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 were observed in Large Helical Device (LHD). The toroidal flow driven by NBI is dominant in plasma core while its contribution is small near 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 plasma edge. The direction of the spontaneous toroidal flow due to the radial electric field near plasma edge is observed to be opposite to that in plasma core where the helical ripple is small.

Keywords: toroidal flow, spontaneous flow, charge exchange spectroscopy

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1. Introduction

The transport in 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 toroidal flow contributes to the stabilization of resistive wall mode in tokamaks [1]. Therefore, spontaneous toroidal flow becomes important in the next fusion devices such as ITER, where the toroidal flow velocity driven by external momentum is expected to be insufficient to stabilize the MHD mode. The mechanism of driving the spontaneous toroidal flow is interesting from the viewpoint of momentum transport physics and has been investigated in tokamaks, both experimentally and theoretically [2–8].

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

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2. Lines of Sight of CXS on LHD

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 fully ionized carbon is used for the CXS measurement. The extreme hollow profile of carbon impurity is observed to be associated with the peak of the ion temperature profile in LHD. Because the finite beam width is 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 becomes hollow. Therefore, the CXS measurements in the toroidal view are applied to measure the ion temperature more accurately in the plasma with peak 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 a plasma with the magnetic axis R_{ax} of 3.6 m, magnetic field strength B of 2.85 T, pitch parameter γ of 1.254, and counter-dominant neutral beam injection (deposition power is 6.8 MW with counter-beam and 3.1 MW with co-beam). The central ion temperature reached 4.5 keV after injection of three tangential neutral beams. The increase in 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 strong toroidal flow driven by NBI is accompanied by high ion temperature at the plasma core. This is the result of effective heating with parallel NBI. The spontaneous toroidal flow in the counter-direction (negative) is observed at all radial positions before the injection of parallel NBI. The spontaneous toroidal flow in the opposite direction to the dominant NBI is observed at the mid-minor radius (R = 4.2 m), where the ion temperature gradient be-

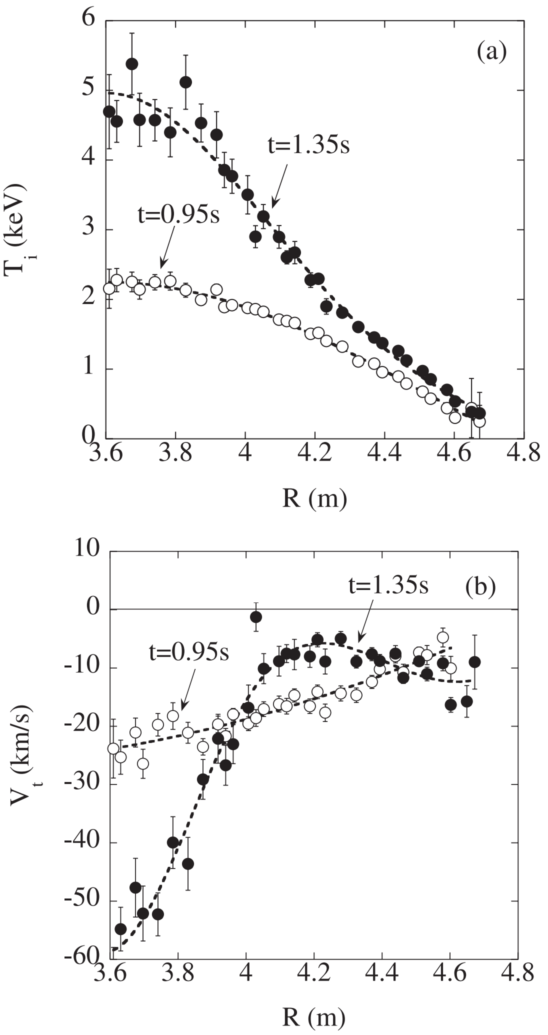

Fig. 1 Radial profiles of (a) ion temperature and (b) toroidal flow velocity before (open circle) and after (close circle) the injection of tangential neutral beams in the plasma with R_{ax} = 3.6 m, B = 2.85 T, and γ = 1.254.

comes steep after the injection of the parallel NBI. Thus, the combination of NBI driven flow near the plasma core and the spontaneous flow at the 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 tangential NBI. The toroidal flow in the counter-direction, which is observed along the entire major radius in the plasma with balance-injected NBI, shows the existence of a spontaneous component. The toroidal flow 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, as a result

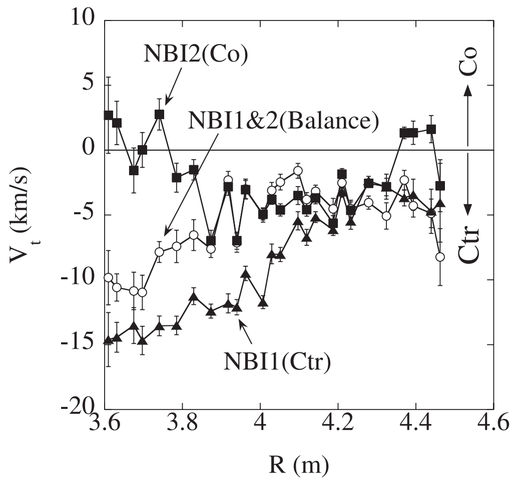

Fig. 2 Radial profiles of toroidal flow velocity in the plasma with R_{ax} = 3.6 m, B = 1.5 T, and γ = 1.174. Tangential NBI is selected for co-injection (square), counter-injection (triangle), and balanced injection (circle).

of the strong helical ripple and small deposition of the NBI power. Therefore, the effect of the radial electric field on the spontaneous flow becomes more apparent at the edge.

4. Spontaneous Toroidal Flow at the Edge

Figure 3 shows profiles of poloidal and toroidal flows near the plasma edge, where the effect of the radial electric field on the spontaneous flow is large. The sign of poloidal flow, which has a dominant contribution to the radial electric field, is changed from negative to positive by decreasing the plasma density and 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 ($E_r < 0$: the ion root) to positive ($E_r > 0$: the electron root). The ratio of the helical ripple to the toroidal ripple, $\varepsilon_h/\varepsilon_t$, is 4.17 at R = 4.35 m. Figure 4 shows the relation between the toroidal flow velocity and the radial electric field at the plasma edge (R = 4.4 m). The counter flow (negative) increases when the radial electric field becomes more positive. These results are consistent with an 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 $<E_r \times B_\theta>$ drift. The spontaneous toroidal flow is driven in the opposite direction, thereby reducing the radial electric field. This is because the viscosity tensor re-directs some fraction of $E \times B$ flows into the direction of minimum gradient of magnetic field strength. The direction of the parallel flow re-directed by the viscosity in helical plasma is opposite to that in tokamaks, because the pitch angle of minimum gradient B is

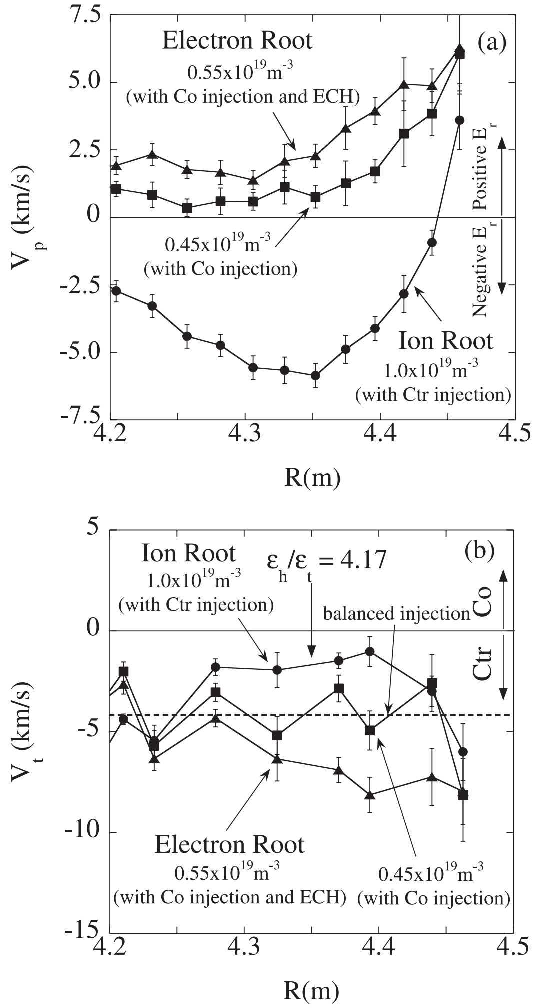

Fig. 3 Radial profiles of (a) poloidal flow velocity and (b) toroidal flow velocity near the plasma edge in the case of electron root (triangle and square) and ion root (circle), in the plasma with R_{ax} = 3.6 m, B = 1.5 T, and γ = 1.174. Dashed line indicates the Vt with the balanced injection of NBI.

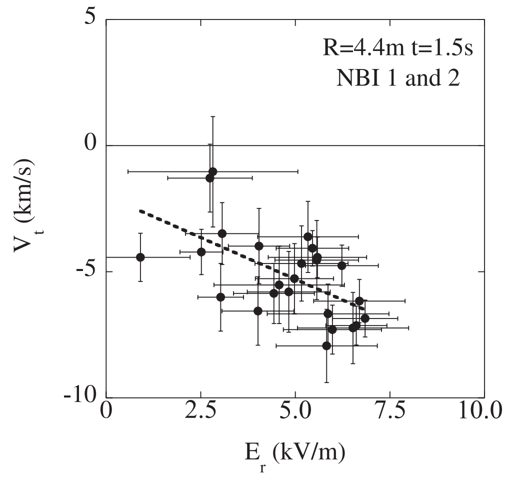

Fig. 4 Dependence of toroidal flow velocity on radial electric field at R = 4.4 m in the plasma with R_{ax} = 3.6 m, B = 1.5 T, and γ = 1.174.

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.

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 a center-focused ECH to a low-density plasma [10–13]. When the transition to the electron ITB occurs, the positive radial electric field is formed in the plasma core. The spontaneous toroidal flow driven by the $E \times B$ flow associated with the electron ITB is observed in the plasma core. The tangential NBI is balanced to minimize the NBI driven toroidal flow in the plasma core. The profiles of the electron temperature, ion temperature, and toroidal flow velocity in the plasma with and without the ECH are shown in Figs. 5, 6, and 7, respectively. The electron ITB profile is observed in the electron temperature profile during the ECH pulse (t = 1.3-1.8 s), while no significant change in the ion temperature profile is observed. Associated with the transition to the electron ITB, which is characterized by the peak electron temperature, a large positive radial electric field appears in the plasma core [13] as predicted by neoclassical theory. The toroidal flow in the co-direction is clearly observed during the ECH. The ratio of the helical ripple to the toroidal ripple, $\varepsilon_h/\varepsilon_t$, is 1.15 at R = 3.85 m. 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 comparable to that due to the toroidal effect ($\varepsilon_h \sim \varepsilon_t$). The direction of the spontaneous toroidal flow near the magnetic axis is parallel to the direction of $<E_r \times B_\theta>$ drift, which is in contrast

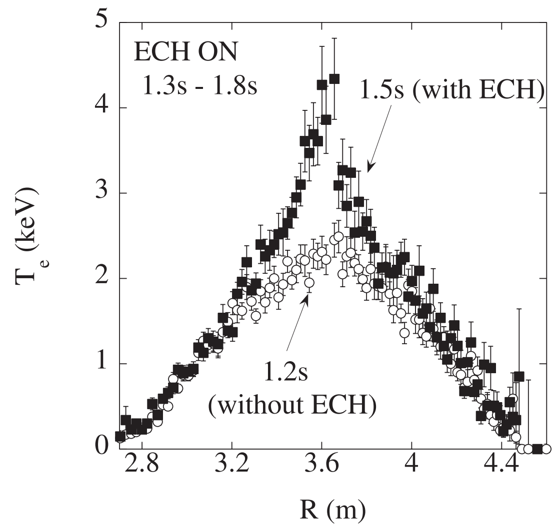

Fig. 5 Radial profile of electron temperature with (square) and without (circle) ECH in the plasma with R_{ax} = 3.6 m, B = 1.5 T, and γ = 1.174.

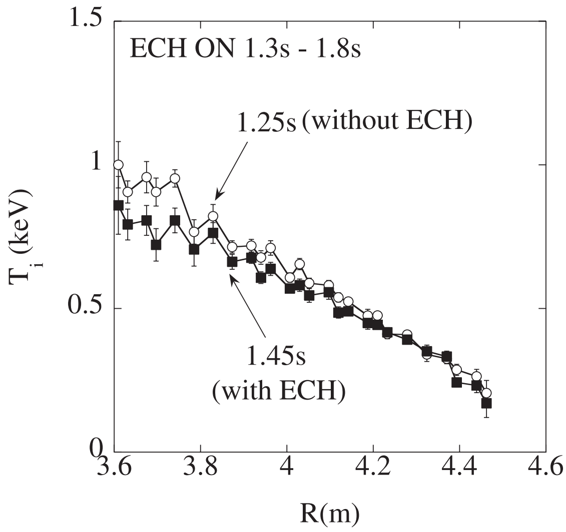

Fig. 6 Radial profile of ion temperature with (square) and without (circle) ECH in the plasma with R_{ax} = 3.6 m, B = 1.5 T, and γ = 1.174.

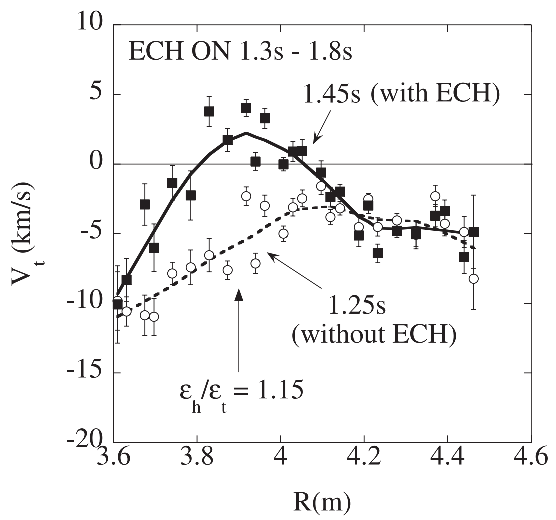

Fig. 7 Radial profile of toroidal flow velocity with (square) and without (circle) ECH in the plasma with R_{ax} = 3.6 m, B = 1.5 T, and γ = 1.174.

to the spontaneous toroidal flow anti-parallel to the direction of $<E_r \times B_\theta>$ drift near the plasma edge, as shown in Figs. 3 and 4.

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

6. Summary

Radial profiles of the plasma flow velocity in both the toroidal and poloidal directions are measured by CXS 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. The positive radial electric field drives the spontaneous flow in the counter direction near the plasma edge and in the co-direction near the magnetic axis. This observation shows that the spontaneous flow near the magnetic axis is opposite to that near the plasma edge. The difference in the direction of spontaneous flow between the core and the 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, with $E \times B$ flow re-directed 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 tokamaks.

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