

PAPER • OPEN ACCESS

Effect of edge magnetic islands on poloidal flow in electron cyclotron heated Heliotron J Plasmas

To cite this article: Y Kondo *et al* 2025 *Plasma Phys. Control. Fusion* **67** 075027

View the [article online](#) for updates and enhancements.

You may also like

- [Data driven prediction of the neutral gas pressure in the stellarator Wendelstein 7-X](#)
D Angelis, F Sofos, S Misdanitis et al.
- [Nonlinear evolution of ideal pressure-driven MHD modes and their conversion into tearing-type modes](#)
J Ma, W Guo and Q Yu
- [Large-scale tearing-mode hazard function analysis with standard matched equilibrium reconstructions](#)
K E J Olofsson, C Akcay, X Sun et al.

Effect of edge magnetic islands on poloidal flow in electron cyclotron heated Heliotron J Plasmas

Y Kondo¹, K Nagasaki^{2,*} , S Ohshima^{2,3} , K Inoshita¹ , D Kuwahara⁴ ,
R Matsutani¹ , Y Yamanaka¹, S Kobayashi² , S Kado² , S Inagaki² , F Kin² ,
H Okada², T Mizuuchi² , S Konoshima²  and T Minami² 

¹ Graduate School of Energy Science, Kyoto University, Uji, Kyoto, Japan

² Institute of Advanced Energy, Kyoto University, Uji, Kyoto, Japan

³ University of California, Irvine, CA, United States of America

⁴ College of Science and Engineering, Chubu University, Kasugai, Japan

E-mail: nagasaki.kazunobu.4x@kyoto-u.ac.jp

Received 27 February 2025, revised 3 June 2025

Accepted for publication 26 June 2025

Published 7 July 2025



Abstract

Magnetic islands are formed at the plasma edge in Heliotron J, a stellarator/heliotron device, by controlling the rotational transform, and the effect of the magnetic islands on the poloidal flow profile was investigated using a Q-band Doppler reflectometer. Comparative measurements were performed for the magnetic configurations with magnetic islands at the plasma edge, referred to as ‘island configuration,’ and those without the magnetic islands, referred to as ‘non-island configuration.’ In all configurations, poloidal flow in the electron diamagnetic direction was observed at the edge in electron cyclotron heated plasmas. In the non-island configuration, the sheared flow maximum was inside the last closed flux surface (LCFS), whereas in the island configuration, the sheared flow was formed around the magnetic island independent of the LCFS position, and increases in electron temperature, T_e , and density, n_e , were observed at the edge. The fine control of the magnetic island position around the LCFS shows that the poloidal flow structure, particularly the flow shear position, correlates with the position of magnetic islands. An increase in T_e and n_e is observed at the edge only when the magnetic islands are located outside the LCFS. These results indicate that the edge magnetic islands are a possible means to control the poloidal flow shear position and the edge plasma parameters.

Keywords: edge magnetic island, doppler reflectometry, poloidal flow, Heliotron J

1. Introduction

It is believed that magnetic islands influence the plasma profile and performance in magnetically confined plasmas [1–8]. The

plasma confinement is known to be affected by the magnetic island placed in the confinement region in the absence of magnetic shear [1, 2, 5, 8]. It is also demonstrated that the magnetic islands, even with magnetic shear, play an important role in core transport in a medium-sized stellarator/heliotron device, U-3M [9]. Low-order rational surfaces can also affect core confinement and transport [10–12]. For example, a low-order rational number of rotational transform can benefit electron heat transport in TJ-II [13]. It is theoretically considered that it should modify plasma flows in non-axisymmetric toroidal devices [14]. It has been reported that the magnetic islands with finite magnetic shear have a role in the internal

* Author to whom any correspondence should be addressed.



Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](https://creativecommons.org/licenses/by/4.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

transport barrier in both tokamaks and stellarator/heliotron devices [15–21] and the transition to H-mode in stellarator/heliotron devices [22–25]. These phenomena are correlated with local changes in poloidal flow and the formation of flow shear around magnetic islands. A vortex-like flow structure is observed near the O -point when the magnetic island is wide in LHD [6]. A W -shaped flow structure inside the magnetic island and a decrease in the electron density fluctuation, $\tilde{n}_e$, level have been observed around the magnetic island at W7-X [26]. A local change in the poloidal flow structure and $\tilde{n}_e$ level around the magnetic island has been observed in several tokamaks and stellarator/heliotron devices [27–29]. The poloidal flow structure is important in determining the effect of the magnetic island on the plasma profile and performance.

In a rotational transform scan experiment with magnetic islands in W7-X, the plasma performance was found to change with the radial position of the magnetic islands [30]. When 5/5 magnetic islands were located inside and near the last closed flux surface (LCFS), the plasma confinement was improved, and a notable increase in the electron temperature was observed around the magnetic island. Rotational transform scan experiments related to the H-mode have also been performed in the stellarator/heliotron device, Heliotron J [23], and the enhancement factor $H_{\text{ISS95}} (= \tau_E^{\text{exp}} / \tau_E^{\text{ISS95}}$ where τ_E^{exp} and τ_E^{ISS95} are the experimental global energy confinement time and confinement time scaling from the international stellarator database, respectively), was observed to be high when the $\iota/2\pi(a)$ values are slightly less than $n/m = 4/8, 4/7, 12/22$, where n and m are the toroidal and poloidal mode numbers, respectively. Note that n should be a multiple of 4 due to the toroidal pitch number of the helical coil. These results indicate that the magnetic islands and the rotational transform influence the plasma profile and performance, although the mechanism is not yet understood.

In this study, to investigate the influence of the magnetic island on the local plasma profile, the poloidal flow was measured in magnetic configurations with magnetic islands near the LCFS (island configuration) and those without the magnetic island (non-island configuration) plasmas in Heliotron J. A flexible rotational transform scan in Heliotron J can control the vacuum edge magnetic islands that form either the island or non-island configuration. This paper presents the experimental results on the influence of the edge magnetic islands on the poloidal flow, $u_\perp$, structure, and the local plasma profile in Heliotron J.

The remainder of this paper is organized as follows. The experimental setup is described in section 2, and the experimental results about the plasma profiles and $u_\perp$ structures are shown in section 3. Discussions about the electron density profile changes in the magnetic island are provided in section 4. The conclusion is given in section 5.

2. Experimental setup

Heliotron J is a medium-sized plasma experimental stellarator/heliotron device [31, 32]. Its main parameters are the plasma major radius, $R = 1.2$ m; averaged minor radius,

$a = 0.1$ – 0.2 m; and magnetic field strength on the axis of $B_0 \leq 1.5$ T. The coil system of Heliotron J consists of a helical coil, two types of toroidal coils, and inner and outer vertical coils. Because each coil can independently change the current ratio, Heliotron J has a high flexibility on the magnetic configuration. This allows us to control the rotational transform finely, generate vacuum magnetic islands, and scan their positions. A magnetic well ($\sim 1.5\%$) is formed in the entire plasma region.

In our experiment, the vacuum rotational transform at magnetic axis, $\iota/2\pi(0)$, was scanned in the range $0.465 \leq \iota/2\pi(0) \leq 0.599$ to form $n/m = 4/8$ magnetic islands in the plasma edge region. The magnetic shear in these configurations is weak. Plasma is generated and heated by the second harmonic X-mode ECH at 70 GHz. In this paper, all plasmas were heated by ECH injection perpendicular to the magnetic axis to avoid the current drive, with an injection power $P_{\text{ECH}} = 0.25$ MW and an injection time of 0.14 s. The plasma current was up to 0.8 kA, which may have a weak effect on the position of the magnetic islands. A neoclassical calculation for bootstrap current, which is the main component in the experiment reported here, showed that the bootstrap current density profile had a radial peak at $\rho \sim 0.5$ and the current density was very low at the peripheral region [33]. A VMEC calculation of rotational transform including the plasma current for a non-island configuration showed that the change in rotational transform around LCFS was weak at $\iota(0)/2\pi = 0.48$ and the bootstrap current of 1.5 kA [34]. Edge profile measurement in an island configuration also showed that edge plasma parameters such as T_e and n_e had a spatial structure according to a vacuum magnetic island [35]. Precise study is left in future to determine the effect of plasma current on the edge magnetic island.

The energy stored in the plasma, toroidal current, and line-averaged electron density are measured using a diamagnetic loop, Rogowski coils, and a 130 GHz microwave interferometer, respectively. The electron density, n_e , and temperature, T_e , profiles are obtained by a Thomson scattering (TS) system with temporal and spatial resolutions of $\Delta t = 20$ ms and $\Delta r \doteq 0.01$ m, respectively. The cross-section of the TS laser path is different from that of the reflectometer wave path. The averaged minor radius for T_e and n_e profiles is calculated using the KMAC code data [31, 36]. The plasma beta is so low, $\sim 0.1\%$, that we may neglect the beta effect on ρ . The spatial resolution in normalized minor radius $\Delta\rho$ is approximately 0.07, although it varies slightly because of the change in plasma shapes as the magnetic configuration changes. The TS laser trajectory crosses a magnetic island at the low magnetic field side in the island configurations. However, since the measurement point is just one inside the magnetic island, it is hard to identify the island structure in T_e and n_e profiles.

The experimental results on poloidal flow presented in this study were obtained using a Doppler reflectometer (DR). DR is a unique measurement technique that combines the microwave cut-off and the backscattering caused by the electron density fluctuation. The DR can measure the intensity of electron density fluctuation and its propagation velocity $u_\perp$ in the plasma. The $u_\perp$ measurement using a DR has been performed in both

tokamaks and stellarator/heliotron devices [26, 37, 38]. The $u_{\perp}$ obtained by DR is the sum of the phase velocity v_{ph} and the background $E \times B$ drift velocity $v_{E \times B}$, expressed as $u_{\perp} = v_{ph} + v_{E \times B}$. If $v_{ph} \ll v_{E \times B}$ as assumed in [37], then $u_{\perp}$ might be put in relation with the radial electric field as $E_r = u_{\perp} B$, where B is the absolute value of the magnetic field. However, because the $u_{\perp}$ measurement in this study was performed around the magnetic island, $u_{\perp}$ was used instead of E_r to account for the contribution of the magnetic island to the plasma flow [26].

A Q-band (33–50 GHz) DR system working in X-mode polarization was used to measure the $u_{\perp}$ structures in Heliotron J [39]. This system was installed at the corner section of the Heliotron J, where the mod B contour has a tokamak-like shape. Here, the mod B contour means the contour of the magnetic field strength in the poloidal cross-section. Two antennas for transmitting and receiving, and a focusing mirror were installed inside the vacuum vessel. The angle of the probing beam incidence was fixed at 15° based on the normal vector of the LCFS in the standard configuration. In typical ECH plasmas of Heliotron J, the DR can measure the radial position $0.85 \leq \rho \leq 0.97$ and the perpendicular wave number $1.56 \leq k_{\perp} \leq 1.66 \text{ cm}^{-1}$ at $n_e = 1.0 \times 10^{19} \text{ m}^{-3}$. Because the saturation-type I/Q detector was used in the system to amplify and saturate the input IF signal, the Doppler-shifted frequency could be obtained even if the reflected wave intensity was low. However, because the IF signal was saturated, the electron density fluctuation level, $\tilde{n}_e$, was unavailable.

To estimate the DR measurement position ρ and the perpendicular wavenumber $k_{\perp}$, the fitting curves of the electron density profiles obtained from the TS system and ray-tracing calculations with the TRAVIS code [40] were used. Since TRAVIS works on the magnetic field provided by the equilibrium code, VMEC [41], which cannot treat a magnetic island, ray-tracing calculations were performed using a similar magnetic configuration but without the magnetic island on the DR line of sight for island configurations. In this magnetic configuration, as the magnetic field strength profile on the DR line of sight was almost the same as that of the magnetic configuration with the magnetic islands, it was considered that there was no significant change in the DR measurement position. For non-island configurations, the VMEC equilibrium generated by the K MAG code output with the same coil setting is used. Here, we expect density profiles on the DR line of sight not to be significantly different from the TS profiles. Moreover, as discussed in section 3, the initial analysis of $u_{\perp}$ was performed assuming a non-flat n_e profile inside the magnetic islands. However, because a flat n_e profile in the magnetic islands is possible, we will discuss such a case related to the measurement position of the DR in section 4.

3. Experimental results

3.1. Plasma profiles with and without magnetic island

First, comparative profile measurements were conducted in an island configuration and two non-island configurations to investigate the effect of the magnetic islands on the plasma

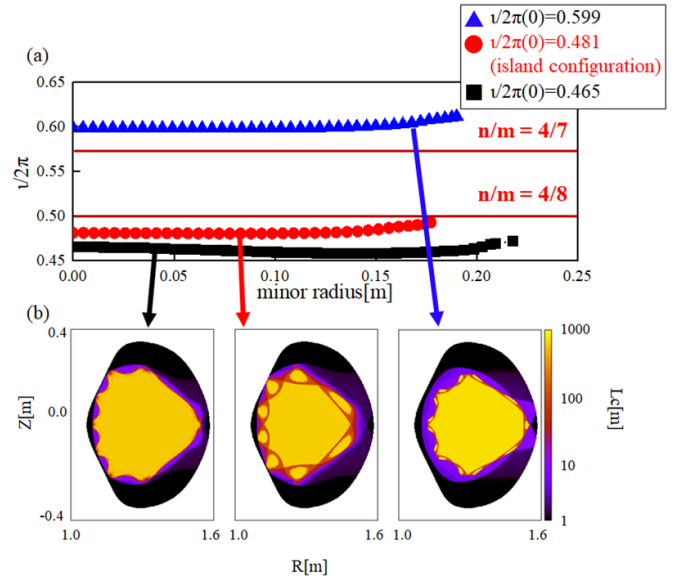


Figure 1. (a) Rotational transform profiles of the island configuration (red symbol) and non-island configurations (blue and black symbols). (b) Connection length profiles for each configuration.

profiles. The rotational transform and connection length profiles are shown in figure 1. The connection length L_c is defined as the path length of the magnetic field line from the starting point to the two termination points on the vacuum chamber surface in the clockwise and counterclockwise toroidal directions. It is numerically obtained by tracing the magnetic field lines and integrating the length using the K MAG code. The LCFS is defined as the LCFS at which the connection length is infinite. Since it should be ideally infinite within the LCFS, the calculation is terminated when the condition $L_c > 500 \text{ m}$ is satisfied [42]. Outside the LCFS, L_c is finite, and the tracing calculation is terminated when a magnetic field line touches a vacuum wall surface. In the case of the island configuration of $u/2\pi(0) = 0.481$, the magnetic islands were located outside the LCFS; therefore, the magnetic island region was excluded from the confinement region. The plasma volume is determined by the LCFS, which has the normalized minor radius, $\rho = 1$, and changes depending on whether the magnetic island is included. The magnetic field strength and plasma volume were almost similar in these three configurations at 1.24 T and 0.96 m^3 , respectively. When the magnetic island was excluded from the plasma confinement region in the island configuration, the plasma volume was 0.72 m^3 . Figure 2(a) shows an example of the time evolution of an ECH plasma discharge at the $u(0)/2\pi = 0.599$ configuration. In all configurations, the plasma current flows in the toroidal direction that makes the rotational transform increase. The time evolution of plasma current is similar, that is, it monotonically increases in time, and almost saturates at the poloidal flow measurement timing, although it fluctuates a little shot by shot with an error of $\pm 20\%$. The line-averaged electron density is controlled by adjusting gas-puff fuelling so that the density is almost constant at the poloidal flow measurement timing. The neutral

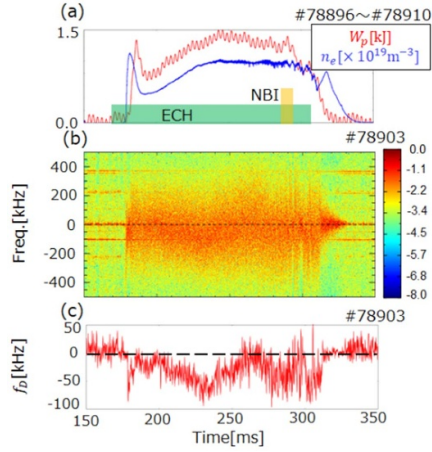


Figure 2. Time evolution of (a) discharge waveform, (b) spectrogram obtained from DR, and (c) Doppler-shifted frequency obtained from a center-of-gravity method at $\iota(0)/2\pi = 0.599$ configuration.

beam injection (NBI) is used at the end of the discharges for another experimental purpose, and we do not use the poloidal flow data during the NBI. A fluctuation of 1–10 kHz is observed in this configuration, while no such clear fluctuation is observed in the other configurations reported in this paper. The spectrogram obtained by the DR and the time evolution of the Doppler-shifted frequency estimated by the center-of-gravity method are shown in figures 2(b) and (c), respectively. The plasma profiles were measured at 250 ms and 270 ms. During this period, the plasma was in a quasi-steady state in which the line-averaged electron density $\bar{n}_e$ was approximately $1.0 \times 10^{19} \text{m}^{-3}$. However, the Doppler-shifted frequency fluctuated during this period, which may be caused by the changes in the n_e profile. As many such cases were observed in the experiments, the $u_\perp$ analysis was performed only when the n_e profile was approximately the same. In the case of the shot in figure 2, the $u_\perp$ analysis was performed at 270 ms.

The T_e and n_e profiles for these three configurations are shown in figure 3. The red symbols denote the measurement results for the island configuration, and the blue and black symbols denote those for the non-island configurations. Compared to the results for the non-island configurations, an increase in T_e and n_e was observed for $\rho = 0.5$ – 1.0 in the island configuration. The increase in T_e and n_e was more pronounced around $\rho = 0.6$ – 0.7 and 0.9 – 1.0 , with differences of 0.2 keV and $0.6 \times 10^{19} \text{m}^{-3}$, respectively. In the non-island configuration, the local maximum value in the n_e profile was located at approximately $\rho = 0.6$, whereas in the magnetic island configuration, it was located farther out, at approximately $\rho = 0.8$. In the island configuration, the T_e and n_e gradients at the edge region were more than twice as large as those in the non-island configuration. The T_e and n_e profile shapes at $\iota(0)/2\pi = 0.481$ configuration depend on whether the magnetic island is located inside the LCFS or not. If we assume that the magnetic island is located inside the LCFS, the possible maximum change in ρ is 0.1. Even for such a change, the edge T_e is higher than in the other configuration cases. The electron

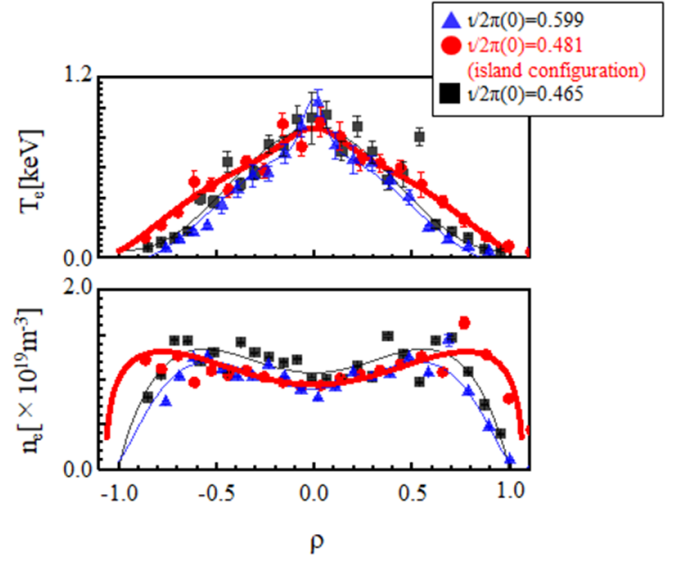


Figure 3. T_e and n_e profiles of the island configuration (red marker) and non-island configurations (blue and black marker).

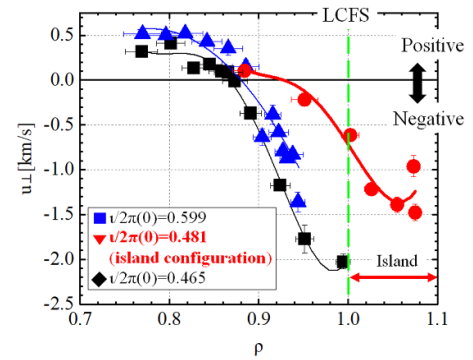


Figure 4. Radial $u_\perp$ structure of the island configuration (red marker) and non-island configurations (blue and black marker) obtained by DR.

kinetic energy estimated from the TS data, W_{pe} , within the LCFS is 0.50, 0.92, and 0.75 kJ for $\iota(0)/2\pi = 0.465$, 0.481, and 0.599 configurations, respectively, and the stored energy measured with the diamagnetic loop, W_p , is 0.97, 0.95, 0.85 kJ for $\iota(0)/2\pi = 0.465$, 0.481, and 0.599 configurations, respectively. It should be noted that the W_p data are rather scattered due to a coil ripple noise in this experiment. The finite pressure outside the LCFS might affect the total electron kinetic energy.

Figure 4 shows the radial $u_\perp$ structure obtained by the DR for the three configurations. The red circle symbol denotes the results for the island configuration, and the blue and black symbols denote those for the non-island configurations. The range of $k_\perp$ measured with the DR was 3–7 cm^{-1} . A negative $u_\perp$ corresponds to the flow in the electron diamagnetic direction. Negative $u_\perp$ with a negative shear, $du_\perp/d\rho < 0$, was observed at the peripheral region for all configurations. Here we define the peripheral region as $0.8 \leq \rho \leq 1.1$. The maximum $u_\perp$ shear, $d \ln u_\perp / d\rho$ is 34 ± 6 , 14 ± 4 , and 38 ± 1 at $u_\perp \sim 0.6 \text{ km s}^{-1}$, and $du_\perp/d\rho/a$ is -100 ± 20 , -40 ± 10 , and

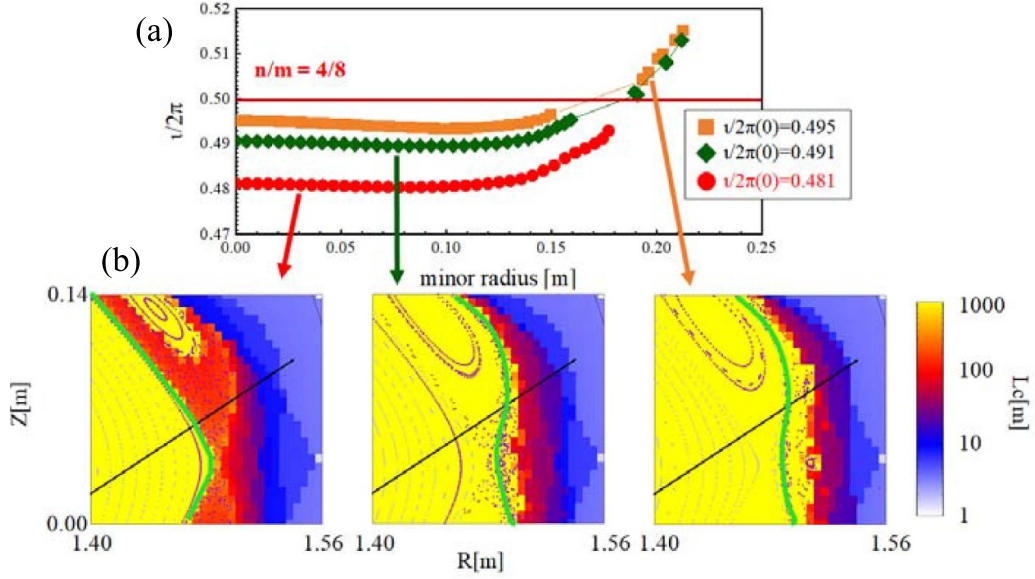


Figure 5. (a) Rotational transform profiles of the three island configurations. (b) Connection length profiles around the DR line of sight in each configuration. The black line shows the DR line of sight, and the green line shows the LCFS. The yellow color indicates values above 1000 m.

$-110 \pm 3 \text{ s}^{-1}$ for $\iota(0)/2\pi = 0.465, 0.481$, and 0.599 configurations, respectively. Although the measurement point was not enough in the island configuration to discuss the entire $u_\perp$ structure, a flat $u_\perp$ structure was observed in the positive $u_\perp$ region at approximately $\rho = 0.8$. The points where $u_\perp$ changed from positive to negative were around $\rho = 0.92$ in the island configuration and around $\rho = 0.88$ in the non-island configuration. The position where the $u_\perp$ shear is the maximum is more outwardly located in the island configuration than in the non-island configuration. These results suggest that the magnetic islands influence the local $u_\perp$ structure. The maximum value of the $u_\perp$ shear was larger for the non-island configuration than for the island configuration. These results suggest that the influence of the position of the sheared flow on the T_e and n_e profiles was more significant than that of the intensity of the sheared flow. The $u_\perp$ and its shear are small, the order of 1 km s^{-1} and 100 s^{-1} , respectively. This flow shear is very small in comparison with typical turbulence frequencies, so that an effect on transport via turbulence shearing seems weak. The W -shaped shearing flow structure inside the magnetic island, which was observed in TJ-II [28] and W7-X [26], could not be observed clearly because of an insufficient number of data points in the magnetic island region.

3.2. Effect of magnetic island position on plasma profiles

To discuss the effect of the magnetic island position on the plasma profile, comparative profile measurements were conducted by finely controlling the magnetic island position in the radial direction near the LCFS. The rotational transform profiles and the connection length profiles around the DR line of sight are shown in figures 5(a) and (b), respectively. The DR line of sight (black line) and LCFS (green line) are also shown in figure 5(b). The DR measures near the X -point of

the magnetic island. In one of the three island configurations, the $n/m = 4/8$ magnetic island was outside the LCFS, which is the same configuration as described in section 3.1 as the island configuration corresponding to $\iota(0)/2\pi = 0.481$ and referred to as the ‘0.481 configuration.’ In the other configurations, $\iota(0)/2\pi = 0.491$ and $\iota(0)/2\pi = 0.495$ (referred to as the ‘0.491 configuration’ and ‘0.495 configuration,’ respectively), the $n/m = 4/8$ magnetic islands were inside the LCFS. The plasma profiles are measured in a quasi-steady state, with $W_p \sim 1.0 \text{ kJ}$ and $\bar{n}_e \sim 1.0 \times 10^{19} \text{ m}^{-3}$, similar to the measurements discussed in section 3.1.

The T_e and n_e profiles for the three configurations are shown in figure 6. The red symbol denotes the measurement results for the 0.481 configuration, and the green and orange symbols denote those for the 0.491 and 0.495 configurations. Note that the density obtained from the fitting curve was not zero at $\rho = 1.0$ in the 0.481 configuration with the magnetic island outside the LCFS because the magnetic island was located outside the LCFS at $\rho = 1.0$ – 1.1 . The magnetic island was located at $\rho = 0.83$ – 0.95 and 0.77 – 0.92 in the 0.491 and 0.495 configurations, respectively. Similar to the results in section 3.1, in the 0.481 configuration, compared to the 0.491 and 0.495 configurations, an increase in T_e and n_e was observed at $\rho = 0.5$ – 1.0 . The large gradient region of the n_e profile was radially shifted outside the plasma, and the T_e and n_e gradients at the edge region were more than twice as large as those in the 0.491 and 0.495 configurations. The electron kinetic energy, W_{pe} , within the LCFS is $0.92, 0.67, 0.68 \text{ kJ}$ for $\iota(0)/2\pi = 0.481, 0.491$, and 0.495 configurations, respectively, and the stored energy measured with the diamagnetic loop, W_p , is $0.85, 0.84, 0.99 \text{ kJ}$ for $\iota(0)/2\pi = 0.481, 0.491$ and 0.495 configurations, respectively. It should be noted that W_p data are rather scattered due to a coil ripple noise in this experiment, similar to the experiment in section 3.1. The finite

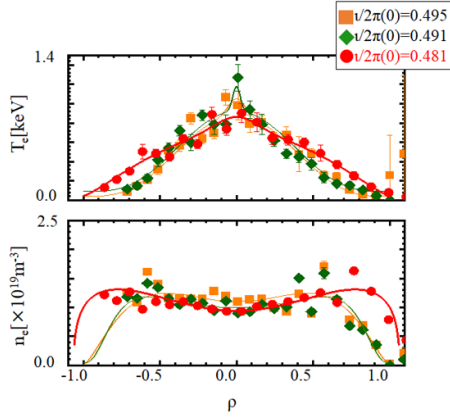


Figure 6. T_e and n_e profiles of the island configurations with the magnetic island outside the LCFS (red marker) and inside the LCFS (green and orange marker).

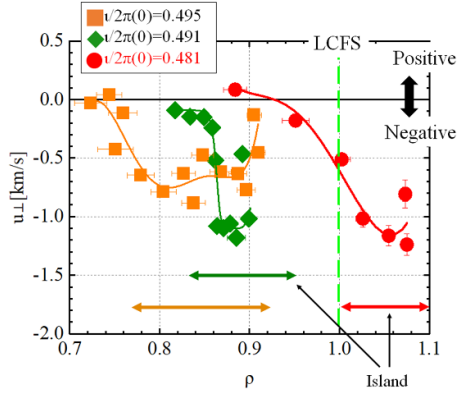


Figure 7. Radial $u_{\perp}$ structures of the island configurations with the magnetic island outside the LCFS (red marker) and inside the LCFS (green and orange marker) obtained by DR. The arrows show the magnetic island in the corresponding magnetic configuration.

pressure outside the LCFS might also affect the total electron kinetic energy.

Figure 7 shows the radial $u_{\perp}$ structure obtained by the DR for the three configurations. The range of $k_{\perp}$ measured with the DR was 3–8 cm^{-1} . Negative $u_{\perp}$ and negative $u_{\perp}$ shears were observed in the peripheral regions for all the configurations. The $u_{\perp}$ shear was observed around the magnetic island, regardless of the LCFS position. The maximum $u_{\perp}$ is similar for all configurations, $u_{\perp} = -1.2$, -1.1 and -0.8 km s^{-1} for $u(0)/2\pi = 0.481$, 0.491 , and 0.495 configurations, respectively. The maximum $u_{\perp}$ shear, $d \ln u_{\perp} / d\rho$ is 14 ± 4 , 40 ± 10 , and 13 ± 3 at $u_{\perp} \sim 0.6$ km s^{-1} , and $du_{\perp} / d\rho/a$ is -40 ± 10 , -110 ± 30 , and -30 ± 8 s^{-1} for $u(0)/2\pi = 0.481$, 0.491 and 0.495 configurations, respectively. Therefore, tuning the position of the magnetic island could be a unique technique to control the $u_{\perp}$ shear position. The largest $u_{\perp}$ shear was observed in the 0.491 configuration; however, there was no significant change in the T_e and n_e profiles compared to those in the 0.495 configuration, which exhibited a smaller $u_{\perp}$ shear. Furthermore, comparing the T_e and n_e profiles in the 0.481 and 0.491 configurations, which had similar $u_{\perp}$ shear intensities,

showed that the T_e and n_e profiles in the 0.481 configuration changed significantly, suggesting that the influence of the position of $u_{\perp}$ shear on the T_e and n_e profiles was more significant than that of its intensity.

4. Discussion

The initial analysis of $u_{\perp}$ was performed assuming a non-flat n_e profile inside the magnetic islands in section 3. In this section, we evaluate and discuss the errors in the radial position $\Delta\rho$ and perpendicular wavenumber $\Delta k_{\perp}$ under the assumption of a flat n_e profile in the magnetic islands.

The $\Delta\rho$ values evaluated from ray-tracing calculations using flat n_e profiles were 0.135, 0.054, and 0.093 for the island configurations of $u(0)/2\pi = 0.481$, $u(0)/2\pi = 0.491$, and $u(0)/2\pi = 0.495$, respectively. The $u_{\perp}$ shear position shifted towards the magnetic island boundary, and the $u_{\perp}$ shear was formed near the magnetic boundary. This result suggests that the $u_{\perp}$ structure is related to the magnetic island position, even if the n_e profiles caused by the magnetic islands are considered. In all configurations, the measurement points were concentrated near the magnetic island boundary under the assumption of flat n_e profiles. This is probably why the W-shaped shearing flow structure observed at W7-X was not observed in these cases.

The maximum values of $\Delta k_{\perp}$ were 1.097, 0.415, and 0.555 cm^{-1} for the island configurations of $u(0)/2\pi = 0.481$, $u(0)/2\pi = 0.491$, and $u(0)/2\pi = 0.495$, respectively. The relative errors in $\Delta k_{\perp}$ were up to 10%. In these $k_{\perp}$ values, because the poloidal wavenumber, $k_{\perp}\rho_i$, was approximately 1.0, it is believed that the DR measures the ITG/TEM-driven turbulence [43–45].

The $u_{\perp}$ structure measurements described in this study were based on the ray-tracing calculations using the TRAVIS code. Because the equilibrium code VMEC cannot treat a magnetic island, ray-tracing calculations were performed using the magnetic configuration in which the LCFS shape and magnetic field strength profiles are nearly identical, but no magnetic islands exist. Therefore, the magnetic island structure could not be accurately considered, particularly when estimating $k_{\perp}$. The injected microwave beam crosses the magnetic island near the X-point. Since the injected microwave beam in the DR system has a beam width of about 30 mm, the detected signal may include the poloidal flow structure inside the magnetic island. Thus, for example, if we assume the presence of a nested magnetic surface inside the magnetic island, the poloidal flow may be inverted before and after crossing the center of the magnetic island. However, the measurement result described in this study, which shows that the flow direction is constant inside the magnetic island, is consistent with the flow measurement results in W7-X [26]. Detailed measurements inside the magnetic islands are an issue for the future.

While the rotational transform in vacuum is estimated using the field line tracing calculation code, KMAG, it is not experimentally available due to the lack of related diagnostics. We set up magnetic configurations by carefully choosing each coil

current based on the field line tracing calculation. Previous experiments, such as the magnetic field scan for ECH/ECCD [46] and the fluctuation measurement inside the edge magnetic islands [35] show that the magnetic field is set up in the experiment well as the calculation. However, the effect of non-inductive current and finite pressure should be further studied for more accurate analysis, which may affect the magnetic field structure.

5. Conclusion

Comparative profile measurements were performed for magnetic configurations with and without vacuum magnetic islands at the plasma edge in Heliotron J to investigate the influence of magnetic islands on the local plasma profile. Negative $u_{\perp}$ (electron diamagnetic direction flow) and negative $u_{\perp}$ shear were observed in the peripheral region in ECH plasmas for all magnetic configurations considered. The position where the sign of $u_{\perp}$ changes and the $u_{\perp}$ shear is the maximum was shifted more towards the island position in the island configuration than the corresponding positions of the $u_{\perp}$ structure in the non-island configurations. An increase in T_e and n_e was observed for $\rho = 0.5$ – 1.0 in the island configuration.

To investigate the effect of the magnetic island position on the plasma profile, comparative profile measurements were conducted by finely controlling the magnetic island position in the radial direction around the LCFS. Negative $u_{\perp}$ and negative $u_{\perp}$ shears were observed in the peripheral region in ECH plasmas for all the magnetic configurations. $u_{\perp}$ shear was observed inside the magnetic island regardless of the LCFS position. Compared to the values for the island configurations with the magnetic island located inside the LCFS, an increase in T_e and n_e was observed for $\rho = 0.5$ – 1.0 in the island configuration with the magnetic island located outside the LCFS. These results indicate that the magnetic island outside the LCFS affects the T_e and n_e profiles for middle-range radii ($\rho = 0.5$ – 1.0).

These results indicate that the edge magnetic islands are a possible means to control the poloidal flow shear position and that the island location affects the core transport. Although the effect of magnetic islands on shear flow was studied experimentally and theoretically [47–49], we need further investigation of the edge magnetic islands to understand the role in confinement and transport. For more detailed measurements of the $\tilde{n}_e$ level and $u_{\perp}$ inside the magnetic islands, we plan to install a frequency comb DR system that can operate at multiple frequencies. Measurements and analysis inside the magnetic island are a work in progress.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

The authors thank the Heliotron J staff for conducting the plasma experiments. This study was carried out with the support of the NIFS Collaborative Research Program (NIFS10KUHL030, NIFS18KUHL082, and NIFS18KUHL086) and ‘PLADyS’, JSPS Core-to-Core Program, A. Advanced Research Networks, Grant-in-Aid for Scientific Research, MEXT (Kiban (A) 22H00117), JST SPRING, Grant Number JPMJSP2110, DAAD-Kyoto Univ. partnership program.

References

- [1] Erckmann V, Janzen G, Kasperek W, Müller G, Schüller P G, Schwörer K, Thumm M and Wilhelm R 1985 *Fusion Technol.* **7** 275
- [2] Renner H et al 1989 *Plasma Phys. Control. Fusion* **31** 1579
- [3] Lopes-Cardozo N J et al 1997 *Plasma Phys. Control. Fusion* **39** B303
- [4] Shaing K C 2001 *Phys. Rev. Lett.* **87** 245003
- [5] Brakel R (the W7-AS Team) 2002 *Nucl. Fusion* **42** 903
- [6] Ida K et al 2001 *Phys. Rev. Lett.* **88** 015002
- [7] Harris J H 2004 *Plasma Phys. Control. Fusion* **46** B77
- [8] Ascasíbar E et al 2008 *Plasma Fusion Res.* **3** S1004
- [9] Dreval M B et al 2018 *Plasma Phys. Control. Fusion* **60** 05400
- [10] Castejón F, Fujisawa A, Ida K, Talmadge J N, Estrada T, López-Bruna D, Hidalgo C, Krupnik L and Melnikov A 2005 *Plasma Phys. Control. Fusion* **47** B53
- [11] Yakovlev M, Inagaki S, Shimoizuma T, Kubo S, Morisaki T, Nagayama Y, Kawahata K and Komori A 2005 *Phys. Plasmas* **12** 092506
- [12] Ph. van Milligen B, Voldiner I, Carreras B A, García L and Ochando M A 2023 *Nucl. Fusion* **63** 016027
- [13] López-Bruna D, Estrada T, Medina F, de la Luna E, Romero J A, Ascasíbar E, Castejón F and Vargas V I 2008 *Europhys. Lett.* **82** 65002
- [14] Shaing K C, Ida K and Sabbagh S A 2015 *Nucl. Fusion* **55** 125001
- [15] Joffrin E et al 2003 *Nucl. Fusion* **43** 1167
- [16] Austin M E et al 2006 *Phys. Plasmas* **13** 082502
- [17] Estrada T et al 2004 *Plasma Phys. Control. Fusion* **46** 277
- [18] Castejón F, López-Bruna D, Estrada T, Ascasíbar E, Zurro B and Baciero A 2004 *Nucl. Fusion* **44** 593
- [19] Estrada T et al 2007 *Nucl. Fusion* **47** 305
- [20] Kenmochi N et al 2017 *Plasma Phys. Control. Fusion* **59** 055013
- [21] Narushima Y et al 2011 *Nucl. Fusion* **51** 083030
- [22] Hirsch M et al 2008 *Plasma Phys. Control. Fusion* **50** 053001
- [23] Sano F et al 2005 *Nucl. Fusion* **45** 1557
- [24] López-Bruna D et al 2011 *Plasma Phys. Control. Fusion* **53** 124022
- [25] Estrada T et al 2009 *Plasma Phys. Control. Fusion* **51** 124015
- [26] Estrada T et al 2021 *Nucl. Fusion* **61** 096011
- [27] Zhao K J et al 2015 *Nucl. Fusion* **55** 073022
- [28] Estrada T, Ascasíbar E, Blanco E, Cappa A, Hidalgo C, Ida K, López-Fraguas A and van Milligen B P 2016 *Nucl. Fusion* **56** 026011
- [29] Bardóczi L, Rhodes T, Carter T, Bañón Navarro A, Peebles W, Jenko F and McKee G 2016 *Phys. Rev. Lett.* **116** 215001
- [30] Andreeva T et al 2022 *Nucl. Fusion* **62** 026032
- [31] Wakatani M et al 2000 *Nucl. Fusion* **40** 569
- [32] Obiki T et al 2001 *Nucl. Fusion* **41** 833

- [33] Motojima G *et al* 2006 *J. Korean Phys. Soc.* **49** S87
- [34] Motojima G *et al* 2008 *Plasma Fusion Res.* **3** S1067
- [35] Miyashita A *et al* 2024 *Plasma Phys. Control. Fusion* **66** 075008
- [36] Nakamura Y *et al* 1993 *J. Plasma Fusion Res.* **69** 41
- [37] Hirsch M, Holzhauer E, Baldzuhn J, Kurzan B and Scott B 2001 *Plasma Phys. Control. Fusion* **43** 1641
- [38] Conway G D, Schirmer J, Klengel S, Suttrop W and Holzhauer E (the ASDEX Upgrade Team) 2004 *Plasma Phys. Control. Fusion* **46** 951
- [39] Kondo Y *et al* 2022 *JINST* **17** C05023
- [40] Marushchenko N B, Turkin Y and Maassberg H 2014 *Comput. Phys. Commun.* **185** 165
- [41] Hirshman S P and Whitson J C 1983 *Phys. Fluids* **26** 3553
- [42] Matoike R *et al* 2021 *Plasma Phys. Control. Fusion* **63** 115002
- [43] Ishizawa A, Kishimoto Y, Watanabe T-H, Sugama H, Tanaka K, Satake S, Kobayashi S, Nagasaki K and Nakamura Y 2017 *Nucl. Fusion* **57** 066010
- [44] Carralero D *et al* 2022 *Plasma Phys. Control. Fusion* **64** 044006
- [45] Weir G M, Faber B J, Likin K M, Talmadge J N, Anderson D T and Anderson F S B 2015 *Phys. Plasmas* **22** 056107
- [46] Nagasaki K *et al* 2010 *Nucl. Fusion* **50** 025003
- [47] Perseo V, Effenberg F, Gradic D, König R, Ford O P, Reimold F, Ennis D A, Schmitz O and Sunn Pedersen T 2019 *Nucl. Fusion* **59** 124003
- [48] Mahapatra J, Bokshi A, Ganesh R and Sen A 2021 *Phys. Plasmas* **28** 072103
- [49] Garcia L, Carreras B A, Lynch V E, Pedrosa M A and Hidalgo C 2001 *Phys. Plasmas* **8** 4111–9