Development of a Wide Band and Compact X-Ray Crystal Spectrometer for Iron Charge State Distribution Measurement on LHD

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A wide band and compact X-ray spectrometer has been developed using a Johan-type crystal and a back-illuminated CCD detector for charge state distribution measurement of highly ionized iron in LHD. In order to observe all charge states of iron ions a curved crystal of LiF(220) with a curvature of 430 mm was selected for the spectrometer. A wide energy range of 6.4-7.0 keV could be observed with use of CCD detector in a size of $26.6 \times 6.7\,\mathrm{mm}^2$. An energy resolution of the spectrometer was 10 eV at full width at half maximum (FWHM). Time-developed Fe Kα spectra were thus measured with a time interval of 10 ms in the full binning mode of the CCD. The charge states from Fe ions of FeXXI to FeXXV were clearly observed, but FeXXVI has not been observed. In the next step, then, the charge state distribution measurement is focused on the measurement of FeXXI-XXV and a quartz(2023) curved crystal is selected to measure the energy range of 6.40-6.75 keV. The expected energy resolution is 4 eV at 6.7 keV for the quartz crystal, which is enough for further analysis of the iron charge state distribution.

Keywords: X-ray crystal spectrometer, Johan-type crystal spectrometer, iron Kα

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1. Introduction

Large Helical Device (LHD) produces high-temperature plasmas with plasma parameters of $T_\mathrm{e} \leq 4\,\mathrm{keV}$, $T_\mathrm{i} \leq 10\,\mathrm{keV}$ and $n_\mathrm{e} = 5 \times 10^{14}\,\mathrm{cm}^{-3}$ for NBI plasmas and $T_\mathrm{e} \leq 10\,\mathrm{keV}$, $T_\mathrm{i} \leq 2\,\mathrm{keV}$ and $n_\mathrm{e} = 3 \times 10^{13}\,\mathrm{cm}^{-3}$ for ECH plasmas. Spectroscopic studies of LHD plasmas have been actively done over a wide area of visible to X-ray ranges. The emissions from the LHD plasma core are mainly dominant in the X-ray range because of the high central electron temperature. Then, X-ray emissions from the plasma core have been observed using a high-resolution crystal spectrometer [1] and the ion temperature has been routinely measured using He-like X-ray resonance lines of Ar and Ti with a good energy resolution better than 1 eV.

In order to observe the charge state distribution of iron ions, on the other hand, we started to develop a wide and compact X-ray crystal spectrometer. A proto-type crystal spectrometer was developed and installed on the LHD [2]. Although analysis of the charge state distributions of impurity ions can determine the transport coefficients, the Fe Kα X-ray line measurement becomes also important for understanding detailed processes on the ionization and recombination of highly ionized ions. For the purpose the Johan-type crystal spectrometer was adopted for the Fe Kα measurement. An iron-coated impurity pellet injection was also prepared to increase the intensity from iron ions [3]. The impurity pellet injection is also useful for the detailed understanding of the ionization and recombination processes of highly ionized Fe ions when the Kα spectra can be observed with high-time resolution. The Fe Kα lines structure measured from the LHD can be compared with those from astrophysical plasmas observed by SUZAKU X-ray satellite [4]. In the astrophysical plasmas a different excitation mechanism is expected for the Fe Kα lines, such as photo-excitation, whereas excitations by thermal and non-thermal electrons are expected in such laboratory high-temperature plasmas.

2. Experimental Setup

2.1 X-ray crystal spectrometer

A wide band and compact X-ray spectrometer with a Johan-type crystal and a back-illuminated CCD detector has been installed at #1-O port on the LHD as shown in Fig. 1. The spectrometer is set at a distance of 9 m from the plasma center. X-ray emissions from LHD plasmas come up to the spectrometer through a beryllium window of 200 μm in thickness and are diffracted by the curved crystal. The spectral image is focused on the Rowland cir-

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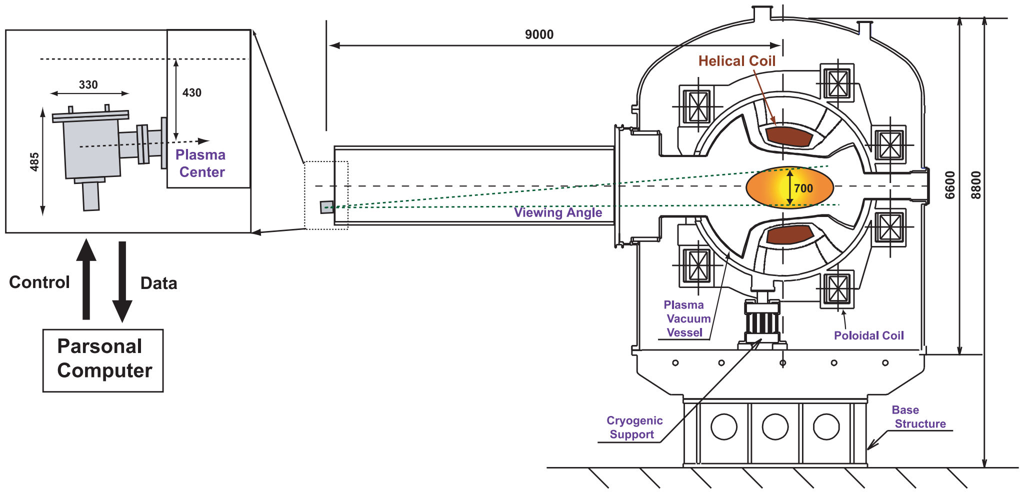

Fig. 1 Side view of LHD and crystal spectrometer installed at #1-O port.

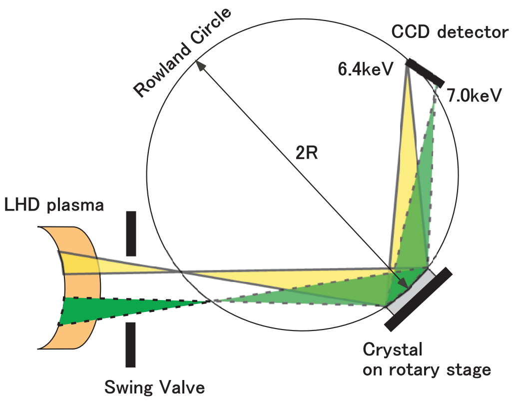

Fig. 2 Illustration of Johann geometry used in the present experiment. Curved crystal is set at distance of 9 m from plasma center. 2R is a curvature of curved crystal.

cle. Any visible and VUV emissions are masked by the Be window. Each X-ray with different energies has a different Bragg angle, and therefore each Kα line with different energies is collected from slightly different toroidal locations. However, the measured charge state distribution is however, affected by the difference, since the plasma parameters are homogeneous along the toroidal direction in the plasma core. The Johann geometry is illustrated in Fig. 2.

2.2 CCD (Charge Coupled Device)

A back-illuminated CCD (Andor model DO420-BN) [1] is used as an X-ray detector, which is originally manufactured for the VUV detection. The CCD is mounted on a focal position of the spectrometer with a tilted angle of 30° in order to delete the deviation from the Rowland circle and improve the spectral resolution at shorter and longer wavelength sides of the detector. The total size of the CCD exposure area is 26.6 mm in direction of dispersion (1024 ch) and 6.7 mm in vertical direction (256 ch). The pixel size is $26\times26\,\mu m^2$. The X-ray detection efficiency is 45-35% at X-ray energy of 6.4-7.0 keV. The energy resolution in the single photon counting mode is 430 eV at 6.4 keV. The CCD is operated at a temperature of −20 degree. The data is taken with a time interval of 10 ms under a vertical charge shift speed of 16 µs. The CCD is operated by a personal computer (PC) located in the LHD experimental room and is externally controlled from the diagnostic room through RS-232C communication. The CCD data are temporally saved on the PC and immediately sent to the UNIX work station after discharge through the LAN network to store the data into RAID (redundant array of independent disks).

3. Experimental Results

Two Johan-type curved crystals are adopted for the iron charge state distribution measurement, which are directly obtained from Kα X-ray spectra. The lithium fluoride crystal (LiF(220)) was used for the measurement of full charge states from iron ions in energy range of 6.4-7.0 keV. The quartz(2023) is used for narrower energy range measurement of 6.40-6.75 keV with better energy resolution, which observes the Fe charge state distribution except for only FeXXVI. Here, it should be noticed that the transition energy of FeXXVI is much separated from transition energies in other charge states. The curved crystal is set with a crystal holder on a rotary disk connected to an electric pulse motor and rotated by an external controller to adjust an appropriate Bragg angle, as shown in Fig. 3.

3.1 Lithium fluoride (220)

The curvature radius of $2R = 430$ mm is selected for the LiF crystal ($2d = 2.848$ Å) to measure the wide energy range of 6.4-7.0 keV. The size of the crystal is 15×15 mm^2. The distance between the crystal and detector is 279.4 mm and the energy dispersion is 0.6 eV/ch. The energy resolution of the spectrometer has been evaluated using the He-like Fe Kα resonance line and estimated to be 10 eV at

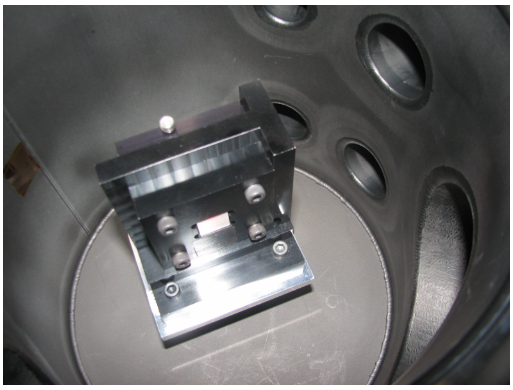

Fig. 3 Photograph of Johann-type crystal. Curved crystal is set with crystal holder on rotary stage.

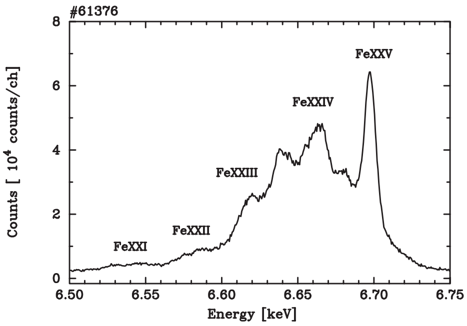

Fig. 4 Typical example of Fe Kα spectrum observed with LiF(220) crystal.

6.7 keV as a value of FWHM. Figure 4 shows a typical example of Fe Kα spectra emitted from LHD plasmas with electron temperatures of 1.7 keV. The electron temperature is measured with Thomson scattering diagnostic. The iron density is evaluated from X-ray energy spectra measured with Si(Li) detectors to be in order of 10^{-4} to the electron density [5]. This means significantly less amount of iron impurity in LHD. Then, the obtained data exhibit an enough brightness of the present LiF crystal spectrometer and the intensity has a good signal to noise ratio to analyze the charge state distribution. However, any H-like FeXXVI emission has not been observed at present. The reason why we had no emissions from FeXXVI is mainly due to the lack of electron temperature. The impurity transport code suggests we need electron temperature greater than 4 keV for the FeXXVI observation. It is also seen that the dominant charge states of Fe ions at plasma center move from FeXXIII (Be-like) to FeXXV (He-like) according to the temperature, as shown in Fig. 5. The vertical axis of the Kα intensities is traced in logarithmic scale, not in linear scale.

3.2 Quartz (2023)

In order to measure the energy range of 6.40-6.75 keV the curved quartz crystal ($2d$ = 2.7498 Å) with a curvature radius of $2R$ = 630 mm is selected. The size of the crystal is the same as the LiF case and the distance between the crystal and detector is 433 mm. The energy dispersion is 0.4 eV/ch. The accuracy of the crystal curvature was measured by a method of the non-contact three-dimensional

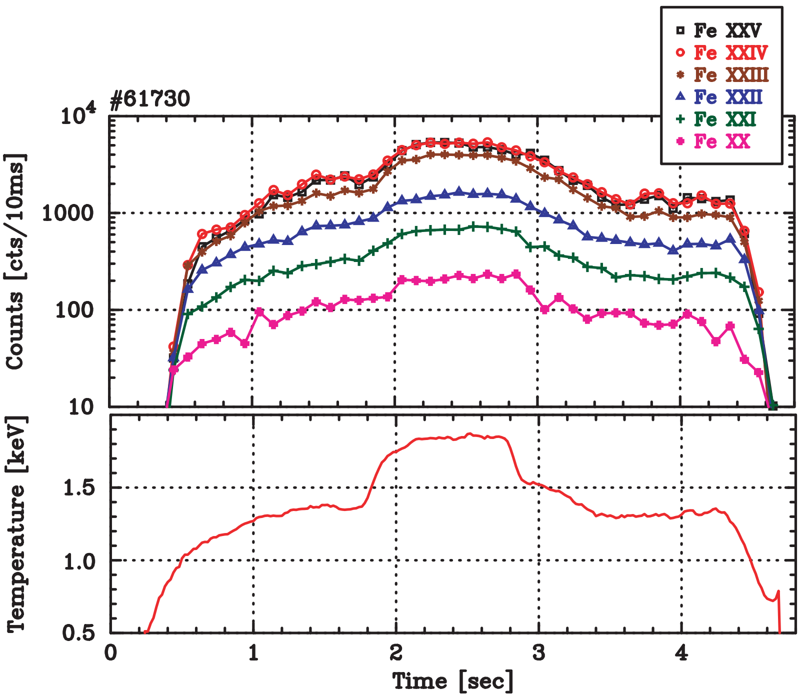

Fig. 5 Temporal behaviors of FeXXI (N-like)-XXV (He-like) Kα transitions and central electron temperature.

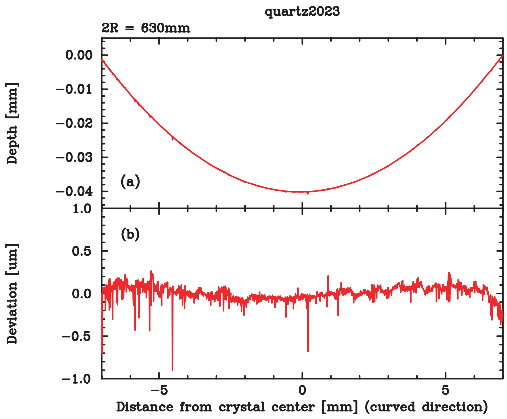

Fig. 6 Surface depth of curved quartz(2023) (a) and deviation from circle of the crystal (b) as a function of distance from crystal center along dispersion direction.

measurement technique. Figure 6 shows measured surface depth of the quartz (2023) and a deviation from the circular curvature of the crystal. The accuracy of the curvature radius is within $2R = 630 \pm 0.5$ mm and the deviation from the circle is $\Delta R = \pm 0.5\,\mu$m. A ray trace computer simulation is done and the energy resolution of the quartz(2023) crystal spectrometer can be estimated from the present calibration to be 4 eV at 6.4 keV. This result guarantees well resolved Kα spectra compared with LiF crystal case (10 eV at 6.7 keV).

4. Discussions and Summary

The impurity charge distribution is mainly a function of the electron temperature, but significantly affected by the radial transport of the impurity ions. The Fe Kα lines shown in Fig. 4 are analyzed using a simulation code [6] under plasma parameters of $T_e = 1.7$ keV and $n_e = 5 \times 10^{14}$ cm^{-3} in collisional ionization equilibrium (CIE) model. The result is shown in Fig. 7. The experimentally observed spectrum in Fig. 4 can be reproduced by the calculation, but the detailed line intensities do not agree with the calculation at present. The radial structures of electron temperature and density have to be included in

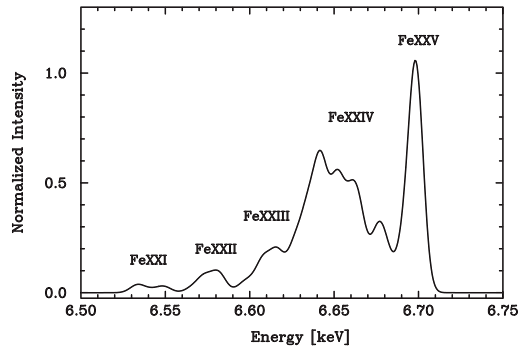

Fig. 7 Calculation of Fe Kα spectrum using a simulation code [6] under plasma parameters of $T_e = 1.7$ keV and $n_e = 5 \times 10^{14}$ cm^{-3} in collisional ionization equilibrium (CIE) model. The spectrum is compared with Fig. 4.

the calculation in addition to the transport effect.

In summary the full Fe Kα spectra were observed from LHD plasmas using the wide band crystal spectrometer with LiF (220) and the charge state distribution in the plasma core was successfully measured. The Fe Kα measurement with better energy resolution using the quartz crystal is now progressed. Further detailed comparison between the experiment and calculation on the Fe Kα spectra will be possible in near future.

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[1] S. Morita and M. Goto, Rev. Sci. Instrum., **74**, 2375 (2003).
[2] I. Sakurai *et al.*, Rev. Sci. Instrum., **77**, 10F328 (2006).
[3] H. Nozato *et al.*, Rev. Sci. Instrum., **74**, 2032 (2003).
[4] K. Mitsuda *et al.*, Proc. SPIE, **177**, 5488 (2004).
[5] S. Muto and S. Morita, Rev. Sci. Instrum., **72**, 1206 (2001).
[6] J.S. Kaastra *et al.*, *UV and X-ray spectroscopy of astrophysical and laboratory plasmas* (1996).