Abstract. Heliotron J is a flexible concept exploration facility for the helical-axis heliotron concept. One of the major objectives of the Heliotron J study is to experimentally confirm the effects of the new ideas introduced into this concept to improve the plasma performance. As a part of such experiments, the bumpiness ($\varepsilon_b$) and rotational transform ($\iota \pi/2$) control studies have been performed. The $\varepsilon_b$-control experiments have revealed the $\varepsilon_b$-dependence of the fast ion confinement is qualitatively consistent with the drift optimization viewpoint. However, the bulk plasma confinement studies suggest that the low effective helical ripple configuration seems to be preferable for the confinement improvement for ECH-only plasma. The $\iota \pi/2$-control experiments for ECH-only and/or ECH+NBI plasmas have revealed the existence of windows in the vacuum $\iota(a)/2\pi$ for the high quality H-mode. In NBI-only plasmas, it was found out that the transition in NBI-only plasma occurs at a certain toroidal current, which depends on the vacuum $\iota(a)/2\pi$ and the bumpiness but is independent of $P_{\text{inj}}$. This suggests the relation of the onset of the transition to the modification of the rotational transform caused by the plasma current.

Keywords: Enter Helical-Axis Heliotron, Drift Optimization, Rotational Transform, Transition to Improved Confinement Mode, Non-Inductive Current

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INTRODUCTION

In stellarator/heliotron devices, the suppression of trapped particle loss in the rare collision region is one of the key issues, since particles trapped in helical ripple have net radial drift and increase the ripple-loss in the low-collision regime. In order to reduce such ripple-loss, the advanced helical concepts try to improve particle orbit through recovering of symmetry (quasi-symmetry concept) or tailoring the field
harmonics (quasi-omnigeneous concept). The helical-axis heliotron [1] is one of the latter concept by using continually wound helical coil(s) instead of modular coils.

The Heliotron J device with an L/M = 1/4 helical coil ($<R_0>$ = 1.2 m, $B_0 \leq 1.5$ T) [2, 3] is a flexible concept exploration facility for the helical-axis heliotron concept, where the bumpiness, $\varepsilon_b (= B_{40}/B_{00})$, is introduced as a third measure to the control neoclassical transport in addition to the other major field harmonics in Boozer coordinate system [4], helicity ($\varepsilon_h = B_{14}/B_{00}$) and toroidicity ($\varepsilon_t = B_{10}/B_{00}$). Here, $B_{mn}$ is the Fourier component with the poloidal and toroidal mode numbers of $m$ and $n$, respectively. From the drift optimization viewpoint, the bumpiness control has an important role in this concept. Although this configuration is a low shear one, the magnetic well is realized for the whole confinement area to control MHD activities. One of the objectives of the Heliotron J studies is to extend the understanding of the related role of configuration parameters such as rotational transport and bumpiness in transport reduction and/or toroidal current control of the omnigeneous optimization scenario of a helical-axis heliotron. The configuration control studies are essential parts of the Heliotron J experiment. This paper reviews recent investigations into the effects of the configuration control on the plasma performance in Heliotron J.

**HELIOTRON J DEVICE**

The details of the Heliotron J device is described in [2, 3]. The confinement configuration is composed of four “straight” sections and four “corner” sections; in the corner section, the tokamak-like VB is formed with a local maximum of the poloidally averaged $|B|$ distributed in the toroidal direction, while in the straight section the local toroidal mirror with small VB is formed between the corner sections. Figure 1 shows an example of the magnetic-surface shape at $\rho = 0.9$, where the gray-scale shading

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**FIGURE 1.** Top view of the Heliotron J device showing arrangements of heating equipments and several diagnostics. In the case of the “normal” operation, the direction of the magnetic field is clockwise, where the toroidal current $I_p$ flowing in the counter-clockwise direction enhances the poloidal magnetic field strength. (“additive current”)
indicates contours of constant $|B|$, the nested magnetic surfaces (at a straight- and corner-section) for the standard configuration. The radial dependences of the field strength on the equatorial plane for each section are also plotted. Figure 2 schematically shows the top view of Heliotron J with the main heating and diagnostic systems. The initial plasma is produced by using the 70 GHz second harmonic X-mode ECH launched from a top port located at one of the straight sections. The hydrogen neutral beam (30 keV, 0.7 MW/beam-line) is injected using two tangential beam-lines facing each other (BL1 and BL2). Selecting one of the two beam-lines or changing the direction of the confinement field, Co- or CTR-injection is performed. ICRF heating (19-23 MHz, 0.4 MW/antenna) is performed by using two sets of antenna installed at a corner section.

The field configuration is controlled using the five sets of the external coils, the helical coil (HV), two individual sets of the toroidal coils (TA and TB) and two sets of the vertical coils (AV and IV). The major part of the configuration is determined by the helical and toroidal coil currents. The bumpiness is mainly controlled by changing the coil current ratio of TA and TB coils, $I_{TA}$ and $I_{TB}$, respectively. Trimming of the vertical coil currents, it is possible to control $\varepsilon_h$ within tolerable changes of $\varepsilon_h$ and $\varepsilon_t$.

**FIGURE 2.** Example of the magnetic-surface shape (at $\rho = 0.9$), the nested magnetic surfaces and the mod-B surfaces (at a straight- and corner-section) for the standard configuration. The radial dependences of the field strength on the equatorial plane for each section (right bottom).
\( \tau(a)/2\pi |_{\text{vac}} \) the plasma volume and the averaged major radius \([5]\). On the other hand, \( \tau(r)/2\pi |_{\text{vac}} \) can be controlled by mainly changing the current ratio of the helical coil to the toroidal coils. Here, it is possible to minimize the change of the bumpiness by keeping the current ratio of \( I_{TA}/I_{TB} \) to be constant.

**BUMPINESS CONTROL EFFECTS**

The study of \( \varepsilon_b \)-control effects on the bulk plasma confinement and behavior of fast-ions were performed for ECH plasmas \([5, 6]\) selecting three different \( \varepsilon_b \) (\( \approx 0.01 \) (low-\( \varepsilon_b \)), 0.06 (medium-\( \varepsilon_b \)) and 0.15 (high-\( \varepsilon_b \)) at \( \rho = 2/3 \)) configurations with the same vacuum rotational transform at the last closed flux surface (LCFS), \( \tau(a)/2\pi |_{\text{vac}} \) \( \approx 0.56 \). Here, “vacuum” means no plasma effects on the magnetic field configuration.

As for the \( \varepsilon_b \)-effect on the fast-ion behavior, which was examined by superimposing a tangential-NBI or ICRF pulse on ECH target plasmas, the higher \( \varepsilon_b \) configuration is preferable for the confinement of low- and high-pitch angle fast-ions. These observations are qualitatively consistent with the drift optimization viewpoint.

On the other hand, as for the global energy confinement, \( \tau_{E,\text{exp}} \), the dependence is not so simple and we have tried to understand the observations based on the discussion of the “effective helical ripple”, \( \varepsilon_{\text{eff}} \), which is proposed as a measure of the level of ripple transport \([7]\). In the three configurations, the numerical sequence of \( \varepsilon_{\text{eff}} \) (evaluated with DCOM code \([8]\) calculations) is not the same as that of \( \varepsilon_b \); i.e., the values of \( \varepsilon_{\text{eff}} \) (\( \rho = 2/3 \)) for the low-, medium- and high-\( \varepsilon_b \) configurations are 0.26, 0.13 and 0.22, respectively (See Fig. 3). The preliminary analysis suggests that the lower-\( \varepsilon_{\text{eff}} \) configuration (i.e. the medium-\( \varepsilon_b \) configuration) seems to be preferable, at least for the global confinement for ECH-only plasma.

![FIGURE 3. Radial dependence of \( \varepsilon_{\text{eff}} \) for the three configurations (DCOM-calculation)](image-url)
These experiments have recently expanded to NBI-only plasmas [9]. The preliminary energy balance analysis indicates that the poor confinement in the low-$\varepsilon_b$ configuration (higher $\varepsilon_{\text{eff}}$) is observed similarly as in the ECH-only plasma but the difference of $\tau_E^{\text{exp}}$ in high- and medium-$\varepsilon_b$ configurations is not so clear compared to that observed for ECH-only plasma (See Fig. 4). These observations suggest the possibility of different $\varepsilon_b$(or $\varepsilon_{\text{eff}}$)-dependence of the global energy confinement between ECH-only and NBI-only plasmas, perhaps relating to the confinement of high energy ions.

In helical devices, the direction of bootstrap current due to the helical-ripple is opposite to that of the bootstrap current due to the toroidal ripple. The bumpiness can change the balance of these currents. The $\varepsilon_b$-dependence of the bootstrap current was examined in Heliotron J and the result is consistent with this prediction [10].

**EFFECTS OF ROTATIONAL TRANSFORM CONTROL**

As experimentally demonstrated in W7-AS [11] and Heliotron J [12], the value of the edge rotational transform $\iota(a)/2\pi$ is essential for the good plasma confinement in a low magnetic-shear device, including L-H transition and MHD activities. Recently the effects of low-order rational surfaces have been discussed from the viewpoint of the appearance of external/internal transport barriers or enhanced confinement modes in helical devices [13, 14]. In addition, $\iota(a)/2\pi$ is closely related with the field topology for so-called a “built-in” divertor in heliotron/stellarator systems.

The first step in the study of rotational transform effects on the global confinement in Heliotron J were performed by for ECH-only plasma [15]. Since the discovery of the transition phenomena to the improved confinement mode (H-mode) in Heliotron J, the accessibility condition to the transition and the configuration effect on the
improvement factor have been investigated experimentally for several configurations labeled by the vacuum edge rotational transform $\tau(a)/2\pi_{\text{vac}}$ [12].

ECH-only and ECH+NBI experiments indicate the existence of $\tau(a)/2\pi_{\text{vac}}$-windows for the high quality H-mode ($\tau_{\text{E exp}}/(\tau_{\text{ISS04}}^{\text{vac}}) > 1.5$) close to the low-mode rational numbers of $\tau(a)/2\pi_{\text{vac}}$. Here, $\tau_{\text{ISS04}}^{\text{vac}}$ is the global energy confinement time by the international (inter-machine) stellarator scaling [16, 17]. In this experiment, the power and density thresholds for the transition were also observed to depend on the configuration, but the systematic dependences between them have not been fully understood. It might have to consider the influence of the topology (“shape”) of the magnetic surfaces on the poloidal viscous damping rate, which is considered to influence the plasma poloidal rotation [18]. The poloidal viscous damping rate is also considered to depend on the existence of the rational surface [19].

Even for non-Ohmic heating plasmas in a stellarator/heliotron device, non-inductive plasma current can be driven by the pressure-gradient (bootstrap current), electron cyclotron current drive (ECCD) and neutral beam current drive (NBCD). The modification of $\tau(r)/2\pi$ due to such non-inductive currents can create new rationals in the core region. In the edge region, the change of $\tau(r)/2\pi$ can modify the divertor plasma distribution. In the Heliotron J experiments, it has been experimentally confirmed that the bootstrap current and ECCD current can be controlled by the bumpiness tailoring [10, 20]. The tangential NBI system [21] can also control the direction and intensity of NBCD current. Experimentally, the effects of the plasma current and its radial profile on the edge field topology and divertor plasma distribution have been investigated in Heliotron J from viewpoints of divertor control and bulk plasma confinement [22]. An experimental detection of the rotational transform modification during a discharge has been tried in Heliotron J by using the sensitivity of MHD activities on the rational surfaces [23].

**Plasma Pressure/Current Effects on the Field Configuration**

A free-boundary three-dimensional equilibrium calculation is a useful tool to obtain a prospect of the field deformation caused by plasma pressure and/or current, and, of course, to understand the experimental observations. Figures 5 and 6 show an example of such calculation obtained by using HINT2 code [24] for the STD configuration. Here, we assume rather peaked plasma pressure- and current-profiles: $\beta(s) = \beta_0 \times (1-s)^2$ with $\beta_0 = 0.5\%$, $j_p(s) = j_0 \times (1-s)^2$, where $s$ denotes toroidal flux corresponding to the square of the normalized minor radius ($= \rho^2$). In the figures, “vacuum” means no plasma condition (i.e. $\beta = 0$ %, the net current $I_p = 0$ kA). The case of “additive current” direction (i.e. the current increases $\tau(a)/2\pi_{\text{vac}}$) is indicated as “ad. *kA” and the opposite case is “sub. *kA” in the figure. Figure 6 shows the effects on the rotational transform obtained by the same calculations for Fig. 5. The effects of the plasma pressure on the edge field topology and $\tau(a)/2\pi$ are little although small islands become to appear in the core region. On the other hand, the plasma current can modify not only the rotational transform but also the “shape” of the last closed flux surface. Moreover, as discussed in [22], even for the same net-current value, the difference in current profile $j(s)$ has important effects on the modification.
It should be noted that the effects are not symmetry to the total current direction. The effect of the plasma pressure can be somewhat compensated by the subtractive current. Since the low-mode resonance has an important role on the field topology, the “proximity” to the rational number is important. In the standard configuration, the vacuum rotational transform at the edge is about 0.56 (i.e. less than the rational number 4/7) in the standard configuration. Therefore the edge rotational transform becomes close to the rational number of 4/7 by the additive current, but the subtractive current increases the distance from the resonance condition.

EFFECTS OF PLASMA CURRENT ON THE ONSET OF TRANSITION IN NBI-ONLY PLASMA

To study the effects of the non-inductive current on the transition, we have performed ECH and/or NBI experiments. In this report, we focus on the NBI-only plasmas to simplify the situation and to take advantage of current controllability of NBCD in the density region higher than the critical (lower-limit) density for the transition, which were observed in the previous ECH/NBI experiments [12].

Figure 7 shows an example of NBI-only plasma. During a discharge with a constant heating power and gas-puffing rate, a drop of Hα intensity and increases of the stored energy and/or the plasma density can be observed, indicating the onset of transition to an improved confinement mode. The changes in the radial profile of SX-intensity and the ion saturation current in the scrape-off region (not shown in the figure) indicate that this phenomenon is an edge relating event. It is interesting to note that there is some time delay between the start of NBI and the drop of the Hα intensity. This delay time, Δt, is longer than the “build-up time” of NBI-only plasma.

Firstly, the Co- and CTR-NBI plasmas were compared in the same vacuum configuration with \( t(a)/2\pi|_{\text{vac}} \approx 0.54 \) [25]. Here, “Co-”means the NBCD current increases the vacuum rotational transform (“additive” current). For this comparison, the
same beam line was used and Co- and CTR-NBI were selected by changing the field direction. Although the evaluation of the absorption efficiency of CTR-injection NBI is an on-going task, almost the same values of the stored energy and the density were obtained for the both discharges. The direction of the plasma current for the both cases was opposite, consistent with the NBCD scenario, but the intensity is not the same. Since the bootstrap current I_{BS} always flows to the additive direction in this configuration, NBCD current in the CTR-NBI case is somewhat compensated by I_{BS}. This cancellation effect usually becomes large in higher stored energy (or higher density) range due to the increase of I_{BS}.

The transition was observed in the Co-NBI case, but no clear change in Hα intensity or the growth rate of the stored energy were observed in the CTR-NBI case. The transition has not been observed for CTR NBI-only plasmas in the range of P_{ inj} \sim 0.25-0.6 MW for all configurations examined with different \frac{\iota(a)}{2\pi|{\nu}|_{vac} or \varepsilon_b.

The P_{ inj}-scan experiment in two vacuum configurations with \varepsilon_b = 0.06 (medium \varepsilon_b) and 0.15 (high \varepsilon_b) shown that the delay times between the start of NBI and the drop of the Hα intensity are almost the same and depend on the injected power; \Delta t \sim 20 ms at P_{ inj} \sim 0.6 MW, and it elongates to \Delta t \sim 40 ms at \sim 0.3 MW. Since the density was controlled in the range of 1.5-2.0\times10^{19} m^{-3} (higher than the empirical critical (lower-limit) density for the transition) in this experiment, the absorption efficiency of NBI is considered to be almost the same (~ 30%) for the both configurations. The similar power-scan experiment was also performed for the vacuum configuration with \varepsilon_b = 0.01 (low \varepsilon_b), but no clear transition event was observed for the low-\varepsilon_b configuration. It should be noted that for ECH+NBI plasmas, the transition was rather easily observed in the previous experiment although the improvement factor was low compared to that for the medium-\varepsilon_b case [5].

Since the plasma current modifies the field configuration, the value of the plasma current at the onset timing of the transition event was investigated for different \varepsilon_b-configurations with the same \frac{\iota(a)}{2\pi|{\nu}|_{vac}. It was clearly shown that the transition
happens when the toroidal current reaches a critical $I_p$ value which depends on the configuration but is independent of $P_{\text{inj}}$: $0.7 \pm 0.1 \text{kA}$ for the medium-$\varepsilon_b$ and $1.3 \pm 0.2 \text{kA}$ for the high-$\varepsilon_b$ configurations, respectively.

In order to investigate the effect of $\iota(a)/2\pi|_{\text{vac}}$ on the critical current discussed in the previous subsection, the $\iota(a)/2\pi|_{\text{vac}}$-scan experiment was performed. Figure 8 shows the toroidal current at the onset timing of the transition as a function of $\iota(a)/2\pi|_{\text{vac}}$. The density and NBI power range were $1.5-2.0 \times 10^{19} \text{ m}^{-3}$ and $P_{\text{inj}} \sim 0.25-0.6 \text{ MW}$, respectively. As shown in the figure, the critical current exists for all configurations and its value decreases as increase of $\iota(a)/2\pi|_{\text{vac}}$.

Although we tried Co- and CTR-injection experiments in the same configurations, no transition has been observed in the CTR-injection case, where the total current becomes lower than that in Co- injection case and the current profile would be different. We should also take care of the effect of different momentum input direction from NBI, since the rotation can influence the transition as discussed in tokamaks.

**SUMMARY**

An overview of recent experimental investigations into the effects of the configuration control on the plasma performance in Heliotron J was reported.

The bumpiness control study has revealed that

1. The fast ion confinement is better in the high bumpiness configuration, which is qualitatively consistent with the drift optimization viewpoint.
2. The low $\varepsilon_{\text{eff}}$ configuration seems to be preferable for the global confinement.
3. The observed $\varepsilon_b$-dependence of bootstrap current is qualitatively consistent with the theoretical prediction based on the neo-classical transport.

The rotational transform control study has revealed that

1. ECH and ECH+NBI experiments indicate the existence of $\iota(a)/2\pi|_{\text{vac}}$-windows for the high quality H-mode close to the low-mode rationals.
In NBI-only plasmas, transition was observed for medium- or high-ε_b, but not for low-ε_b for Co-NBI.

Under the experimental condition, no transition has been observed in the CTR-NBI-only plasmas.

The transition in NBI-only plasma occurs at a certain toroidal current, which depends on the vacuum configuration but is independent of P_inj.

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