Temperature-Dependent EUV Spectra of Xenon Plasmas Observed in the Compact Helical System

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We carried out spectroscopic measurements of extreme ultraviolet (EUV) emissions from xenon (Xe) plasmas generated in the Compact Helical System (CHS) by a grazing incidence spectrometer with a spectral resolution of 0.05 nm. Spatial profiles of the electron density and temperature of the plasmas have been measured by laser Thomson scattering diagnostic system. A remarkable variation in spectral features by different electron temperatures was observed, and was attributed to the difference in dominant charge states of Xe ions in the plasma.

Keywords:
EUV spectrum, xenon, CHS, grazing incidence spectrometer, wavelength calibration

Extreme ultraviolet (EUV) emissions from laser-produced xenon (Xe) plasmas have been extensively investigated as a prospective light source for the next-generation lithography process in semiconductor device fabrication [1]. Many experimental databases of Xe ion spectra observed under various plasma parameters are desired for the development of reliable theoretical models. In contrast to laser-produced plasmas, magnetically confined plasmas utilized for fusion research are suitable for this purpose, since they have relatively mild temperature and density gradients measured by reliable diagnostic tools. In this study we measured the EUV spectra of pure Xe plasmas produced in the Compact Helical System (CHS) [2], a medium-size fusion-oriented torus device at the National Institute for Fusion Science (NIFS). A remarkable variation in spectral features observed for the first time is reported here, and detailed discussions based on comparisons with other experiments and theoretical models will be described elsewhere.

The CHS generates helical torus plasmas whose average major and minor radii are 1 m and 0.2 m, respectively. Low-density ($\leq 10^{19}$ m^{-3}) optically thin plasmas are produced by electron cyclotron resonance heating using a 53 GHz gyrotron with a maximum duration of 100 ms under a magnetic field of 0.88 T at the plasma center. Spatial profiles of electron density and temperature are measured by an existing laser Thomson scattering diagnostic system [3]. Plasma parameters can be changed by controlling the gyrotron power or the amount of Xe gas puffing. EUV spectra were measured by a flat field grazing incidence spectrometer (GIS) equipped with a charge coupled device (CCD) detector (Hamamatsu, C4880) cooled by liquid nitrogen. The spectrometer consists of a flat field grating whose groove density and focal length are 1200 mm^{-1} and 235 mm, respectively, in the spectral range of 5–30 nm. The exposure time of the CCD was fixed at 10 ms and controlled by a mechanical shutter set in front of an entrance slit of 50 μm width. The overall spectral resolution was about 0.05 nm. Note that the viewline of the spectrometer is along the equatorial plane within the horizontally elongated cross section, implying that the measured spectra correspond to integration along a line of sight crossing both the center and the edge regions of the plasma.

The wavelength of the spectrometer was carefully calibrated according to the following procedure. First, the three spectral lines of the He II Lyman series in the region of 23.73–25.63 nm were observed in a helium plasma. We then calibrated this wavelength region correctly by fitting these three points to the dispersion relation of the grating. Next, an intense second order spectral line at 24.03 nm in a Xe plasma was observed without changing the spectrometer setup. The half of this wavelength (12.01 nm) was assigned to its first order line. After re-fitting by adding this point, we determined the wavelength with an accuracy of ±0.03 nm over the whole spectral region.

Figure 1 shows the representative EUV spectra in 10–20 nm for the gyrotron powers of (a) 270 kW and (b) 130 kW. Plasmas were almost in the steady state during the CCD

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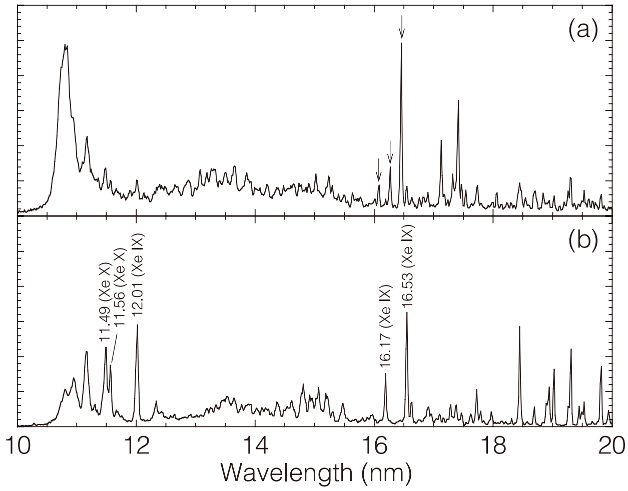

Fig. 1 EUV spectra observed in CHS Xe plasmas for the heating powers of (a) 270 kW and (b) 130 kW.

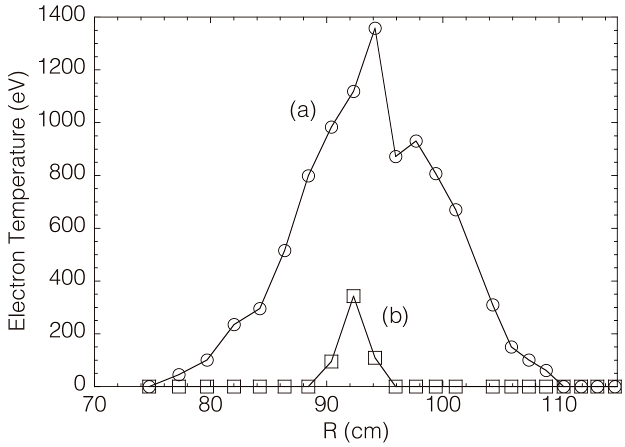

Fig. 2 Spatial profiles of the electron temperature corresponding to the two cases in Fig. 1 measured by laser Thomson scattering diagnostic system. The plasma center is located at R = 92.1 cm.

exposure time (10 ms). Spatial profiles of the electron temperature corresponding to the spectra are plotted in Fig. 2 as a function of the major radius of the torus, and their values are about 1200 eV and 300 eV at the center (R = 92.1 cm) for (a) and (b), respectively. Substantial shrinkage of the plasma column was unavoidable for the low heating power as shown in Fig. 2. The central electron densities are 4.8×10^{18} m^{-3} and 4.0×10^{18} m^{-3} for (a) and (b), respectively. The spectral features appear to be largely different between the two cases. According to theoretical calculations of Xe ion energy levels, several broad peaks observed in 10.5–11.2 nm region are originated from 4d-4f transitions of charge states higher than Xe^{10+} [4]. These peaks are relatively stronger in (a) than in (b), which could reasonably be attributed to the difference in electron temperature, since the electron density was almost the same in the two cases. The five prominent lines whose wavelengths and charge states are indicated in (b) have certainly been identified so far. These lines are emitted from 4d-4f and 4d-5p transitions of Xe^{8+} and Xe^{9+} ions [5,6], and observed also in other low temperature plasma sources. The unknown three lines indicated by arrows in (a) are also found in a high temperature Large Helical Device (LHD) plasma [7], and are now being analyzed carefully by considering various possibilities.

Recently several spectral observations for highly charged Xe ions have been compiled [8]. Comparisons of our results and these experimental data with model calculations are necessary to understand the atomic processes associated with the EUV emissions, and such comparisons are currently underway. These detailed analyses combined with electron density and temperature data will provide more useful information for benchmarking the model calculations of Xe EUV spectra.

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