Doppler profile diagnostics on VUV spectra for the impurity ion temperature in edge plasmas of Large Helical Device

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Abstract. A space-resolved VUV spectroscopy using a 3 m normal incidence spectrometer is utilized to measure the impurity emission profile in the edge and divertor plasmas of the Large Helical Device in the wavelength range of 300 - 3200 Å. The ion temperatures derived from the Doppler profile fitting for the spectra of carbon CII $1335.71 \times 2$ Å, CIII $977.02 \times 2$ Å, and CIV $1548.20 \times 2$ Å are comparable to ionization potential for each charge state. The vertical profile of the ion temperature measured from CIV line has higher values in the edge observation chords compared to those in the central chords.

1. Introduction
In the study of the impurity behavior in the edge region of magnetically-confined torus plasmas for fusion research, the vacuum ultraviolet (VUV) line of impurity ions is attractive for the impurity diagnostics because the emission from the correct charge states is located in the edge plasmas with a considerably low electron temperature. The impurity species and its concentration can be examined through the identification of impurity lines and the line intensity, respectively. In addition, the spectral shape of impurity lines can also provide information on the ion temperature and the plasma flow based on Doppler-broadening and Doppler-shift measurements, respectively [1].

In this paper, the ion temperature and its vertical profile derived by measuring the Doppler profile of line emission from intrinsic carbon impurity ions sputtered from the carbon divertor plates of the Large Helical Device (LHD), which are the most abundant impurity in LHD, are investigated by using the VUV spectroscopy.

2. Experimental setup
Space-resolved VUV spectroscopy using a 3 m normal incidence spectrometer has been developed to measure the radial distribution of VUV lines in wavelength range of 300 - 3200 Å in the edge plasmas of LHD [2]. LHD has the major/minor radii which are 3.6/0.64 m in the standard configuration with maximum plasma volume of 30 m\textsuperscript{3} and toroidal magnetic field of 3 T. The high spectral resolution of
the spectroscopic system with the wavelength dispersion of 0.037 Å/CCD-pixel enables us to measure the Doppler profiles of impurity line spectra precisely. The vertical observation range covers the entire vertical size of the LHD plasmas at the horizontally-elongated poloidal cross section as illustrated in figure 1. Observation chords are aligned vertically in the observation range and the obtained data is line-integrated along each observation chord. At present, inversion data processing such as Abel inversion is not applied. The edge plasma of LHD consists of stochastic magnetic fields with three-dimensional structure intrinsically formed by helical coils called “ergodic layer,” while well-defined magnetic surfaces exist inside the last closed flux surface [3]. The VUV spectroscopy is appropriate for the edge impurity study because the emissions are only located inside the ergodic layer with electron temperatures distributing in ranges of 10 to 500 eV.

3. Results

Figure 2 shows the edge electron density dependence of the impurity ion temperature for (a) CII 1335.71 × 2 Å (1s²2s²2p-1s²2s2p), (b) CIII 977.02 × 2 Å (1s²2s²-1s²2s2p), and (c) CIV 1548.20 × 2 Å (1s²2s-1s²2p) obtained in hydrogen discharges. It has been experimentally certificated that the CII, CIII, and CIV emissions are located in the outermost region of the ergodic layer or in the region close to the edge X-points because the ionization potential, $E_i$, of 24 eV, 48 eV, and 65 eV for C⁺, C²⁺, C³⁺ ions, respectively, is extremely low compared to the edge temperature of LHD plasmas [4]. Thus, measuring CII, CIII, and CIV emission gives as information of plasma parameters in the ergodic layer. VUV spectroscopy is attempted under the conditions of a 50-μm-wide entrance slit. A CCD data acquisition operation which is called “full-binning” mode in which all CCD-pixels aligned in the vertical direction are replaced by single channel and the vertical spatial resolution is entirely eliminated. The line shape of the wavelength spectrum has a Gaussian profile if the ions are assumed to have a Maxwellian velocity
distribution. The ion temperature $T_i$ in eV is given by $T_i = 1.68 \times 10^8 M (\Delta_{\text{FWHM}} / \lambda_0)^2$, where $M$ is the atomic mass number, $\lambda_0$ is the central wavelength, and $\Delta_{\text{FWHM}}$ is the Doppler width at full width at half maximum (FWHM). As shown in Fig. 2, $T_i$ ranges around or below the ionization potential for each ionization stages and has a negative correlation with the electron density as has been widely observed in the fusion plasma experiments. Thus, Doppler profiles of VUV spectra have been successfully observed for the carbon impurity.

In addition, when the intensity is sufficient, the spatial profile of the ion temperature can be measured. Figure 3 shows a full vertical profile of $C^{3+}$ ion temperature derived from CIV line emission. A synthetic profile of the $C^{3+}$ ion temperature calculated by the impurity transport simulation based on a three-dimensional simulation code, EMC3-EIRENE, is also plotted [5,6]. $T_i$ (CIV) in the edge observation chords has higher values compared to those in the central chords both in the experiment and in the simulation. In order to explain the vertical profile, we attempted comparison between $T_i$ (CIV) and the connection length of the magnetic field lines and we found some positive correlation as preliminary results. It is reasonable that $T_i$ (CIV) has higher value when the connection length are longer at the region of CIV emission because both of the heat and particle transport parallel to the magnetic field lines are dominant in the transport processes in the ergodic layer. Further detailed investigation on the relationship between $T_i$ (CIV) and the connection length should be addressed as future studies.

4. Summary
A space-resolved VUV spectroscopy using a 3 m normal incidence spectrometer is utilized to measure the impurity emission profile in the edge and divertor plasmas of LHD in wavelength range of 300 - 3200 Å. The ion temperatures derived from the Doppler profile fitting for the spectra of carbon CII 1335.71 $\times$ 2 Å, CIII 977.02 $\times$ 2 Å, and CIV 1548.20 $\times$ 2 Å are comparable to ionization potential for each charge state. The vertical profile of the ion temperature measured from CIV line has higher values in the edge observation chords compared to those in the central chords. The spatial profile may be explained by considering relationship between the distribution of the connection length at the region of CIV emission and geometry of the observation.

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