Effects of Magnetic Islands on Poloidal Flow in TU-Heliac*)

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The Tohoku University Heliac (TU-Heliac) surveyed the effects of island width on poloidal plasma flow. We determine that poloidal flow is driven externally by hot cathode biasing and an $m = 3$ magnetic island was produced by two pairs of external perturbation field coils. The electrode current required for poloidal flow at the plasma periphery jumping point increases with island width expansion and shows weak dependency at the core region of the plasma. These dependencies suggest that the magnetic island located at the plasma periphery affects poloidal flow as a drag term.

Keywords: stellarator, heliac, magnetic island, perturbation field, electrode bias

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1. Introduction

To achieve a nuclear fusion reactor, it is important to study the effect of island on plasma flow at the plasma periphery because this process is expected to lead to an advanced control method at the plasma edge [1–4]. It is particularly important to understand the effect of island on plasma peripheries in order to control edge-localized modes of ITER [5]. A theoretical work on the transport processes in the vicinity of a magnetic island in tokamaks is in progress [6].

The Tohoku University Heliac (TU-Heliac) has the following advantages for researching island effects on plasma flow: (1) The rotational transform can be changed by selecting the ratio of coil current; (2) island formation can be controlled by external perturbation field coils; and (3) the radial electric fields and plasma flow can be controlled externally by electrode biasing. In addition, it is possible to obtain a transition to an improved mode by electrode biasing using a hot cathode composed of LaB_6. The driving force for poloidal plasma rotation $\boldsymbol{J} \times \boldsymbol{B}$ was externally controlled, and the poloidal viscosity was successfully estimated from the external driving force [7, 8]. Electrode biasing has advantages of form a radial electric field and driving the flow in plasma surrounded by magnetic islands, which enables research of the island effect on the plasma flow. In recent experiments, the ion viscosity in biased plasma with islands was roughly estimated. It suggested that the ion viscosity increased with an increase in magnetic island width [9]. Therefore, it is important to understand the effects of magnetic islands on plasma flow by changing island width. The purpose of this paper is to survey the relationship between the threshold of the external driving force required for plasma flow jumping and an island width.

2. Experimental Setup

Experiments were performed in the TU-Heliac, which is a four-period heliac containing three set of coils: a center conductor coil, two vertical coils, and 32 toroidal coils, as shown in Fig. 1. The major radius was $R_0 = 0.48$ m, the average minor radius was $r = 0.07$ m and the magnetic field was $B_0 = 0.3$ T. The typical discharge time was 10 ms,

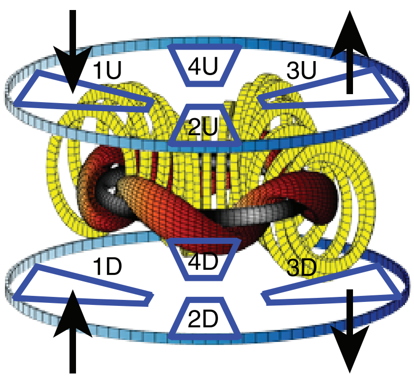

Fig. 1 Top view of TU-Heliac. Four pairs of upper and lower external perturbation field coils are located at the toroidal angles $\phi = 0°, 90°, 180°$ and $270°$.

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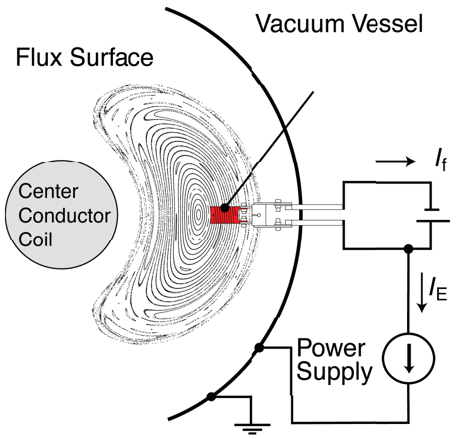

Fig. 2 Process by which a hot cathode composed of LaB_6 is inserted in the inner side of islands (core plasma) and biased negatively against the vacuum vessel.

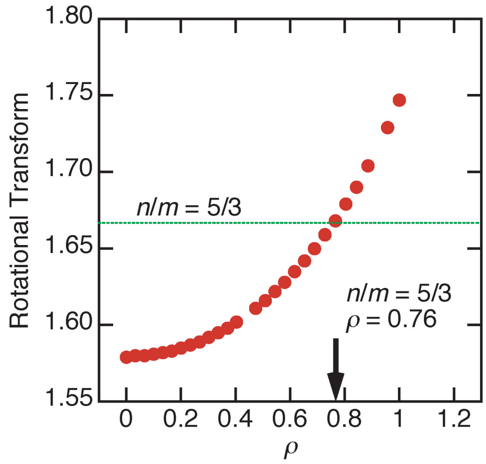

Fig. 3 Radial profile of rotational transform.

which was the confinement time for the coil current flat top. The plasma was produced by the low-frequency joule heating (f = 18.8 kHz, $P_{\mathrm{out}} \sim 35$ kW).

The working gas was He ($P_0 \sim 2.6 \times 10^{-2}$ Pa). The electron density and temperature measured by a Langmuir probe (triple probe) were $n_e \sim 1\times10^{18}$ m^{-3} and $T_e \sim 20$ eV, respectively.

2.1 Driving plasma flow

As a method for driving the plasma flow externally, we adopted the biasing of an electrode composed of LaB_6, as shown in Fig. 2. The electrode was inserted into ρ = 0.18, in the inner sides of islands (core plasma) and was biased negatively against the vacuum vessel. The electrode current was externally controlled by a current-controlled power supply. The plasma flow was evaluated from the current ratio measured by a Mach probe.

2.2 External perturbation field

To generate the m = 3 island at the plasma periphery, we used external perturbation coils. Four pairs of upper and lower coils located at toroidal angles ϕ = 0°, 90°, 180° and 270° generated a cusp field at each toroidal angle, as shown in Fig. 1. The vacuum field calculations showed that the perturbation field produced by these coils can produce the m = 3 magnetic island at a rational flux surface. By using alternative currents and phase control in the perturbation field coil current, these coils can produce a rotating magnetic island [10]. In this experiment, to study the relationship between plasma flow and magnetic island at a fixed poloidal position, we used only two pairs of external perturbation field coils at toroidal angles ϕ = 0° and 180°. Using these coils, m = 3 islands were also generated on a magnetic configuration that with a rational flux surface ($n/m = 5/3$) at $\rho \sim 0.76$. The rotational transform profile is shown in Fig. 3. An external perturbation field coil current I_{ex} flowed up to 3.6 kAT in each coil, which produced the radial component of the perturbation field $B_r/B_0 = 5.7 \times 10^{-3}$ at the positions on the rational surface ($n/m = 5/3$) closest to the perturbation fields. Here, B_0 is the magnetic field strength at the magnetic axis.

To study island formation, we measured island profile by a Langmuir probe. Radial profiles of the electron temperature and plasma space potential in the island region showed a magnetic islands structure with a width linearly proportional to $I_{\mathrm{ex}}^{1/2}$ [11].

3. Experimental Results

3.1 Threshold of external driving force

The flow velocity was measured by a Mach probe, as shown in Fig. 4, and was proportional to the probe current ratio R_{Mach},

$$R_{\mathrm{Mach}} = \frac{I_{s1} - I_{s2}}{I_{s1} + I_{s2}}, \quad (1)$$

where, I_{s1} and I_{s2} are currents on the surface of ion collection [12]. The s1 and s2 suffixes indicates that the probe surface faces upstream or downstream of plasma flow, respectively.

We measured the dependency of the Mach probe current ratio on the angle between the normal vector of collecting surface and the magnetic line of force in the biased plasma, as shown in Fig. 5. The tangential and perpendicular directions of the line of force corresponded to θ = 238° and 328°, respectively. Figure 5 clearly shows that the plasma flow in the biased plasma was poloidal. This direction was consistent with that of $\boldsymbol{E} \times \boldsymbol{B}$ direction, here $\boldsymbol{E}$ is the electric field produced by negative electrode biasing.

To study the effects of magnetic islands on poloidal plasma flow, we externally controlled the flow velocity by changing the electrode current with the current-controlled power supply. Next, we surveyed the relationship between the threshold of the external driving force required for plasma flow jumping and the island width. Figure 6 shows (a) LaB_6 electrode current, (b) electrode voltage, (c) electron temperature, (d) electron density measured by a triple

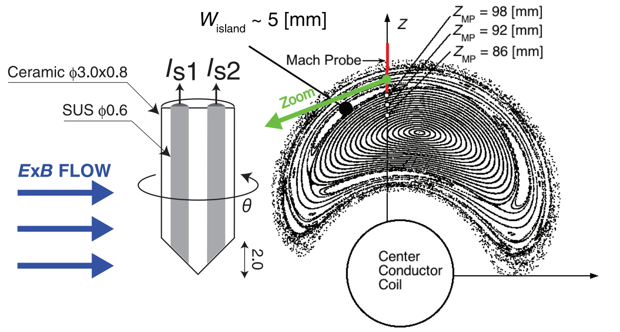

Fig. 4 Magnetic surface with $m = 3$ islands at toroidal angle $\phi = 159°$. Z_{MP} is the vertical position of the Mach probe.

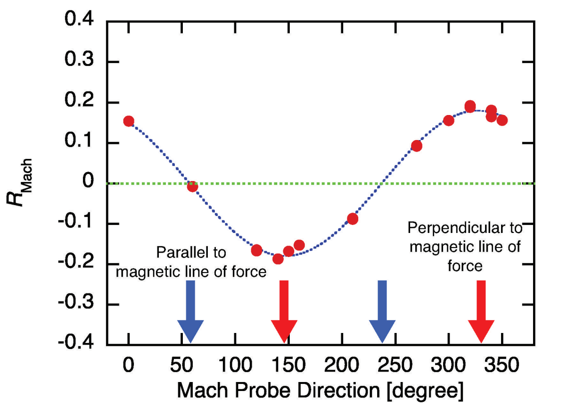

Fig. 5 Plasma flow measured by the Mach probe at Z_{MP} = 98 mm.

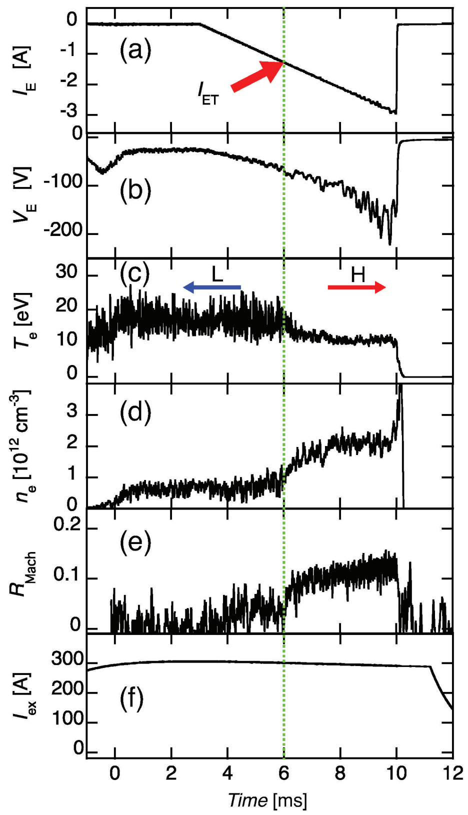

Fig. 6 Typical time evolution of (a) LaB_6 electrode current, (b) electrode voltage, (c) electron temperature, (d) electron density measured by a triple probe located at ρ = 0.43, (e) Mach probe current ratio measured by a Mach probe located at Z_{MP} = 98 [mm] (ρ = 0.63), and (f) external perturbation field coil current.

probe located at $\rho = 0.43$, (e) Mach probe current ratio measured by the Mach probe located at Z_{MP} = 98 [mm] (ρ = 0.63) and (f) external perturbation field coil current. We adopted a sawtooth function for the current-controlled power supply to the electrode. The electrode current began at t = 3 ms and was ramped up linearly to 3 A at t = 10 ms.

It is evident that the Mach probe current ratio (Fig. 6 (e)) increased suddenly at t ~ 6 ms. In addition, temperature fluctuation was significantly suppressed after this point (Fig. 6 (c)) and the electron density increased by a factor of 3 (Fig. 6 (d)), which suggests improved mode transition. Therefore, we adopted the electrode current required for the transition I_{ET} as the index for the island effect on the poloidal flow. The product $I_{ET}B$ in Fig. 6 (a) indicates the external driving force threshold for the poloidal flow transition; here, B is the magnetic field strength.

3.2 Effect of island width

Figure 7 shows a time evolution of the Mach probe current ratio at three radial locations, Z_{MP} = 86, 92 and 98 mm (ρ = 0.39, 0.46 and 0.63), as seen in the magnetic configuration with three island width cases in Fig. 4. Here, the case of I_{ex} = 300 A corresponded to the radial component of the perturbation field $B_r/B_0 = 5.7 \times 10^{-3}$ at the positions on the rational surface. The island width W_{island}

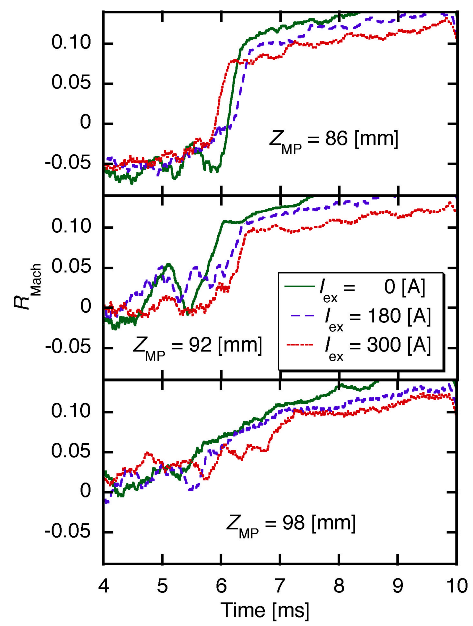

Fig. 7 Time evolution of Mach probe current ratio.

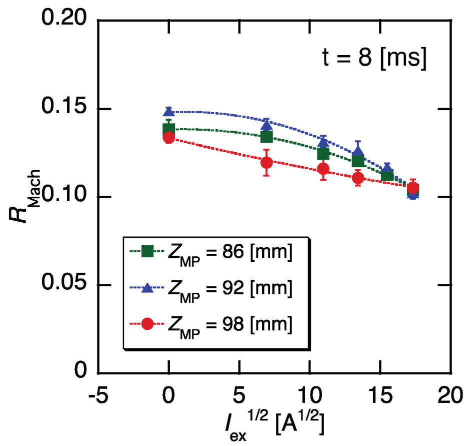

Fig. 8 Dependency of island width on saturated Mach probe current ratio.

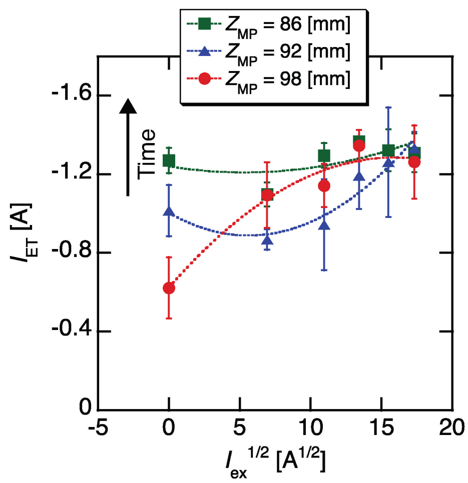

Fig. 9 Dependency of island width ($I_{\mathrm{ex}}^{1/2}$) on electrode current required for the transition I_{ET}.

at the O-point was approximately 5 mm in the island near the Mach probe, as shown in Fig. 4. In addition, and W_{island} is was proportional to the $I_{\mathrm{ex}}^{1/2}$.

Poloidal flow jumps at $t \sim 6$ ms were clearly observed inside the plasma. In addition, the saturated Mach probe current ratio at t = 8-10 ms depended on the magnetic island width ($I_{\mathrm{ex}}^{1/2}$) shown in Fig. 8. That is, the poloidal flow velocity decreased with an increase in the island width.

We focused on the electrode current I_{ET} at the transition, as shown in Fig. 6. The dependency of the island width ($I_{\mathrm{ex}}^{1/2}$) on the electrode current required for the transition I_{ET} is shown in Fig. 9. The electrode current I_{E} was proportional to the plasma driving force. It is clearly seen that the electrode current required for the transition I_{ET} increased with island width expansion at the plasma periphery (Z_{MP} = 98 mm) and showed weak dependency inside the plasma (Z_{MP} = 86 mm). These dependencies shown in Fig. 9 suggest that the magnetic island located at the plasma periphery affects the poloidal flow as the drag term. We estimated the poloidal Mach number $M_{\mathrm{p}} = E_{\rho}/B_{\mathrm{p}}v_{\mathrm{t}}$ at

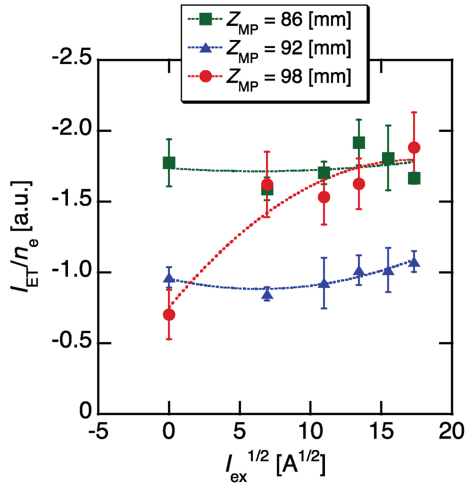

Fig. 10 Dependency of island width ($I_{\mathrm{ex}}^{1/2}$) on the normalized electrode current required for the transition I_{ET}.

the transition $\rho \sim 0.63$ in the case of I_{ex} = 300 A. Here, E_{ρ} is the averaged radial electric field on the flux surface, B_{p} is a poloidal field, and $v_{\mathrm{t}} = (2T_{\mathrm{i}}/m_{\mathrm{i}})^{1/2}$ is an ion thermal velocity. respectively. The poloidal Mach number was M_{p} = 1-2, which had the same order as the M_{p} estimated as the local maxima of ion viscosity predicted by the neoclassical theory in previous studies of magnetic configuration without magnetic islands [7].

However, the driving force for poloidal flow depends on ion pressure, and the plasma parameter slightly changed in the varied island width configuration. Therefore, estimation of ion viscosity and friction is necessary. The driving force normalized by ion pressure corresponds to ion viscosity and friction [8]. In this estimation, we assumed that ion temperature was not dependent on magnetic configuration, because the measured electron temperature hardly depended on the configuration. Moreover, the ion and electron temperature ratio was almost constant in the previous experiments. Thus, we estimated normalized driving force by dividing the electrode current required for the transition I_{ET} by only the electron density, which was measured along the chord through the magnetic axis by spectroscopy using interference filters. The dependency of the island width ($I_{\mathrm{ex}}^{1/2}$) on the normalized electrode current required for the transition I_{ET} is shown in Fig. 10. It is evident that the normalized electrode current required for the transition $I_{\mathrm{ET}}/n_{\mathrm{e}}$ increased with island width expansion at the plasma periphery (Z_{MP} = 98 mm) and the showed weak dependency at the inside of the plasma (Z_{MP} = 86, 92 mm).

4. Summary

We surveyed the relationship between the threshold of the external driving force required for plasma flow jumping and an island width. The electrode current required for the transition increased with island width expansion at the plasma periphery and showed weak dependency inside the plasma. We estimated the normalized driving force required for the transition, which also increased with island width expansion at the plasma periphery. These dependencies suggest that the magnetic island located at the plasma periphery affects poloidal flow as the drag term.

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