Observation of $m/n=2/1$ magnetic island on the foot point of electron internal transport barrier using soft x-ray CCD camera in the Large Helical Device

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Abstract. The existence of $m/n=2/1$ magnetic islands in the plasma with an electron internal transport barrier (ITB) is identified in tangential soft x-ray emission images measured with a soft x-ray CCD camera using the Fourier-Bessel expansion reconstruction technique in the Large Helical Device. A clear $m/n=2/1$ magnetic island is observed in the discharge with ECRH and NBI in the direction antiparallel to the equivalent plasma current (counter-NBI), where the magnetic shear is expected to become small enough to cause the formation of a magnetic island. On the other hand, no magnetic island is observed in the ECRH and NBI in the direction parallel to the equivalent plasma current (co-NBI), where the magnetic shear is expected to be sufficiently high.

1. Introduction
The internal transport barriers (ITBs) characterized by the large temperature gradient interior of the plasma have been observed in many tokamaks [1-6]. The ITBs in the electron thermal energy have been observed with dominant electron cyclotron heating in plasmas with negative magnetic field shear in many tokamaks and stellarator/heliotron plasmas. The understanding of thermal transport barriers physics in plasmas is important to obtain high performance plasma with high temperature and improved energy confinement. In this paper, the role of magnetic shear in formation of the electron internal transport barrier is discussed. The electron ITB has been observed associated with the transition from ion root to the electron root of the radial electric field ($E_r$) in low-density plasmas heated by neutral beam injection (NBI) and electron cyclotron resonance heating (ECRH) in many stellarators [7-9]. In the Large Helical Device (LHD), the ITB with respect to electron thermal transport were observed when the ECRH power was highly localized on the center of the plasma sustained by the NBI [10, 11]. Although the electron ITB is observed regardless of the direction of NBI, both in the direction parallel (co-injection) and antiparallel (counter-injection) to the equivalent plasma current, the radial profile of electron temperature observed shows differences between the co-NBI and counter-NBI plasma because of the existence of magnetic islands. In the counter-NBI discharge, as the foot
point of ITB is located just on the inner side of the magnetic island, a clear foot point is typically observed. This is in contrast to the unclear foot point of ITB in co-NBI discharge, where there is no magnetic island. The existence of a magnetic island also affects the hardness of the transition from L-mode to ITB mode. A sharper transition is observed in the discharge with counter-NBI than the discharge with co-NBI. Transport analysis shows that both a standard electron thermal diffusivity and an incremental electron thermal diffusivity are reduced significantly in the ITB [12]. The improvement of electron transport in the ITB is resulted from the relation of these two diffusivities. In the LHD, the size of 2/1 magnetic island can be controlled by the cancellation magnetic field using external field coils and it has been demonstrated that the 2/1 magnetic island contributes to the formation of the ITB. Studies of the magnetic island physics and active control of magnetic islands have been reported [13-15]. The shear of the rotational transform is strongly dependent on the radial profile of the net toroidal plasma current [16]. The weak shear of the rotational transform causes the growth of the magnetic island. The measurement system with the multichannel detector sensitive to electron cyclotron emission (ECE) or soft x-rays has been applied to observed the rotating island using tomography techniques [17, 18]. A high-speed x-ray camera with a micro-channel plate (MCP) detector coupled with a scintillator and a fast intensified charge-coupled device (ICCD) are employed to measure a tangential x-ray image for the study of magnetohydrodynamics (MHD) instabilities [19]. In the LHD, a tangential x-ray CCD camera has been applied for measurement of the magnetic axis [20, 21] and the magnetic island.

In this paper, measurement of the magnetic island with a soft x-ray CCD camera for ITB plasmas in the LHD is described. The relationship between the magnetic island and the magnetic shear of the rotational transform in the ITB plasma sustained by co-NBI and counter-NBI with additional ECRH is discussed.

2. Experimental setup and analysis

The LHD is a heliotron type device, which has superconducting coils with poloidal and toroidal period numbers of $L/M = 2/10$, plasma major radius $R_{ax}$ of 3.5-4.1 m, and averaged minor radius of the last closed magnetic surface $a$ of 0.6 m [22]. The target plasma has been sustained using three NBI (two counter-NBI and one co-NBI) with a beam energy of around 140-180 keV and absorbed power of 1-3 MW. The plasma with the electron ITB is formed by injection of ECRH [82.7 GHz/250 kW, 84 GHz/420 kW and 168 GHz/400 kW] highly localized on the magnetic axis as shown in figure 1 (a).

The radial profile of the electron density ($n_e$) is measured with a 13-channel far-infrared (FIR) laser interferometer system at vertically elongated cross-section, while the radial profile of the electron temperature ($T_e$) is measured with a 200-channel YAG-laser Thomson scattering system at the horizontally elongated cross-section in the LHD [23, 24].

The net toroidal plasma current is measured with a Rogowski coil. The co-NBI and counter-NBI drive the net toroidal current in the direction parallel and antiparallel to the equivalent plasma, respectively (see figure 1 (b)). (Here the positive current represents the current parallel to the equivalent plasma current.) The net toroidal plasma currents at the time slice of the soft x-ray image measurements are +3 kA/T and -15 kA/T with co-NBI and counter-NBI, respectively. The current radial profiles used in this calculation for the discharge with positive and negative current are $(1 - \rho^2)$ and $(1 - \rho^2)^2 - 0.9(1 - \rho^2)^3$, respectively, as shown in figure 2.

The radial profiles of toroidal current used here are consistent with the measurements of rotational transform by Motional Stark effect spectroscopy, which suggest the peaked current profile for co-NBI phase and hollow profile in counter-NBI [16]. The difference in the radial profile of the current profile is due to the difference in deposition profiles of NBI. The deposition of counter-NBI is peaked off-axis, while the beam deposition of co-NBI is peaked on-axis. The current profile in the discharge with counter-NBI tends to be hollow because the inductive
current (return current) flows in the direction to compensate the current driven by NBI near the plasma center, where the current diffusion time scale is large due to high temperature. The soft x-ray CCD camera system, which consists of pinholes, Be filters, a shutter and a CCD detector sensitive to soft x-rays, has been installed on a tangential view port on the LHD to measure the shape of the magnetic flux surface from a tangential soft x-ray image [25]. By choosing the appropriate combinations of pinhole size and thickness of Be filters, the soft x-ray image can be measured for the plasmas over a wide range of electron temperatures and densities. The soft x-ray images were measured with an exposure time of 0.1 s and with an interval of 0.55 s. The interval is limited by the maximum readout speed of the CCD camera. It should be noted that this soft x-ray CCD camera is applied to measure non-rotation magnetic islands, and not to measure the rotating magnetic island often observed in tokamaks.

The magnetic island structure can be expressed by introducing the x-ray emissivity \( g(\rho, \theta, \phi) \) with the Fourier-Bessel expansion [26] as

\[
g(\rho, \theta, \phi) = \sum_{m=0}^{M} \sum_{n=0}^{N} \sum_{l=0}^{L} \left[ a_{m,n}^{l} \cos(m\theta - n\phi) + b_{m,n}^{l} \sin(m\theta - n\phi) \right] J_{m}(\lambda_{m}^{l+1}\rho),
\]

where \( \rho, \theta \) and \( \phi \) are the normalized minor radius and the poloidal and toroidal angels, respectively. \( \lambda_{m}^{l} \) is the \( l \)-th zero of \( m \)-th order Bessel function \( J_{m}(z) \). Here, the number of expansion terms, \( L \), is taken to be 6, which is sufficiently large to reconstruct the soft x-ray emission profile measured [20]. The soft x-ray intensity, \( I_{ij}^{c} \), can be calculated by integrating the soft x-ray emission, \( g(\rho, \theta, \phi) \), numerically along the line-of-sight for each zone from the wall to the pinhole using the database of the MHD equilibrium calculated with three-dimensional free boundary code VMEC [27], as

\[
I_{ij}^{c} = \int g(\rho, \theta, \phi)ds.
\]
The expansion coefficients of $a_{m,n}$ and $b_{m,n}$ are determined by the best fit of calculated intensity $I_{ij}^m$ to the intensity $I_{ij}^c$ measured with the soft x-ray CCD camera. Differences between these two intensities measured and calculated using best fit $a_{m,n}$ and $b_{m,n}$ are given as

$$\chi^2 = \frac{\sum_{i=1}^{N_x} \sum_{j=1}^{N_y} (I_{ij}^m - I_{ij}^c)^2}{N_x N_y}. \quad (3)$$

Here, $N_x$ and $N_y$ are the number of spatial zones in horizontal and vertical directions, respectively. Figure 3 shows the square of the difference $\chi^2$ between two-dimensional profiles of the calculated emission and that measured with the soft x-ray CCD camera as a function of the magnetic axis of the MHD equilibrium calculated with the VMEC code, which gives the minimum difference. Then, the x-ray intensity measured is fitted with the intensity integrated along the line-of-sight assuming the x-ray emission is constant on the same magnetic flux surface.

The database of the MHD equilibrium consists of a few hundred magnetic configurations with several different pressure profiles. Many MHD equilibria are calculated to cover the range of pressure profiles from a peaked to a broad profile, which is realized in the LHD.

3. Observation of the $m/n=2/1$ magnetic island using the soft x-ray emission image measured the soft x-ray CCD camera

The tangential x-ray images are measured with the soft x-ray CCD camera with a pinhole 0.4 mm in diameter and a Be filter 190 µm in thickness from a low-density ($n_e = 0.5 \times 10^{19} \text{ m}^{-3}$) ITB plasma. The vacuum magnetic axis, $R_{\text{ax}}$, is 3.5 m and the magnetic field, $B_t$, is 2.854 T. The plasma net current, $I_p$, measured with the Rogowski coil is +3 kA/T and -15 kA/T at the time slice of soft x-ray image measurements in the discharge with co-NBI + ECRH and counter-NBI + ECRH, respectively. Figures 4 (a) and (b) show the tangential images of the soft x-ray intensity measured with the soft x-ray CCD camera for the ITB plasma sustained by co-NBI and counter-NBI with additional ECRH, respectively. Figures 4 (c) and (d) show contour plots of the two-dimensional tangential x-ray intensity profiles measured with the soft x-ray CCD camera for the plasma with the ITB sustained co-NBI and counter-NBI with the additional ECRH, respectively. It is difficult to identify the structure of magnetic islands clearly.
in the raw data, as shown in figure 4, because of the integration effect of the viewing line of the CCD camera.

To be clarify the magnetic island structure in the ITB plasma, three poloidal/toroidal mode structures of $m/n=1/1$, $2/1$, $3/1$ are included in the x-ray emissivity $g(\rho, \theta, \phi)$ expressed in equation (1), then the analysis that the best fitted MHD equilibrium is taken from database, is curried out. The squares and circles indicate the results of analysis evaluated from the Bessel function including the poloidal/toroidal mode structure with $m/n=0/0$ mode and $m/n=0/0$ mode with $m/n=2/1$ mode, respectively. The minimum of $\chi^2$ for the mode structure including $m/n=2/1$ is smaller than that with the mode number $m/n=0/0$. This result suggests that the magnetic island exists in the ITB plasma sustained by counter-NBI.

**Figure 4.** (color online) Tangential soft x-ray emission images measured with the soft x-ray CCD camera for the ITB plasmas sustained by (a) co-NBI and (b) counter-NBI with the additional ECRH. (c), (d) Contour plots of the tangential soft x-ray emission images measured with the soft x-ray CCD camera.

**Figure 5.** Contour plots of the soft x-ray emission reconstructed from the tangential soft x-ray emission images at a horizontal elongated cross-section for each mode structure including $m/n=1/1$, $m/n=2/1$ and $m/n=3/1$. 
Two-dimensional soft x-ray emission profiles are reconstructed from the soft x-ray images measured with the soft x-ray CCD camera using best fitted coefficients of the Bessel function including each mode. The contour plots of two-dimensional x-ray emission profile at a horizontal elongated cross-section for each mode structure including $m/n=1/1$, $m/n=2/1$ and $m/n=3/1$ are shown in figure 5. The magnetic island for each mode is reconstructed in the contour plots of the two-dimensional soft x-ray emission.

Figure 6 shows a comparison of the minimum $\chi^2$, $\chi_{\text{min}}^2$, evaluated for the mode number $m/n=0/0$ with that considered including three mode numbers, $m/n=1/1$, $m/n=2/1$ and $m/n=3/1$, respectively. There is only a slight improvement in the $\chi^2$ for the cases with $m=1$ and $m=3$ modes compared with the case with $m=0$ mode. A large decrease in the minimum $\chi^2$ is seen by taking $m/n=2/1$ mode. This result clearly shows the existence of the $m/n=2/1$ magnetic island in the ITB plasma.

4. Properties of the rotational transform in the plasma with ITB sustained by co-NBI and counter-NBI with additional ECRH

In the LHD, the magnetic islands with $m/n=2/1$ mode have been observed from the tangential soft x-ray emission images measured with a soft x-ray CCD camera in the plasma with the electron ITB. The radial profile of the normalized soft x-ray emission on the mid-plane for the ITB plasma with counter-NBI shows a flattening region in the magnetic island, while no such flattening region is observed in the discharge with co-NBI, as shown in figures 7 (a) and (b).

It should be noted that the large gradient of emission (indicating large gradient of electron temperature) near the core region compensate for the flattening in the region of the magnetic island in the discharge with counter-NBI. Therefore, the central electron temperature in the discharge with counter-NBI is as high as that in the discharge with co-NBI, despite the existence of a flat region at the magnetic island. The radial profile of soft x-ray emission is consistent with the electron temperature measured by YAG Thomson scattering.

Figure 8(a) shows the radial profiles of the rotational transform calculated with VMEC code for the vacuum magnetic field and the magnetic field with a negative current and a positive current. The current profile used in the calculation of the rotational transform is $(1-\rho^2)$ for the positive current of +3 kA/T and $(1-\rho^2)^2-(1-\rho^2)^3$ for the negative current of -15 kA/T, as shown in figure 2.

Although the rotational transforms in the outer region $\rho > 0.4$ change as expected from the sign of total current (increase in $\iota$ for positive current and decrease in $\iota$ for negative current), the rotational transform near the magnetic axis always increases. This is because the change in rotational transform due to the shift in the magnetic axis is associated with the change in net
Figure 7. Radial profiles of the normalized soft x-ray emission reconstructed from the tangential soft x-ray emission images measured with the soft x-ray CCD camera for the ITB plasmas sustained with (a) co-NBI + ECRH and (b) counter-NBI + ECRH.

Figure 8. (color online) (a) The radial profile of rotational transform for vacuum magnetic field and magnetic field with net toroidal plasma current of +3 kA/T with current radial profile of \((1 - \rho^2)\) and -15 kA/T with \((1 - \rho^3)^2 - (1 - \rho^2)^3\). (b) Normalized minor radius(\(\rho\)) at the rotational transform, \(\iota\), of 0.5. (c) Magnetic shear \(\left(\frac{d\iota}{d\rho}\right)\) at the location of \(\iota = 0.5\).

In this magnetic field configuration in LHD, when the net current is positive, the magnetic axis shifts outward, and rotational transform tends to decrease. However, the increase in rotational transform due to the peaked positive current is typically larger than the decrease due to magnetic axis shift. In contrast, when the net current is negative, the magnetic axis shifts inward and rotational transform increases and overcomes the decrease of rotational transform due to the inward shift of the magnetic axis.

Figures 8(b) and (c) show the location (\(\rho\)) of the rotational transform of 0.5 for the net toroidal plasma current and the shear of the rotational transform \(\left(\frac{d\iota}{d\rho}\right)\). The \(\iota = 0.5\) location moves gradually inside and the magnetic shear becomes weaker as the magnitude of the negative current is increased. This decrease in magnetic shear enhances the growth of the magnetic island. Therefore, the magnetic island is expected to grow in the discharge with counter-NBI. However, as the magnetic shear becomes weak, the rational surface moves to the plasma center, where the detection of magnetic island is difficult because of the small gradient of temperature and x-ray emission. That the magnetic island is not observed in the discharge with co-NBI because
of the decrease in magnetic shear or disappearance of the \( \nu = 0.5 \) surface is expected.

5. Conclusion

The Fourier-Bessel expansion reconstruction technique has been applied to soft x-ray measurement with a soft x-ray CCD camera to identify the non-rotating \( m/n = 2/1 \) magnetic island in the plasma with electron ITB in the LHD. The magnetic island of \( m/n = 2/1 \) mode in the ITB plasma has been observed in the discharge with counter-NBI, where the magnetic shear decreases due to the hollow NBI-driven current. In contrast, the magnetic island is not observed in the discharge with co-NBI, where the magnetic shear is sufficiently high. The two-dimensional soft x-ray image measured with the soft x-ray CCD camera confirms that the flattening observed near the foot point of ITB is due to the existence of the magnetic island.

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