Toroidal Spin-Up and Velocity Shear of a Field-Reversed Configuration Plasma

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A spatial distribution of toroidal flow in a field-reversed configuration plasma generated by the field-reversed theta-pinch method has been measured by an ion Doppler spectroscopy (IDS) system with a line-spectrum of impurity carbon (CV: 227.2 nm) and a Mach probe. With the IDS system, the axial profile of toroidal flow was observed. The observed results show different time evolutions of toroidal spin-up at around the midplane and end regions of the FRC. The radial profile of toroidal flow has also been observed on the weakly ionized plasma outside the separatrix with the Mach probe method. These results indicate propagation of toroidal momentum to the scrape-off plasma outward from the center.

Keywords: field-reversed configuration, $n = 2$ mode rotational instability, toroidal flow, flow shear, ion Doppler spectroscopy, Mach probe

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1. Introduction

A field-reversed configuration (FRC) plasma has a self-generated toroidal rotation and it causes rotational instability with a deformation of the toroidal mode number $n = 2$. In most of the experimentally generated FRC plasmas, this rotational instability with the mode number $n = 2$ is the only destructive instability to terminate the configuration lifetime.

Several possible mechanisms of toroidal spin-up have been discussed, such as selective loss of ions [1], end-shorting [2], and flux-decay [3]. However, only a few experimental investigations have been performed so far. In previous experiments, it was found that the FRC plasma rotates in the paramagnetic direction just after the formation phase. Then, plasma accelerates in the diamagnetic direction and then reverses the rotation direction to diamagnetic at around 15 μs from formation. The toroidal flow velocity becomes comparable with an ion diamagnetic velocity at 25 μs. However, the flow velocity outside the separatrix keeps settled at a small value. This indicates that a FRC has a different spin-up mechanism from what has been discussed in the past and that flow shear exists in the vicinity of the separatrix [4].

In this work, to obtain more detailed spatial distribution of toroidal flow, the axial velocity profile of toroidal flow in a FRC plasma has been measured with an ion Doppler spectroscopy (IDS) system and the radial velocity profile of the low temperature plasma layer at around the FRC plasma has been measured with the Mach probe method.

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2. Experimental Device and Diagnostics

Figure 1 shows a schematic view of a cross-section of the discharge tube and the arrangement of diagnostics. The FRC plasma is formed by a negative-biased theta-pinch method in NUCTE (Nihon University Compact Torus Experiment) –III [5].

This device has a 1.5 m long one-turn solenoidal theta-pinch coil. This coil consists of a 0.9 m long center region with 0.34 m I.D. of the coil elements and two 0.25 m long end mirror regions with 0.30 m I.D. The mirror ratio of the passive magnetic mirror is about 1.22. A slow bank of 5 kV-1920 μF and a fast bank of 32 kV-67.5 μF are con-

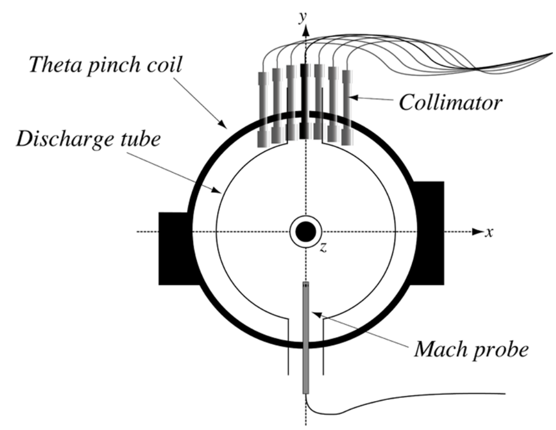

Fig. 1 Schematic view of a toroidal section of the NUCTE-III device and arrangement of the diagnostics.

nected to the theta pinch coil through a collector plate. The coil produces a bias field up to 0.032 T with a rise time of 90 ms and a confinement field up to 0.6 T with a rise time of 4 μs crowbarred for a decay time of 120 μs. A transparent fused quartz discharge tube 0.256 m in diameter and 2.0 m in length is evacuated to about 1.5×10^{-6} Torr by a turbo molecular pump. The tube is filled with 4 mTorr of deuterium gas and pre-ionized by the z-discharge method or θ-discharge method. A flux loop and 18 magnetic probes for measuring an excluded flux to obtain the axial separatrix profile $r_s(z)$ are arranged on the surface of the discharge tube. A length of FRC plasma l_s and its time evolution can also be estimated as;

$$l_s = z_+(r_{s\_\max}/2) - z_-(r_{s\_\max}/2). \quad (1)$$

A wobble motion of FRC plasma is observed by an optical detector array with 28 channels arranged along the x axis at z = -11 cm. It measures radiation from the plasma in the wavelength range of 550 ± 5 nm, consisting mainly of bremsstrahlung radiation. An averaged electron density is estimated by the line-integrated electron density, which is measured by a quadrature 3.39 μm He-Ne laser interferometer at z = 5 cm. The IDS system consists of a collimator with a convex-plane lens (focal length f = 100 mm), a quartz optical fiber tube of 5 m in length, a Czerny-Turner monochrometer, and a 16-channel photo-multiplier tube (PMT). Ion temperature and ion flow velocity are obtained from shifting and broadening of the line spectrum of impurity carbon (CV: 227.2 nm). The wavelength resolution per channel is about 0.04 nm in the system. A mach probe to measure the radial velocity profile in the weakly ionized plasma around the FRC plasma is mounted on the port at the mid-plane.

3. Experimental Results

3.1 Axial profile of toroidal flow velocity

The axial profile of toroidal flow has been observed by a non-invasive IDS system. In the series of experiments, a FRC has been generated with the z-preionization technique which has good reproducibility of plasma parameters. Typical FRC plasma parameters at the equilibrium phase (t = 20 μs) of this experiment are 3×10^{21} m^{-3}, T_i: 130 eV, $r_s(0)$: 0.06 m, l_s: 0.76 m, particle confinement time: 80 μs and decay time of poloidal flux: 100 μs, respectively. Typical time evolution of separatrix length is shown in Fig. 5.

Figure 2 shows the time evolution of the toroidal flow velocity at the center (z = 16.5 and 22.0) and end (z = 27.5 and 33.0 cm) regions of the FRC along the chords (x = -4, -2, 2 and 4 cm) measured by the IDS. Hereafter, positive values refer to the diamagnetic direction for the main compression magnetic field on the positive side of x axis. At z = 33 cm, the flipped rotation direction has not been observed. The toroidal flow has a diamagnetic direction from the beginning of equilibrium.

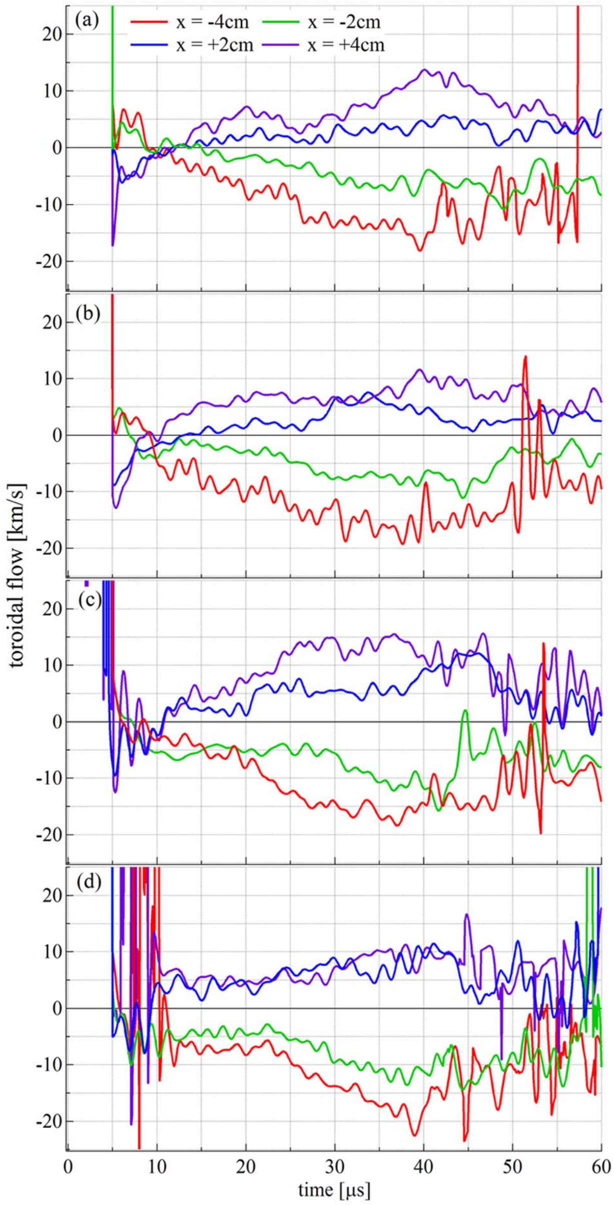

Fig. 2 Time evolution of toroidal flow along the chords at (a) z = 16.5 cm, (b) 22.0 cm, (c) 27.5 cm and (d) z = 33.0 cm.

3.2 Radial profile of toroidal flow velocity

In the case with Mach probe measurements, θ-preionization has been employed to avoid a breakdown onto the internal probes. Typical parameters in this case at the equilibrium phase of this experiment are 3.6×10^{21} m^{-3}, T_i: 90 eV, $r_s(0)$: 0.05 m, l_s: 0.84 m, particle confinement time: 60 μs and decay time of poloidal flux: 80 μs.

Figure 3 shows the time evolution of the toroidal flow velocity at z = 11 cm along the chords (x = -4, -2, 2 and 4 cm) measured by the IDS system. The curves have higher fluctuation levels though denote the same behavior as with the case of z preionization. Figure 4 shows the time evolution of the Mach number at the midplane (z = 0) along the

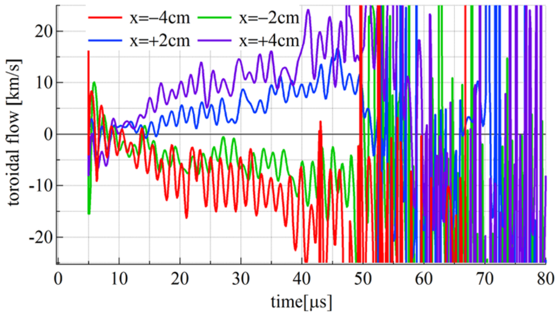

Fig. 3 Time evolution of toroidal flow at z = 11 cm in the case with θ pre ionization.

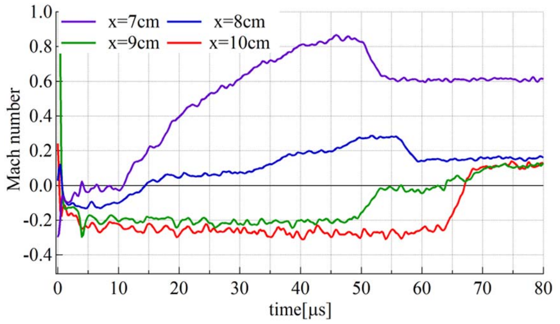

Fig. 4 Time evolution of Mach number at midplane.

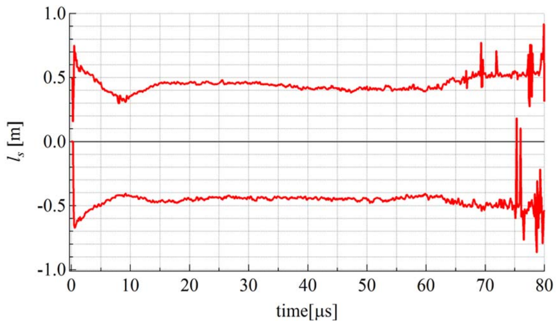

Fig. 5 Typical time evolution of separatrix length in the case with z pre ionization.

chords (x = 7, 8, 9 and 10 cm). Here, the positive sign indicates plasma flow in the direction diamagnetic to the main field, the same as was indicated in IDS measurements. The result indicates gradually propagated diamagnetic direction of toroidal flow outwards. Then, the paramagnetic rotation direction is being reversed into the diamagnetic one. Then Mach number is increased depending on the distance from the separatrix surface.

Also, reversal timing of rotation direction has a dependence on radial distance from the core plasma. This may indicate that the torque of toroidal rotation is transferred outward to weakly ionized plasma in the scrape-off region.

Table 1 Summary of theoretical predictions.

Mechanism	Plasma rotation	Ion flow (inside)	Ion flow (out side)
Particle loss [1]	Diamag	Diamag	Paramag
End-shorting [2]	Diamag	Diamag	Diamag
Flux decay [3]	Diamag	Diamag	Diamag

4. Discussion

Table 1 shows the past proposed theoretical predictions. Inside the separatrix, the optically observed acceleration direction is diamagnetic and is consistent with the theoretical predictions in Table 1. However, experimental observation indicates direct spin-up of core FRC plasma and its propagation out to the peripheral region. This is discrepant to the prediction of end shorting and particle loss. Furthermore, the initial rotation in a paramagnetic direction in the very first stage of discharge has not been explained in any previous theoretical work. Quick build-up of magnetic flux is one of the possible driving forces of this initial rotation.

An axial difference in the spin-up process has been observed in this series of experiments. Reversing the rotation direction is caused earlier on both ends of the FRC plasma column. The rotation of paramagnetic direction has not been observed at z = 33 cm. These indicate the relation between the build-up of magnetic configuration and spin-up. In addition, relative measurement position on the FRC plasma is varying especially at the first phase of discharge because of the dynamic axial contraction of FRC (Fig. 5). Therefore, observation of relative measurement position has to be performed in detail for further discussion of the spin-up process, especially until the axial contraction phase.

As shown in Fig. 4, the scrape-off plasma has a radial difference of reversal timing depending on the distance from the geometrical axis. This indicates that a toroidal torque is transferred outward gradually into weakly ionized plasma in the edge region potentially by the viscosity.

Both optical and probe measurements indicate paramagnetic rotation of plasma at the initial stage of the FRC discharge, which provides a mechanism that torques bulk plasma inside a chamber.

5. Summary

Detailed flow profile and its time evolution have been observed with an IDS system and a Mach probe for the first time. They reveal that the toroidal rotation of the FRC plasma has axial and radial structure. The acceleration direction is consistent with previous theoretical works. However, spatial distribution and its time evolution contradict those mechanisms except in the flux decay spin-up model. This also may explain the initial paramagnetic rotation of

FRC.

Conveyance of flow from the core FRC region to the scrape-off plasma region has also been observed. This viscosity potentially has a stabilization effect on the core plasma, especially on the global tilt motion. Detailed observation and discussion have proceeded and the results will be presented elsewhere.

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