Vertical Profiles and Radial Locations of He II and C IV Line Emissions Observed at Different Toroidal Angles in LHD*)

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Vertical profiles of edge impurity line emissions of He II and C IV have been measured at different toroidal locations of Large Helical Device (LHD) by scanning horizontally a space-resolved EUV spectrometer in order to observe the edge distribution at different poloidal locations. Radial location of He II with ionization energy of E_i = 54.4 eV reflects the penetration depth of neutral helium and radial location of C IV with E_i = 64.5 eV expresses the index of plasma edge boundary in ergodic layer of LHD. The result indicates that the radial position of He II is located at inner side than that of C IV, whereas the ionization energy of He II is smaller than that of C IV. It is found that the radial position of He II estimated from the C IV position has a nearly constant distance of 4 mm from the plasma edge against different poloidal locations including region near X-points. The distance is in a good agreement with analysis assumed neutral helium influx with room temperature (300 K). It suggests that the neutral helium mainly enter the plasma as background gas in the vacuum vessel, but not as recycling particle.

Keywords: helium neutral, EUV spectrometer, plasma boundary

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1. Introduction

In magnetically confined fusion devices, plasma always contains impurities in addition to working gas of hydrogen isotopes or helium. The impurities usually originate in a variety of plasma facing components such as the first wall on vacuum vessel, poloidal limiter, divertor plates and radio frequency antennas [1]. The energy loss through radiation is enhanced and the fuel is diluted by the presence of impurities. Therefore, it is important to measure the impurity behavior and to understand the transport mechanism of impurities in addition to the study on the influence of impurities giving to the plasma performance.

Spectroscopy is an essential diagnostic to monitor the impurity behavior, providing measurements of ion and electron temperatures, plasma rotation, particle influx and so on [2]. Since the electron temperature in LHD ranges from a few tens of eV at plasma edge to several keV at plasma center, spectral lines from impurities are emitted in wider range of wavelength from visible to X-ray. Various types of spectrometers observing different wavelength ranges have been developed for LHD diagnostics. Recently, a space-resolved extreme ultraviolet (EUV) spectrometer is upgraded to observe the line emission at different toroidal positions of LHD plasma in addition to the extension of observable wavelength range to 30-650 Å. Two-dimensional image of impurity line emission from several elements such as helium, carbon, neon and iron have been observed from long pulse discharges of LHD by scanning horizontally the observation chord during a discharge. He II (303.78 Å: E_i = 54.4 eV) and C IV (312.4 Å: E_i = 64.5 eV) are generally used to study the edge impurity transport because of their low ionization energies, E_i, and strong line emission intensities [3]. In addition, both spectra can be simultaneously measured, since the wavelengths are very close each other. Unfortunately, hydrogen emission can not be measured with present EUV spectrometer.

Magnetic surfaces of LHD have three-dimensional structure due to the absence of toroidal symmetry, and edge magnetic field structure is stochastic due to the presence of higher orders of Fourier component in magnetic field generated by helical coils, forming characteristic topology called ergodic layer. Therefore, the position of last closed flux surface (LCFS) in LHD is defined by the outermost flux surface on which the deviation of the magnetic field line is less than 4 mm while it travels 100 turns along the torus. The ergodic layer surrounding the LCFS and the magnetic surfaces are shown in Fig. 1. The ergodic layer formed by stochastic magnetic field lines with various connection lengths of 10-2000 m becomes thicker as the magnetic axis is outwardly shifted by controlling vertical field or β ($\equiv$ plasma pressure/magnetic pressure) value increases [4]. The electron temperature inside the ergodic layer typically ranges from 10 to 500 eV [5].

In reference [6], the plasma boundary near upper O-

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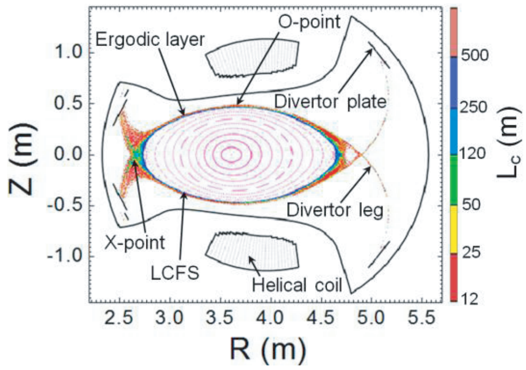

Fig. 1 Structures of magnetic surfaces, ergodic layer and divertor legs at R_{ax} = 3.6 m in LHD.

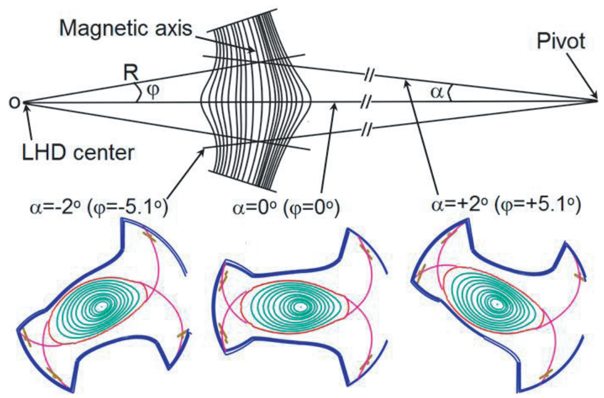

Fig. 2 Poloidal cross sections of LHD against three different observation chords of space-resolved EUV spectrometer.

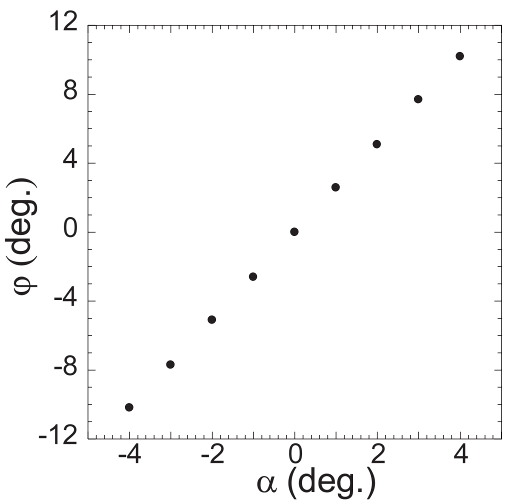

Fig. 3 Relation between horizontal angle, α, of observation chord and toroidal angle, φ of LHD.

point is studied using He II and C IV profiles at horizontally elongated plasma cross section. It is found that the peak position of C IV does not change at all in a wide range of electron temperature at LCFS ($10 < T_e(\rho = 1) < 500$ eV) and can be used as the index of edge plasma boundary. In this paper, the radial position of He II estimated from the C IV peak position is analyzed against different poloidal positions. Discussion is made with neutral helium behavior.

2. Experimental Setup

The space-resolved EUV spectrometer consists of an entrance slit, a spatial resolution slit placed in front of the entrance slit, a varied-line-spacing (VLS) grating and a charge-coupled device (CCD) detector. The vertical spatial resolution is 10 mm when the spatial resolution slit of 0.2 mm width is used The spectral resolution is 0.22 Å at 200 Å when the CCD is operated in full image mode [7]. In the present experiment, the spatial resolution slit of 0.5 mm is used and the CCD detector is operated in sub-image mode, by which five pixels are converted into one channel, with exposure time of 200 ms. A vertical range of nearly 53 cm can be observed with the present space-resolved spectrometer. The range corresponds to half of the plasma diameter at horizontally elongated plasma cross section (see Fig. 1).

A stepping motor is used to change horizontal angle, α, of the observation chord. The horizontal angle is defined by an angle measured from the central observation chord perpendicular to toroidal magnetic field, which passes through horizontally elongated plasma cross section of LHD plasma, as shown in Fig. 2. The space-resolved spectrometer is usually positioned at $\alpha = 0°$ to monitor vertical profile at upper half of LHD plasmas. When the horizontal angle is scanned around the pivot, the spectrometer observes different toroidal position. Here, the toroidal angle of φ is defined as the relation seen in Fig. 2. The observation chord defined with α intersects the line defined with φ at magnetic axis of plasma, R_{ax}. The relation between toroidal angle, φ, and horizontal angle, α, is plotted in Fig. 3. It shows a nearly linear relation because the distance between the pivot of EUV spectrometer and the plasma center is long, e.g., 9241 mm at R_{ax} = 3.60 m, and the scanning range of horizontal angle is relatively small.

Three cross sections of elliptical LHD plasma are also plotted in Fig. 2 at different horizontal angles of $\alpha = -2°$, 0° and +2°, which correspond to toroidal angles of $\varphi = -5.1°$, 0° and +5.1°, respectively. The vertical profile at upper half of LHD plasma can be observed in range of $\varphi = -7°$ to +4° which is limited by diamond-shaped LHD port and rectangular spectrometer port. Therefore, the top or the bottom observation chord passing through the plasma edge can measure different poloidal location when the toroidal angle of spectrometer is scanned. In LHD, in particular, edge diagnostics is important at both the X- and O-points because magnetic field structure has a special feature at the two regions, i.e., maximized stochastic region and minimized stochastic region, respectively. When the spectrometer is positioned at $\alpha = 0°$, the observation chord has to pass through both of X-points at inboard and outboard sides. The change of toroidal angle in the observation chord is then necessary for individual observation of the two X-points. The spatial resolution in horizontal direction is estimated to be 75 mm.

3. Results and Discussion

The impurity profiles are studied in discharges heated by neutral beam injection (NBI). Typical electron temperature and density profiles measured by Thomson scattering system are shown in Figs. 4 (a) and (b), respectively. The measurement is done along major radius direction, R, at horizontally elongated plasma cross section of $\varphi = 0°$. In the NBI discharge of LHD the density profile is flat or hollow, whereas the temperature profile is always peaked except for discharges with hydrogen pellet injection. The central electron temperature ranges in 2-4 keV and the central electron density exceeds 10^{14} cm^{-3} in gas-puffed NBI discharges at high-field operation.

Edge temperature and density profiles in the outboard side are shown in Figs. 4 (c) and (d) as the extension of Figs. 4 (a) and (b). The position of LCFS calculated by variation moments equilibrium code (VMEC) is 4.548 m [8], which is denoted with arrow in the figure. The electron temperature and density at LCFS are 300 eV and 3.3×10^{13} cm^{-3}, respectively. It can be seen that high electron density, which corresponds to 10-50% of the central density, is maintained even in the ergodic layer located outside the LCFS. Magnetic field lines are enough long to sustain such a high-density edge plasma, although the field lines are accompanied by radial deviation or diffusion in the ergodic region. Therefore, He^+ (E_i = 54.4 eV) and C^{3+} (E_i = 64.5 eV) ions, which emit spectral lines of He II and C IV, respectively, are always located in the outside edge of ergodic layer even in low-magnetic field discharges of LHD, since the ionization energies of He II and C IV are entirely low compared to electron temperature in the ergodic layer. In LHD, the edge electron temperature profile does not change so much in most of discharges even if the operational density is changed. A few dips or flattening are seen in the edge temperature and density profiles. It is believed that they reflect island structures in the ergodic layer.

The vertical profiles of He II and C IV in the upper half of LHD plasma are shown in Fig. 5 at different horizontal angles. The vertical position is carefully calibrated by a rectangular-corrugated toroidal slit placed between EUV spectrometer and LHD plasma. The profile mainly consists of two parts of edge peaked emission and emission near X-points. The emission structure near X-points is considerably complicated reflecting the presence of many islands in addition to the mixture of long and short magnetic field lines. The analysis of the emission profile near X-points is not simple, and then, the result is presented later in another paper. The edge peak emission forms a clear intensity peak due to a long integration of impurity emission along the observation chord. Here, the peak position is defined by the vertical position of the maximum value of He II and C IV.

Carbon ions originated in the divertor plates made of carbon move upward through the divertor legs as shown in Fig. 1. The low charge states of C^+ (E_i = 24.4 eV) and C^{2+} (E_i = 47.9 eV) only exist between the divertor plates

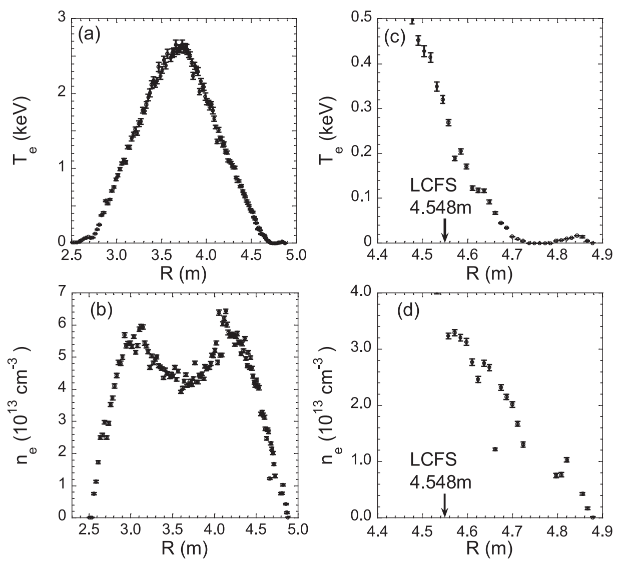

Fig. 4 (a) Electron temperature and (b) density profiles and enlarged edge (c) temperature and (d) density profiles at R_{ax} = 3.6 m.

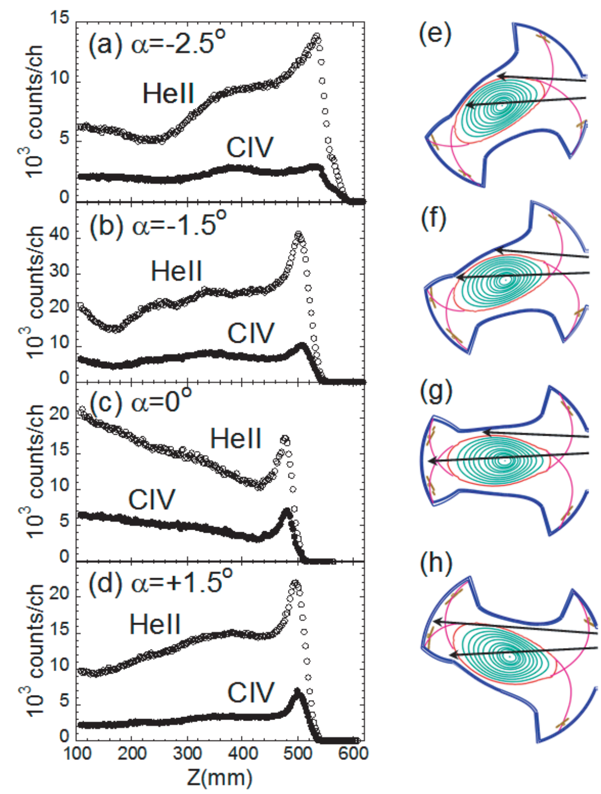

Fig. 5 (a)-(d) Vertical profiles of He II (open circles) and C IV (closed circles) at different horizontal angles, α, and (e)-(h) corresponding plasma cross section. Observation range is indicated with two arrows.

and X-points because of the short ionization length, e.g., λ_i = 1-2 m for C^+ and λ_i = 5-40 m for C^{2+}. The C^{3+} (E_i = 64.5 eV) ion has relatively long ionization length of λ_i = 40-300 m and it can reach the ergodic layer. It is reported that the peak position of C IV is not sensitive to edge electron temperature at LCFS except for extremely low temperature case [6]. Then, the position of C IV can indicate the index of edge boundary position of LHD plasmas.

On the other hand, the peak position of He II reflects the penetration depth of neutral helium because the neutral density decays with the production of He^+ ion. This situation is clear if the peak position is compared between C IV and He II. The peak position of He II with lower ionization energy (E_i = 54.4 eV) is located at inner side than that of C IV with higher ionization energy (E_i = 64.5 eV). If the He^+ ions originates in the recycling on divertor plates and move to the plasma edge along magnetic field lines, the He II location should be positioned outside the C IV according to the ionization energy. Therefore, the deeper penetration of the He^+ ions indicates that the neutral helium is directly deposited in the plasma, not coming from the divertor plate. In LHD, high recycling has been observed near X-points [9], in particular, near inboard side X-point. The peak position of He II is analyzed against different poloidal position to examine the recycling of helium neutral.

Radial location of He II measured from the peak position of C IV is plotted in Fig. 6 against horizontal angle of observation chord. The poloidal position determined by the horizontal angle is also denoted in the figure (also see Fig. 5). It is clear from the figure that the position of He II is located at 4 mm inside compared to the C IV position and seems to be constant against the poloidal location.

The neutral helium density at the penetration depth, x, is given by a simple equation of

$$n_0 = n_0(0)\exp\left[-\int_0^x \frac{n_e\langle\sigma v\rangle_{\rm ioni}}{v_0}\right], \quad (1)$$

where n_0 is the helium neutral density, $\langle\sigma v\rangle_{\rm ioni}$ the ionization rate coefficient and v_0 the helium velocity. The helium ion density, $n(He^+)$ is obtained from the neutral density as

$$n(He^+) = n_e \times n_0 \times \langle\sigma v\rangle_{\rm ioni}. \quad (2)$$

He II intensity is calculated from the helium ion density considering excitation rate coefficient. When a room temperature (300 K) for the neutral helium and the edge plasma boundary at the foot point of C IV are assumed, we obtain the He II peak position of a few mm inner side than the C IV peak position, which is similar to the observation. The helium penetration depth at different poloidal locations are nearly the same, as seen in Fig. 6. It means that the neutral helium energy coming into plasmas is equal for all the poloidal location. Then, we conclude that the neutral helium is caused by thermal gas existing in the vacuum vessel, but the recycling is not dominant even in region near the inboard side X-point. The present result is in a good agreement with helium neutral measurement based on Zeeman effect in visible spectroscopy [10].

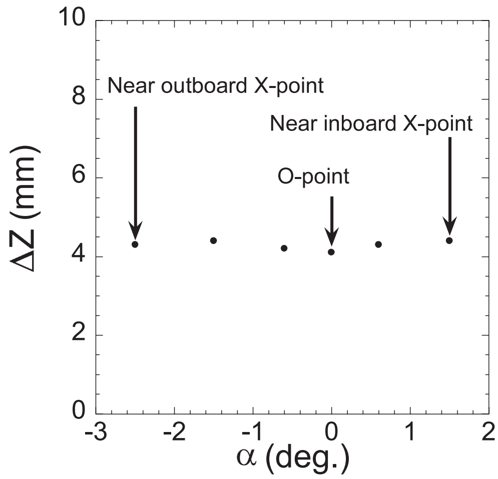

Fig. 6 Radial location of He II measured from peak position of C IV against different horizontal angles.

4. Summary

A space-resolved EUV spectrometer is developed to observe impurity line emissions at different toroidal angles of LHD plasmas. The vertical profiles of He II and C IV are observed at upper half of plasma against different toroidal locations. It is found that the He II with lower ionization energy of 54.4 eV is located at inner side than the C IV with higher ionization energy of 64.5 eV and the distance between the He II and C IV peak positions is nearly constant (4 mm) against the poloidal location. The result suggests the source of helium neutral is caused by thermal gas existing in the vacuum vessel, but not by recycling neutral from divertor plates. In order to understand the edge impurity behavior in more details, however, the whole profile including different toroidal locations has to be analyzed. The analysis is done using three-dimensional edge simulation code in the near future.

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