Radiation Hydrodynamic Simulation on EUV light from 2μm Laser-irradiated Tin Droplet

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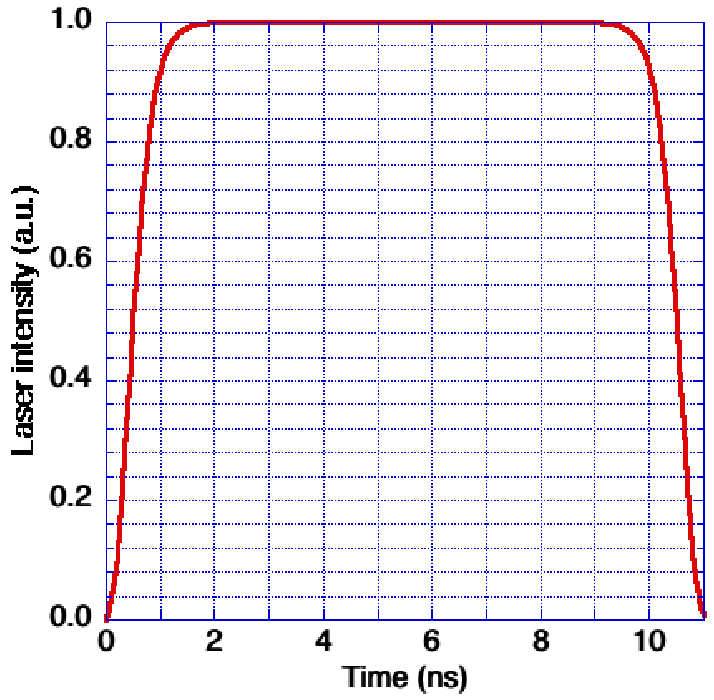
Outline of talk

- Summary of simulation results
  conversion efficiency / EUV spectra
  time dependent 2-dimensional electron & ion densities
  and electron temperature profiles

- Plasma properties near the optimum condition and discussion
  laser absorption efficiency, energetics, plasma parameters

- Radiation hydro code 2d “STAR” and code performance
  comparison of CE and spectra with 1 um laser experiments
  brief explanation of model (atomic, EOS and 2-d radiation hydro)

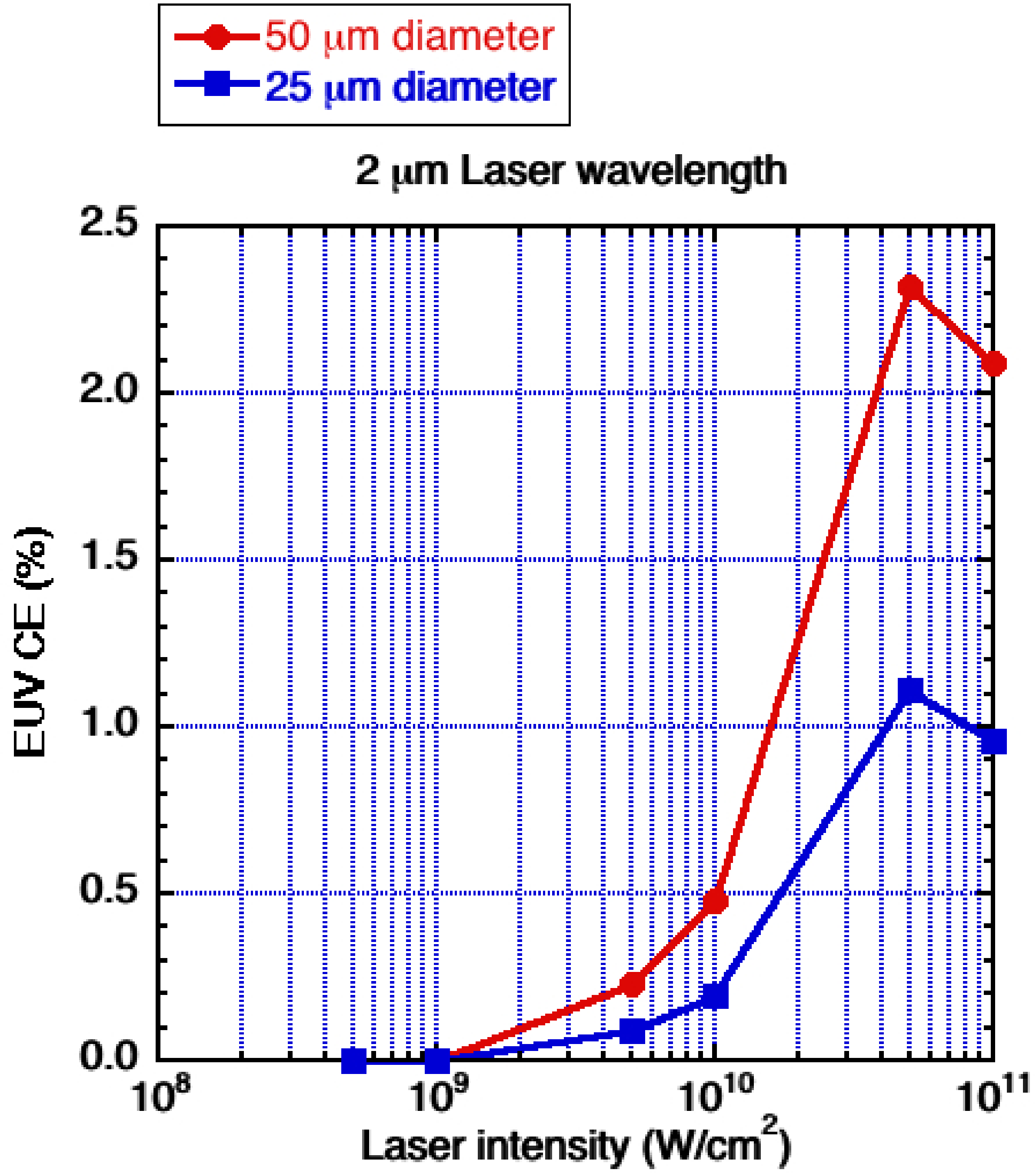
- Conclusion

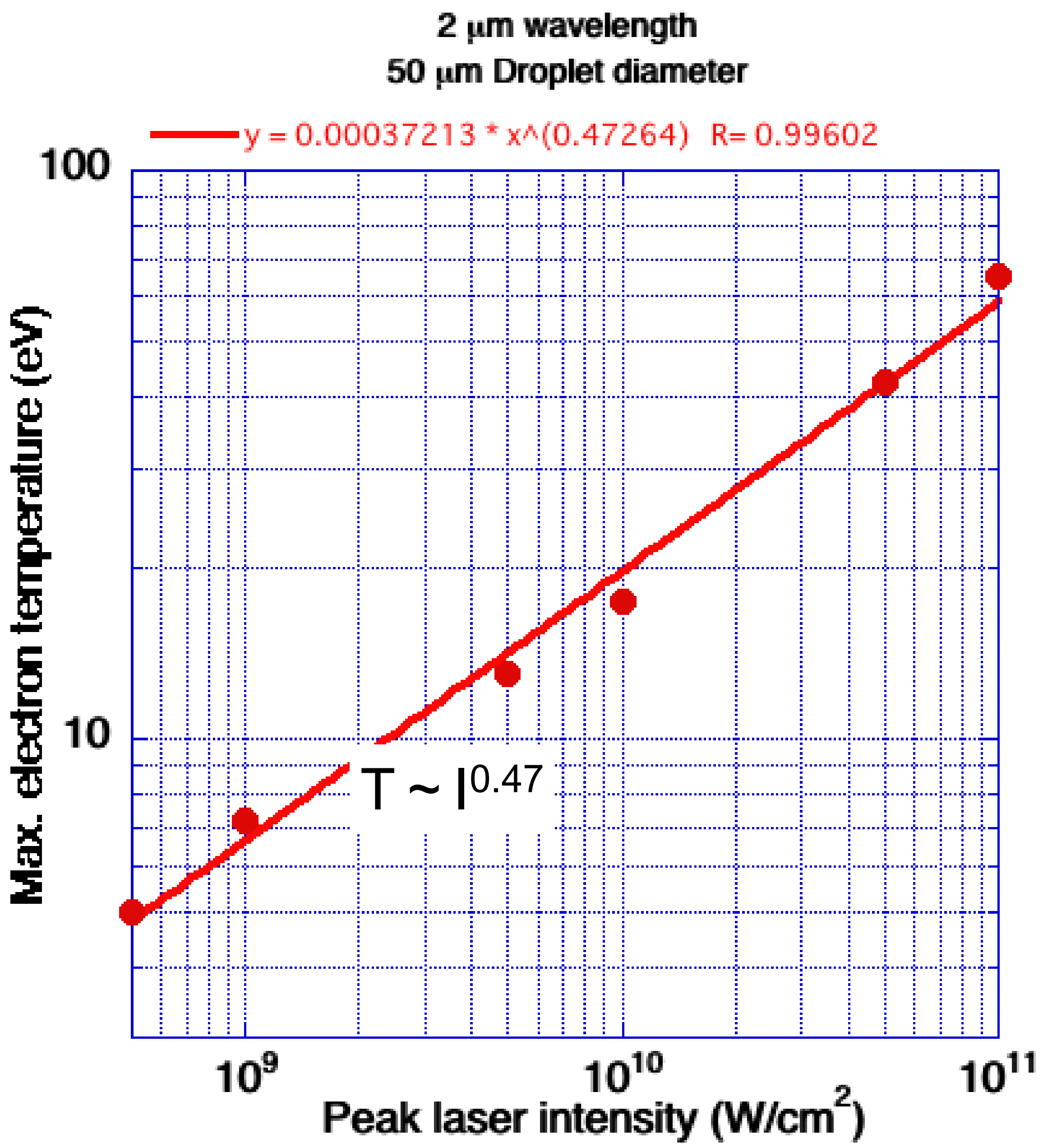


Laser temporal profile; Super Gaussian

summary 1

EUV Conversion efficiency (CE) vs laser intensity for different target sizes





Highest CE of 2.3 % has been obtained for the large droplet at 5×10^{10} W/cm^2, where electron temperature is about 40 eV.
Laser intensity of 5×10^{10} W/cm^2 gives a peak of CE for both target sizes.

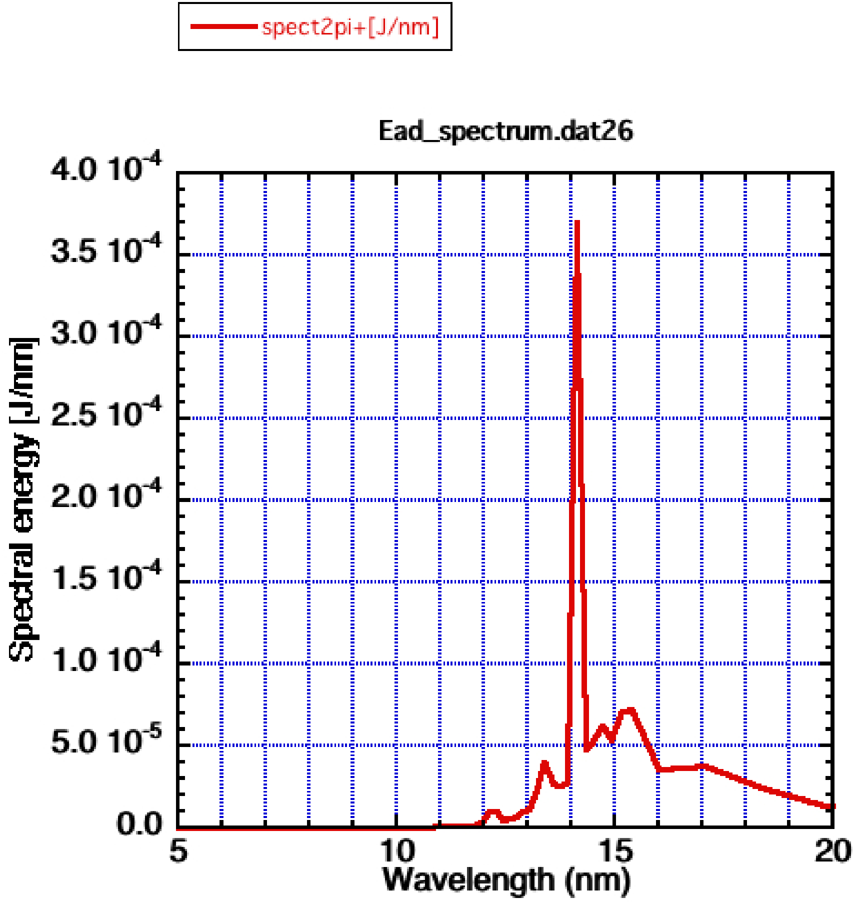
summary2

EUV spectra from large droplets

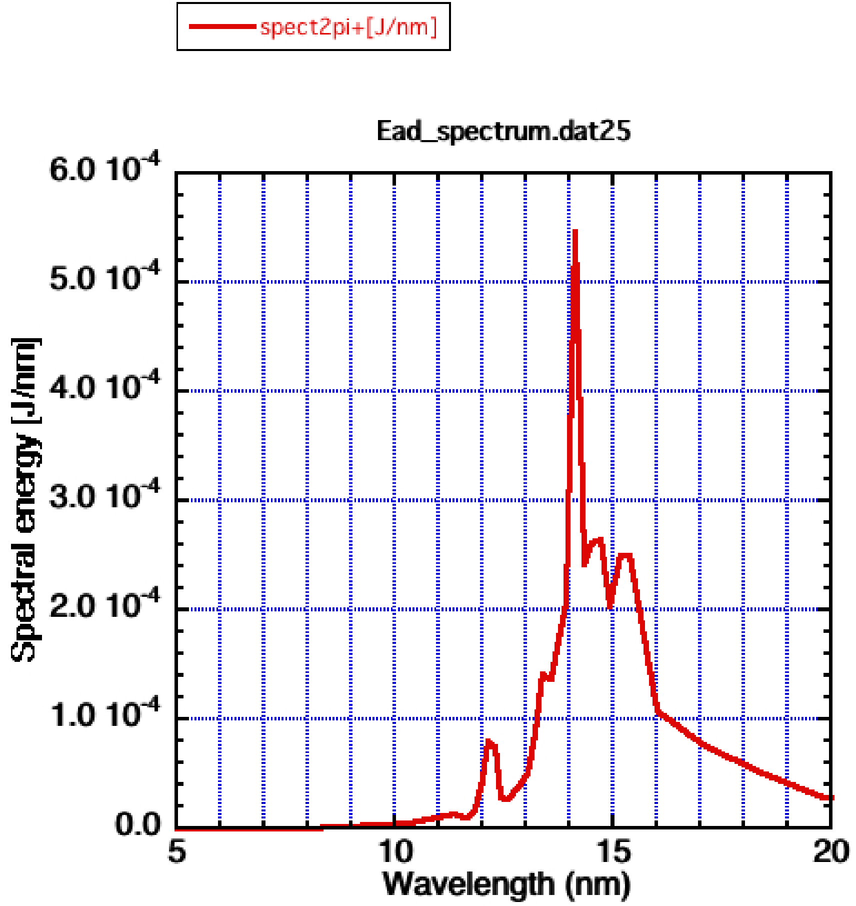
Spectral peaks shift slightly to shorter wavelengths with increase of laser intensity.

Laser intensity (W/cm^2)

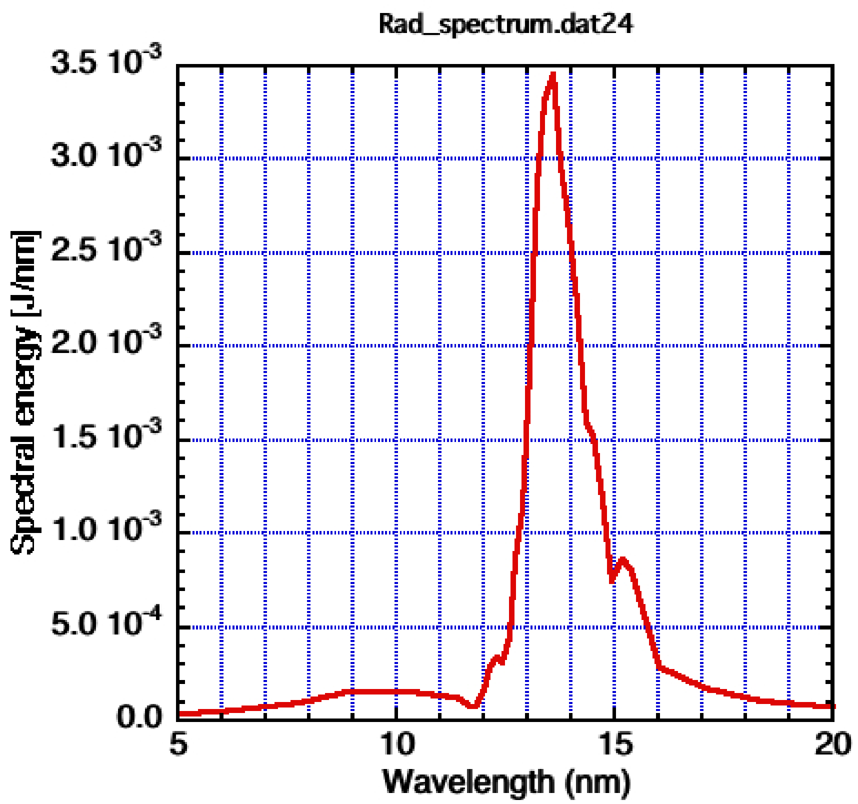
$5x10^9$



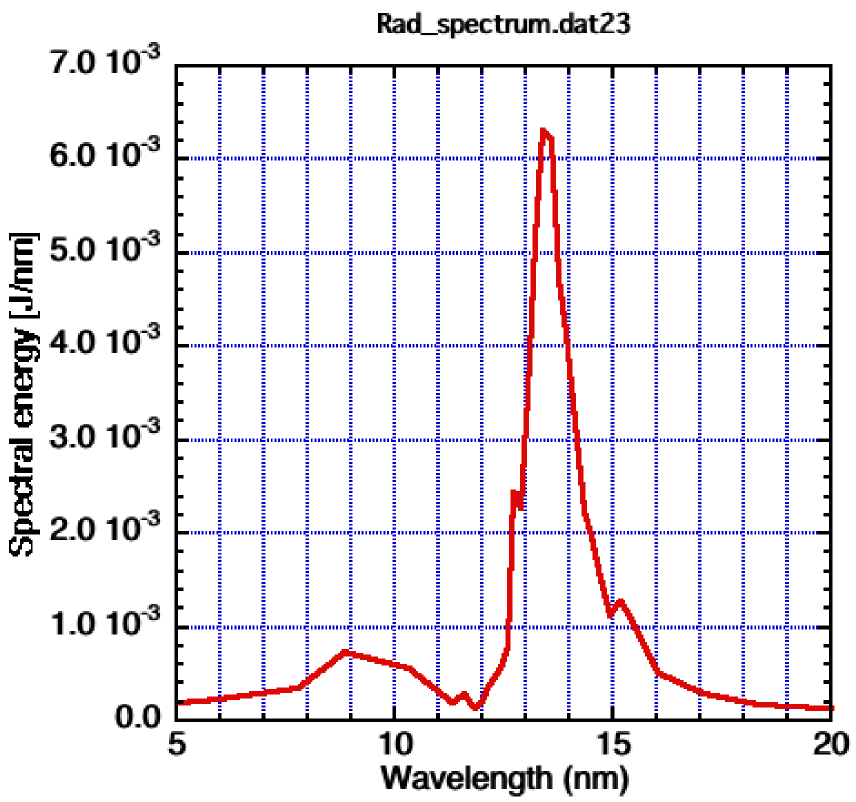
10^{10}



$5x10^{10}$



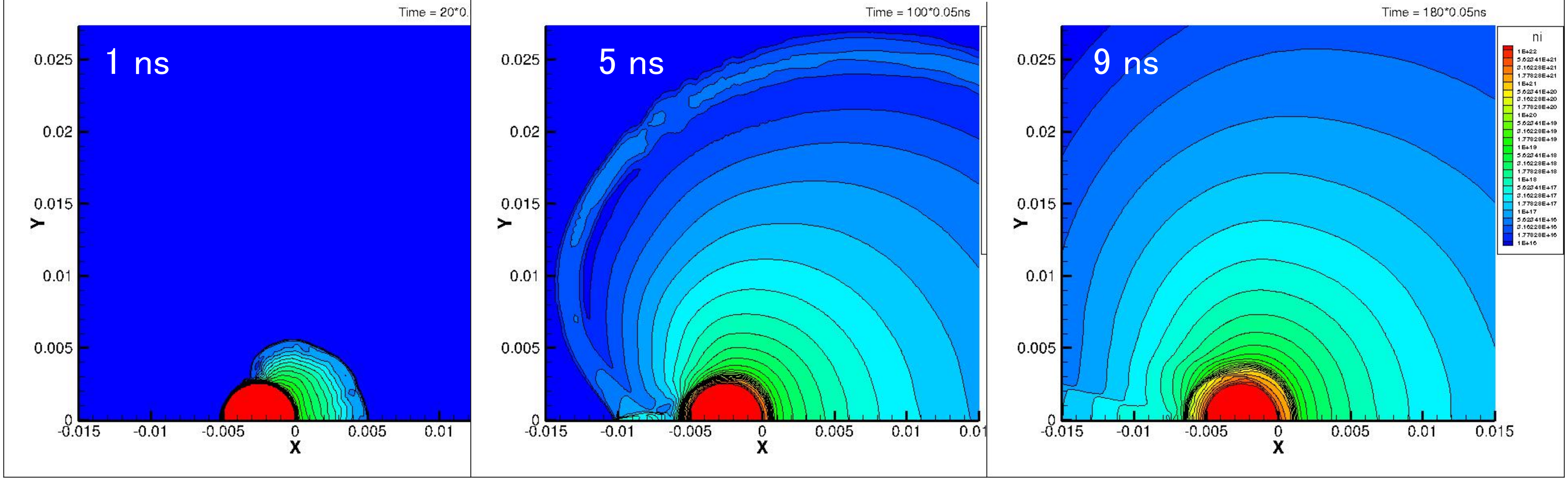
10^{11}



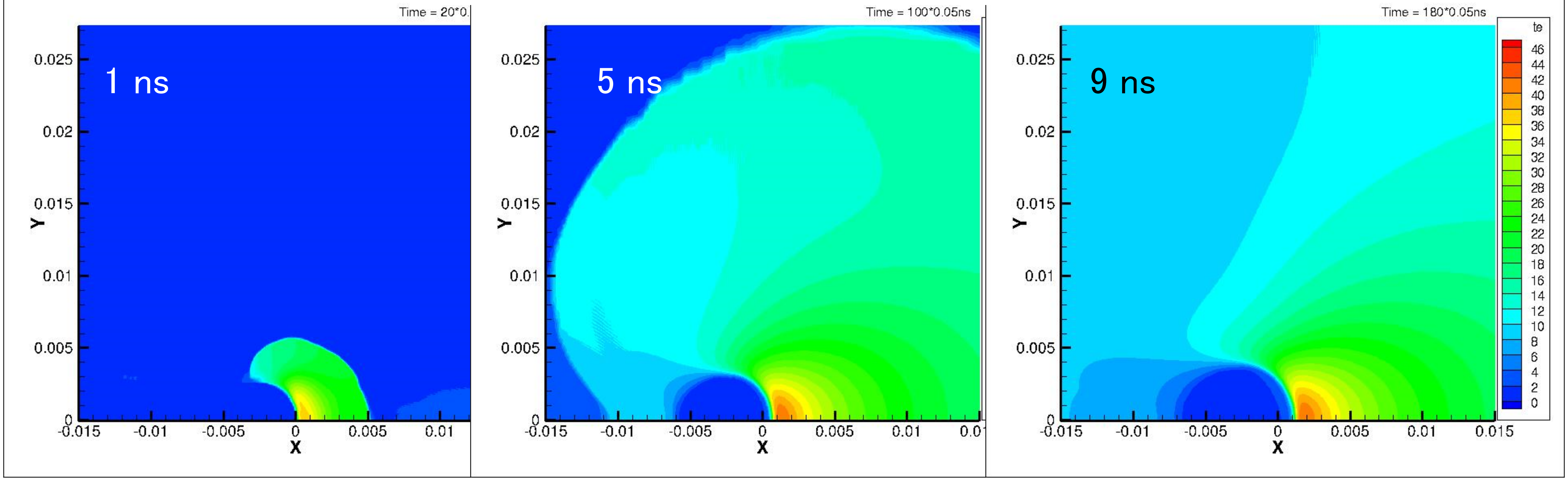
density
temperature 1

Time dependent profiles of electron density and temperature for 5x10^{10} W/cm^2

ion density (10^{16} – 10^{22} cm^{-3})



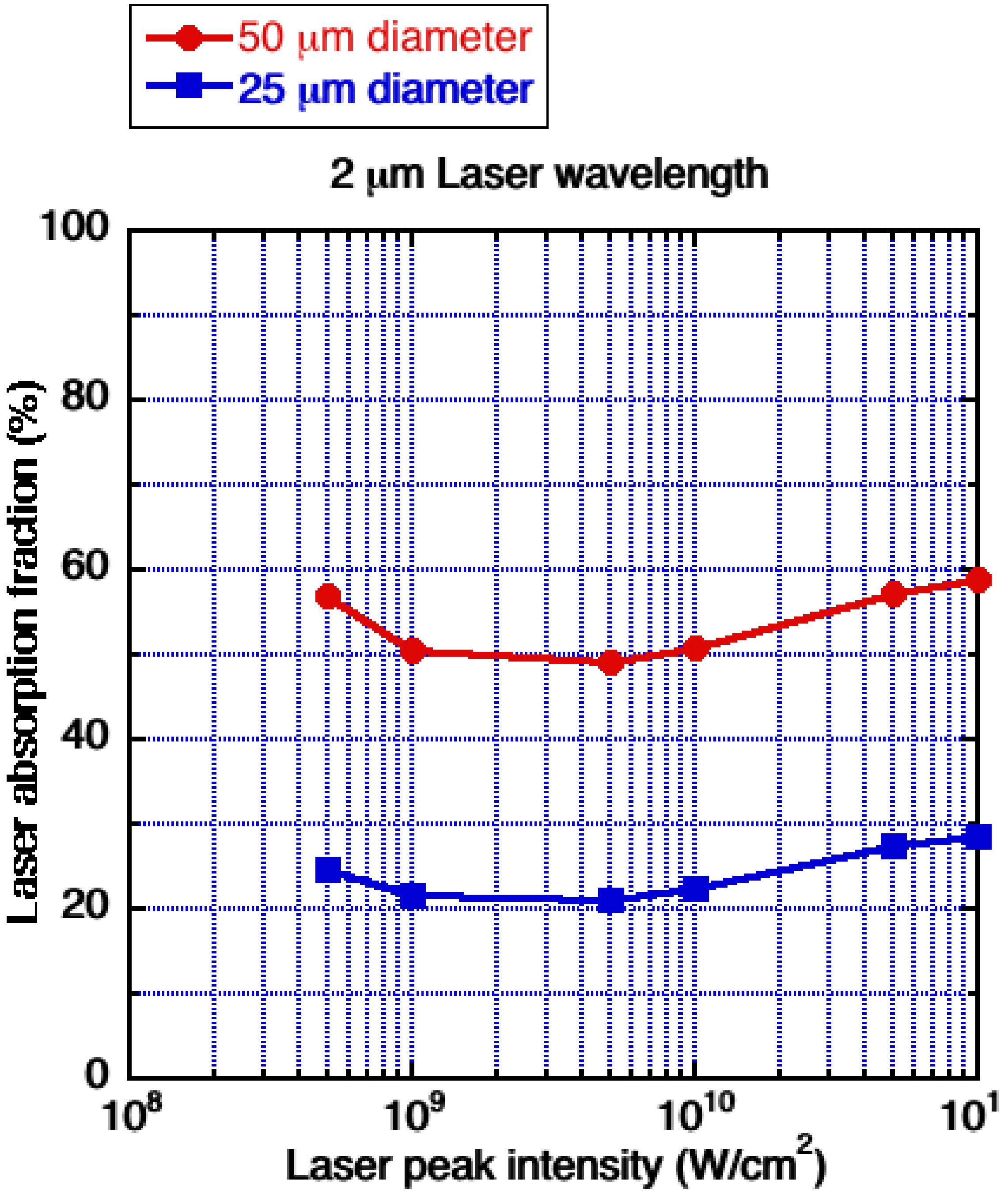
electron temperature (0 – 46 eV)



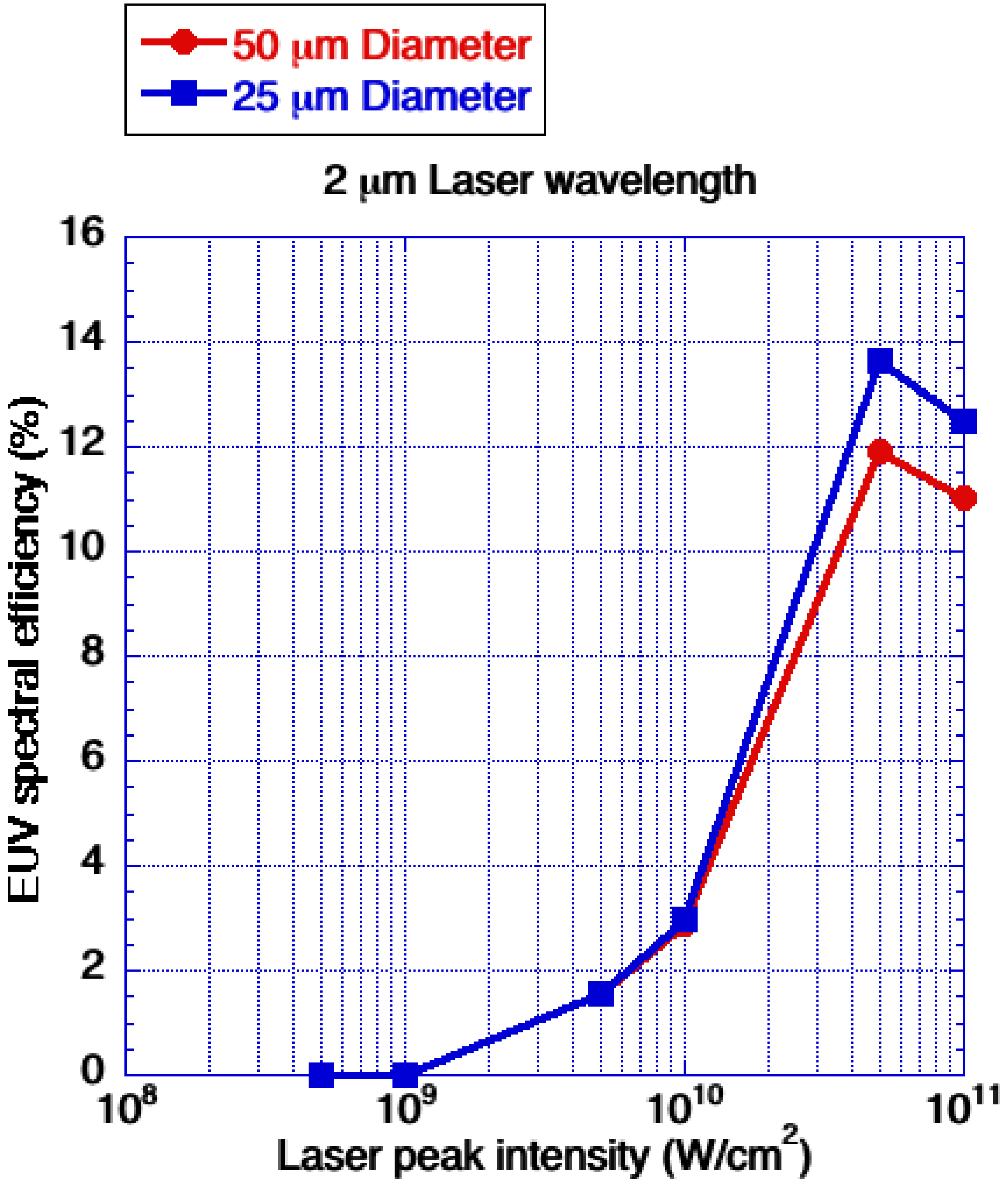
energetics 1

Laser absorption efficiency (LAE) is relatively low because of small target size. Dependence of LAE on targets size can be explained by plasma expansion radius.

laser absorption efficiency



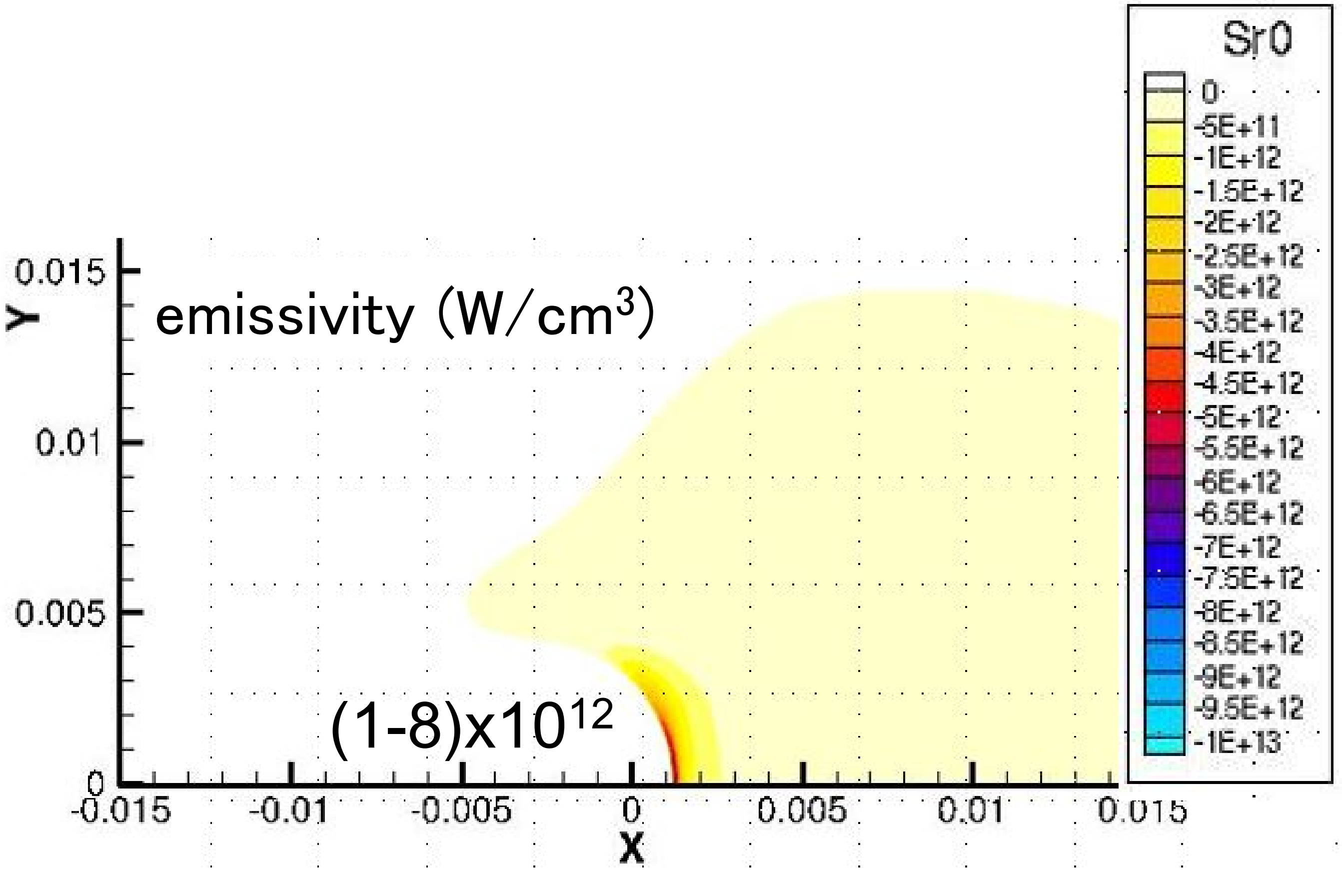
spectral efficiency

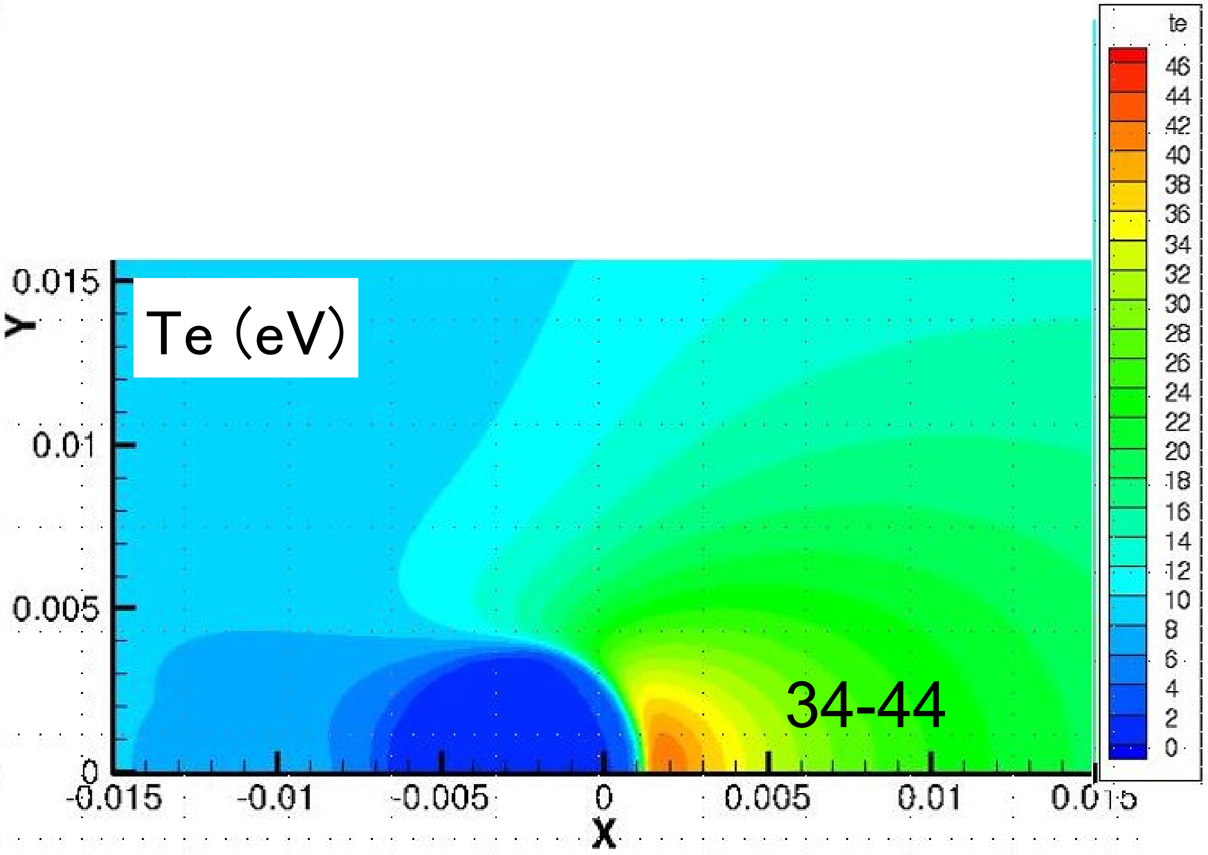


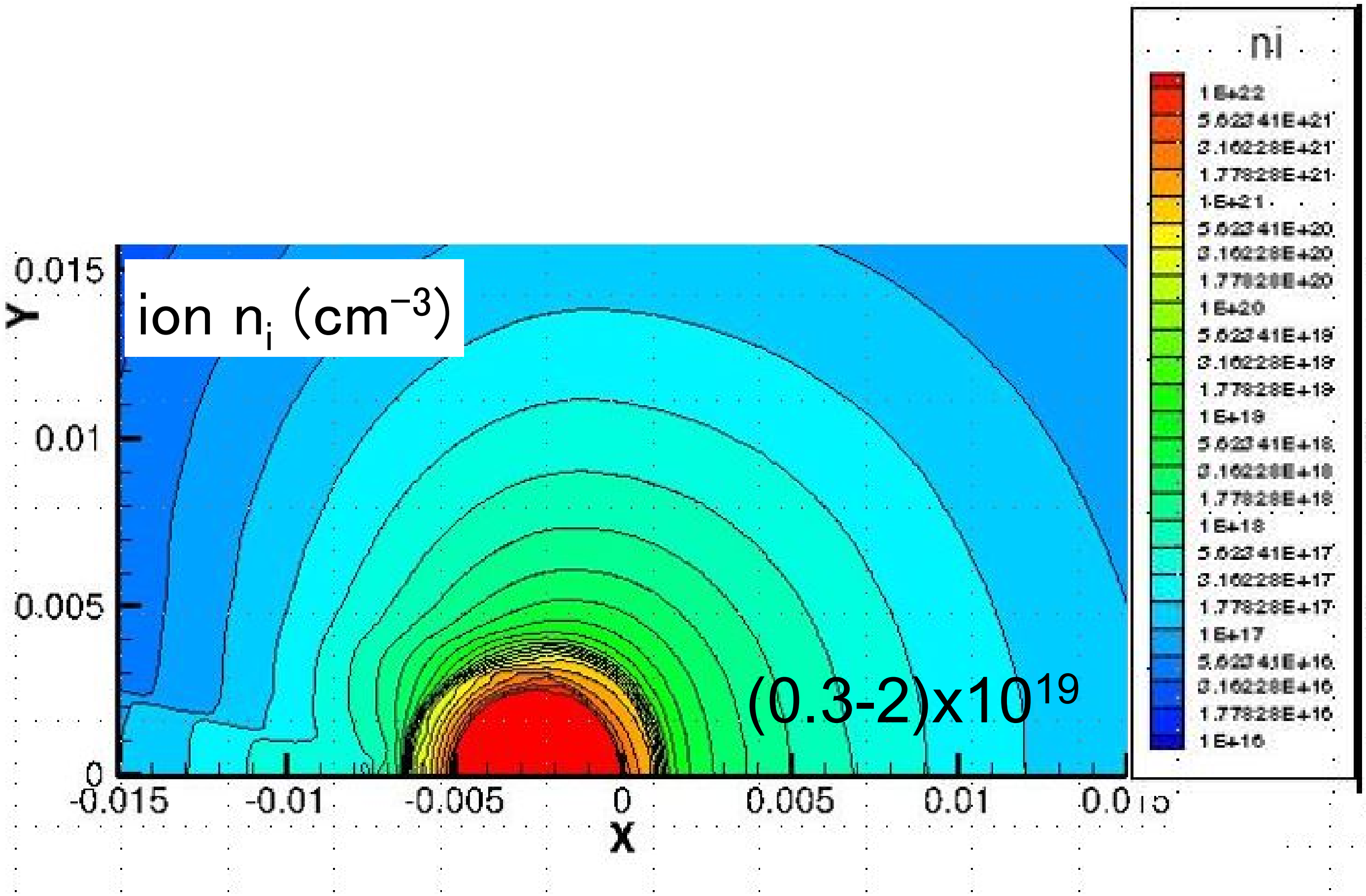
High spectral efficiency results in high CE from laser to EUV.

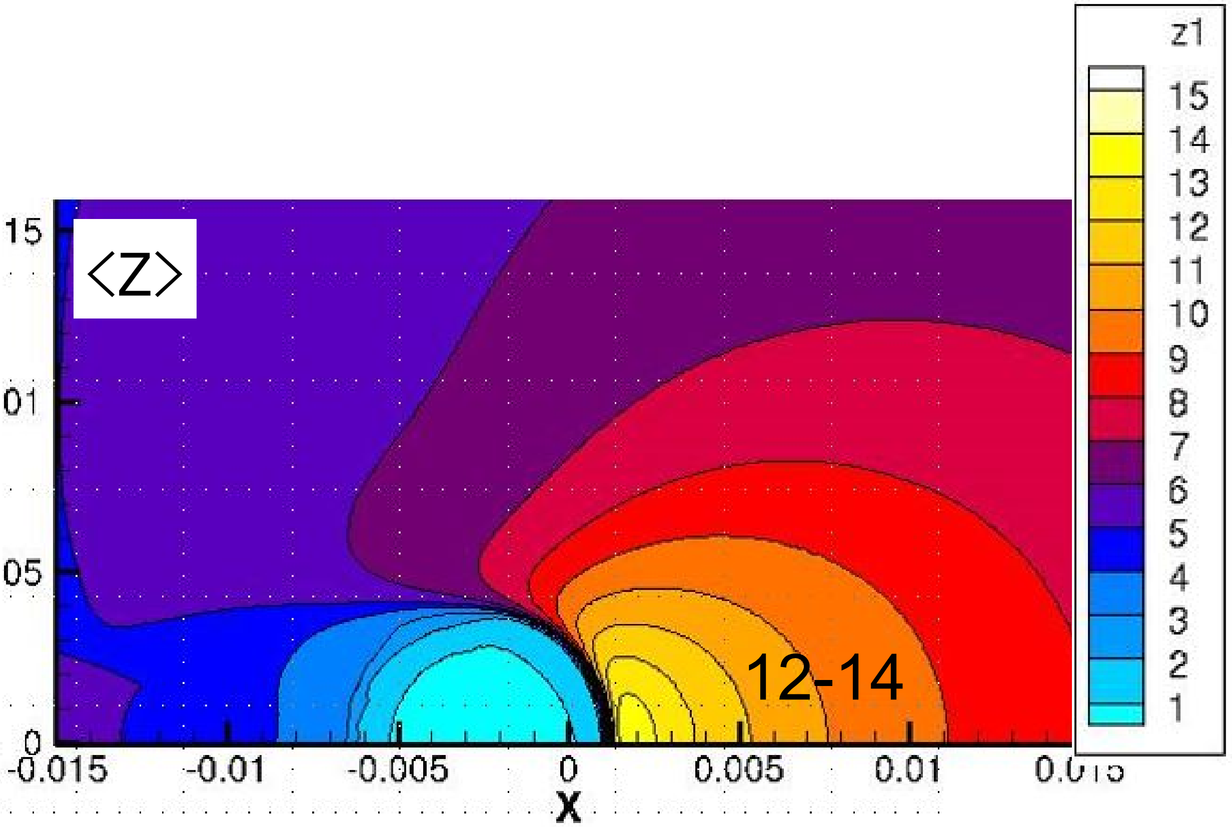
plasma
property 1

2D profiles of emissivity, electron temperature, ion density and ionization at 9 ns for $5x10^{10}$ W/cm^2

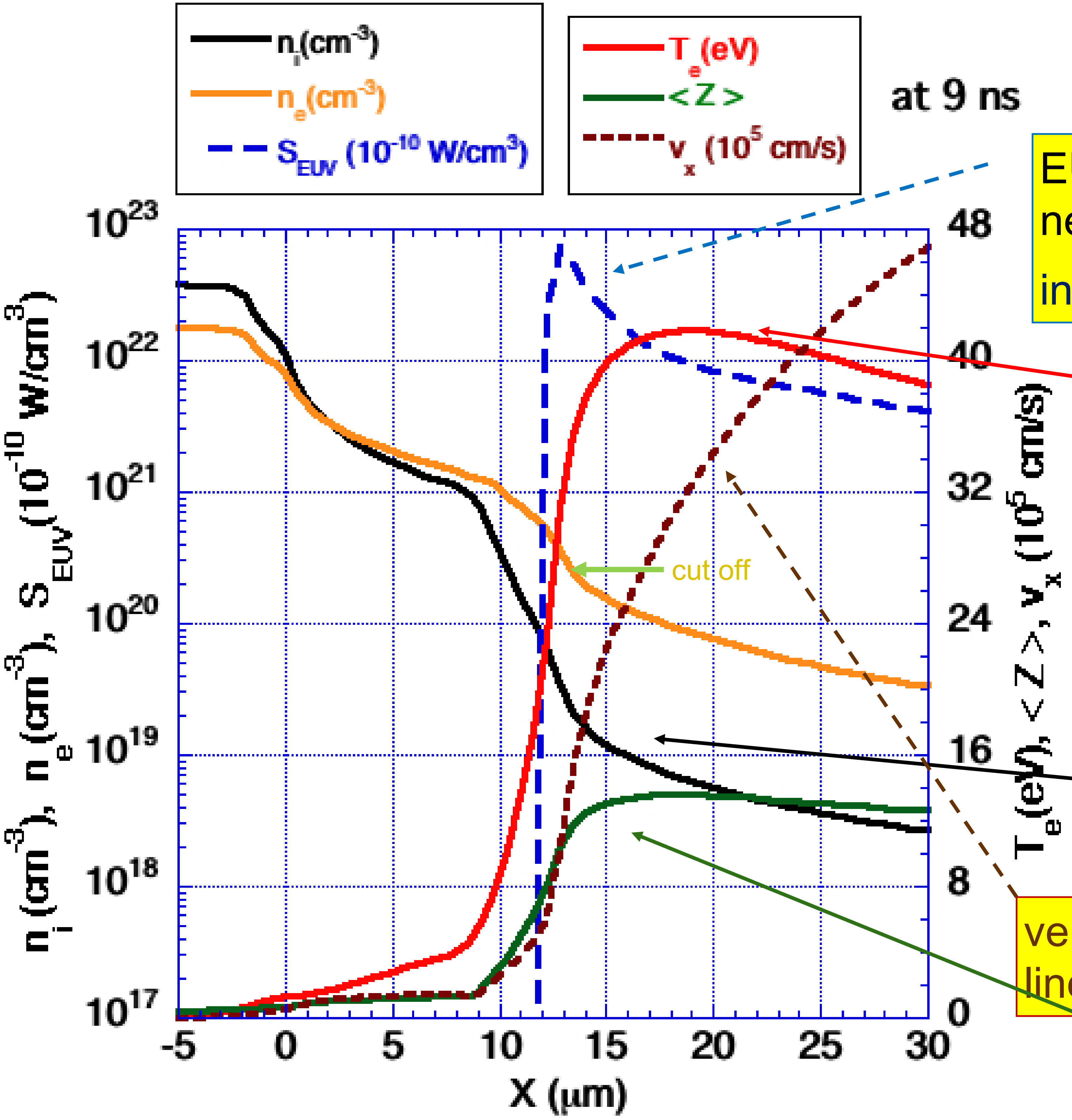








Spatial profiles of electron / ion densities, electron temperature, emissivity and ionization at 9 ns for 5×10^{10} W/cm^2 along the laser axis



EUV emission is localized
near the cut-off surface

inband emissivity: 10^{12}-10^{13} W/cm^{-3}

Isothermal
electron temperature: 34-42 eV

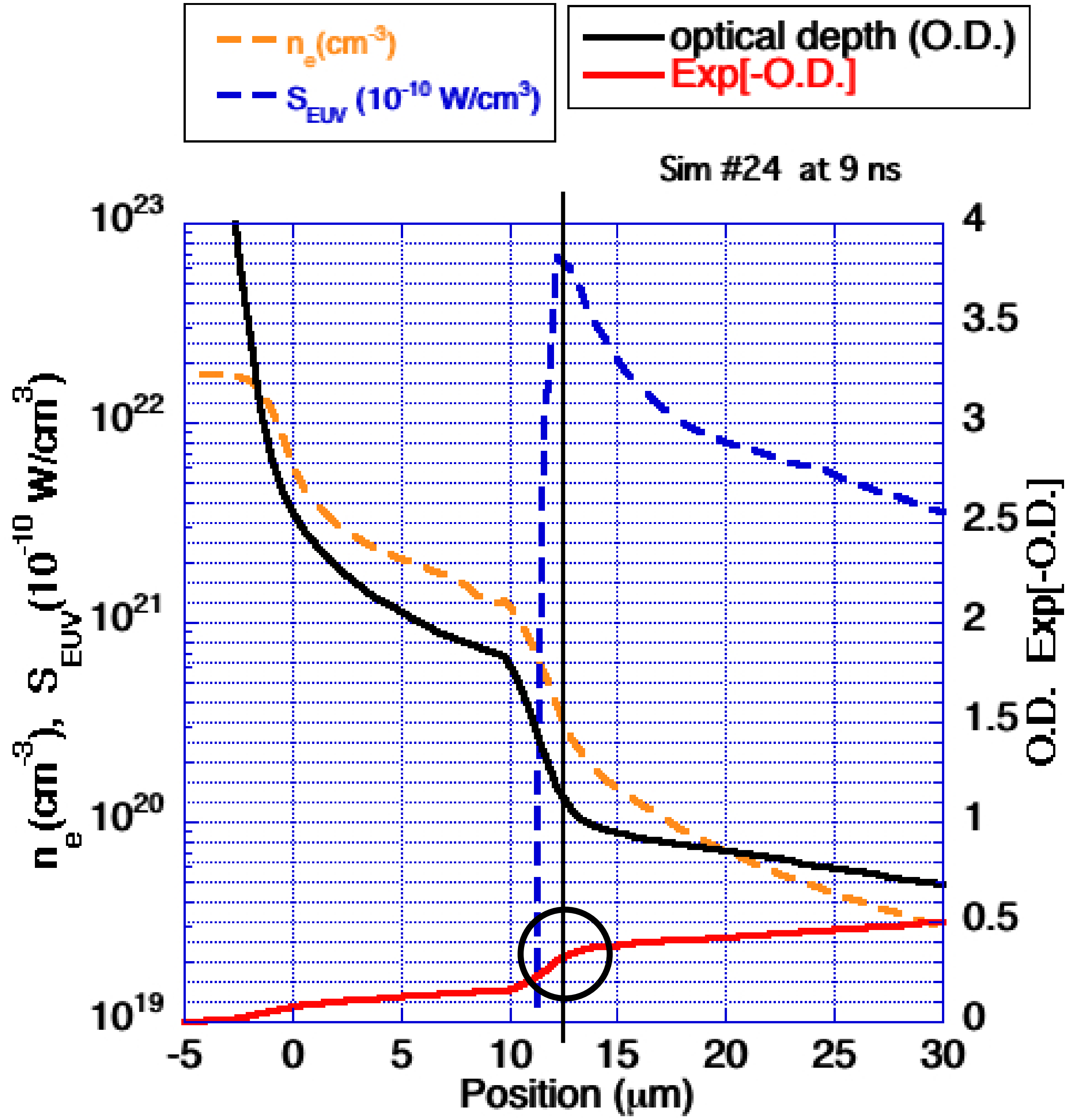
exponential decrease
ion density: 0.7-3×10^{19} cm^{-3}

velocity increases
linearly with distance: 5×10^6 cm/s

average ionization: 12-13

plasma property 3

Spatial profiles of emissivity, optical depth from surface, and electron desnity at 9 ns for 5x10^{10} W/cm^2 along the laser axis



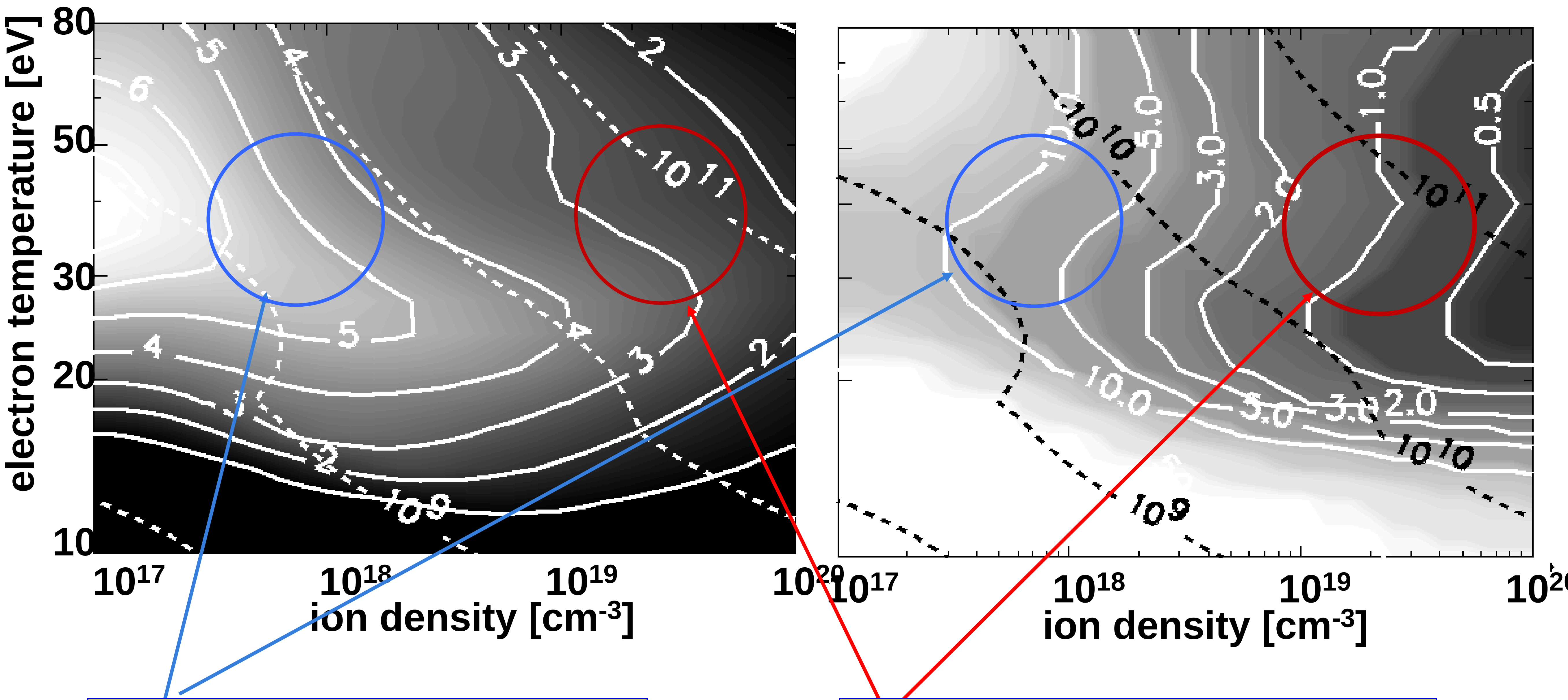
At this time (9ns), only about 30 % of EUV emitted at the peak emittance reaches to the surface. (not optimum pulse duration)

Flux conservation model shows that there exists an optimum pulse duration depending on the laser wavelength. (2008).

Laser intensity required (dotted line: W/cm²)

(a) Conversion efficiency (solid line %)

(b) Optimum pulse duration (solid line: ns)



10 μm laser (CE > 5 %)
low density, low intensity,
and long pulse

1 μm laser (CE > 3%)
medium density & intensity,
short pulse

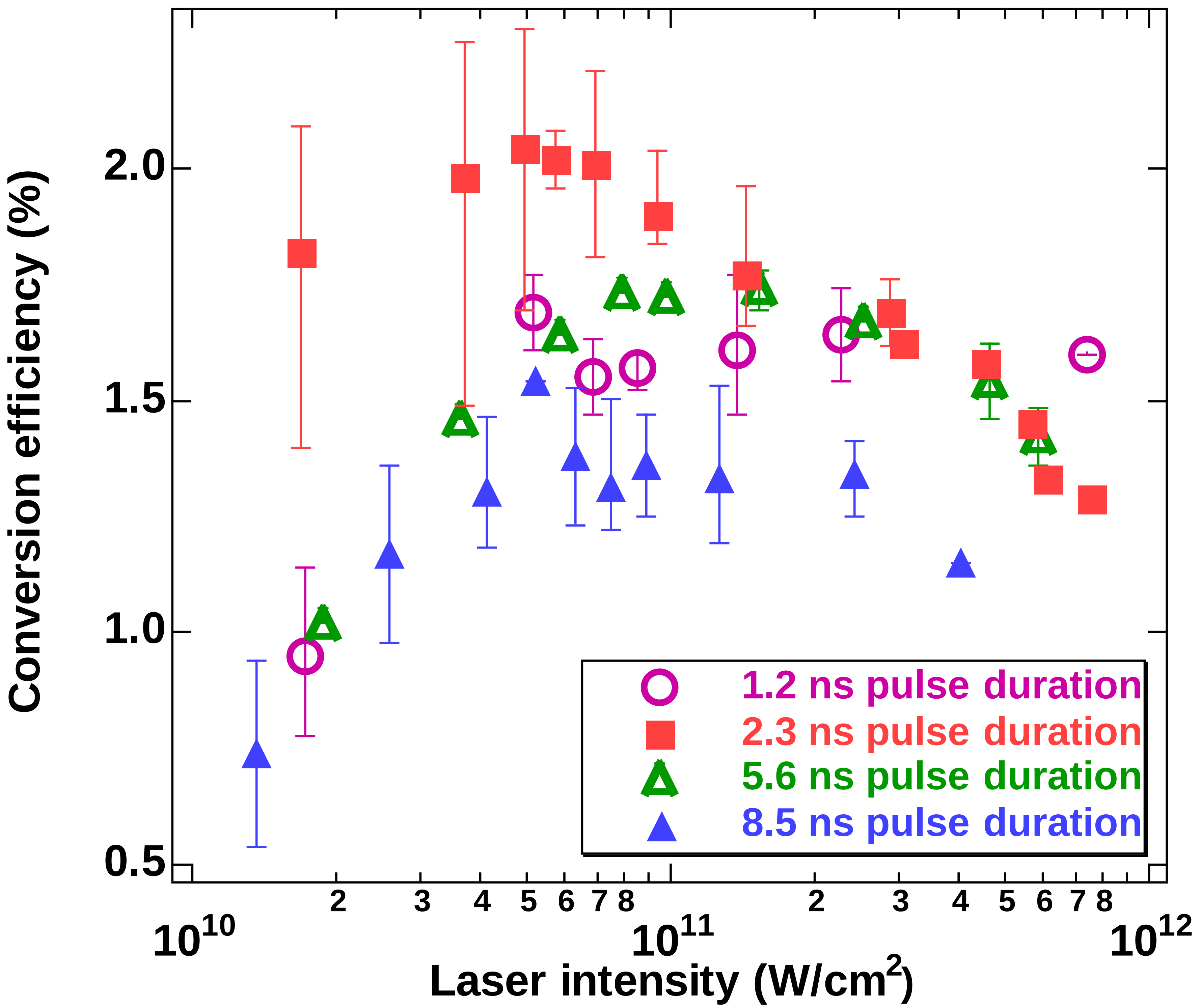
Nishihara et al EUVL Symposium (2003) and EUV Source for Lithography (2006)

Nishihara et al PoP (2008)

modeling 2
optimization

High conversion efficiency was obtained at 2.3 ns pulse duration, which agrees with theoretical model prediction for 1 μm laser.

Dependence of CE on pulse duration and laser intensity



Ando et al APL (2006)

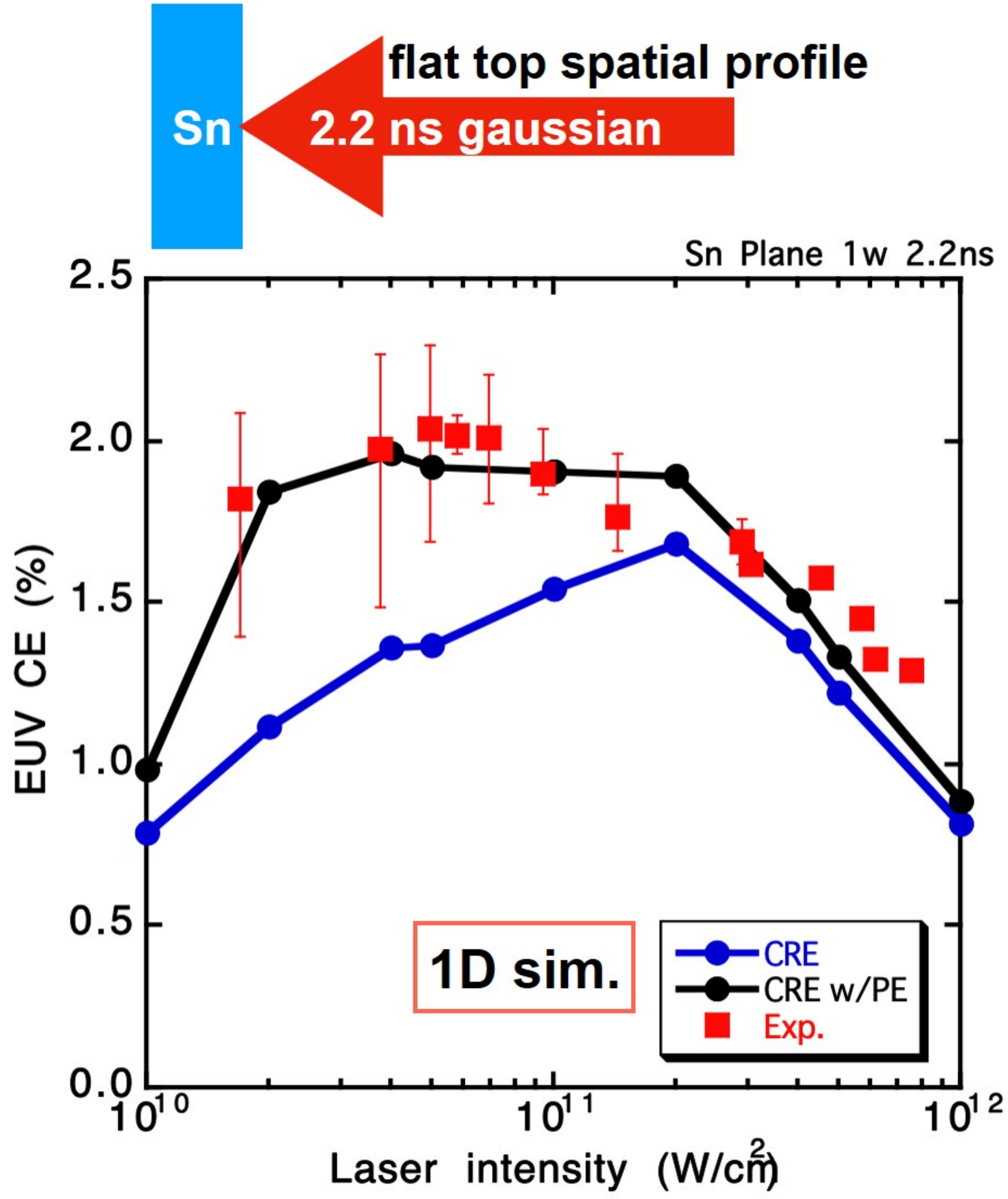
comparison 1

Simulation results of EUV CE agree fairly well with the experiments at least for planar targets with 1.06 μm laser.

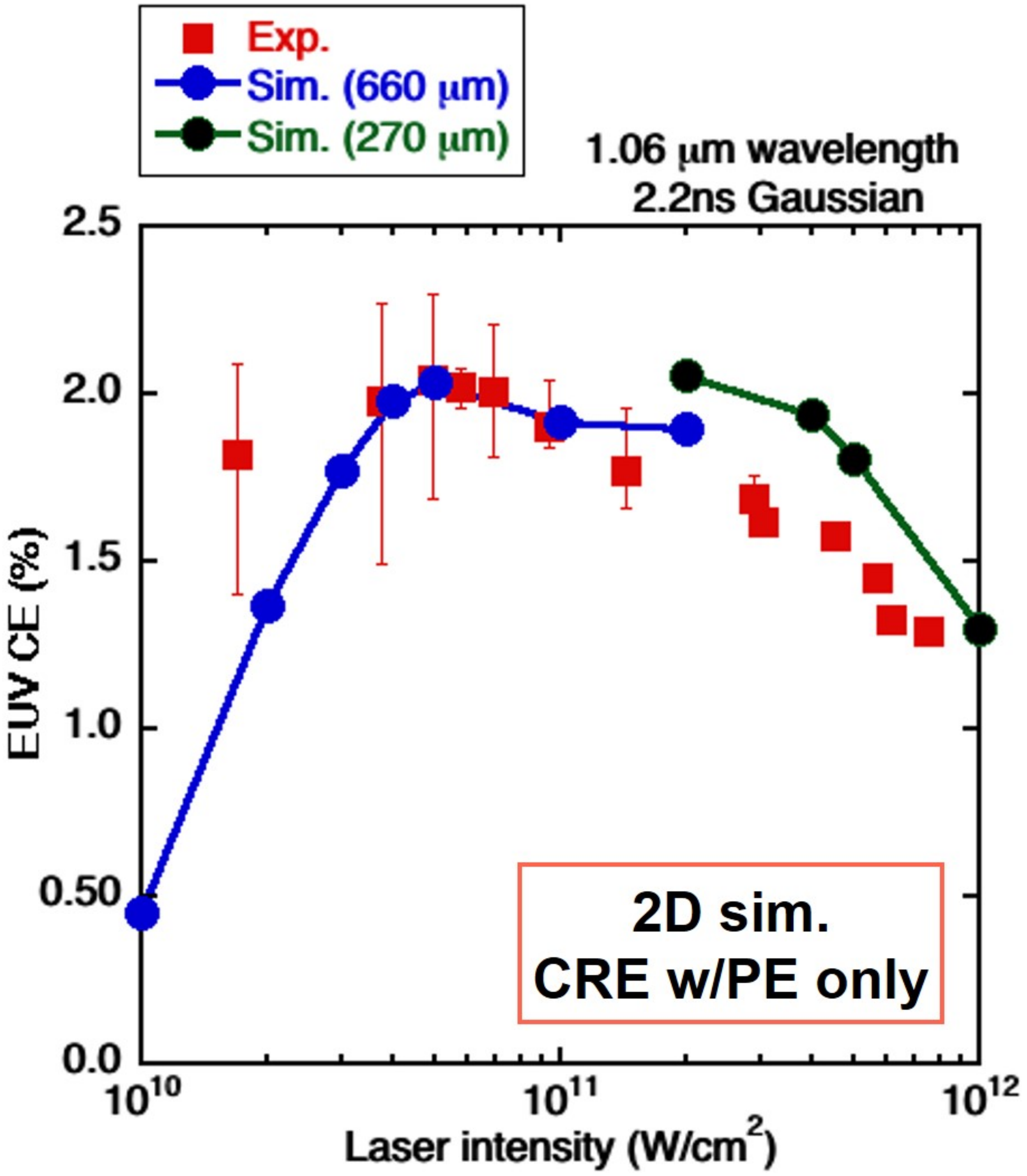
EUV symposium
2006 Oct. 19@Barcelona, Spain

→ **2019**

Star1D



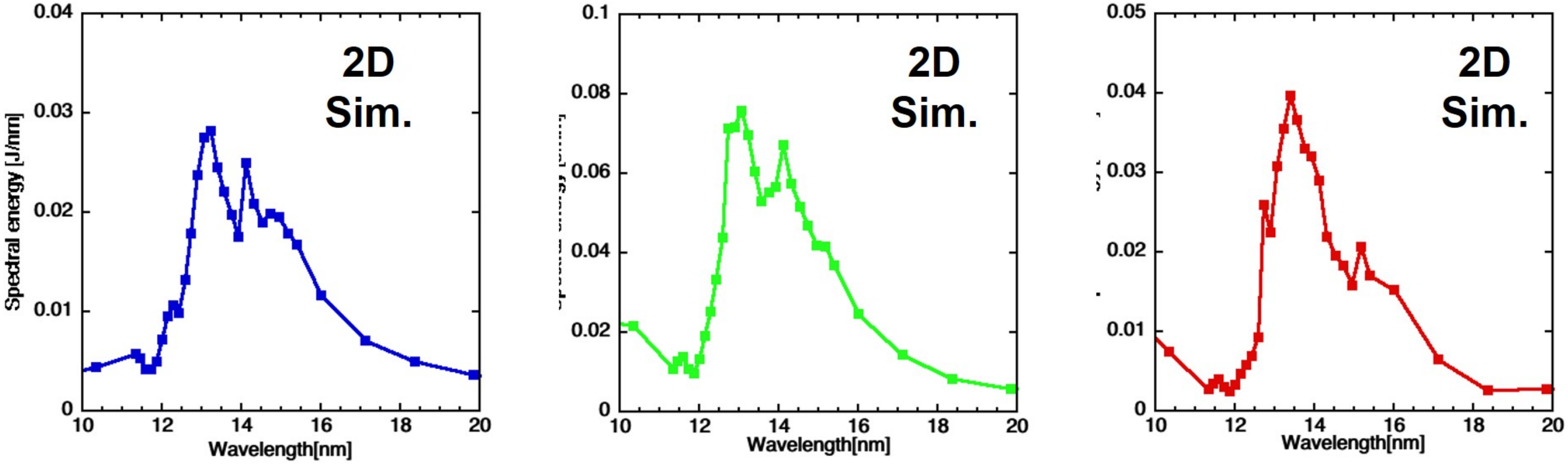
Star2D latest version



comparison 2

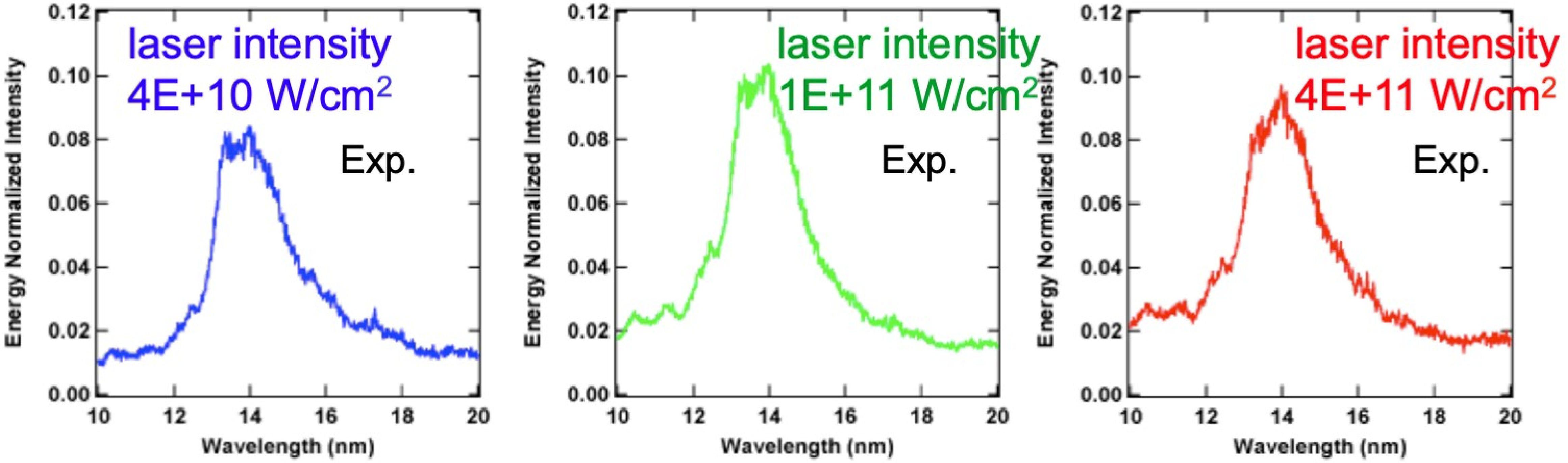
Simulation results of EUV spectra agree fairly well with the experiments at least for planar targets with 1.06 mm laser.

2d simulation



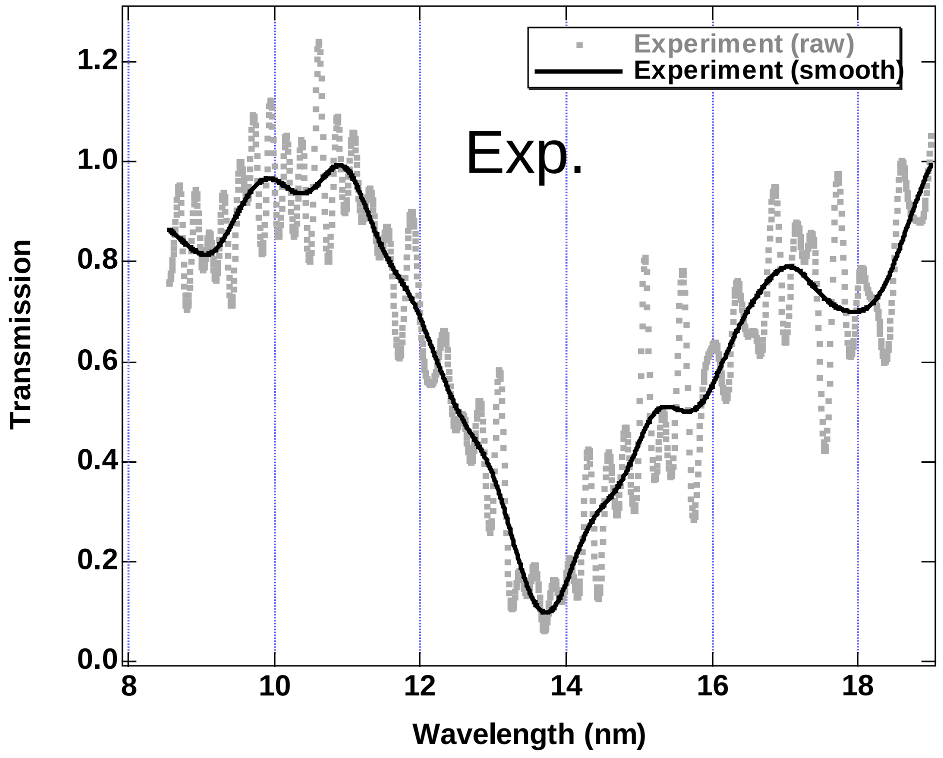
experiments

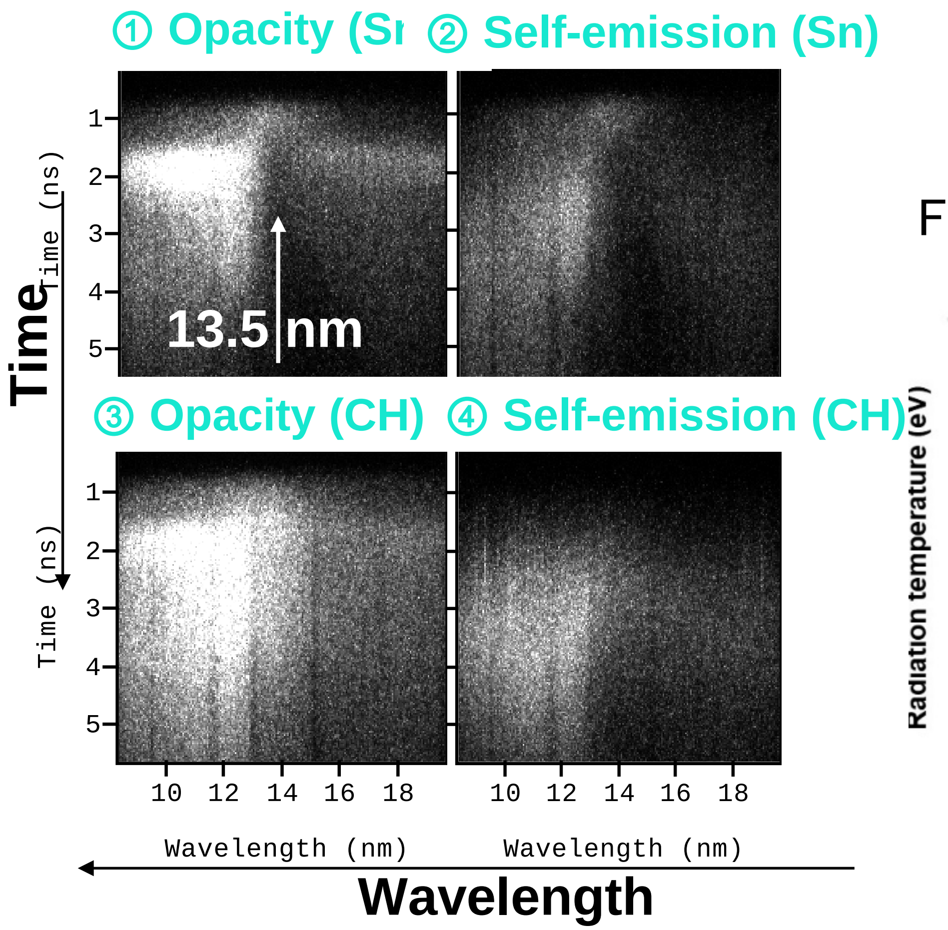
2.2ns 1w plane



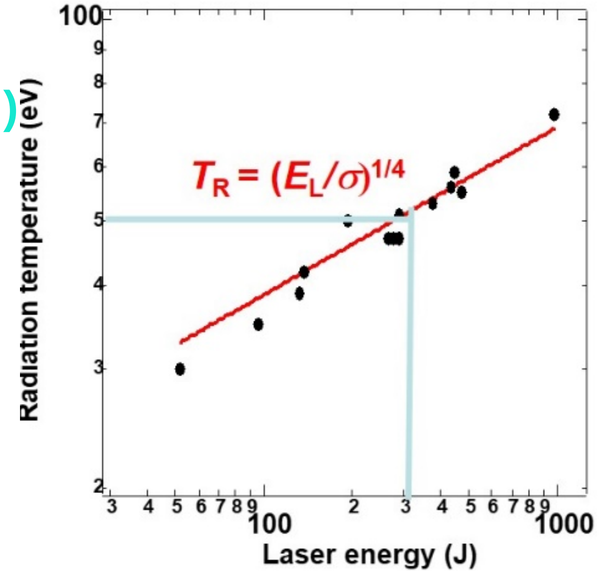
atomic
physics 7
opacity

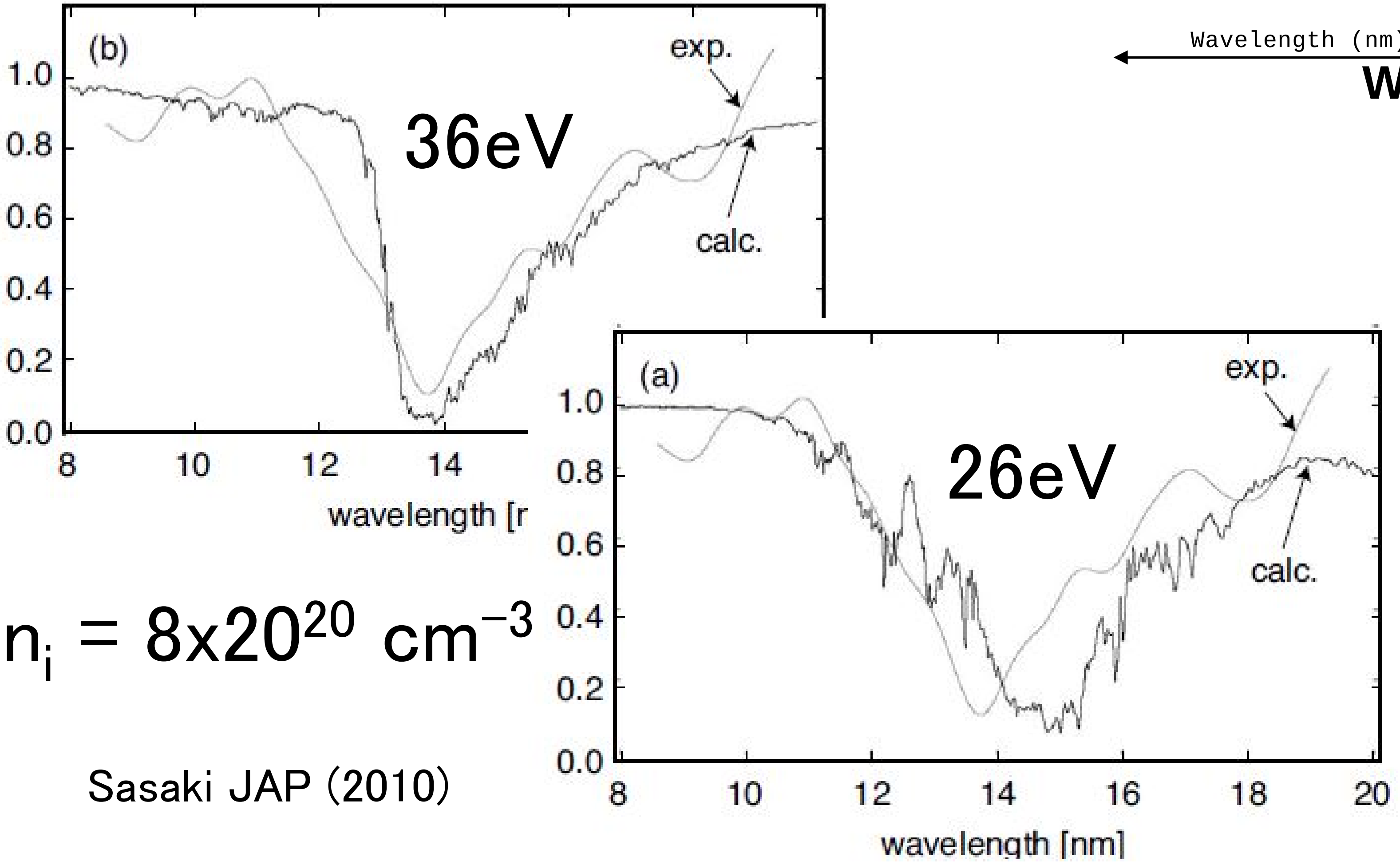
Opacity of Sn heated by thermal radiation (T_R = 50 eV) has been measured and is almost identical with HULLAC, but not details.





Fujioka PRL (2005)

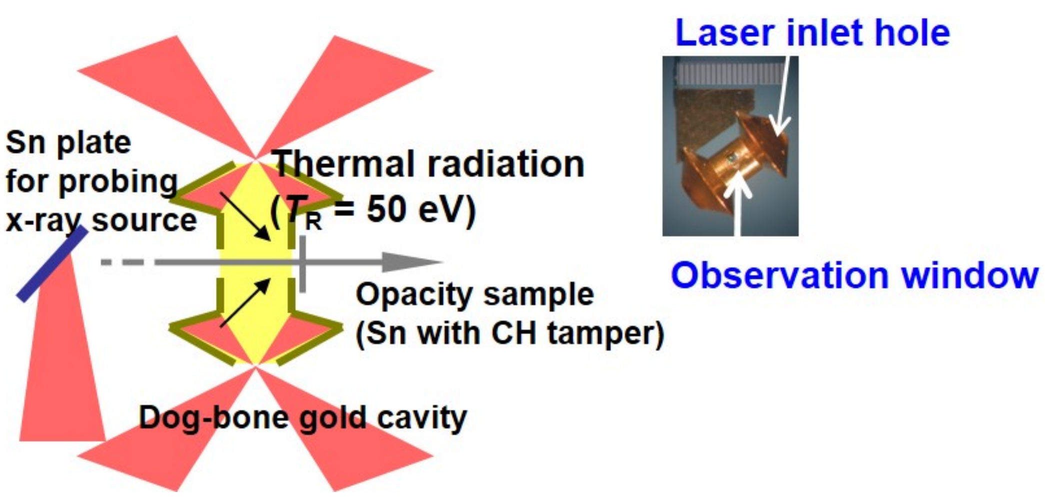




n_i = 8x20^{20} cm^{-3}

Sasaki JAP (2010)

Schematic of opacity measurement



atomic 1

Model of JATOM code to calculate Sn opacity

A. Sasaki et al., J. Appl. Phys. 107, 113303 (2010)

Atomic kinetics (calculation of population)

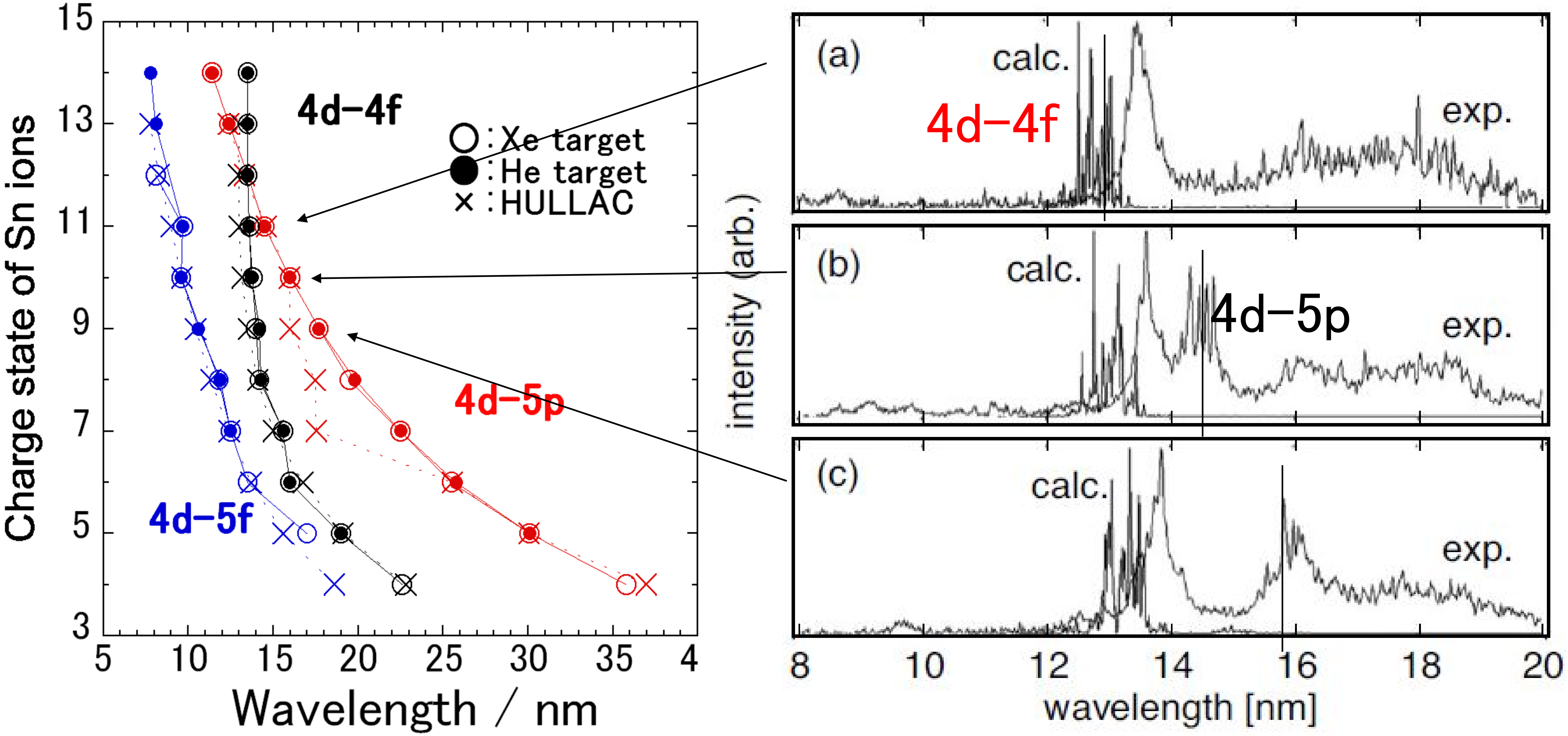
- LTE and nLTE (CRE) plasmas.
- Configuration averaged levels;
  defined by (*n*, *l*), neutral Sn – Sn^{32+} , ≈100 levels/ion.
- Energy levels, rate of radiative decay, and autoionization from Hullac
- Rate of collisional ionization and excitation, and radiative recombination using empirical formula (Lotz and Mewe), as a function of excited (ionization) energy and oscillator strength for dipole transitions.
- Dielectronic recombination process is taken into account by including double excited states explicitly.

Emissivity & Opacity

- Bound-bound, bound-free, free-free transitions are taken into account.
- Spectral profile of 4d-4f, 4p-4d arrays (UTA) determined by the effect of configuration interaction (CI) in EUV wavelength region are taken into account.
- Wavelength of UTA is corrected based on experimental spectrum.
- Spectral grid size; ΔE=0.2 eV

Schematic differences of 0.4 nm exist for 4d-4f transitions Δn = 0 because of the configuration interaction for Sn.

comparison of theory (HULLAC) and experimental Sn energy levels



We fitted the calculated profiles to CXS at 13.5nm peak.

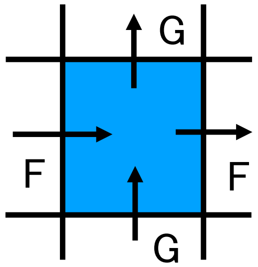
Sasaki et al HEDP (2007) & JAP(2010)

Star2D code calculates one-fluid 2D Eulerian hydrodynamic equations with the two temperature model of ion and electron subsystems.

■ Conservative form of Euler equations

$$\boxed{\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{F}}{\partial x}+\frac{\partial \mathbf{G}}{\partial y}=\mathbf{S}}$$

geometrical tensor components



$$\mathbf{U}=\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ \rho e_t\end{pmatrix},\ \mathbf{F}=\begin{pmatrix}\rho u\\ \rho u^2+p_T\\ \rho v u\\ (\rho e_t+p_T)u\end{pmatrix},\ \mathbf{G}=\begin{pmatrix}\rho v\\ \rho u v\\ \rho v^2+p_T\\ (\rho e_t+p_T)v\end{pmatrix}$$

conservative variables

x-directional flux

y-directional flux

ρ	mass density
$\mathbf{v}=\begin{pmatrix}u\\ v\end{pmatrix}$	velocity
T_i T_e	temperature
$e_t=e_{int}+\frac{1}{2}\lvert\mathbf{v}^2\rvert$	specific total energy
$e_{int}=e_{i\ int}+e_{e\ int}$	specific internal energy
$e_i=e_i(\rho,T_i)$	(ion part)
$e_e=e_e(\rho,T_e)$	(electron part)
$p_T=p_i+p_e$	total pressure
$p_i=p_i(\rho,T_i)$	ion pressure
$p_e=p_e(\rho,T_e)$	electron pressure with cold part

■ Non-conservative form of temperature equations

$$\rho c_{vi}\left\{\frac{\partial T_i}{\partial t}+(\mathbf{v}\cdot\nabla)T_i\right\}=-\left\{T_i\left(\frac{\partial p_i}{\partial T_i}\right)_\rho+q\right\}(\nabla\cdot\mathbf{v})+\nabla\cdot(\kappa_i\nabla T_i)+\alpha(T_e-T_i)$$

$$\rho c_{ve}\left\{\frac{\partial T_e}{\partial t}+(\mathbf{v}\cdot\nabla)T_e\right\}=-\left\{T_e\left(\frac{\partial p_e}{\partial T_e}\right)_\rho\right\}(\nabla\cdot\mathbf{v})+\nabla\cdot(\kappa_e\nabla T_e)-\alpha(T_e-T_i)+S_L+S_{rad}$$

specific heat

advection term

pdV term

artificial viscosity

conduction

e-i relaxation

laser

radiation

Radiation transport is calculated based on the multi-group flux limited diffusion [5] with Novikov photo-excitation model [6].

$$\rho \frac{D}{Dt}\left(\frac{E_\nu}{\rho}\right) + \nabla \cdot D_\nu \nabla E_\nu = 4\pi\eta_\nu - c\chi_\nu E_\nu$$

Multi-group diffusion approximation

$$S_{Rad} = -\int (4\pi\eta_\nu - c\chi_\nu E_\nu) d\nu$$

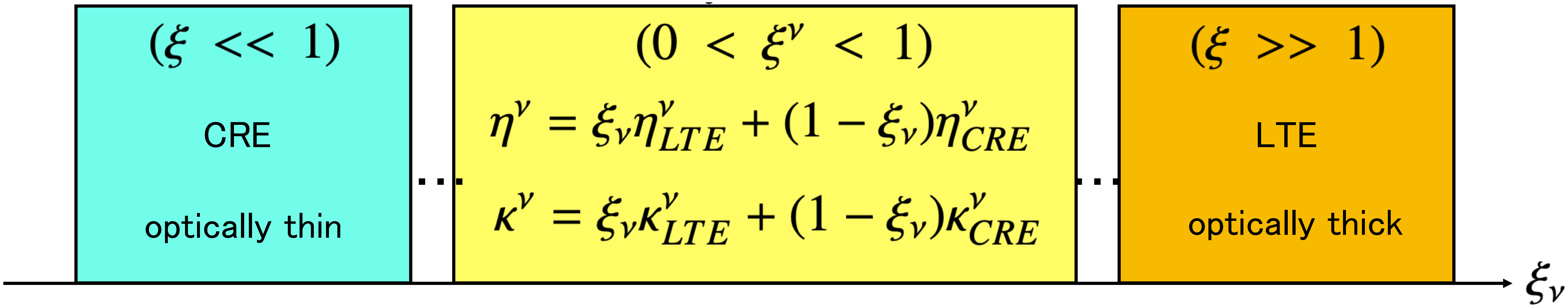
Radiation heating term

$$\xi_\nu = E^\nu(x,t)/U^\nu(T_e(x),t)$$

Degree of planckian

Radiation energy density

Planck function



$(\xi << 1)$

CRE

optically thin

$(0 < \xi^\nu < 1)$

$$\eta^\nu = \xi_\nu \eta^\nu_{LTE} + (1-\xi_\nu)\eta^\nu_{CRE}$$

$$\kappa^\nu = \xi_\nu \kappa^\nu_{LTE} + (1-\xi_\nu)\kappa^\nu_{CRE}$$

$(\xi >> 1)$

LTE

optically thick

$$< Z >_{CRE} (n_e, T_e^*) =< Z >_{LTE} (n_e, T_e(x'))$$

We consider photo-excitation only.

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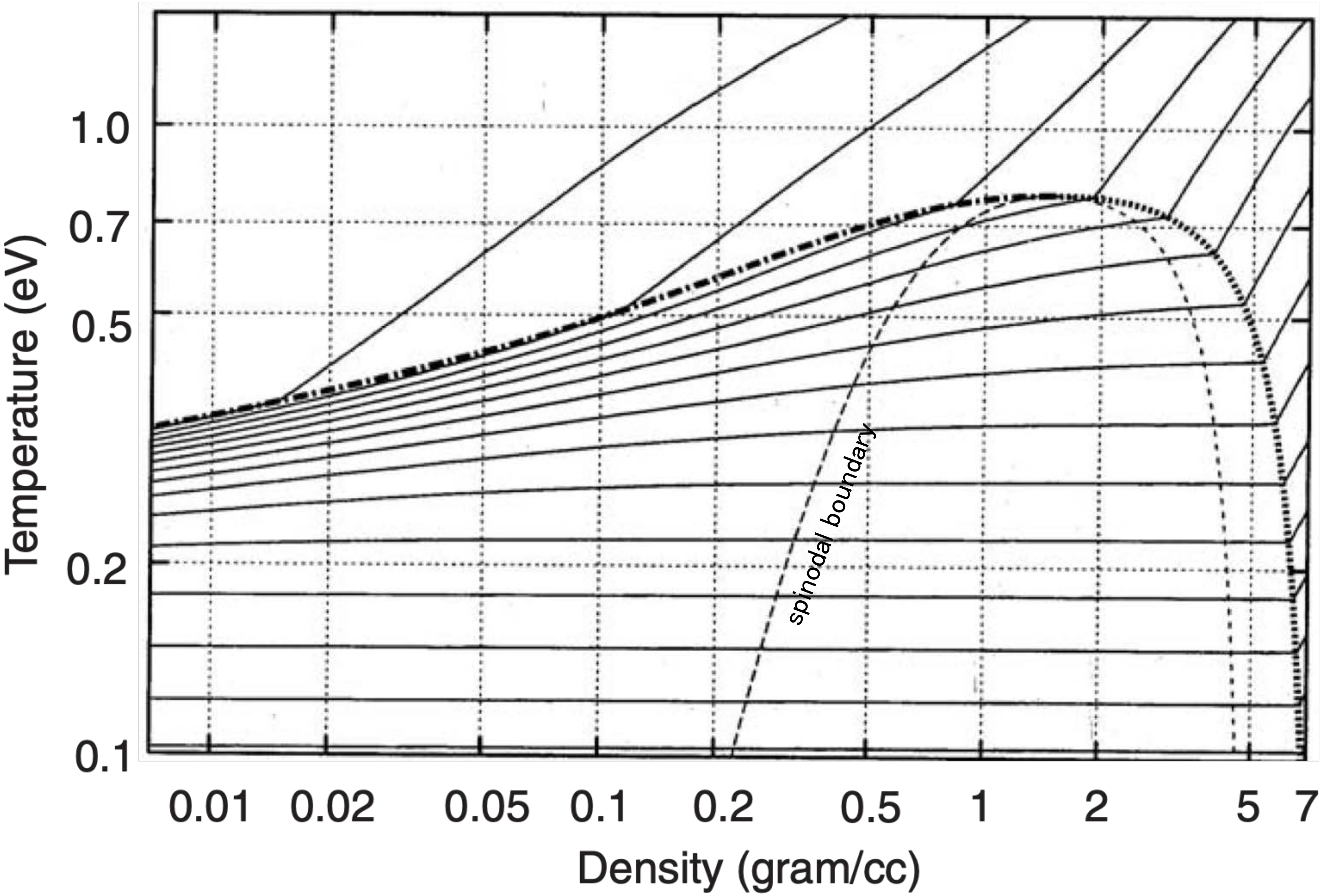
[5] D. Mihalas and B. W. Mihalas, ”Foundations of Radiation Hydrodyanmics” Oxford Univ Press New York 1984.

[6] A. F. Nikiforov, V. G. Novikov, V. B. Uvarov and A. Iacob, “ Quantum−Statistical Models of Hot Dense Matter:Methods for Computation and Equation of State ”, Progress in Mathematical Physics, Birkhauser, (2005).

Liquid - gas two phase equation of state (EOS) for tin was introduced to the hydro simulation.

pressure



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[12] R. More et al. / Journal of Quantitative Spectroscopy & Radiative Transfer 99 (2006) 409–424

Conclusion

- We have presented the simulation data proposed for the code comparison work shop by Drs. J. Sheil and O. Versolato. Simulations were performed with use of 2d radiation hydrodynamic code “STAR” developed.

- The results showed that the conversion efficiency of 2.3 % could be achieved by using 2 μm laser with the laser intensity of 5x10^{10} W/cm^2 and the pulse duration of 10 ns. We also discussed plasma conditions and physics related to the results.

- The pulse duration of 10 ns may not be an optimum condition (too long) for 2μm laser.

- Models in “STAR” have been briefly explained with some comparisons with 1.06 mm experiments performed at Osaka University.