Determination of Iron Density at the Plasma Center Using Radial Profile of FeKα Lines in LHD

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Radial profiles of Kα 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 equipped with a radial scanning system, which gives us detailed profile information, especially in long pulse discharges. The local emissivity profiles of the Fe-Kα 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-Kα spectra with the help of an impurity code analysis. As an example of the present method, the iron density of $1.2 \times 10^9$ cm$^{-3}$ in the plasma center is obtained at the line-averaged electron density of $2.6 \times 10^{13}$ cm$^{-3}$.

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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, $Z_{eff}$ 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 Kα line from different impurities can be well resolved. In addition, the number of X-ray photons is quantitatively measured. The Kα lines of the metallic impurities heavier than argon are generally observed in LHD [3].

The radial profiles of the Kα lines emitted from the metallic impurities such as titanium, chromium, and iron have been routinely observed using the assembly. The energy shifts of the Kα lines are also evaluated as a function of the plasma radius. On the other hand, the emission profile of the Kα 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 Kα lines.

2. Assembly for X-Ray Measurement

The performance of the assembly has been already reported with the observed Kα 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-Kα 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-
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 bremsstrahlung and the Kα 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 Kα-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 Kα line emitted from iron at the radius of ρ = 0.5 shifts toward the lower energy side than that of ρ = 0.2, because the Kα line shifts toward the lower energy side when the electron temperature becomes low. This is an important result for obtaining the density profile of impurity ion in respective charge state.

Figure 2 shows the typical profiles of the Kα 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 Kα lines emitted from two different radial positions in LHD plasma. In the case of ρ = 0.2, the results from the impurity transport code calculation are also shown by the solid line with the detailed position of the Kα lines. The energy of the Kα emission depends on the charge state indicating the amount of the density in each charge state [6–9]. The total Kα 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 ρ = 0.2. The Kα line emitted from the radius of ρ = 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. 4  Radial profiles of iron-K\textsubscript{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\textsubscript{α} lines. Filled circles with error bars represent the experimental energy shifts and lines represent results from the code calculation in several diffusion coefficients.

Fig. 6  Emissivity profile of all iron K\textsubscript{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.

The radial profiles of the total K\textsubscript{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\textsubscript{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 ≤ ρ ≤ 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 helium-like iron in the plasma core of ρ ≤ 0.4.

By using the present method, the concentration of iron is determined to be 4.5 × 10\textsuperscript{-3}% to the electron density of 2.6 × 10\textsuperscript{13} cm\textsuperscript{-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\textsubscript{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\textsubscript{α} lines. From the analysis with the impurity transport code, the radial profile of iron density is determined.

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