# Scaling of electron temperature and soft x-ray intensity in laser-produced heavy element highly charged ions


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## 1. Abstract


EUV and soft x-ray (SXR) sources are very important to study radiation hydrodynamics, opacities, photo-ionized plasmas, and plasma diagnostics. There is particular interest in the relationship between electron temperature and emission spectra, which result from the balance between the emissivity and opacity in the spectral region of interest. On the other hand, it is important to understand the energy flow, related to the radiation transport, by highly charged ions (HCIs) in heavy element (high-*Z*) plasmas. We successfully achieved an optically thin state in laser-produced heavy element plasmas at determined electron temperatures, which have been predicted by the power balance and the collisional-radiative (CR) models. We also mapped the power-loss processes in sub-ns and ns laser-produced high-*Z* plasmas. The electron temperature evaluation was in good agreement with the power balance model and was supported by the spectral analysis. The output flux in the soft x-ray region was stronger at higher critical density.


## 2. Background

EUV and SXR sources are deeply related to heavy elements highly charged ions. These sources are expected for EUV lithography, condensed matter physics, SXR microscope etc. . In applications, it is necessary to reduce the size of light source due to the optical systems behind light source. Therefore, we use laser produced plasma (LPP) that the size of light source is sub-millimeter order.

We need to consider the conditions such as electron temperature and laser intensity for generating a light source suitable for each objectives. It is expected that it becomes possible to contribute to the application field of the light source by clarifying these conditi-ons for heavy elements.

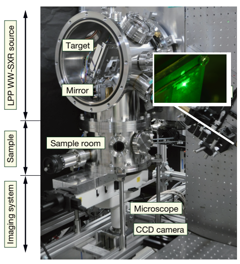


Fig. 2-1: SXR microscope.

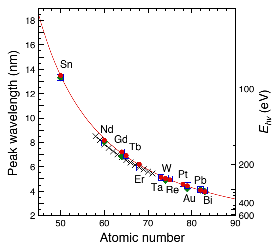


Fig. 2-2: Quasi Moseley's law.

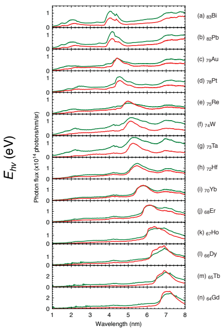

Fig. 2-3: Spectra from various element plasmas,

## 3. Objective

We focused on the bismuth plasma used in our microscope for *in vivo* biological imaging in water-window SXR spectral region. ***Our objective is to observe the SXR spectra and to evaluate the electron temperature of a laser-produced bismuth plasma.***

The calibrated spectrometer was a flat-field grazing incidence type with an unequally ruled 2400 grooves/mm variable line space grating with a spectral resolution of 0.01 nm. The spectrometer was positioned at 30° with respect to the incident laser axis.

We evaluate the contributed ionic charge states of the UTA spectral peaks by the FAC and the electron temperature dependence of the ion fraction by the collisional-radiative (CR) model at different critical densities for two laser wavelengths of 1064 and 532 nm, respectively.

## 4. Results and discussion

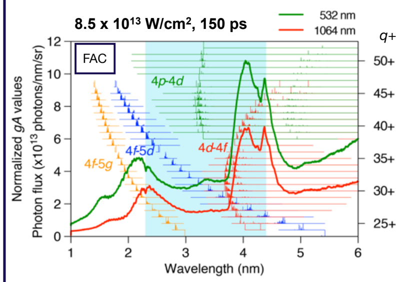


Fig. 4-1: Time integrated bismuth spectra and valance separated *gA* values by the FAC.

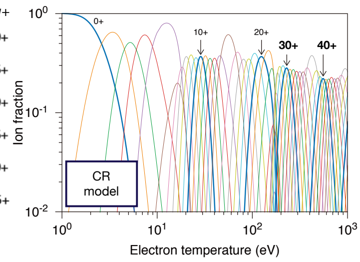


Fig. 4-2: Electron temperature dependence of ion fraction by the collisional-radiative model.

**✓ Peak wavelengths of bismuth spectra are same for both laser wavelengths.**
**✓ The photon flux for the 532-nm laser irradiation are larger than that for the 1064-nm irradiation.**
**✓ UTA peaks were attributed to highly charged ions ranging from $Bi^{32+}$ to $Bi^{42+}$.**

**Electron temperature was evaluated to be 250-650 eV which was attributed to highly charged ions of $Bi^{32+}$ - $Bi^{42+}$.**

## 5. Power balance model

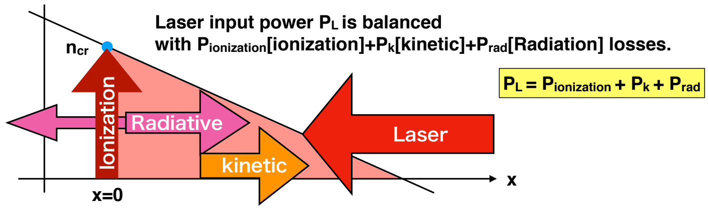


Fig. 5-1: Schematic diagram of power balance model.

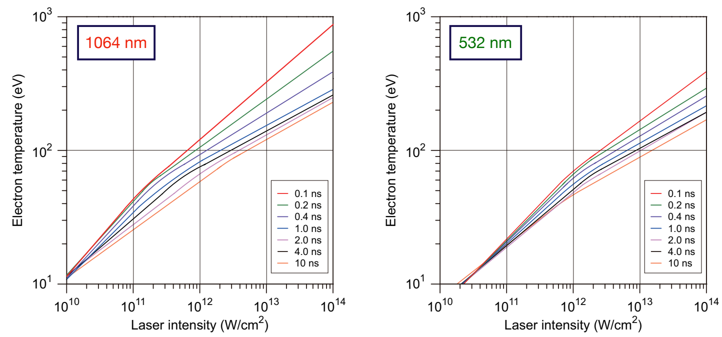


Fig. 5-2: Laser intensity and pulse duration dependences of the electron temperatures at different laser wavelengths of 1064 nm and 532 nm, respectively, using the power balance model.

## 6. Summary

We have investigated the spectral behaviors at different laser wavelengths at 1064 nm and 532 nm in sub-nanosecond pulse duration. We also have evaluated the electron temperatures by the CR model.

- The UTA peaks was around 3.9 nm at different laser wavelengths.
- The photon flux for 532-nm irradiation was larger than that for 1064-nm.
- The output photon flux was 1 x 10$^{14}$ photons/nm/sr for 532-nm.
- The UTA peaks were attributed to $Bi^{32+}$ - $Bi^{42+}$.
- The optimum electron temperature was broadly 250-650 eV.