Observation of Space and Energy Distributions of High Energy Electrons Produced in ECH Plasmas of LHD

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Hard x-ray spectrum has been studied with x-ray pulse-height analyzer (PHA) in Large Helical Device (LHD). The hard x-ray emissions have been observed in high temperature plasmas heated by electron cyclotron heating (ECH). The radial distribution of the hard x-ray emissions is quantitatively derived from the line-integrated spectrum through an Abel inversion. When the bulk electron density ranges at 2.0×10^{18} m^{-3}, the hard x-ray emissions are measured to be the most intense. From an analysis on the spectrum it is quantitatively proved that the energy-distribution function of the suprathermal electrons produced by ECH remarkably deviates from that of thermal electrons. The relaxation time of the high energy electrons is estimated to be 70 ms from the exponential decay rate after turning off the ECH pulse.

Keywords: hard x-ray emission, pulse height analyzer, suprathermal electron, Large Helical Device

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1. Introduction

Observation of hard x-ray is important to investigate the behavior of high energy electrons. Hard x-ray measurements with semiconductor detectors have been widely done in tokamaks [1].

The hard x-ray measurements have been also tried in ECH plasmas of many helical devices, but no hard x-ray has been observed. Experimental reports have been seldom published in relation to the high energy electrons. These negative results are closely connected with the confinement and the generation of the high energy electrons. In Large Helical Device (LHD: R = 3.9 m, $<a>$ = 0.6 m, $B_t \leq 3$ T), better confinement can be expected for such the high energy electrons.

It is important to investigate the suprathermal electrons which mean the high energy electrons produced by ECH. The temperature of thermal electrons can be obtained from line-integrated soft x-ray energy spectra. In order to confirm the existence of the suprathermal electrons, however, it is necessary to prove its non-maxwellian energy-distribution function in a local position of the plasmas. Accordingly, it is also important to observe the radial profile of the suprathermal electrons. In LHD an assembly of x-ray PHA makes it possible to measure the x-ray energy spectra with multiple sight lines [2].

In the present article experimental results on the hard x-ray measurement using the PHA system are reported. The existence of high energy electrons as suprathermal electrons is also quantitatively investigated.

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2. Assembly for X-ray Measurement

The x-ray energy spectra have been measured with conventional x-ray PHA. A germanium-semiconductor detector is installed at a horizontal port in LHD [3]. Hard x-ray spectra up to 250 keV can be measured with the detector. The assembly equipped with Si(Li) semiconductor detectors is installed at a bottom port. The assembly also consists of a radial scanning system which modulates the sight lines in the radial direction of the LHD plasma. The diameter of the sight lines is 20 mm at the mid plane. There are only 3 sight lines. However, 10 times fixed discharges have been performed to scan the sight lines shot-by-shot. The fine radial profile of an x-ray spectrum has been then measured with 30 sight lines. The detailed performance of the assembly has been already reported with the analysis of the continuum x-ray emission in a reference [2].

3. Experimental Results

Figure 1 shows the time evolution of the hard x-ray spectrum obtained with the conventional germanium-semiconductor detector. The plasma has been heated by only ECH. The bulk electron density is maintained to be 2.0×10^{18} m^{-3}, since the maximum intensities of the hard x-rays can be detected in such low density range [3]. After the heating pulse is turned off at 750 ms, the emission immediately starts to decay and gradually decreases in an exponential decay rate of 70 ms. In the decay phase the high energy electrons are disappeared much faster than the thermal electrons. The decay rate of the high energy x-ray emissions is independent on the energy.

Figure 2 shows x-ray energy spectra obtained with the

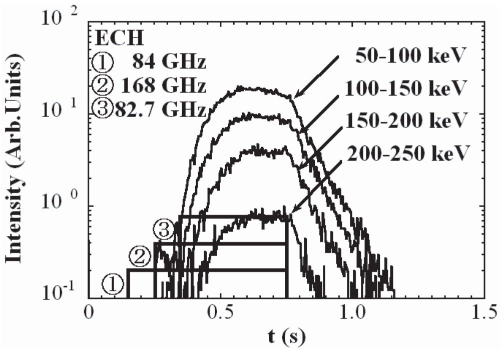

Fig. 1 Time evolution of the hard x-ray emissions measured with the germanium-semiconductor detector. The heating duration of ECH is also illustrated.

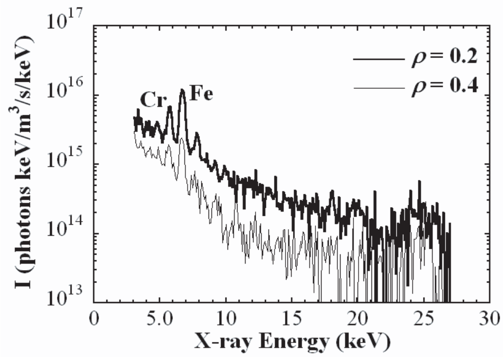

Fig. 2 Abel inverted x-ray energy spectra obtained with soft x-ray PHA assembly installed at the bottom port. Thick and thin lines represent x-ray spectra at ρ = 0.2 and 0.4, respectively. K_α lines from metallic impurities of Cr and Fe are also observed at 5.6 and 6.7 keV, respectively.

PHA assembly. The spectra are measured from the ECH plasmas. The spectra are quantitatively corrected by the transmission rate of a 1-mm-thick beryllium window and the quantum efficiency of the Si(Li) semiconductor detectors. This assembly does not directly see divertor plates from which strong x-rays are emitted due to the bombardment of energetic electrons. Therefore, it is available to obtain the local emission from the plasmas through the Abel inversion [4]. It is difficult to analyze these energy spectra using single exponential function. This fact qualitatively means that the electrons in the ECH plasma are not in thermal equilibrium. Particularly, the higher energy part of the x-ray spectra is remarkably enhanced. For example, the energy region higher than 15 keV is suggested to be a high energy tail. The existence of the high energy tail is clearer in the case of ρ = 0.4.

Figure 3 shows the radial profiles of the x-ray emissions measured with the assembly of PHA. The profiles are peaked in all the energy regions. The radial profiles tend to be more peaked with the energy. It is suggested that the density of the higher energy electrons becomes larger at the plasma center.

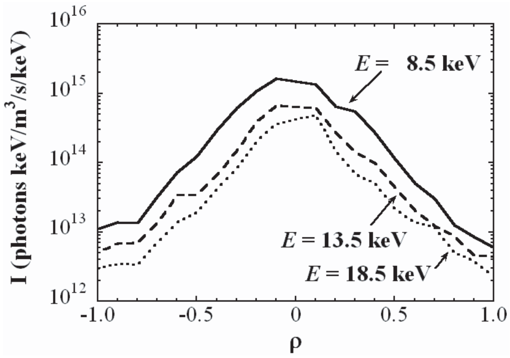

Fig. 3 Radial profiles of Abel inverted x-ray spectra at energies of 8.5, 13.5 and 18.5 keV.

4. Analysis and Discussion

The energy spectra obtained in the present study seem to be explained by two components of continuum x-ray emissions, as shown in Fig. 2. One component is the x-ray emissions from the bulk electrons. The other is the x-ray emission from the high energy electrons driven by ECH. Here, the emissions are analyzed assuming thermal component and high energy tail. Figure 4 shows the results analyzed at a normalized radius of $\rho = 0.1$. The electron densities of the bulk and suprathermal electrons are estimated to be 1.25×10^{18} and 7.50×10^{17} m^{-3}, respectively. The total electron density is 2.00×10^{18} m^{-3}. Then, the density ratio between the bulk and suprathermal electrons is 0.62:0.38. The electron temperature of the bulk plasma is estimated to be 5.4 keV from the x-ray energy spectrum. The average energy of the suprathermal electrons is 40 keV.

The radial profiles of the total electron density and the density ratio of the suprathermal electrons to the total electron density are shown in Fig. 5. The high energy component becomes small with the normalized radius. It is less than 10 % at $\rho \geq 0.6$. The bulk electrons dominantly exist in $\rho \geq 0.2$. The density of the suprathermal electrons rapidly increases at $\rho \leq 0.2$. Particularly, the suprathermal electron density is comparable to the bulk electrons at $\rho \leq 0.1$ indicating ECH power deposition focused on the plasma center.

Figure 6 shows the estimated radial profiles of the electron temperature and the average energy for the suprathermal electrons. The electron temperature of the bulk plasmas is of course a function of the normalized radius. However, the radial profile of the average energy for the suprathermal electrons is approximately constant against the normalized radius. Accordingly, the low-density ECH discharge in LHD is confirmed to be non-equilibrium plasma since the confinement time of the bulk electrons are much shorter than the relaxation time. The relaxation time derived by electron-electron collision is expressed as follows,

$$\tau = \frac{(2\pi)^{1/2} 3\pi \varepsilon_0^2 m_e^{1/2}}{n_{\mathrm{Bulk}} e^4 \ln \Lambda} \left(kT_{\mathrm{Bulk}} + \frac{2}{3} E_{\mathrm{h}} \right)^{3/2}, \qquad (1)$$

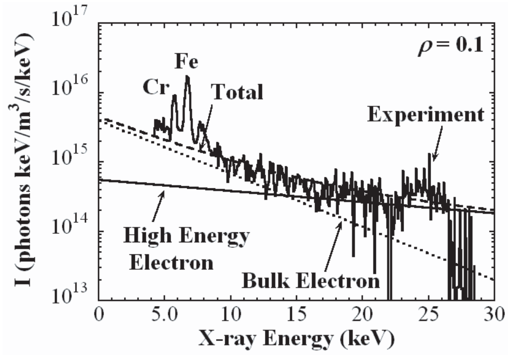

Fig. 4 Abel inverted x-ray energy spectra obtained from the experimental and calculated results. X-ray energy spectra calculated for the bulk component (dotted line) and the high energy component (solid line) are plotted with the total spectrum of two components (dashed line).

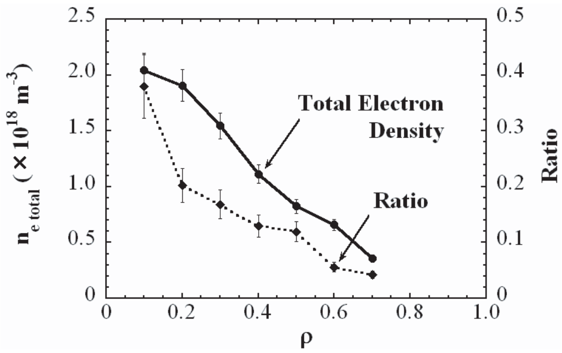

Fig. 5 Radial profiles of total electron density (solid line) and ratio of suprathermal electrons to total electron density (dashed line), respectively.

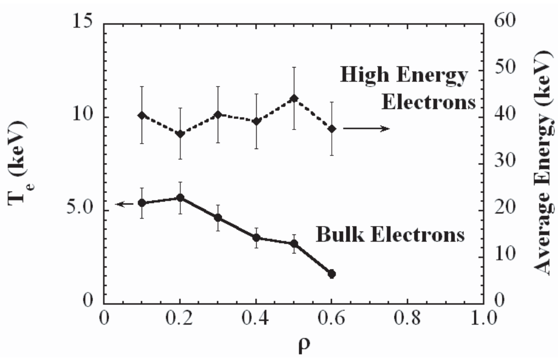

Fig. 6 Radial profiles of bulk electron temperature (solid line) and average energy of suprathermal electrons (dotted line).

where n_{Bulk}, e, m_e, ε_0, $\ln\Lambda$, kT_{Bulk}, E_h, and τ are the average bulk electron density, the electron charge, the electron mass, the dielectric constant, the coulomb logarithm, the average bulk electron temperature, the average energy of suprathermal electrons, and the relaxation time [5]. Using the equation, the relaxation time is estimated to be

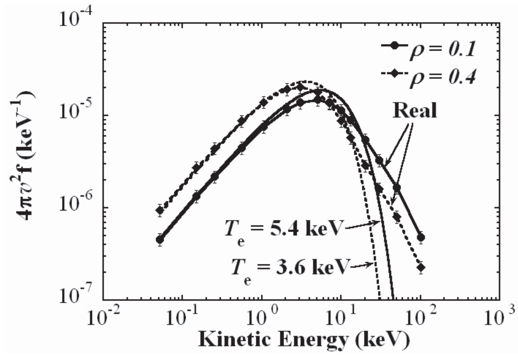

Fig. 7 Real and maxwellian energy-distribution functions for the low-desnity ECH plasmas. Real distribution is obtained from experimental x-ray energy spectra. For the bulk maxwellians, $T_e(0)$ is 5.4 and 3.6 keV at $\rho = 0.1$ and 0.4, respectively.

80 ms in conditions of $n_{\mathrm{Bulk}} = 5.5 \times 10^{17}$ m^{-3}, $\ln\Lambda = 18.5$, $kT_{\mathrm{Bulk}} = 3.3$ keV and $E_h = 40$ keV. As a result, the decay time of 70 ms shown in Fig. 1 is suggested to be consistent with that derived from Eq. (1). The relaxation time between bulk ions and the high energy electrons is three orders longer than τ. Then, the total relaxation time is almost equal to that due to electron-electron collision.

Finally, we try to obtain a real energy-distribution function from the observed x-ray energy spectrum instead of the maxwellian distribution. In an assumption with non relativistic approximation, the energy spectrum of the bremssstrahlung emissions is expressed as follows,

$$I(E) = \frac{2^7 \pi^3}{3\sqrt{3}} \frac{Z_{\mathrm{eff}} e^4 n_e^2}{(4\pi\varepsilon_0)^3 c^3 m_e^3} \int_E^{\infty} \mathrm{d}E_0 f(E_0), \tag{2}$$

where E, I, E_0, n_e, c, Z_{eff} and $f(E_0)$ are the x-ray energy, the x-ray intensity, the electron-kinetic energy, the total electron density, the light velocity, the effective Z of ions, and the electron-distribution function, respectively. The distribution function satisfies the following boundary condition,

$$\int \mathrm{d}\vec{v} f(E(\vec{v})) = 1, \tag{3}$$

where $\vec{v}$ is the velocity of the electrons. Accordingly, the distribution function is simply analyzed from the differential of Eq. (2) as follows,

$$f(E_0) = -\frac{3\sqrt{3}}{2^7 \pi^3} \frac{(4\pi\varepsilon_0)^3 c^3 m_e^3}{e^4 Z_{\mathrm{eff}} n_e^2} \frac{\mathrm{d}}{\mathrm{d}E} I(E)|_{E=E_0}, \tag{4}$$

The electron density is also obtained from the observed continuum through Eq. (3) and Eq. (4), even though the electron-energy distribution function is not in the thermal equilibrium.

Figure 7 shows the real energy-distribution functions, which include both of the bulk and suprathermal electron-energy distributions, derived from the present experimental result through Eq. (4). In the analysis the differential operator in Eq. (4) is replaced by Fourier transform of the energy spectrum in order to cancel the noise. In the figure the maxwellian energy-distributions from the bulk electrons (T_e = 5.4 keV at ρ = 0.1 and 3.6 keV at ρ = 0.4) are also plotted. The real energy-distribution probability in ECH plasmas is several orders larger than the maxwellian distribution probability at 100 keV.

5. Conclusion

Radial profiles of x-ray spectra have been measured in ECH plasmas of LHD. Analyzing the data, it has been clear that the high energy electrons exist as suprathermal electrons in ECH plasmas. It has been confirmed that the density of the suprathermal electrons is comparable to that of the bulk electrons at plasma center in low-density ECH plasmas. The radial profile of the suprathermal electrons is fairly flat with average energy 40 keV.

Acknowledgements

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[1] Y. Peysson and R. Arslanbekov, Nucl. Instrum. Methods **380**, 423 (1996).
[2] S. Muto *et al.*, Rev. Sci. Instrum. **72**, 1206 (2001).
[3] S. Muto *et al.*, Rev. Sci. Instrum. **74**, 1993 (2003).
[4] S. Muto *et al.*, Plasma Fusion Res. **2**, S1069 (2007).
[5] K. Miyamoto, *Plasma Physics for Nuclear Fusion Revised edition* (The MIT Press, Massachusetts Institute of Technology, 1989) p.94.