# Study on Radial Position of Impurity Ions in Core and Edge Plasma of LHD Using Space-Resolved EUV Spectrometer*

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**Abstract** Radial profiles of impurity ions of carbon, neon and iron were measured for high-temperature plasmas in large helical device (LHD) using a space-resolved extreme ultraviolet (EUV) spectrometer in the wavelength range of 60 Å to 400 Å. The radial positions of the impurity ions obtained are compared with the local ionization energies, $E_i$ of these impurity ions and the electron temperatures $T_{eZ}$ there. The impurity ions with 0.3 keV$\leq E_i \leq$ 1.0 keV are always located in outer region of plasma, i.e., $0.7 \leq \rho \leq 1.0$, and those with $E_i \leq$0.3 keV are located in the ergodic layer, i.e., $1.0 \leq \rho \leq 1.1$, with a sharp peak edge, where $\rho$ is the normalized radial position. It is newly found that $T_{eZ}$ is approximately equal to $E_i$ for the impurity ions with $E_i \leq$0.3 keV, whereas roughly half the value of $E_i$ for the impurity ions with 0.3 keV$\leq E_i \leq$ 1.0 keV. It is known that $T_{eZ}$ is considerably lower than $E_i$ in the plasma edge and approaches to $E_i$ in the plasma core. Therefore, this result seems to originate from the difference in the transverse transport between the plasma edge at $\rho \leq$1.0 and the ergodic layer at $\rho \geq$ 1.0. The transverse transport is studied with an impurity transport simulation code. The result revealed that the difference appearing in the impurity radial positions can be qualitatively explained by the different values of diffusion coefficient, e.g., $D$=0.2 m$^2$/s and 1.0 m$^2$/s, which can be taken as a typical index of the transverse transport.

**Keywords:** impurity radial profile, EUV spectrometer, diffusion coefficient

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## 1 Introduction

Impurity transport is an important subject in the magnetically confined plasma research, since the plasma performance is affected by the impurities through radiation loss, and the dilution of fuel ions due to the presence of impurities leads to a decrease in fusion output. So far the impurity transport has been extensively studied in both tokamak [1~3] and helical devices [4~9]. One of the special properties in view of impurity transport found in large helical device (LHD) is characterized by the edge magnetic topology. The ergodic layer surrounding the LHD plasma is formed by stochastic magnetic fields with long connection length of 10 m$\leq L_c \leq$ 2000 m [10], whereas the scrape-off layer in tokamaks is formed by well aligned magnetic fields with a shorter connection length of $L_c \leq$ 100 m. In LHD, therefore, the transverse transport becomes important in the ergodic layer in addition to the parallel transport which is dominant in the scrape-off layer of tokamaks.

In LHD the radial profile of impurity ions such as carbon, neon and iron were measured using a space-resolved flat-field extreme ultraviolet (EUV) spectrometer. The radial positions of each impurity ion are accurately determined at both core and edge regions of the plasma in LHD through careful calibration of the radial position for each observation chord. The results are correlated with both local ionization energies, $E_i$, of the impurity ions and electron temperature $T_{eZ}$ where the impurity ions are located, in both core and edge regions. In the present paper, the transverse transport in the ergodic layer is studied through an analysis of $E_i$ and $T_{eZ}$.

## 2 Experimental setup

The radial profiles of impurity ions studied here are measured from plasmas at the magnetic axis of $R_{ax}$ = 3.60 m using the space-resolved EUV spectrometer system [11], which is illustrated in Fig. 1(a). The EUV spectrometer installed on LHD is perpendicular to toroidal magnetic field to observe the radial profiles of impurity ions in a wavelength range of 60 Å to 400 Å. In order to elevate the signal quality, the width of entrance slit is enlarged from 30 $\mu$m to 100 $\mu$m. A spatially resoluted slit of 0.5 mm in width is placed in front of the entrance slit. This combination leads to a favorable spectral resolution ($\Delta\lambda$) of 4 pixels, which corresponds to $\Delta\lambda$=0.3 Å at 100 Å and $\Delta\lambda$ = 0.5 Å at 400 Å, and a vertical spatial resolution ($\Delta Z$) of

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15 mm, respectively, keeping a good throughput. A back-illuminated charge-coupled device (CCD) with an array of 1024×255 pixels and a size of 26.6×6.6 $mm^2$ is used to record the spectral line emissions.

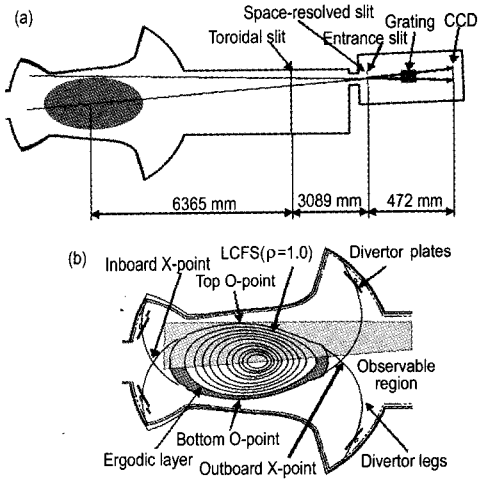


**Fig.1** Schematic diagram of (a) space-resolved flat-field EUV spectrometer system and (b) cross section of LHD plasma

The vertical profile of EUV spectra can be measured with an observation length of 52 cm, which corresponds roughly to half size of short axis for the elliptical LHD plasma. It is notable that all the radial profiles of impurity emissions studied here are taken from the upper half of a horizontally elongated plasma cross section for the elliptical LHD plasmas, as shown in Fig. 1(b). A spectral observation range, which is determined by the CCD horizontal size of 6.6 mm, is a function of wavelength, e.g., 35 Å for $\lambda = 60$ Å and 65 Å for $\lambda = 400$ Å. In order to have a good temporal resolution of 200 ms, a binning mode of CCD is selected as $\Delta X = 5$ pixels, which means that five pixels are summed up and converted into one channel. Although this binning leads to a slightly lower spectral resolution, most of the spectral lines are not blended even in such a relatively lower spectral resolution, since the spectral lines distribute separately in the EUV range.

A toroidal slit placed between the LHD plasma and the EUV spectrometer consists of two large flat plates made of stainless steel with a size of 1 m in vertical height and 0.5 m in width. It can shift horizontally to adjust the opened area. A series of rectangular-corrugated edge with vertical opened widths periodically changed between 2 mm and 9 mm is attached to the end of the toroidal slit. A projected image of rectangular-corrugated edge can be observed on the CCD detector when the toroidal slit is opened to 10 mm in horizontal width remaining only the periodically opened vertical rectangular hole. The black and white vertical image with a periodically changed width indicates an exact angle of each observation chord. Therefore, the vertical position of each observation chord can be accurately determined from the geometry among the LHD plasma, the rectangular-corrugated slit, the spectrometer entrance slit and the CCD detector. The vertical locations of the upmost and the lowest observation chords are shown in Fig. 2, as $Z_{max}$ and $Z_{min}$, respectively. The value of $Z_{max}$-$Z_{min}$ denotes the observable vertical range in the present EUV system. Here, $Z = 0$ denotes the equatorial plane in the plasma core. The observable range is a weak function of wavelength having a little wider range at the shorter wavelength side.

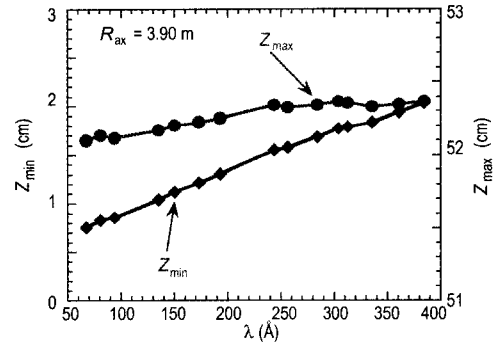


**Fig.2** Observable vertical range of EUV spectrometer system. Values of $Z_{max}$ and $Z_{min}$ mean the upmost and the lowest observation chords when the upper half of elliptical LHD plasma is measured.

# 3 Radial profiles of impurity ions in core and edge plasma

The emission from iron ions was routinely measured in the EUV range as a typical metal impurity in LHD, though the density of iron ions is negligibly small, namely, $n_{Fe}/n_e < 10^{-4}$. The highest ionized state of the iron ions observed within the EUV range is FeXXIV (192.017 Å), which is associated with a high ionization energy of $E_i = 2.046$ keV. Since the iron ions are highly ionized in LHD plasmas, most of the dominant iron emissions in the EUV range are located in the plasma core. Therefore, the radial location of the highly ionized iron ions is a strong function of the electron temperature. In order to confirm the electron temperature dependence, FeXX (132.85 Å) with a lower ionization energy of 1.58 keV is selected for the measurement because the iron spectra with higher ionization energy such as FeXXIV does not appear in relatively low-temperature plasmas. The profiles of FeXX measured from plasmas with different electron temperatures are shown in Fig. 3(b), with corresponding electron temperature profiles shown in Fig. 3(a), measured by Thomson scattering system. The whole electron and density profiles from inboard to outboard plasma edges are measured routinely by the Thomson system in LHD. Both profiles are taken from discharges with the same plasma axis position of $R_{ax} = 3.60$ m and similar line-averaged electron densities of $1.4\times10^{13}$ $cm^{-3}$ and $1.3\times10^{13}$ $cm^{-3}$ for $T_e(0) = 2.9$ and 1.6 keV, respectively. The intensities of both FeXX radial profiles

are normalized to the maximum value. As is clearly seen in Fig. 3(b), the radial locations of FeXX for these two cases differ significantly. In the case with $T_e(0)$=1.6 keV the FeXX ion is located at $\rho = 0.24$, close to the plasma center, with $\rho$ the normalized radial location to the plasma minor radius, $a_p$. In LHD the position of LCFS is defined by the outermost flux surface on which the deviation of the magnetic field line is below 4 mm when it travels 100 turns toroidally. In our study $\rho$ is calculated with the three-dimensional equilibrium code VMEC as a function of plasma pressure profile. The final relation between real coordinates and $\rho$ is then determined at a certain plasma pressure or $\beta$ value at which a symmetric temperature profile is obtained by comparing temperature gradients at inboard and outboard sides. For the case with $T_e(0) = 2.9$ keV, on the other hand, FeXX ion is located at $\rho$=0.65, far from the plasma center. However, it is found that the FeXX ions for these two discharge cases are located at the place with a same temperature of $T_e = 1.56$ keV. It is revealed that, the radial position of FeXX ion is close to the location with an ionization energy of $E_i = 1.58$ keV and not dependent on the central electron temperature.

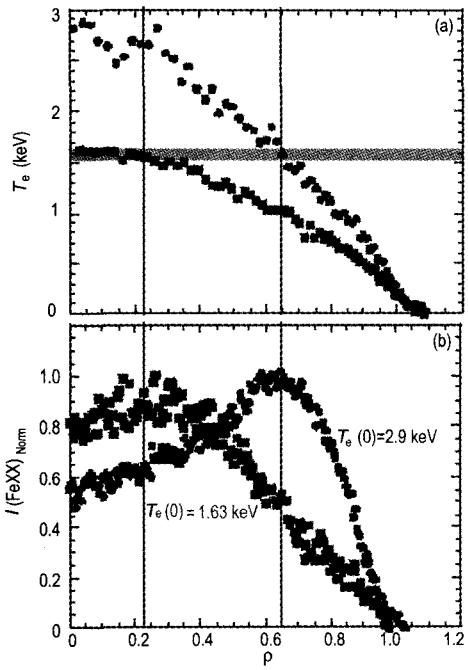


**Fig.3** Electron temperature profiles and (b) profiles of FeXX (132.85 Å) for different central electron temperatures, as shown in (a)

The radial profiles of impurity ions are also function of the ionization energy. Fig. 4(a) shows the radial profiles of iron ions in different charge states. The radial profile expressed by a chord-integrated profile is shown as a function of the normalized radius. The Abel inversion has not been carried out yet, because several spectral lines emitted from outer region of LHD plasmas shows poloidal nonuniformity. Since the ionization energy of three iron ions are quite different based on the charge states, i.e., $E_i = 0.46$ keV for FeXV (284.147 Å), $E_i = 1.58$ keV for FeXX (132.85Å)) and $E_i = 2.05$ keV for FeXXIV (192.017 Å), their radial profiles distribute in a wide range of plasma. The FeXXIV emission can be observed when the electron temperature is increased up to 3 keV, whereas the FeXV emission is always observable. Here, it is noticed that the emission intensity from impurity ions at the plasma center is relatively weak because of the small emission volume. An expansion of the emission volume is necessary to observe such impurity ions located at the plasma center as FeXXIV with sufficient intensity.

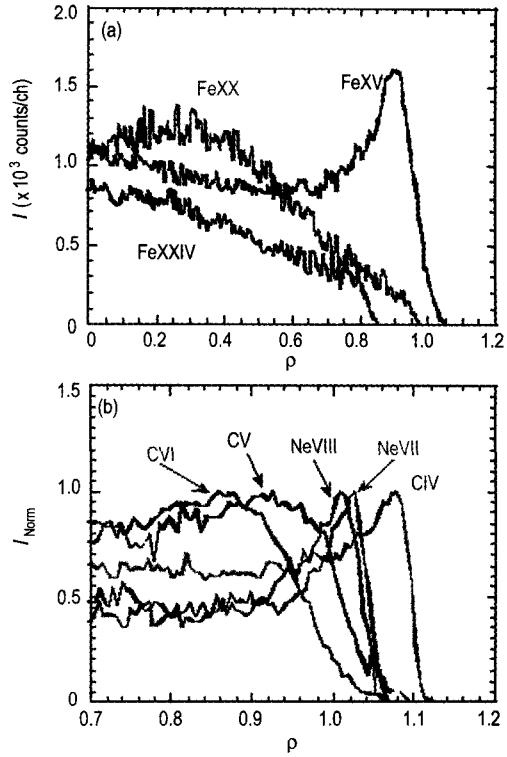


**Fig.4** Radial profiles of (a) iron impurity ions in different charge states near plasma core and (b) carbon and neon impurity ions in different charge states near plasma edge and ergodic layer

The radial profiles of impurity ions of CVI (2×33.73 Å), CV (2×40.268 Å), NeVIII (88.09 Å), NeVII (106 Å) and CIV (312.4 Å) near the plasma edge are also successfully observed with an excellent spatial resolution. The results are shown in Fig. 4(b) with an expanded horizontal scale in $0.7 \leq \rho \leq 1.2$. It is also clearly seen that the ions are located at different radial positions depending on their ionization energies, i.e., CVI: $E_i = 0.59$ keV, CV: $E_i = 0.39$ keV, NeVIII: $E_i = 0.24$ keV, NeVII: $E_i = 0.21$ keV and CIV: $E_i = 0.064$ keV. The carbon is a dominant intrinsic impurity in LHD, which mainly comes through divertor legs from divertor plates made of carbon, as is seen in Fig. 1(b) and the neon is introduced externally through gas puffing. CIV is actually the lowest ionization state for carbon ions in the ergodic layer. The intensity of CIII (386.2 Å) is usually not visible in the present EUV spectrometer. Both CV and CVI are located at $\rho = 0.92$

and 0.87, respectively. On the other hand, CIV, NeVII and NeVIII are located beyond $\rho = 1$, the last closed flux surface (LCFS), which means that these ions are in the ergodic layer consisting of stochastic magnetic fields surrounding the main plasma of LHD defined by the LCFS.

## 4 Analysis on radial positions of impurity ions near edge

The radial positions of impurity ions near the plasma edge ($0.8 \leq \rho \leq 1.0$) and in the ergodic layer ($1.0 \leq \rho \leq 1.1$) are analyzed via their ionization energies. The ionization energy of impurity ions is plotted against their radial positions and shown in Fig. 5(a). The spectral lines emitted from the plasma edge and the ergodic layer are named as group I and group II, respectively. The location of impurity ions shifts outwardly with the decrease in $E_i$. As $E_i$ falls to 0.3 keV, the impurity ions are in the ergodic layer. The ionization energy is correlated with the local electron temperature $T_{eZ}$ where the impurity ions are located, and the result is shown in Fig. 5(b). The solid line denotes the relation of $T_{eZ} = E_i$. From the figure the presence of two different correlations can be observed. The impurity ions from group I, i.e., CV, CVI, FeXV and FeXVI, exhibit certain relation with $T_{eZ} < E_i$. The ratios of $T_{eZ}/E_i$ distribute around one-half. [what does this sentence mean? Please illustrate more clearly.] In the calculation using impurity transport code with conventional transport parameters, typical ratio of $T_{eZ}/E_i$ is given as one-third for the impurity ions near the plasma edge and as unity for the impurity ions near the plasma center. Since the ionization rate coefficient for impurity ions in lower ionization states is still high even for $T_e < E_i$, the impurity ions are ionized before they arrive at the radial location with $T_e = E_i$. However, the impurity ions in higher ionization states located in the plasma core are ionized at a position with $T_e = E_i$, because the ionization rate coefficient is relatively small for $T_e < E_i$. Therefore, the experimentally obtained ratios indicated by FeXX in Fig. 3 and group I in Fig. 5 are rather reasonable.

On the other hand, it is also found that group II, such as CIV, NeV, NeVII and NeVIII, is located in the ergodic layer of $1.0 \leq \rho \leq 1.1$, which is with $T_{eZ} = E_i$. The result regarding group II can not be understood from the knowledge about the conventional impurity transport. It strongly suggests a different transverse transport mechanism in the ergodic layer.

In order to understand the relation of $T_{eZ} = E_i$ for group II, the edge carbon transport as a function of inward convective velocity, $V$, and diffusion coefficient, $D$ is analyzed using the impurity transport code. In the simulation, electron density of $5 \times 10^{13}$ cm$^{-3}$ and electron temperature of 2 keV are assumed. A relative shift of radial positions of carbon ions is plotted in Fig. 6(a) and (b) as a function of $V$ and $D$, with $D$ and $V$ set to

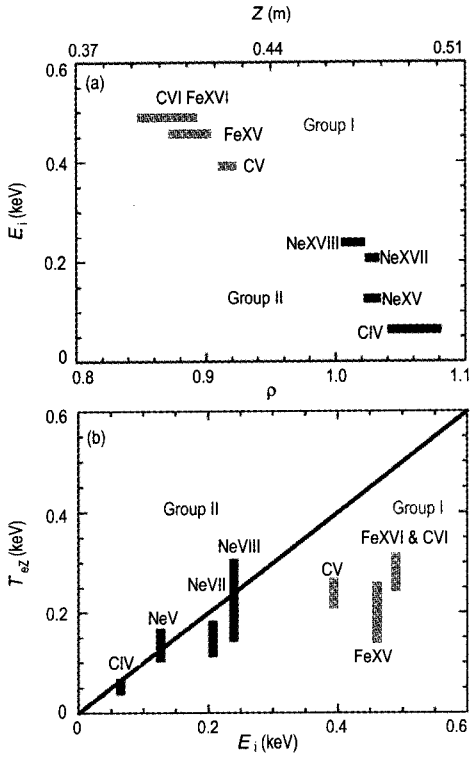


**Fig.5** (a) Ionization energy of impurity ions as a function of normalized minor radius and (b) local electron temperature at which the impurity ions are located as a function of ionization energy. Magnetic surface data in vacuum ( =0%) are used in plotting vertical positions of Z in the upper horizontal axis of (a)

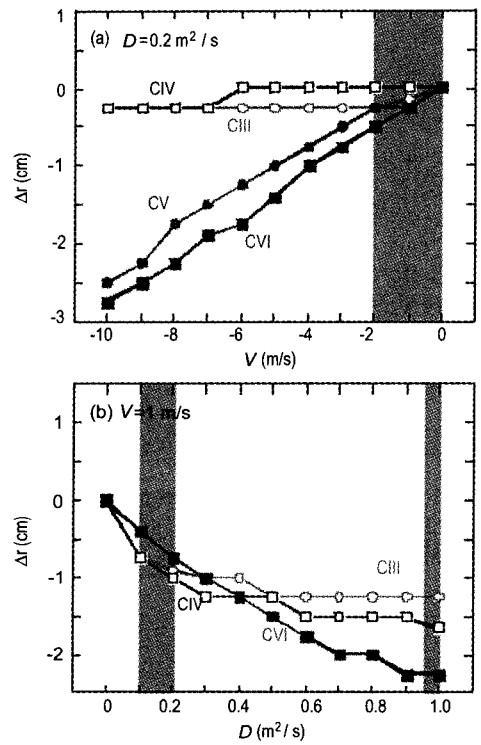


**Fig.6** Radial shift of impurity positions as a function of (a) inward velocity and (b) diffusion coefficient for carbon emissions of CIII to CVI

be 0.2 $m^2/s$ and 1 m/s, respectively. As seen in Fig. 6(a), the radial positions of CIII and CIV seem not entirely depending on $V$, although those of CV and CVI are functions of $V$. The result basically originates from the different temperature dependence of the ionization rate coefficient. The value of $V$ experimentally observed in the previous study [4] is shown with a shaded square hatch in Fig. 6(a). Therefore, the effect of $V$ on the radial position of impurity ions is actually small. However, the radial positions of CIII and CIV as well as CVI can be functions of $D$, as shown in Fig. 6(b). In the previous study in LHD the value of $D$ is known to be 0.2 $m^2/s$ [4]. The radial position of CVI does not shift so much even if the value of $D$ varies around 0.2 $m^2/s$. In the ergodic layer an enhanced transverse transport is attributed to the stochastic magnetic fields, and the diffusion coefficient is a typical index to express the transverse transport. Although the global value of $D$ in the ergodic layer has not yet been studied, it is believed to be in a range of 1 to 10 $m^2/s$. If $D$ is set to be 1 $m^2/s$ for CIII and CIV, their radial positions can shift inward by 1 cm to 2 cm. This inward shift of radial position would cause an increase in $T_{eZ}$. The large diffusion coefficient, which suggests an enhanced transverse transport in the ergodic layer, can qualitatively explain the high $T_{eZ}$ seen for the group II in Fig. 5(b).

## 5 Summary

Radial profiles of impurity ions were observed from plasma in LHD using the space-resolved flat-field EUV spectrometer. The radial positions are analyzed via $E_i$ and $T_{eZ}$. It is found that for the impurity ions in the ergodic layer the relation $T_{eZ} = E_i$ is valid, whereas for those impurity ions near the edge the relation $T_{eZ} = E_i/3$ is usually valid. A high $T_{eZ}$ can be quantitatively explained by adopting a large diffusion coefficient in the ergodic layer. However, the stochastic magnetic field in the ergodic layer is rather complicated. In order to analyze the data quantitatively, employment of three dimensional edge transport code is necessary.

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