MHD Relaxation and Plasma Flow Driven by Coaxial Helicity Injection in the HIST Spherical Torus Device

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We have investigated a role of plasma flow during the dynamics of plasma current reversal of helicity-driven spherical torus (ST) plasma. An ion flow was locally measured with Mach probes, and a line-averaged flow measurement was performed by using an ion Doppler spectrometer in the HIST spherical torus device. During the transition from the normal ST to flipped ST configuration, a strong toroidal ion flow was generated in the flipped region, which was accompanied by the spontaneous reversal of toroidal plasma current. The strong ion flow could originate from a magnetic reconnection event during the reversal process. It was revealed that the strong ion flow has a significant contribution to the generation of negative toroidal plasma current in the flipped region.

Keywords: Spherical torus, coaxial helicity injection, MHD relaxation, flipped ST, plasma flow

1. Introduction

Coaxial helicity injection (CHI) using a magnetized coaxial plasma gun (MCPG) is one of the most attractive methods for non-inductive plasma current drive and plasma start-up in magnetically confined fusion devices. It is considered that the mechanism of CHI current drive relies on MHD relaxation processes such as kinking behavior and magnetic reconnection [1]. The Helicity Injected Spherical Torus (HIST) device can generate various ST configurations by changing the external toroidal magnetic field [2]. Especially, the flipped ST (F-ST) configuration has been for the first time found in the HIST device [3]. In the F-ST plasma, the toroidal plasma current is self-reversed by changing rapidly the polarity of the external toroidal magnetic field during the normal ST (N-ST) discharge. The mechanism of the self-reversal of toroidal plasma current in the F-ST has been investigated by mainly internal magnetic probe measurements in the previous study. On the other hand, a role of plasma flow in the self-reversal process of toroidal plasma current is one of the underlying physics. In this study, we performed measurements of the toroidal ion flow during the transition from the N-ST to F-ST configuration.

This paper is organized as follows; section 2 describes the HIST spherical torus device and the diagnostics used in the present study. The observed flow dynamics and its effect on the current reversal during the transition from the N-ST to F-ST configuration are discussed in section 3. Finally, conclusions are summarized in section 4.

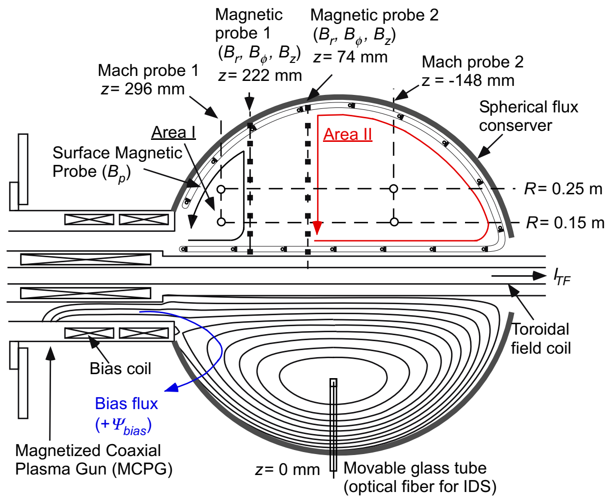

Fig. 1 Schematic diagram of the HIST spherical torus device and diagnositcs used in the present study.

2. Experimental Setup

The HIST device has a major radius R = 0.30 m, a minor radius a = 0.24 m and an aspect ratio A = 1.25. Hydrogen is used as a working gas in this study. The detail experimental description of HIST is shown in ref. [2]. Figure 1 shows a schematic view of the HIST device and diagnostics used in this study. Three axis magnetic probes (B_r, B_ϕ, B_z) are installed in the plasma at a distance of z = 74 mm and 222 mm form the midplane (z = 0 mm) of the flux conserver (FC). Magnetic pick-up coils (16 channels for B_z) are located in the poloidal direction along the inner surface of the FC to calculate the total toroidal plasma current I_t. Figure 2 shows poloidal flux topology of the F-ST configuration which was estimated by internal magnetic fields measured in the previous study.

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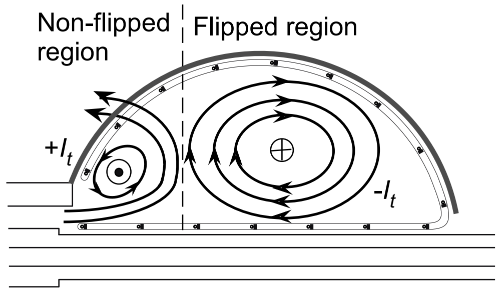

Fig. 2 Poloidal flux topology of F-ST configuration.

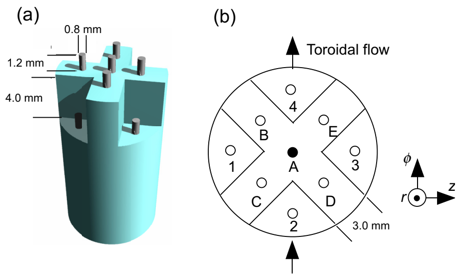

Fig. 3 Schematic view of Mach probe in this study.

Since non-flipped region exists near the plasma gun in the F-ST discharge as shown in Fig. 2, the I_t measured by the all surface probe channels includes not only the flipped region but also the non-flipped region. Therefore, I_{t1} and I_{t2} calculated by an integration of magnetic fields with path-integrals shown in Fig. 1 are newly introduced to divide the toroidal plasma current into the non-flipped and flipped regions. The line-averaged electron density $\bar{n}_e$ is measured by a CO_2 laser interferometer.

Ion flow measurements are performed by Mach probes in this study as follows; An ion Mach number M_i can be obtained from the ratio of ion saturation current densities collected by each electrode, $R = J_{up}/J_{down}$, where J_{up} and J_{down} are current densities collected by upstream and downstream probes, respectively. Then, $M_i = M_c \ln R$, where M_c is a proportionality constant. An ion flow velocity V_i is expressed as $V_i = C_s M_i$, where C_s is an ion sound velocity. A Mach probe shown in Fig. 3 is used to measure toroidal and poloidal ion flow in the N-ST and F-ST discharges. The Mach probes are located at the area I and II shown in Fig. 1 to investigate the plasma flow in non-flipped and flipped regions. The Mach probe consists of nine tungsten rods surrounding glass-ceramic (Macor). The probe radius is smaller than the ion Larmor radius ($\sim$ 1 cm), so that the unmagnetized condition should be used in the theoretical model which determines the M_c [4]. Then, $M_c = 0.53$ in this study, where it is assumed that the electron temperature T_e is equal to the ion temperature T_i. The two directional electrodes (#2 and #4) are biased negatively (-10 V) with respect to the base electrode (#A) to collect ion saturation current, when the toroidal ion Mach number $M_{i,t}$ is measured. Note that the positive (negative) value of $M_{i,t}$ corresponds that the ion flow is in the same direction of $+I_t$ ($-I_t$).

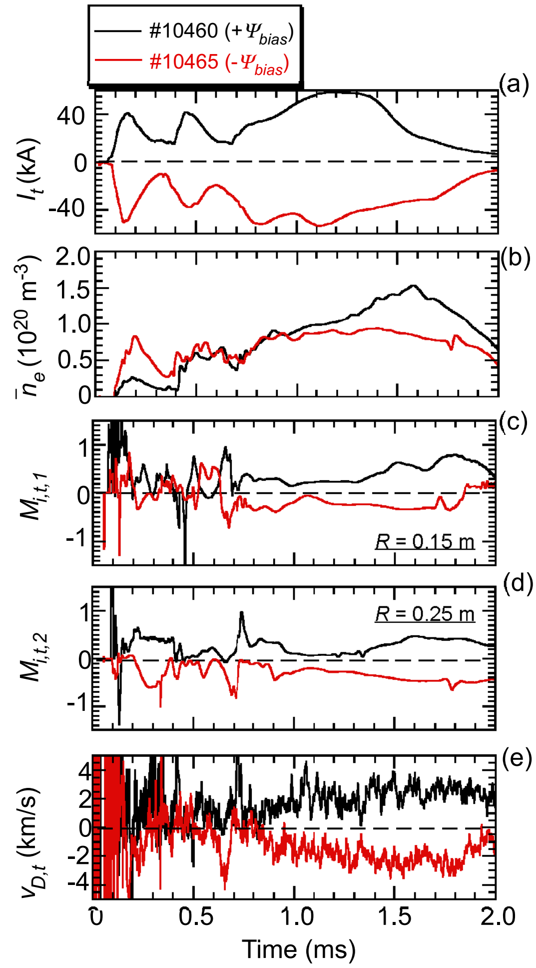

Fig. 4 Time evolutions of (a) I_t, (b) $\bar{n}_e$, (c) $M_{i,t,1}$, (d) $M_{i,t,2}$, (e) $V_{D,t}$ in the N-ST plasma. The radial locations of $M_{i,t,1}$ and $M_{i,t,2}$ are $R = 0.15$ m and $R = 0.25$ m, respectively. Note that the positive (negative) value of $M_{i,t}$ corresponds that the ion flow is in the same direction of $+I_t$ ($-I_t$).

We also have started to develop an ion Doppler spectrometer (IDS) system using a compact 16 channel photomultiplier tube (PMT) in order to measure ion temperature and plasma flow velocity. The IDS system consists of a light collection system including optical fibers, 1 m-spectrometer (model No. MC-100N, Ritsu Ouyou Kougaku Co. Ltd.) and the PMT detector. Technical details of the similar IDS system are described in ref. [5]. In this study, the optical fiber covered with glass tubes is inserted into the plasma, and the toroidal flow velocity $V_{D,t}$ is measured from Doppler shift of H_β line spectra ($\lambda = 486.1$ nm).

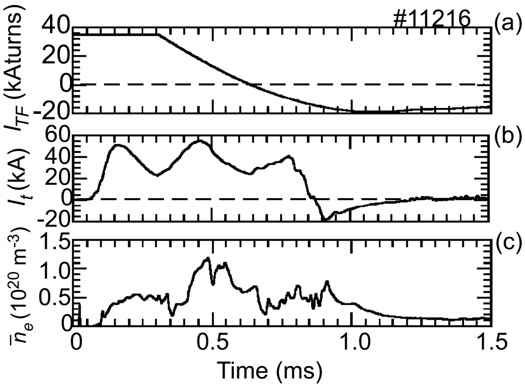

Fig. 5 Time developments of (a) I_{TF}, (b) I_t, (c) $\bar{n}_e$ in the F-ST discharge.

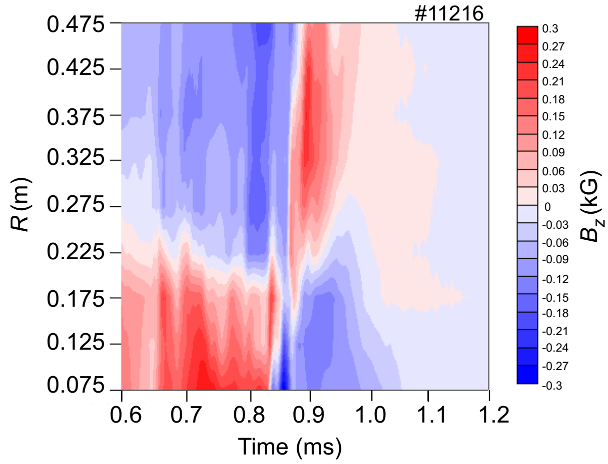

Fig. 6 Time evolutions of B_z measured by internal magnetic probe arrays.

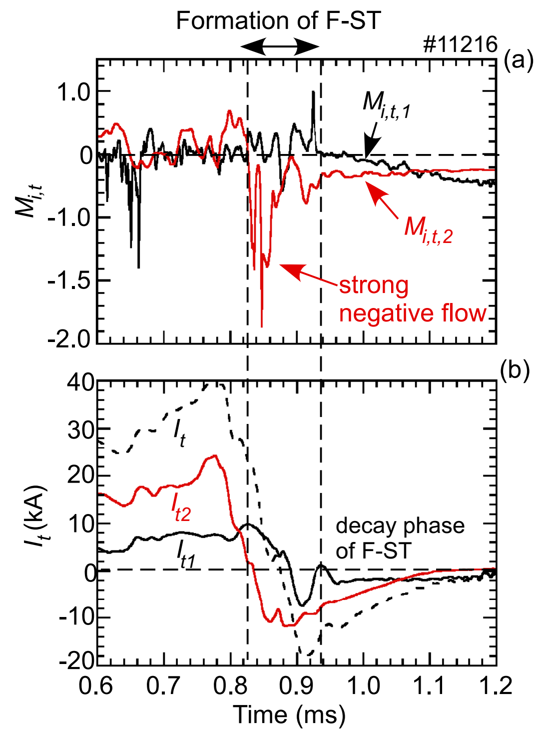

Fig. 7 Time evolutions of (a) $M_{i,t,1}$ and $M_{i,t,2}$, (b) I_t(dashed line), I_{t1} (black line) and I_{t2} (red line). Note that the positive (negative) value of $M_{i,t}$ corresponds that the ion flow is in the same direction of $+I_t$ ($-I_t$).

3. Experimental Results

3.1 Ion flow measurement in the normal ST plasma

Figure 4 shows time developments of I_t, $\bar{n}_e$, $M_{i,t}$ and $V_{D,t}$ in the N-ST plasma. It is found the $M_{i,t}$ is 0.3∼0.4, and the ion flow is in the same direction of I_t. The toroidal ion flow velocity $V_{i,t}$ is roughly evaluated as 10∼15 km/s in the N-ST plasma, where the T_e is set to 10 eV (triple probe measurement) in the calculation of C_s. On the other hand, the direction of ion flow matches the externally applied $E \times B_{bias}$ direction. Here, the B_{bias} is the magnetic field produced by the bias coil shown in Fig. 1. The relation between the directions of ion flow and I_t is successfully confirmed by changing the polarity of B_{bias}, as shown in Fig. 4. It is also confirmed that the $V_{D,t}$ is in the same direction as the I_t and $E \times B_{bias}$ rotation. Here, the $V_{D,t}$ is determined by the line-averaged Doppler-shift of H_β, so that the $V_{D,t}$ could be originated from the ion flow at the peripheral region. This is one of the reason why the $V_{D,t}$ is much smaller than the $V_{i,t}$ measured by the Mach probe in this study. Note that there is no significant difference between the $M_{i,t}$ at the area I ($M_{i,t,1}$) and II ($M_{i,t,2}$) in the N-ST discharge.

3.2 Ion flow measurement during the transition phase from the N-ST to F-ST configuration

Figure 5 indicates time evolutions of toroidal field coil current I_{TF}, I_t, $\bar{n}_e$ in the F-ST discharge. The N-ST plasma with a peak I_t of 60 kA is initially produced by CHI and the reversed TF circuit is triggered at $t = 0.32$ ms. Since the Kruskal-Shafranov stability condition is violated by decreasing of I_{TF}, the I_t starts to drop and reverse its sign as shown in Fig. 5. Time developments of the internal poloidal magnetic fields at $z = 74$ mm during the transition from the N-ST to F-ST plasma are shown in Fig. 6. It is found that the magnetic axis exists at around $R = 0.225$ m, and the sign of poloidal magnetic field is clearly reversed after the transition. The F-ST plasma decays with the resistive time scale (~ 0.2 ms) after the reversal.

Figure 7 shows time developments of $M_{i,t,1}$, $M_{i,t,2}$, I_t, I_{t1} and I_{t2} during the transition phase from the N-ST to F-ST configuration. Here, the Mach probes are set at $R = 0.15$ m in the area I and II. It is clearly found that the I_{t2} starts to reverse earlier than the I_{t1}. Thus, it could be considered that the toroidal plasma current near the plasma gun is in the positive direction just after the transition from the N-ST to F-ST configuration, as shown in Fig. 2. Furthermore, a rapid growth of negative ion flow appears at the same time when the I_{t2} reverses. However, there is no significant change in $M_{i,t,1}$. Therefore, this result suggests that the ion flow has a significant contribution to the generation of negative toroidal plasma current in the flipped region. In contrast, three-dimensional MHD numerical simulations [6] predict that a large helical distortion of the open flux and the following magnetic reconnection between open and closed field lines play a major role in the self-reversal process. Therefore, one possible reason to explain the production of the strong negative ion flow is a magnetic reconnection during the transition phase. Concerning an evaluation of the $V_{i,t}$ during the transition from the N-ST to F-ST configuration, it is necessary to measure T_e and T_i spontaneously, because magnetic reconnection could be accompanied by plasma flow, electron and ion heating [7].

4. Summary

We have investigated plasma flow which is one of the key roles in self-organization and magnetic reconnection processes of helicity-driven ST and spheromak. In the present study, the toroidal ion flow was measured by mainly Mach probes in the HIST spherical torus device. It was found that the toroidal ion flow is in the same direction of the toroidal plasma current and the $E \times B$ rotation in the N-ST plasma. The results agree with the preliminary result of flow measurement with the IDS system. The most interesting finding of the present experiment is the role of ion flow on the transition from the N-ST to F-ST configuration. From the local measurement of the toroidal ion flow in the flipped region by the Mach probe, it was revealed that the strong toroidal ion flow was generated by the magnetic reconnection during the transition phase between the N-ST to F-ST configuration. The observed phenomena agree with the prediction by the MHD numerical simulation [6].

Acknowledgements

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[1] R.C. Duek *et al.*, Plasma Phys. Controlled Fusion **39**, 715 (1997).
[2] M. Nagata *et al.*, Phys. Plasmas **10**, 2932 (2003).
[3] M. Nagata *et al.*, Phys. Rev. Lett. **90**, 225001 (2003).
[4] A. Ando *et al.*, J. Plasma Fusion Res. **81**, 451 (2005).
[5] P. Gu *et al.*, Rev. of Sci. Instrum. **75**, 1337 (2004).
[6] Y. Kagei *et al.*, Plasma Phys. Controlled Fusion **45**, L17 (2003).
[7] M.R. Brown *et al.*, J. Fusion Energy **27**, 16 (2008).