Japan MEXT Leading Project
for Laser-Produced Plasma EUV Light Source Development

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Outline of talk

- requirement of light source and design window
- laser intensity scaling of the conversion efficiency
  - experiments and modeling (Sn, SnO_2)
  - opacity and satellite line effect (Xe)
- further improvement of conversion efficiency (Sn, SnO_2)

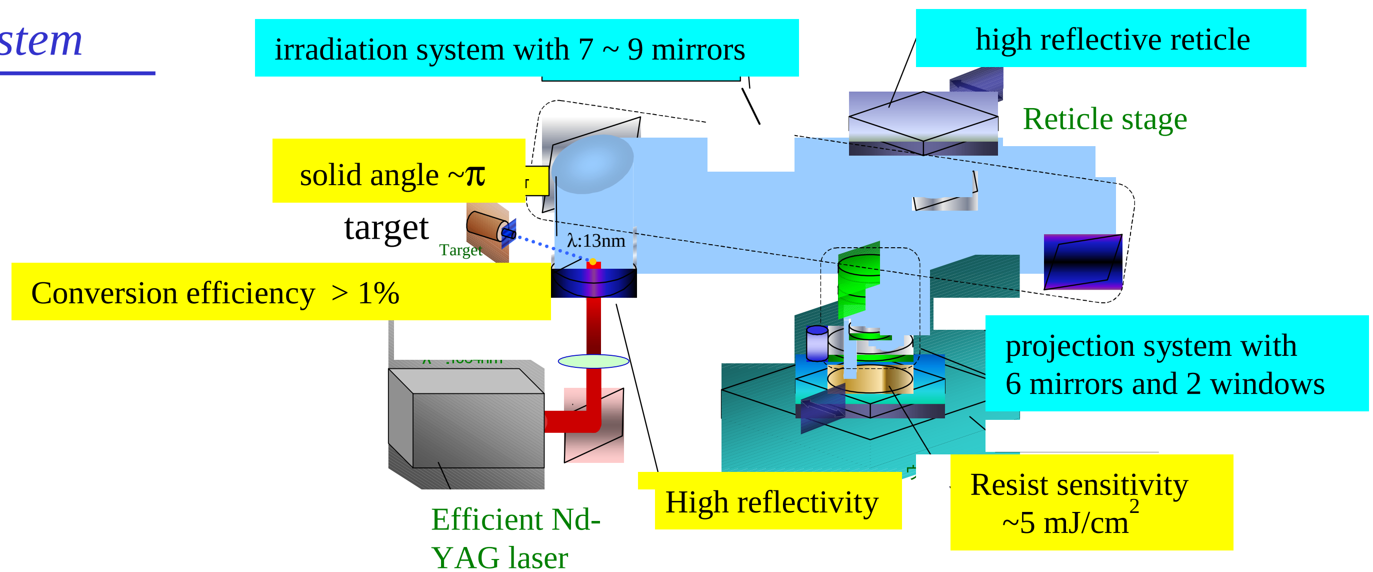
In collaboration with
(theory) : T. Nishikawa, A. Sasaki, T. Kawamura, A. Sunahara, H. Furukawa, M. Murakami, R. More, K. Fujima, F. Koike, T. Kagawa, V. Zhakhovskii, T. Kato and H. Tanuma,
(experiments) : H. Nishimura, M. Nakai, K. Shigemori, Y. Shimada, S. Uchida, S. Fujioka, K. Hashimoto,T. Hibino, R. Matsui, T. Okuno, F. L. Sohnatzadeh, Y. Tao, M. Yamaura, K. Nagai, T. Norimatsu, M. Nakatsuka, H. Fujita, Y. Fujimoto, K. Tsubakimoto, H. Yoshida, N. Miyanaga and Y. Izawa

EUVL03, Antwerp, Belguim, Sep. 30 –Oct. 2, 2003

A new-five-year-long project for LPP EUV light source development has been started as the Leading Project promoted by MEXT.

The project aims at understanding physics of EUV light source for lithography, and providing database and guideline for practical use in collaboration with METI project (EUVA).

EUVL system



The project includes high performance laser development (5kW, 5kHz), plasma experiments, theory and simulation, and target fabrication.

Requirements of the light source and possible design windows

wavelength: 13.5 nm @2%BW / EUV power: > 115 W (after intermediate focus)
repetition: 10 kHz / etendue: 1 $mm^2 str$ / conversion efficiency: > 1 %

EUV power at source / repetition :	300 W / 10 kHz
EUV energy per shot :	30 mJ / shot
source plasma size ($S \pi = \pi^2 r^2 = 1\ mm^2 str$) :	$\Phi \approx 600\ \mu m$
EUV intensity ($I_{EUV} = E_{EUV} / (S \tau_{EUV})$) :	$10^9 \sim 10^{10}\ W/cm^2$
(pulse width : $\tau_{EUV} = 1 \sim 10$ ns)	
laser intensity ($I_L = I_{EUV} / \eta_{EUV}$) :	$10^{11} \sim 10^{12}\ W/cm^2$
(conversion efficiency : $\eta_{EUV} = 0.01$)	
ion density (Xe : $n_{5p\text{-}4d}$, Sn : $n_{4f\text{-}4d}$) :	$10^{18} \sim 10^{20}\ cm^{-3}$

(photon number per unit time and area :

$E_{EUV} / (h\nu\ \tau_{EUV}\ S) = 4\ l_{OD=1}\ n_{4f\text{-}4d \text{ or } 5p\text{-}4d}\ A_{Eien}$

opacity : $l_{OD=1} = 10\mu m$, oscillator strength : $g_{n'}/g_n\ f_{n'n} = 1$,

abundance of $n_{4f\text{-}4d \text{ or } 5p\text{-}4d} = 0.1$)

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Executive summary

- **The conversion efficiency of a few % to 13.5 nm EUV light of 2 % bandwidth has been attained at 1 - 2x10^{11} W/cm^2. (Sn)**

- **Considering power balance, we present a scaling low of the conversion efficiency, which agrees fairly well the experiments.**

- **We show that13.5 nm EUV light is emitted in both the high-temperature corona and the high-density region, depending on the laser intensity.**

- **We also show that the Planckian intensity can be achieved for the lines due to the effects opacity and satellite lines in the high-density region.**

- **$2\omega_o$ laser irradiation on SnO_2 target leads to further improvement of the conversion efficiency at intensity of .5-1x10^{11} W/cm^2, although further study is required.**

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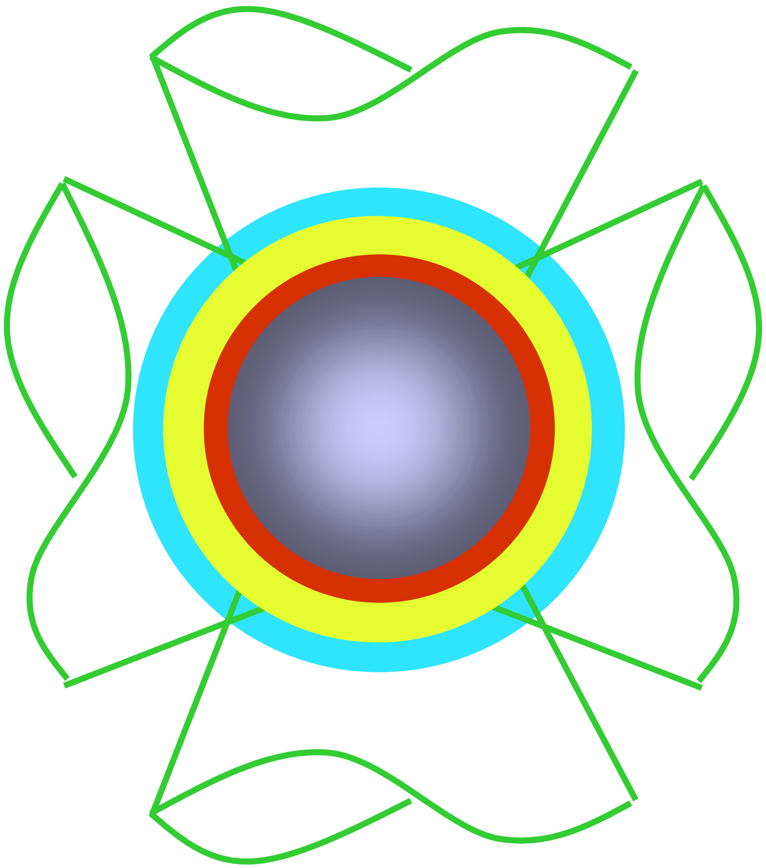
An ideally "uniform" EUV radiator was produced by GEKKO-XII laser, to obtain laser intensity dependence of the conversion efficiency without lateral energy loss and geometrical effects.



spherically uniform plasmas

Laser :

- GEKKOXII, 12 beams
- wavelength: ω (1.056 μm), 2ω (0.527 μm)
- intensity: $5\times10^{10} \sim 1\times10^{12}$ W/cm^2
- pulse width: 1.2 ns (FWHM, Gaussian)

Target :

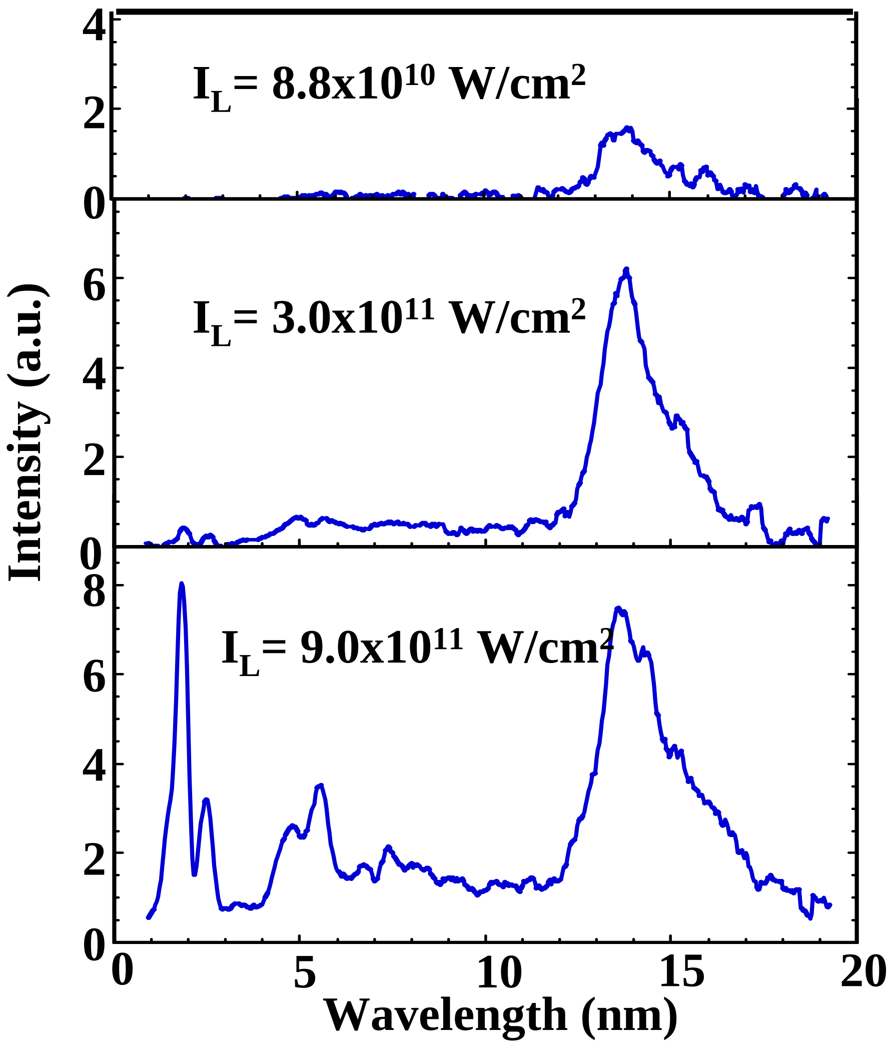
- Sn or SnO_2 coated glass ball
- 300~2000 μm$^{\phi}$ (mostly 700 μm$^{\varphi}$)

Diagnostics (XST: time resolved):

- transmission grating (TDI) + CCD
- grazing incident spectrometers (GIS)
- x-ray backlight: density profile

See Nakai(101), Nishimura(102), Yamamura(92) posters for detail experimental results

Laser intensity dependence of spectra shows that short wavelength (1-3nm) emission appears at high intensity (10^{12}W/cm^2), while long wavelength (>10nm) emission dominates at low intensity (10^{11}W/cm^2).



target Sn, laser ω
transmission grating + CCD

- **Emission with wavelength of 13-15 nm is mainly due to 4d-4f transition.**
- **M-shell emission causes short wavelength emission < 3nm (1 - 0.5 keV), while N-shell emission does longer wavelength emission > 4nm (< 0.5 keV).**

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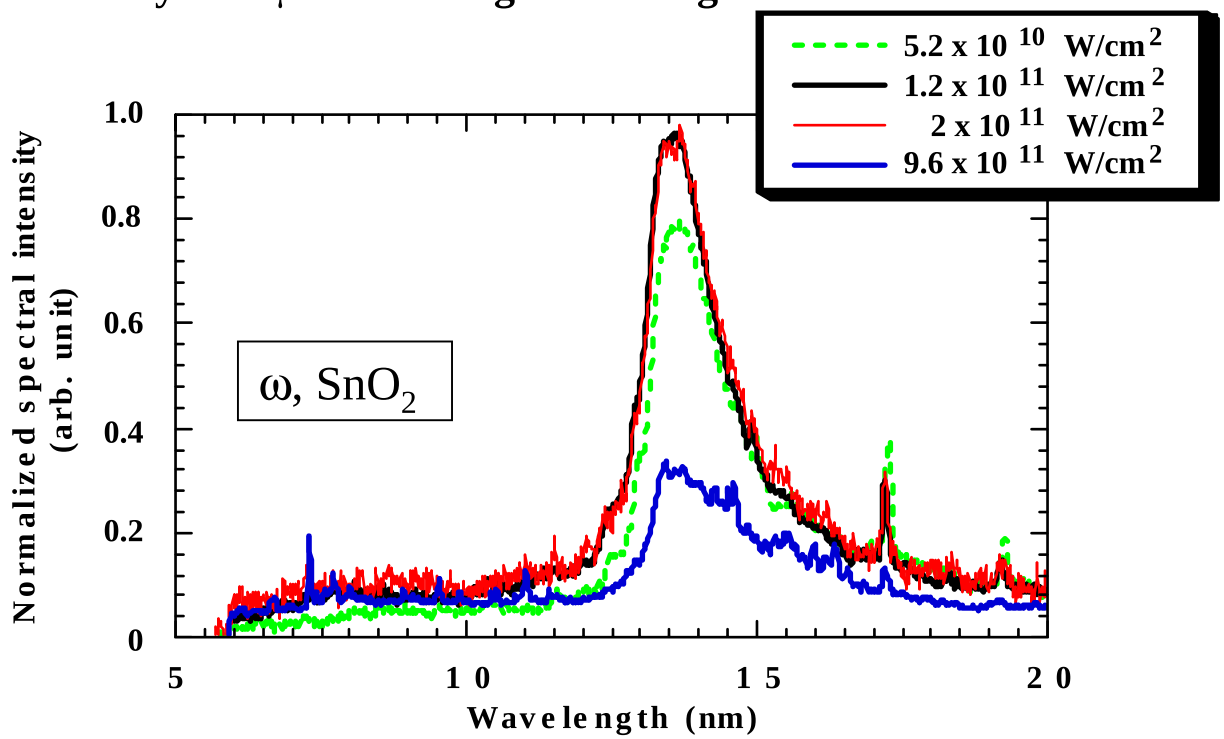
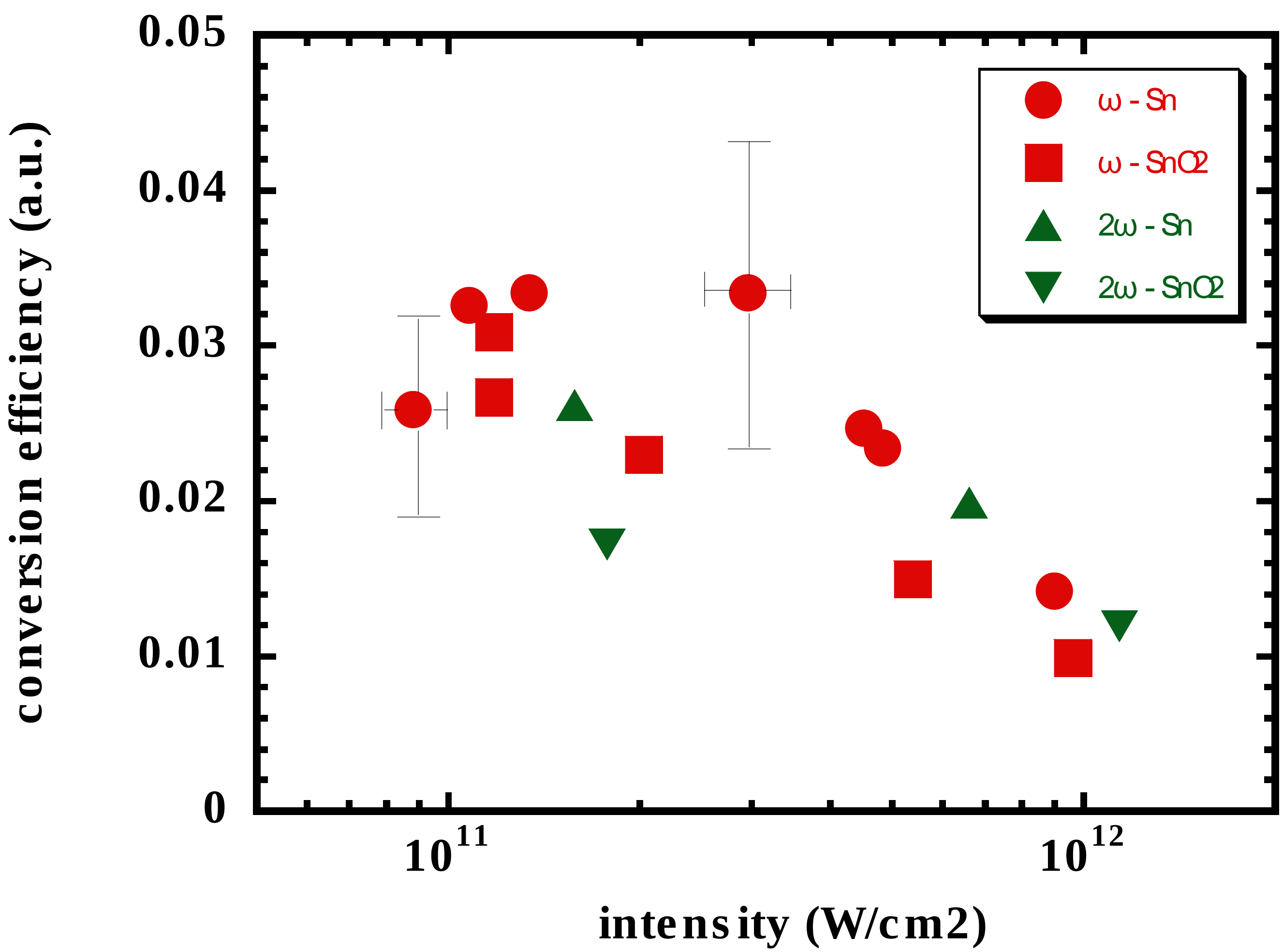
Spectral intensity normalized by laser intensity shows that conversion efficiency has its maximum around 1- 2 x 10 ^{11} W/cm^2.

Intensity dependence of EUV spectrum from spherical tin-oxide targets illuminated by 1.05-μm wavelength laser light.



Detailed spectral features are observed by using grazing incident spectrometers (GIS) coupled with a back illumination CCD camera and an x-ray streak camera.

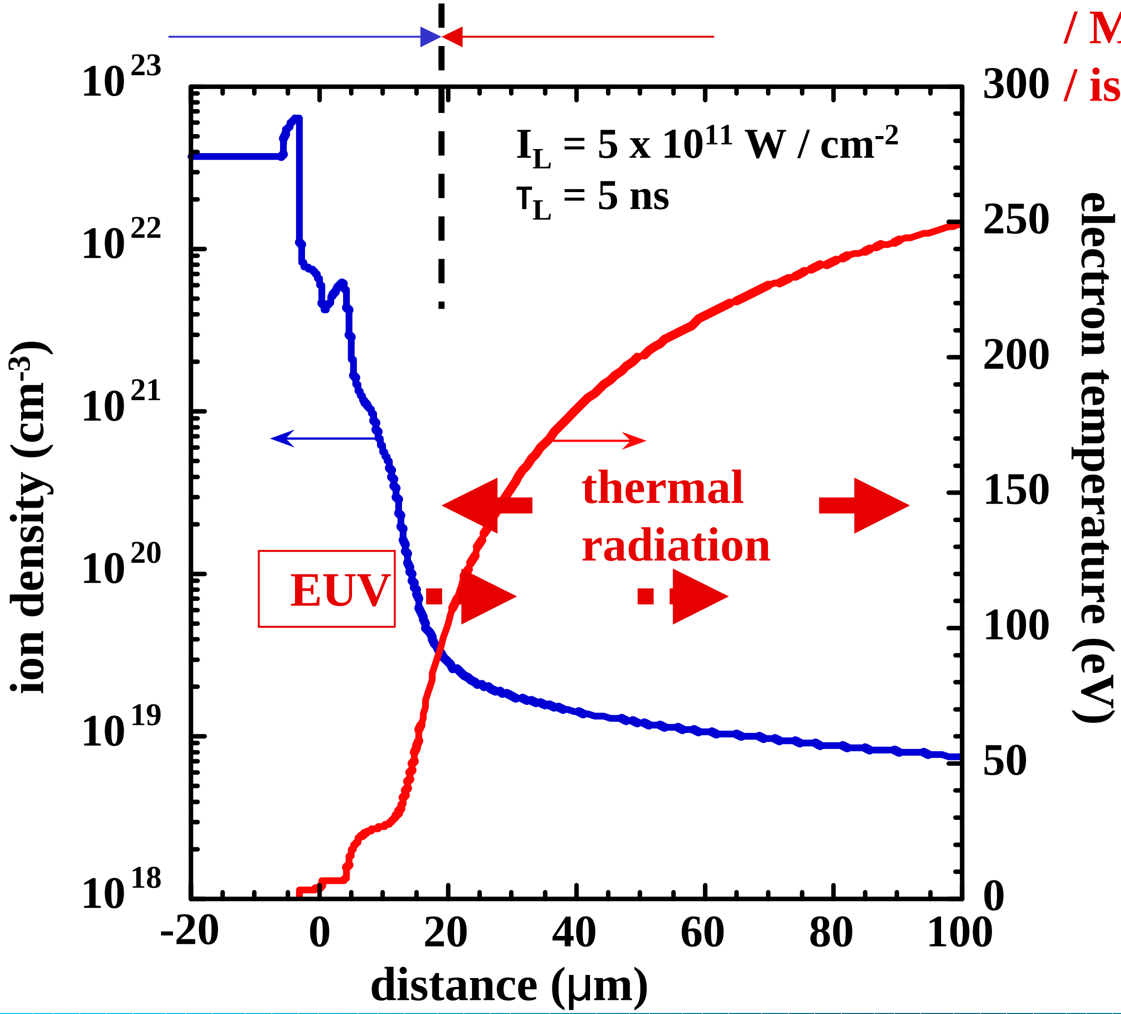
Transmission grating data also shows high conversion efficiency near 1-2x10^{11} W/cm^2 and relatively weak laser wavelength dependence.



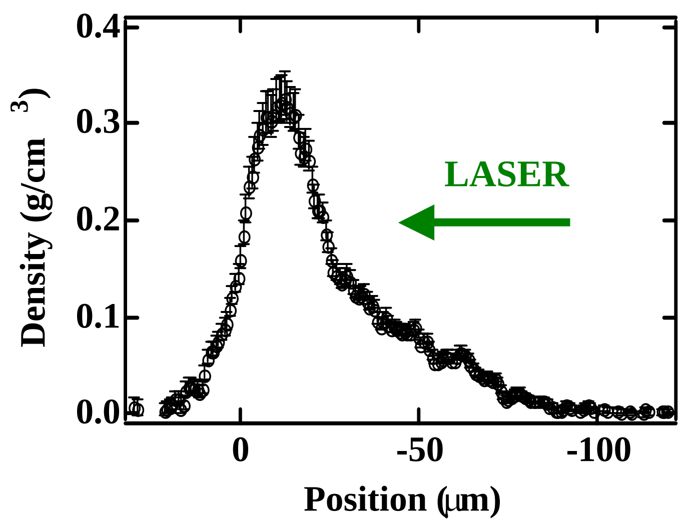
Features of Laser Produced High-Z Plasma

High density region : high density / low temperature / LTE / b-f absorption

Corona region : high temperature / low density / CRE / M-, N- band emission / isothermal expansion



High density region was observed by side-on x-ray back light method .
I_L = 1.2 x 10^{12} W / cm^{-2}



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See Sunahara's(85) posters for details

Modeling of EUV-LPP (power balance)

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.

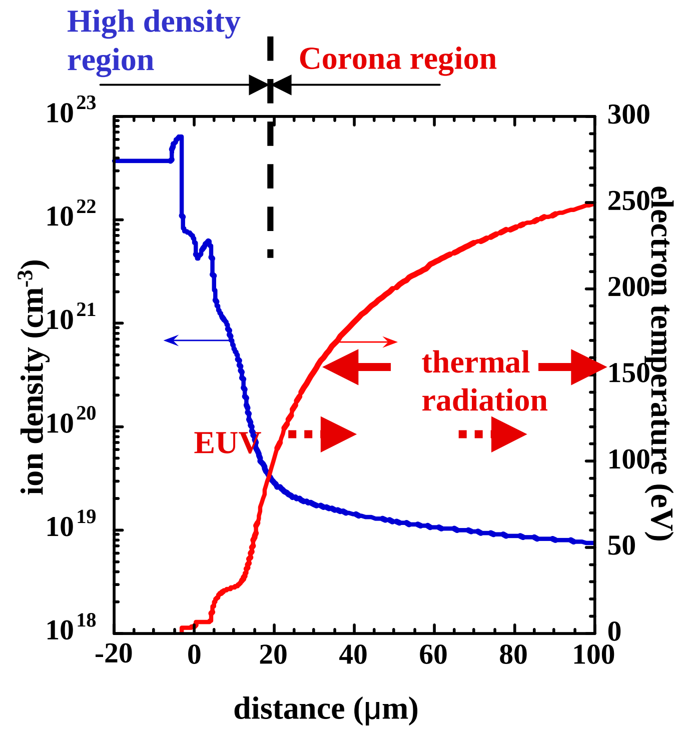
$$I_L = E_k + E_i + E_R$$

Assume isothermal expansion in corona

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

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

where Z^* : ionization state, n_i : ion density,
T_e : electron temperature, c_s : sound speed
τ_L : laser pulse duration, α (≈ 1.5) : $P_R \propto n_i^\alpha$,



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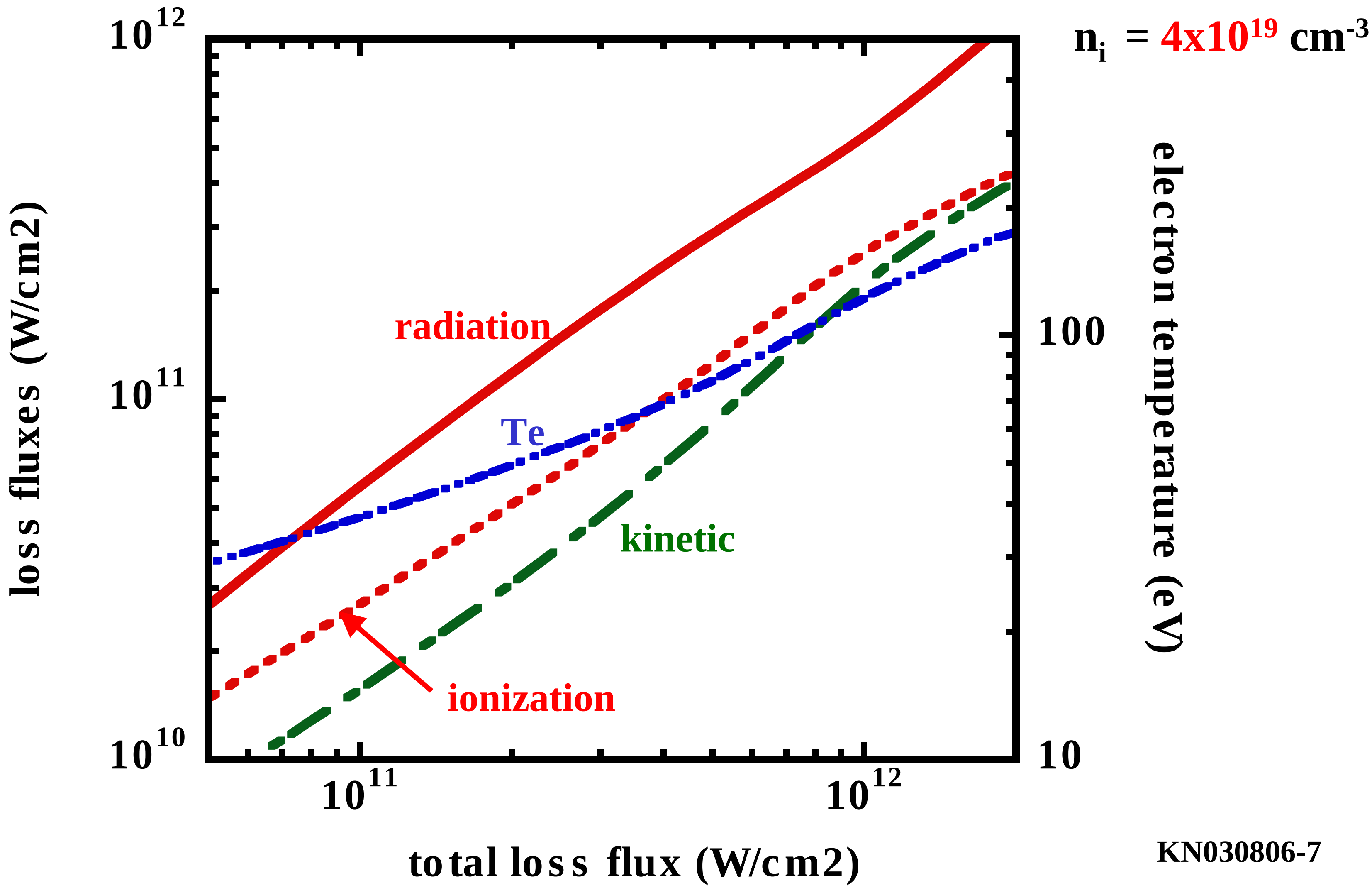
See Nishikawa(81) and Sunahara's(85) posters for details

Dependence of the losses on laser intensity indicates that radiation loss is dominate (50%),ionization loss is large at low intensity and kinetic loss becomes large at high intensity, but still small.



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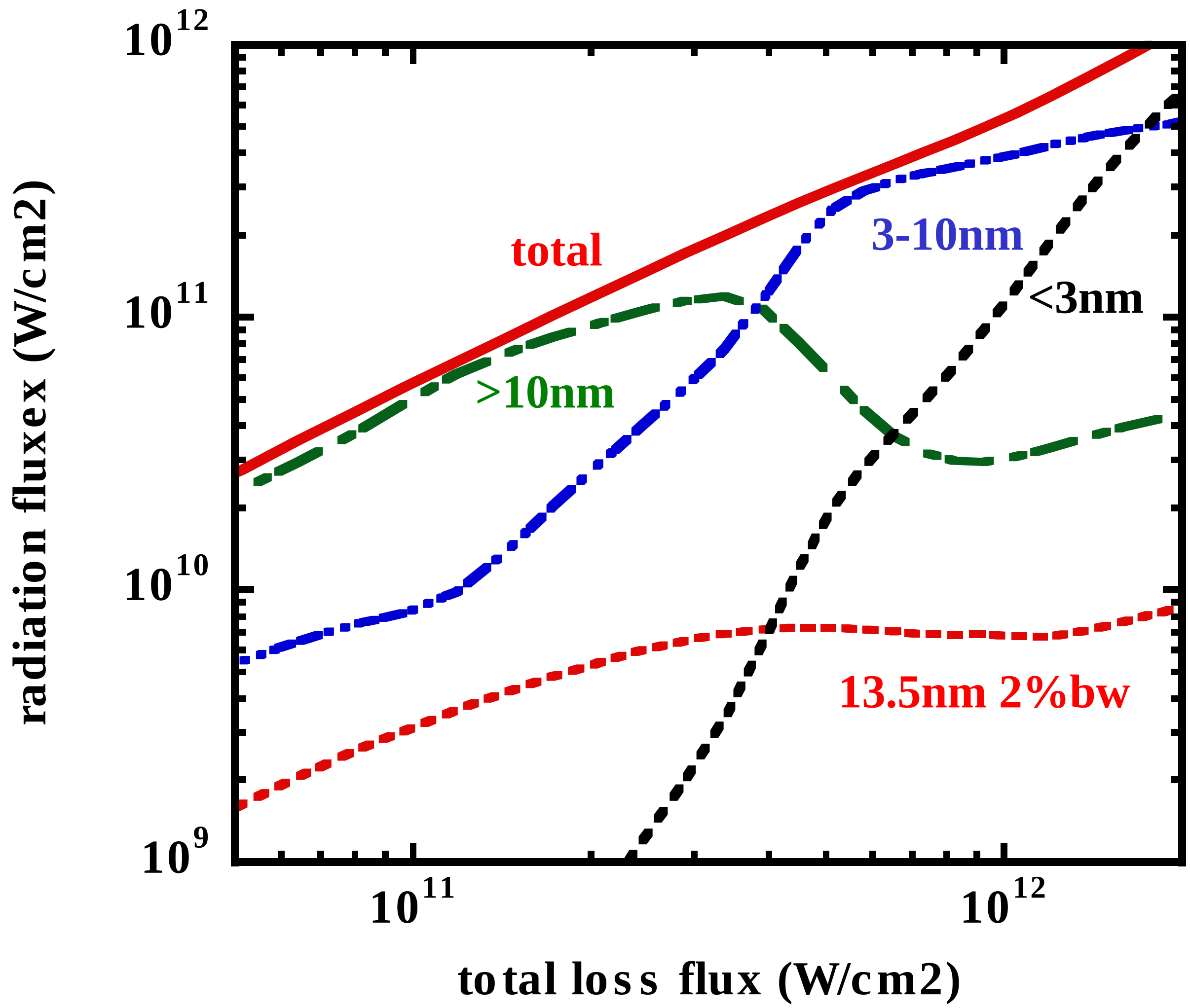
Model indicates that
radiation spectra may drastically change with laser intensity,
which agrees well with the experiments.

n_i = 4x10[19] cm[-3]



13.5 nm with 2% bandwidth

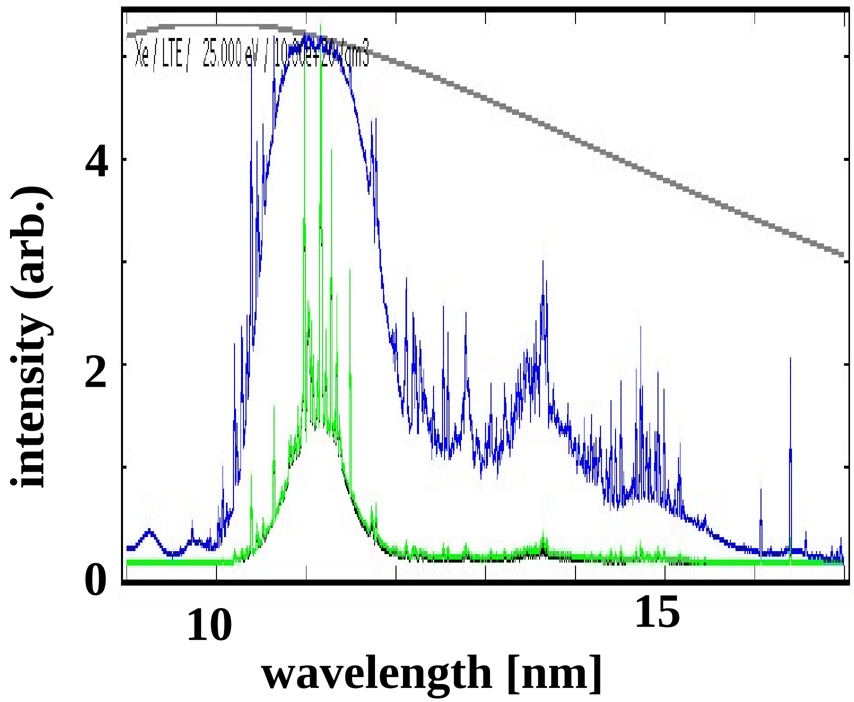
assumptions

- **10% of 12.4-14.5 nm emission from the corona calculated from AAM with (*n*,*l*) splitting**
- **Planck radiation from the high-density region with radiation temperature estimated from the total radiation from the corona.**

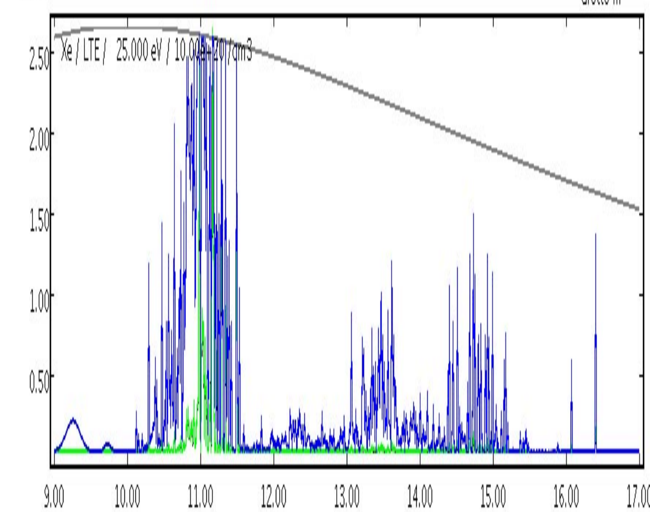
Both opacity and satellite lines play important roles in LPP.
(Xe plasma with 4d-4f, 4p-4d and 4d-5p satellite lines)

Plasma parameters
T_e=25eV
n_e=10^{21}/cm^3
r=10μm

with satellites

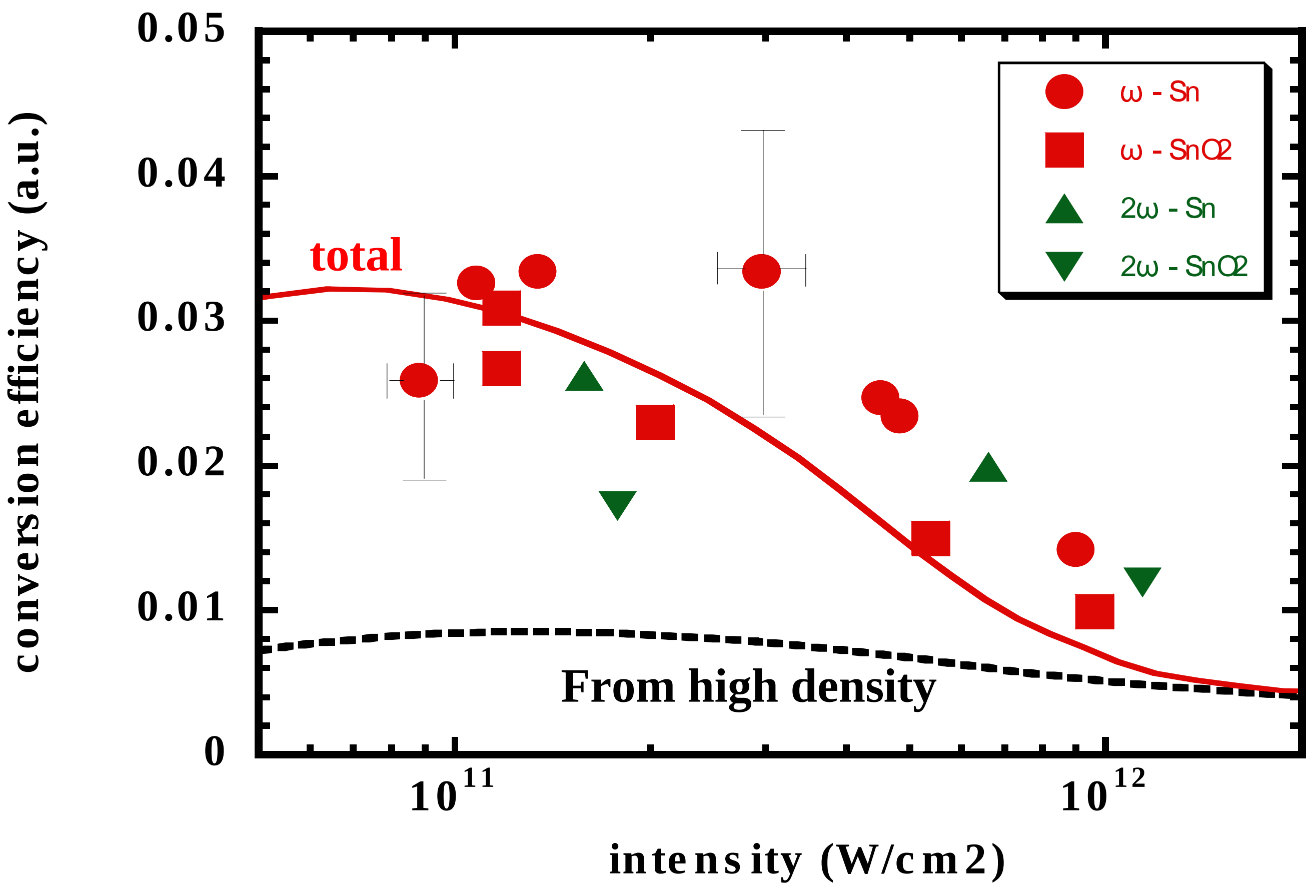


no satellites



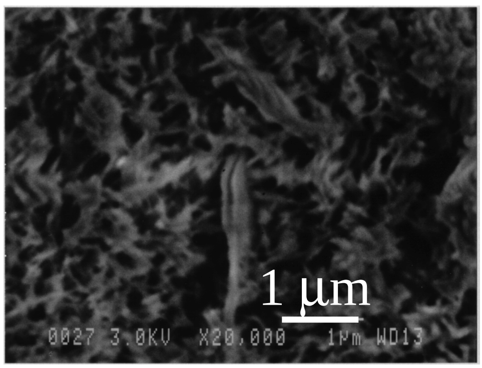
See Sasaki's(79) posters for details

**Theoretical conversion efficiency agrees fairly well with the experiments.
At low intensity, emission from the corona is dominate,
while that from the high density region becomes large at high intensity.**

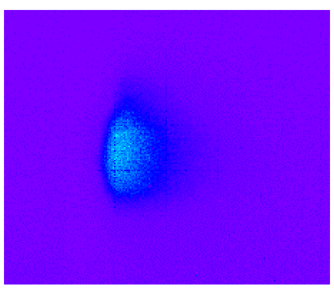


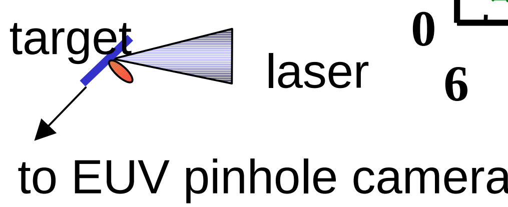
With decrease in density, spectrum becomes narrower but emission at 13.5 nm does not largely change. (planar target)

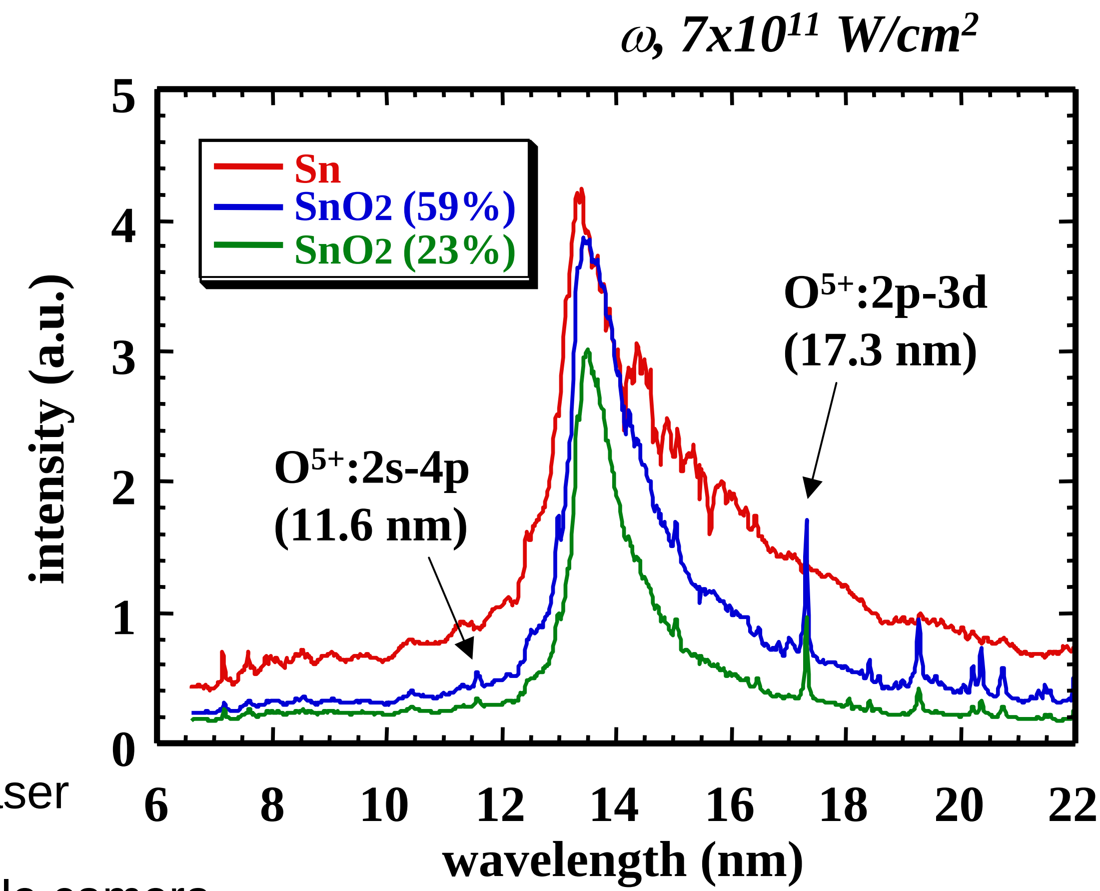
low density SnO_2
(23% of solid density)



pinhole image
(@13.5 nm 2%BW)

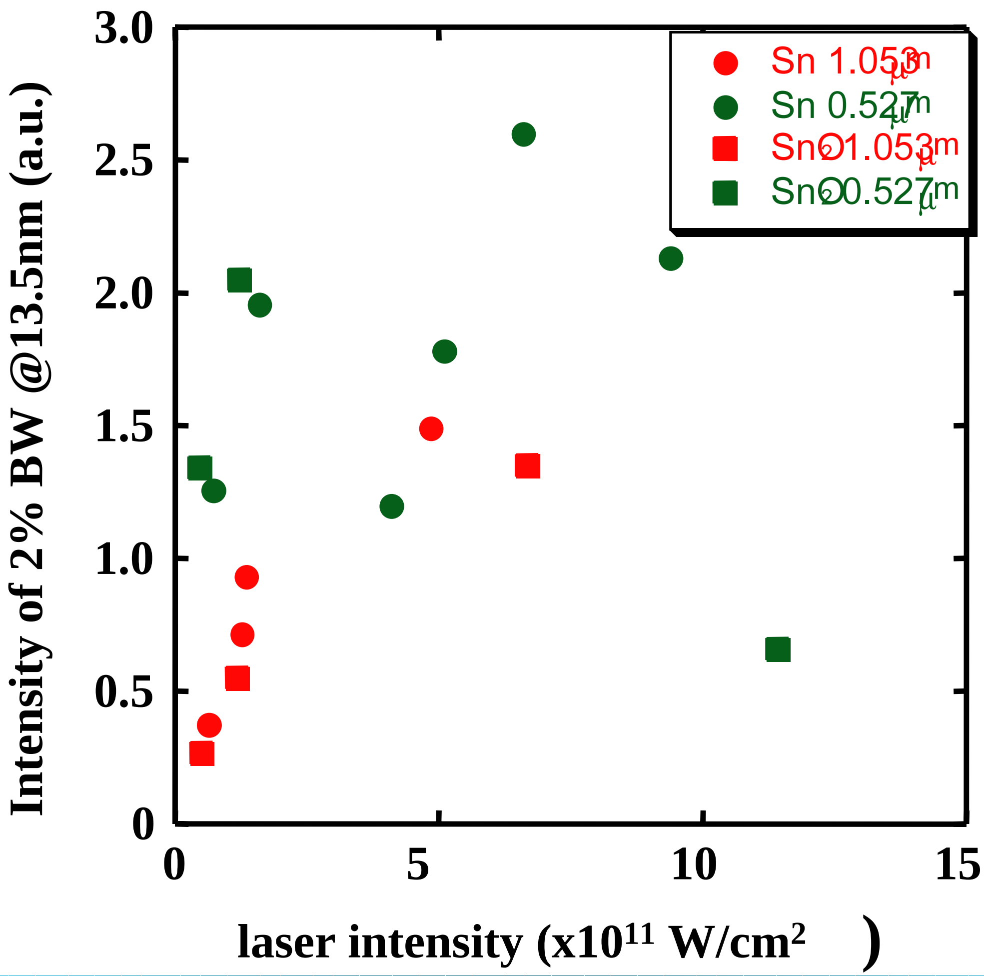






See Nishimura(102), Nagai(93)
posters for detail experimental results

At low intensity of .5 – 1 x10^{11} W/cm^2, 2ω laser irradiation results in higher conversion efficiency, and SnO_2 is higher Sn (?).



See Yamaura(92) posters for detail experimental results

Conclusions

- The conversion efficiency of a few % to 13.5 nm EUV light of 2 % bandwidth has been attained at 1 - 2x10^{11} W/cm^2.
- Considering power balance, we present a scaling low of the conversion efficiency, which agrees fairly well the experiments.
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- We also show that the Planckian intensity can be achieved for the lines due to the effects opacity and satellite lines in the high-density region.
- $2\omega_o$ laser irradiation on SnO_2 target leads to further improvement of the conversion efficiency at intensity of .5-1x10^{11} W/cm^2, although further study is required.

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