Observations of Spontaneous Toroidal Flow on LHD

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Abstract. Spontaneous toroidal flows driven by radial electric field and ion temperature gradient are studied in the Large Helical Device (LHD). The positive radial electric field drives spontaneous flow in the counter direction at the plasma edge and in the co-direction near the magnetic axis. The difference in the direction of spontaneous flow between the core and the edge is considered to be due to the difference in a ratio of the helical ripple to the toroidal ripple. Ion temperature gradient causes the spontaneous toroidal flow is clearly observed and becomes one of a dominant component of the toroidal flows in the high ion temperature discharges in LHD.

1. Introduction

Flow structures in the plasma have been considered to be an important for the transport in magnetic confinement devices. A moderate shear of poloidal flow can suppress turbulence and reduce transport. And, it has been pointed out that the toroidal flow contributes the stabilization of resistive wall mode in tokamaks [1]. The velocity of toroidal flow driven by external momentum is expected to be not enough to stabilize the MHD mode in the next fusion device such as ITER, and the mechanism of spontaneous toroidal flow is watched with keen interest. There is a great interest in the driving mechanism of the spontaneous toroidal flow and the momentum transport physics of course, the spontaneous toroidal flow has been investigated in tokamaks experimentally and theoretically [2-8].

It is important for an investigation of the toroidal flows to distinguish the component of toroidal flows driven with the radial electric field and the ion temperature gradient, because a radial momentum flux is considered to be connected to a gradient of potential (electric field) and temperature as a coefficient of the off-diagonal terms. The ways to control the radial electric field have been studied on LHD. The radial electric field can be controlled by changing the collisionality as predicted with calculations of neoclassical transport in helical systems. 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 under the normal field configuration ($B > 0$). Various combinations of these three beams give scanning of an input power to the plasma in a wide range. The ion temperature and the momentum input for the direct driving of a toroidal flow are changed by controlling the input power. In this paper, we report observations of the toroidal flows and identification of the spontaneous toroidal flows driven by radial electric field and gradient of ion temperature by using the active controll of the radial electric field and the gradient of ion temperatures in LHD.

2. Observations of a NBI driven toroidal flow

Profiles of a toroidal flow driven by the injection of neutral beams are described in this section before the sections where the spontaneous flows are described in. The profiles of the toroidal flows are measured by the charge exchange spectroscopy (CXS) with toroidal lines of sight. The CXS has been used to measure the profiles of ion temperature, toroidal flow velocity, and impurity in neutral beam heated plasmas in LHD. The light emitted from the carbon impurity by a charge exchange between a fully ionized carbon in the plasmas and the neutral beam, which is perpendicularly injected into the plasma and has beam energy of 40 keV, is used for the CXS measurement.

Three neutral beams are injected tangentially into the plasma with the magnetic axis R_{ax} of 3.75 m, the magnetic field strength B of 2.64 T, the pitch parameter γ of 1.254 and the canceling rate of the quadrupole field B_q of 100%. Figure shows the radial profiles of the toroidal flow velocity in the plasma with the case of 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 torque of the tangential NBI is almost zero in the balance-injected NBI case. The toroidal flow in the counter-direction, which is observed whole the major radius in the plasma with balance-injected NBI, shows the existence of a spontaneous component. The large velocity of a toroidal flow is observed in the co-injected NBI case and counter-injected NBI case. The toroidal flow near the magnetic axis depends on the direction of the combinations of the NBIs, while no significant change of toroidal flow is observed near the plasma edge. It is suggested that the NBI driven toroidal flow is small near the plasma edge, because of the strong helical ripple and small deposition of the NBI power near the plasma edge. Therefore the effect of the radial electric field and ion temperature gradient on the spontaneous flow becomes more visible near the plasma edge.

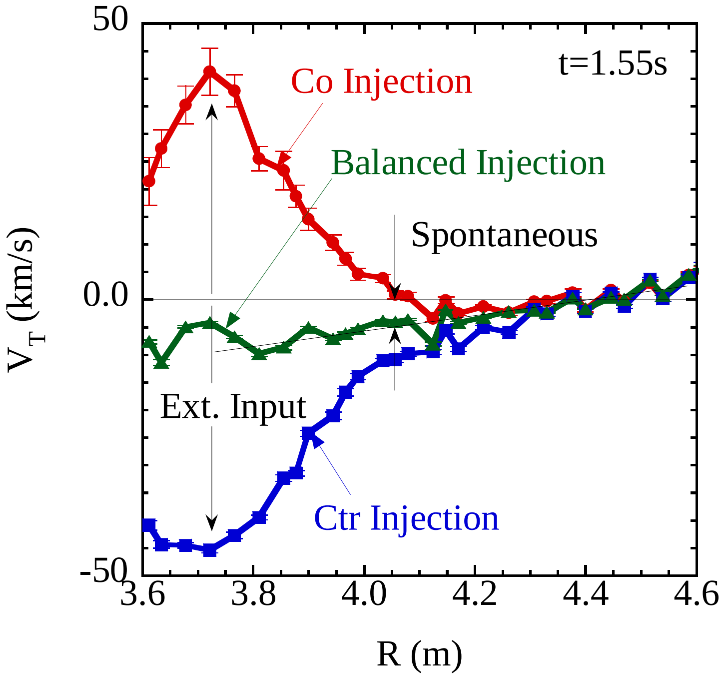

FIG. 1. Profiles of toroidal flow velocity in the plasma with co-injected NBI (circle), counter-injected NBI (square), and balanced-injected NBI (triangle).

3. Observations of Spontaneous Flows

3.1. E_r driven flow at the plasma edge

The spontaneous toroidal flow is expected to be driven by the coupling of ExB force and viscosity tensor. The viscosity tensor re-directs some fraction of ExB poloidal flows into the direction of minimum gradient of magnetic field strength, and the toroidal component of the flow will be produced. A radial electric field can be controlled by changing collisionality as predicted with the calculation of a neoclassical transport in helical systems independently of the direction of the toroidal flow externally driven by the NBIs.

To investigate the relation between the spontaneous toroidal flows and the radial electric field, we performed density scan experiments and control the radial electric field actively. The electron density is controlled with gas-puffing into the NBI plasma with R_{ax}=3.6 m, B=1.5 T, γ=1.174, and B_q=100%. Figure 2 (a) and (b) shows the radial profiles of the radial electric field E_r and toroidal flow velocity, respectively, near the plasma edge. The component of troidal flow driven by NBIs is very small near the plasma edge, and this is favorable to observation of the toroidal flow driven by the radial electric field. The radial electric field changes its sign from positive (ion root) to negative (electron root) associate with the increasing of electron density at the plasma edge. The magnitude of the toroidal flow in the counter direction increases when the E_r changes from negative to positive as shown in Fig.2 (b). Figure 3 shows the dependence of the toroidal flow on the radial electric field at the plasma edge (R=4.4m). The positive E_r drives the toroidal flow into the counter-direction, and this is 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 flow driven by the radial electric field is opposite to that in tokamaks. This is because the viscosity tensor re-directs some fraction of ExB flows into a direction of minimum-gradient of magnetic field strength B which is along to the helical symmetry. A projection of the minimum-gradient-B direction to a parallel-direction is opposite to that in tokamaks in which the pitch angle of minimum-gradient-B is zero. If the helical ripple is small as comparable as toroidal ripple, the direction of the spontaneous flow driven by an E_r will be expected to behave like tokamaks. The ratio of the helical ripple to the toroidal ripple $\varepsilon_h/\varepsilon_t$ is 4.17 at R=4.35 m in this experiment.

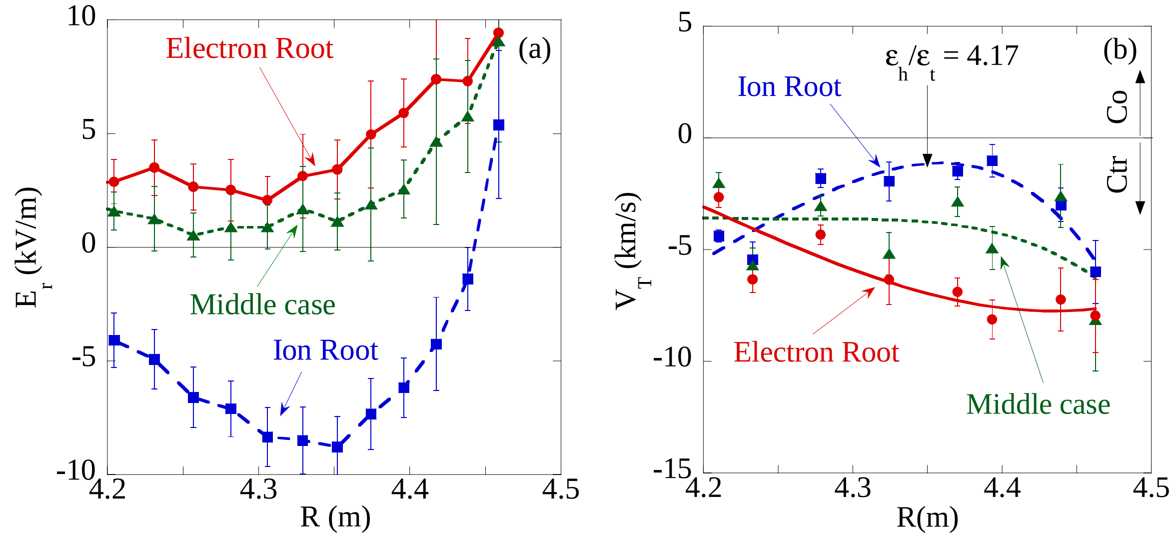

FIG. 2. Profiles of radial electric field and toroidal flow velocity near the plasma edge in the case of an ion root (squares) and an electron root (circles and triangles).

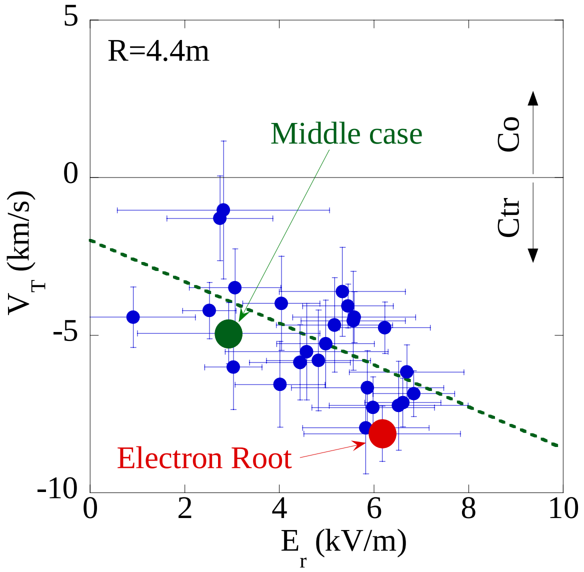

FIG. 3. Dependence of toroidal flow velocity on the radial electric field at the plasma edge (R=4.4m). The data shown in Fig.2 are plotted as the larger symbols.

3.2. E_r driven flow near the plasma core

How about the spontaneous toroidal flow driven by radial electric field near the plasma core where the helical ripple is small as comparable as the toroidal ripple? We have tried to observe the spontaneous toroidal flow driven with positive E_r near the plasma core by using the formation of electron ITB. 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 [10-12]. When the transition to the electron ITB takes place, the positive radial electric field is produced in the plasma core.

The experiments are performed in the plasma with R_{ax}=3.6 m, B=1.5 T, γ=1.174, and B_q=100 %. The tangential NBI is balanced to make the NBI driven toroidal flow to be minimized in the plasma core. Figure 4 shows the radial profiles of the electron temperature. The loccal peaked profile is observed in the electron temperature is observed during the ECH pulse (t=1.3-1.8 sec) while the ion temperature at the center of the plasma is 0.9 keV and there is no significant change in the ion temperature during the ECH pulse. Associated with the transition to the 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 near the plasma core as shown in Fig.5. 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 to the spontaneous toroidal flow anti-parallel to the direction of $<E_r \times B_\theta>$ drift near the plasma edge as mentioned in the section 3.1. There is a difference in the direction of the toroidal flow driven by the positive E_r between the direction near the plasma core and that at the plasma edge. 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 toroidal effect ($\varepsilon_h \sim \varepsilon_t$). In tokamak, in which the toroidal effect is dominant, the spontaneous toroidal flow in the counter direction is observed in the plasma with negative E_r as reported in JFT-2M [3]. The spontaneous toroidal flow becomes most significant in the ITB region where the strong negative E_r appears [13]. The direction of the spontaneous toroidal flow in tokamaks is parallel to the direction of $<E_r \text{ x } B_\theta>$ drift.

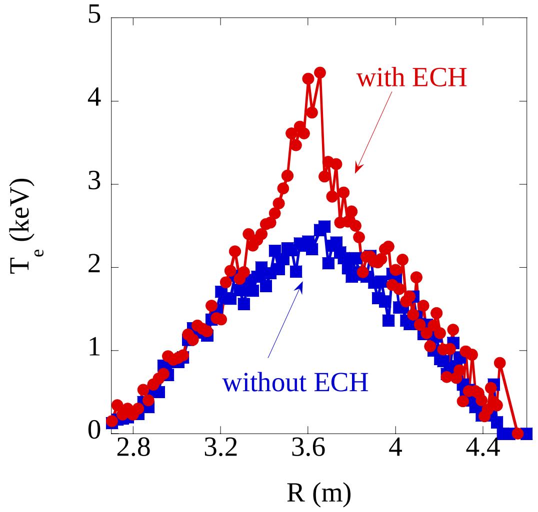

FIG. 4. Radial profiles of electron temperatures in the plasma with (circle) and without (square) ECH.

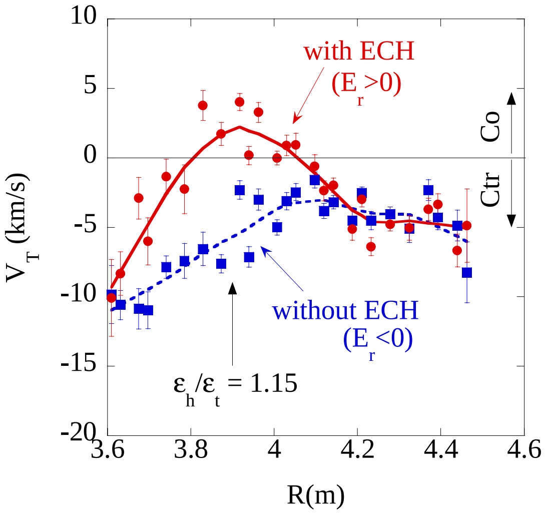

FIG.5. Radial profiles of toroidal flow velocity in the plasma with (circle) and without (square) ECH.

3.3. Ion temperature gradient driven flow

It has been observed that the toroidal flow driven in the direction anti-parallel to the injected NBI in high ion temperature discharges in LHD. The direction of the toroidal flow can not be explained with the effect of the radial electric field described above. Then we tried to observations of the toroidal flow with the changing of the gradient of the ion temperature.

The gradient of the ion temperature is changed whit the control of the heating power of the plasma (R_{ax}=3.75 m, B=2.64 T, γ=1.254, B_q=100 %) while the line averaged electron density of 1x10^{19} m^{-3} is kept constant during the discharge and there is no significant change of the E_r. Figure 6 (a) and (b) shows the profiles of the ion temperature and toroidal flow velocity, respectively, when the number of the heating sources is changed. Steep gradient of ion temperature is produced by increasing the heating power as shown in Fig. 6 (a). The profile of the toroidal flow velocity clearly changes around the R=4.3 m as shown in Fig. 6 (b). The toroidal flow in the co-direction is increased with a proportionality factor of 4.3 km/s / 1 keV/m associated with the increasing of ion temperature gradient.

The dependence of the toroidal flow velocity V_T on the ion temperature gradient is shown in Fig.7. The offset, finite value of V_T without the gradient of T_i, is considered to be due to the other driving terms of the spontaneous toroidal flow besides the ion temperature gradients, such as density gradients and radial electric field described above. The direction of the grad-T_i driven flow is anti-parallel to that of tokamaks observed at ITB [5, 6] and is parallel to that observed in ICRF and ohmic H-mode on Alcator C-Mod [6]. There is strong connection between toroidal flow and E_r in tokamaks, it is considered to be difficult to distinguish between an effect of grad-T_i and an effect of E_r. The toroidal flow driven by the ion temperature gradient is clearly observed in large helical device.

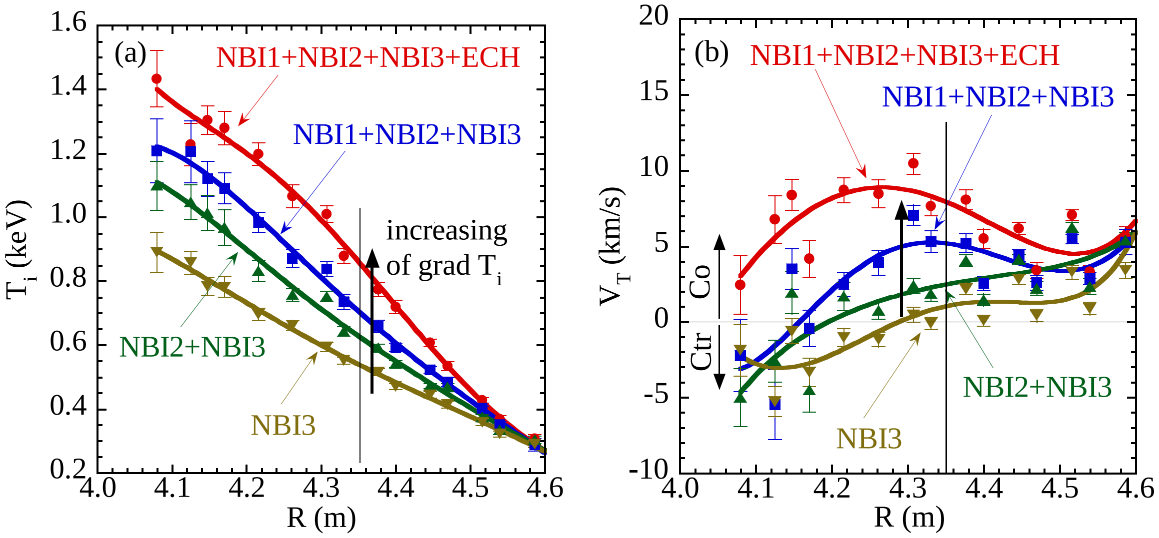

FIG.6. Radial profiles of (a) ion temperature and (b) toroidal flow velocity with changing the heating power.

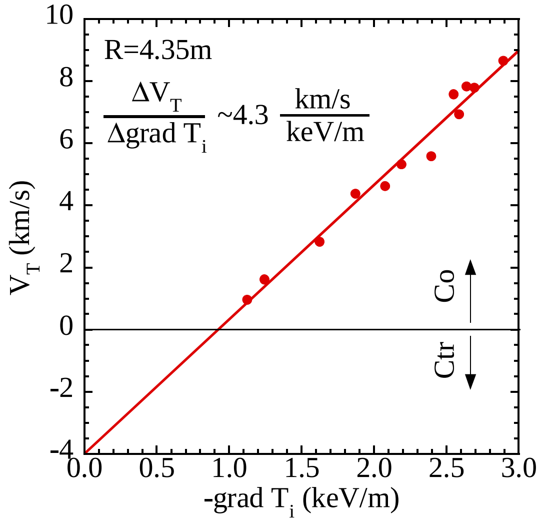

FIG. 7. Dependence of toroidal flow velocity on the gradient of the ion temperature at the plasma edge (R=4.35m).

4. Understandings of the flow profile in High T_i plasma

We have observed the effect of the radial electric field, ion temperature gradient and the injection of NBI on the toroidal flows and we can understand the profiles of toroidal flow observed in a high ion temperature discharges. Figure 8 shows the radial profiles of the ion temperature and the toroidal flow velocity in the discharge achieved the high ion temperature with a steep gradient of the ion temperature at the mid radius of the plasma. The plasma is produced with R_{ax}=3.6 m, B=2.85 T, γ=1.254, and B_q=100 % and sustained with the perpendicularly injected neutral beam. The ion temperature at the plasma center increases after the injection of the counter dominant tangential NBIs as shown in Fig.8 (a). The toroidal flow is driven into the counter-direction by the tangential NBIs near the plasma center. It is noted that the toroidal flow is driven in the co-direction around the R=4.2 m. The direction is anti-parallel to the direction of the torque of the NBIs, The gradient of the ion temperature changes from 2.4 keV/m to 5.7 keV/m by injection of the tangential NBIs at R=4.2 m. The toroidal flow driven in the co direction around the R=4.2 m is considered to be the troidal flow driven with the difference of the ion temperature gradient of the 3.3keV/m. The difference of the flow velocity at the R=4.2 m is consistent with the flow velocity of 14 km/s expected with the ion temperature gradient and the proportionality factor shown in Fig.7. Small change of the toroidal flow into the counter direction at the plasma edge is considered to be due to the change of the radial electric field from negative to positive. The spontaneous flow driven by a gradient of an ion temperature becomes one of a dominant component of the toroidal flow in the high ion temperature discharges in LHD.

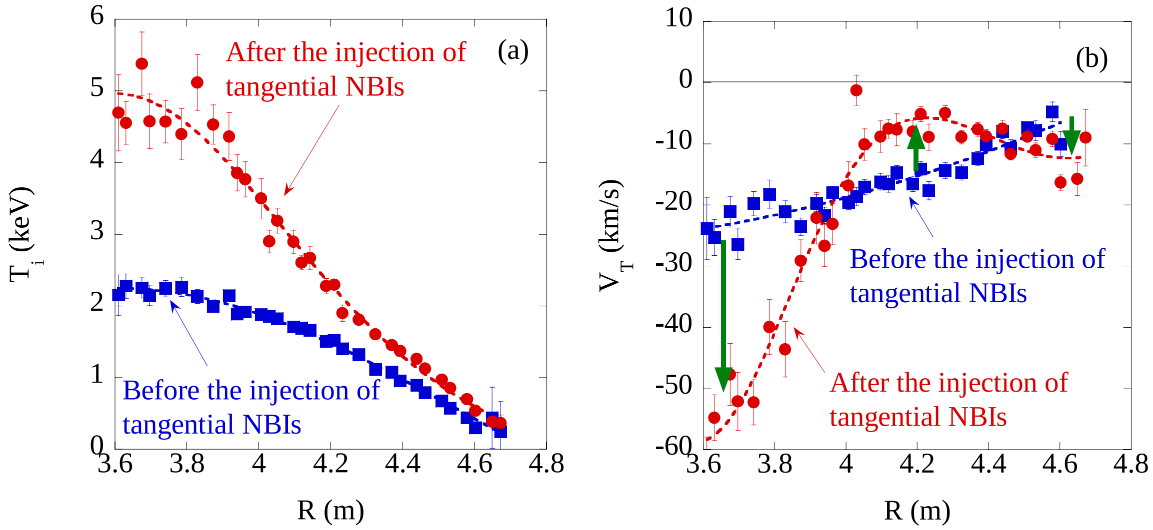

FIG.8. Radial profiles of (a) ion temperature and (b) toroidal flow velocity before (square) and after (circle) the NBI injection in the high ion temperature discharge.

5. Summary

The spontaneous toroidal flows driven by the radial electric field and the gradient of ion temperature are observed in LHD. The positive radial electric field drives spontaneous flow in the counter direction near the plasma edge and in the co direction near the plasma core. 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. The spontaneous toroidal flow driven by the radial electric field is parallel to that observed in tokamaks in the core region where the helical ripple is small as comparable to the toroidal effect, and the spontaneous flow is anti-parallel to that in tokamak near the plasma edge where the helical ripple is large. The spontaneous toroidal flow driven by ion temperature gradient is clearly observed near the plasma edge, and the spontaneous flow driven by a gradient of an ion temperature becomes one of a dominant component of the toroidal flow in the high ion temperature discharges on LHD.

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