§14. EUV Spectra from Highly Charged Tin Ions Observed in LHD

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Since the electron temperature easily exceeds 1 keV in the plasma core region, the LHD can be considered as a unique light source from highly charged ions by injecting impurity materials of interest. As an application of this capability of the LHD to another scientific field, we have observed extreme ultraviolet (EUV) spectra from highly charged tin (Sn) ions generated in LHD plasmas in this study. Recently the needs for experimental databases of radiation from highly charged tin ions have been increasing in terms of the development of light sources around 13.5 nm for the next generation semiconductor lithography process.[1] Contrary to laser produced plasmas, low density plasmas in the LHD are more suitable for the benchmarking with theories because the spectra can be measured under optically thin conditions.

A small amount ($\simeq$0.1 % of bulk ion) of tin was introduced into a hydrogen plasma by a tracer encapsulated solid pellet (TESPEL). The EUV spectra were monitored by a grazing incidence spectrometer SOXMOS[2] whose groove density and focal length are 600 mm^{-1} and 1 m, respectively. The overall spectral resolution is about 0.01 nm. The absolute wavelength was calibrated by observing iron lines with an accuracy of $\pm$0.005 nm over the whole spectral region.

An example of the evolutions of the discharge parameters for this experiment are displayed in Fig. 1. When the pellet was injected at 1.3 s, the total radiation power rapidly increased and the stored energy began to decrease simultaneously due to radiative cooling. The measured EUV spectrum (normalized) around 13.5 nm integrated during 1.4–1.6 s in this discharge is drawn in Fig. 2 (a). On the other hand, the spectrum in Fig. 2 (b) was measured in higher temperature condition in another discharge. Consequently the measured spectra in this study can be categorized into the two types shown in Fig. 2 depending on the discharge condition.

The feature of the spectrum (a) is characterized by the dense structure around 13.5 nm arising from the 4*d*-4*f* unresolved transition array (UTA) of open 4*d* subshell tin ions. As a result of the comparison with the experimental data of charge exchange collisions,[3] the dominant emitters in the case (a) are found to be Sn^{11+}–Sn^{14+}. As for the sparse structure with sharp discrete lines in 13.9–14.7 nm (indicated by arrows) in Fig. 2 (b), the emitting charge states are expected to be higher than those in the case (a) because of the difference in the electron temperature. Actually spectral features similar to these lines can be found in the charge exchange collisions data for Sn^{19+} and Sn^{20+}. The brightest line at 14.58 nm may arise from Sn^{21+} because a 4*p*-4*d* spectral line appears nearby at 14.62 nm in a Hullac code calculation.

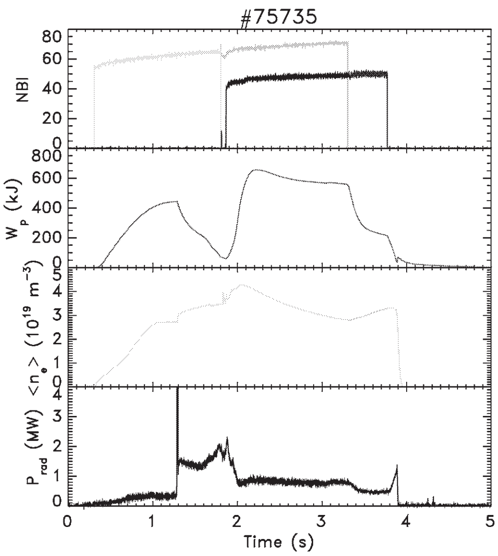

Fig. 1: Time sequences of heating, stored energy (W_p) and total radiation power (P_{rad}) in a LHD discharge with a tin pellet injection at 1.3 s.

1) Nishihara, K. et al.: Phys. Plasmas **15** (2008) 056708.

2) Schwob, J. L., Wouters, A. W., and Suckewer, S.: Rev. Sci. Instrum. **58** (1987) 1601.

3) Tanuma, H. et al.: J. Phys.: Conf. Series. **58** (2007) 231.

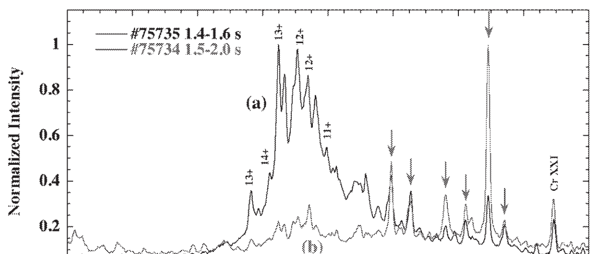

Fig. 2: The two types of EUV spectra (normalized) of tin ions measured in LHD. The case (a) was measured during 1.4–1.6 s in the discharge shown in Fig. 1.