Modeling of LPP EUV Light Source at Japan MEXT Leading Project

Outline of talk

- power balance model and conversion efficiency
  laser wavelength, pulse duration, tin and xenon
- improvement of atomic models
  Xe energy level, configuration interaction, opacity
- comparsion with experiments
  EUV spectra, electron density profile, fast ion

K. Nishihara, K. Fujima[1], H. Furukawa[2], K. Gamada, T. Kagawa[3], Y-G. Kang, T. Kato[4], T. Kawamura[5], F. Koike[6], R. More[4], M. Murakami, T. Nishikawa[7], Sasaki[8], A. Sunahara[2], H. Tanuma[8], V. Zhakhovskii, H. Nishimura, Y. Shimada[2], S. Uchida[2], S. Fujioka, N. Miyanaga and Y. Izawa

Institute of Laser Engineering, Osaka University, [1] Yamanashi University,
[2] Institute for Laser Technology, [3] Nara Women's University,
[4] National Institute for Fusion Science, [5] Tokyo Institute of Technology,
[6] Kitazato University, [7] Okayama University,
[8] Advanced Photon Research Center, JAERI-KANSAI, [9] Tokyo Metropolitan University,

EUVL 2004 Symposium, Miyazaki, Japan, Nov. 2 – 4, 2004

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Power Balance Model of EUV-LPP presented at EUVL03, Antwerp

Consider following energy losses

- kinetic energy loss due to expansion, E_k
- ionization loss, E_i
- radiation loss, E_R ,

and assume a sum of the losses equals to laser flux.

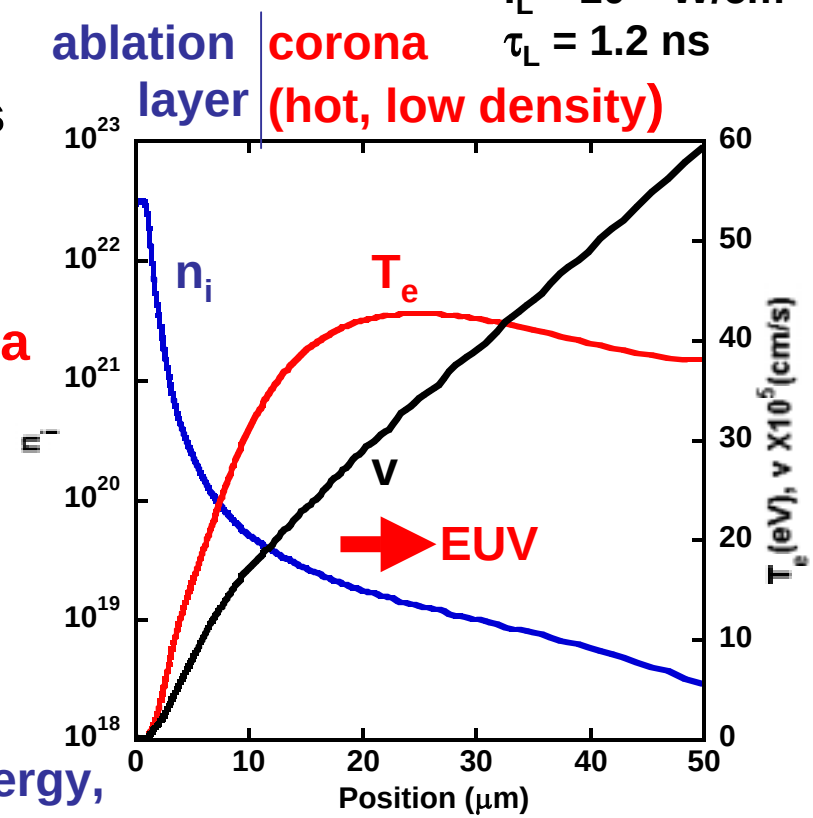
$$I_L = E_k + E_i + E_R$$

Assume isothermal expansion in corona

$$n = n_o \exp(- x/c_s t), \quad v = c_s + x/t$$

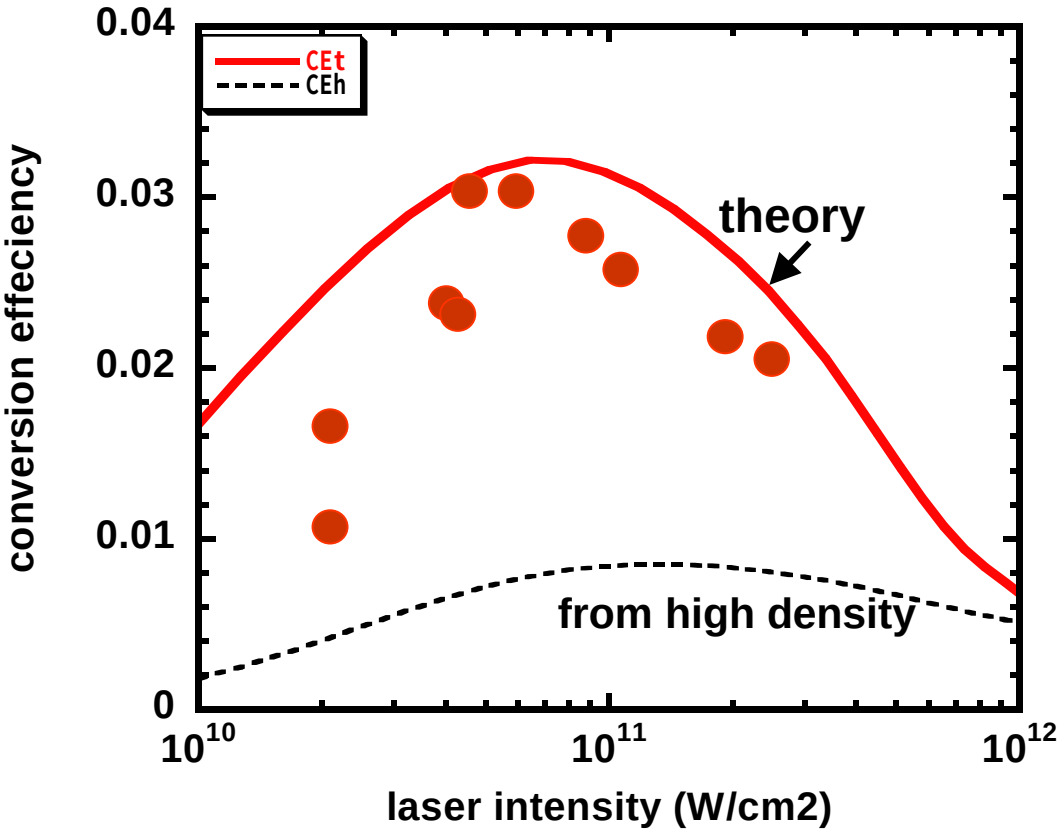
$$E_k = 3\, Z^*(n_i, T_e)\, n_i\, T_e\, c_s ,$$
$$E_i = E_i (n_i, T_e , Z^*(n_i, T_e))\, n_i\, c_s ,$$
$$E_R = P_R(n_i, T_e)\, c_s\, \tau_L / \alpha ,$$

$I_L = 10^{11}$ W/cm^2
τ_L = 1.2 ns



where Z^* : ionization state, E_i : ionization energy,
P_R : emissivity, α (? 1.35(total), 1.1(EUV)) : $P_R \propto n_i^{\alpha}$,
(atomic data and atomic physics !!!!!)
c_s : sound speed, τ_L : laser pulse duration,

Theoretical conversion efficiency obtained from the power balance model agrees fairly well with the experiments with tin, that CE 3% is achieved at 5×10^{10} - 10^{11} W/cm^2.



EUV power at intermediate focus point

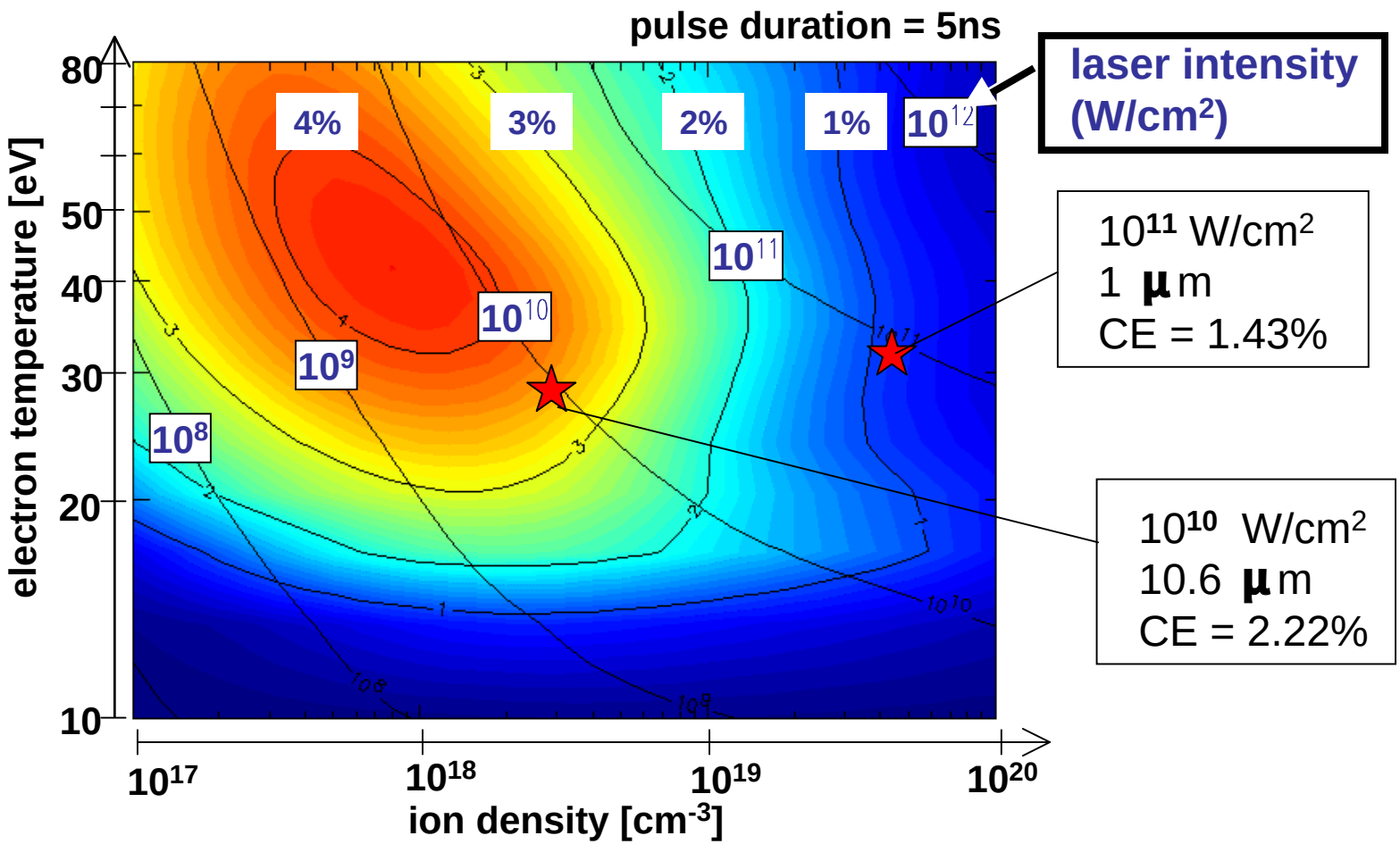
$$P_{EUV} = \eta_{EUV}\, S\, I_L\, \tau_{EUV}\, \varepsilon_{total}\, R_p = 280\ \mathrm{W}$$

laser intensity : $I_L = 10^{11}$ W/cm^2,
pulse width : $\tau_{EUV} = 5$ ns,
repetition rate : $R_p = 10$ kHz ,
plasma size ($\varepsilon_t = 3$ mm^{2}str) :
$\phi \approx 870\mu$m
conversion efficiency :
$\eta_{EUV} = 0.03$
efficiency of focusing system :
$\varepsilon_{total} = \varepsilon_\Omega\, \varepsilon_R\, \varepsilon_{te}\, \varepsilon_{td} = 0.32$

Those results indicate that the source parameters for practical use can be achieved.

Power balance model indicates relatively weak dependence of the conversion efficiency on laser wavelength for tin, which suggests the use of CO_2 laser.

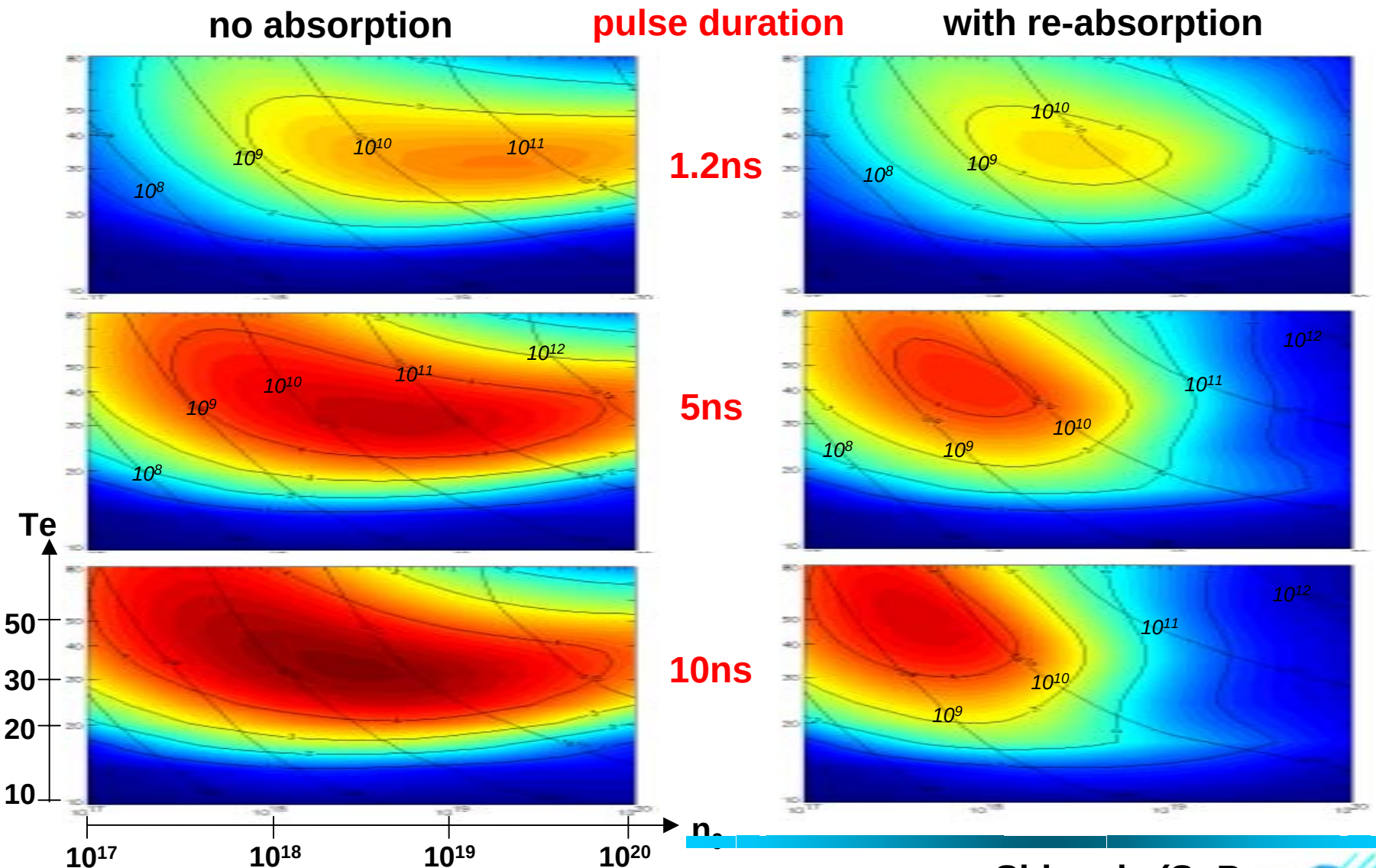
Sn



iso-contour of the conversion efficiency

wavelength dependence: Sunahara(SoP50),Yamaura(SoP25)

Re-absorption of EUV reduces the CE, and optimum density shifts to lower which strongly depends on pulse duration. (tin)

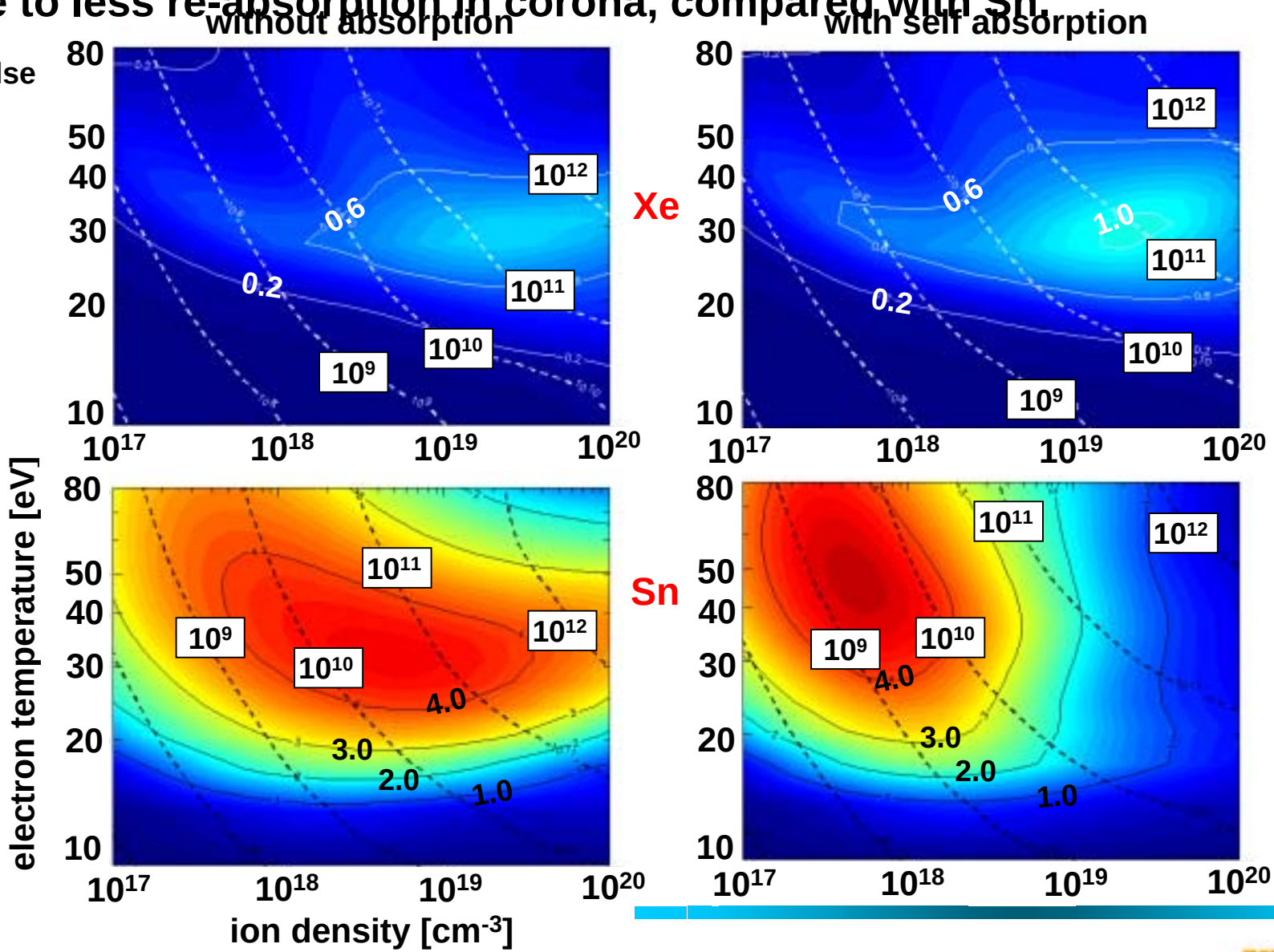


iso-contour of the CE
w/wo reabsorption of EUV

Shimada (SoP
After Gamada

For Xe, high conversion efficiency appears at relatively high density due to less re-absorption in corona, compared with Sn

laser pulse
5.0ns



This suggests relatively longer pulse can be used for Xe compared to Sn

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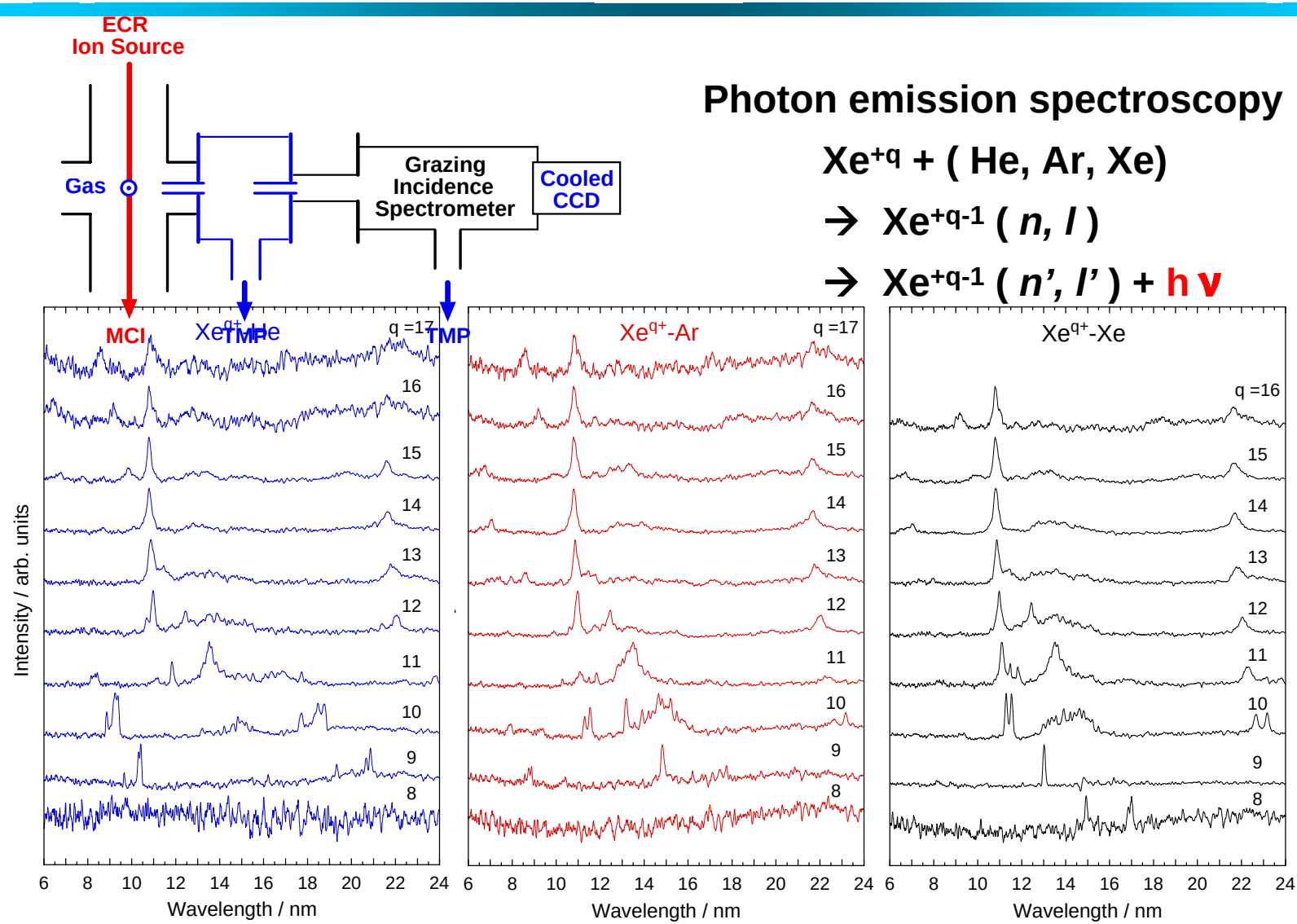
Observation of EUV emission from Xe in charge exchanging collision with rare gas atoms (TMU/OsakaU)



Photon emission spectroscopy :

Xe^{+q} + (He, Ar, Xe)

→ Xe^{+q-1} (*n*, *l*)

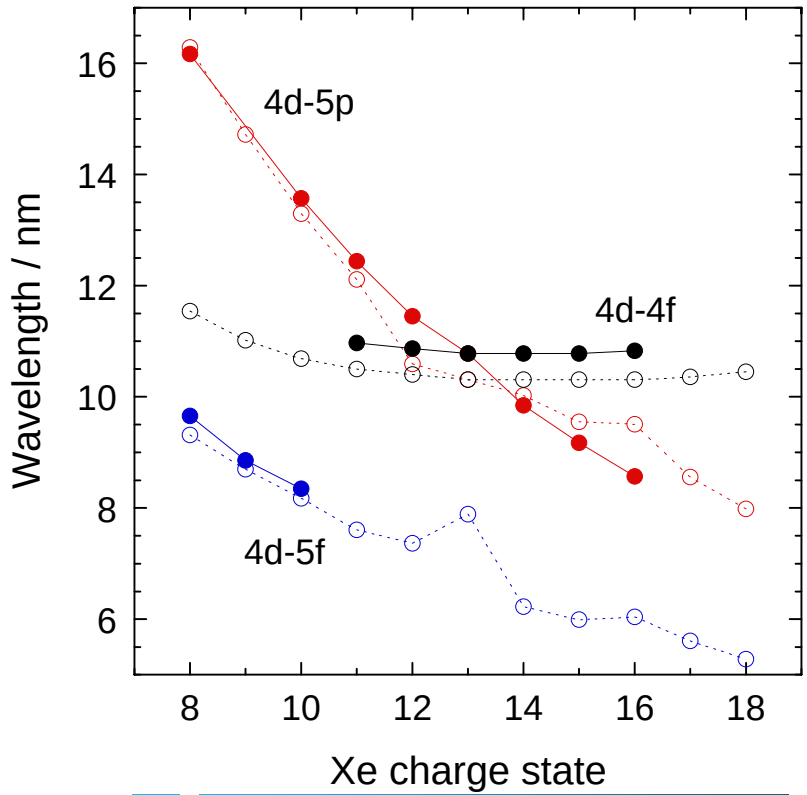
→ Xe^{+q-1} (*n'*, *l'*) + h ν

H. Tanuma (SoP32)

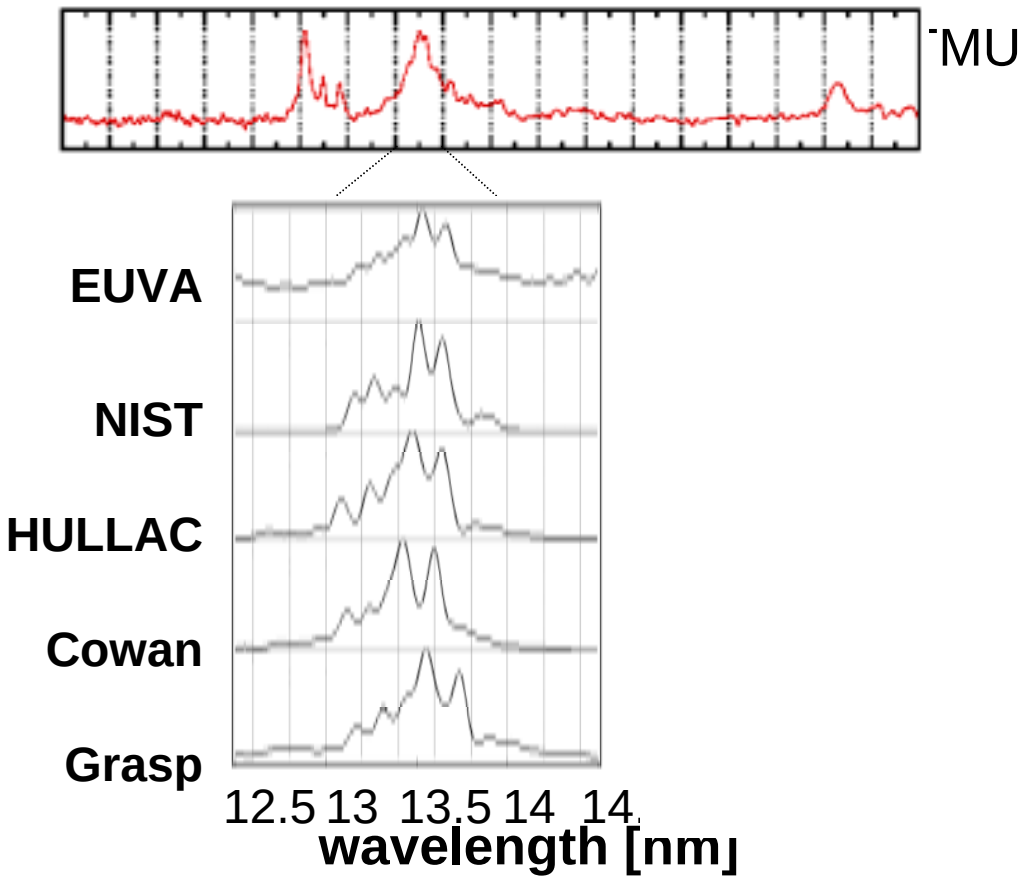
Xe EUV spectra are also observed in CHS and LHD
T. Kato (SoP53)

Experimental wavelengths qualitatively agree with calculation, but not exactly for 4d – 4f transitions

Observed peaks and the HULLAC calculation



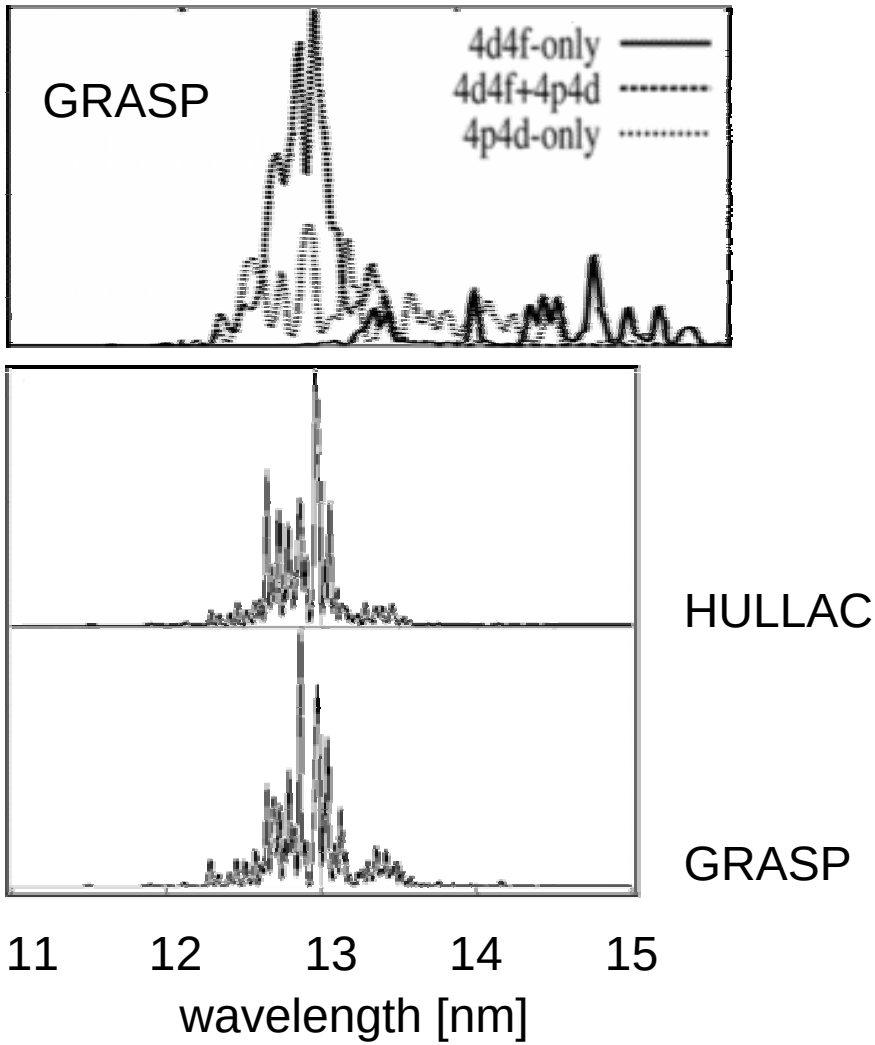
calculated and observed spectra show reasonable agreement of wavelength of 4d-5p transition array of Xe10+.



H. Tanuma (SoP32), A. Sasaki (SoP52), H. Koike (SoP48)

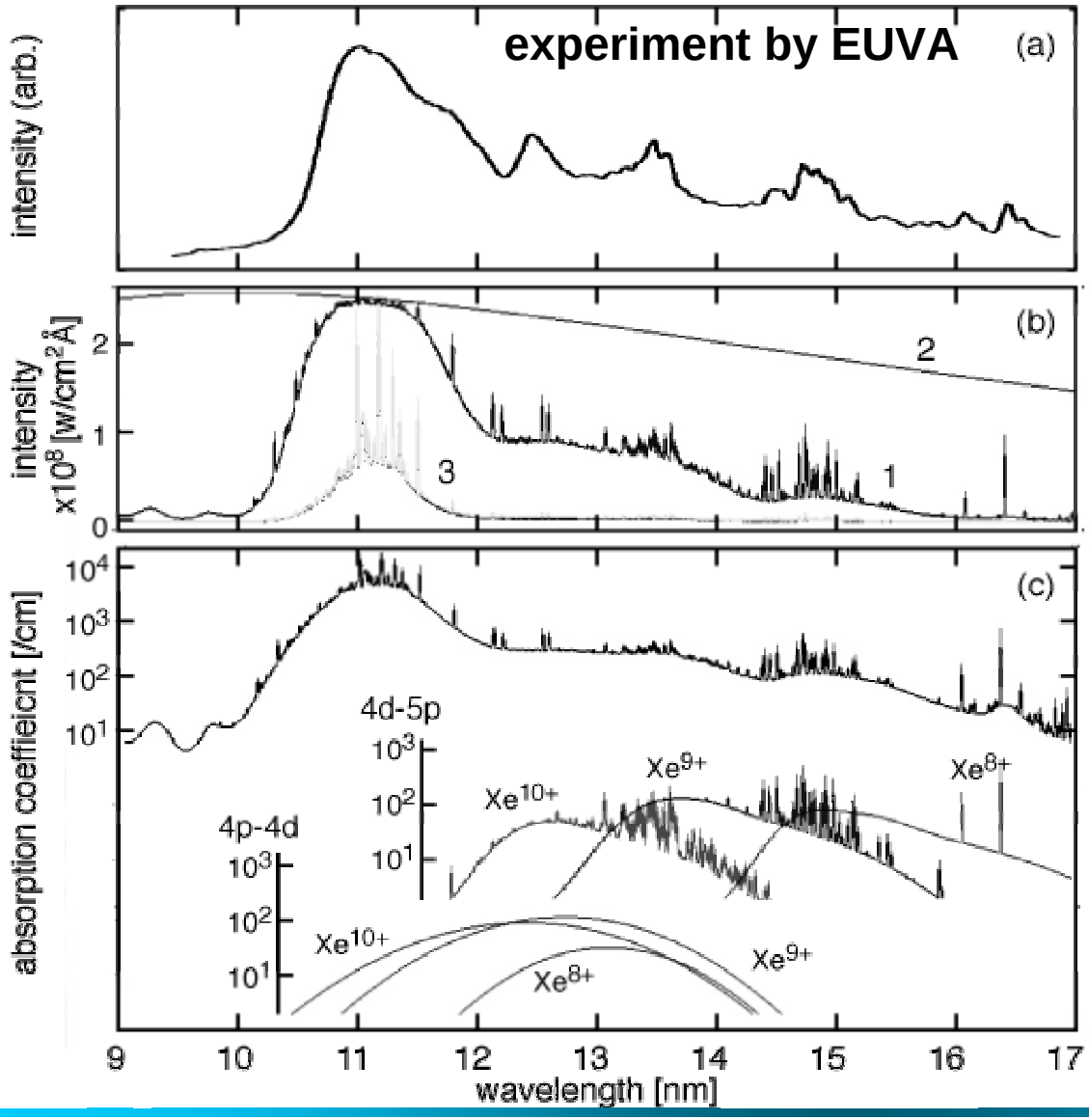
The narrowing of 4f-4d spectra pointed out by O'Sullivan is refined with use of GRASP and HULLAC (Sn^{+12})

Configuration interaction is important : [4d+4f ⟷ 4d+4p]



H. Koike (SoP48), A. Sasaki (SoP52)

Both opacity and satellite lines play important roles in LPP.
(Xe plasma with 4d-4f, 4p-4d and 4d-5p satellite lines)



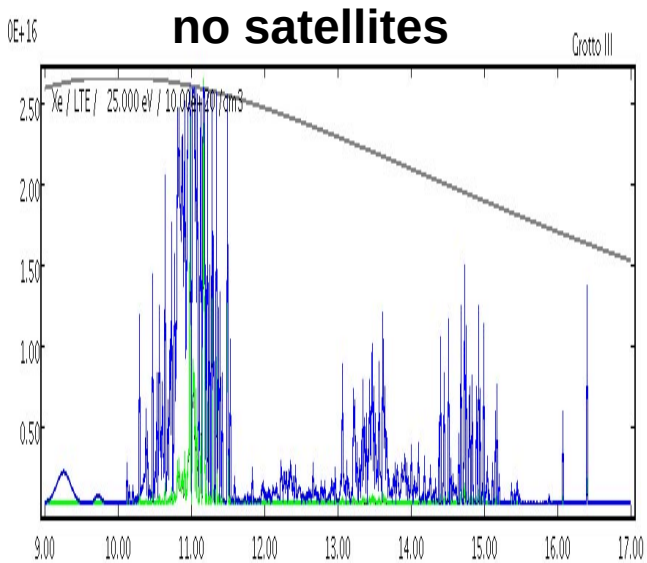
plasma parameters

T_e=25eV

n_e=10^{21}/cm^3

r=10μm

no satellites



Sasaki (SoP52)

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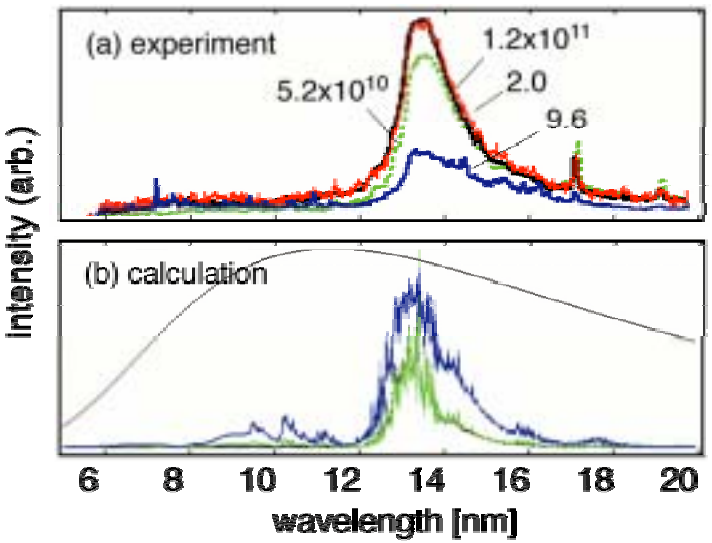
Application of atomic data calculated by the HULLAC or Average Atom with *n, l* splitting to the modeling of the EUV source

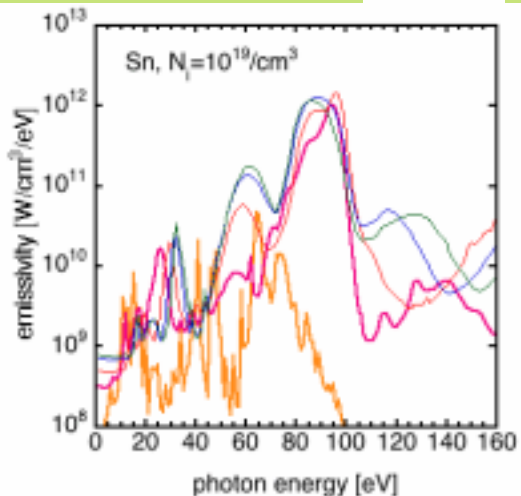
HULLAC / AA → **collisional radiative model** → **radiation hydro-dynamics code**

- energy levels
- oscillator strength
- collisional cross sections

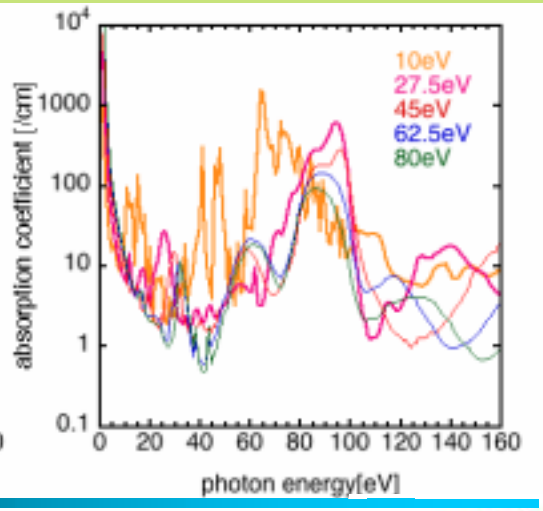
- emissivity
- opacity
- equation of state (EOS)



assignment of emission lines

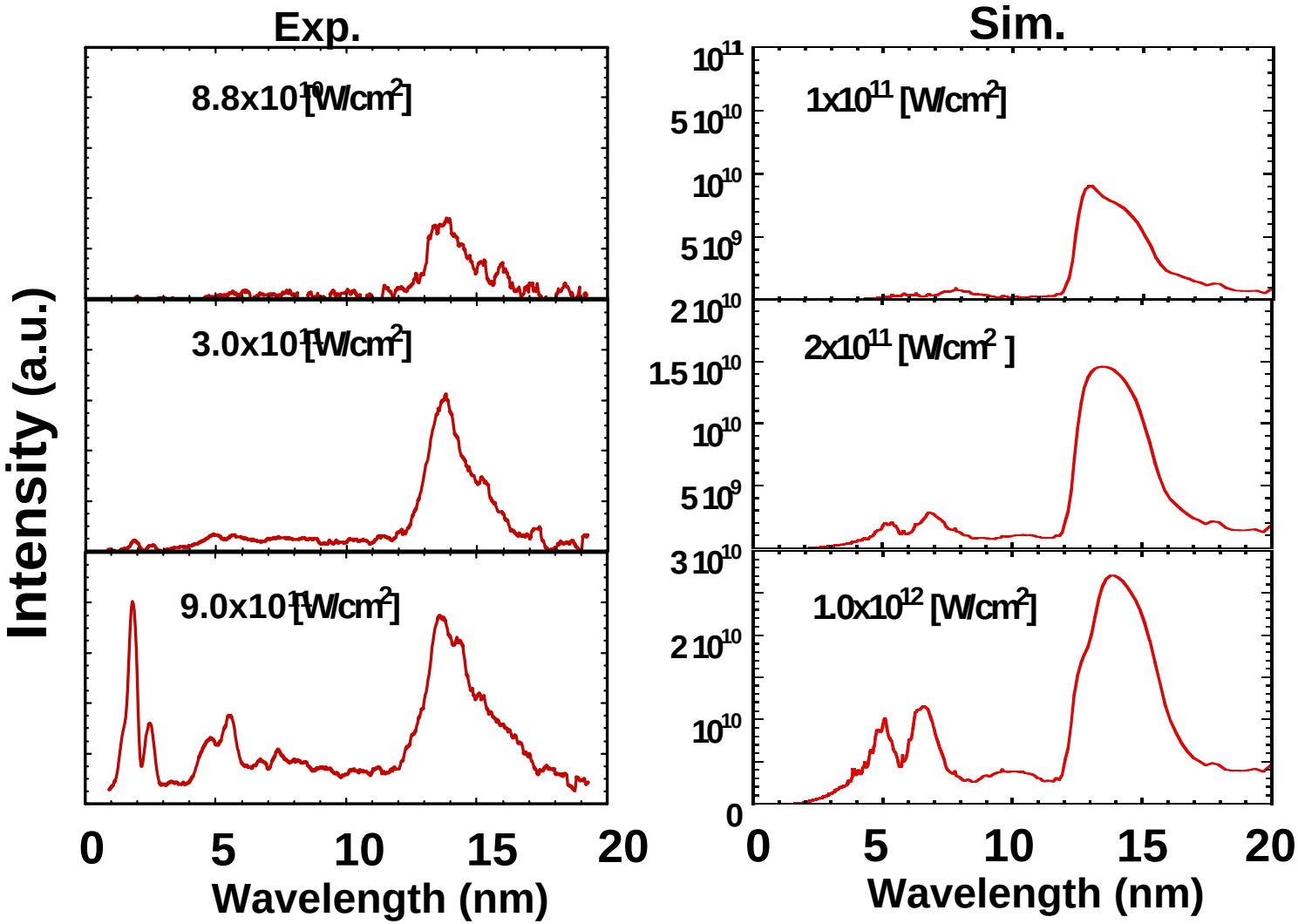


estimation of efficiency optimization



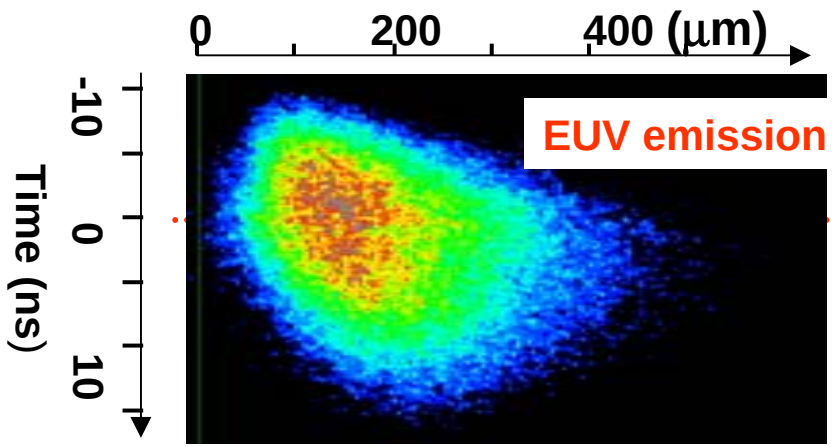
HULLAC / CRE: Sasaki, AA / CRE: Nishikawa,
EOS: Furukawa, R-Hydro: Sunahara

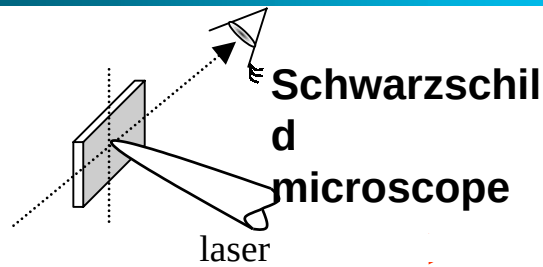
Radiation hydrodynamic simulation predicts that radiation spectra may drastically change with laser intensity, which agrees well with the experiments.



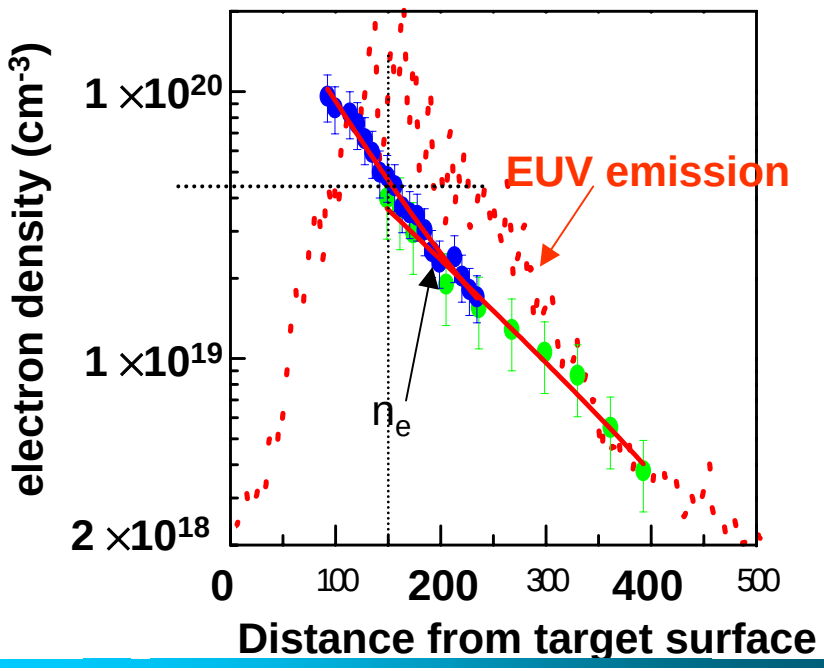
detail of spectra: Nishikawa(SoP49), Kawamura(SoP51)

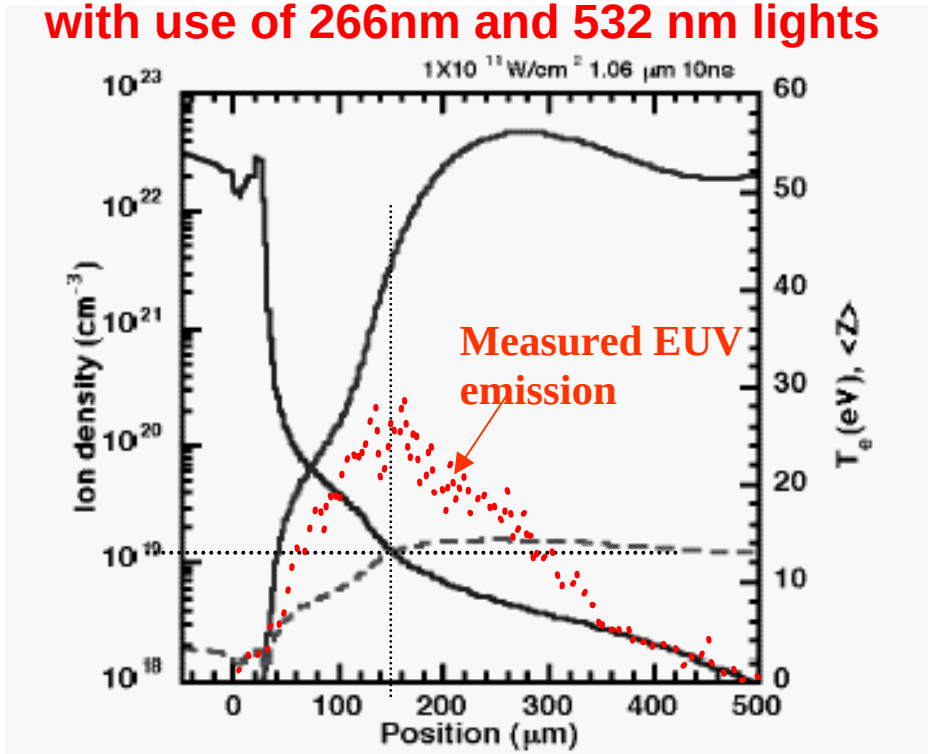
Electron density in EUV emission region measured by Y. Tao et al roughly agrees with simulation.





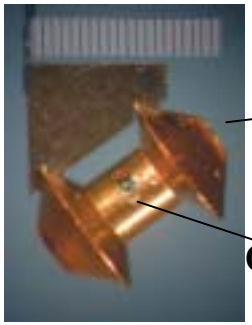
Interferometer measurement of electron density profile with use of 266nm and 532 nm lights

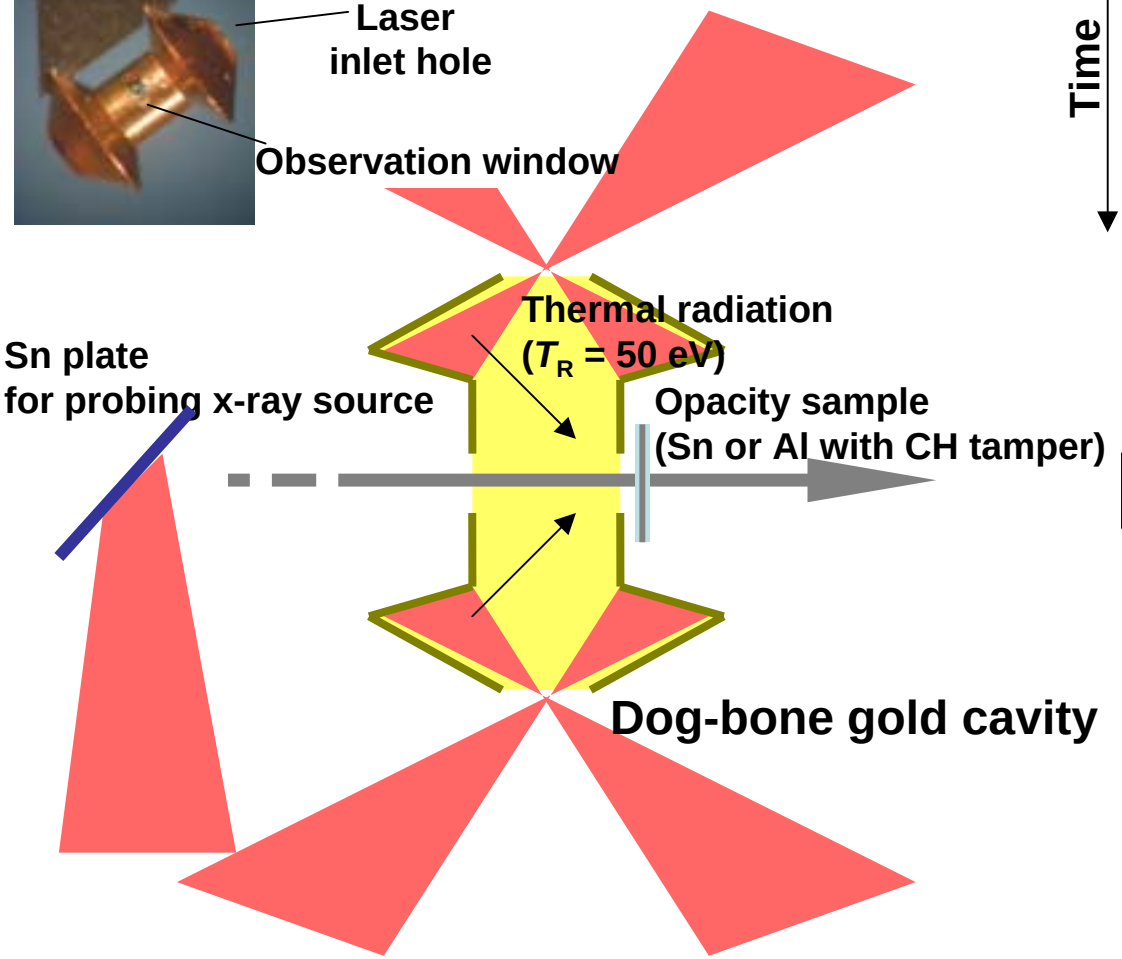


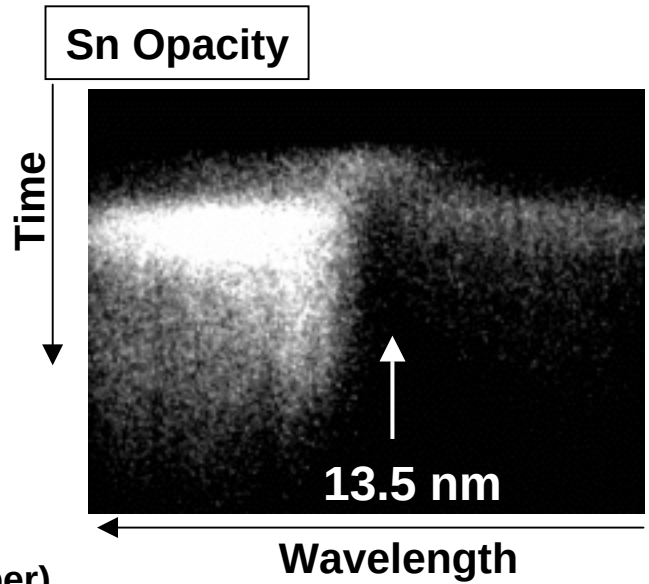


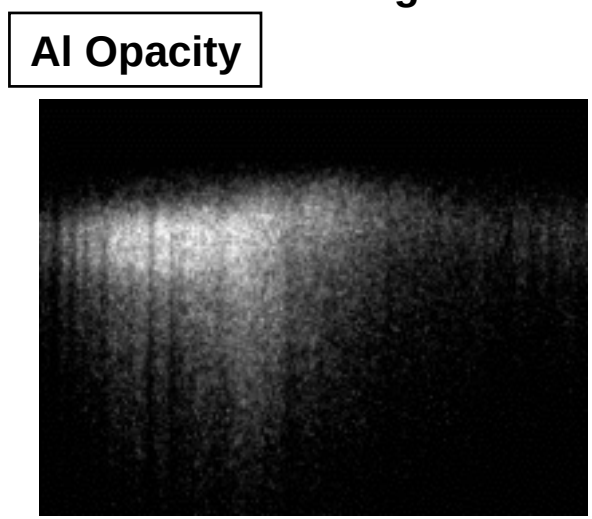
Tao (SoP30), Sunahara (SoP52)

Opacity measurements of Sn plasmas heated by thermal radiation (T_R = 50 eV) are in progress.



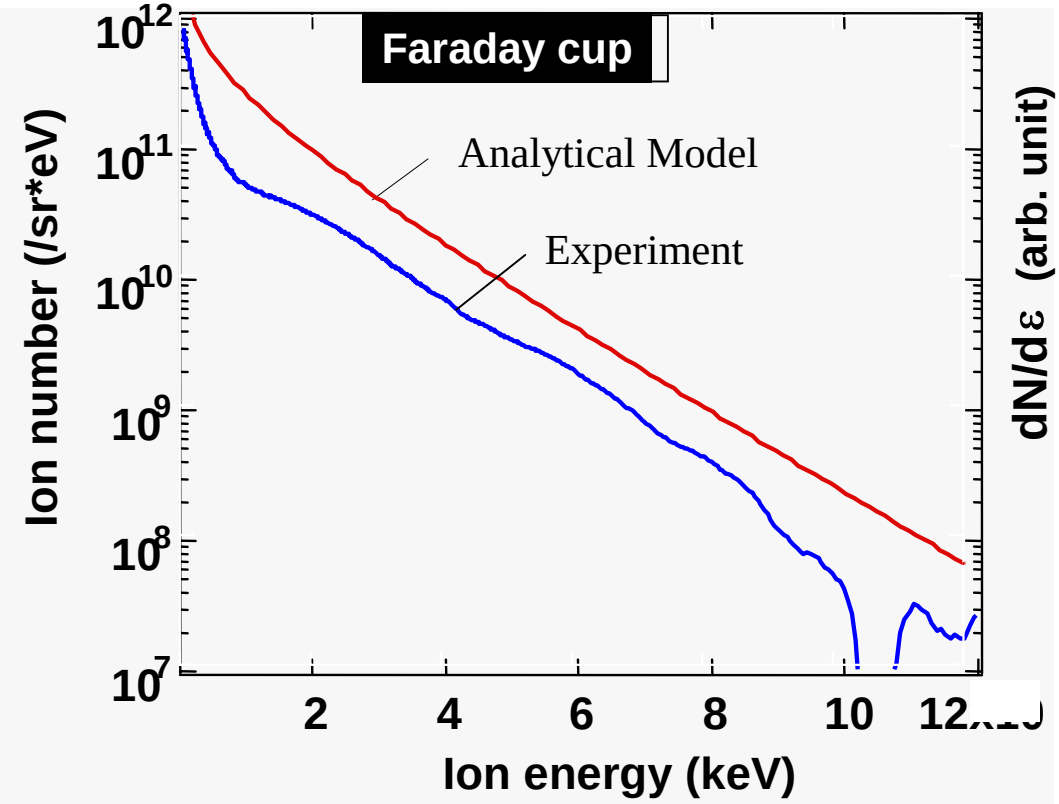


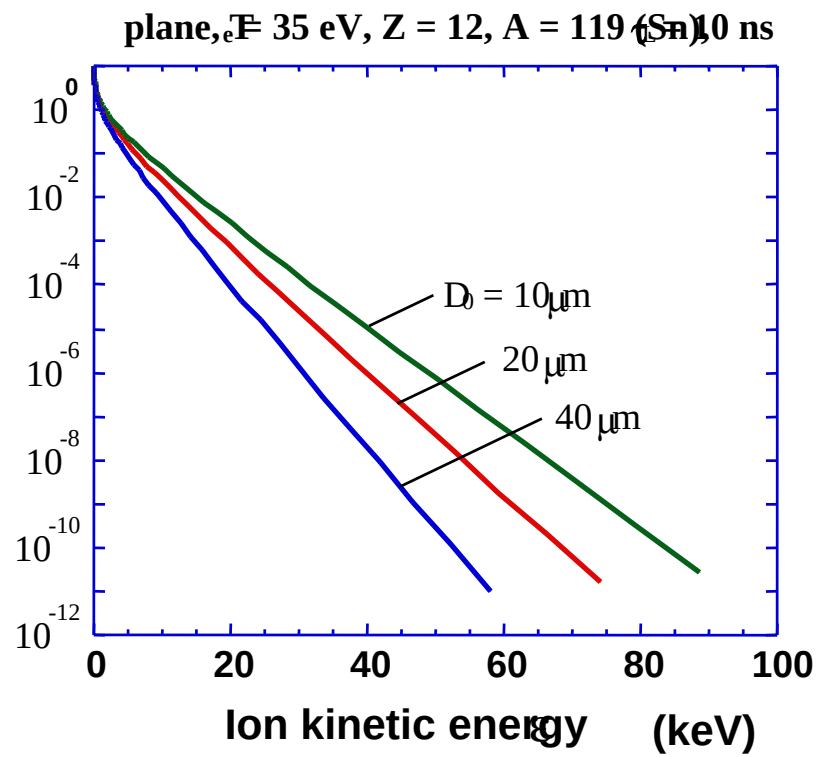




After Nishimura, Fujioka, Okuno et al

Isothermal expansion model can explain ion spectrum fairly well. It may cause fast ions with several tens keV.





Recombination process should be understood more.

Fujioka (CoP15), Furukawa(Co03), Kang (CoP12)

Conclusion

- Based on the power balance, we present a scaling low of the conversion efficiency, which agrees fairly well with the experiments, and discussed its dependence of laser wavelength and pulse duration for tin and xenon.
- Improvement of atomic modeling is in progress, such as on identification of energy levels with various experiments, configuration interaction and opacity.
- Detail comparisons between simulations and experiments provide us useful knowledge of LPP-EUV for future design.

EUV power at intermediate focus point

$$P_{EUV} = \eta_{EUV}\ S\ I_L\ \tau_{EUV}\ \varepsilon_{\Omega}\ \varepsilon_R\ \varepsilon_{te}\ \varepsilon_{td}\ R_p = 280\ \mathrm{W}$$

laser intensity : $I_L = 10^{11}\ \mathrm{W/cm^2}$, pulse width : $\tau_{EUV} = 5\ \mathrm{ns}$
repetition rate : $R_p = 10\ \mathrm{kHz}$, plasma size ($\varepsilon_t = 3\ \mathrm{mm^2\,str}$) : $\phi \approx 870\mu\mathrm{m}$
conversion efficiency : $\eta_{EUV} = 0.03$
efficiency of focusing system : $\varepsilon_{total} = \varepsilon_{\Omega}\ \varepsilon_R\ \varepsilon_{te}\ \varepsilon_{td} = 0.32$

Those results indicate that the source parameters for practical use can be achieved.