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

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Development of shorter wavelength sources in the extreme ultraviolet (EUV) and soft x-ray (SXR) spectral regions is currently of major interest and has been motivated by their application in a number of high profile areas of science and technology where high resolution is required, such as lithography and imaging of molecular structures. It is known that optically thick plasmas can strongly self-absorb resonance line emission. Optically thin plasmas thus provide more efficient light sources. Therefore, systematic LPP studies with up-to-date intense ps-lasers are needed to determine available light source wavelengths for future applications. A magnetically confined fusion plasma was also employed to provide an optically thinner plasma than a ps-LPP to investigate the effect of optical thickness for spectral structure studies to optimize LPP sources for use in a laboratory scale microscope.

Optically thinner LHD plasma spectra from Au, Pb, and Bi are shown in Figs. 1(a)–1(c). Spectral behavior generally depends on the electron temperature of the plasma. There was however no significant dependence at temperatures higher than 1.0 keV while there was an obvious dependence at lower temperatures. The primary contribution to the main UTA peak arises from $4d^{10}4f^{N}$–$4d^{9}4f^{N+1}$ transitions from open $4d$ subshell ions in each plasma. The UTA peak position shifts toward shorter wavelength with increasing atomic number, Z. We scaled this dependence, for ps-LPPs which are almost similar to LHD plasmas, with a quasi-Moseley's law.[1)]

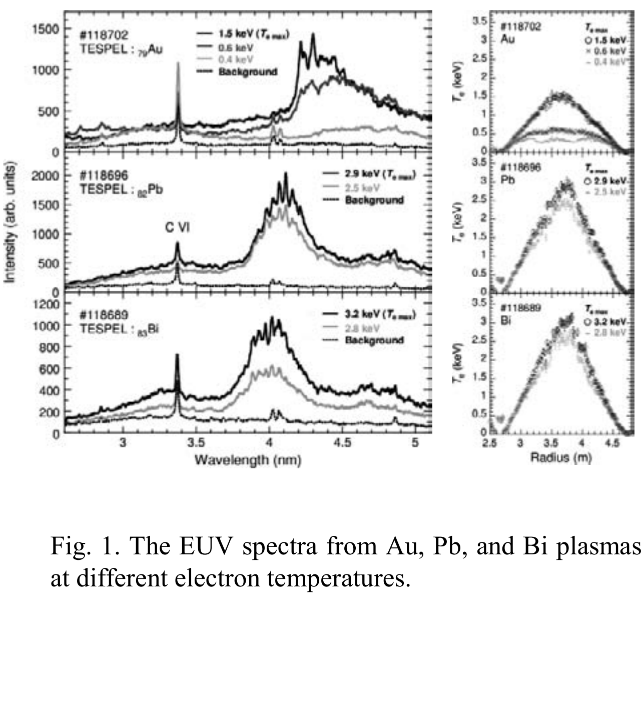

Fig. 1. The EUV spectra from Au, Pb, and Bi plasmas at different electron temperatures.

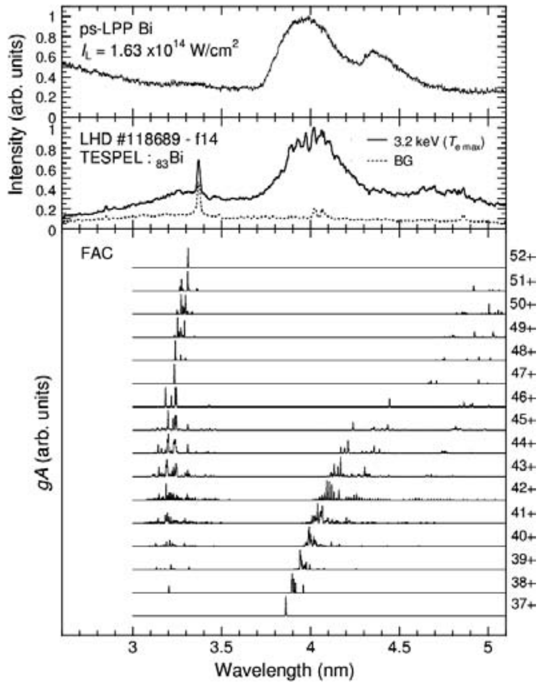

Fig. 2. Comparison of LHD Bi and LPP Bi spectra obtained with a pulse duration of 150 ps [full width at half-maximum (FWHM)] and FAC predictions.

Figure 2 shows a comparison of Bi LHD plasma spectra with a Bi ps-LPP spectrum, and calculated weighted transition probabilities (gA) for transitions of the type $4p$-$4d$ ($4p^{6}4d^{N}$-$4p^{5}4d^{N+1}$ and $4p^{N}$-$4p^{N-1}4d$) and $4d$-$4f$ ($4p^{N-1}4d$-$4p^{N-1}4f$ and $4d^{N}$-$4d^{N-1}4f$) obtained with the flexible atomic code (FAC). The dominant emission peak at 4 nm consists of $4d$-$4f$ transitions from several charge states with open $4d$ subshells. It should be noted that the electron temperatures of the LHD plasma were higher than in the ps-LPPs. As a result, we have not observed significant emission of the type $4f^{N}$–$4f^{N-1}5l$ from stages with open $4f$ subshells in LHD spectra. Comparing LPP and LHD spectra, the UTA widths in the LHD spectra are relatively narrower than in the LPP especially for lighter elements. This arises as a result of a number of factors: the increased contributions from ions with an outermost $4d^{10}4f^{N}$ configuration from transitions of the type $4d^{10}4f^{N}$–$4d^{9}4f^{N+1}$ in LPP spectra; the differences in opacity that reduce the intensity of the strongest lines and the increased contribution from satellite emission. In addition, earlier research demonstrated that if the majority of radiation originates from open $4f$ subshell ions, whose complexity inhibits the emission of strong lines then no strong isolated lines are expected to appear throughout the EUV, which is clearly seen for the LPP spectra. An optically thinner plasma reduces the self-absorption effects and increases the spectral efficiency of $n = 4$–$n = 4$ UTA emission.

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1) Ohashi, H. et al.: Appl. Phys. Lett. 104, 234107 (2014).