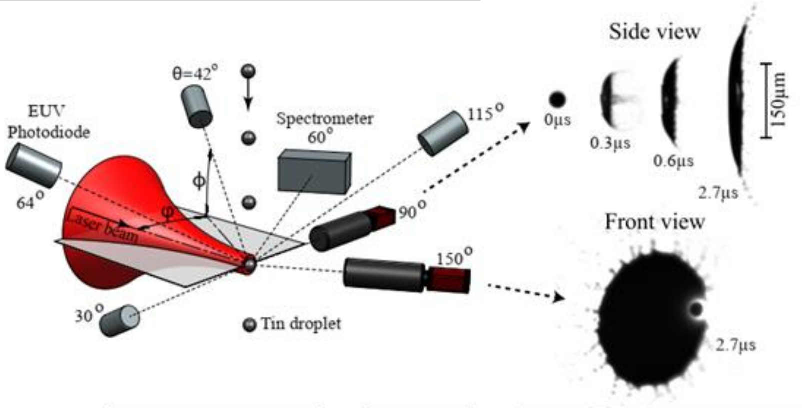
Push the limits of CE

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



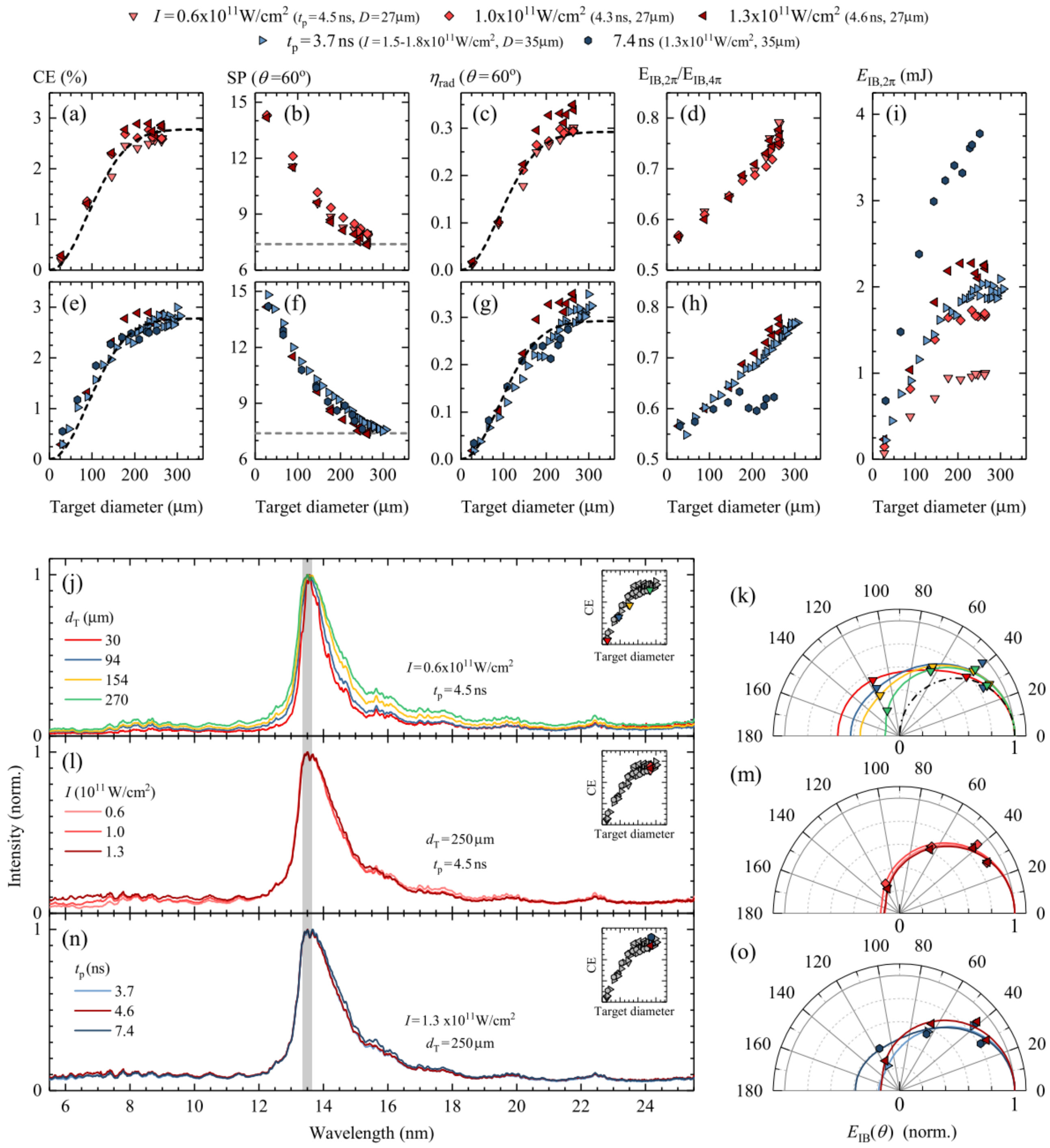




R. Schupp and L. Behnke et al, under review;
L. Behnke and R. Schupp, et al., Opt. Express **29**, 4475 (2021);
R. Schupp and L. Behnke, et al., Phys. Rev. Res. **3**, 013294 (2021)

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



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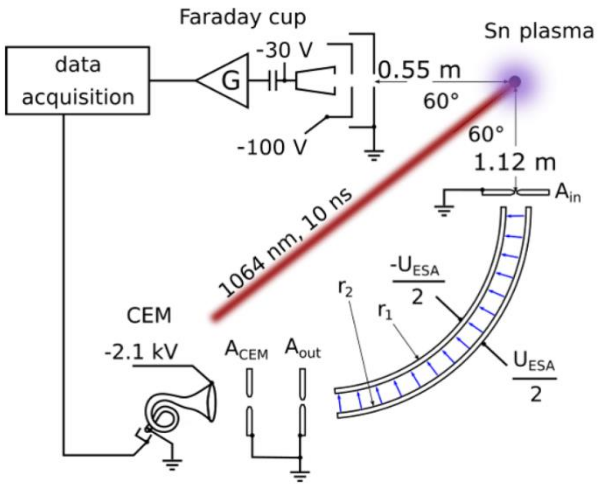
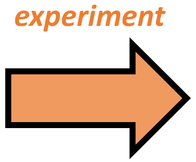
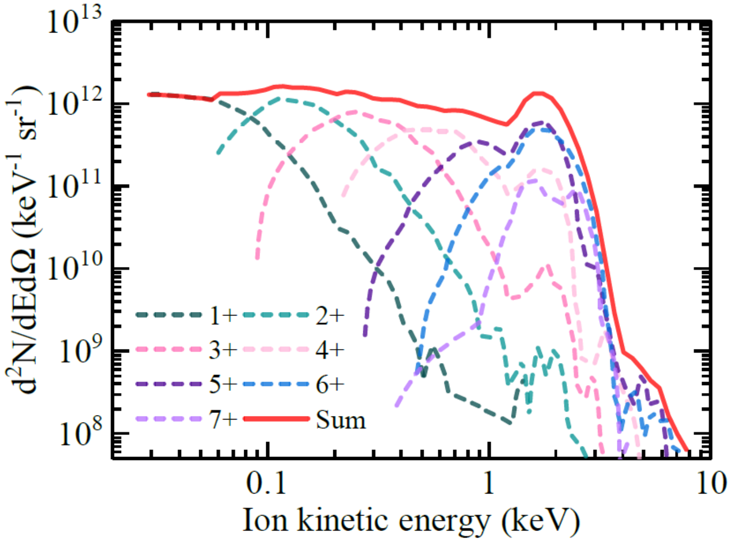






D. Hemminga and L. Poirier, et al., in preparation

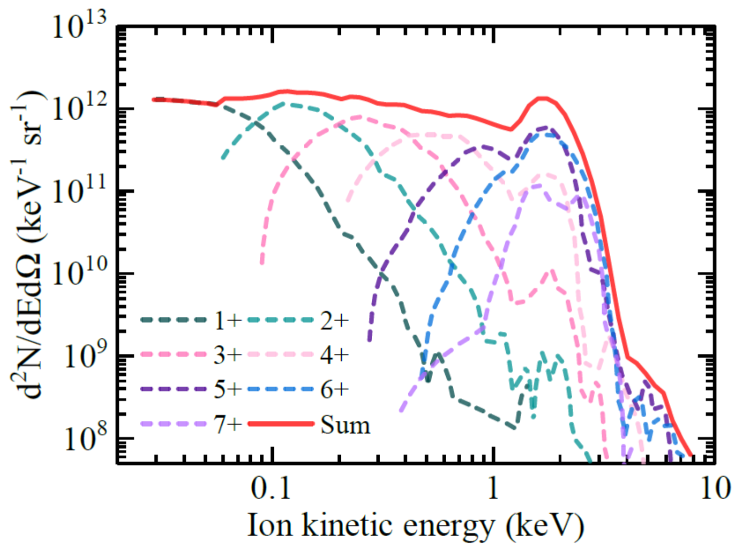
What is the cause of the ion energy distribution?

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

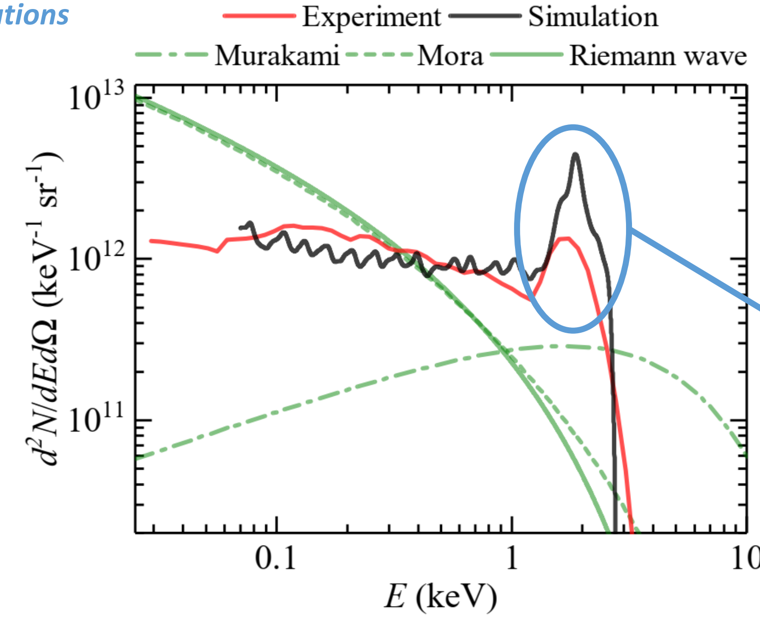
High pressure in hot, dense plasma drives expansion. For an ideal gas with moderate ionization degrees:

$$P \approx n_e k T_e = \boldsymbol{Z} n_{ion} k T_e$$

experiment



Rad hydro simulations



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

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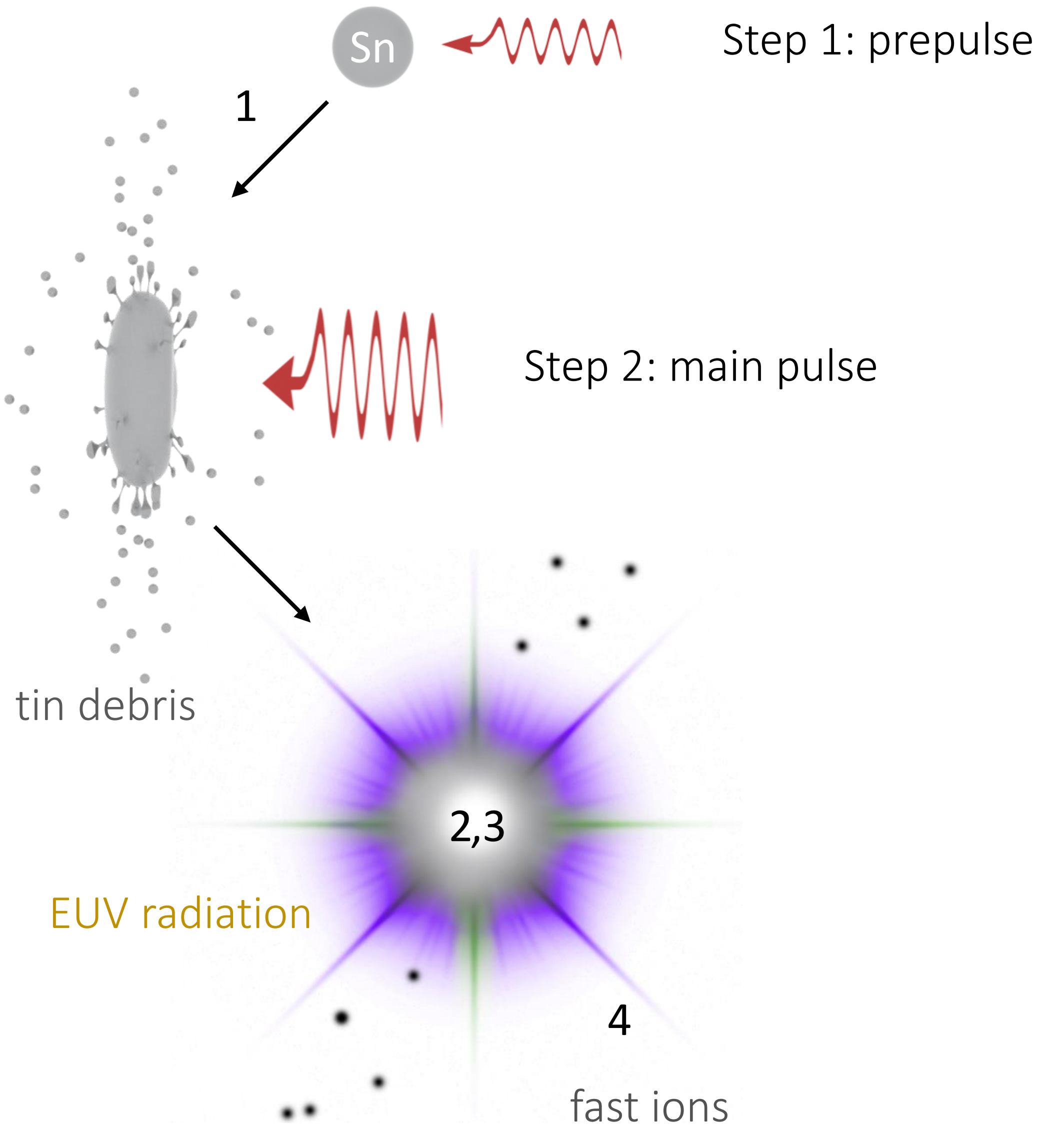

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Mutations w.r.t. last year

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)

rijksuniversiteit groningen

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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