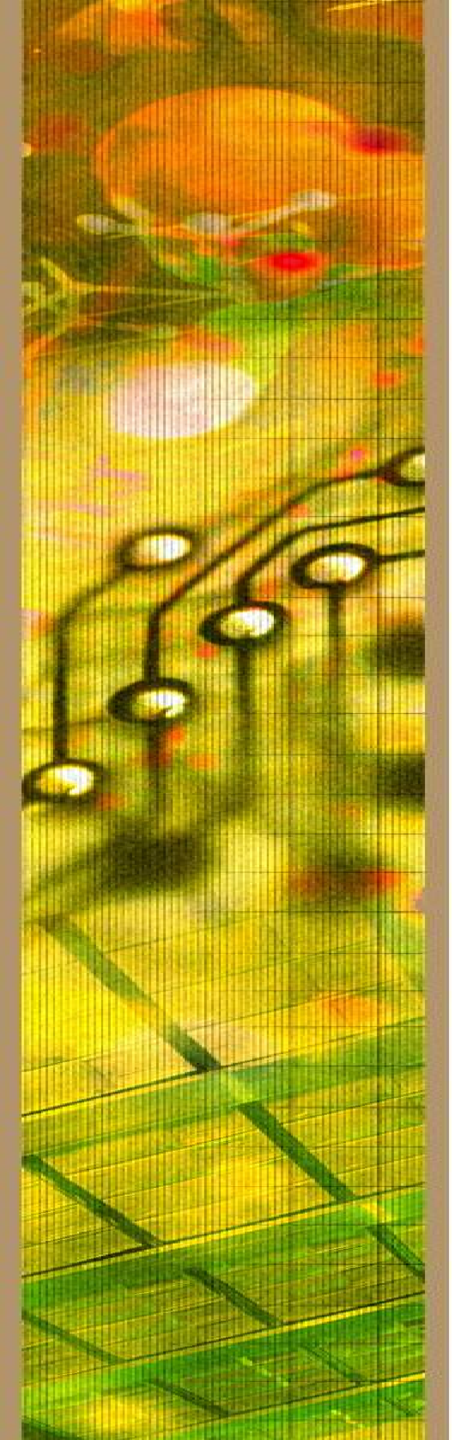


Effect of laser wavelength on EUV plasma dynamics, source efficiency, and ionic debris evolution

Tatyana Sizyuk

Center for Materials Under Extreme Environment (CMUXE)
School of Nuclear Engineering, Purdue University, USA

EUVL Workshop
13 June 2019
LBNL Berkeley

PURDUE
UNIVERSITY

Outline

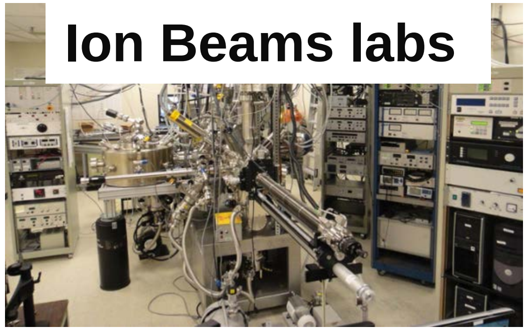
- HEIGHTS Simulation Package for EUV Lithography
- CMUXE Experiments for Source Optimization
- Effects of Laser Parameters on Source Performance
- The Effects on the Resulting Ion Kinetic Energies
- Summary & Conclusions

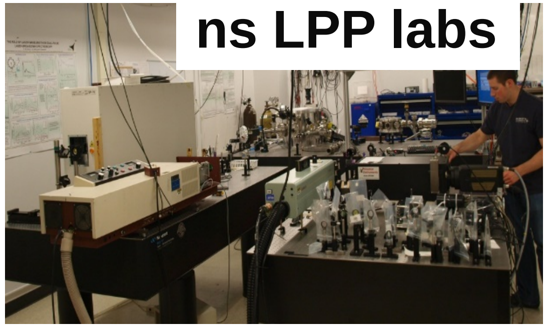
Combining State-of- the Art Modeling & Experiments

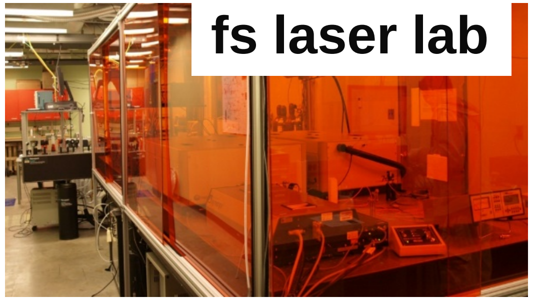
Center for Materials Under Extreme Environment (CMUXE)

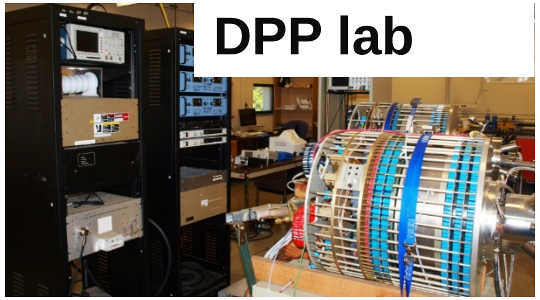
High Energy Interaction with General Heterogeneous Target Systems (HEIGHTS)

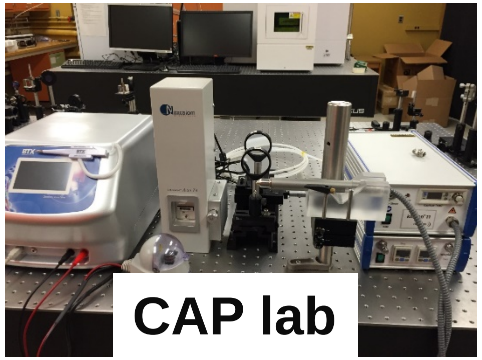
CMUXE Laboratories


Ion Beams labs

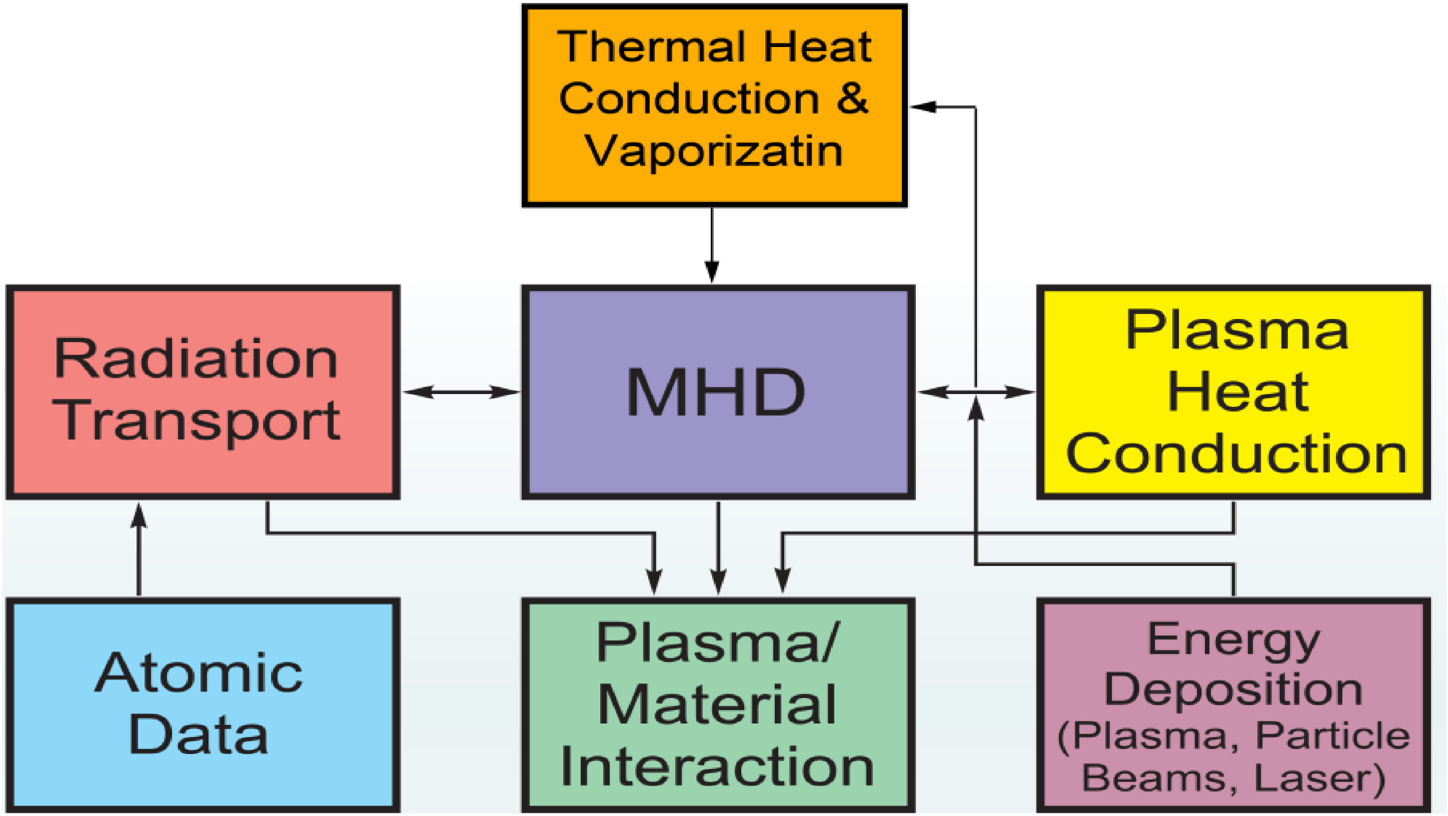

ns LPP labs


fs laser lab


DPP lab


CAP lab

HEIGHTS: Integrated Full 3-D Simulation Package



- Excellent agreement with various worldwide applications/devices
- In-house benchmarking as well with CMUXE experiments
- Very flexible to solve new problems/designs and challenges

HEIGHTS Simulation Package is Fully 3D

- ❑ **3D Monte Carlo models for laser deposition/absorption in solid, liquid, vapor, and plasma**
- ❑ **3D MHD target evolution for various geometries**
- ❑ **3D heat conduction in target; 3D heat conduction in plasma**
- ❑ **3D Monte Carlo and Gaussian quadrature models for radiation transport**
- ❑ **Moving boundaries with receding surfaces in 3D geometry**
- ❑ **Parallelized version of HEIGHTS based on MPI**

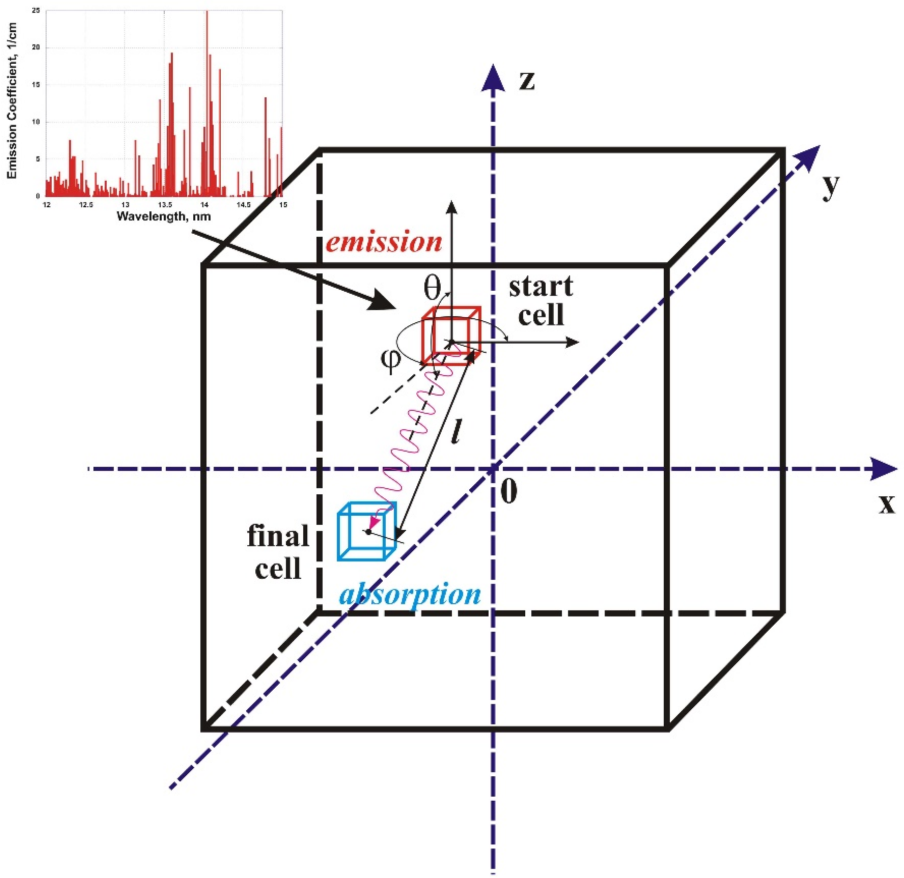
Monte Carlo Radiation Transport

Emission

$$N_{emi} = \int_{E_{\min}}^{E_{\max}} \frac{k_{emi}(E,\rho)}{\hbar^3\pi^2c^2}\frac{E^2}{e^{E/T}-1}dE$$

Absorption

$$N(E,L) = N_{emi}(E)\,e^{-\int_0^L k_{abs}(E,l)dl}$$



N_{emi} – number of emitted photons; $[E_{\min}, E_{\max}]$ – energy range;

E – photon energy; T, ρ – temperature and density of the plasma;

κ_{emi}, κ_{abs} – emission and absorption coefficients;

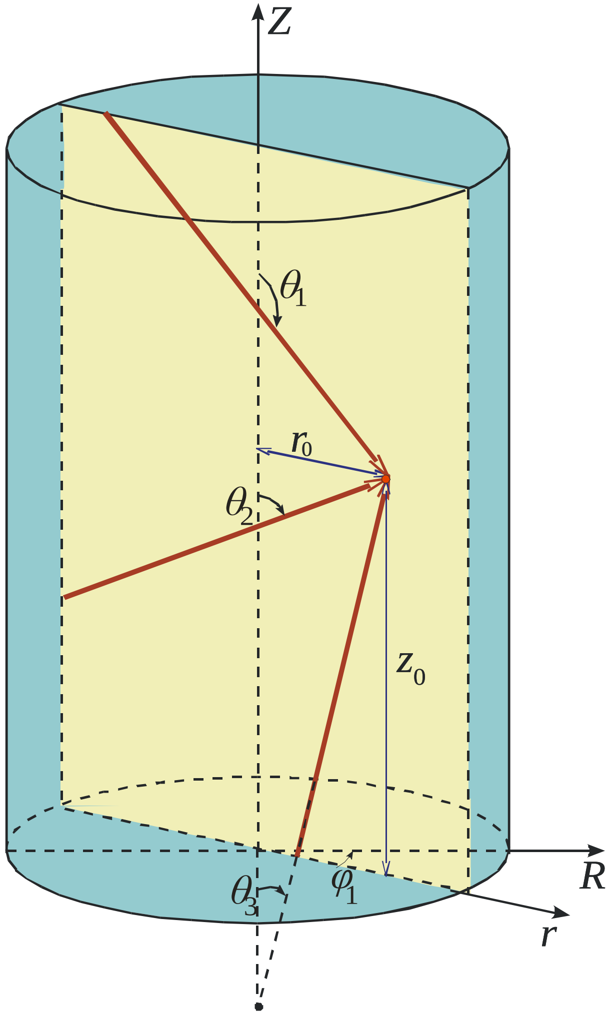
$\hbar$ – Plank constant, c – speed of light, L – photon absorption length.

Gaussian Quadrature Integration for Radiation Transport

- **Specified Directions, Spanning Total Solid Angle**
- **High-Order Gaussian Integration (up to 96×96 angles)**

$$\frac{dI_E}{dt} = \kappa_{emi} B_E - \kappa_{abs} I_E$$

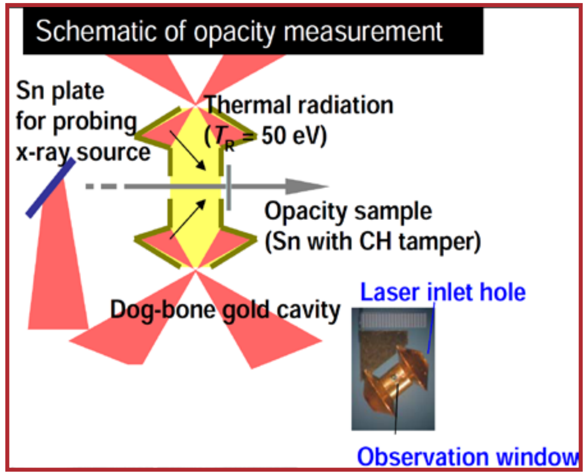
$$\mathbf{S}_{rad} = \int \left(\int_0^{2\pi} d\varphi \int_0^{\pi} I_E(\theta,\varphi)\cos\theta \sin\theta \, d\theta \right) dE$$

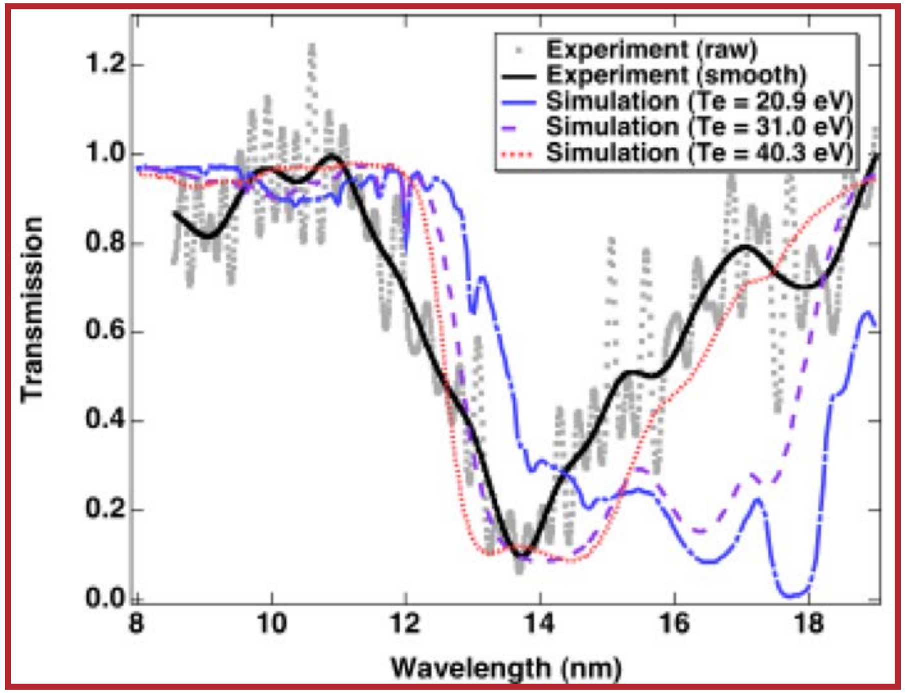


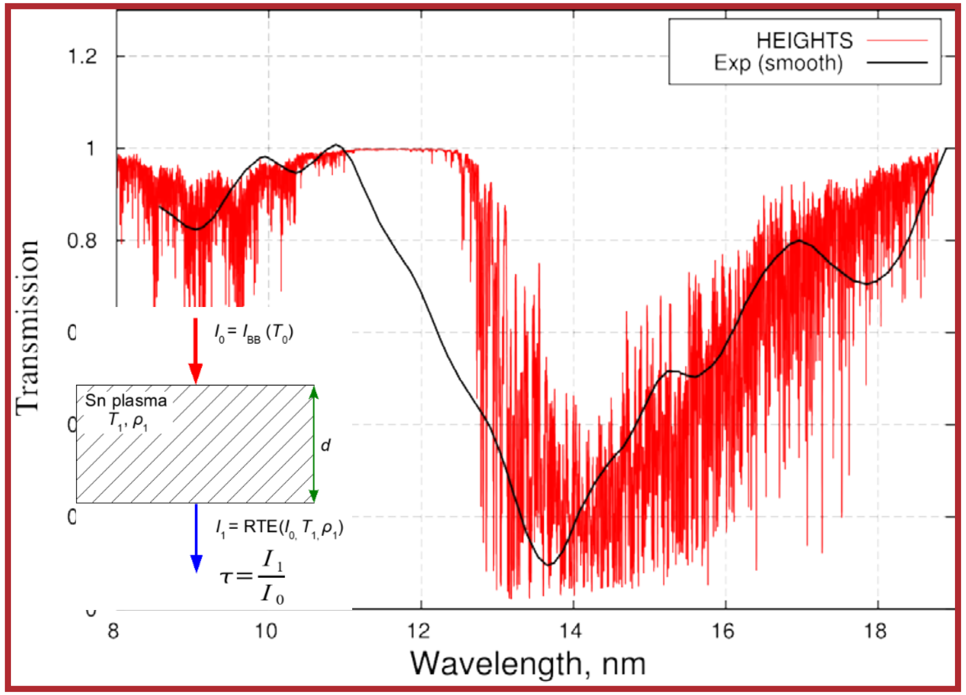
HEIGHTS-ATOM Calculation of Optical Coefficients

- Free-Free, Bound-Free, and Bound-Bound Processes:
- Populations and Ion Compositions by CRE Based on HFS, HF, and Experimental Data for Low-Z Elements
- Populations and Ion Compositions by CRE Based on HFS Splitting for High-Z Elements
- LS and Intermediate Coupling Approximations
- Radiation, Stark, Doppler, and Resonance Broadening Mechanisms with Detail Spectral Profiles
- Planck and Rosseland Group Averaging with Strong Lines Resolution
- Planck and Rosseland Group Averaging for Different Temperature Regions

Sn Transmission @ 30 eV, 0.01 g/cm^3





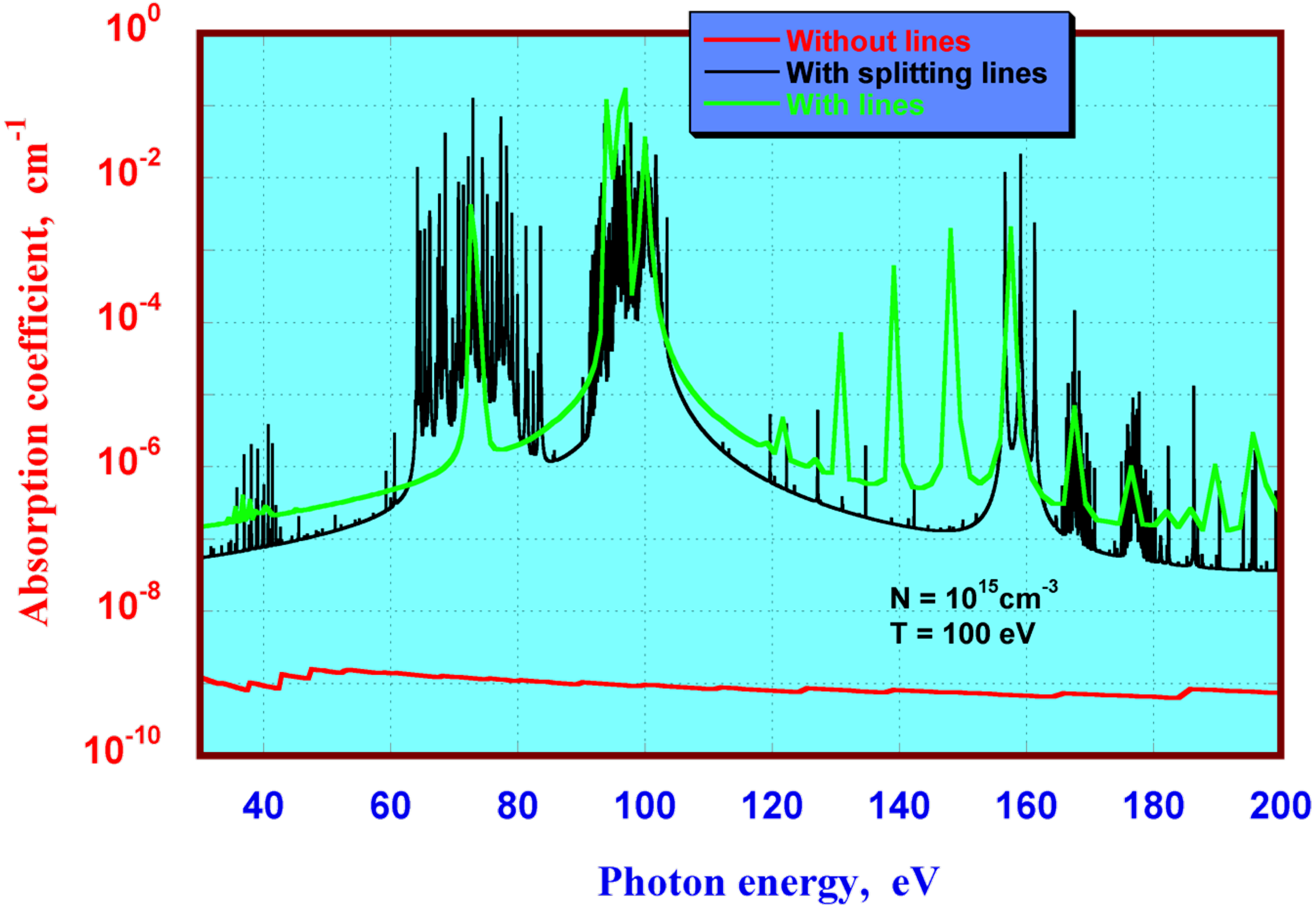


S. Fujoka et al., Phys. Rev Lett 95, 235004 (2005): Reported transmission of EUV photons through 30 eV 0.01 g/cm^3 Sn plasma.

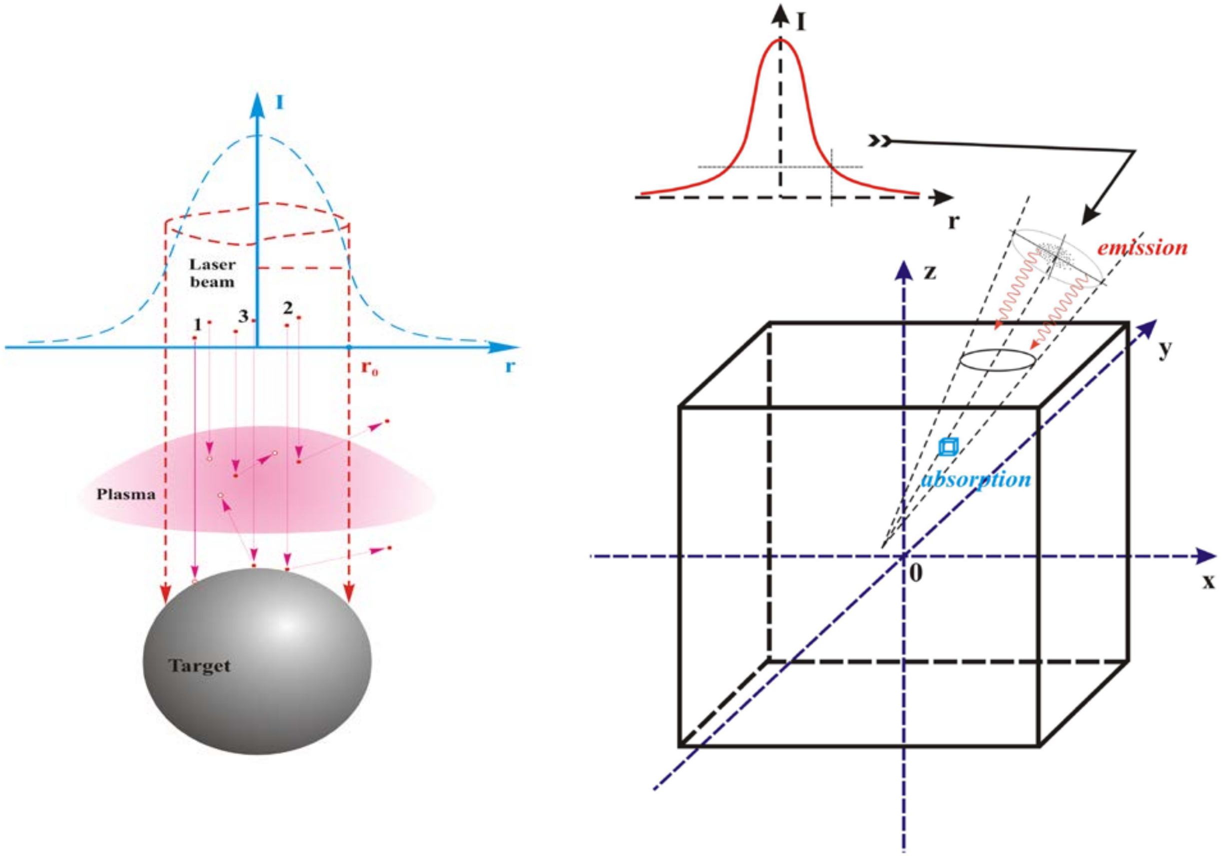
RHD simulation by the ILESTA-1D code
Opacity simulation by the HULAC code

HEIGHTS-CRE
Detail Transition Accounting
EUV photons through
30 eV 0.01 g/cm^3 Sn plasma

Importance of Detail Atomic Models: Xenon Plasma Opacities



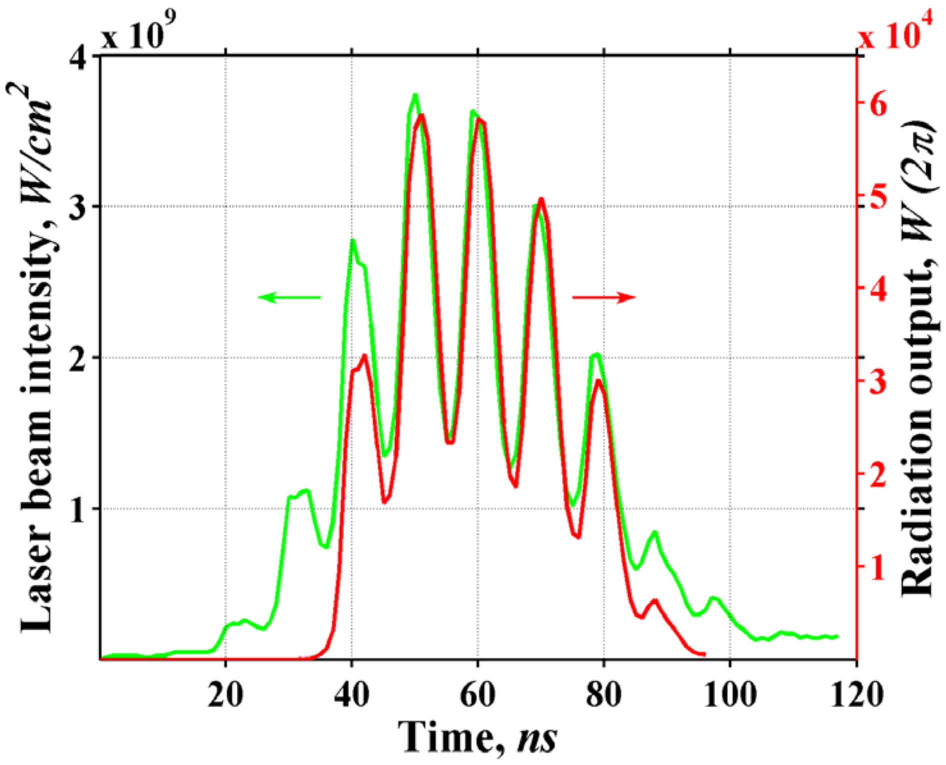
Monte Carlo Laser Absorption



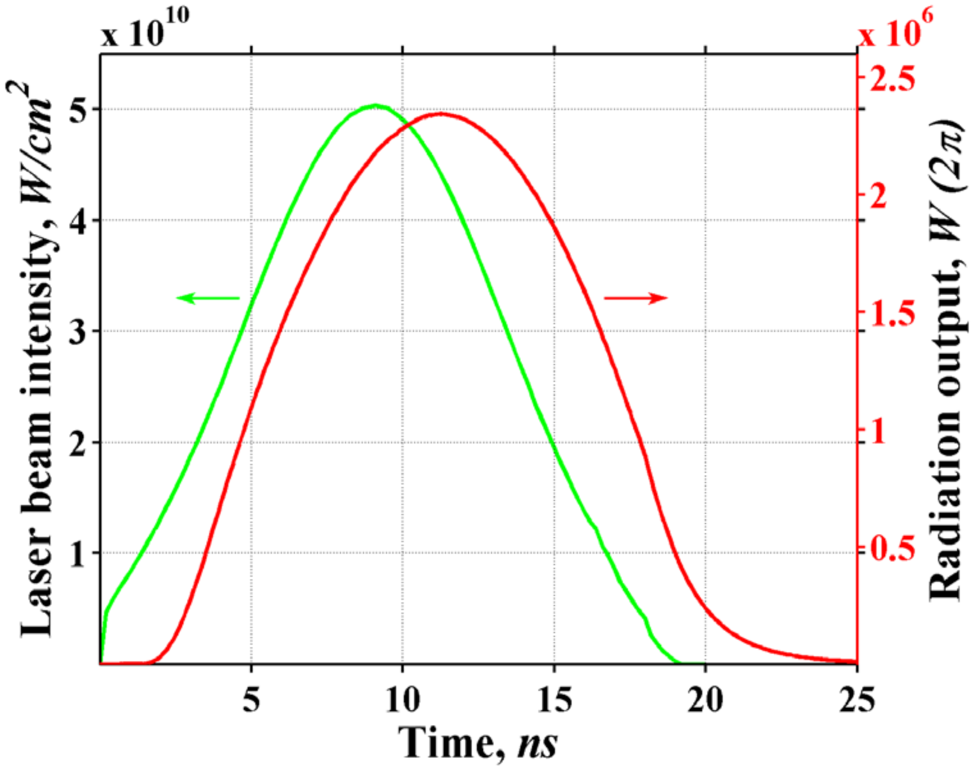
Interaction of laser energy photons with target

- Monte Carlo models in 3D
- Laser absorption, reflection, reabsorption, recycling, etc.
- Various laser beam directions
- Arbitrary distribution of laser power in time and space
- Laser beam focusing
- Capability of multiple laser sources with various configurations
- Simultaneous or time delayed laser beams

Dependence of EUV output on laser pulse temporal profile



Experimental laser beam temporal profile used in modeling and EUV radiation output for CO_2 laser

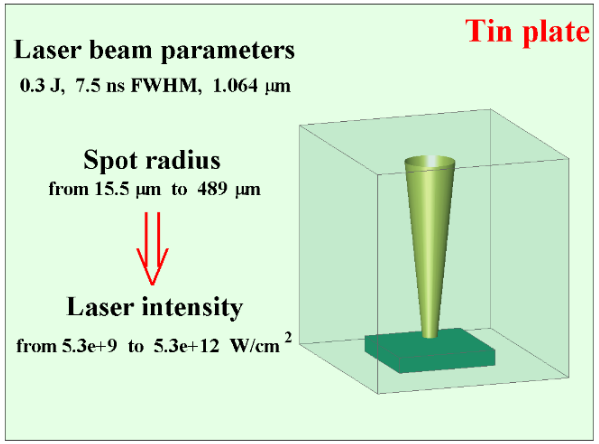


Nd:YAG laser with Gaussian temporal profile and EUV radiation output

A. Hassanein, et al., Proc. of SPIE Vol. 7636 76360A-1 2010

Benchmarking: Modeling of Sources for EUVL

Sn foil



Tin plate

Laser beam parameters

0.3 J, 7.5 ns FWHM, 1.064 μm

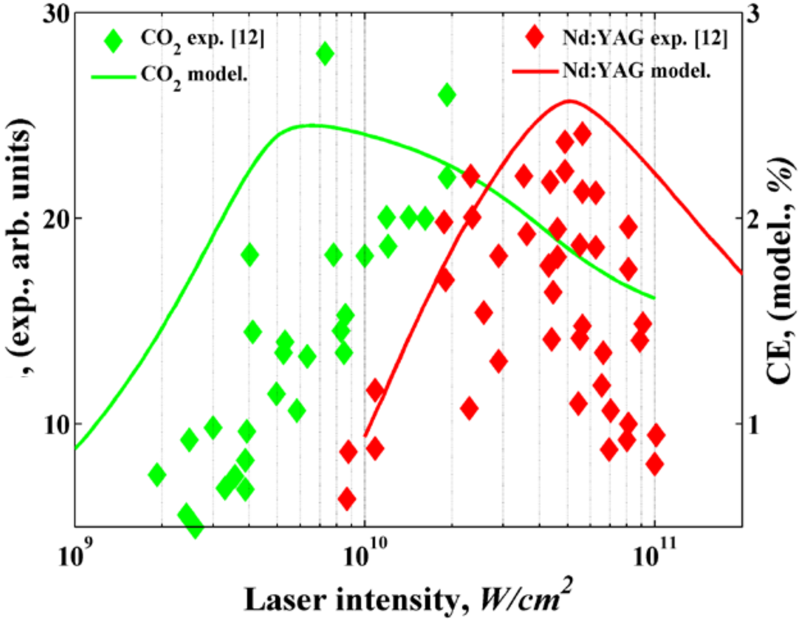
Spot radius

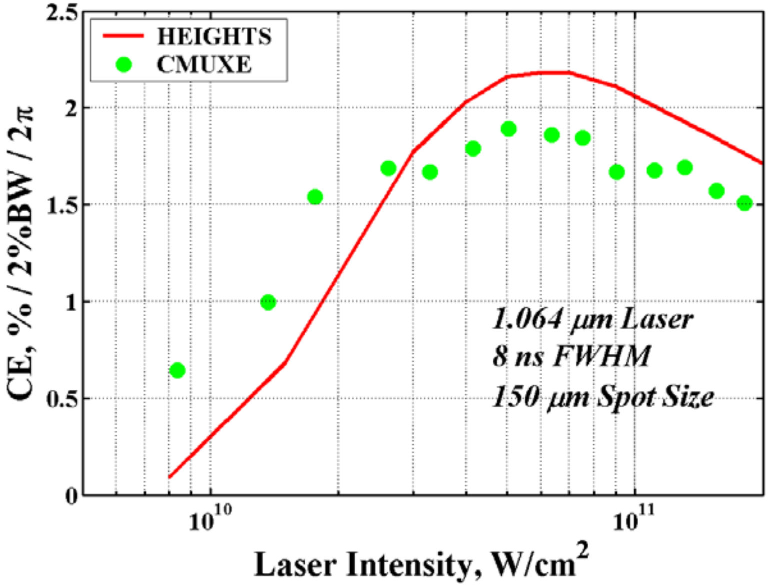
from 15.5 μm to 489 μm

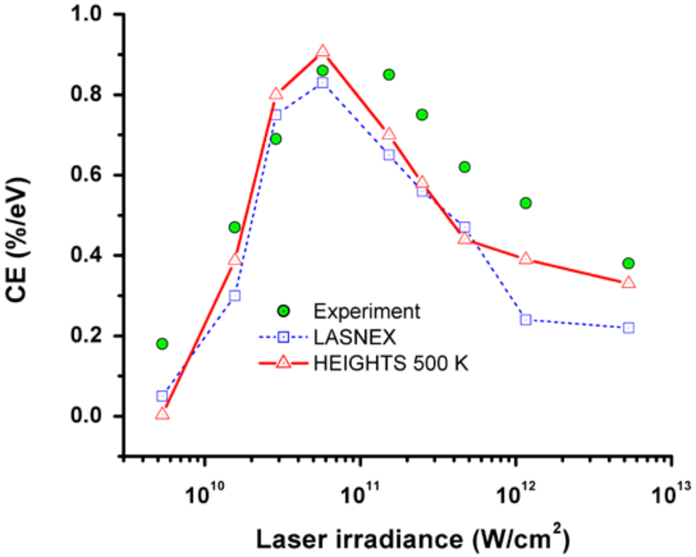
⇓

Laser intensity

from 5.3e+9 to 5.3e+12 W/cm^2







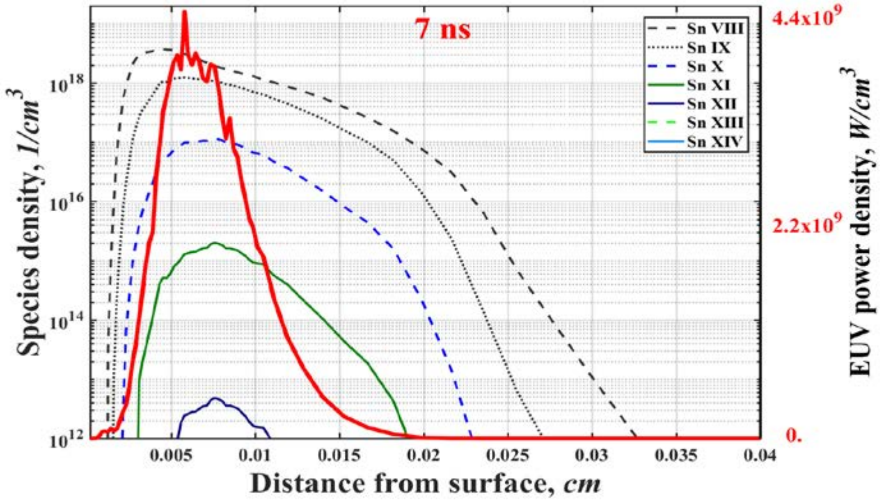
[12] H. Tanaka, et al., Appl. Phys. Lett. 87 (2005)

T. Sizyuk and A. Hassanein, Physics of Plasmas 21 (2014)

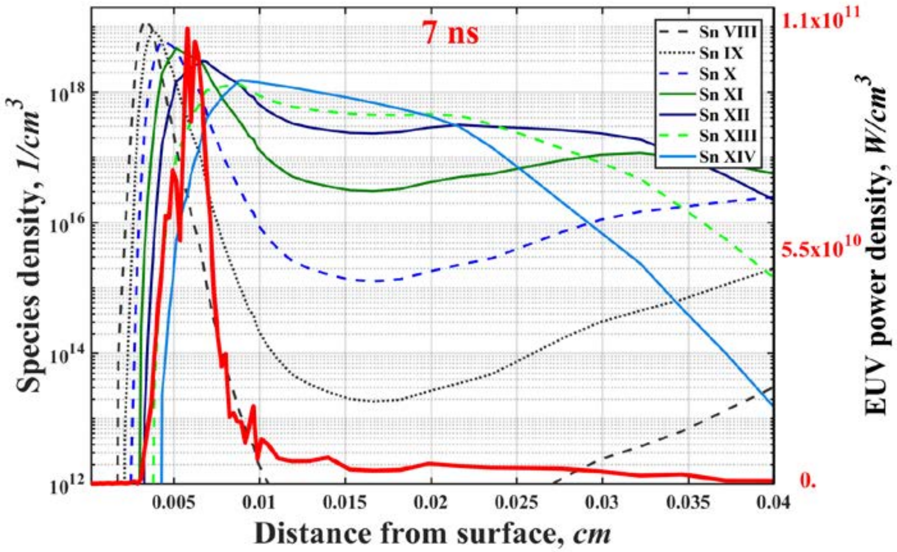
*Hassanein, A., et al., J. Micro/Nanolith. MEMS MOEMS 84, 041503 Oct–Dec 2009

*Spitzer, R.C., et al., *J. Appl. Phys.* 79, (1996) p. 2251-2258

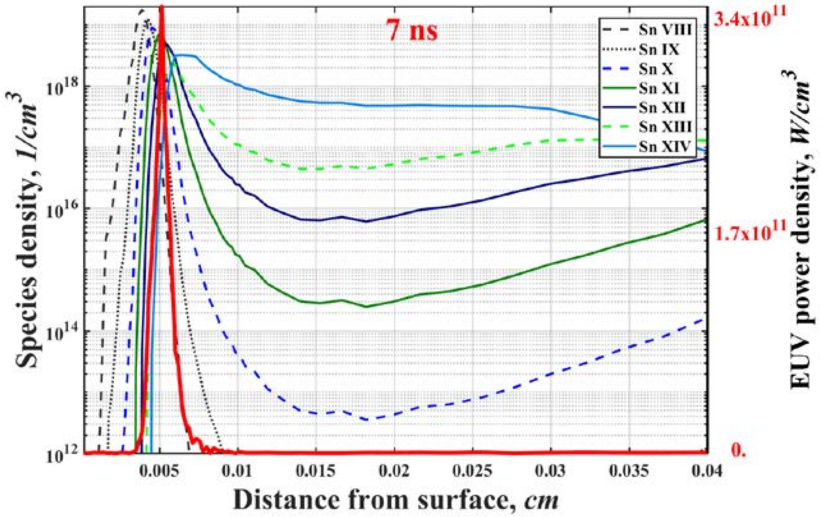
The Role of Sn^{11+} and Sn^{+12} ions in EUV Production



5x10^9 W/cm^2



2.4x10^{10} W/cm^2

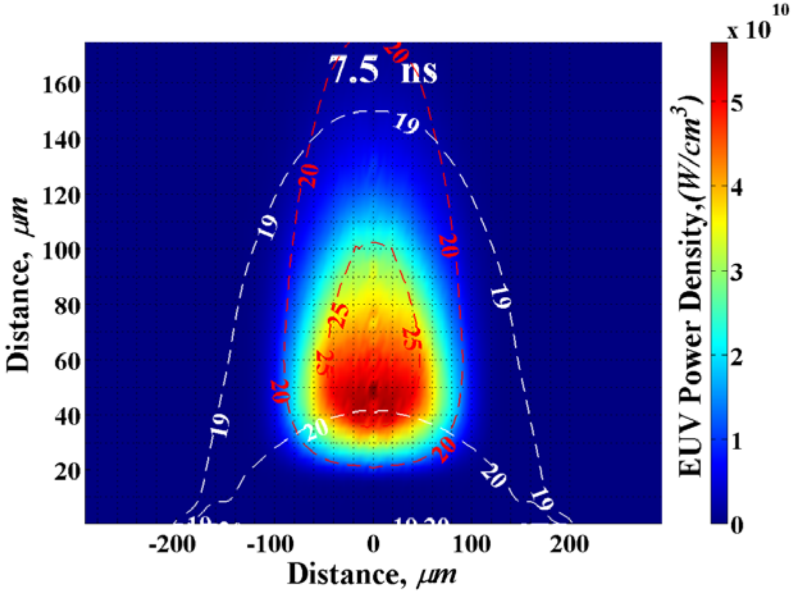


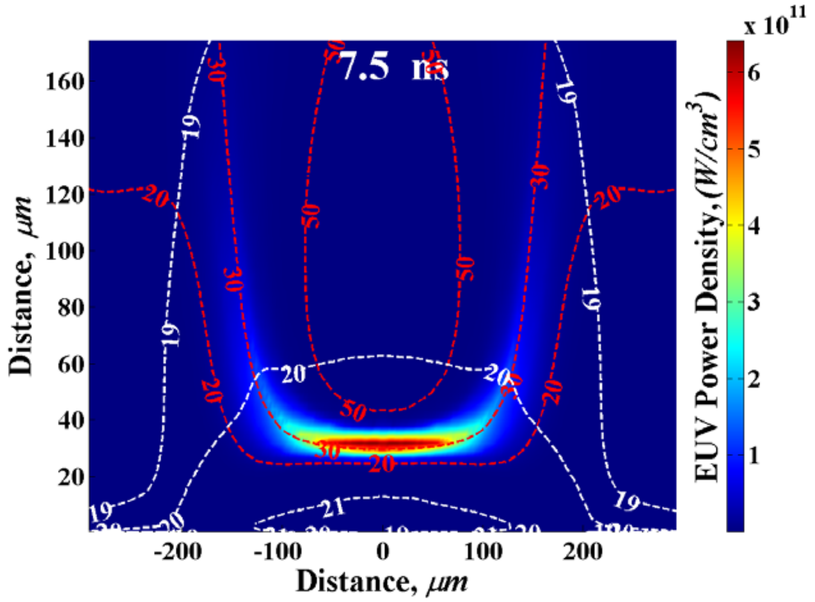
5x10^{10} W/cm^2

T. Sizyuk, Proc. of SPIE Vol. 10957, 109571A 2019

Optimization – EUV Source Location and Intensity

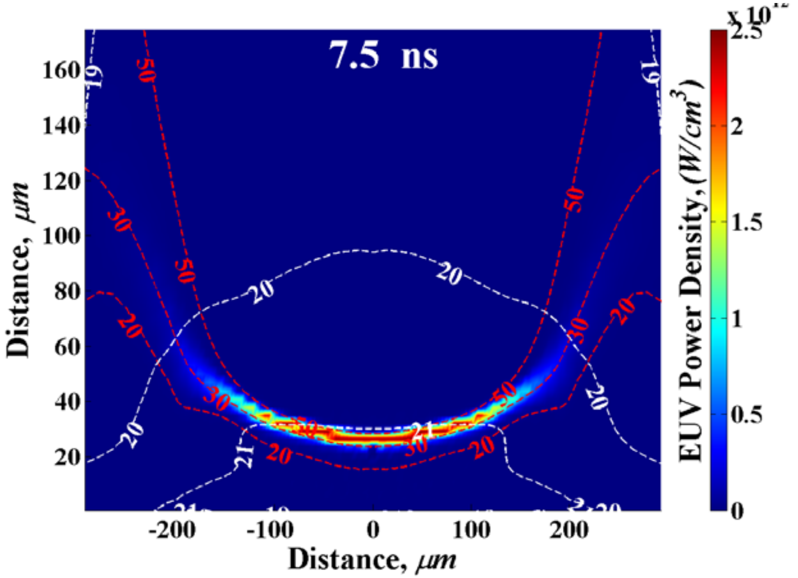
1.5×10^{10} W/cm^2

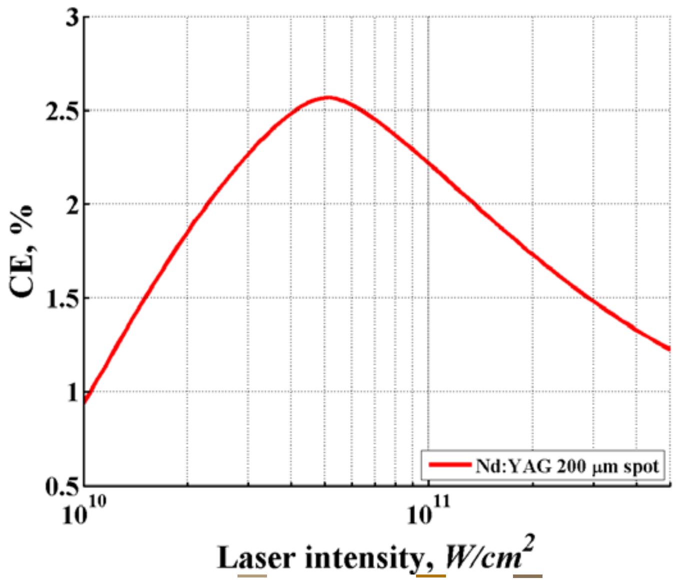




7.5×10^{10} W/cm^2

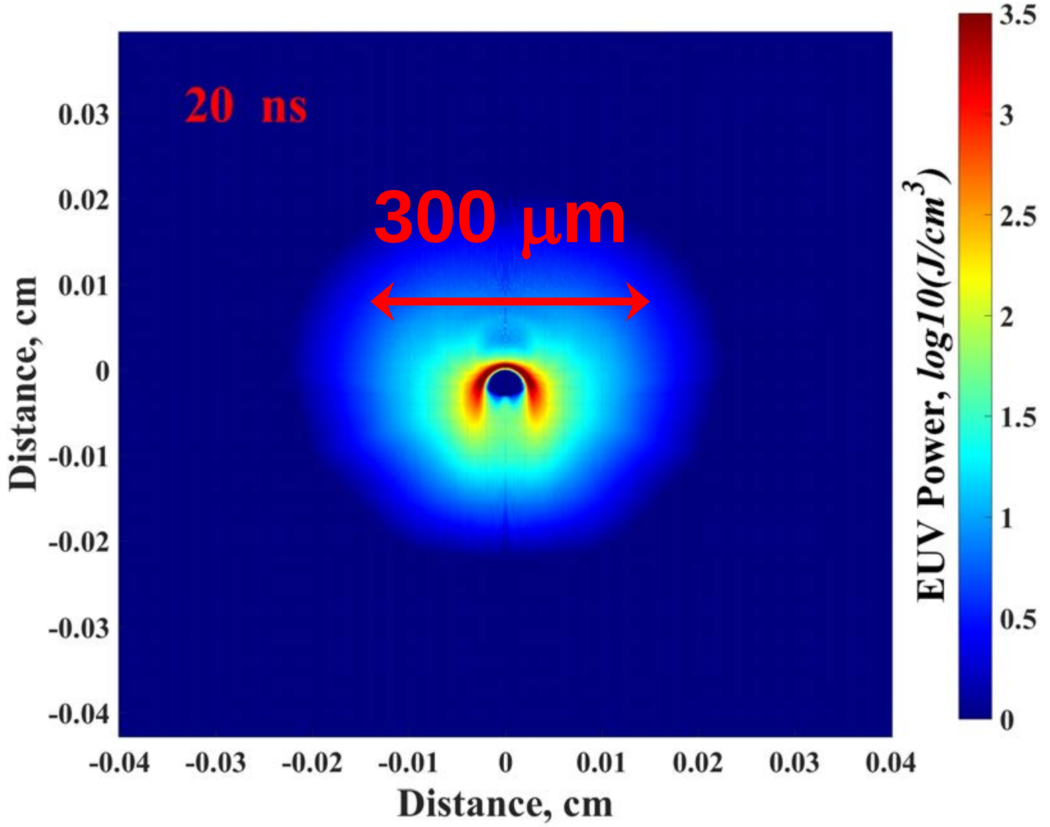
5×10^{11} W/cm^2



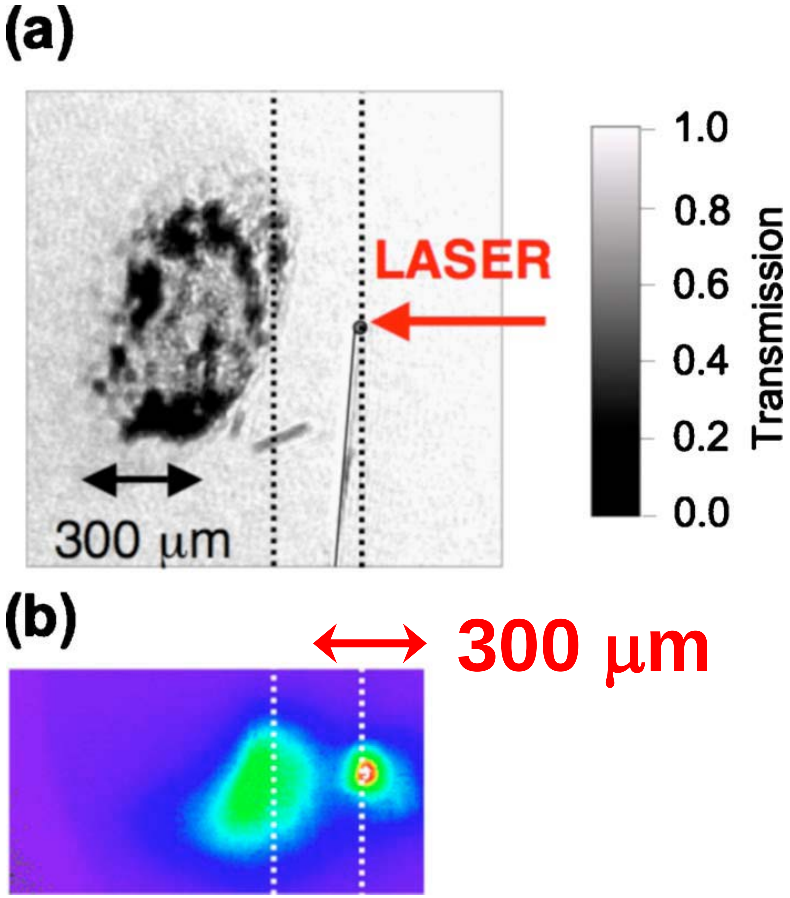


HEIGHTS Benchmarking: EUV Source Image

30 µm droplet; Nd:YAG, 1.06 µm



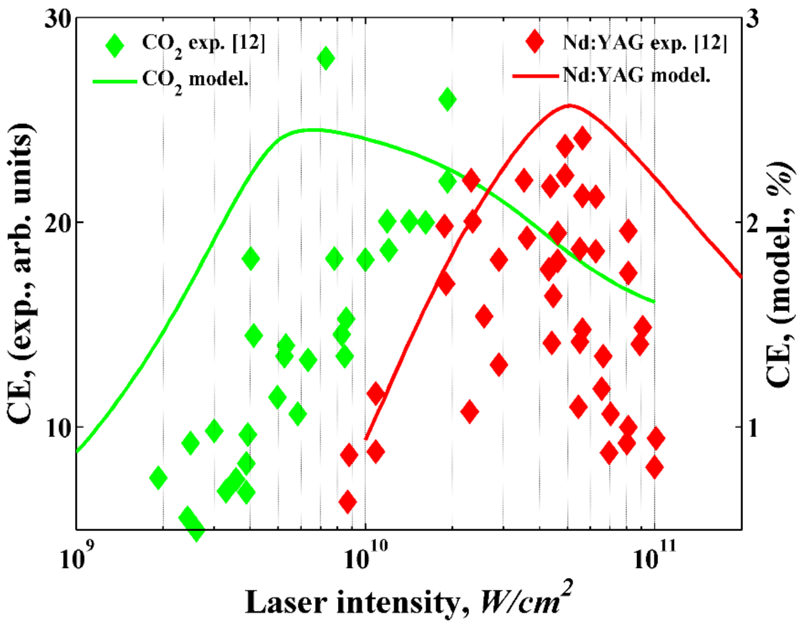
HEIGHTS Simulation



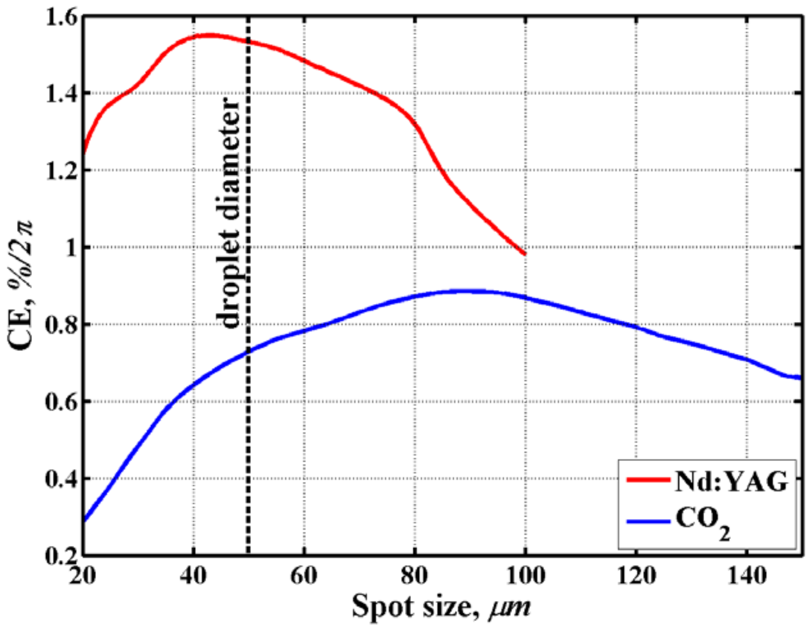
[*] S. Fujioka, et al., Applied Physics Letters 92, 241502 (2008)

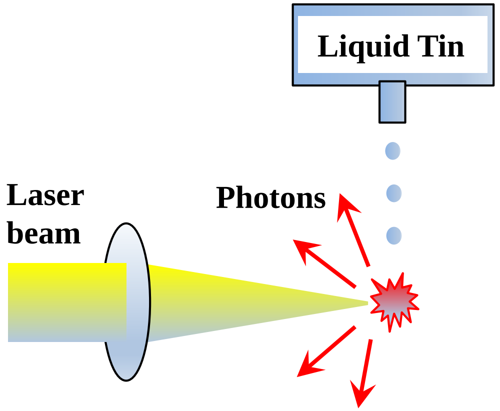
Efficiency of EUV sources from Sn: laser wavelength effects

Sn foil



50 μm Sn droplets





Liquid Tin

Laser beam

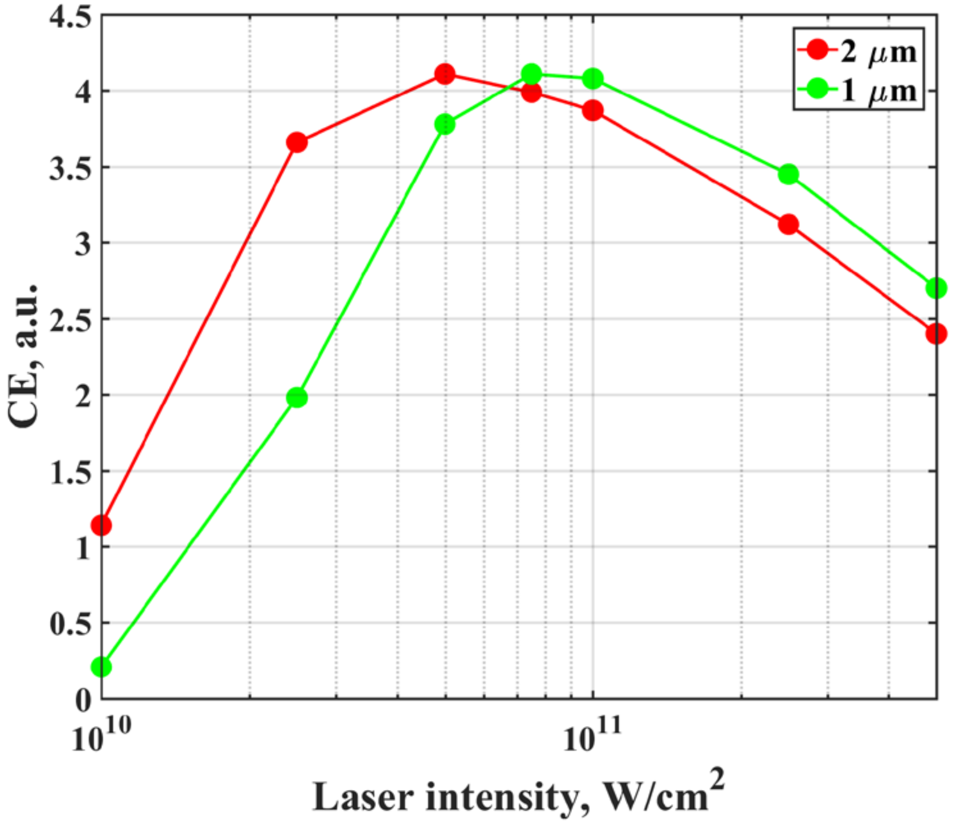
Photons

HEIGHTS Simulation

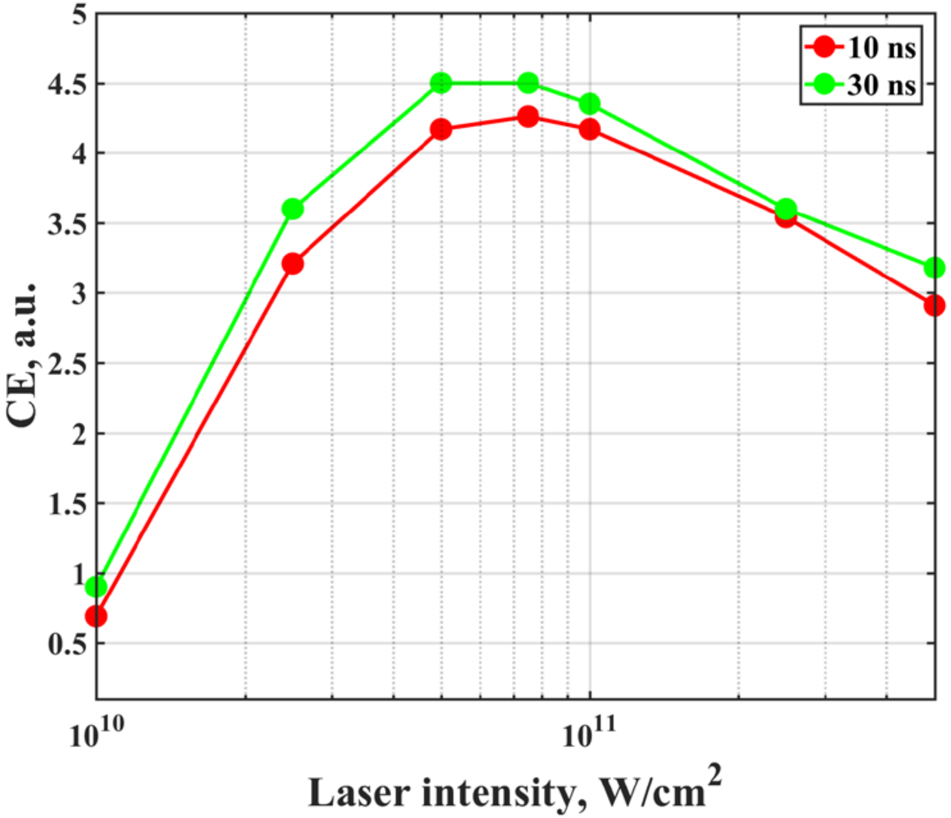
H. Tanaka, et al., Appl. Phys. Lett. 87 (2005)

T. Sizyuk and A. Hassanein, Physics of Plasmas (2014)

Efficiency of EUV sources from Sn: laser wavelength and pulse duration effects



50 µm droplet; 10 ns laser pulse

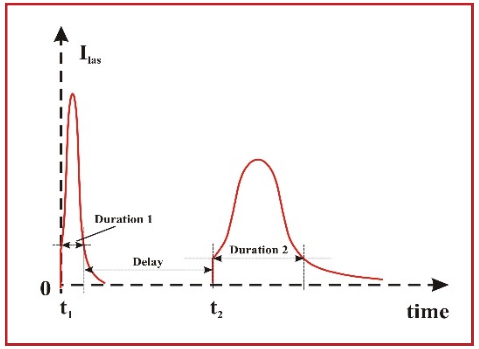


50 µm droplet; 2 µm

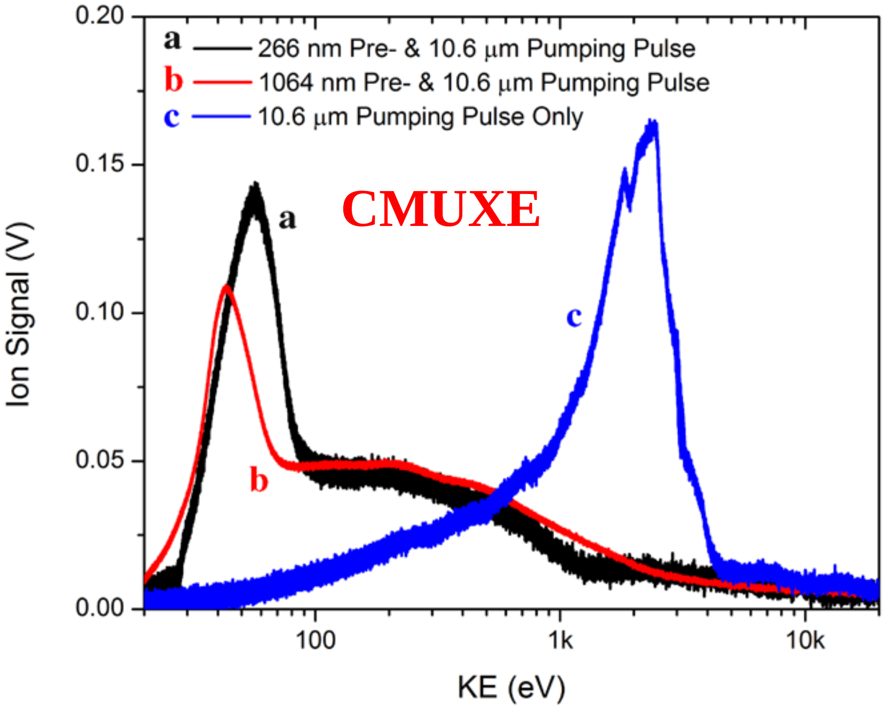
HEIGHTS Simulation

HEIGHTS Benchmarking with CMUXE Experiments

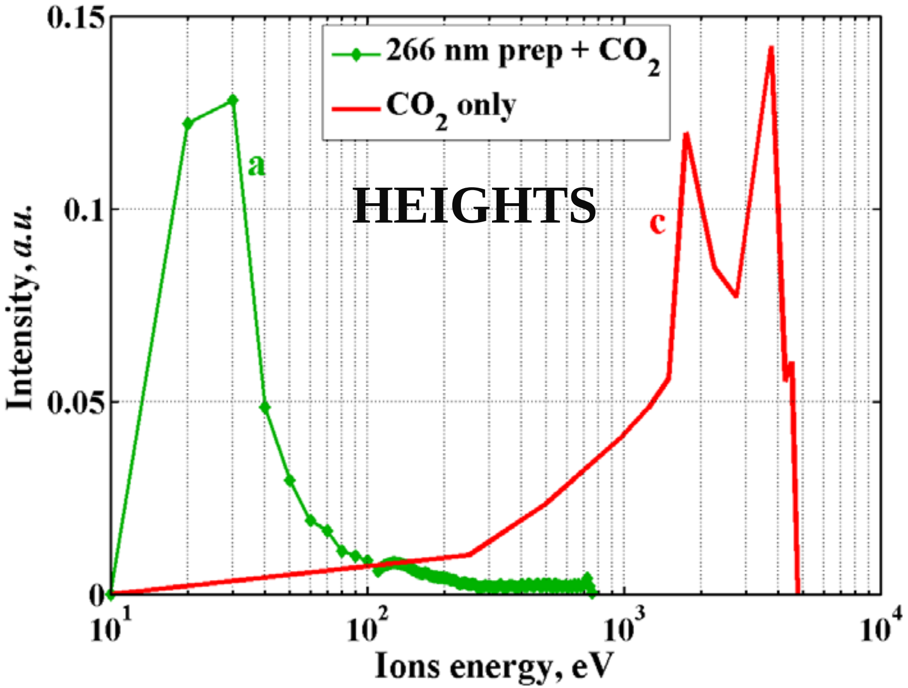
Ions kinetic energies in experiments[1] and in modeling[2] from planar Sn target
15 mJ for pre-pulse Nd:YAG laser and 90 mJ for CO_2 laser



CMUXE Experiments



HEIGHTS Simulation



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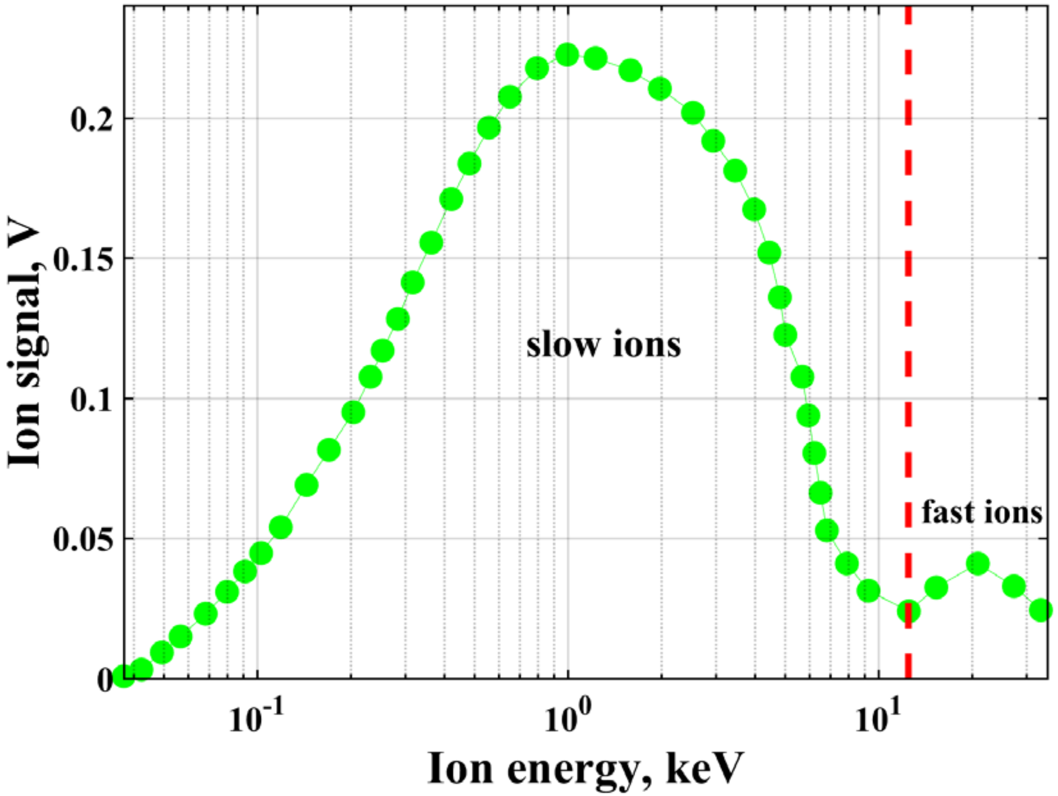
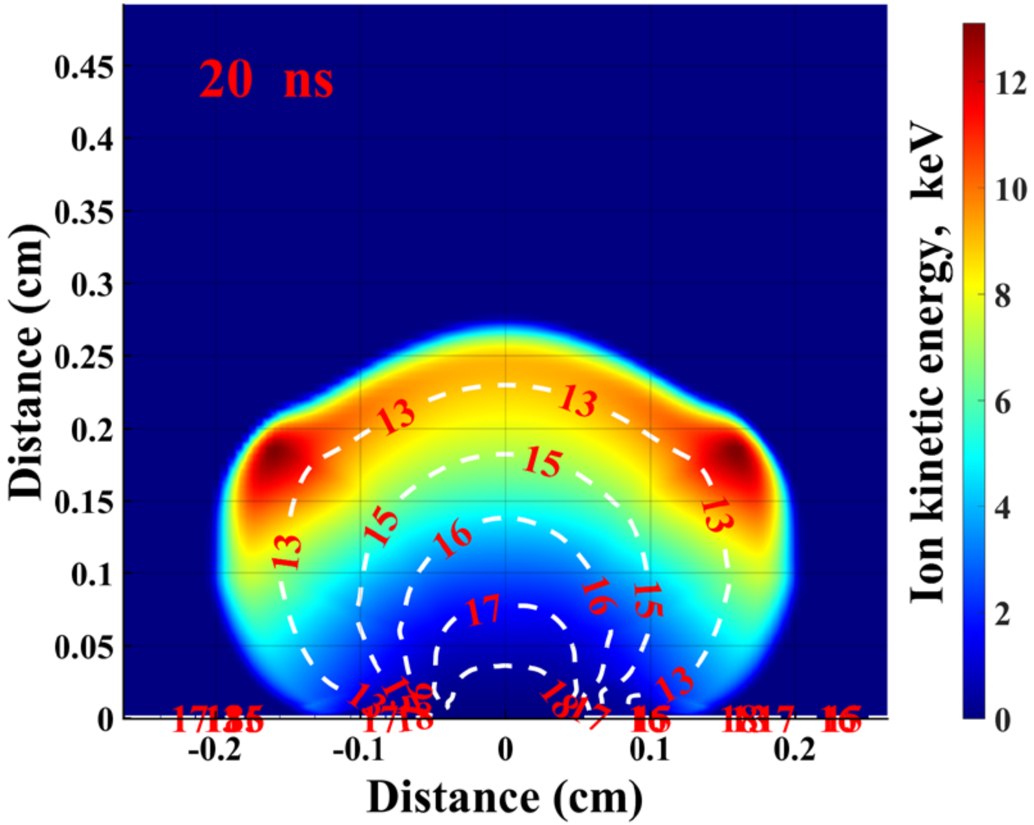
[1] J.R. Freeman, S.S. Harilal, A. Hassanein, B. Rice, Applied Physics A (2013)
[2] A. Hassanein and T. Sizyuk, Physics of Plasmas (2013)

HEIGHTS Benchmarking with CMUXE Experiments

Kinetic energy of ions from Mo[1] and Sn[2] plasma. Laser parameters: Nd:YAG, 2.4x10^{10} W/cm^2.



CMUXE Experiments



HEIGHTS Simulation

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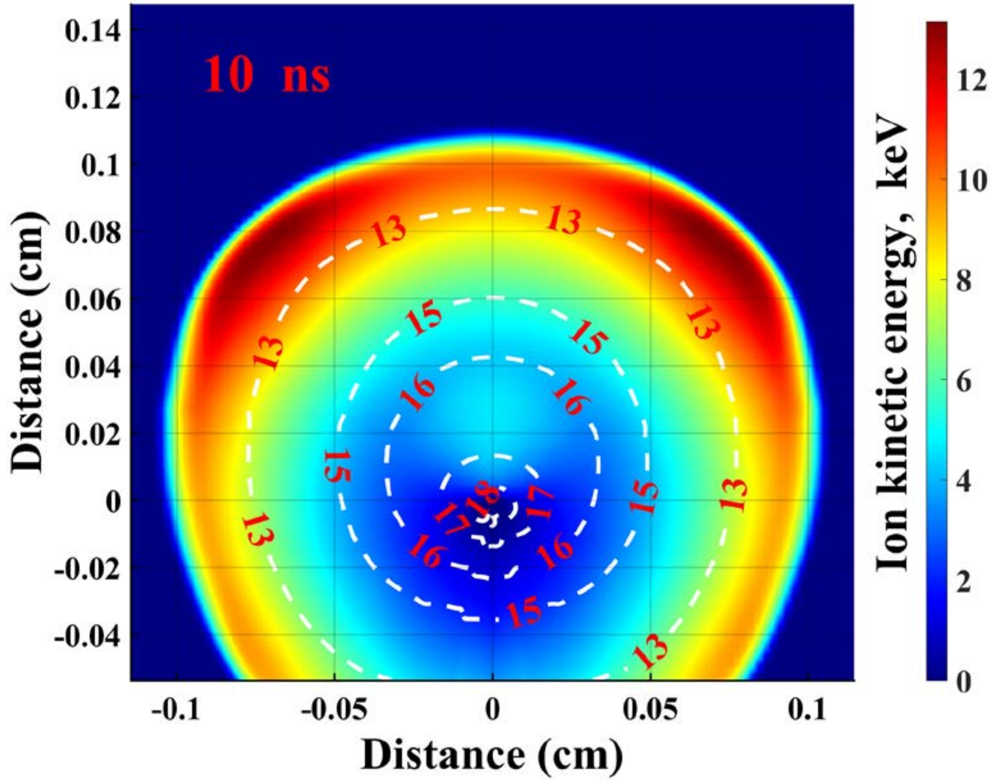
[1] N. Farid, S. S. Harilal, H. Ding, A. Hassanein, Physics of Plasmas 20, 073114, 2013

[2] T. Sizyuk, Proc. of SPIE Vol. 10957, 109571A , 2019

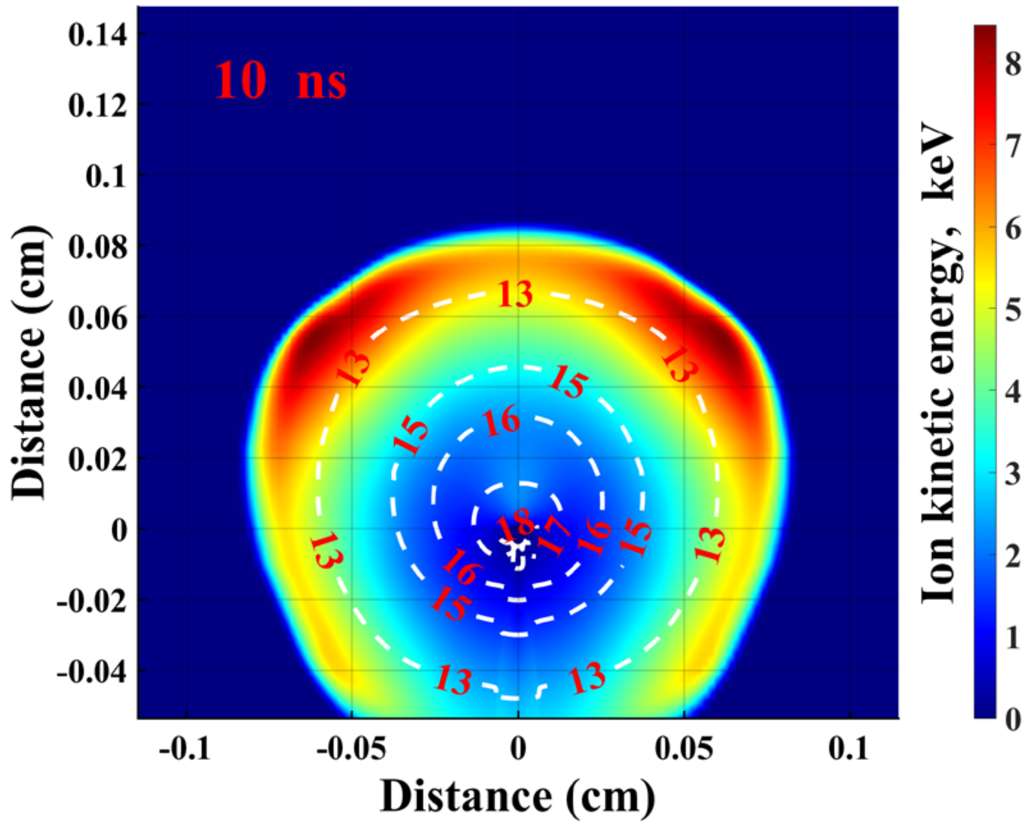
Ion Kinetic Energy – Laser Pulse Effect

HEIGHTS Simulation

10 ns



30 ns



2 μm laser, 7.5x10^{10} W/cm^2

Summary & Conclusions

- **Accurate computer simulation with sufficient 3D details can be used to understand, accelerate, and optimize design of LPP plasma devices**
- **HEIGHTS simulations and CMUXE experiments showed important effects of laser parameters on CE and on debris fluence and energy. Results are in good agreements with each other and other worldwide experiments**
- **Adjustment of laser spot size to droplet size differs for different lasers that related to the difference in created plasma evolution.**
- **Increasing of pulse duration leads to the slight increase in the CE, however, to noticeable decrease in kinetic energies of ions.**
- **Further optimizations in laser/target interactions, pre-pulse lasers, target fragmentation/mist formation, low-density targets, etc. are possible to enhance EUV**