Spatial Distribution of Toroidal Flow in a Field-Reversed Configuration

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A radial profile of toroidal flow in a field-reversed configuration plasma has been measured with a newly built ion Doppler spectroscopy system with a line-spectrum of impurity carbon (CV: 227.2nm). With this system, radial profile of toroidal flow was observed preliminary on the theta-pinch FRC plsma. The toroidal flow inside the separatrix starts to spin-up just after the formation and the flow velocity is gradually increased. The velocity is comparable with an ion diamagnetic velocity at 25μs from the formation. However, the flow velocity out side the separatrix keeps small value or settled. It indicates the existence of flow shear in vicinity of the separatrix. The observed results were also compared with a numerical calculation by newly proposed toroidal spin-up mechanism which employs direct conversion of the kinetic angular momentum from the magnetic flux [T. Takahashi, *et al.*, Plasma Fusion Res. **2** (2007) 008]. The calculated results are consistent with the presented experimental results.

Keywords: field-reversed configuration, n = 2 mode rotational Instability, toroidal flow, flow shear, toroidal spin-up

1. Inroduction

Rotational instability with toroidal mode number n = 2 is the only destructive instability in a field-reversed configuration (FRC) plasma. Also, the toroidal velocity shear potentially has a stabilization effect on an interchange instability with highr toroidal mode numbers $n \geq 3$. Therefore, investigation of mechanism of toroidal spin-up and its spatial structure are longstanding problems in the FRC research to improve confinement and stability property. The toroidal plasma current just after formation is primarily carried by electrons, while ions are approximately at rest [1]. The ions, however, gradually gain angular momentum in the direction with the ion diamagnetic before the onset of the n = 2 deformation due to rotational instability. The mechanism of toroidal spin-up has been discussed theoretically with several possible mechanisms of selective loss of ions [2-4], end-shorting [5-8], and both [9]. However, only a few experimental investigations have been performed so far.

In this work, radial velocity profile of toroidal flow in a FRC plasma has been measured with a newly built ion Doppler spectroscopy (IDS) system in detail. From the ion Doppler shift measurement of impurity ions, radial profile of toroidal flow and its time evolution are observed preliminary on the theta-pinch FRC plasma.

The experimental observation will also be compared with the newly proposed toroidal spin-up mechanism, which employs direct conversion of the kinetic angular momentum from the magnetic flux [10].

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2. Experimental Apparatus and Diagnostic

Figure 1 shows a schematic view of experimental apparatus and diagnostic. The FRC plasma is formed by a negative-biased theta-pinch method in the Nihon University Compact Torus Experiment (NUCTE) –III device.

The device has a 1.5m one-turn solenoidal theta-pinch coil. It consists a center confinement coil with a diameter of 0.34m and a length of 1.0m and a mirror coil with a diameter of 0.30m and a length of 0.25m at the both end. A ratio of the passive mirror is about 1.22. A slow bank with 5kV-1980μF and a first bank with 32kV-67.5μF are connected with the theta pinch coil through a collector plate. The coil produces a bias field up to 0.064T with a rising time of 90ms and a

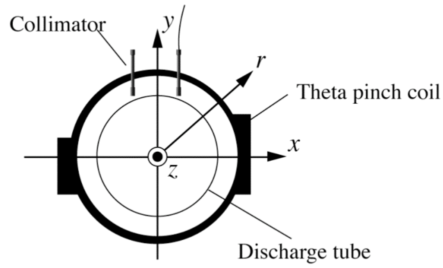

Fig.1 Toroidal section of NUCTE-III device and arrangement of collimators for IDS.

confinement field up to 0.6T with a rising time of 4ms and a decay time of 120μs. The transparent fused silica discharge tube with a diameter of 0.256m and a length of 2.0m is evacuated to about 1.5×10^{-4} Pa using a turbo molecular pump. A 10mTorr of deuterium gas is filled and pre-ionized by a *z*-discharge method.

An axial separatrix profile ($r_s(z)$) is observed by an excluded flux measurement. An averaged electron density ($\bar{n}_e$) is estimated by a line integrated electron density, which is measured by a quadrature 3.39μm He-Ne laser interferometer on the midplane (z = 0). A total plasma temperature ($T_t = T_i + T_e$: sum of a ion and electron temperature), is calculated from a radial pressure and an axial force balances,

$$T_t = (1 - 0.5(r_s/r_w)^2)B_e^2/2\mu_0\bar{n}_e \,. \qquad (1)$$

A poloidal flux and its time evolution can also be estimated by the equation,

$$\phi_p = 0.32\pi r_s(0)^2 B_e/r_w \qquad (2)$$

which is given by the assumption of a rigid rotor profile equilibrium model.

The IDS system consists of a collector with f = 100 convex-plane lens, a quartz optical fiber tube with 5m of length, a Czerny-Turner grating monochrometer, and a 16

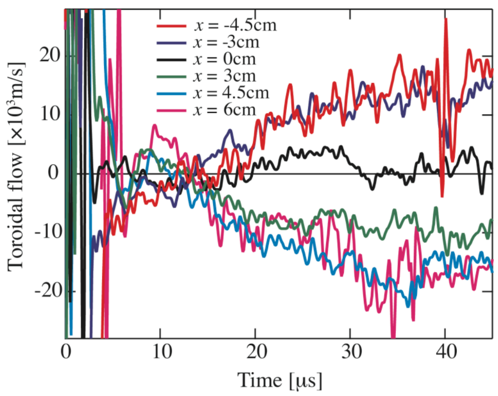

Fig.2 Time evolution of toroidal flow velocity measured by the IDS measurement.

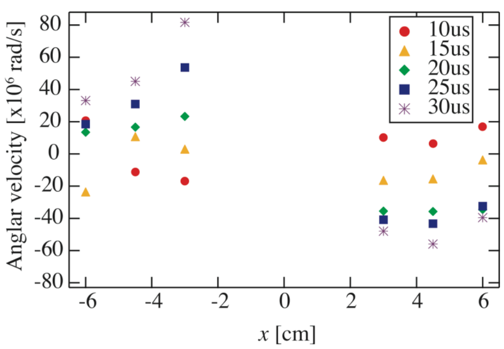

Fig. 3 Time evolution of radial profile of toroidal angular velocity.

channels photo-multiplier tube (PMT). Dispersed light is magnified by a cylindrical lens with a diameter of 5 mm and detected on the PMT. An impurity line intensity of CV (227.1nm) emitted from the FRC plasma is collected by the collector and transferred to the IDS system through the optical fiber tube. Wavelength resolution and sensitivity between channels are calibrated by Hg line spectrum of 254 nm. The optical resolution per channel is about 0.05 nm in the system. From the obtained shift and broadening of the line spectrum, ion temperature and ion flow velocity. To confirm a motion of the FRC plasma and reproducibility of FRC formation, a visible light multi-channel optical detector is arrayed in the *x*-direction at the same toroidal cross section with the IDS.

3. Experimental Results

Typical FRC plasma parameters of this experiment at equilibrium phase (t = 20 μs) are $\bar{n}_e$: 2×10^{21} m^{-3}, T_t: 190 eV, $r_s(0)$: 0.06 m, Trapped poloidal flux: 0.5 mWb, particle confinement time: 80 μs and decay time of poloidal flux: 100 μs.

Figure 2 shows the time evolution of the toroidal flow velocity at the midplane along the chords (x = - 4.5, -3, 0, 3, 4.5 and 6 cm) measured by the IDS system. The rotation velocity already has a finite value just after formation period of field-reversal phase. The velocity of CV ion is increased gradually during the equilibrium phase. The rotation velocity at 20 μs is approximately 10 km/s at x = ±4.5 cm. The measured velocity and direction are corresponded to the ion diamagnetic drift. Flow velocity on the chord at x = 0 is almost at rest during the discharge.

The time evolution of radial profile of toroidal flow is shown in Fig.3. The radial profile of toroidal velocity is almost flat in the very early phase of FRC discharge pulse. However, the rotation velocity outside of the separatrix is not accelerated compared to the rotation inside of the separatrix. It indicates the existence of velocity shear near the separtrix. The stability effect of this observed shear on higher toroidal mode number of interchange instability could be a reason why the higher mode of toroidal deformation predicted in the theoretical works has never been observed in the FRC experiments. In Table 1, the results of these toroidal flow measurements are summarized.

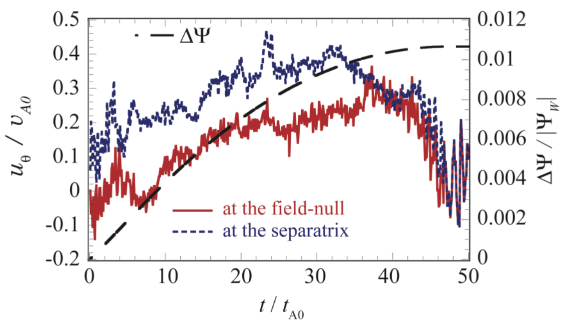

Fig. 4 Time evolution of the flux decay and numerically calculated troidal flow velocity.

Table 1 Summary of experimental results

Position	Rotation direction	Radial profile
Inside of Separatrix	Diamagnetic	Uniform (like rigid body)
Outside of Separatrix	No rotation	-

Table 2 Summary of past theoretical predictions

Mechanism	Plasma rotation	Ion flow (inside)	Ion flow (outside)
Particle loss	Diamagnetic	Diamagnetic	Paramagnetic
End-shorting	Diamagnetic	Diamagnetic	Diamagnetic

4. Discussion

The past proposed theoretical predictions are summarized in Table 2. The presented experimental results show faster spin-up of the plasma column inside the separatrix. Also directions of the toroidal flow are same with ion diamagnetic direction. It is not consistent with past theoretical prediction of toroidal ion spin-up shown in Table 2. Recently, some of the authors have proposed new mechanism of toroidal spin-up [10]. In the scenario, flux decay is directly converted toroidal momentum of ions. Under the assumtion of axisymmetry and canonical momentum conservation, every ion gains angular momentum in the ion diamagnetic direction when the polodial flux decays. While the flux is decreasing, change of ion trajectory type, *i.e.* figure-8 shape trajectory changes into betatron one results in increment of the toridal angular momentum. Inductive electric field by the poloidal flux decay is also a possible cause of the rotation.

To compare the experimental result with the new theory, particle simulation has been performed taking into account of these possible sources of ion spin-up for the plasma parameter in the presented experiment. Figure 4 indicates the calculated time evolution of the flux decay and the toroidal flow velocity. The time, the toloidal flow velocity and the decay flux are normalized by Alfven time

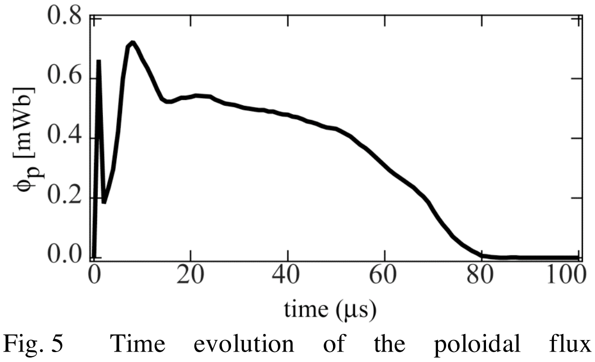

Fig. 5 Time evolution of the poloidal flux estimated under the assumption of rigid rotor profile model.

t_{A0}, Alfven velocity v_{A0} and the magnetic flux at coil wall Ψ_W, respectively. In this calculation, toroidal flow velocity is shown as a function of the amount of change in the poloidal flux $\Delta\Psi$. In this experiment, Alfven velocity and Alfven time are about 140 km/s and 1.2 μs. Figure 5 shows the time evolution of the poloidal flux which is obtained experimentally on the NUCTE-III FRC. In Fig. 3, the decayed flux can be estimated about 0.31mWb. Also decayed flux in the experiment is about 0.12mWb for 40μs of equilibrium phase. The normalized toroidal flow velocities in the experiment and the calculation at 35 t_{A0} are 0.15 v_{A0} and 0.25 v_{A0}, respectively. The calculation is consistent with the presented experiment results. It will be expanded to discuss the radial profile of flow.

5. Summary

Investigation of the toroidal flow profile and its time evolution has been started with both methods of experiments and numerical approach. Experimentally observed flow profile is not consistent with past theoretical predictions. Then the experimental results are compared with the newly proposed theory and it is shown that the calculated result agrees with the experimental result. Detailed flow profile measurements and confirmation of the new theory will be continued.

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