Observation of the whole Thomson scattering spectrum for diagnostics of EUV and Soft X-ray light source plasmas

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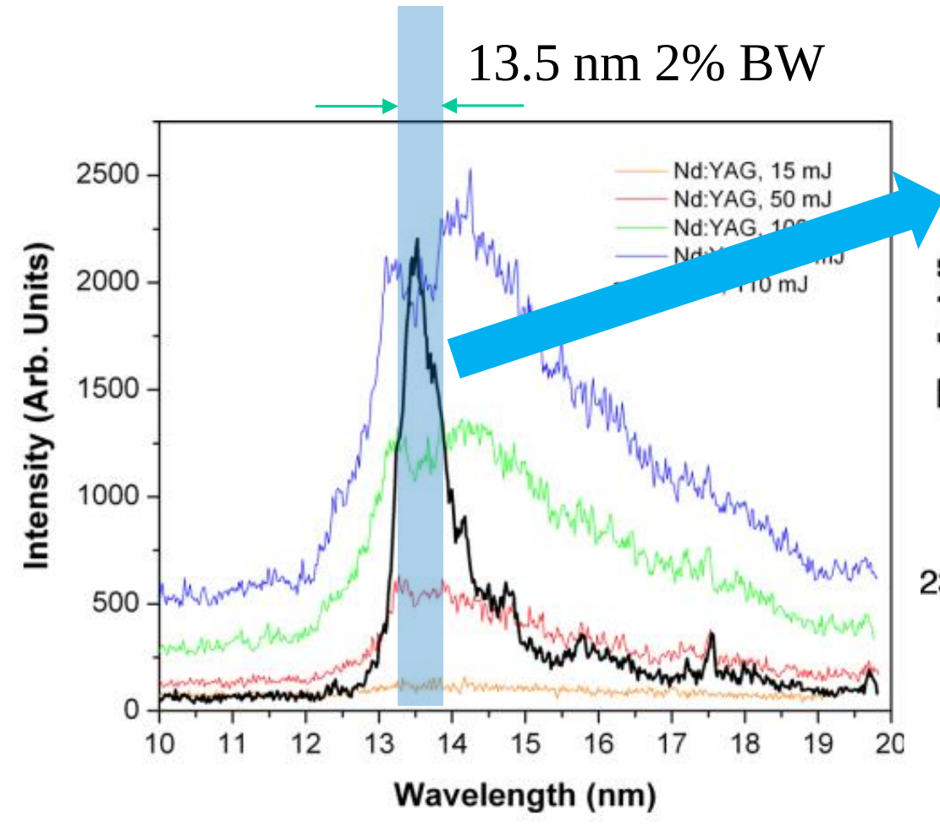
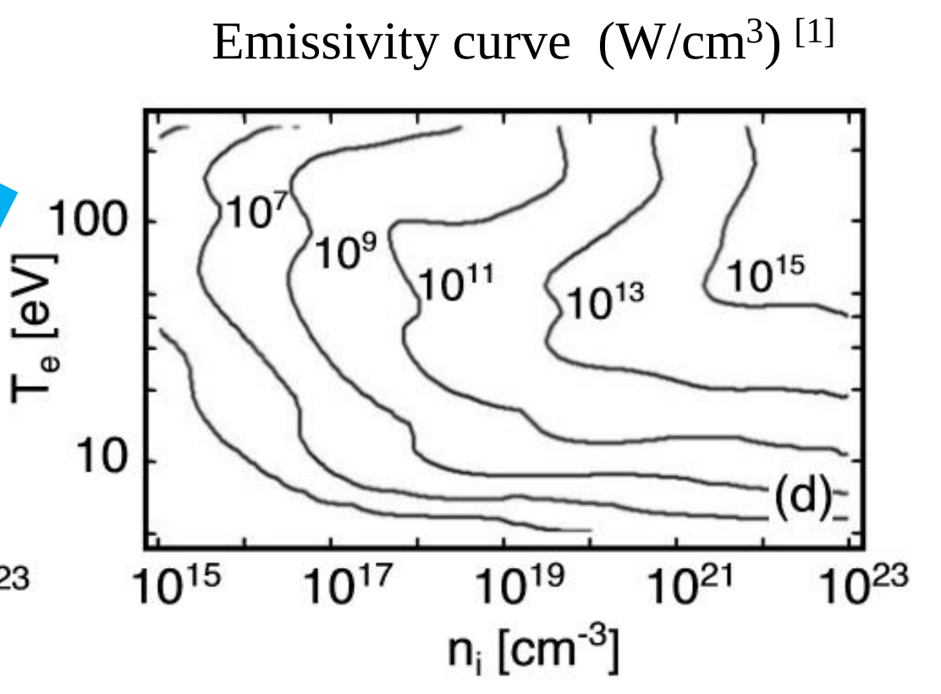
Introduction

- ➢ EUV and Soft X-ray (SXR) radiation (electron transition) profiles from high-Z plasmas strongly depend on electron temperature (T_e), density (n_e), and ionic charge (Z) [1].
- ➢ Using collective Thomson scattering (CTS) technique, we are trying to measure n_e, T_e, and Z of EUV and SXR light source plasmas. [3-5]

Example of EUV spectra [2]



Emissivity curve (W/cm^3) [1]



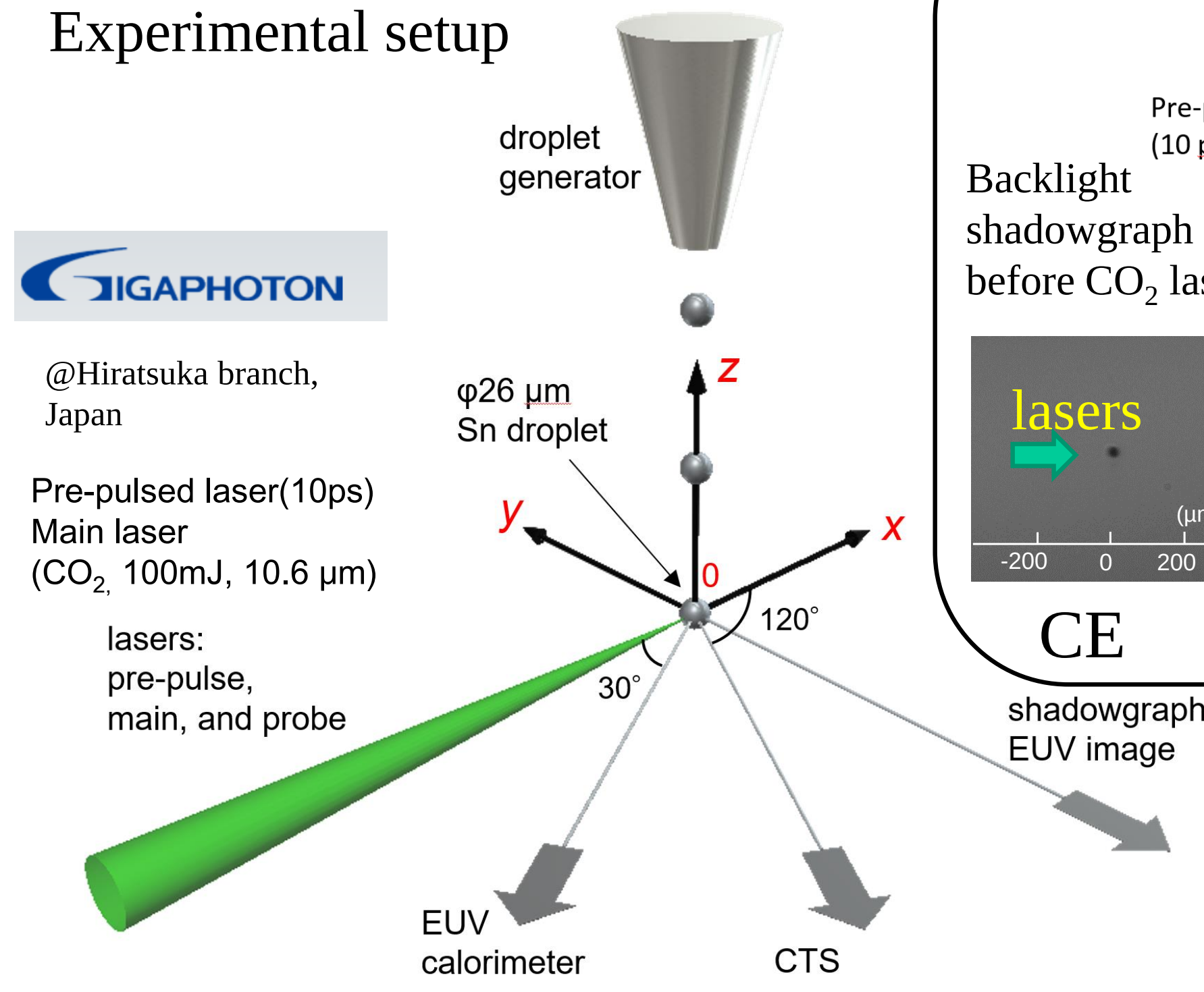
in-band EUV emissivity (and opacity) depends on Te and ion density n_i (= ne/Z) [1].

Especially, T_e is a key parameter to improve emissivity.

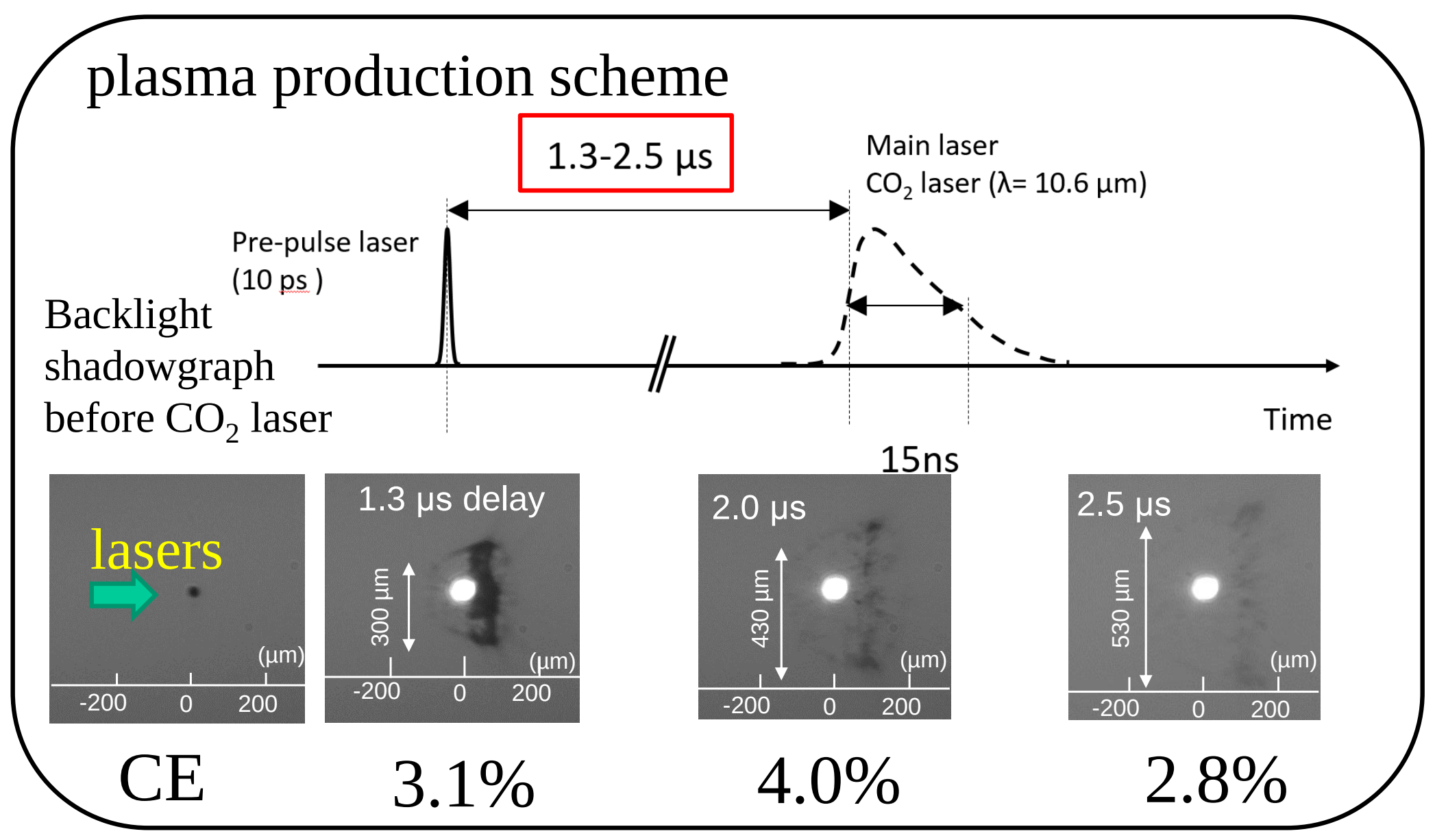
Previous studies -Thomson scattering for EUV sources -

To measure ne, Te, and Z simultaneously, we have applied laser **collective Thomson scattering** (CTS) to laser-produced EUV light source plasmas (Droplet Sn +CO$_2$ laser). CTS consists the ion component and the electron component. In the previous studies, we have fabricated a special spectrometer having 6 gratings, and successfully detected the ion component for the first time.

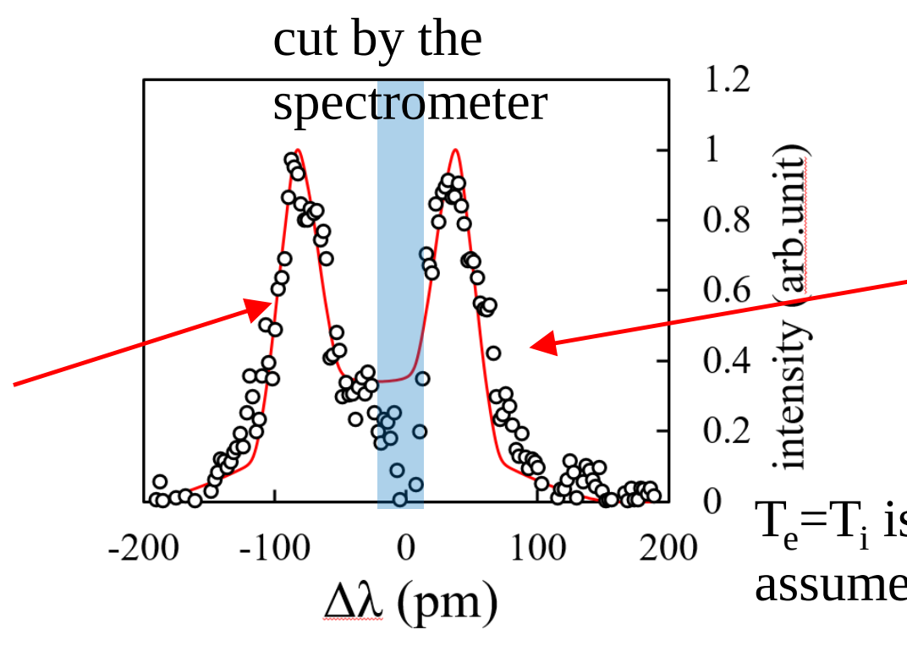
Experimental setup



plasma production scheme



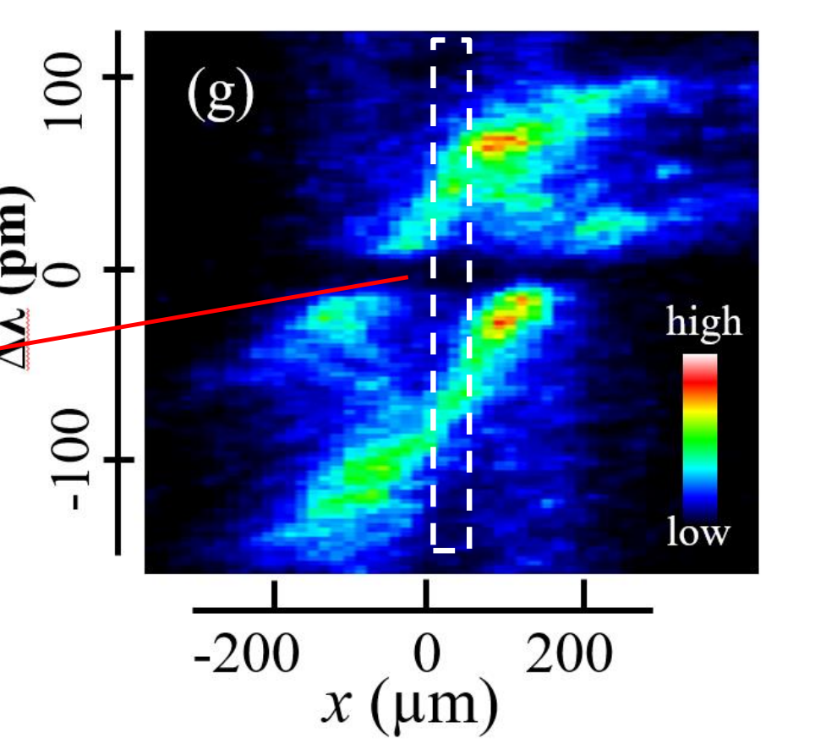
shadowgraph, EUV image

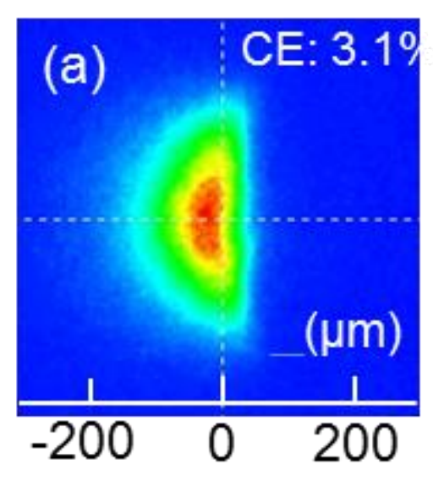


From absolute intensity, spectral width , and shape, ne, Te, and Z are determined.

T_e=T_i is assumed

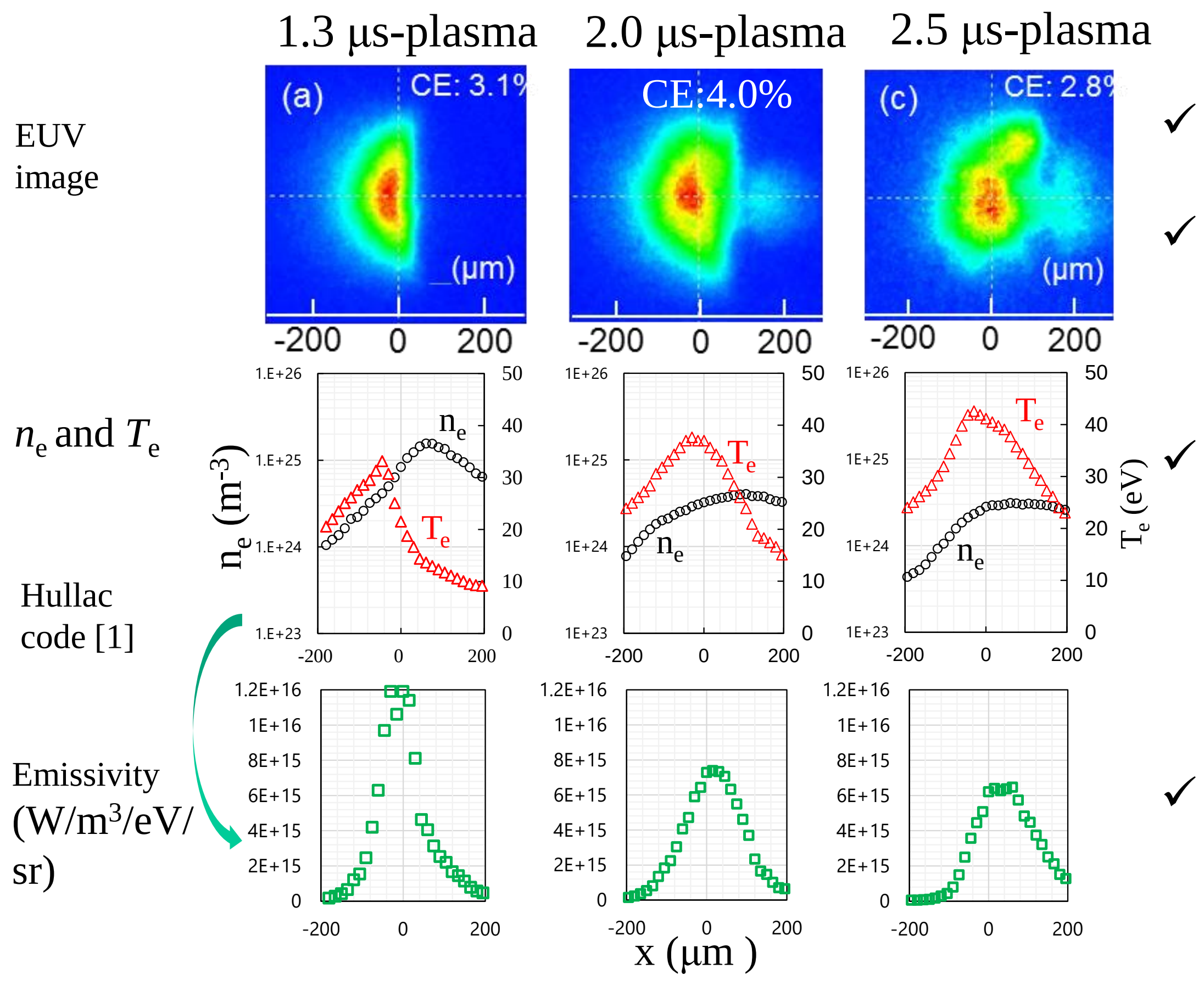
the ion component of CTS





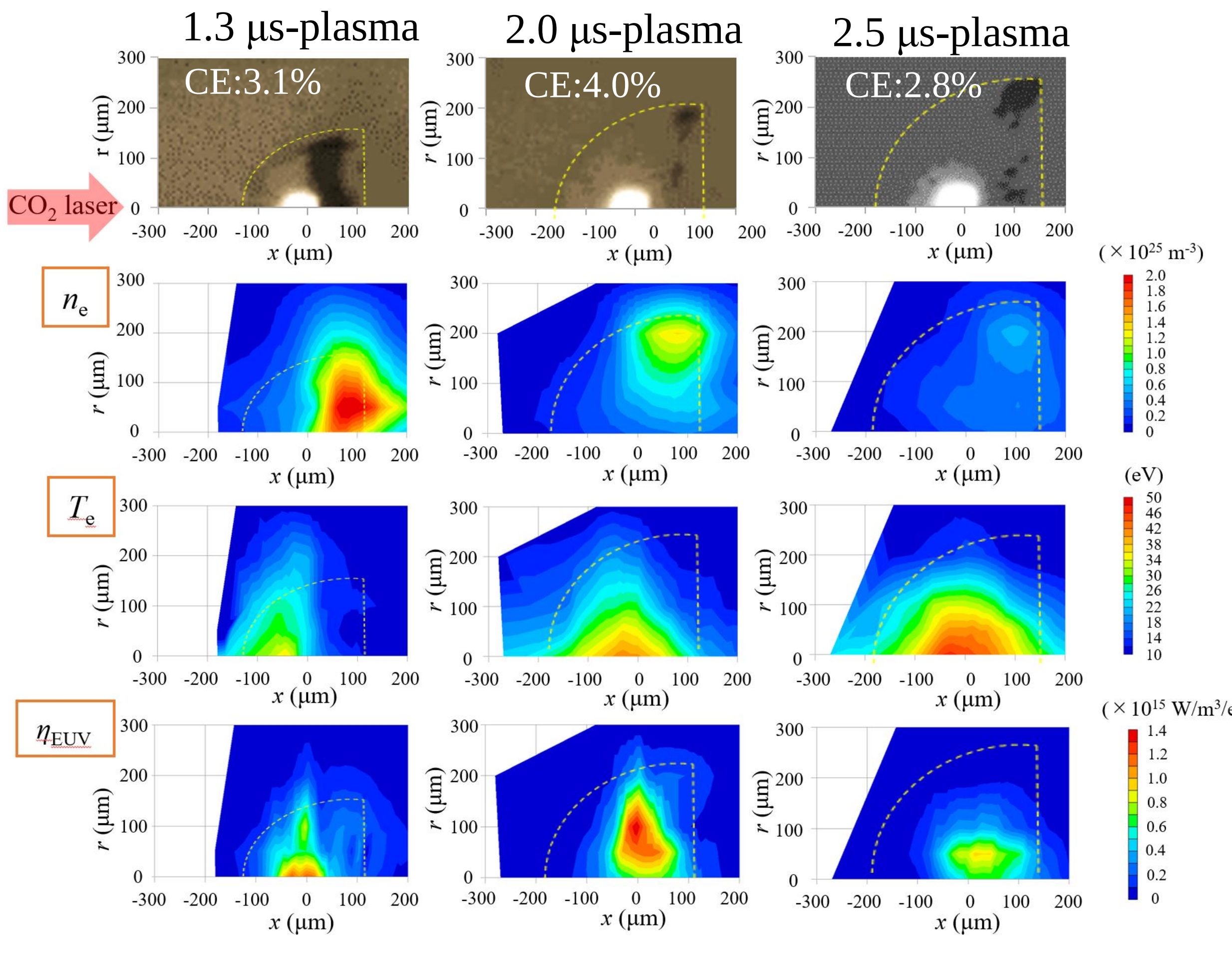
EUV image (line-integrated)

1D profiles of n_e and T_e [3]



- ✓ The CEs of the three types of plasmas differed (2.8 to 4.0%).
- ✓ The spatial profiles of n_e and T_e, were clearly changed with the delay time between the pre- and main lasers
- ✓ However, under all plasma conditions, intense EUV was only observed at a sufficiently high T_e (>25 eV) and in an adequate n_e range [10^{24} – (2×10^{25}) m^{-3}].
- ✓ These plasma parameters lie in the efficient-EUV light source range, as predicted by simulations [1].

2D profiles of n_e and T_e [4]



- ✓ In the 1.3 μs-plasma, the high n_e (> 4×10^{24} m^{-3}) and the high T_e (25 eV) regions were clearly separated.
- ✓ In the 2.5 μs-plasma, n_e is too low.
- ✓ In the 2.0 μs-plasma, the regions of the high n_e and the high T_e largely overlapped in both directions (the laser path axis and radial axis). A hollow-like density profile was observed.

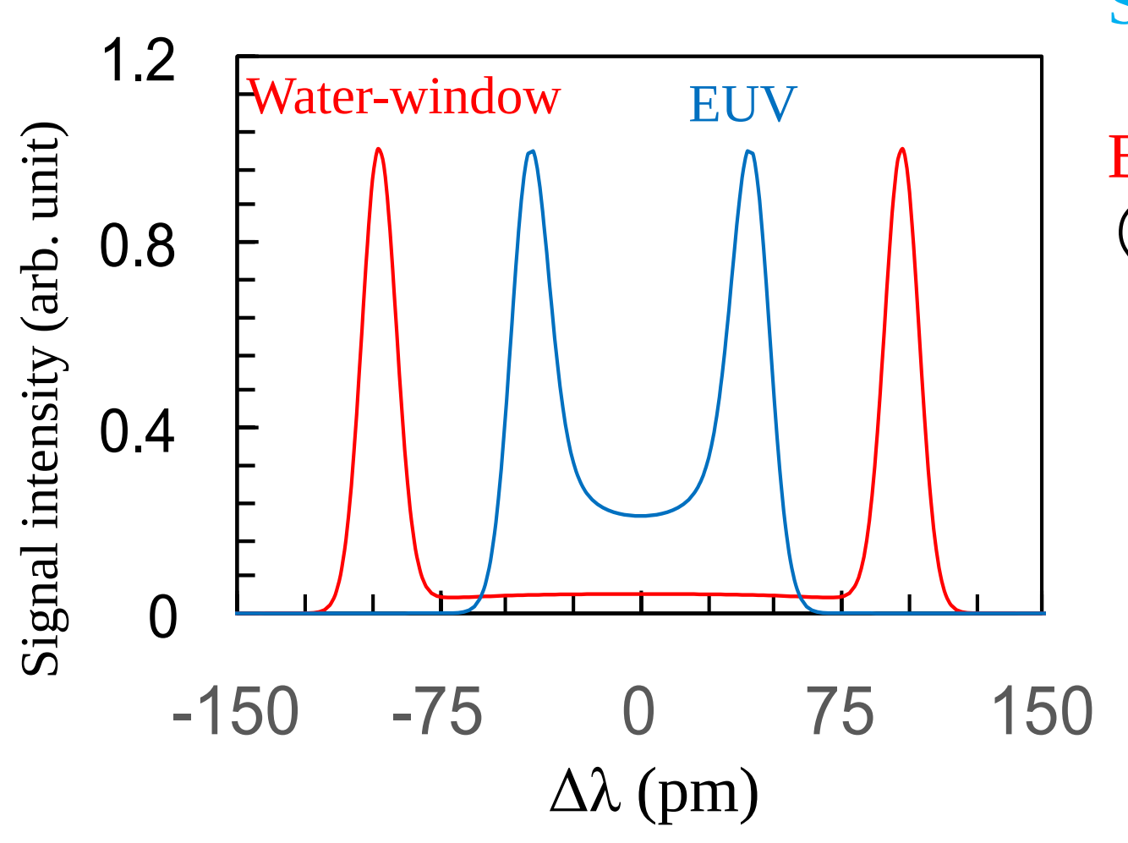
Thomson scattering for SXR sources

- ➢ Higher Z (>20) from heavier element are needed for shorter wavelength (< 13.5 nm) light sources.
- ➢ In this case, the ion component is not sufficient to determine n_e, T_e, and Z because of a lack of spectral shape information (ion acoustic wave is not strongly dumped).
- ➢ Then, we have fabricated customized spectrometers to detect the whole Thomson scattering spectrum (the ion and the electron components).

・From the ion component
1. peak width (T_e, T_i, Z)
2. ~~shape (T_e, T_i, Z)~~ (when Z>20)
(n_e, T_e, Z) (assume T_e = T_i)
3. intensity (~n_e)

・From the electron component
4. peak width (n_e, T_e)
5. shape (n_e, T_e)
6. intensity (n_e, T_e)

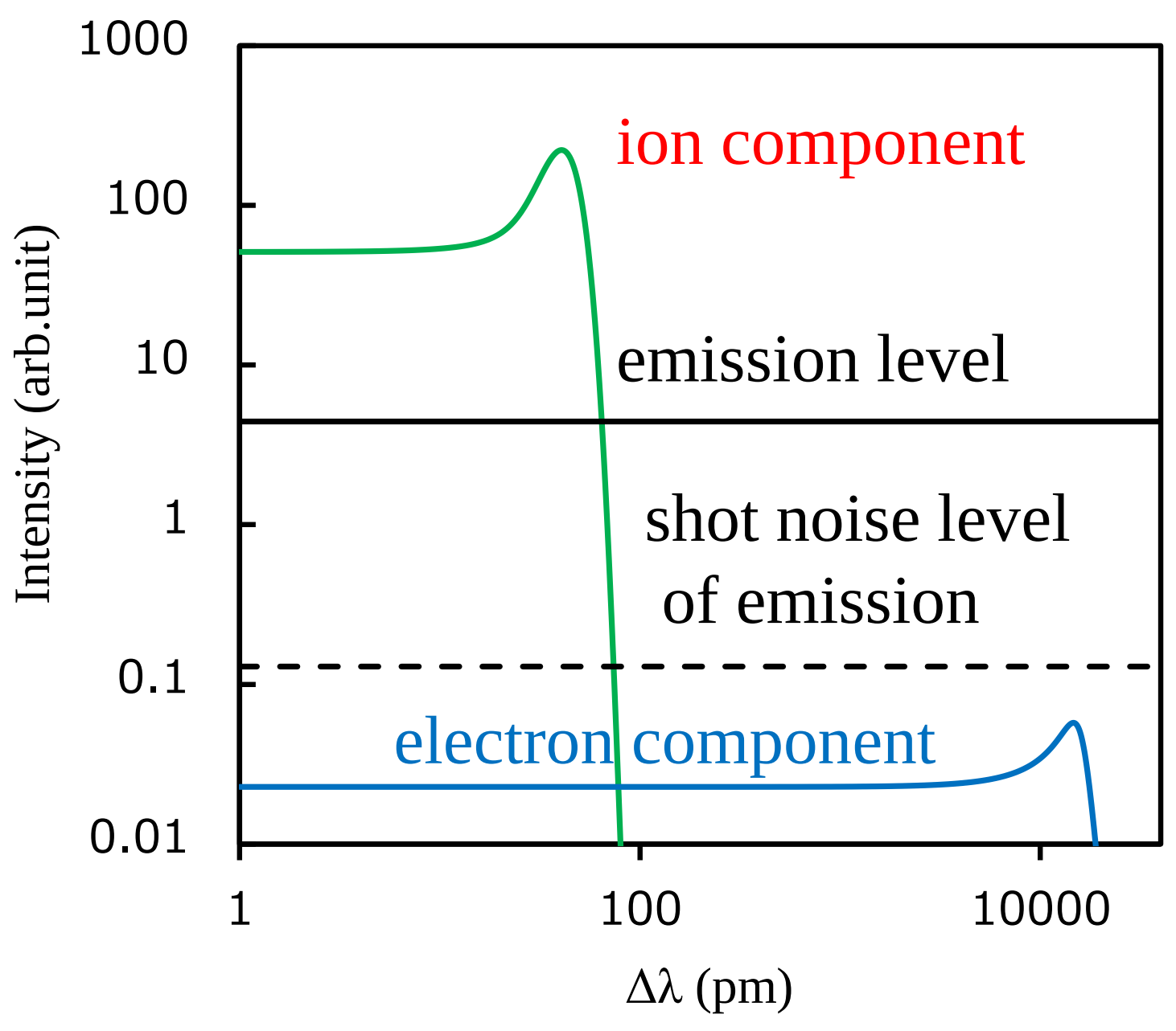
Calculated ion component spectra (532 nm probe, scattering angle=135 deg.)



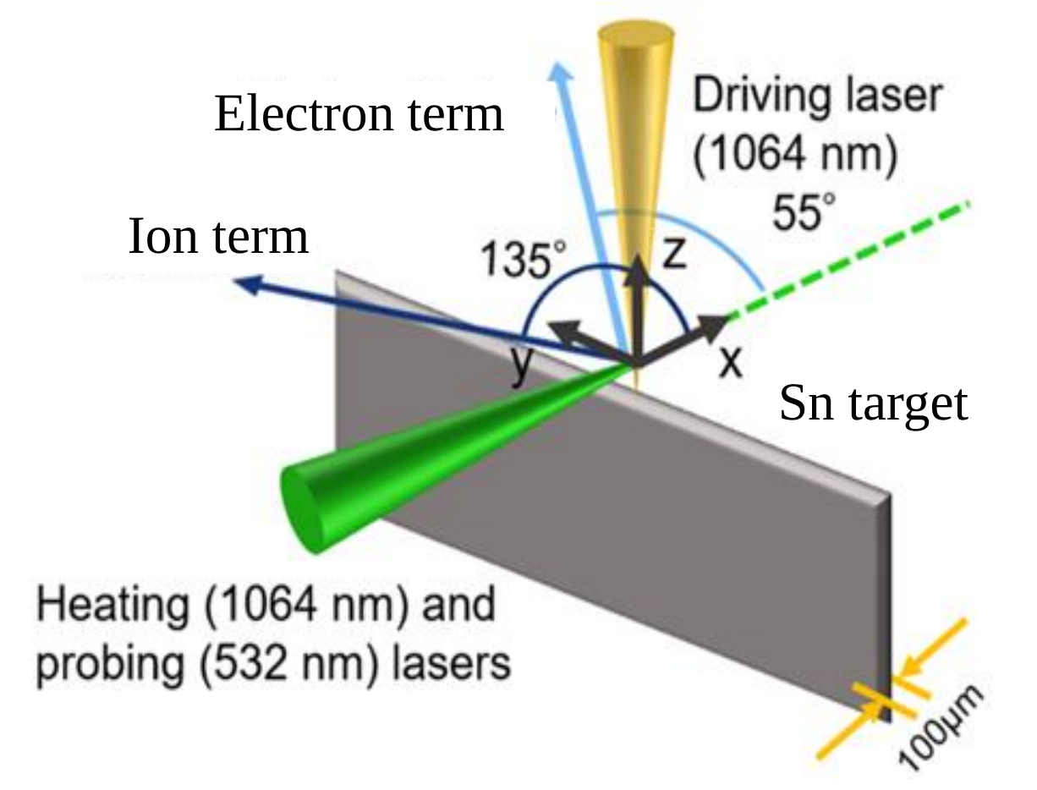
Sn for EUV
（Z=10, T_e=30eV）
Bi for Water-window
（Z=40, T_e=500eV）

Problems to detect electron component

1. Very different spectral width and intensity
   - fabricate two spectrometers
2. Weak signal intensity
   - concentrate to detect the peak wavelength of the electron component.
   - to subtract large self-emission correctly, measured spectrum was divided in two parts (emission w/ or w/o TS) using polarization of TS.



Experiment



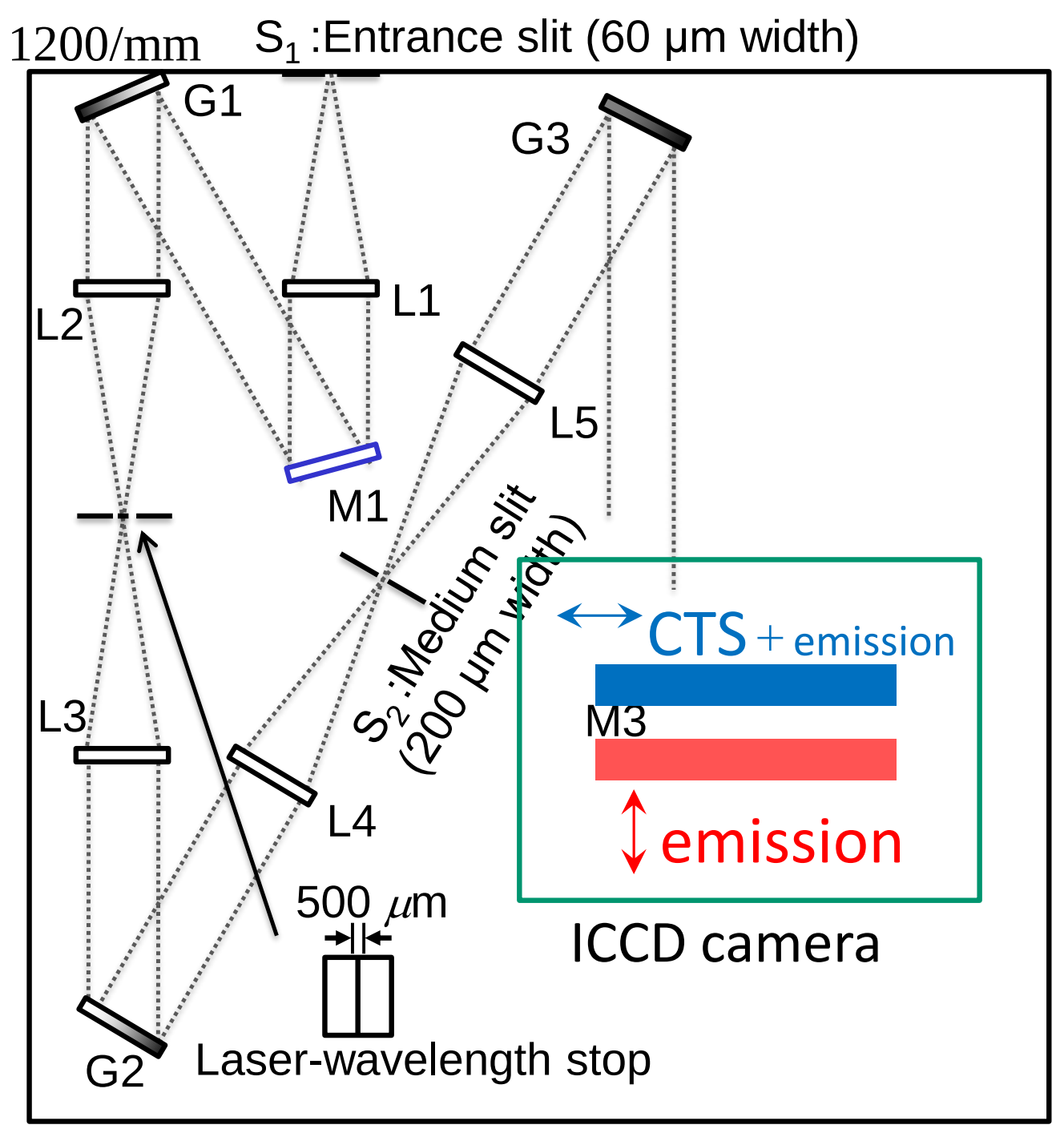
experimental condition

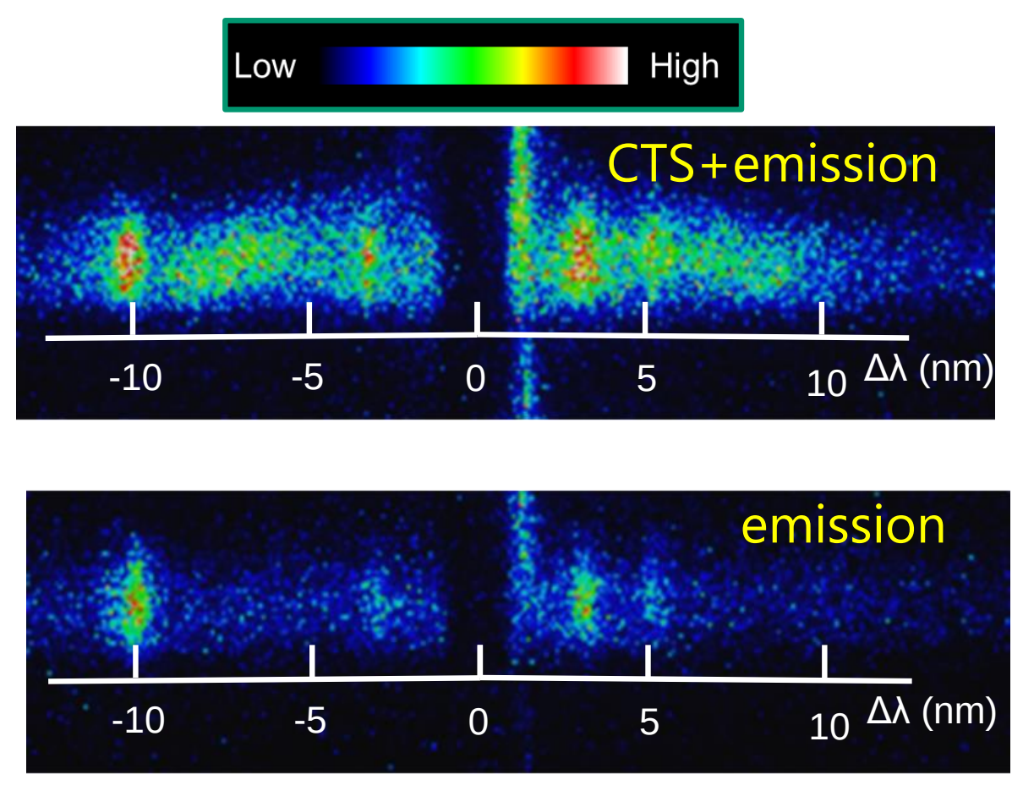
・Driving laser
λ = 1064 nm
250 mJ/pulse
8ns duration

・probe laser
λ = 532 nm
80 mJ/pulse
8ns duration

・heating laser
λ = 1064 nm
300 mJ/pulse
8ns duration

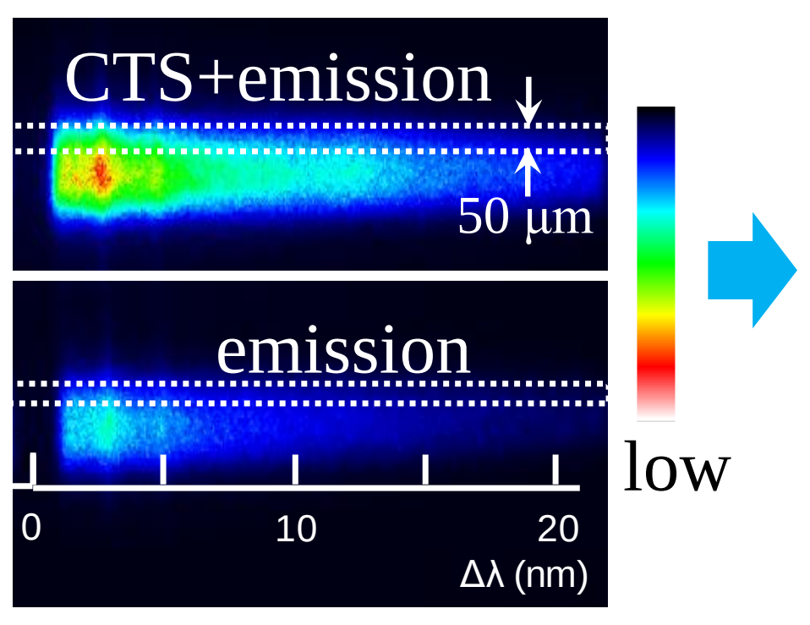
the spectrometer for the electron component



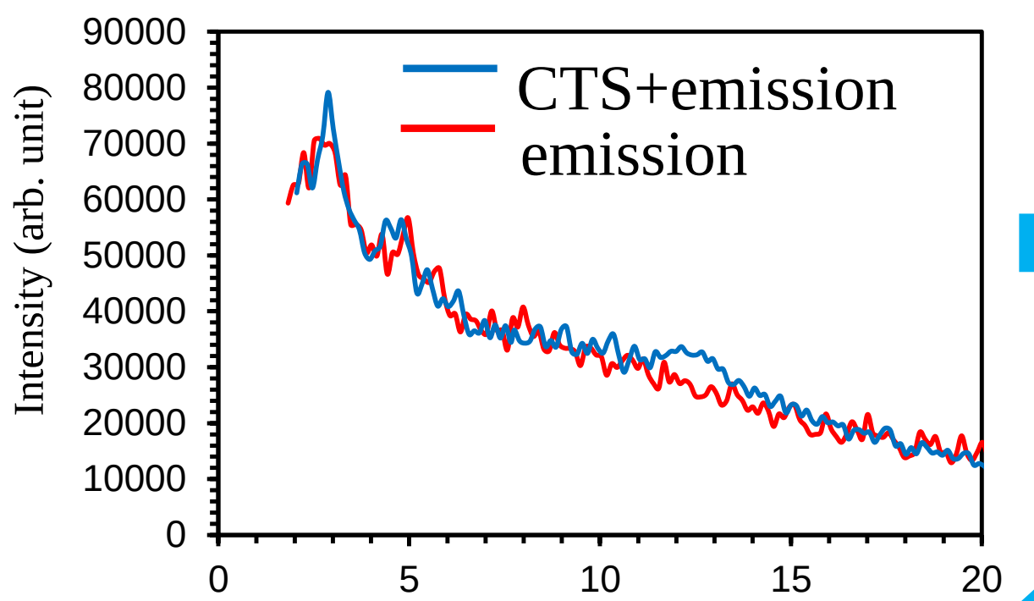


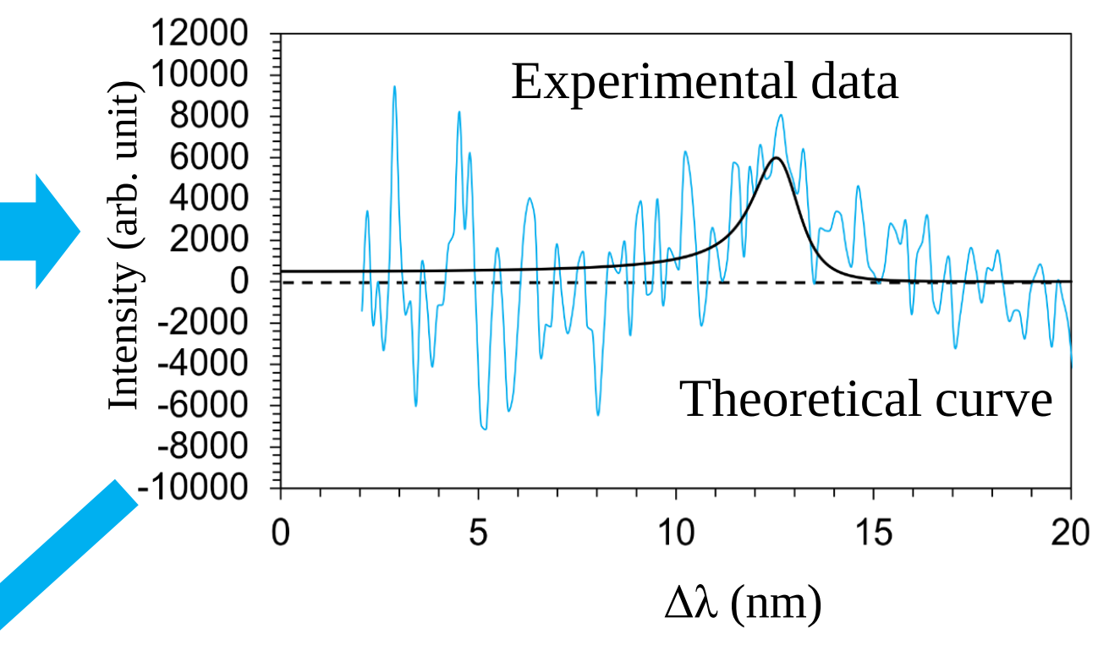
1st results [5]

As the first step, we used Sn plasmas and measured the electron component.

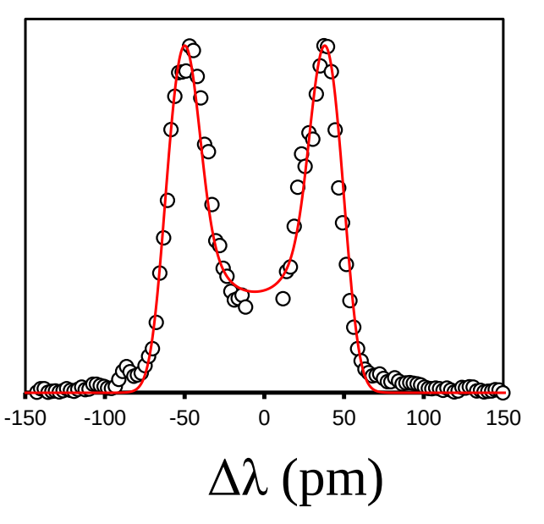


electron component spectrum



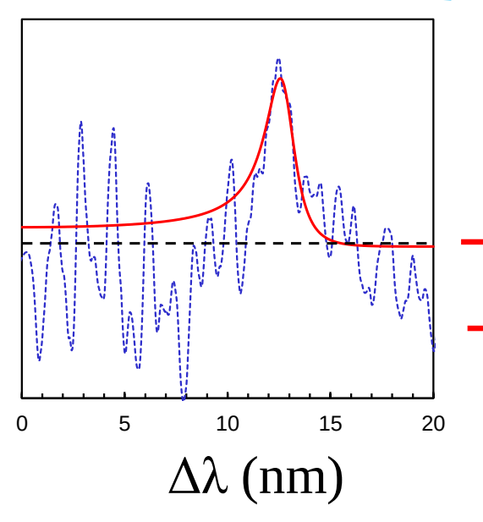


ion component



3 parameters
intensity (~n_e)
shape (T_e, T_i, Z)
peak width (T_e, T_i, Z)

electron component



1 parameter
peak width (n_e, T_e)
~~intensity (n_e, T_e)~~
~~shape (n_e, T_e)~~

n_e	1.3×10^{24} [m^{-3}]
T_e	33 [eV]
Z	8.2
T_i	28 [eV]

Simultaneous measurements enables to determine 4 parameters of LPP-EUV plasma.

Conclusions

- ➢ 2D-spatial profiles and temporal evolutions of ne, Te, and Z of EUV light sources (Sn droplet + CO$_2$ laser) were revealed using collective Thomson scattering. In this case, only the ion component was observed.
- ➢ To measure n_e, T_e, and Z of the SXR light sources, whose Z > 20, observation of the whole Thomson scattering spectrum (the ion and the electron components) are necessary.
- ➢ As the first step, the whole CTS spectrum was observed from Sn plasmas and the four parameters (n_e, T_e, T_i, and Z) were determined simultaneously.

References
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[2] J. R. Freeman *et al*., J. Appl. Phys. **110**. 083303 (2011),
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[4] K. Tomita *et al*., Sci. Rep. **7** 12328 (2017)
"Time-resolved two-dimensional profiles of electron density and temperature of laser-produced tin plasmas for extreme-ultraviolet lithography light sources"
[5] Y. Sato *et al*., Engineering Sciences Reports, Kyushu University, **40 (2)**. pp. 11-15 (2019)
"Observation of the whole Thomson scattering spectrum of laser-produced plasmasfor EUV light"