Summary of Japanese Academic Support Program for LPP EUV Source

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Contributors

Theory and simulation

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Experiments

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Laser developments

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Basic research on EUV plasma is important.

MEXT project
(2003 - 2007)

Collaboration

METI project
EUVA
(2002 - 2007)

Objectives

1) Understanding physics of EUV source plasma and providing guidelines for practical EUV source design

- **High power and high efficiency**
  - EUV data base (experiments and simulations)
  - Optimization of EUV plasma (laser and target)
- **Clean, debris free source**
  - Data base on ion and neutral atom emission
  - Suppression of high energy ions

2) Development of new targets

low density,minimum-mass, high feed rate

3) Development of laser technology

5 kW/5 kHz DPSSL

compact, high efficiency, good beam quality, long life

Objectives: EUVL system R&D

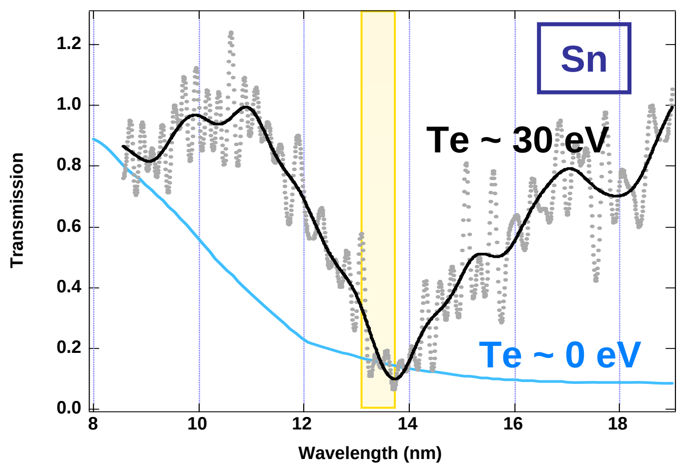
MEXT: Ministry of Education, Culture, Science and Technology
METI; Ministry of Economy, Trade and Industry

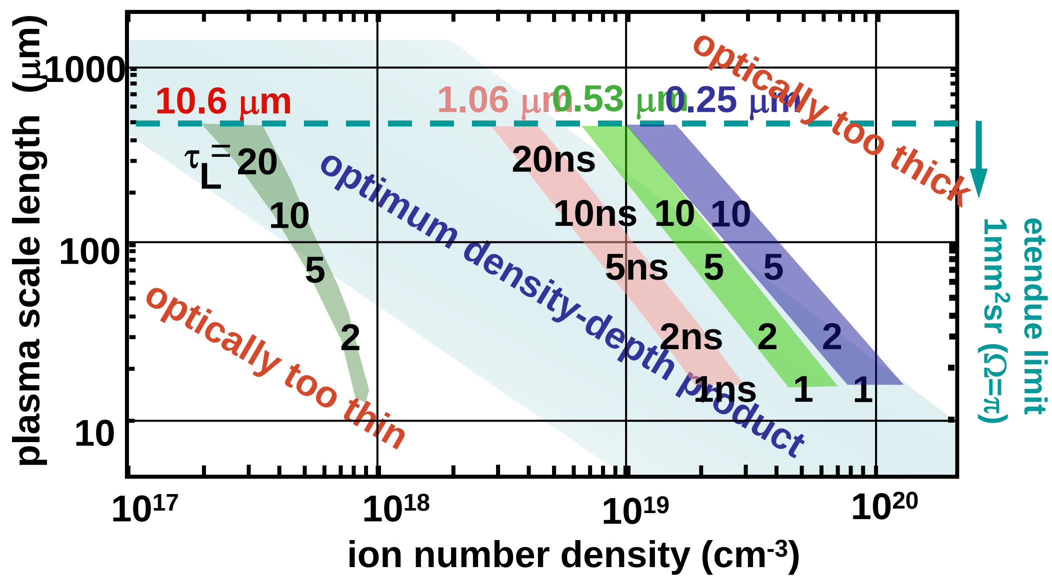
Design windows for high power EUV source

EUV power : 300W at source @10 - 30kHz

- **Large size plasma: 400 ~ 700 μm**
- **Low laser intensity: ~ 10^{11} W/cm^2**
- **Low electron density: 10^{19} ~ 10^{21} cm^{-3}** → **low density target foam, double pulse, punch-out**
- **Electron temperature: 20 ~ 40 eV**

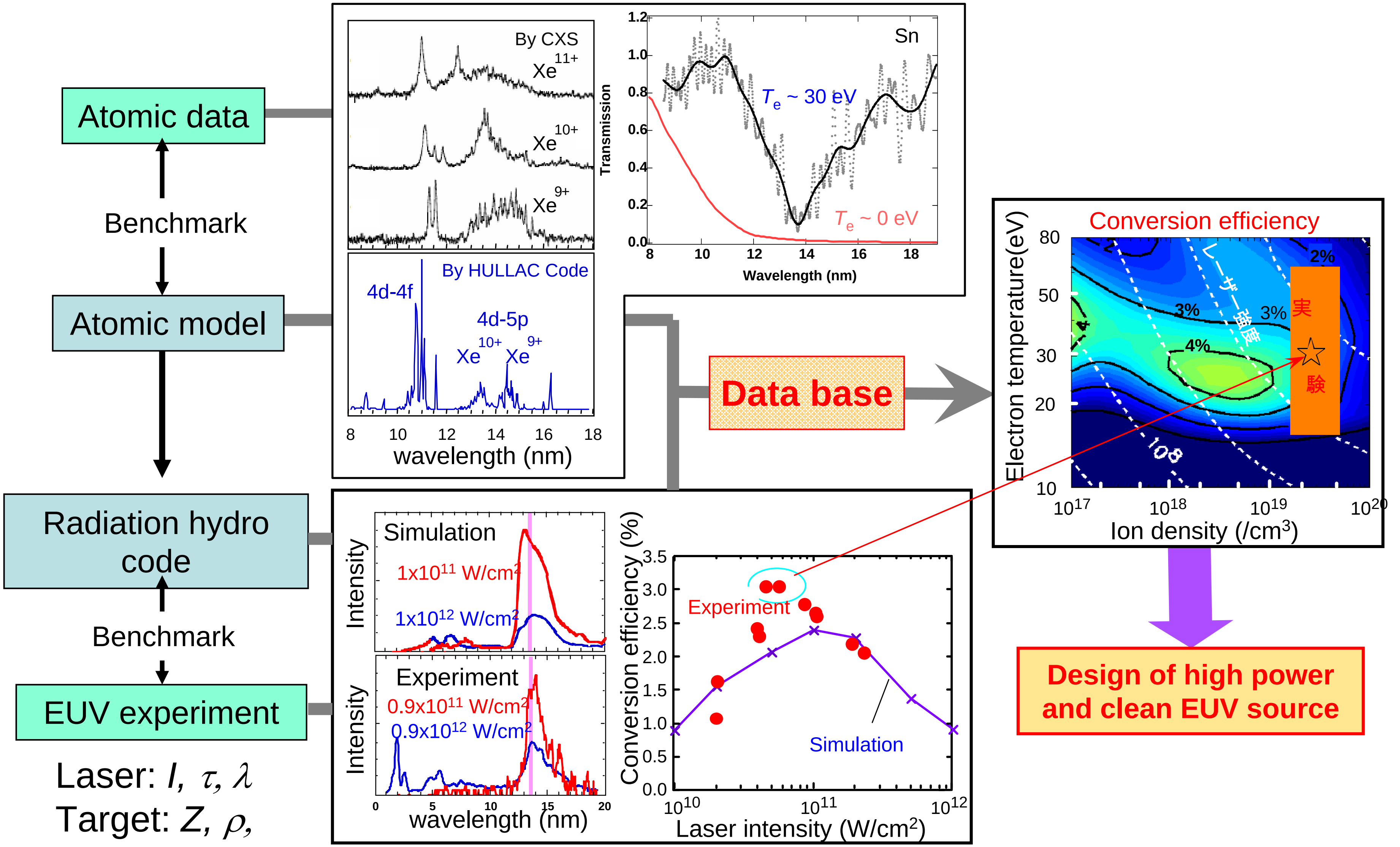
For Sn, selection of laser wavelength and pulse width is important because of large opacity for EUV emission.





Sn plasma absorbs EUV emission.

Research flow to high power and efficient EUV source

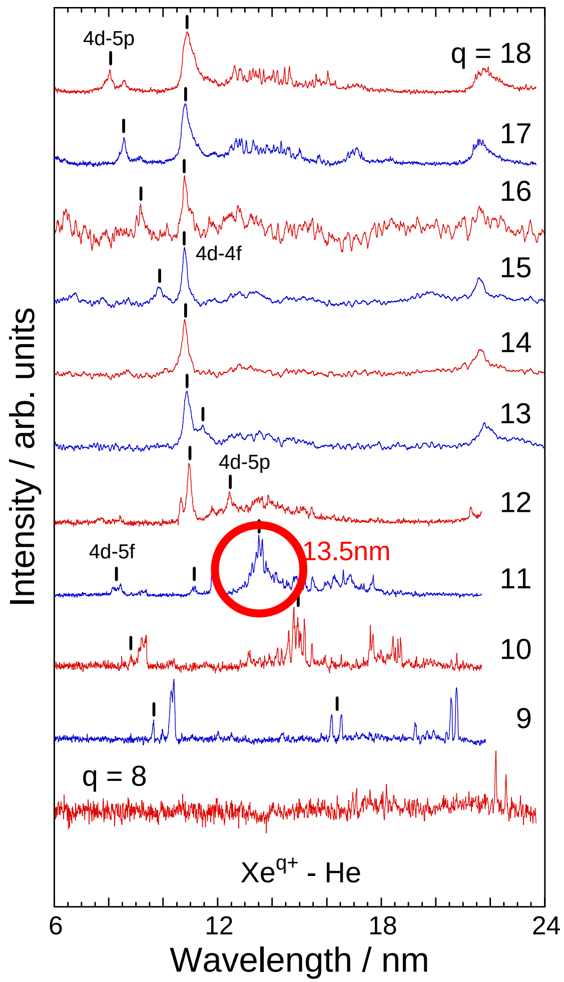


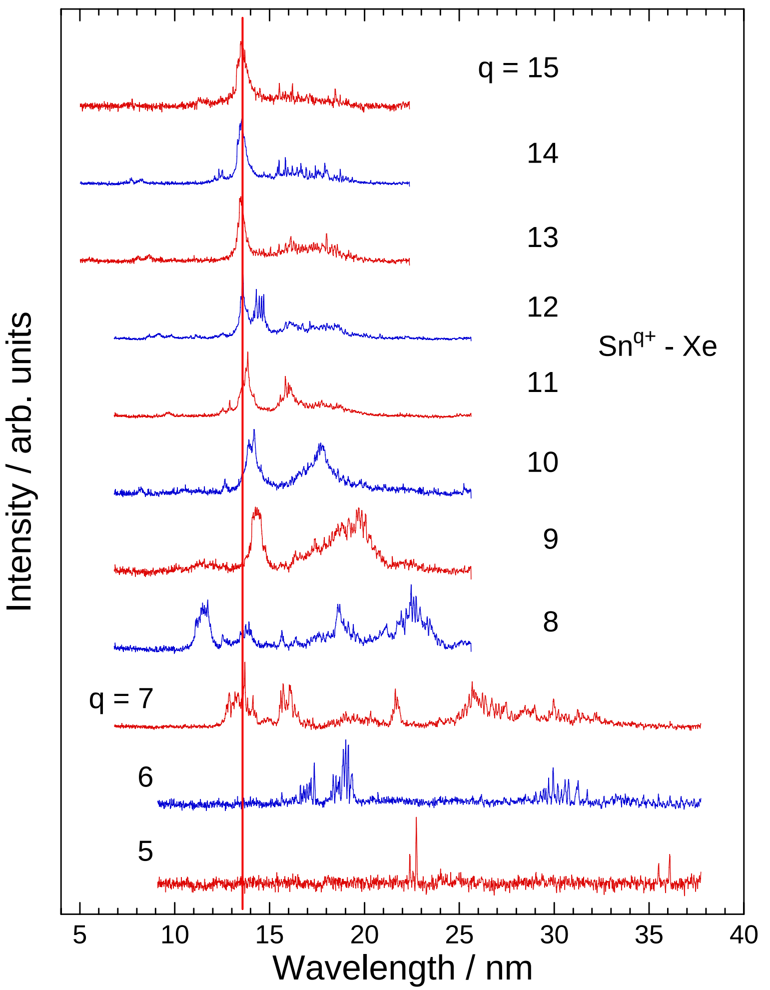
Emission spectra from charge-selected Xe and Sn ions were measured.

Charge exchange spectroscopy (CXS)

Xe^{+q} + (He, Ar, Xe) → Xe^{+q-1} (*n, l*)

→ Xe^{+q-1} (*n', l'*) + hv





Atomic codes were improved by measured spectra.

Observed peaks and HULLAC calculations

Xe

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Sn

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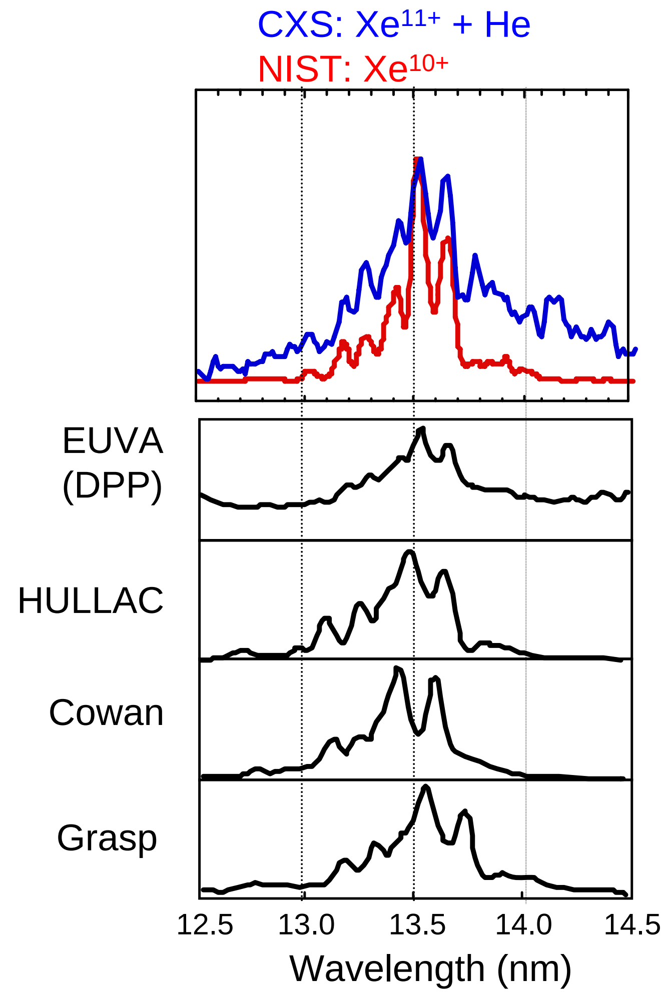
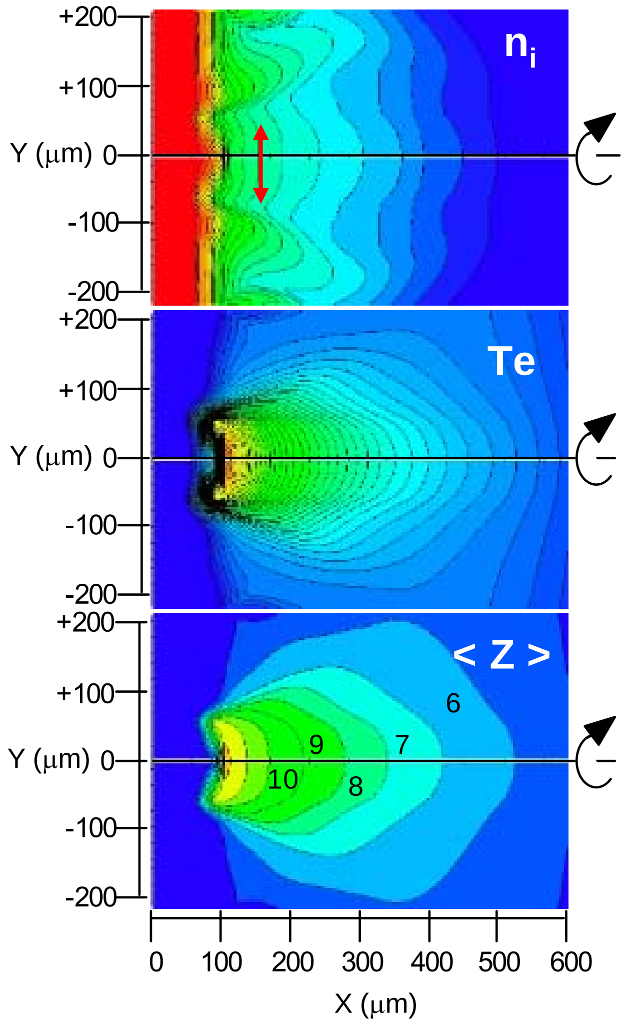


2D radiation hydro-code was developed.

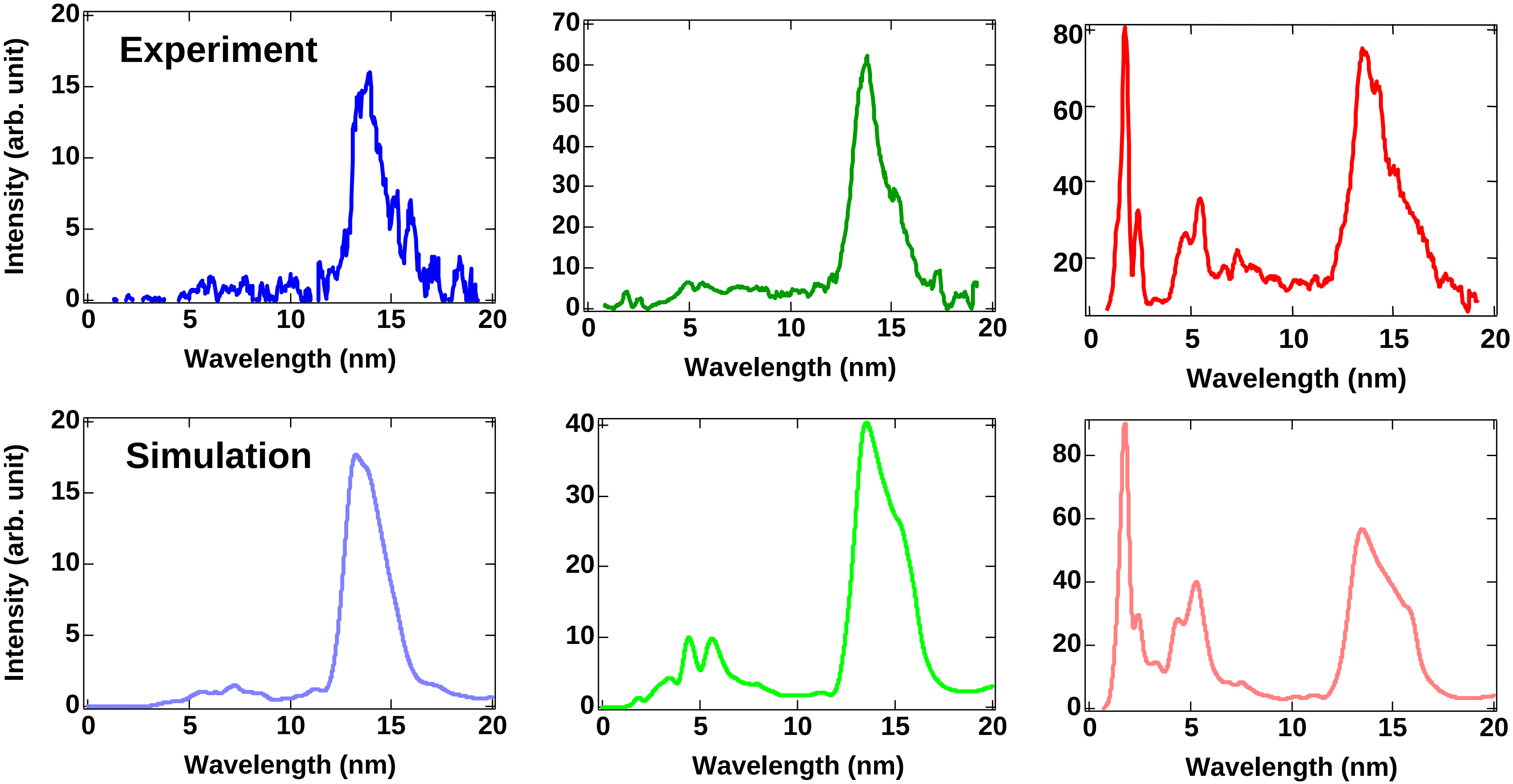
Sn plane target, laser diameter: 100μm



Electron density distribution was reproduced well by 2D code.

Radiation hydrodynamic simulation reproduces well the measured spectra.

Laser intensity 9×10^{10} W/cm^2 | **Laser intensity 3×10^{11} W/cm^2** | **Laser intensity 9×10^{11} W/cm^2**



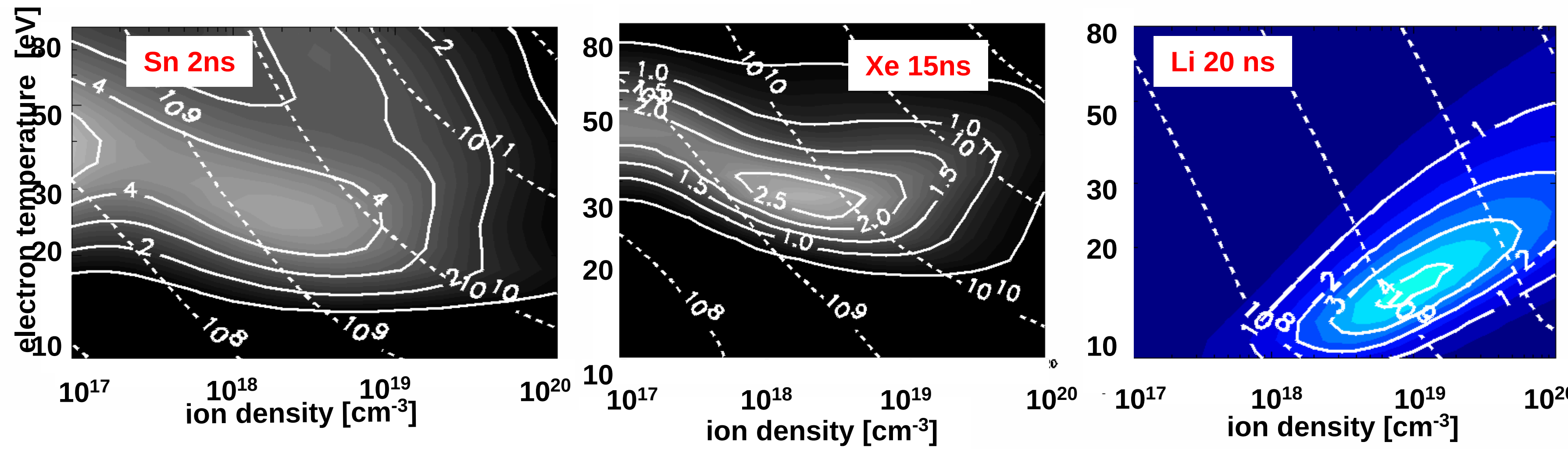
Optimum conditions for high conversion were obtained.

For solid target

Sn: short pulse laser (~ 2 ns), CE > 4%

Xe: long pulse laser (> 10 ns), CE ~ 2%

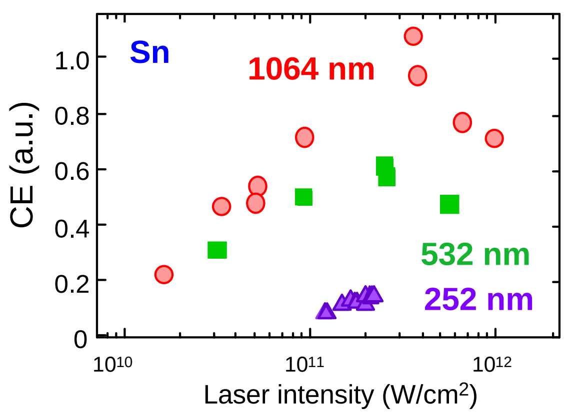
Li: long pulse laser (> 10 ns), CE ~ 4%

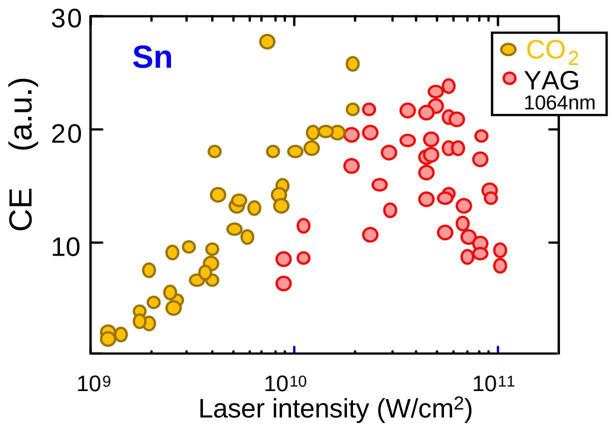


For Sn, opacity effect is important. → **Low density target is better.**

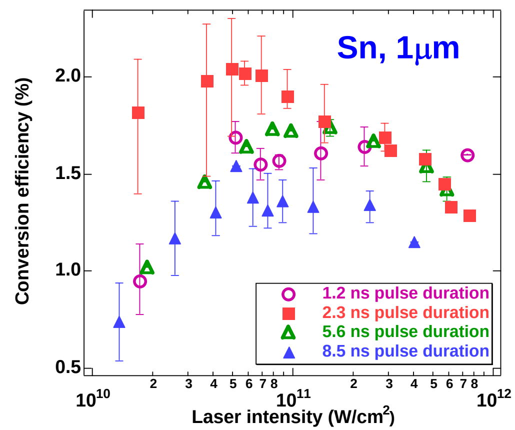
For solid Sn target, opacity effect is important.

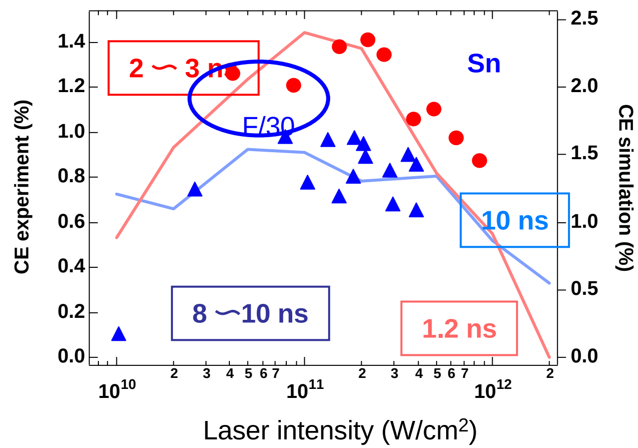
Wavelength dependence

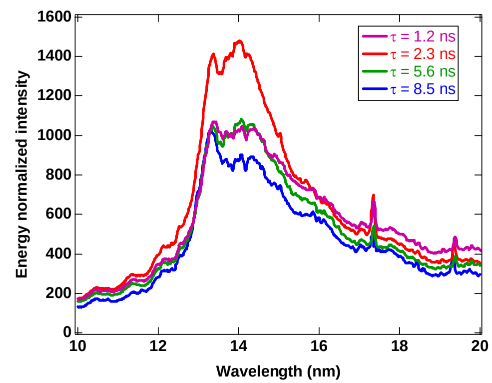




Pulse width dependence







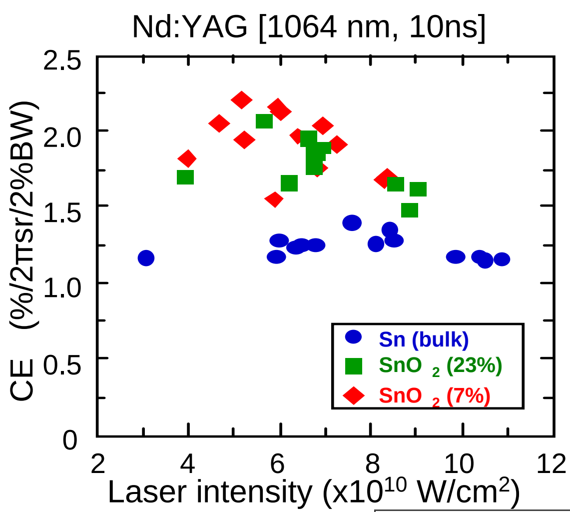
Experimental results are well reproduced by simulation.

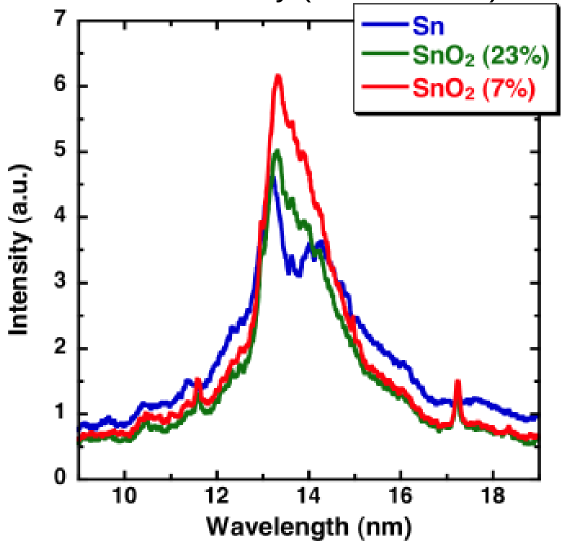
For long τ, EUV emission decreases due to self-absorption in plasma.

Solid Sn target: high CE for short pulse (~ns), long λ laser

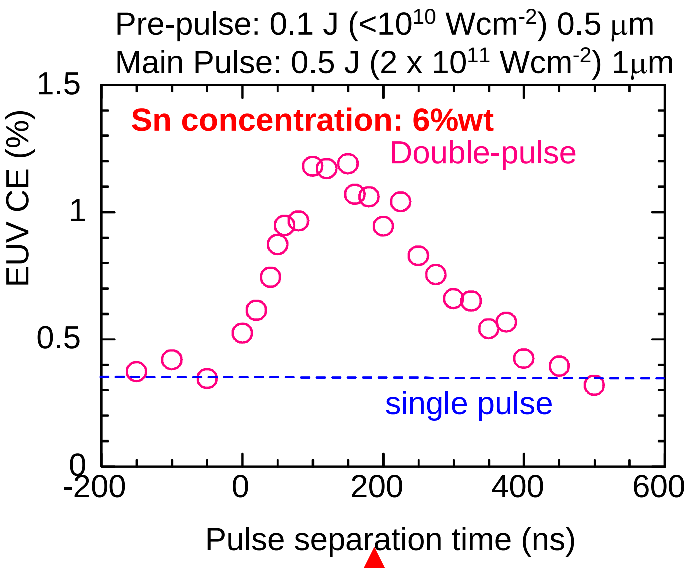
Conversion efficiency is improved by reducing target mass-density for long pulse laser.

Low-density Foam





Colloidal jet containing nanoparticles (double pulse irradiation)



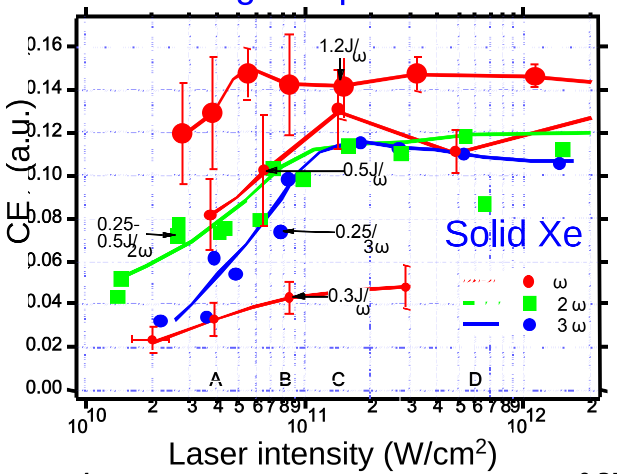
Double pulse irradiation is effective for high efficiency.

With decrease of mass-density, CE and spectral purity are improved.

Long pulse (~10ns) laser can be applicable for low density target.

Conversion efficiency was measured for different laser and target conditions.

Wavelength dependence: Xe



Wavelength dependence: Li

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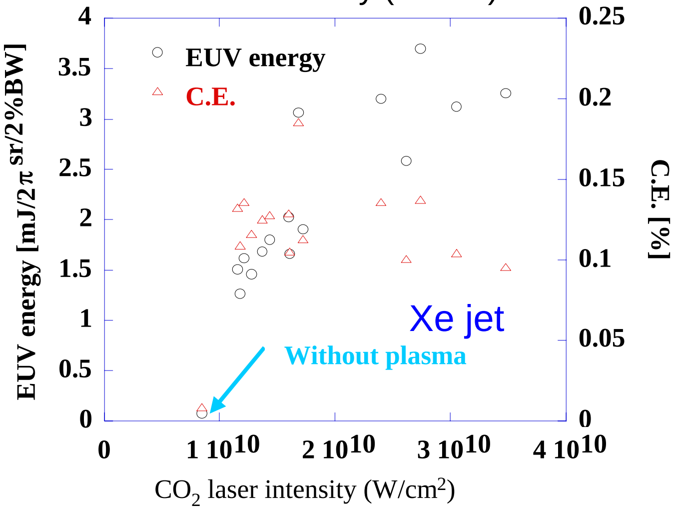
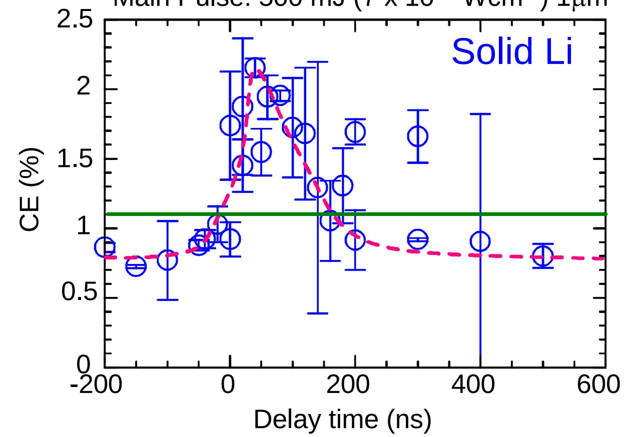
Solid Li



Pre-pulse: 60 J (<10^9 Wcm^{-2}) 0.5μm
Main Pulse: 500 mJ (7 x 10^{10} Wcm^{-2}) 1μm

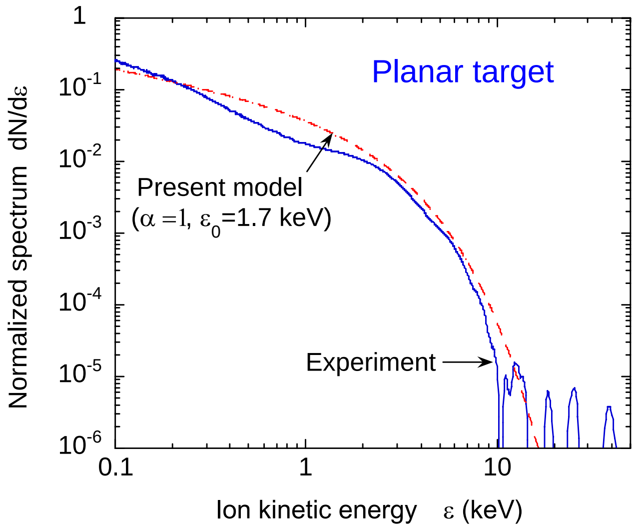


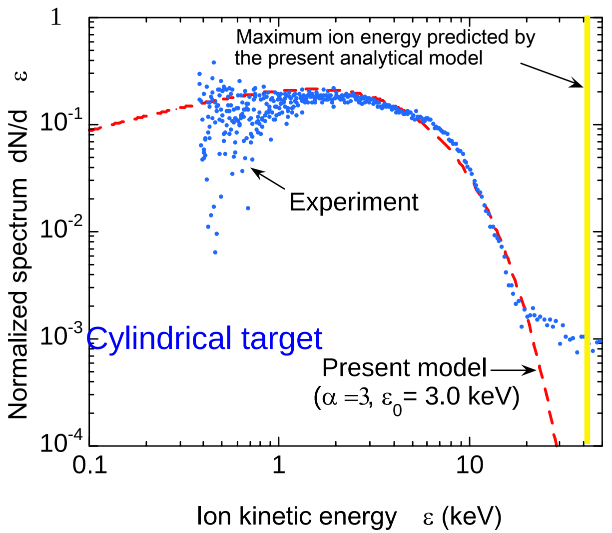
Double pulse irradiation

Xe target: high CE by long λ laser

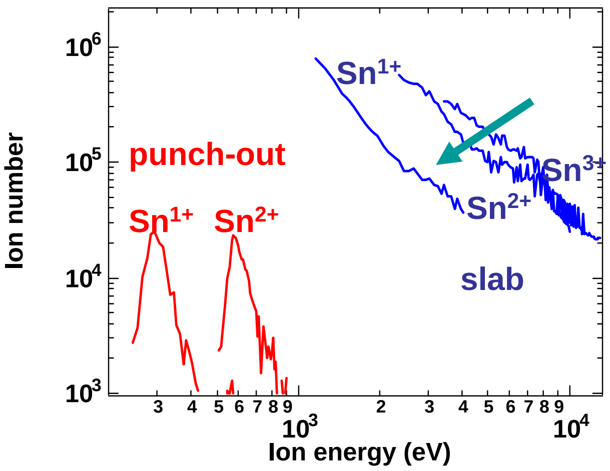
Li target: high CE by short λ laser

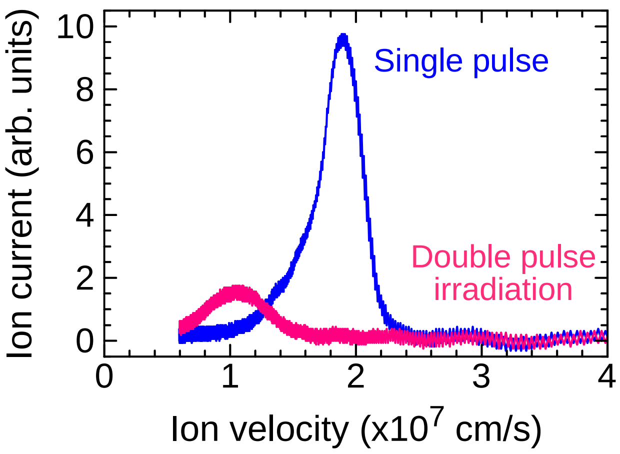
Isothermal expansion model reproduces well ion energy distribution.





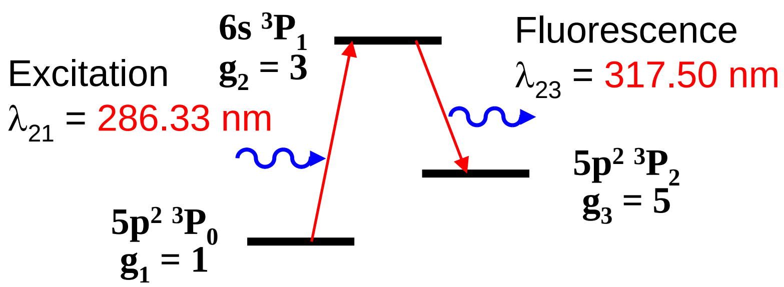
Maximum ion energy drastically decreases for low density target.



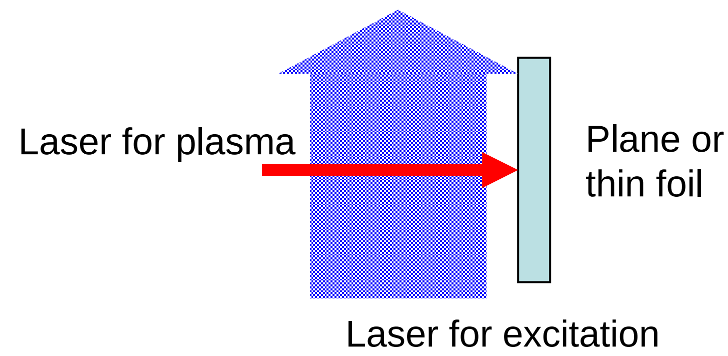


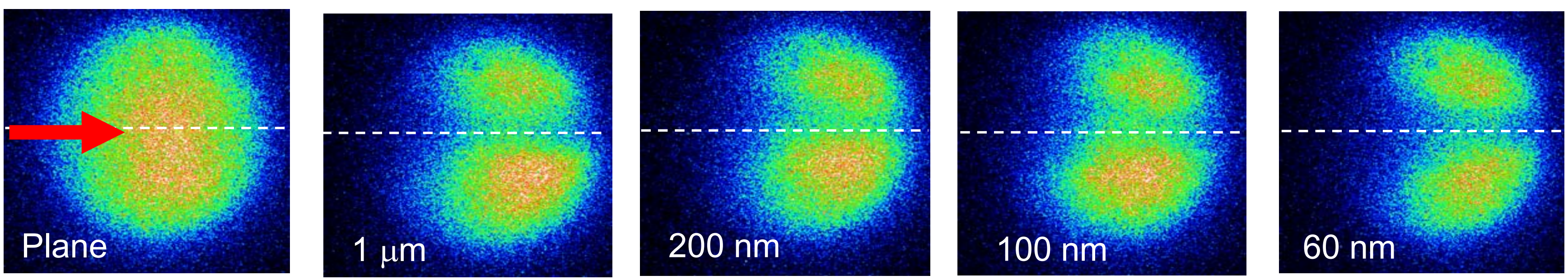
Neutral atom: Sn

LIF (Laser Induced Fluorescence) to measure neutral atomic density of Sn



Energy level of atomic Sn



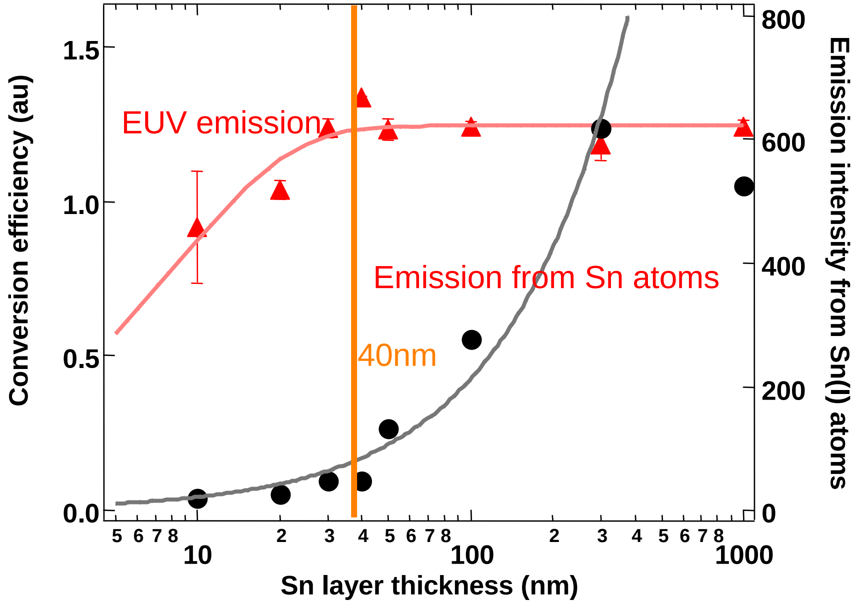


With reducing target thickness, almost all Sn atoms in the laser irradiated region are ionized, and fluorescence on the laser axis decreases. Fluorescence in the outer region is due to Sn atoms ablated from the outer region of laser irradiation.

↓

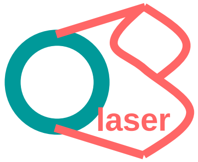
Importance of minimum-mass target

Coating thickness of 40 nm is enough to produce high power EUV emission. : minimum-mass target

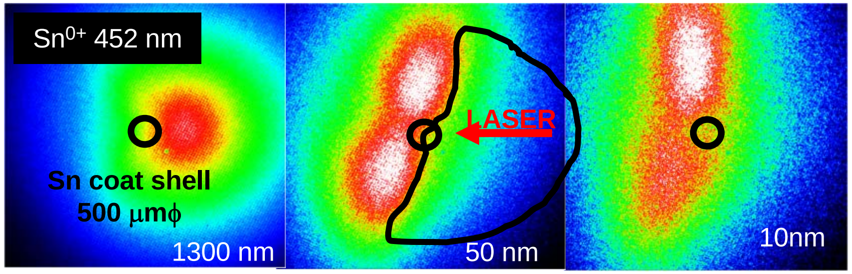


Emission from Sn neutrals linearly increases with coating thickness while keeping constant EUV intensity.

Target: Sn coated sphere
Intensity : 10^{11}W/cm^2
Pulse width : 2ns



Emission from Sn atoms



With decrease of Sn thickness emission to laser direction decreases,

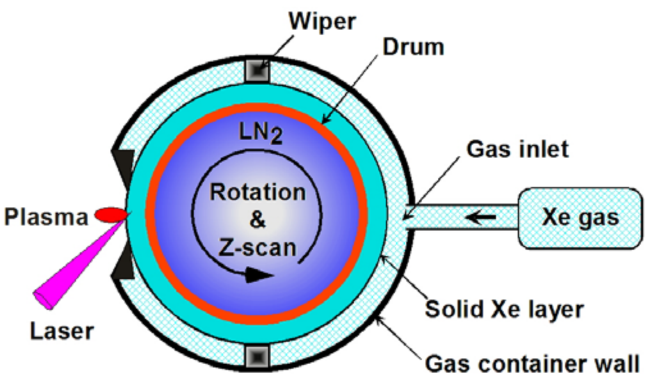
↓

Suppression of debris to C1 mirror

Number of EUV photon required ～number of ions: 30mJ/pulse ⟶ 2 x 10^{15} ions

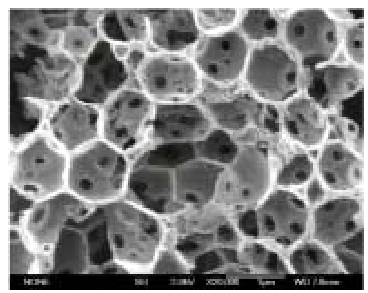
Novel targets have been proposed and developed.

Rotating drum (solid Xe)

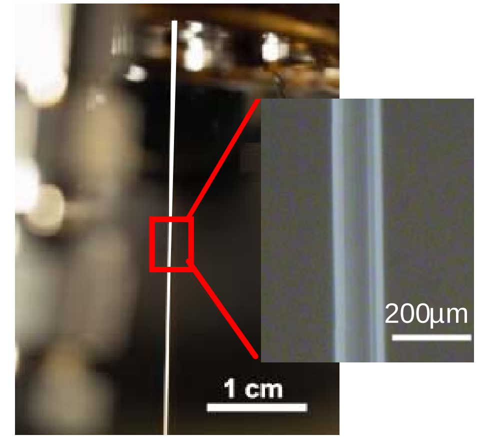


Xe frost (low density foam)

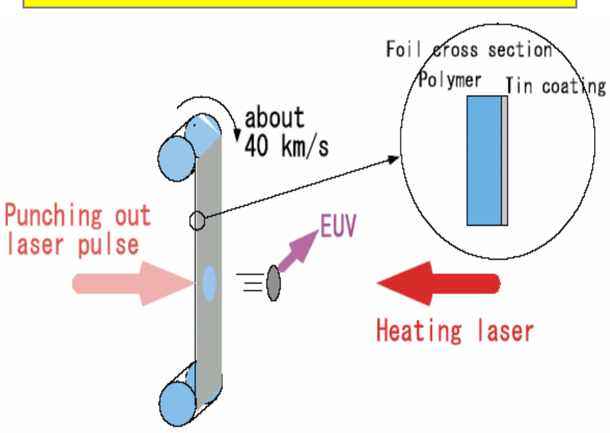
Low density foam (Sn)



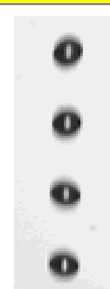
Annular jet (liquid Xe)



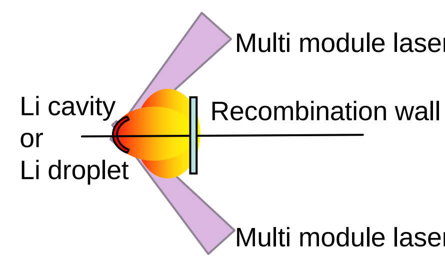
Punch out (tape or disc, Sn, Li)



Liquid droplet with Sn or Li



Forced cooling by recombination (Li)



Two ways for minimum-mass Sn target

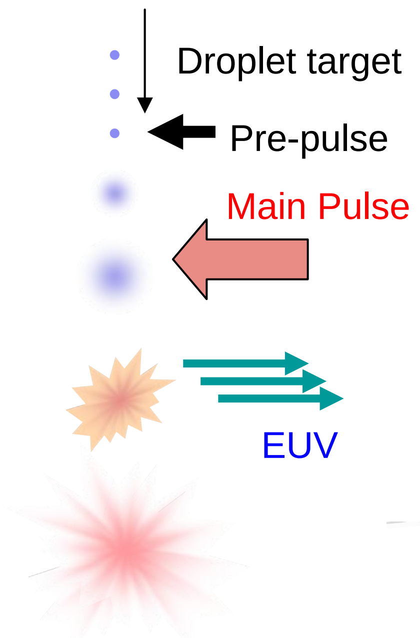
 # Double pulse irradiation : for 10 (100) kHz repetition

EUV energy / pulse : ~ 30 (3) mJ → number of Sn atoms : ~ 2 x 10^{15} (10^{14})

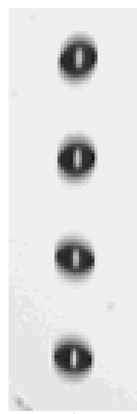
→ Diameter of droplet : ~ 50 (20) μm

↓ Pre-pulse to expand plasma

Diameter of plasma : ~ 400 (150) μm ← Main pulse Intensity: ~10^{11} W/cm^2 Pulse width: ~10 ns

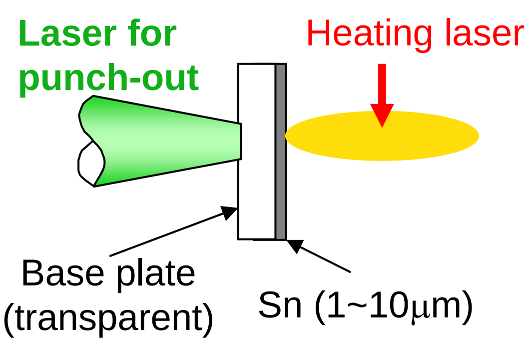


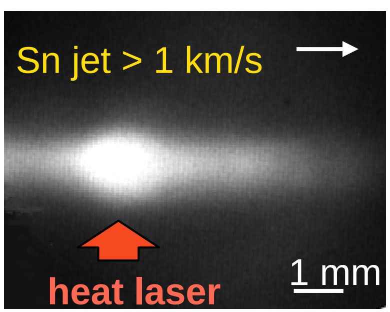
Sn droplet



Colloidal droplet containing Sn nanoparticles

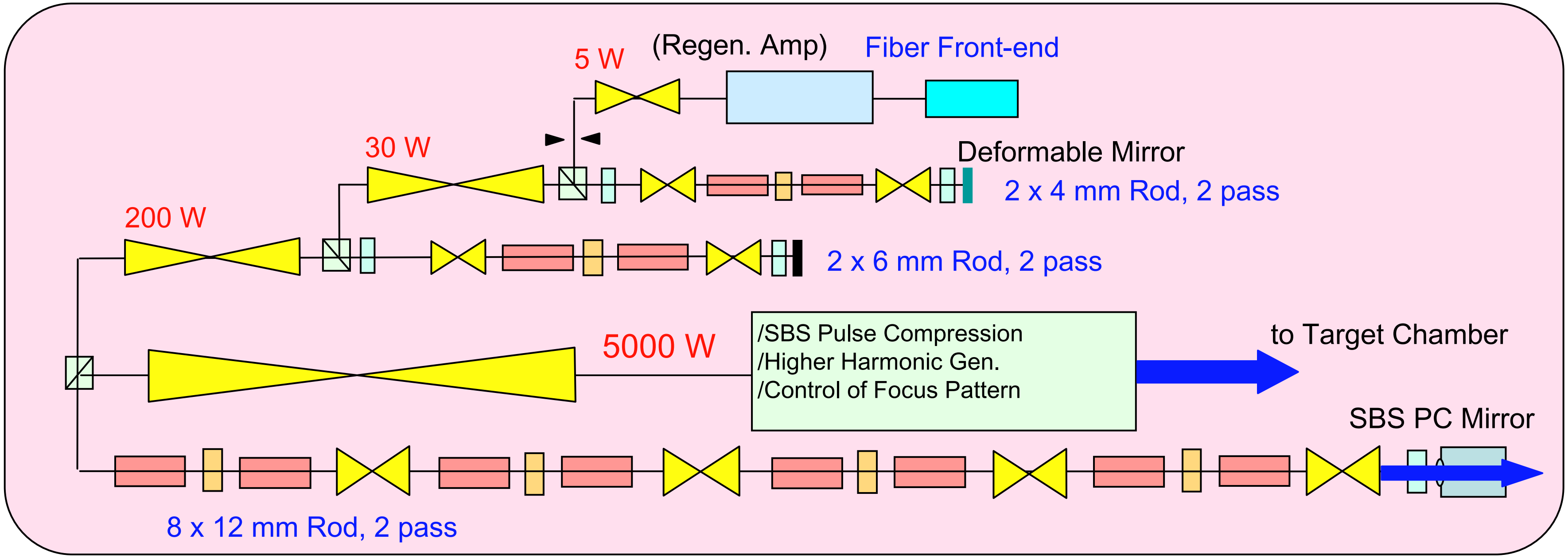
 # Punch-out target





1J/ 5kHz/ 5kW laser is under development.

- Front end: Fiber oscillator + Fiber amplifier
- Rod amplifier: Ceramic YAG, Uniform and high density pumping
- Compensate for thermal effect: Image relaying and SBS PCM
- System design: Simulation code (pumping, amplifier, propagation including diffraction)



Summary

- Guideline to achieve high conversion from laser to EUV radiation has been established by the experiments and the simulation.
- For Sn plasma, opacity effect is important, and short pulse laser and low density target will be effective for high efficiency.
- High conversion efficiency was achieved.
  Sn: 3 % (spherical plasma), SnO_2 foam: 2.5 %,
  Xe (solid): 1.1 %, Li: > 2%
- Minimum-mass targets were proposed.
  Sn droplet with double pulse irradiation and punch-out target
- 5kHz/5kW laser is under development, and will be applied for high power EUV experiment.

Please visit our poster presentations.

- **S. Kubodera et al., Low-debris EUV source using a colloidal microjet target containing tin dioxide nanoparticles.**
- **T. Kagawa et al., Comparison of EUV spectra from Sn ions between theoretical RCI simulation and experiment.**
- **H. Nishimura et al., Laser and target optimization for the highest conversion to 13.5 nm EUV light with laser produced minimum-mass tin plasma.**
- **A. Sasaki et al., Modeling of the atomic processes in EUVL source plasma.**
- **T. Aota et al., Temperature and density measurement of laser-produced EUV plasmas.**
- **A. Takahashi et al., Emission characteristics of neutral atoms and ions of laser-produced tin plasma.**
- **H. Tanuma et al., EUV emission spectra of charge-selected Sn ions in charge exchange spectroscopy.**
- **K. Tsubakimoto et al., Development of high-peak, high-average LD pumped solid-state laser system for EUV generation.**
- **S. Amano et al., LPP-EUV source using cryogenic Xe and lithium new scheme targets.**
- **K. Nagai et al., Development of low-density target for highly efficient EUV generation.**
- **K. Nishihara et al., Theoretical guidelines of LPP-EUV sources for HVM.**
- **F. Koike et al., Systematics of atomic 4d-4f transitions of atomic ions in EUVL source plasmas and neighboring atomic numbers.**
- **A. Sunahara et al., Radiation hydrodynamic simulation for LPP EUV sources.**