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Effects of Rotating Magnetic Islands Driven by External Perturbation Fields in TU-Heliac

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New method of rotating the magnetic islands by the external perturbation fields was proposed. The perturbation fields were produced by 4 pairs of cusp field coil, in which the alternating currents flowed and the currents had the π/2 phase shift. The phase shifter for the coil currents was designed and constructed. The phase difference in the floating potential signals measured by the two Langmuir probes confirmed that the rotation of the magnetic islands in the counterclockwise direction (c/c) direction. The clockwise (c/w) rotation was also observed in the plasma biased by the hot cathode electrode. These experimental results suggest the ability of the plasma poloidal rotation driven by rotating islands.

Keywords: stellarator, heliac, magnetic islands, poloidal rotation, perturbation field, electrode bias

1. Inroduction

Study of magnetic island effects on the transport in helical devices is important, because it leads to the advanced control method for a plasma periphery in a fusion reactor. For the research on island effects on confinement modes, the Tohoku University Heliac (TU-Heliac) has advantages that (1) the position of a rational surface is changeable by selecting the ratio of coil currents, (2) the island formation can be controlled by external perturbation field coils, (3) a radial electric field and particle transport can be controlled by the electrode biasing. In TU-Heliac the improved mode transition has been triggered by electrode biasing using a hot cathode made of LaB_6. The driving force $\boldsymbol{J} \times \boldsymbol{B}$ for a plasma poloidal rotation was externally controlled and the poloidal viscosity was successfully estimated from the external driving force [1-3]. In recent experiments the ion viscosity in the biased plasma with islands was roughly estimated. It suggested that the ion viscosity increased according to the increase of the magnetic island width [4]. Therefore it is expected that plasma poloidal rotation will be driven by the poloidal rotation of the island. The purposes of this experiment are, to propose the new method of rotating islands by the external perturbation fields, to survey the ability of the plasma poloidal rotation driven by rotating islands and, to study the rotating island effects on confinement modes in TU-Heliac.

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2. Experimental Setup

2.1. TU-Heliac

The TU-Heliac is a 4-period heliac (major radius, 0.48 m; average plasma radius, 0.07 m). The heliac configurations were produced by three sets of magnetic

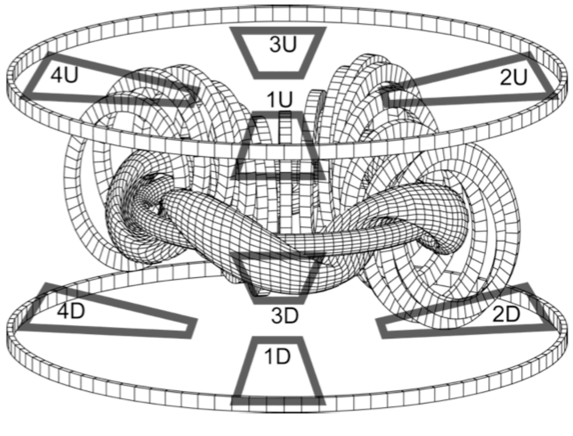

Fig. 1 Bird's eye-view of TU-Heliac and 4 pairs of upper and lower external perturbation field coils. 4 pairs of coils were divided into two groups (the first group consists of 1U1D and 3U3D, the second group of 2U2D and 4U4D).

field coils: 32 toroidal field coils, a center conductor coil, and one pair of vertical field coils as shown in Fig. 1. Three capacitor banks consisting of two-stage pulse forming networks separately supplied coil currents of 10 ms flat top [5]. The target plasma for external perturbation fields was He plasma produced by low frequency joule heating (f = 18.8 kHz, P_{out} ~ 35 kW). The joule heating power was supplied to one pair of poloidal coils wound outside the toroidal coils [6]. The vacuum vessel was filled with fueling neutral He gas and sealed from the evacuation system before every discharge. The electron density and temperature measured by a Langmuir probe (triple probe) were ~ 6 x 10^{17} m^{-3} and ~ 20 eV at the magnetic axis and the magnetic field strength at the axis was 0.3 T.

2.2. External Perturbation Coils

In TU-Heliac we selected the current ratio to locate a rational flux surface (n/m = 5/3) in the plasma periphery. The efficient configuration of perturbation coils for generating islands (m = 3) has been searched. We decided 4 pairs of upper and lower external perturbation field coils, which located at the toroidal angle ϕ = 0°, 90°, 180° and 270°, and generated cusp field at each toroidal angle as shown in Fig. 1. We explored the possibility of the poloidal rotation of islands by changing the phase of the each perturbation coil current. We tried the method that, dividing perturbation coils into two groups (the first group consists of 1U1D and 3U3D, the second group of 2U2D and 4U4D), changing perturbation current separately, one group's current was $I_{\mathrm{ex}} = I_0\sin(\omega t)$ and other was $I_{\mathrm{ex}} = I_0\sin(\omega t - \pi/2)$. Each coil produces an alternating cusp field with the frequency ω. The result of magnetic surface calculations suggested that islands rotate to poloidal direction with the poloidal velocity of $\langle r\rangle\omega/m$. Here, $\langle r\rangle$ is the average radius of the rational flux surface (n/m = 5/3) and m is the mode number of magnetic islands. The poloidal rotation velocity can be changeable by the frequency ω. Furthermore we can select the poloidal rotation direction (clockwise c/w or counterclockwise direction c/c) by changing the polarity of the phase shift. Here the c/c direction means the ion diamagnetic direction.

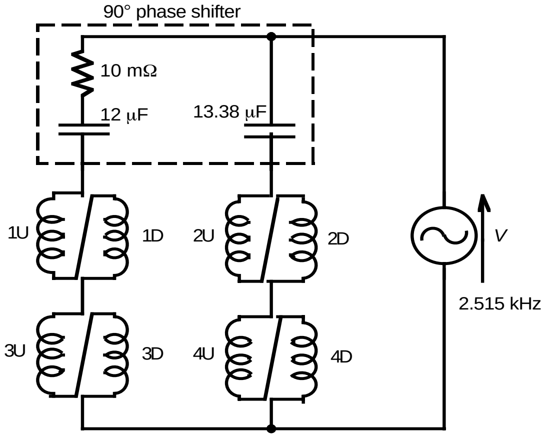

Fig.2 Schematic circuit for the external perturbation coils.

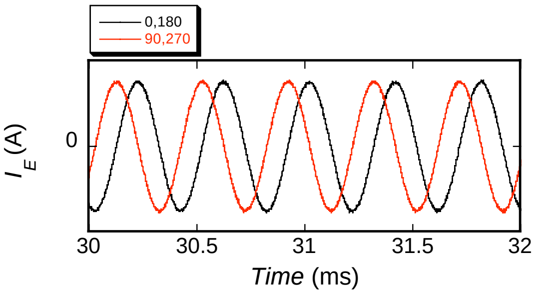

Fig. 3 Perturbation coil currents measured by the Rogowsky coils. Two group coil currents have π/2 phase shift and same values.

In the experiment we adopted the phase shifter shown in Fig. 2, which consisted of precisely tuned capacitors and resister. The perturbation field coil current was 1.2 kAT and the frequency was 2.515 kHz. The current and the frequency were selected to perform the preliminary experiments and we have the plan of increase in current and frequency. Figure 3 shows the perturbation coil currents measured by the Rogowsky coils. We can see that two group coil currents have π/2 phase shift and same values.

Figure 4 shows the magnetic surfaces with m = 3 magnetic islands which were produced by the external perturbation fields. The m = 3 magnetic islands rotated by

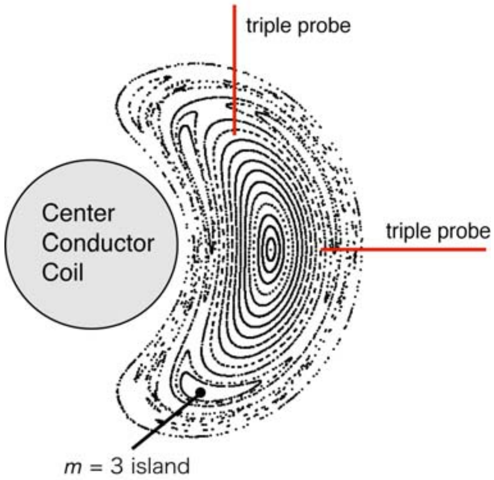

Fig. 4 Cross section of magnetic surfaces with m = 3 magnetic island. Two Langmuir probes on the magnetic surface at the positions which were separated about a half of the poloidal length of the island.

the alternating perturbation fields.

3. Phase shift in Probe Measurements

To check experimentally the effect of the external perturbation field, we measured the floating potential by a Langmuir probe (high speed triple probe [7, 8]), which was inserted from the low field side at the toroidal angle $\phi = 0^\circ$. In Fig. 5 it is clear that the floating potential signal has the frequency component of the perturbation fields (lower trace) and the phase shift to the external perturbation coil current (upper trace). Then we measured the radial profile of the FFT power spectrum in the floating potential signals. Figure 6 shows the relation between the power spectrum of the floating potential and the radial position of the Langmuir probe. Figure 6 clearly shows that the frequency of the perturbation field coil current (f = 2.515 kHz) was excited around the m = 3 magnetic island.

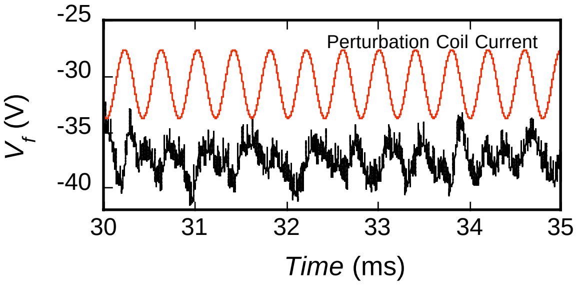

Fig. 5 External perturbation coil current and the floating potential measured by a Langmuir probe (high speed triple probe).

In order to confirm the rotation of magnetic islands we set two Langmuir probes on the magnetic surface at the positions which were separated about a half of the poloidal length of the island. These probes were set at the same meridian plane at the toroidal angle $\phi = 0^\circ$ as shown in Fig. 4. We measured the phase shift in the frequency of the perturbation fields (f = 2.515 kHz) between two probe signals. Figure 7 shows the difference of the phase between the floating potential signals at the three radial points. The open symbols and closed symbols denote the c/w and c/c directions of the rotating islands which were expected by the calculations. We can confirm that at the inside the m = 3 islands the phase difference was about π in the c/c direction case, which was consistent with the calculation results and suggested the rotation at the inside of the island (R = 102 mm), and corresponded to the poloidal rotation velocity of ~ 0.2 km/s. These experimental results suggest the ability of the plasma poloidal rotation driven by rotating islands. However in the c/w case the phase difference had the small positive values, which were inconsistent with the calculation, because it should be -π. In these experiments the target plasma had the weak positive radial electric fields ($E_r \sim 2$ kV/m), thus the bulk plasma rotated in the c/c direction by the $\boldsymbol{E} \times \boldsymbol{B}$ rotation. Therefore we can explain that there are some restrictions on the rotation of the islands in the direction which is opposite to the natural direction of the bulk plasma rotation (c/c direction).

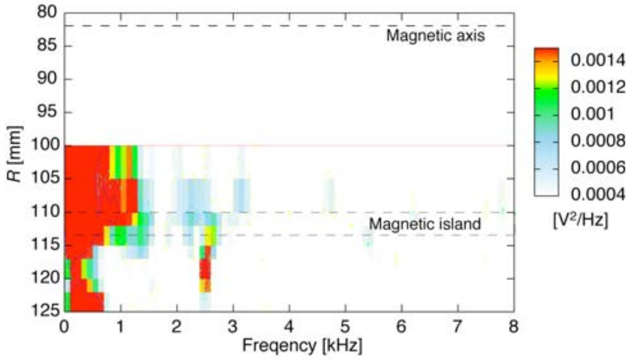

Fig. 6 Relation between the FFT power spectrum of floating potential and the radial position of the Langmuir probe.

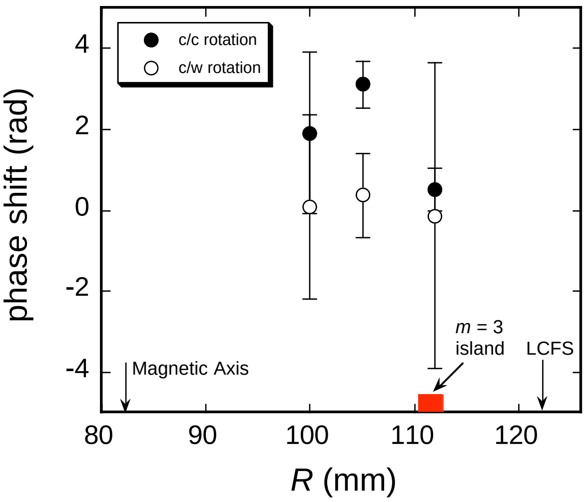

Fig. 7 Difference of the phase between the floating potential signals at the three radial points. The open symbols and closed symbols denote the c/w and c/c directions of the rotating islands which are expected by the calculations.

In TU-Heliac we can bias the potential to the plasma by the hot cathode electrode made of LaB_6. We can control the negative radial electric field externally by the electrode biasing. The hot cathode (diameter, 10 mm; length, 17 mm) was inserted horizontally into the plasma from the low magnetic field side at a toroidal angle $\phi = 270°$. The $m = 3$ islands were formed at the outside of the hot cathode. The direction of the $\boldsymbol{E} \times \boldsymbol{B}$ rotation was the c/w direction, thus we can decelerate the natural c/c plasma rotation. Here $\boldsymbol{E}$ is the radial electric field made from the biasing. We tried to apply the external perturbation fields to rotate the islands in the biased plasma. Figure 8 shows the relation between the differences of the phase in two floating potential signals and the electrode current used for the plasma biasing. The increase in the electrode current means the increase in the c/w plasma rotation velocity. We showed again the results without the electrode biasing (I_E = 0 A) shown in Fig. 7. Before the application of the external perturbation fields we tried to measure the velocity of the plasma poloidal rotation by the phase velocity of high frequency fluctuations in floating potential [2, 9]. From this results the plasma poloidal rotation disappeared in the case which the electrode current was about 2 A. In Fig. 8 we can see that in the c/w island rotation case the phase difference had about -2 rad at I_E = 2 A, which was consistent with the calculations and suggested the rotation of the magnetic island, although in the c/c island rotation cases the phase difference decreased compared with the experimental results in Fig. 7. This suggested that the bulk plasma rotation by the biasing was overdriven.

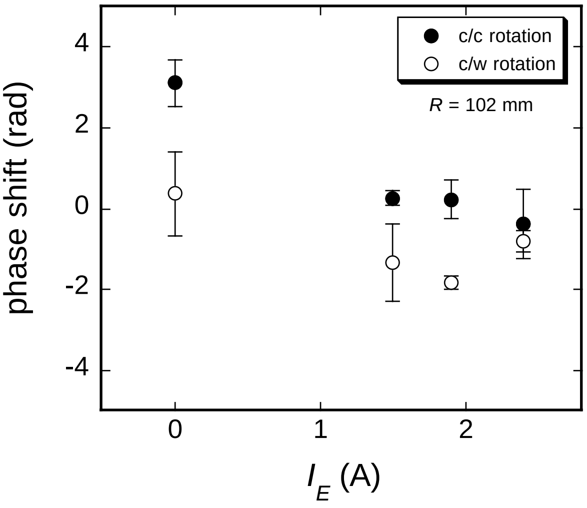

Fig. 8 Relation between the differences of the phase in two floating potential signals and the electrode current. The increase in the electrode current means the increase in the velocity of the c/w bulk plasma rotation.

4. Summary

We proposed the method to rotate the magnetic islands by the external perturbation fields which were produced with 4 pairs of cusp field. The alternating currents for the perturbation coils have the π/2 phase shift. We designed and constructed the phase shifter for the coil currents and we measured the phase difference in the floating potential signals by two Langmuir probes, which confirmed that the rotation at the inside of the magnetic islands in the c/c direction. Furthermore the c/w rotation was also observed in the plasma biased by the hot cathode electrode. These experimental results suggest the ability of the plasma poloidal rotation driven by rotating islands, though the island rotation was affected by the rotation of the target plasma. We can expect the higher poloidal rotation velocity by increasing in the frequency of the perturbation coil current.

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