Observation of Toroidal Flow on LHD

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In order to investigate the formation of toroidal flow in helical systems, both NBI driven flow and spontaneous toroidal flow are observed in the Large Helical Device (LHD). The toroidal flow driven by NBI is dominant in the plasma core while the contribution of the NBI driven toroidal flow is small near the plasma edge. The spontaneous toroidal flow changes its direction from co to counter when the radial electric field is changed from negative to positive at the plasma edge. The direction of the spontaneous toroidal flow due to the radial electric field near the plasma edge is observed to be opposite to that in the plasma core where the helical ripple is small.

Keywords: Toroidal Flow, Spontaneous Flow, Charge Exchange Spectroscopy

1. Introduction

The transport in the plasma is considered to be sensitive to the profile of flow velocity. A moderate shear of poloidal flow can suppress the turbulence and reduce the transport. On the other hand, it has been pointed out that the toroidal flow contributes the stabilization of resistive wall mode in tokamaks [1]. Therefore the spontaneous toroidal flow becomes important in the next fusion device such as ITER, where the toroidal flow velocity driven by external momentum is expected to be not enough to stabilize the MHD mode. The mechanism of driving the spontaneous toroidal flow has a great interest in the momentum transport physics and has been investigated in tokamaks experimentally and theoretically [2-8].

Besides the toroidal flow driven by the external momentum input of neutral beam injected tangentially, there is the spontaneous toroidal flow driven by the coupling of ExB force and viscosity tensor. Stress tensor re-directs some fraction of diamagnetic and ExB flows into parallel flows. The radial electric field can be controlled by changing the collisionality as predicted by neoclassical transport in the helical system. The radial electric field at the plasma edge changes its sign from negative to positive by reducing the electron density in the NBI plasma, while the radial electric field in the plasma core becomes positive by applying the center focused ECH to NBI plasma in LHD. There are three NBI tangentially injected; one is injected in CW direction and the other two are injected in CCW direction. The various combinations of these three beams give the scan of momentum input to the plasma in the wide range. Both the toroidal and poloidal rotation velocities are measured with the charge exchange spectroscopy using the charge exchange line of fully ionized carbon. In this paper, we will report the observations of both the NBI driven toroidal flow and spontaneous toroidal flow in helical plasma.

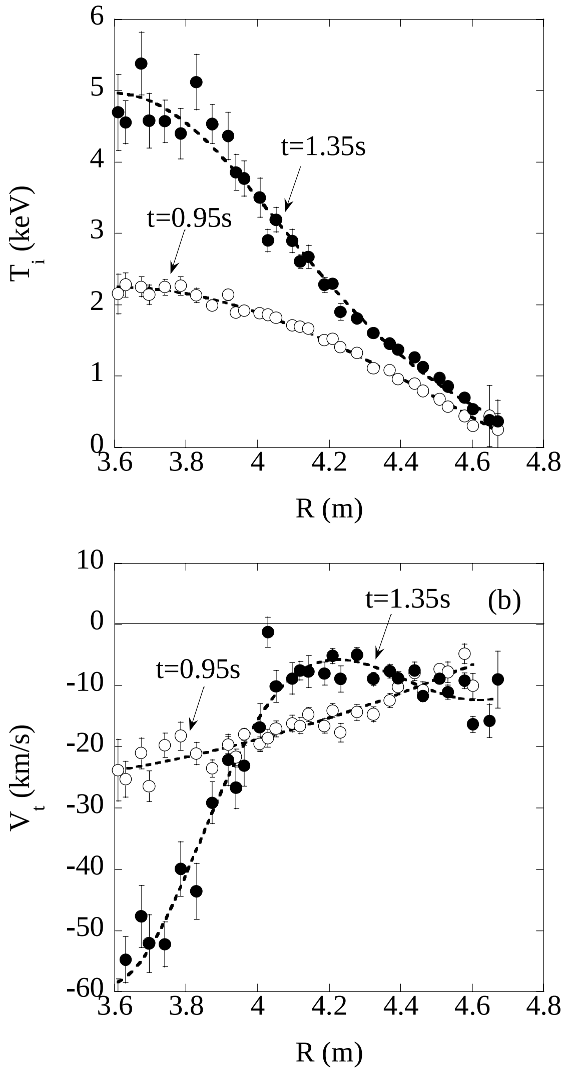

Fig.1 Radial profiles of (a) ion temperature and (b) toroidal flow velocity before (open circle) and after (close circle) the injection of tangential neutral beams in the plasma with R_{ax}=3.6m, B=2.85T **and** γ=1.254.

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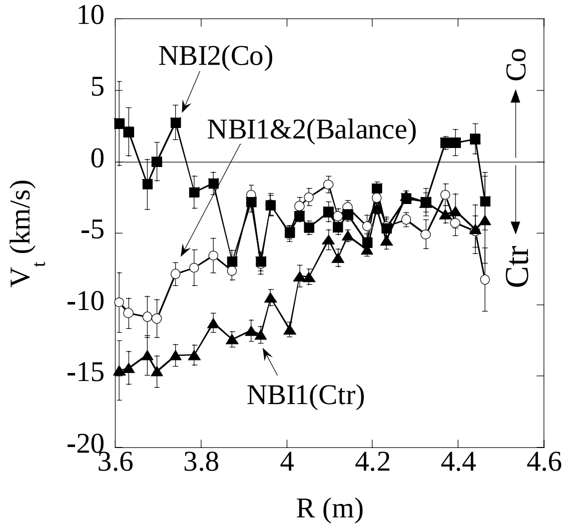

Fig.2 Radial profiles of toroidal flow velocity in the plasma with R_{ax}=3.6m, B=1.5T and γ=1.174. The tangential NBI is selected for co-injection (square), counter-injection (triangle), and balanced injection (circle).

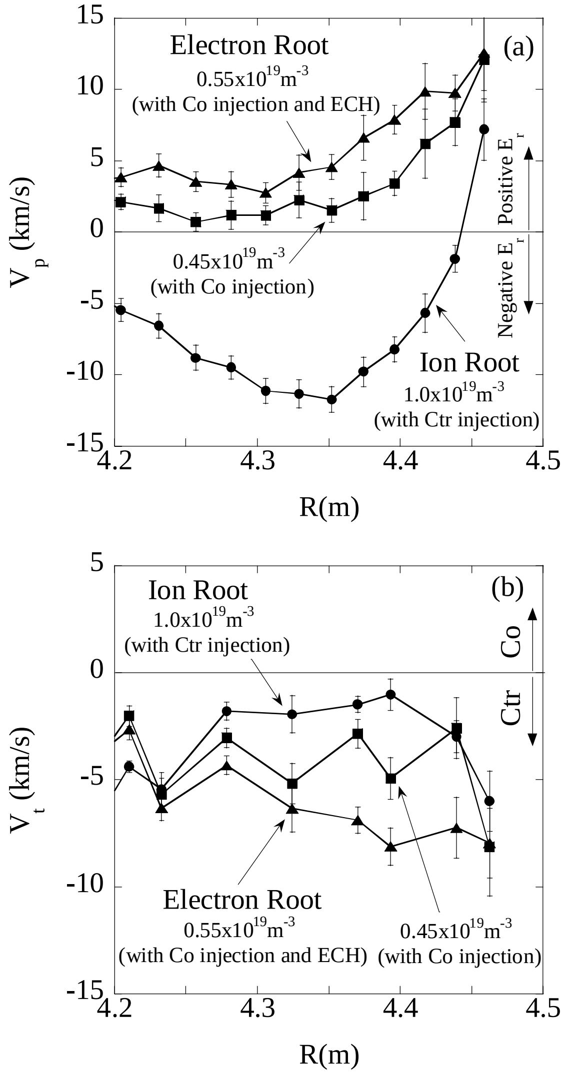

Fig.3 Radial profiles of (a) poloidal rotation velocity and (b) toroidal rotation velocity near the plasma edge in the case of electron root (triangle and square) and ion root (circle), in the plasma with R_{ax}=3.6m, B=1.5T and γ=1.174.

2. Lines of Sight of CXS on LHD

The charge exchange spectroscopy (CXS) has been widely used to measure the profiles of ion temperature, toroidal flow velocity, and impurity in neutral beam injected plasmas. In LHD, charge exchange line of the fully ionized carbon is used for the CXS measurement. The extreme hollow profile of carbon impurity is observed associated with the peaking of the ion temperature profile in LHD. Because of the finite beam width comparable to the half of the plasma minor radius, the integration effect along the line of sight can be a serious problem in the poloidal view when the carbon density profile become hollow. Therefore the CXS measurements with the toroidal view are applied to measure the ion temperature more accurately in the plasma with peaked ion temperature where the carbon density profile tends to be hollow. Figure 1 shows the example of the CXS measurement with toroidal line of sight in the plasma with the magnetic axis R_{ax} of 3.6m, magnetic field strength B of 2.75T, pitch parameter γ of 1.254 and counter dominant neutral beam injection. The central ion temperature achieved to 4.5keV after the injected of three tangential neutral beams. The increase of the ion temperature gradient and strong toroidal flow near the magnetic axis in the direction parallel to the momentum input of NBI are observed. The spontaneous toroidal flow in the opposite direction to NBI is observed at the mid minor radius (R=4.2m) where the ion temperature gradient becomes steep. Thus, the combination of NBI driven flow near the plasma core and the spontaneous flow at mid minor radius produces the interesting radial profile of toroidal flow.

3. NBI driven Toroidal Flow

Figure 2 shows the radial profiles of the toroidal flow velocity in the plasma with co-injected (parallel to the equivalent toroidal plasma current), counter-injected (anti-parallel to the equivalent toroidal plasma current), and balance-injected of tangential NBI. The toroidal flows in the counter-direction are observed whole the major radius in the plasma with balance-injected NBI shows the existence of spontaneous component. The toroidal flow

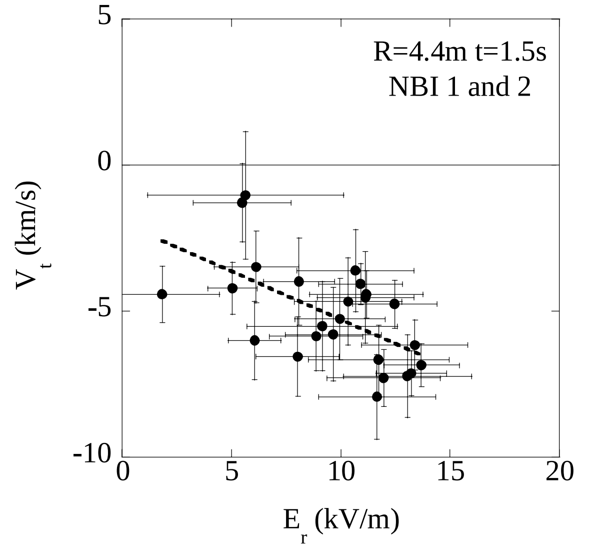

Fig.4 Dependence of toroidal rotation velocity on radial electric field at R=4.4m in the plasma with R_{ax}=3.6 m , B=1.5T and γ=1.174.

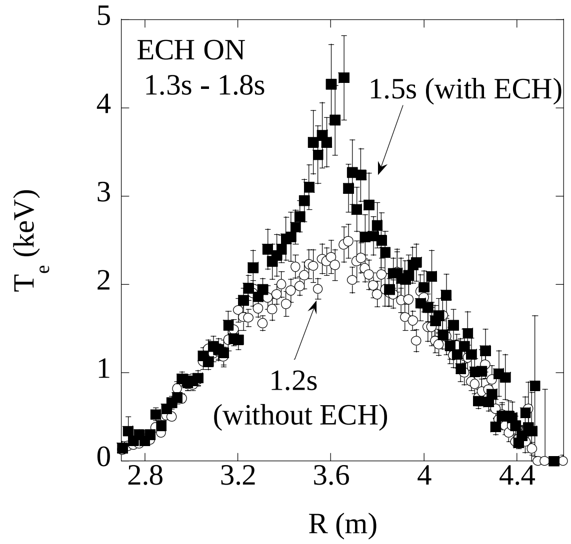

Fig.5 Radial profile of electron temperature with (square) and without (circle) ECH in the plasma with R_{ax}=3.6m, B=1.5T and γ=1.174.

near the magnetic axis depends on the direction of NBI, while no significant change of toroidal flow is observed near the plasma edge. It is suggested that the NBI driven toroidal flow is small at the plasma edge, because of the strong helical ripple and small deposition of the NBI power. Therefore the effect of the radial electric filed on the spontaneous flow becomes more visible at the edge.

4. Spontaneous Toroidal Flow at the Edge

Figure 3 shows profiles of poloidal flow and toroidal flow near the plasma edge where the effect of the radial electric filed on the spontaneous flow is large. The poloidal flow, which has a dominant contribution to the radial electric field, is changed from negative value to positive value by decreasing the plasma density and by increasing the heating power. The magnitude of the toroidal flow velocity in the counter direction increases when the sign of the poloidal flow velocity changes from negative value (E_r < 0 : the ion root) to positive value (E_r > 0 : the electron root). Figure 4 shows the relation between the toroidal flow velocity and on the radial electric field at the plasma edge (R=4.4m). The counter flow (negative) increases when the radial electric field becomes more positive. Theses results are consistent with the experiment in CHS, where the spontaneous toroidal flow in the counter direction appears associated with the transition from the ion root with small negative E_r to the electron root with large positive E_r [9]. It should be noted that the direction of the spontaneous toroidal flow is anti-parallel to the direction of $\langle E_r x B_\theta \rangle$ drift. The spontaneous toroidal rotation flows in the direction reducing the radial electric field rather. This is

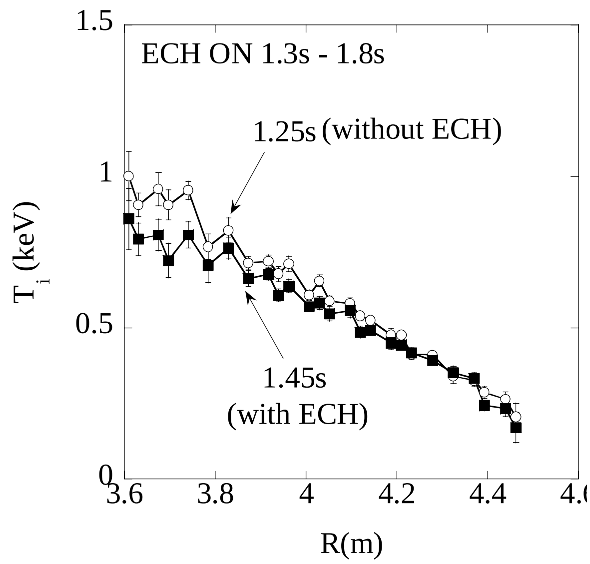

Fig.6 Radial profile of ion temperature with (square) and without (circle) ECH in the plasma with R_{ax}=3.6m, B=1.5T and γ=1.174.

because the viscosity tensor re-directs some fraction of ExB flows into the direction of minimum gradient of magnetic field strength. The direction of the parallel flows re-directed by the viscosity in helical plasma is opposite to that in tokamaks because the pitch angle of minimum gradient B is larger than the pitch angle of magnetic field averaged in magnetic flux surface in helical plasma, while the pitch angle of minimum gradient B is zero in tokamaks.

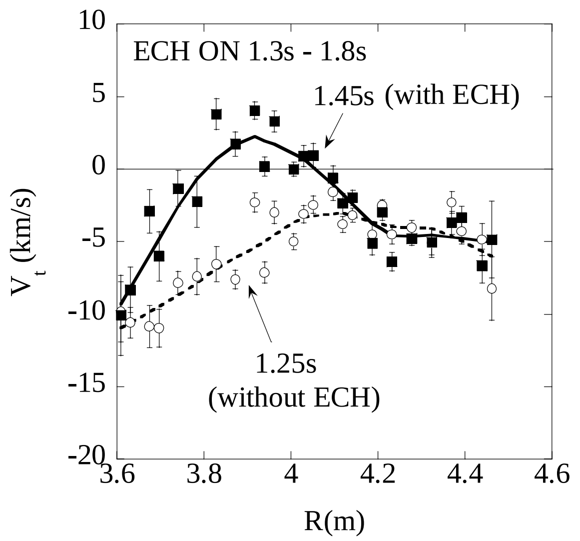

Fig.7 Radial profile of toroidal rotation velocity with (square) and without (circle) ECH in the plasma with R_{ax}=3.6m, B=1.5T and γ=1.174.

5. Spontaneous Toroidal Flow in the Core

The improvement of electron heat transport near the magnetic axis (electron ITB) is observed in various helical systems by applying the center focused ECH to the low density plasma [10-13]. When the transition to the electron ITB takes place, the positive radial electric field is formed in the plasma core. The spontaneous toroidal flow driven by the ExB flow associated with the electron ITB is observed in the plasma core. The tangential NBI is balanced to make the NBI driven toroidal flow to be minimized small in the plasma core. The profiles of the electron temperature, the ion temperature and the toroidal flow velocity in the plasma with and without the ECH are shown in Fig 5, Fig. 6 and Fig.7, respectively. The electron ITB profile is observed in the electron temperature profile during the ECH pulse (t=1.3–1.8 sec) while no significant change in the ion temperature profile is observed. Associated with the transition to electron ITB, which is characterized by the peaked electron temperature, a large positive radial electric field appears in the plasma core [10] as predicted by neoclassical theory. The toroidal flow in the co-direction during the ECH is clearly observed. This result shows that the positive electric field drives the toroidal flow in the co-direction in the plasma core where the modulation of the magnetic field due to helical ripple is smaller than that due to toroidal effect ($\varepsilon_h < \varepsilon_t$). The direction of the spontaneous toroidal flow near the magnetic axis is parallel to the direction of $\langle E_r x B_\theta \rangle$ drift, which is in contrast to the spontaneous toroidal flow anti-parallel to the direction of $\langle E_r x B_\theta \rangle$ drift near the plasma edge as shown in Fig.3 and Fig.4.

In tokamak, the spontaneous toroidal rotation in the counter direction is observed in the plasma with negative E_r as reported in JFT-2M [3]. The spontaneous toroidal rotation becomes most significant in the ITB region where the strong negative E_r appears [14]. The direction of the spontaneous toroidal rotation in tokamaks is parallel to the direction of $\langle E_r x B_\theta \rangle$ drift.

6. Summary

Radial profiles of the plasma flow velocity both in the toroidal direction and poroidal direction are measured with the charge exchange spectroscopy using the charge exchange line of fully ionized carbon. Toroidal flow parallel to the momentum input of NBI is observed to be localized in the core region of the plasma. The relations between the spontaneous toroidal flow and radial electric field are investigated and the positive radial electric field drives spontaneous rotation in the counter direction near the plasma edge and in the co direction near the magnetic axis. This observation shows the spontaneous rotation near the magnetic axis is opposite to that near the plasma edge. The difference in the direction of spontaneous flow between core and edge is considered to be due to the difference in the ratio of the toroidal effect to the helical ripple. In LHD, the spontaneous toroidal flow re-directed ExB flow by the viscosity tensor in the core region is parallel to that observed in tokamaks, while the spontaneous toroidal flow near the plasma edge is anti-parallel to that in tokamak.

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