§3. Optimization of Soft X-ray Spectra in the Water Window from Multi-charged Ion Plasmas

Higashiguchi, T., Miyazaki, T., Suzuki, Y., Hara, H., Arai, G. (Utsunomiya Univ.),
Ohashi, H. (Univ. Toyama),
O'Sullivan, G., Dunne, P., Sokell, E., Li, B. (Univ. Coll. Dublin (UCD))
Suzuki, C., Sakaue, H.A., Kato, D., Murakami, I.

Development of shorter wavelength light sources has been motivated by their applications for technology and science in the extreme ultraviolet (EUV) and soft x-ray spectral regions. Challenging topics include the three-dimensional imaging and single-shot flash photography of biological structures in living cells. A laboratory-scale table-top laser-produced plasma (LPP) source has been developed using a liquid nitrogen jet with zone plate focusing for microscopy and has achieved a resolution less than 25 nm with synchrotron-like quality images. An exposure time longer than a few seconds, however, is required that allows Brownian motion of the target cells in the solution. To circumvent thermal effects a high brightness light source is thus required for single-shot imaging.

The emission, which is attributed to the transition of $n = 4–n = 4$ ($\Delta n = 0$) unresolved transition array (UTA) spectral structure from LPPs of other elements could also provide light sources for x-ray microscopy in the water window, 2.3–4.4 nm, and the carbon window, 4.4–5.0 nm. The peak wavelength of $n = 4–n = 4$ UTA spectral structure depends on the atomic number and follows a quasi-Moseley's law: a higher Z gives a shorter peak wavelength.[1] The highest Z non-radioactive element that can be used is bismuth (Bi, $Z = 83$) and its peak wavelength observed in a 150-ps pulse duration LPP lies in the water window around 4.0 nm. On the other hand, theoretical calculations, which assume that the spectra simply mirror gA distributions, where g is the statistical weight and A is the Einstein A coefficient, have predicted an UTA emission feature at 3.2 nm in Bi plasmas with an electron temperature T_e higher than 1 keV that could not be observed in previous 150-ps LPP studies.[2] Bi plasmas radiate strongly near 3.9 nm while at electron temperatures higher than 900 eV, strong UTA emission around 3.2 nm is expected. This result is supported by LHD Bi experiment.[3] Besides requiring lower laser fluxes as they originate from lower ion stages, plasma emission based on these transitions has the advantage of being less optically thick since it is well known that the emission from $n = 4–n = 5$ ($\Delta n = 1$) transitions shifts almost monotonically to higher energy with increasing ion stage so that radiation trapping amongst overlapping transitions is not a problem. In addition, the emission from satellites, which are favored in emission from solid targets, can to some extent fill in the regions between the resonance arrays in adjacent stages giving an almost continuous distribution of intensity. Zr is an important element in astrophysical and nuclear physics and consequently many experiments and calculations have been performed in the past decades. According to the previous LPP experiment, the Zr plasma has a potential of the high output energy under lower laser fluxes and lower power density. For middle-Z and/or high-Z elements, accurate theoretical calculations are difficult due to relativistic effects and the lack of suitable experimental data for benchmarking their precision.

Optically thinner LHD plasma spectra from Zr at the electron temperature of 300–400 eV are shown in Fig. 1. It is noted that the strong line emission at 3.37 nm is originated from C^{4+}. The origin of a number of transition arrays observed in LHD plasmas that dominate zirconium spectra in the 2–6 nm region are almost identified as resulting from resonant $3d^n–3d^{n-1}4p$ and $3d^n–3d^{n-1}4f$ transitions. According to the collisional-radiative (CR) model, the ion fraction is expected to be around $q = 2x+$. The spectral structure would be reproduced by use of the atomic code of HULLAC in near future. [4]

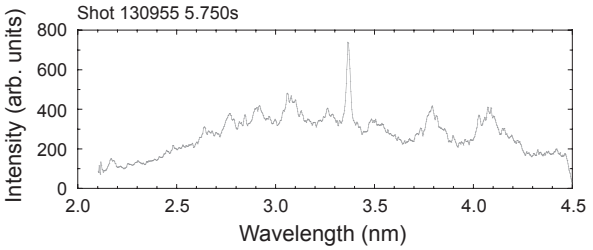

Fig. 1. EUV spectrum of highly charged Zr ions at the electron temperature of 300–400 eV in LHD.

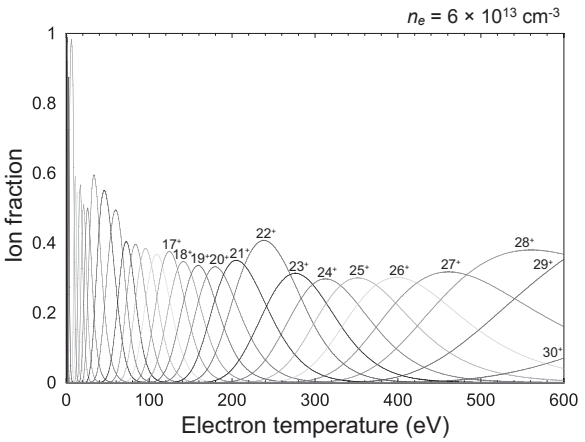

Fig. 2. Electron temperature dependence of the ion fraction at the electron density of 6 × 10^{13} cm^{-3} by collisional-radiative (CR) model.

This work is performed with the support and under the auspices of the NIFS Collaboration Research program (NIFS13KLPH020).

1) Ohashi, H. et al.: Appl. Phys. Lett. **104** (2014) 234107.
2) Higashiguchi, T. et al.: Appl. Phys. Lett. **100** (2012) 014103.
3) Ohashi, H. et al.: J. Phys. B (accepted for publication).
4) Miyazaki, T. et al.: (to be submitted).