Observation of Xenon EUV Spectra in Compact Helical System

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Abstract

We have carried out spectroscopic measurements of xenon (Xe) extreme ultraviolet (EUV) emissions in plasmas produced by a medium-size fusion-oriented torus device, Compact Helical System (CHS), for the development of reliable spectroscopic data of Xe ions. The EUV spectra have been measured in low density ($<10^{19}$ m^{-3}) hydrogen plasma with Xe gas injection by an existing grazing incidence spectrometer. Electron density and temperature profiles are measured by Thomson scattering diagnostic. Observed spectral lines are compared with the results of HULLAC code calculation and charge exchanging collisions experiment. The charge states of Xe ions and transitions are inferred for several prominent peaks.

Keywords:

EUV light source, lithography, xenon, CHS, grazing incidence spectrometer, HULLAC

1. Introduction

Optical lithography is one of the essential processes in the fabrication of semiconductor devices. According to the technological target for the next generation lithography process, bright extreme ultraviolet (EUV) light source for the wavelength of 2 % bandwidth around 13.5 nm is indispensable for processing patterns less than 50 nm. Though laser-produced xenon (Xe) plasma is one of the promising candidates for the EUV light source [1,2], construction of theoretical model for detailed atomic processes and benchmarking with various experimental data of Xe ion spectra are required to optimize the efficiency of the light source. However, the laser-produced plasmas are unsuitable for the benchmarking since detailed measurements of plasma density and temperature profiles are generally difficult due to their sharp spatial and temporal variations. On the other hand, magnetically confined plasmas utilized for fusion research have relatively mild temperature and density gradients measured by reliable diagnostic tools.

In this study, we have carried out spectroscopic measurements of Xe EUV emissions in discharge plasmas produced in a medium-size fusion-oriented torus device, Compact Helical System (CHS) [3], to contribute to the development of reliable spectroscopic data of Xe ions. Though electron densities in magnetically confined plasmas are generally much lower than those in laser produced ones, they are more suitable for spectroscopic data analyses because of easier control of plasma parameters and dominance of line spectra. In this article we concentrate on the experimental setup and preliminary results of the spectroscopic measurements by an existing spectrometer, and detailed discussions on physical processes will be reported elsewhere.

2. Experimental details

Compact Helical System (CHS) is a medium-size torus plasma device utilized for fusion research at National Institute for Fusion Science (NIFS) [3]. A top view of the standard boundary configuration of CHS plasma is shown in Fig. 1(a). The shape of the plasma cross section is like an ellipse which is twisted 8 times during one toroidal rotation. The average major and minor radii of the torus plasma are 1 m and 0.2 m, respectively. In this study, the plasmas are produced by electron cyclotron resonance heating (ECH) using a 53 GHz gyrotron with the maximum duration of 100 ms. The gyrotron power is injected vertically from the upper port indicated in Fig. 1(a), and the plasmas are confined by a magnetic field of 0.88 T (at the plasma center).

Electron density and temperature profiles are mea-

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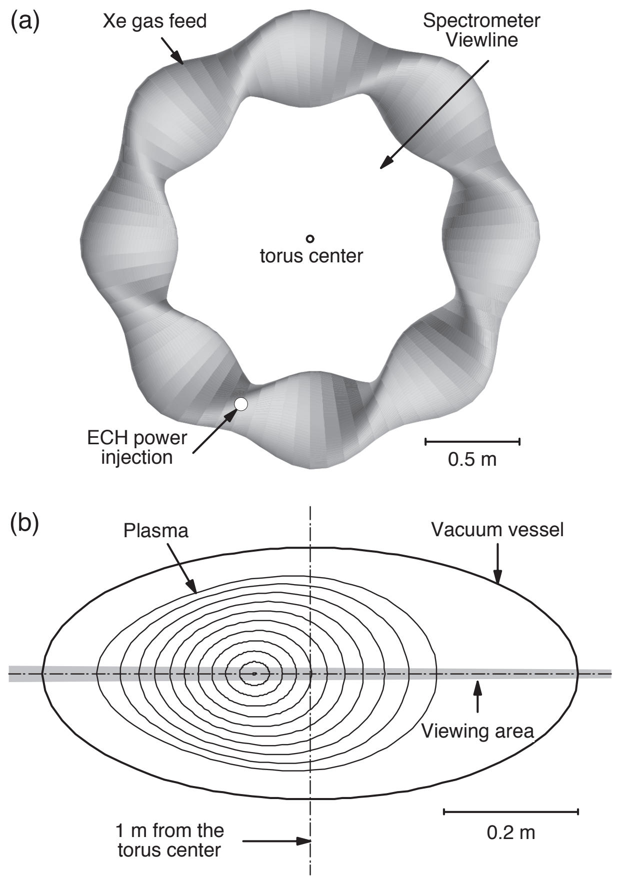

Fig. 1 (a) Top view of the standard configuration of Compact Helical System (CHS) plasma. ECH power is injected vertically from the upper viewport.
(b) Crosssectional view of the plasma and the viewline of the spectrometer.

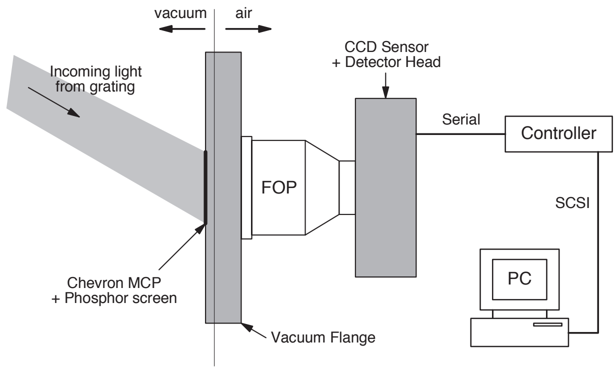

Fig. 2 Schematic diagram of the detector system of the spectrometer.

sured by an existing Nd:YAG laser Thomson scattering diagnostic system [4]. Line-averaged electron density is measured by a millimeter wave interferometer. Typical electron density of the ECH plasma is below 10^{19} m^{-3}, which means that the plasma is optically thin. Electron temperature is typically 1 keV at the plasma center, while much lower near the plasma edge.

We have used a flat field grazing incidence spectrometer (Shinku-Kogaku, model JYF-306) installed in CHS for impurity monitoring. The viewline of the spectrometer is along the equatorial plane within the horizontally elongated cross section as shown in Fig. 1(b). Therefore the measured spectra correspond to line integrated emissivity along the viewline passing through the center and the edge of the plasma. The grating of the spectrometer is made of platinum coated toroidal concave blank to obtain flat focal image of 40 mm length within the spectral range of 10-110 nm. Groove density and focal length of the grating are 450 mm^{-1} and 306 mm, respectively. Though the active area size of the grating is 8 mm×30 mm, the available area is limited to 3 mm×22 mm by a masking plate to maximize the spectral resolution.

Schematic diagram of the detector system is illustrated in Fig. 2. The Micro Channel Plate (MCP) assembly (Burle, 3040FM) consists of a Chevron type MCP of 40 mm diameter placed along the focal plane. Amplified electrons are transferred into a visible spectral image by a P20 phosphor screen placed behind the exit of the MCP. The spectral image is subsequently reduced to 25 mm diameter via a fiber optic plate (FOP), and then detected by a Charge Coupled Device (CCD) linear image sensor (Hamamatsu, S7010) with the minimum readout time of 10 ms. The pixel number of the CCD array is 1024×252, and pixel charges are summed up vertically by line binning. The analog data output of the CCD are converted to digital data by a CCD controller (Hamamatsu, C7557) which is controlled remotely by a personal computer. The width of the entrance slit of the spectrometer is fixed at 10 μm in this study. In spite of the resolving power of the grating, overall spectral resolution is about 0.3 nm determined mainly by the spread of electron clouds at the exit of the MCP.

3. Preliminary results and analyses

We have already measured VUV spectra of several discharge schemes of pure Xe plasma or hydrogen plasma with Xe gas injection. In this article we only discuss on one representative discharge of the latter case in which relatively strong Thomson scattering signals can be obtained. Temporal variations of plasma parameters in this discharge are displayed in Fig. 3. The ECH power of 193 kW is applied during the period t = 20–120 ms in low pressure (<10^{-2} Pa) hydrogen gas atmosphere. Xe gas whose density is equivalent to 4.8×10^{17} m^{-3} in the vacuum vessel is puffed during the period of t = 50–60 ms. Line averaged electron density is kept constant in 50–80 ms, then gradually decreased until the termination of the discharge. Temporal behaviors of central electron temperature and density mea-

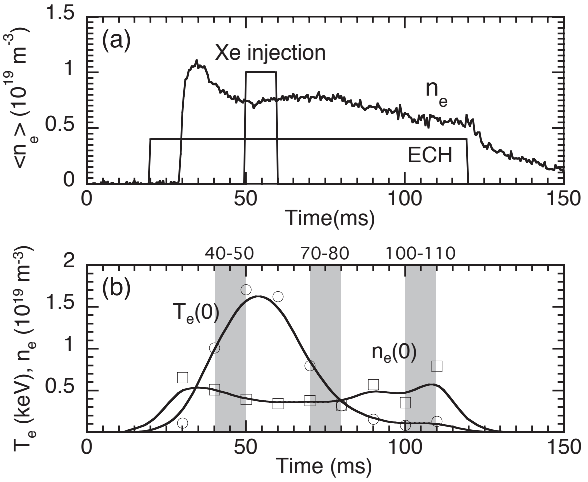

Fig. 3 Temporal variations of plasma parameters analyzed in this study. (a) Line averaged electron density measured by an interferometer, and (b) temporal variations of central electron temperature and density measured by Thomson scattering diagnostic. Gray regions are the time intervals corresponding to the spectra shown in Fig. 4.

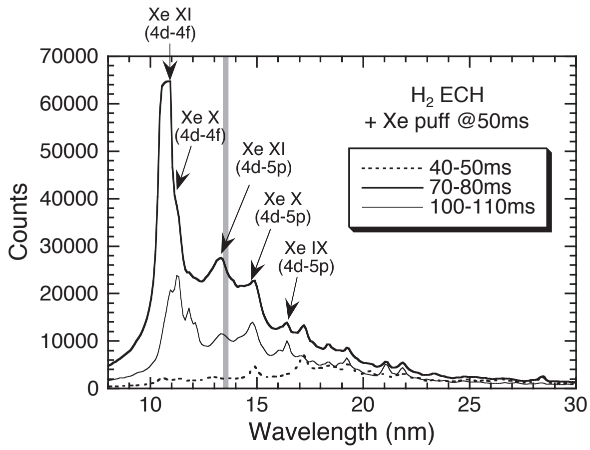

Fig. 4 EUV spectra measured before the Xe injection (40 - 50 ms), after the injection (70 - 80 ms), and in the decay phase (100 - 110 ms).

sured by the laser Thomson scattering system are shown in Fig. 3(b). The central electron temperature reaches above 1 keV before the Xe injection. After that, the temperature is rapidly decreased and is below 100 eV at 100 ms since the plasma is cooled by radiation loss. This implies that the plasma is in recombining phase after the Xe injection. Electron temperature profile is hill shape, while the density profile is almost uniform until 80 ms.

EUV spectra integrated during each 10 ms interval have been measured since the minimum readout time of the detector is 10 ms. Figure 4 shows the EUV spectra around 13.5 nm obtained at three different time periods in this discharge. Spectra before the Xe injection (40–50 ms), after the injection (70–80 ms), and in the decay phase (100–110 ms) are displayed. The 2 % bandwidth of 13.5 nm is indicated by the narrow gray region in Fig. 4. Before the Xe injection (40–50 ms), there are no Xe lines and only several oxygen lines (O V) are found as an impurity. In the recombining phase after the Xe injection, the Xe spectra begins to build up around 60 ms, and the brightness becomes maximum during the period of 70–80 ms, in which the spectrum is indicated by a thick solid line in Fig. 4. The strongest peak around 11 nm and a moderate peak around 13.3 nm are clearly found, which is known to be characteristic structure of Xe ion EUV emissions in other experiments. When the temperature decreases further, Xe emission becomes weak as shown by a thin solid line in Fig. 4 (100–110 ms).

The measured spectral data has been compared with the results of HULLAC code and charge exchanging collisions experiment [5]. It is widely believed that line emissions from Xe XI (Xe^{10+}) would be important in emissivity around 13.5 nm. Charge states and transitions of Xe ions for several prominent spectral peaks inferred from the results of the comparisons are also indicated in Fig. 4. The results of the HULLAC code predicts that 4d–5p transitions of Xe XI would appear in 13.0-13.7 nm, and 4d–4f in 10.8-10.9 nm [6]. These transitions correspond to the strongest two peaks of the spectra. In addition, lines from different charge states (Xe X and IX) are also found in Fig. 4. According to the HULLAC code, a line at 11.2 nm blended with Xe XI 4d-4f peak is assigned to Xe X (4d-4f). If we compare the last two spectra (70–80 and 90–100 ms), it is clearly observed that the intensity ratio between Xe XI and Xe X changes temporally, which means that the principal charge numbers of Xe ions in the plasma become lower with the decrease in the electron temperature.

4. Summary and future plans

We have observed Xe EUV spectra around 13.5 nm in high temperature and low density CHS plasmas with Xe gas injection by the grazing incidence spectrometer. Characteristic spectral peaks of Xe ions in the EUV region were found in the recombining phase of the plasma after the Xe injection. Based on the comparisons with the results of HULLAC code calculation and charge exchanging collisions experiment, charge states and transitions of Xe ions were inferred for several peaks in the spectra.

Before proceeding to the next experimental phase, there are several matters to be considered. The optimum electron temperature to maximize the emissivity of Xe XI is believed to be about 30 eV by several model calculations. Hence the Xe emissions in this discharge are expected to come from the plasma edge since the central electron temperature is too high as shown in Fig. 3. Since it is difficult to measure such low temperature region by the existing Thomson scattering system optimized for high temperature plasma, other diagnostics such as probe measurements should be applied to lower density and temperature plasmas generated by low-power heating methods. Since the viewline of the spectrometer includes both the center and edge of the plasma, we also plan to install another spectrometer with scannable viewline to clarify where the strong emissions of Xe ions come from. Additionally, the poor spectral resolution of the present system should be improved to prevent uncertainties of the spectral lines identification for the detailed analyses. We will employ another spectrometer with narrower wavelength range and better spectral resolution using soft X-ray CCD detector in the near future.

These improvements will provide more detailed information on characteristics of Xe EUV spectra in CHS, which make it easier to benchmark with the model calculation based on the line intensity analyses.

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