Determination of Iron Density at the Plasma Center Using Radial Profile of FeK$_\alpha$ Lines in LHD

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Radial profiles of K$_\alpha$ X-ray spectra of metallic impurities have been measured using an assembly of soft X-ray pulse-height analyzers in Large Helical Device. The assembly is quipped with a radial scanning system, which gives us detailed profile information, especially in long pulse discharges. The local emissivity profiles of the Fe-K$_\alpha$ X-ray spectra have been quantitatively obtained by an Abel inversion technique. The density profile of the iron impurity in each charge state is analyzed using the energy shift profiles of the Fe-K$_\alpha$ spectra with the help of an impurity code analysis. As an example of the present method, the iron density of 1.2×10^9 cm^{-3} in the plasma center is obtained at the line-averaged electron density of 2.6×10^{13} cm^{-3}.

Keywords: pulse height analyzer, iron, chromium, titanium, Large Helical Device

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1. Introduction

X-ray energy spectra of magnetically confined high-temperature plasmas have been used for the measurements of fundamental plasma parameters such as electron temperature, Z$_{\text{eff}}$ value, and densities of metallic impurities and non-thermal electrons [1, 2]. For the X-ray measurements, it is important to obtain the spatial and temporal resolutions in detail for measuring significant information on the shift of magnetic axis, the time evolution of electron-temperature profile, and radial impurity transport [3]. However, in the X-ray region, it is generally difficult to obtain the X-ray spectra with a good energy resolution and temporal behavior with a good time resolution simultaneously.

An assembly of pulse height analyzer (PHA) has been constructed in Large Helical Device (LHD). The assembly is equipped with a radial scanning system, which can modulate the observation sight line of the PHA along the major radial direction of LHD [4]. The system covers the entire plasma region along the direction. The radial profile of the X-ray energy spectrum is thus obtained using the scanning system. A local emissivity profile is calculated from the measured X-ray energy profile by an Abel inversion method.

The advantage of the present PHA system in LHD is based on the high-energy resolution with which each K$_\alpha$ line from different impurities can be well resolved. In addition, the number of X-ray photons is quantitatively measured. The K$_\alpha$ lines of the metallic impurities heavier than argon are generally observed in LHD [3].

The radial profiles of the K$_\alpha$ lines emitted from the metallic impurities such as titanium, chromium, and iron have been routinely observed using the assembly. The energy shifts of the K$_\alpha$ lines are also evaluated as a function of the plasma radius. On the other hand, the emission profile of the K$_\alpha$ line in each charge state is calculated using an impurity transport code. The absolute densities of the metallic impurities can be estimated by comparing the experimental results and the code calculations.

In this paper, the iron density in the plasma core of LHD estimated using the PHA system is reported, along with the experimental results of the radial profiles of the K$_\alpha$ lines.

2. Assembly for X-Ray Measurement

The performance of the assembly has been already reported with the observed K$_\alpha$ lines of the metallic impurities and a continuum in a reference [5]. Some of them must be mentioned here again. The energy resolution of the PHA is 160 eV at 3.2 keV for an argon-K$_\alpha$ line. The maximum counting rate is 10 kcps. The sight lines of Si(Li) X-ray detectors are modulated along the major radial direction of LHD in a few hundred milliseconds. Scanning can begin with the time interval of a few seconds after the previous scanning is complete. Then, the scanning can be performed approximately four times in 10 s. The positions of the sight lines are changed shot-by-shot. As a result, the radial profile of the X-ray energy spectra can be measured with a spatial resolution of approximately 20 mm.

The calculation process of the inversion has been reported quantitatively [3].

3. Experimental Results

Figure 1 shows the examples of the X-ray spectra obtained using the assembly. Considering the transmis-

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sion rate of a beryllium filter with the thickness of 1 mm, the spectrum needs to be modified. The real intensity is stronger in the order in the X-ray energy range below 4.0 keV. The spectra consist of the continuum emission from free electrons as bremssstrahlung and the K_α lines emitted from the metallic impurities. The intensities of the emissions are comparable in the energy range above 4.0 keV, as is shown in the figure.

The continuum and the K_α-line intensities are strong functions of the electron temperature. Therefore, it is possible to estimate the electron temperature from the continuum. It is confirmed that the K_α line emitted from iron at the radius of $\rho = 0.5$ shifts toward the lower energy side than that of $\rho = 0.2$, because the K_α line shifts toward the lower energy side when the electron temperature becomes low. This is an important result for obtaining the density

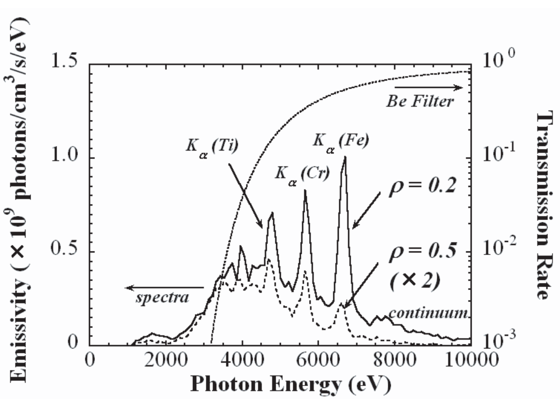

Fig. 1 Typical X-ray spectra from two different radial locations obtained using the Abel inversion. Solid and broken lines represent spectra from $\rho = 0.2$ and $\rho = 0.5$, respectively. Data are measured from NBI plasmas. The emissions from titanium, chromium and iron appear at 4.7 keV, 5.6 keV and 6.6 keV, respectively. Dotted line represents the transmission rate of the beryllium filter.

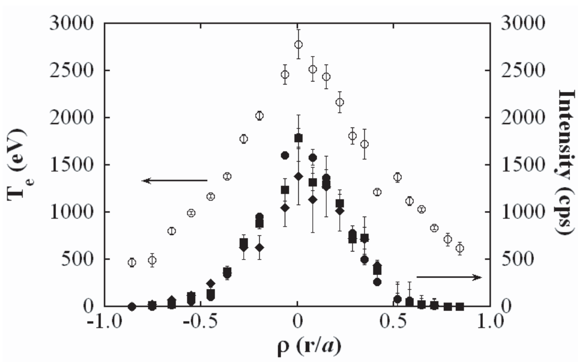

Fig. 2 Typical radial profiles of line-integrated K_α lines from metallic impurities of titanium (filled diamonds), chromium (filled rectangle) and iron (filled circles), respectively. Open circles with error bars represent electron temperature. Accumulation time is 240 msec for each point.

profile of impurity ion in respective charge state.

Figure 2 shows the typical profiles of the K_α line intensities of titanium, chromium and iron observed with the assembly. The radial profile of the electron temperature estimated from the continuum is also plotted. In the present experiment the flat top duration of a discharge is approximately 8 s. The electron temperature and density have been maintained to be constant during the discharge with the X-ray emission rate.

4. Results of Data Analysis and Discussions

Figure 3 shows the emissivities of the iron K_α lines emitted from two different radial positions in LHD plasma. In the case of $\rho = 0.2$, the results from the impurity transport code calculation are also shown by the solid line with the detailed position of the K_α lines. The energy of the K_α emission depends on the charge state indicating the amount of the density in each charge state [6–9]. The total K_α emission is almost dominated by helium, lithium, and beryllium-like ions, as is indicated in the figure. The observed spectrum plotted with filled circles is in a good agreement with the calculation. The densities of hydrogen-like ions are much lower in LHD.

Figure 4 shows the emissivity profiles calculated from the impurity transport code. In the figure, the emissions from the helium- and lithium-like ions are dominant at the radius of $\rho = 0.2$. The K_α line emitted from the radius of $\rho = 0.5$ is mainly composed of the lithium-, beryllium-, and boron-like ions.

The calculated result shown in Fig. 4 is the function of particle transport coefficients. The electron temperature profile measured from the present PHA system is used in the calculation. The diffusion coefficient of the impurity is assumed to be constant radially. Figure 5 shows the energy

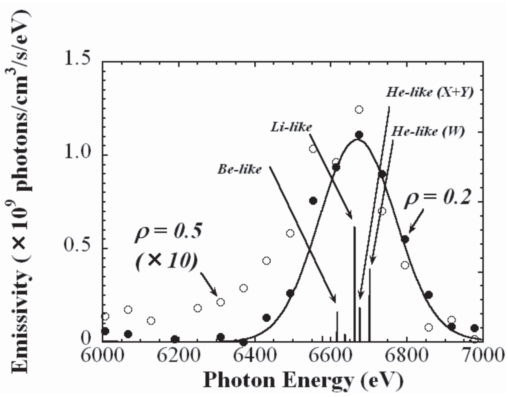

Fig. 3 K_α-line spectra of iron. Filled circles and open circles represent K_α spectra from $\rho = 0.2$ and 0.5, respectively. Solid line represents result from the code calculation in consideration with the experimental energy resolution. Solid vertical lines indicate the position of each K_α line with the relative intensity.

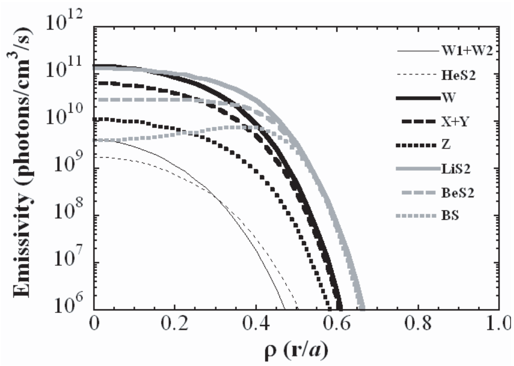

Fig. 4 Radial profiles of iron-K_α lines derived from the code calculation. Each line represents the emission from respective charge state. Thin lines and thick lines represent the emissivities of the hydrogen like and helium like ions, respectively. Gray lines represent the emissivities of the lithium, beryllium, and boron like ions.

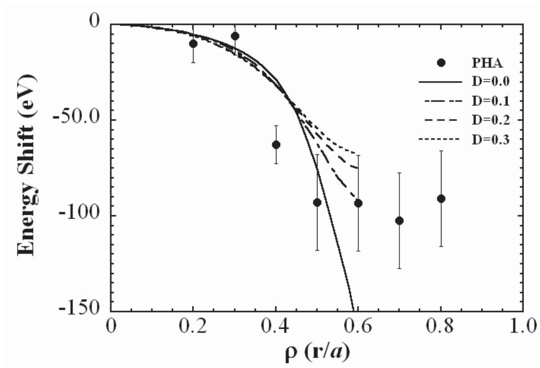

Fig. 5 Energy shift of the iron-K_α lines. Filled circles with error bars represent the experimental energy shifts and lines represent results from the code calculation in several diffusion coefficients.

shift of the iron-K_α lines. The transport code calculation suggests that the energy shift is sensitive to the diffusion coefficient in the region of $\rho \geq 0.5$. The experimental result can be approximately explained by the diffusion coefficient of 0.1 m^2/s. The coefficient estimated here is very close to the values obtained from our previous experimental results in LHD [10, 11].

The radial profile of the total K_α emissivity is also discussed as well as the energy shift for the determination of the iron density in order to check calculation parameters. Figure 6 shows the radial K_α-emissivity profiles for the experiment (filled circles) and the code calculation (solid line). The calculation seems to be a little inconsistent in the radius of $0.4 \leq \rho \leq 0.6$ due to the uncertainties from the electron temperature profile.

Figure 7 shows the final result indicating the density profile of iron. In LHD, the amounts of fully stripped iron- and hydrogen-like iron are much lower than that of helium-like iron. The iron density is dominantly determined by

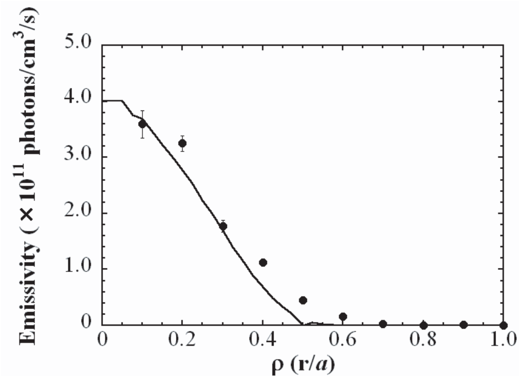

Fig. 6 Emissivity profile of all iron K_α lines. Filled circles with error bars and solid line represent the emissivities obtained from the experiment and the code calculation, respectively.

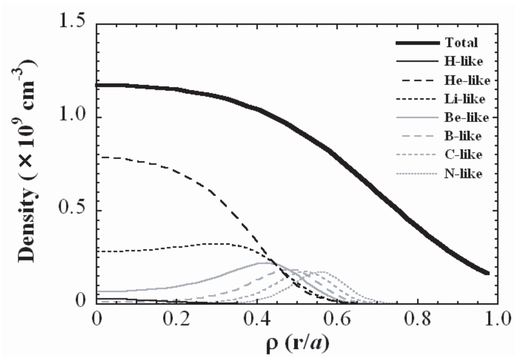

Fig. 7 Typical density profile of iron in LHD.

helium-like iron in the plasma core of $\rho \leq 0.4$.

By using the present method, the concentration of iron is determined to be 4.5×10^{-3}% to the electron density of 2.6×10^{13} cm^{-3} at the plasma core. As a result, it is confirmed that the densities of metallic impurities are much less in LHD.

5. Summary

The radial profiles of X-ray energy spectra have been measured using an assembly with a soft X-ray pulse height analyzer. K_α-line spectra from metallic impurities have been also observed with a good energy resolution and spatial resolution, which is sufficient for the analysis of the energy shift of the K_α lines. From the analysis with the impurity transport code, the radial profile of iron density is determined.

Acknowledgements

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