EUV spectra from highly charged tin ions observed in low density plasmas in LHD

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Abstract. In order to meet the increasing needs for experimental databases of tin (Sn) extreme ultraviolet (EUV) spectra relevant to the next generation EUV lithography, we have measured EUV spectra from highly charged tin ions in low density plasmas produced in the Large Helical Device (LHD) at the National Institute for Fusion Science. A small amount of tin was introduced into a background high temperature and low density hydrogen plasma by injecting a pellet. The EUV spectra were monitored by a grazing incidence spectrometer whose wavelength resolution is about 0.01 nm. Two different types of spectral features were found in the LHD depending on the discharge condition. The well known dense spectral structure around 13.5 nm is measured when the plasma is rapidly cooled and approaching radiative collapse after the pellet injection, while the sparse spectrum with several unidentified discrete lines from 13.8–14.6 nm is observed if the plasma is cooled more slowly and higher temperature is maintained for a while. According to comparison with other charge-separated experimental data, the dominant charge states in the former case are Sn¹¹⁺–Sn¹⁴⁺. The latter case may be explained by considering the spectral lines from charge states higher than Sn¹⁹⁺.

1. Introduction

Recently the needs for experimental databases of extreme ultraviolet (EUV) radiation from highly charged tin (Sn) ions have been increasing in the context of the development of light sources around 13.5 nm for the next generation semiconductor lithography process [1]. Though laser and/or discharge produced high density (>10²³ m⁻³) tin plasmas are promising candidates for these light sources, EUV spectra of such plasmas tend to be complex due to the effects of line broadening, optical thickness and satellite lines. Furthermore, spatial and temporal scales of changes in plasma parameters are extremely steep and rapid in these plasmas, which makes it difficult to benchmark theoretical models with experimental results.

On the other hand, low density plasmas generated in magnetically confined devices utilized for fusion research are more suitable for the benchmarking because they can easily generate highly charged ions of intentionally injected impurity materials (e.g. tin) under optically thin
conditions. In addition, they have relatively mild temperature and density gradients which are easily controlled and can be measured by reliable diagnostic tools.

In fact, we have already studied xenon (Xe) EUV spectra from low density plasmas generated in the Compact Helical System (CHS) and the Large Helical Device (LHD) which are fusion-oriented torus devices at the National Institute for Fusion Science [2, 3]. Since the electron temperature easily exceeds 1000 eV in the core region, LHD plasmas can be utilized as a light source from highly charged ions by injecting impurity materials of interest. In this study, we have observed EUV spectra from highly charged tin ions in LHD plasmas. Solid tin is introduced by a tracer encapsulated solid pellet (TESPEL) [4] injected into a background hydrogen plasma. The measured spectral features are discussed based on comparisons with other experiments and theoretical models.

2. Experimental details

The LHD is one of the largest devices in the field of magnetically confined fusion research which generates large volume ($30 \text{ m}^3$) plasmas with the shape of a helical torus whose average major and minor radii are 3.9 m and 0.6 m, respectively. The plasmas are confined in nested magnetic surfaces formed by unclosed field lines under a magnetic field of 2.75 T at the plasma center. The typical plasma density is much lower ($\leq 10^{20} \text{ m}^{-3}$) than that of laser or discharge produced high density plasmas. Spatial profiles of electron density and temperature are measured by an existing laser Thomson scattering diagnostic system [5]. In this study, a small amount ($\approx 0.1\%$ of bulk ion) of tin was introduced into the high temperature ($\approx 1000 \text{ eV}$) and low density ($\approx 10^{19} \text{ m}^{-3}$) hydrogen plasma by injecting the TESPEL.

The EUV spectra were monitored by a grazing incidence spectrometer SOXMOS [6] whose groove density and focal length are 600 mm$^{-1}$ and 1 m, respectively. The spectral range was fixed to 11.0–15.2 nm in this study. The integration time of the detector of the SOXMOS spectrometer was typically 200 ms and was adjusted according to the brightness. The overall spectral resolution is about 0.01 nm. The viewline of the spectrometer is slightly tilted against the equatorial plane within the horizontally elongated plasma cross section because the core temperature tends to be too high to observe the EUV spectra.

The wavelength of the spectrometer was carefully calibrated by observing iron lines as an intrinsic impurity material in the plasma without tin injection. The spectral lines from iron ions whose wavelengths are already known were observed under the same spectrometer setup. Then these wavelengths were fitted to the dispersion relation of the SOXMOS spectrometer determined by the geometrical arrangement. Consequently, we could determine the absolute wavelength with an accuracy of $\pm 0.02$ nm over the whole spectral region.

3. Results and discussion

We have observed more than ten EUV spectra in various timings in several discharges under different conditions. Consequently, the measured spectral feature can be categorized into two types depending on the discharge condition. The examples of the two types of discharge condition are displayed in Fig. 1 by drawing the time sequences of heating, stored energy ($W_p$) and total radiation power ($P_{\text{rad}}$). The discharges were initiated by electron cyclotron heating (ECH) followed by three neutral beam injection (NBI) heatings. 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 cooling process is apparently faster in case (a) than in case (b) as observed in the waveforms of the stored energy. This difference results in the two types of spectral feature shown in the top row of Fig. 2, where the measured EUV spectra (normalized) around 13.5 nm integrated during the shaded area in Fig. 1 (a) and (b) are drawn. The plasma approached radiative collapse and the total radiated power finally began to increase at the end of the integration time in the case (a), while the radiated power remained
stable during the integration time in the case (b). The line-averaged electron density was about $3 \times 10^{19}$ m$^{-3}$ in both cases. The feature of spectrum (a) is characterized by the well known dense structure around 13.5 nm, while the more sparse spectrum with several discrete lines at 11.94 nm and in 13.9–14.7 nm (indicated by arrows) was observed in (b). The line at 14.98 nm arises from an intrinsic chromium impurity in the plasma.

According to theoretical calculations of tin ion energy levels, the dense spectral structure in 13.5 nm region arises from the 4d-4f unresolved transition array (UTA) of moderately charged open 4d subshell tin ions [7]. Recently charge-separated experimental spectra of tin ions have been reported by charge exchange collisions between charge-selected tin ion beams (up to Sn$^{20+}$) and rare gas targets [8, 9], which are shown in the middle and bottom rows of Fig. 2 for Sn$^{11+}$–Sn$^{14+}$, Sn$^{19+}$ and Sn$^{20+}$. Additional charge-separated spectral data obtained by fitting data
from Cowan code calculations to the experimental spectra in a vacuum spark discharge have recently been published for Sn$^{8+}$–Sn$^{14+}$ [10]. The statistically weighted Einstein A coefficients ($gA$ values) listed in this reference are also plotted in Fig. 2 by vertical bars. As a result of the comparisons, the dominant emitters in case (a) are found to be Sn$^{11+}$–Sn$^{14+}$ and several prominent peaks are identified as indicated in the top row of Fig. 2. These charge states would become dominant when the electron temperature is around 50 eV assuming coronal ionization equilibrium. However, the actual electron temperature near the point of the pellet ablation is much higher (300–400 eV), which implies that the plasma lies far from the ionization equilibrium due to the effects of radial transport of tin ions.

As for the sharp discrete lines in 13.9–14.7 nm that are relatively more intense in case (b), 4d-5p or 4d-4f lines of charge states lower than Sn$^{11+}$ would appear in this wavelength range. However, the dominant charge states in case (b) are expected to be higher than that in case (a) considering the difference in the speed of radiative cooling. Actually spectral features similar to these lines can be found in the charge exchange data for Sn$^{19+}$ and Sn$^{20+}$ as shown in the middle row of Fig. 2. Hence it can be speculated that charge states higher than Sn$^{19+}$ could be observed in this case. The lines at 11.94 nm and 14.58 nm are not found in the other experimental data. The brightest line at 14.58 nm may arise from Sn$^{21+}$ because a 4p-4d spectral line appears nearby at 14.62 nm in a Hullac code calculation [11]. Since the experimental data of charge exchange collisions are unavailable for charge states higher than Sn$^{21+}$ at present, we intend to make comparison with the other theoretical calculations (e.g. Cowan code) to identify them.

Acknowledgments
The authors acknowledge the LHD experimental group for their assistance. This work was partly supported by the MEXT under the leading project for EUV lithography source development.

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