Current Profile Estimation in Full LHCD Plasmas using Hard X-Ray Measurement along the Top and Bottom Identical Line of Sight on TRIAM-1M

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A new technique to measure the current profile in plasmas with asymmetric distribution function such as lower hybrid current drive (LHCD) by using hard X-ray (HXR) energy spectrum measurement along the top and bottom identical line of sights (ILOS) is proposed and is applied to the full and partially LHCD plasmas on the TRIAM-1M tokamak at the first time in the world. The pitch angles were measured at $R - R_0 = \pm 2.5$ cm, where R, R_0 mean the major radii of the ILOS and the magnetic axis, respectively. The measured pitch angle of the magnetic field inverted at the magnetic axis estimated magnetic measurement in partially LHCD plasmas. This indicates that the difference of the measured pitch angles is caused by the plasma current in the plasma and this new method is available in detecting the current profile in tokamaks. In full LHCD plasma, no difference between the HXR signals along the top and bottom ILOS appear. This indicates that the current density around the magnetic axis was reduced compared with that in partially LHCD plasmas. This observation is no contradiction with power deposition of LHCD.

Keywords: lower hybrid current drive, current profile measurement, hard X-ray, tokamak, TRIAM-1M

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1. Inroduction

Current profile measurement in tokamaks is so important to understand plasma confinement as well as equilibrium [1, 2]. The discovery of current hole in tokamaks is ascribed to obtain the reliable current profile [3]. The most popular way to measure the current profile is the method using MSE (Motional Stark Effect) and this has been developed as the most reliable way to measure the current profile in tokamaks. High power NBI (Neutral Beam Injection) and sophisticate detection of polarized light emitted from the atomic process are required to execute the way.

Recently, the current profile control is the key technique to obtain and maintain the high performance plasma [4, 5] and the fast measurement of current profile is required. The method using MSE is available even in the current profile control, however its time resolution is not enough. In the real time control, the time to calculate the physical value from the detected signals should be shortened as possible. In this view, a simple way to detect the current profile should be developed.

On TRIAM-1M, full and partial non-inductive lower hybrid current drive (LHCD) can be obtained. As no NBI are installed, the current profile in LHCD plasma does not have been obtained from the way using MES. Recently an internal transport barrier (ITB) is observed on TRIAM-1M [6]. As the current profile measurement is required to understand the physical mechanism of ITB, the current profile measurement in LHCD plasma is required. A new technique to measure the current profile in LHCD plasmas by using hard X-ray (HXR) energy spectrum measurement along the top and bottom identical line of sights (ILOS) is proposed. An angle between ILOS and the magnetic filed line is out of alignment from the perpendicular by the poloidal magnetic field generated by plasma current and poloidal filed coils in toakamaks. As the emission cross-section of HXR strongly depends on the angle to the drift direction of energetic electrons, that is the magnetic filed line, this disagreement of the angles makes significant difference between the signals of detectors located on the top and bottom. As the result, the poloidal magnetic field is able to be detected by the difference of the HXR emission along the top and bottom ILOS. The method was applied to the full LHCD plasmas on the TRIAM-1M tokamak and the plasma current around the magnetic axis was estimated.

In section 2, the new method to measure the current profile is introduced and in the section 3 the experimental results of the application of the new method are described. In section 4 the contents of this paper is summarized.

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2. The New Method to Measure the Current Profile in Tokamaks

The principle of the new method to measure the current profile in tokamsks is introduced in this section. A schematic view of the configuration to measure the current profile is shown in Fig. 1.

The magnetic filed line is composed of the combination between the toroidal and the poloidal magnetic fileds. When the poloidal magnetic field is not present, the magnetic field line has only toroidal component. In this case, the vertical line of sight is perpendicular to the magnetic filed completely. The electron distribution function has the rotational symmetry of which the axis corresponds to the magnetic axis. In this case, the HXR emission to the detectors installed on the top and the bottom side of the machine is the same in any electron distribution functions. However in tokamaks, no poloidal magnetic filed means no equilibrium of plasmas. Therefore any tokamak plasmas are maintained by poloidal magnetic fileds generated by the plasma current and the poloidal filed (PF) coils. The schematic view of the magnetic field lines in tokamak are shown in Fig. 1. In this case, the vertical line is not perpendicular to the magnetic filed except the magnetic axis and its angle depends on the strength of the poloidal magnetic field. When the asymmetry of electron distribution function is present, this angle makes the difference of the HXR emission detected along the top and bottom ILOS, because the emission crosssection of HXR strongly depends on the angle to the magnetic field [7]. If we can detect this difference of the HXR signals along the top and bottom ILOS, the pitch angle of the magnetic field will be obtained.

As for the LHCD, the asymmetry of energetic electron distribution function makes the plasma current and the asymmetry exists in electron distribution function at any time. The directions of the plasma current, the toroidal magnetic field, and the drift of energetic electron on TRIAM-1M are shown in Fig. 1. The ILOS for the detector located at the inner top side in major radius from the magnetic axis leans to the coming drift direction of electrons. While the ILOS for the inner bottom side leans to the outgoing drift direction. In the case of the detectors located at the outer side, the situation is inverted. The asymmetry of the electron distribution along the drift direction exists in the LHCD plasmas. As the results, the HXR radiation measured with the detectors located on the top side is distinct from that with ones located on the bottom side by the leaning of magnetic filed due to the poloidal field. Although the HXR emission significantly affects plasma density, Z_{eff}, and so on, these effects are well-cancelled by the division process of these top-bottom pair signals. Thus we can be estimated the magnetic pitch angle by using the HXR measurement in LHCD plasmas on TRIAM-1M.

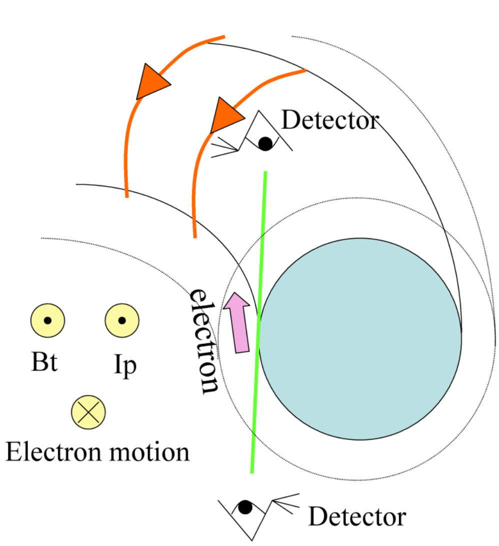

Fig. 1 Principle to measure a current profile in LHCD plasmas by using up-down asymmetry of HXR emission is illustrated.

3. Experimental Apparatus and Results

The measurements were carried out in full and partial non-inductive LHCD plasma on TRIAM-1M, where the two HXR detector systems were installed on the same toroidal direction. One is a 7 ch NaI scintillators detector array covered by lead to shield suborbital HXR, which is installed on the bottom side of TRIAM-1M and is able to move along the major radius shot by shot. Another is installed on the top side, which is an 1ch NaI scintillator detector moving along the major radius shot by shot.

The observations were executed in the LHCD plasmas as shown in Fig. 2 at $R - R_{\mathrm{I}} = \pm 12.5$ mm, where R_{I} shows the position of the current centre estimated by the magnetic measurements. Two detectors were set on the ILOS and were calibrated in energy by some kinds of radio isotopes. The final calibration was carried out by using the HXR emission from LHCD plasmas, based on a consideration that the signals from these detectors should be equated, when these two detectors set on the ILOS passing through the magnetic axis. Time trace of the ratios of these two detectors during full LHCD discharge is plotted in Fig. 3.

Each observed HXR energy spectrum was applied to a smoothing way. The clear difference was observed in the partial LHCD phase and it seems to be smaller with time. This suggests that the current profile becomes broad with time. This is no contradicts to a predicted current profile in LHCD plasmas [6]. To estimate the current density quantitatively, a distribution function of energetic electrons should be assumed. We adopt the well-known three temperature models [8] ($T_{//} = 100$ keV, $T_{\mathrm{P}} = 50$ keV, $T_{\mathrm{B}} = 50$ keV, $f_{\mathrm{FB}} = 0.2$, where $T_{//}$, T_{P}, T_{B}, and f_{FB} show the temperature of the forward, perpendicular, backward directions, and the number ratio of backward-drifting electrons to forward-drifting ones, respectively. The calculated

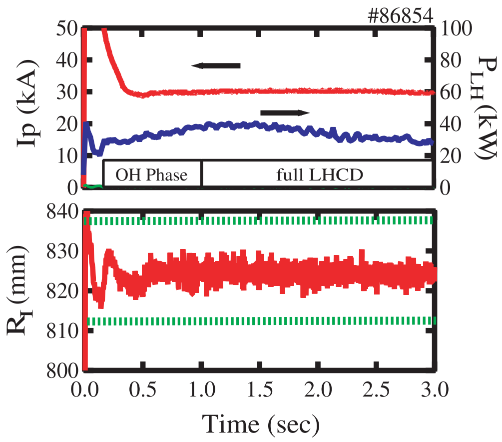

Fig. 2 Typical waveforms to measure the current profile are shown. Top figure shows the plasma current (red line) and the injected lower hybrid wave (LHW) power (blue line). The partial LHCD phase corresponds to 0.2-1.0 sec, because the OH power is used to product the source of the plasma at the early phase in the discharge. After 1 s, the plasma current is maintained by only LHCD to the end of the discharge. Bottom figure shows the position of the current centre, R_I estimated by the magnetic measurement as shown by red line. The positions of the ILOS of the HXR detectors in the measurement are shown in the bottom figure as the green lines.

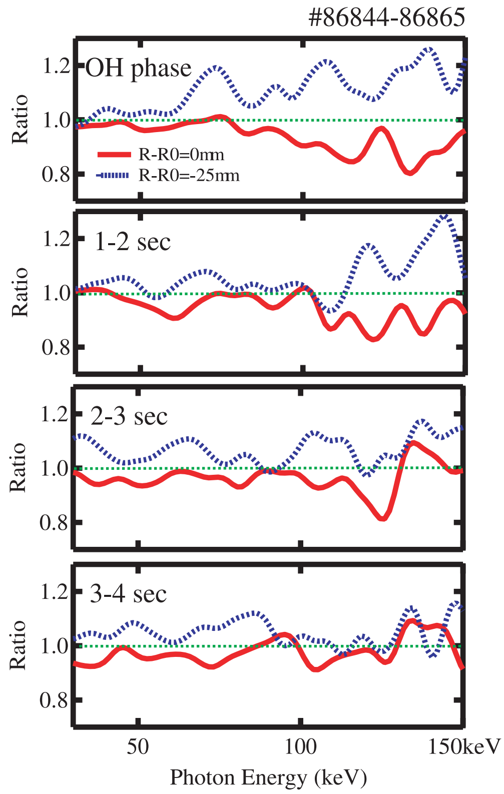

Fig. 3 Time trace of the ratio of HXR energy spectrum from the top detector to that from bottom one in the range of 40-150 keV in the discharges as shown in Fig. 2 is plotted. To make the energy spectrum, more than 20 shots were used. The signals in the energy more than 150 keV are not available by the large signal to noise ratio. Red lines show the ratio at the position of ILOS of $R - R_0 = 0$ mm ($R = 837.5$ mm) and blue lines show that at $R - R_0 = -25$ mm ($R = 812.5$ mm), where the centre of the plasma is controlled at $R - R_0 = -12.5$ mm as shown in the bottom figure in Fig. 2.

and experimental results are shown in Fig. 4.

From this figure, the current including in $r = 12.5$ mm ($a = 110$ mm) corresponds to 15 kA, which is the half of the total current in partial LHCD phase. Although the accuracy of the measurement depends on the number of photon count, in this case the data is almost in the range of 1.0-2.5 degree (7-18 kA). In the case of 1.5 degree (11 kA), the predicted current profile is estimated as the function of $j(r) = j0\left(1-(r/a)^2\right)^5$. This peaked profile eliminates with time and finally the current in the range of $|R - R_0| = 12.5$ mm becomes to be smaller than 4 kA. This absolute value affects on the assumption of the electron distribution function and we may also estimate a distribution function by using these signals. It is a future work. When the variation of electron distribution function is neglected, this difference of the HXR signals can detected in the HXR intensity signal. In this case, we can measure the current profile in better time resolution than MSE measurement.

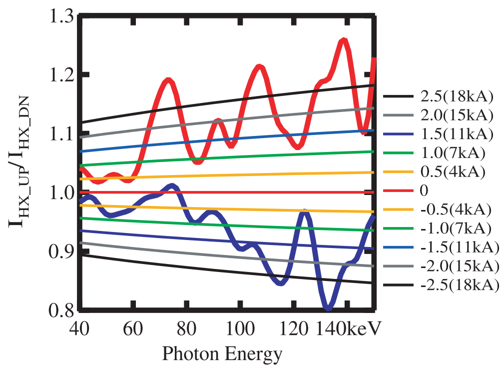

Fig. 4 The calculated up-down asymmetry of HXR based on the assumed distribution function in various current densities is plotted as the function of the photon energy with the experimental data in the OH phase.

4. Summary

We proposed a new method to measure the current profile in the plasmas with asymmetric electron distribution function such as LHCD by using the HXR measurement along the top and the bottom ILOS. The way was applied to the partial and full LHCD plasmas on TRIAM-1M and the difference of the HXR spectrum due to the poloidal magnetic field was detected in partial LHCD plasmas.

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