§10. Experimental Identification of Spectral Lines of Highly Charged Heavy Ions

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Observations of extreme ultraviolet (EUV) and visible spectra from highly charged heavy ions have been extensively performed so far in LHD. Consequently, we have successfully identified EUV spectral lines of ions with relatively simple electron configurations; such as Cu-like, Ag-like ions[1]. On the other hand, there still remain some heavy elements whose spectral lines are not experimentally identified to date. The purpose of this study is to observe a number of emission spectra which lead to discoveries of unknown lines from highly charged ions of a variety of heavy elements using LHD plasmas.

In the last experimental campaign, we have observed EUV spectra from highly charged ions of thulium (Tm), lutetium (Lu), holmium (Ho), hafnium (Hf) and cerium (Ce). Small amount of these elements are introduced into LHD plasmas using the tracer-encapsulated solid pellet (TESPEL)[2]. The EUV spectra were observed around 6 nm region with a frame rate of 10 Hz by a 2 m Schwob-Fraenkel grazing incidence spectrometer[3]. The grating with 600 mm^{-1} groove density was used for better wavelength resolution. The wavelength region was tuned to where unresolved transition array (UTA) emissions of n=4–4 transitions are expected to appear. The absolute wavelength has been calibrated with an uncertainty about 0.003 nm by the positions of second/third order light from H-like/He-like carbon and nitrogen ions.

The feature of the observed EUV spectra dramatically changes according to the change in electron temperature. For example, the spectra in the 4.7–7.9 nm region observed in a discharge with a Tm pellet injection are summarised in Fig. 1 in which temporal evolutions of various parameters are also displayed in the upper panel. The TESPEL was injected at 3.8 s when the total radiated power (P_{rad}) rapidly increased simultaneously. The central electron temperature ($T_e(0)$) was kept around 2.4 keV until the tangential neutral beams (#1–3) were alternated with the vertical ones (#4–5) at 5.3 s. The spectrum is dominated by discrete feature with some isolated spectral lines during this period as shown in the bottom panel in Fig. 1 (f28). Judging from the previous results[1], the discrete spectral lines mainly originate from n=4–4 transitions of Cu-like, Zn-like and Ga-like ions. Indeed, the calculated wavelengths of the $4p_{1/2}$–$4d_{3/2}$ and $4d_{3/2}$–$4f_{5/2}$ transitions[4] of Cu-like Tm^{40+} ions agree well with the observed wavelengths of the peaks indicated as "Cu-like" in Fig. 1. The other unknown lines are under investigation with the help of Hullac and FAC code calculations.

The central electron temperature rapidly dropped until almost zero after the alternation of the neutral beams, which resulted eventually in a hollow temperature profile around 5.6 s. In this phase, the spectra are dominated by a quasi-continuum UTA feature whose mean wavelength is around 5.6 nm together with a characteristic doublet peak located around 5.9–6.0 nm. The previous study on gadolinium suggests that the mean wavelength of the UTA would be close to the position of a singlet line of Pd-like ions and the doublet peak would arise from Ag-like ions[1]. Indeed, the calculated wavelengths of the 4d–4f doublet of Ag-like Tm^{22+} ions[5] are so close to the observed doublet indicated as "Ag-like" in Fig. 1. These observations perhaps give the first experimental identification of the spectral lines of Cu-like and Ag-like Tm ions.

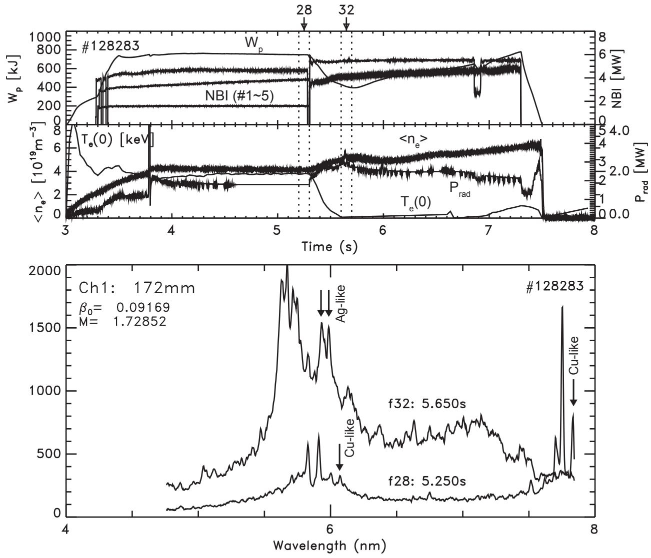

Fig. 1: Temporal evolutions of parameters and EUV spectra in a discharge with Tm TESPEL injection.

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

4) Seely, J. F., Brown, C. M. and Feldman, U.: At. Data Nucl. Data Tables **43** (1989) 145.

5) Sugar, J., Kaufman, V. and Rowan, W. L.: J. Opt. Soc. Am. B **10** (1993) 1321.