Systematic study on soft X-ray spectra from heavy ions in optically thin and thick plasmas

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Soft X-ray emission spectra from highly charged heavy ions in plasmas have recently drawn particular attention in terms of fusion and other applications. For example, tungsten (Z=74) spectra around 5 nm region have been extensively investigated using several different kinds of light sources as it will be used as a divertor material in ITER [1, 2, 3, 4]. Soft X-ray spectra from some of the lanthanide ions have been studied as potential candidates for short-wavelength light sources for the next-generation semiconductor lithography [5, 6, 7]. Bismuth (Z=83) is a candidate material for a tabletop light source in the so-called water window range (2.3–4.4 nm) for high-contrast biological microscopy [8]. Therefore, it would be worthwhile to survey Z dependence of soft X-ray spectra from heavy ions.

In general, a huge number of overlapped lines from heavy ions having 4d or 4f outermost subshells tend to form a quasicontinuum emission called unresolved transition array (UTA) in the soft X-ray region. The spectral feature of the UTA strongly depends on the optical thickness of the emitting plasmas. The typical density and temperature ranges of various types of plasmas are illustrated in Fig. 1. High density laser produced plasmas (LPPs) tend to have higher opacity in comparison with magnetically confined fusion (MCF) plasmas which have densities around 10^{19} m^{-3}. Because the critical density

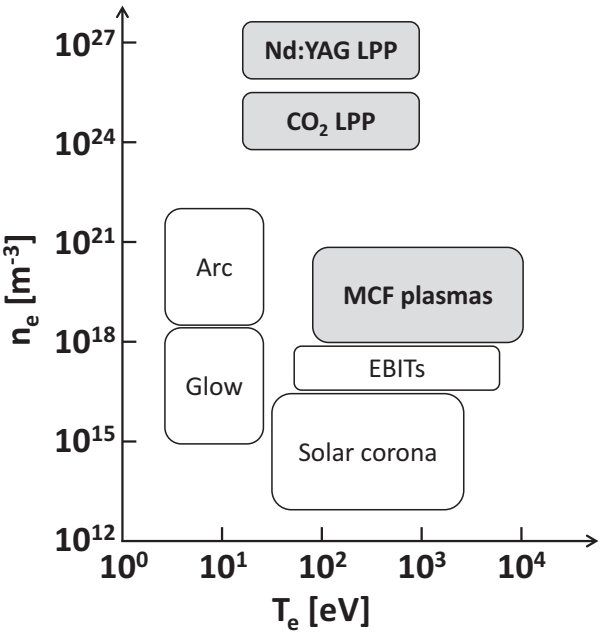

Figure 1: *Temperature and density ranges of various types of plasmas.*

of an LPP is proportional to the square of the laser wavelength, Nd:YAG LPPs are optically thicker than CO_2 LPPs.

In this study, we are developing an experimental database of soft X-ray spectra from a number of heavy ions including tungsten and lanthanides to clarify Z dependence. Also, we employ several types of plasmas having different densities to investigate opacity effects. High temperature and low density MCF plasmas produced in the Large Helical Device (LHD) are exploited to record spectra in optically thin conditions. For higher opacity cases, we have observed spectra from Nd:YAG and CO_2 LPPs, the electron density of which are around 10^{27} and 10^{25} m^{-3}, respectively.

In LHD, a small amount ($\simeq 10^{17}$ atoms) of heavy element is injected as an impurity using a tracer encapsulated solid pellet (TESPEL) [9] into a stably sustained high temperature hydrogen plasma. Temporal evolutions of soft X-ray spectra after the pellet injection are recorded with a 2 m Schwob-Fraenkel grazing incidence spectrometer [10] every 0.1 or 0.2 s. The spectral resolution is around 0.01 nm with a grating of 600 grooves/mm. The LPPs are produced by a Q-switched Nd:YAG laser (Continuum Inc.) and an ultra-shortpulse CO_2 laser operated at the wavelengths of 10.6 μm and 1.064 μm, respectively. The laser beams are focused onto a planar target of a pure metal placed in a vacuum chamber. The maximum laser power densities at the focal spot are evaluated to be 4.8×10^{13} and $(2\text{–}3)\times10^{10}$ W/cm^2 for the Nd:YAG and CO_2 lasers, respectively. Time- and space-integrated soft X-ray spectra are recorded with a flat-field grazing incidence spectrometer equipped with a 2400 grooves/mm grating and a back-illuminated soft X-ray CCD camera (Andor Technology). The spectral resolution is typically better than 0.005 nm.

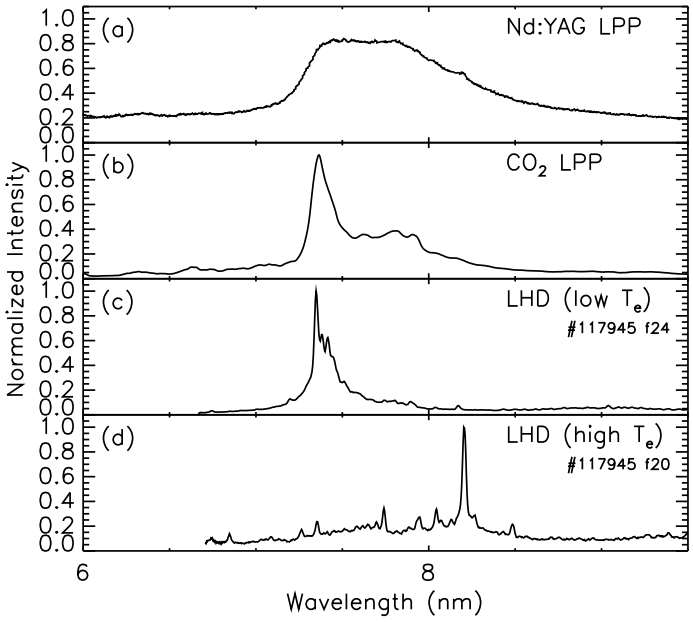

Figure 2: *Soft X-ray spectra from samarium (Sm) ions observed in (a) Nd:YAG LPP, (b) CO_2 LPP, (c) low temperature (0.25 keV) LHD and (d) high temperature (1.5 keV) LHD plasmas.*

Until now, we have systematically observed spectra for more than twenty heavy elements in LHD [11, 12]. As an example, spectra from samarium (Sm) ions

observed in the three types of plasmas are compared in Fig. 2. Two different kinds of LHD spectra recorded in low (0.25 keV) and high (1.5 keV) temperature conditions are plotted in Fig. 2 (c) and (d), respectively. The broadband UTA feature around 7.5 nm in optically thicker Nd:YAG LPP changes into the feature accompanied with some peaks at 7.36 nm in the CO_2 LPP. Finally, fine structure in the UTA is clearly distinguishable in the low temperature LHD plasma.

These UTA features originate from n=4–4 (Δn=0) transitions of highly charged ions with outermost 4d and 4f subshells. The peak positions in Fig. 2 (b) and (c) are almost identical, and agrees well with the previously reported position of the resonance 4d-4f transition of Pd-like Sm^{16+} [13]. In contrast, only discrete spectral feature without any UTA is observed in the high temperature LHD plasma in which higher ion stages having 4s or 4p subshells are dominant emitters. Indeed, the strong line at 8.21 nm is suggested to be the blend of a 4d-4f line of Cu-like Sm^{33+} and a 4s-4p line of Ga-like Sm^{31+}. We have already identified a series of the same type of lines from lanthanide ions, some of them have been found experimentally for the first time in LHD [11].

Figure 3 shows the soft X-ray spectra from dysprosium (Dy) ions observed in the three types of plasmas, compared with line strength (gA values) distributions for Dy ions with outermost 4d or 4f subshells calculated by Flexible Atomic Code (FAC) [14]. It indicates that the main UTA

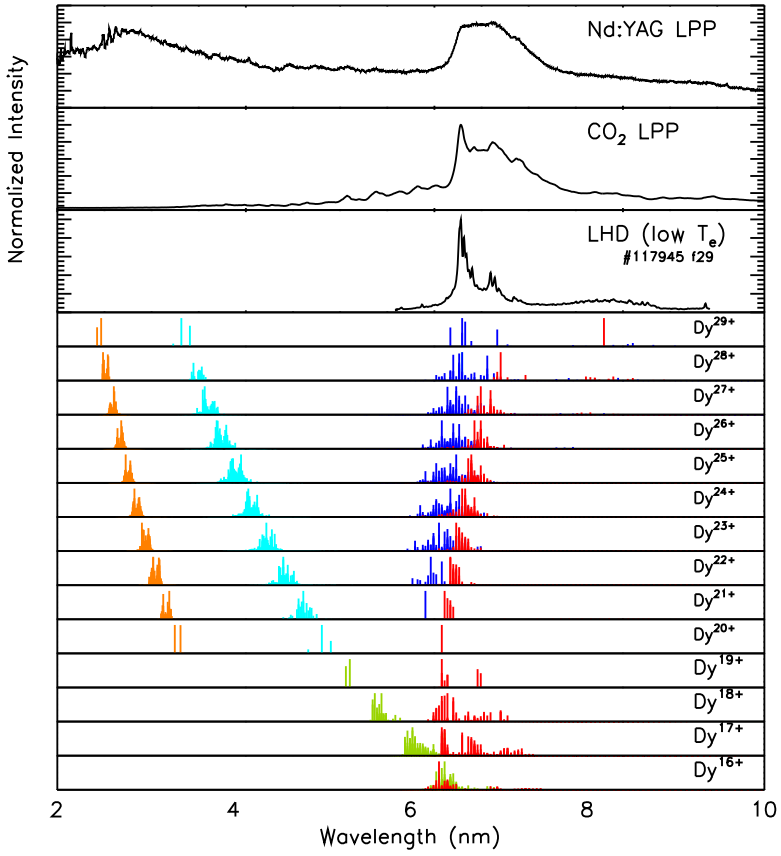

Figure 3: *Soft X-ray spectra from dysprosium (Dy) ions in three types of plasmas and the calculated line strengths for Dy ions with outermost 4d and 4f subshells. The 4d-4f (red), 4p-4d (blue), 4d-5p (light blue), 4d-5f (orange) and 4f-5g (green) transitions are shown.*

feature around 6.3 nm originates from n=4–4 transitions, while the rugged feature observed in the Nd:YAG LPP on the shorter wavelength side would be due to n=4–5 (Δn=1) transitions.

As shown in Fig. 3, the UTAs of the n=4–5 transitions are observed as a number of separate peaks because the position of Δn=1 transition moves to shorter wavelength as the ion charge increases. In the CO_2 LPP, the Δn=1 UTA intensity is relatively weaker in comparison with the main Δn=0 UTA. In the Nd:YAG LPPs, populations of n=5 levels are larger, and n=4–4 feature is easily absorbed by the 4d–4f resonances of lower ion stages (including open 4f ions) in lower temperature region surrounding the core plasma, due to higher electron density. Consequently, the intensity of n=4–5 emission is much more pronounced in the Nd:YAG LPPs than in the CO_2 LPPs. It should be also noted that broader UTA features in the optically thicker Nd:YAG LPPs contain contributions from satellite transitions which appear at slightly longer wavelength side of the resonance transitions.

In summary, we have compared the soft X-ray spectra from highly charged heavy ions observed in the three types of plasmas having different opacities. The comparison clearly demonstrates that the spectral feature drastically changes due to the differences in the effects of self-absorption, satellite transition and collisional excitation depending on the opacity and electron density. Also, we have experimentally identified some of the new lines of lanthanide ions in LHD.

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