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Structure of the Radial Electric Field and Toroidal/Poloidal Flow in High Temperature Toroidal Plasma

IDA Katsumi*, CHS Group, LHD Group and JFT-2M Group[1)]
National Institute for Fusion Science, Toki 509-5292, Japan
[1)] Japan Atomic Energy Research Institute, Naka-machi, Naka-gun, Ibaragi, 319-11, Japan

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Abstract

The structure of the radial electric field and toroidal/poloidal flow is discussed for the high temperature plasma in torodidal systems, tokamak and Heliotron type magnetic configurations. The spontaneous toroidal and poloidal flows are observed in the plasma with improved confinement. The radial electric field is mainly determined by the poloidal flow, because the contribution of toroidal flow to the radial electric field is small. The jump of radial electric field and poloidal flow are commonly observed near the plasma edge in the so-called high confinement mode (H-mode) plasmas in tokamaks and electron root plasma in stellarators including Heliotrons. In general the toroidal flow is driven by the momentum input from neutral beam injected toroidally. There is toroidal flow not driven by neutral beam in the plasma and it will be more significant in the plasma with large electric field. The direction of these spontaneous toroidal flows depends on the symmetry of magnetic field. The spontaneous toroidal flow driven by the ion temperature gradient is in the direction to increase the negative radial electric field in tokamak. The direction of spontaneous toroidal flow in Heliotron plasmas is opposite to that in tokamak plasmas because of the helicity of symmetry of the magnetic field configuration.

Keywords:

radial electric field, toroidal plasma

1. Introduction

A radial electric field has been considered to possibly reduce the ripple loss and to prevent the degradation of confinement in stellarators and helical devices [1]. This is because the neoclassical transport [2,3] is expected to become more important at higher temperature and low collisionality plasmas [4]. In tokamaks, after the transition from low confinement mode (L-mode) to high confinement mode (H-mode [5]) (L/H transition) was found in ASDEX, a spontaneous bifurcation of the radial electric field was theoretically proposed to cause it and thus refreshed the motivation of research [6,7]. The phenomenon, that, associated with the L/H transition, the radial electric field suddenly changes at the plasma periphery (few cm), was observed in DIII-D [8], JFT-2M [9,10], ASDEX [11]. The importance of the radial electric field for the H-mode is now widely recognized.

There are two important mechanisms in the formation of the radial electric field, one is the damping term, which is viscosity in plasma rotations, and the other is a driving force to rotate the plasmas toroidally or poloidally. In the damping term, both the neoclassical parallel viscosity and perpendicular viscosity are discussed. There are external and internal driving forces; the external forces are momentum input or jxB and the internal forces are ion and electron nonambipolar flux

**Corresponding author's e-mail: ida@nifs.ac.jp*

(ion and electron loss induced radial current) due to density and/or temperature gradient or orbit loss.

2. Spontaneous Poloidal Flow

A spontaneous poloidal flow has been recognized to be important in the confinement of toroidal plasmas, since poloidal flow velocity and radial electric field shear were found to contribute an improvement of plasma confinement in H-mode plasmas [8-10]. The turbulence in the plasma is predicted to be suppressed by a $E \times B$ velocity shear through the mechanism of a nonlinear de-correlation [12,13]. It has been confirmed experimentally that the $E \times B$ shearing rate exceeds the growth rate of the turbulence at the transport barrier [14,15].

2.1 Spontaneous Poloidal Flow in Tokamaks

The poloidal flow is in the electron diamagnetic direction and appears suddenly near the plasma edge at the H-mode transition. The poloidal rotation velocity profile in H-mode has a peak at the separatrix. No critical normalized ion collisionality, ν^*_i, for the transition of L- to H-mode is observed. The size of the poloidal flow in H-mode has no dependence on poloidal gyro-radius. The poloidal rotation velocity profiles and ion temperature profiles at ohmic, L-mode and H-mode phase are shown in Figure 1(a). The plasma always rotates in the ion diamagnetic direction outside the separatrix and in the electron diamagnetic direction inside the separatrix. The position, where the plasma does not rotate poloidally, moves outward as the plasma changes from ohmic to L- to H-mode. The poloidal flows outside and inside the separatrix are in the opposite direction to each other.

2.2 Spontaneous Poloidal Flow in Helical System

In the Large Helical Device (LHD) the transition from negative electric field (ion root) to positive electric field (electron root) is observed for the first time in plasmas with neutral beam injection (NBI) heating alone at a low density of $0.4 - 1.0 \times 10^{19}$ m^{-3} [16], regardless the direction of beam (in co, counter and balanced injections). This is because the beam ion loss due to the

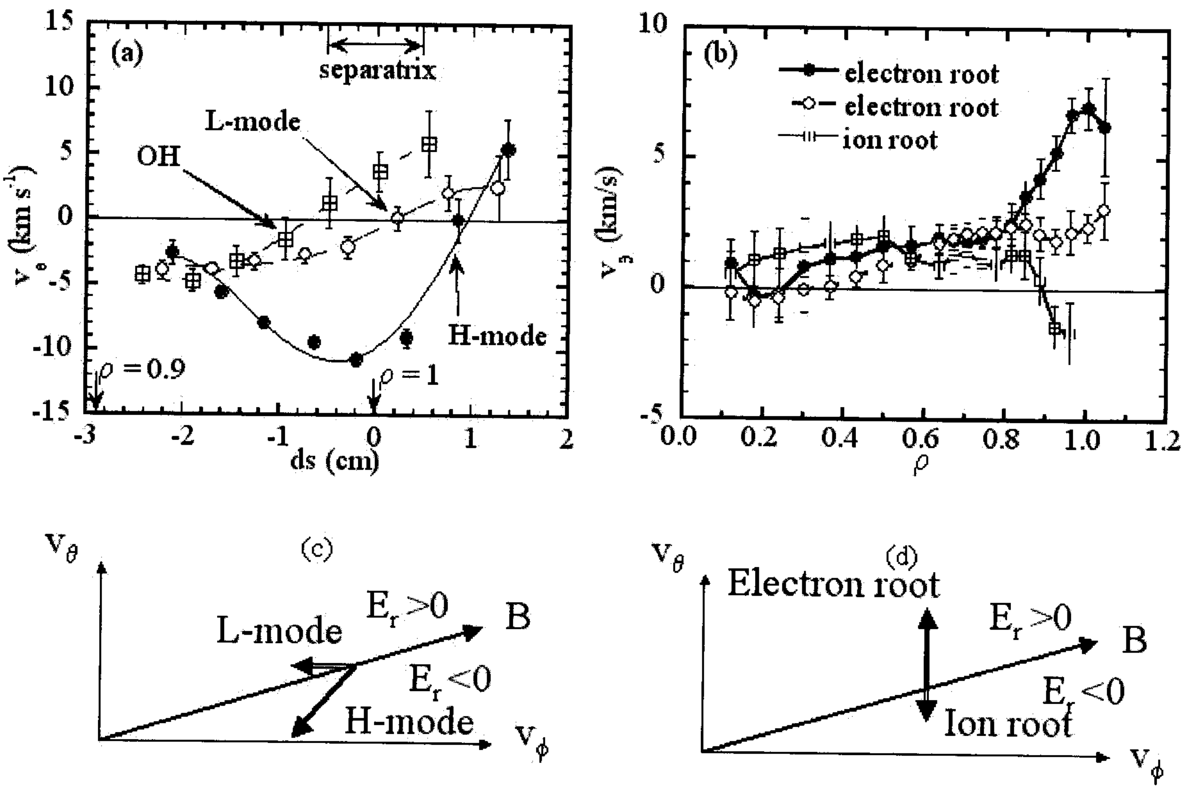

Fig. 1 Radial profiles of poloidal rotation velocity at the transition of (a) L mode to H-mode in JFT-2M tokamak [10] and (b) ion root to electron root in LHD Heliotron plasmas [16]. (c), (d) Flow patterns in tokamak H-mode plasmas and Helical electron root plasmas

drift orbit is small enough compared with the neoclassical non am-bipolar loss. In previous experiments [17-21], the transition from ion root to electron root was observed only in plasmas with ECH, therefore it has been also open to question as to whether the non-thermal electrons driven by ECH are required to achieve the transition. The transition of the radial electric field from ion root to electron root clearly demonstrates that non-thermal electrons are not necessary for the transition, because there are no non-thermal electrons in NBI heated plasma. The edge radial electric field sharply increases up to 15 kV/m in the electron root as the electron density is decreased while the absolute values increase gradually up to –5 kV/m in the ion root over a wide range of electron density of 1.0 – 3.0 × 10^{19} m^{-3}. The transition of poloidal flow in the electron diamagnetic direction (negative E_r) to flow in the ion diamagnetic direction (positive E_r) is observed at $\rho > 0.85$ and there is no large poloidal flow observed in the plasma core. The absolute values of poloidal flow measured in the electron or ion root are the levels predicted by neoclassical theory [3].

3. Spontaneous Toroidal Flow

The toroidal flow has been considered to be determined by the radial transport of momentum driven by neutral beam injection (NBI) with anomalous shear viscosity. Although the $E \times B$ velocity shear due to the toroidal flow can be important in the plasma core, there have been few experiments that demonstrate a spontaneous toroidal flow not driven by NBI in tokamaks [22-25]. It is generally the case in tokamaks that the plasma rotates parallel (anti-parallel) to the plasma current for the co-injected (counter-injected) NBI, which corresponds to a positive (negative) radial electric field (*Er*) in L-mode plasmas. However, when a negative *Er* is produced at the transport barrier, both localized toroidal flow in the counter-direction and localized poloidal flow in the electron diamagnetic direction are observed even for plasmas with co-injected NBI [26,27]. These results show the need for detailed measurements of both toroidal and poloidal flow at the transport barrier, where the toroidal flow profile is not determined by the transport of momentum driven by NBI alone.

3.1 Spontaneous Toroidal Flow in Tokamaks

A non-diffusive term in the toroidal-momentum-transport equation is evaluated by the analysis of the transport of toroidal rotation in the transient phase, where the direction of neutral beam injection is changed from parallel to the plasma current to antiparallel. Non-diffusive momentum transport is found to be in proportion to ∇Ti. Figure 2 displays time evolution and radial profiles for discharges when the direction of the NBI is reversed at t = 750 ms with a plasma current of 243 kA. The co-injection is activated from 550 ms to 750 ms and the counter-injection from 750 ms to 950 ms in Figs. 2(a) and 2(c) and the counter-NBI is activated from 600 ms to 750 ms and the co-NBI from 750 ms to 950 ms in Figs. 2(b), 2(d). The toroidal rotation velocity changes its sign depending on the direction of the beam. The rapid changes in toroidal rotation velocity after t = 750 ms are due to the switching of beam direction from co-injection (driving positive toroidal rotation) to counter-injection (driving negative toroidal rotation) or from counter-injection to co-injection. Gradual changes in toroidal rotation velocity afterwards (800 ms ~) are due to the improvement of momentum confinement associated with density peaking. Although the absorbed momenta of the beam are adjusted to be almost identical (injected power of ctr-NBI is larger than that of co-NBI), the toroidal rotation velocity near the plasma center (R = 1.35 m) in counter-injection is almost twice of that in co-injection. The gradient of toroidal rotation velocity estimated from the difference of toroidal rotation velocity between R = 1.4 m and R = 1.5 m (indicated with arrows in Figs. 2(a) and 2(b)) in counter-injection is 2–3 times larger than that in co-injection. Figure 2 (c), (d) displays profiles of toroidal momentum ($m_i n_i v\phi$) for discharges when the direction of the injected neutral beam changes from co- to counter and from counter to co at the flat top of the plasma current (t = 750 ms). Here, mi is the ion mass and n_i is the ion density of deutrons. As shown in Fig. 3(a), the differences of toroidal rotation velocity between co-injection and counter-injection becomes small, when the plasma current, I_p, is increased (poloidal field is also increased). Figure 3(b) shows the off-diagonal coefficient given by the slope in Fig. 3(a) as a function of plasma current. The off-diagonal coefficients derived at ρ = 0.46 using the transport analysis are also plotted for comparison. This agreement suggests the validity of assumption of f(co-nbi) = -f(ctr-nbi) and that the differences in the magnitude and profile of momentum input between co-injection and counter-injection can be ignored. The off-diagonal coefficient decreases as the plasma current, I_p, is increased. It is not clear whether the off-diagonal term will disappear or simply decrease as proportional to $1/I_p$

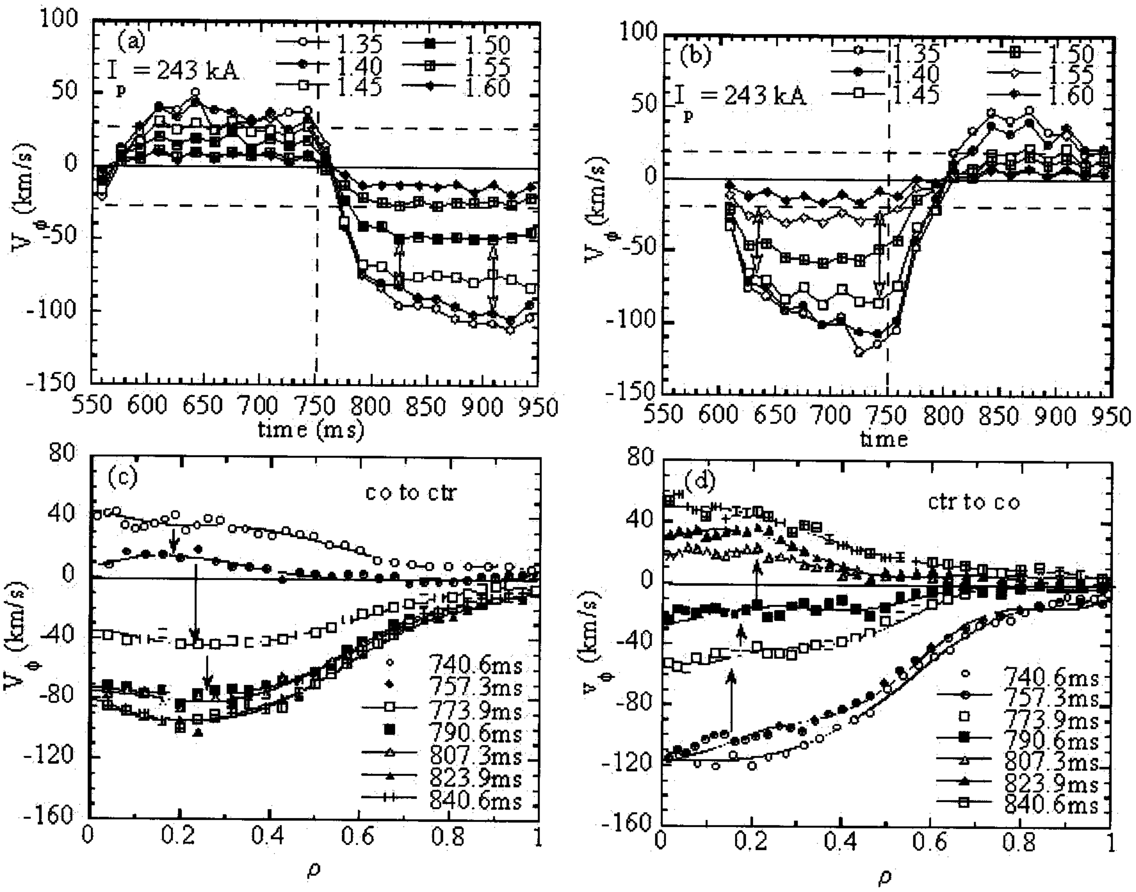

Fig. 2 (a), (b) Time evolution of toroidal rotation velocity at R = 1.35, 140, 1.45, 1.50, 1.55, 1.60 m and (c), (d) radial profiles of toroidal momentum during the transient phase for discharges when the direction of the NBI is reversed. (a), (c) The co-injection is activated from 550 ms to 750 ms and the counter-injection from 750 ms to 950 ms. (b), (d) The counter-NBI is activated from 550 ms to 750 ms and the co-NBI from 750 ms to 950 ms [24].

when the plasma current is increased above 350 kA. The range of plasma current available in the JFT-2M is not wide enough to conclude the Ip dependence of the off-diagonal coefficients. If this current dependence is due to the drift orbit physics, the off-diagonal term should disappear in the plasma with large minor radius and large plasma current, where the drift orbit loss is negligible. However, the off-diagonal term of toroidal momentum is observed in the large tokamak with a large plasma current [28]. Therefore the off-diagonal term is considered to be not due to the orbit physics and it is general characteristic in tokamaks regardless the size of plasma or plasma current. The plasma current dependence of the off-diagonal coefficient observed in JFT-2M at least supports the hypothesis that the off-diagonal coefficient is proportional to $1/I_p$ or $1/B_p$. The ratio of non-diffusive viscosity coefficient to diffusive viscosity coefficient is evaluated to be 0.1 to 0.3, which increases as the plasma current is decreased.

3.2 Spontaneous Toroidal Flow in Helical System

A toroidal flow anti-parallel to the $<E_r \times B_\theta>$ drift direction is observed in the hot electron mode plasmas when a large positive electric field and a sharp electron temperature gradient are sustained inside the internal transport barrier in the Compact Helical System (CHS) [29]. This toroidal flow reaches up to 5×10^4 m/s at the plasma center and it is large enough to reverse the toroidal flow driven by tangentially injected neutral beam. These observations clearly show that the plasma favors flow in the minimum ∇B direction at the transport barrier.

The reversal of toroidal flow is observed when the 2 nd ECH pulse (t = 60–140 ms, P_{ECH} = 0.11 MW) is applied to the NBI plasma (t = 40–200 ms E_{NBI} = 36 kV

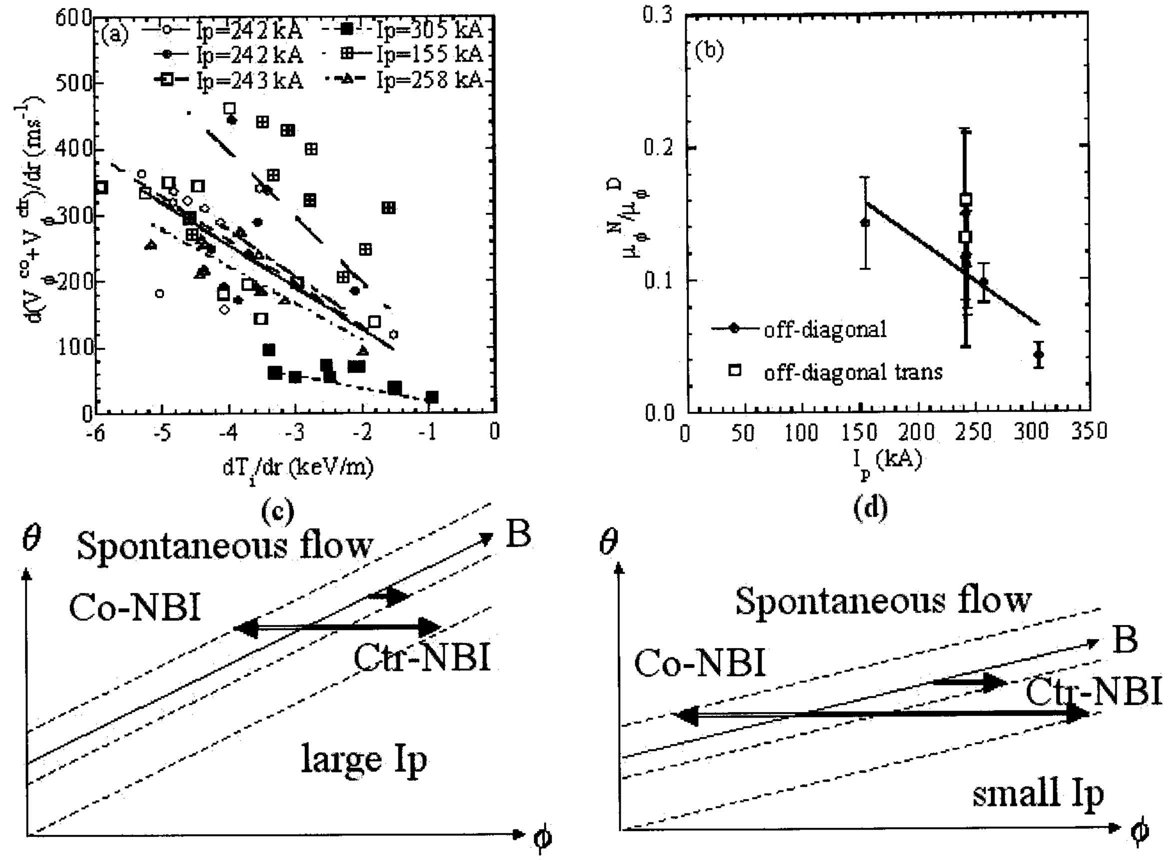

Fig. 3 (a) The difference of gradient of toroidal rotation velocity between co-injection and counter injection as a function of the gradient of ion temperature at R = 1.45 m (ρ = 0.46) for discharges with the various plasma current. (b) Off-diagonal coefficient a function of plasma current with a simple formula and with a transport analysis [24] (c), (d) relation of plasma flow respect to the direction of magnetic field for large and small plasma current (I_p).

P_{NBI} = 0.7 MW) with low electron density below 0.7 × 10^{19} m^{-3}. Here ρ is the normalized averaged minor radius ($\rho \approx r/a$). The electron temperature increases up to 2 keV (hot electron mode), while it is only 0.2 keV when there is no 2nd ECH pulse, which indicates a significant improvement in electron confinement during the 2nd ECH pulse, the electron collisionality is low enough to make the plasma to be in the electron root (positive electric field). The positive radial electric field is mainly contributed by the poloidal flow in the direction parallel to the $<E_r \times B_\phi>$ drift. The Lorenz forces due to the toroidal flow and the force due to the ion pressure are negligible in the radial force balance [30]. The Lorenz force due to the poloidal flow is almost balanced with the force due to the radial electric field and therefor the magnitude of Er is roughly equal to $v_\theta B_\phi$ in CHS plasmas. The radial electric field derived from plasma flow with the radial force balance agrees well with that measured with HIBP [31]. The large electric field of 10–20 kV/m and the large poloidal flow of 10–20 km/s are produced near the plasma center (ρ = 0.3) [Fig. 4(a)].

The neutral beam is injected to the plasma tangentially in the co-direction. Here the "co" direction (positive flow velocity) is defined as parallel to the equivalent toroidal plasma current, which would produce the average transform actually produced by the external coil current. The "counter" direction (negative flow velocity) is defined as anti-parallel to the equivalent toroidal plasma current. As seen in Fig. 4(b), the plasma rotates parallel to the NBI when there is no 2nd ECH. This is simply because the toroidal momentum from the NBI causes the plasma toroidal flow. However, when the 2nd ECH is turned on, the toroidal flow velocity decreases and finally the plasma rotates anti-parallel to the NBI. These measurements clearly show the driven toroidal flow associated with a large poloidal flow (and large positive radial electric

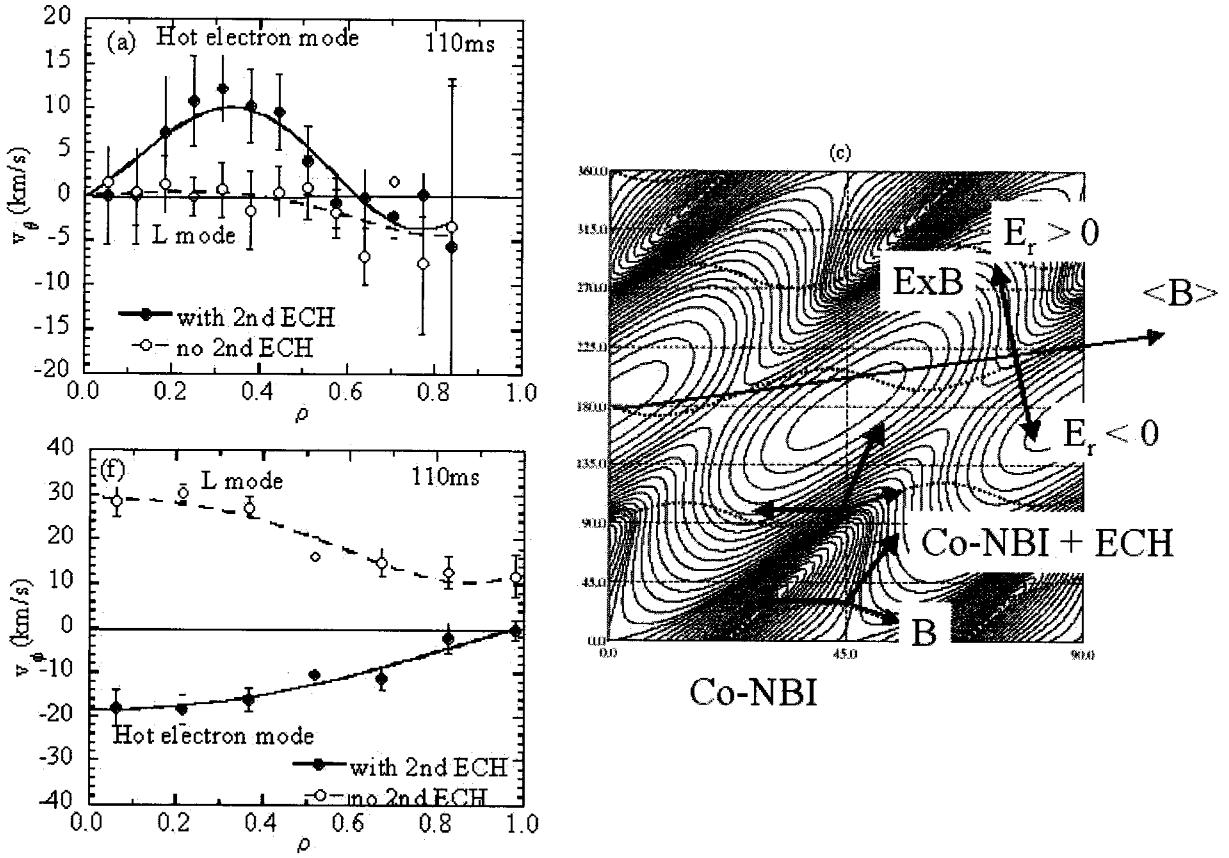

Fig. 4 Radial profiles of poloidal flow velocity at t = 110 ms and (b) toroidal flow velocity at t = 110 ms for the discharges with and without 2nd ECH pulse [29]. (c) Mod-B contour and flow pattern at $\rho = 0.3$ in CHS. The arrows stand for the flows in plasmas for NBI and NBI + ECH discharges.

field) during the 2nd ECH pulse. The driven toroidal flow reaches 5×10^4 m/s at the plasma center and it is large enough to overcome the toroidal flow driven by tangentially injected neutral beam. It should be emphasized that the direction of the toroidal flow is anti-parallel to the direction of $<E_r \times B_\theta>$ drift. This fact has not been predicted before, because a simple analogy from the experiments in tokamaks implies that the direction of the toroidal flow associated with a large radial electric field is parallel to the direction of $<E_r \times B_\theta>$ drift. This is because the toroidal viscosity is nearly zero due to the toroidal symmetry and the direction of the toroidal flow is simply determined by the direction of the $<E_r \times B_\theta>$ drift in most discharges in tokamaks.

4. Discussion

Although the transition of radial electric field and poloidal flow and spontaneous toroidal flow are observed both in tokamak and helical plasmas, there are differences in the direction of flows. The transition of poloidal flow observed in the H-mode in tokamaks is the jump of poloidal flow to the electron diamagnetic direction associated with the sudden increase of negative radial electric field shear. The turbulence levels in the plasma are also reduced as predicted by the anomalous transport models. On the other hand, the transition of poloidal flow observed in helical plasma is the change from electron diamagnetic direction to the ion diamagnetic direction, which is due to the reduction of ripple loss by large radial electric fields as predicted by the neoclassical theory.

The spontaneous toroidal flows are observed in tokamak and helical plasmas. They become more significant at the transport barrier where the ion or electron pressure gradients become large. The spontaneous toroidal flow in tokamaks is parallel to the direction of $<E_r \times B_\theta>$ drift, while the spontaneous toroidal flow in helical plasmas is anti-parallel to the direction of $<E_r \times B_\theta>$ drift. This difference in the direction of spontaneous toroidal flow is due to the difference of symmetry of magnetic field configuration. Since the plasma tends to flow along the minimum ∇B direction, where the parallel viscosity becomes minimum, the spontaneous toroidal flow in tokamak is always parallel to the $<E_r \times B_\theta>$ drift direction. In helical plasmas, the spontaneous flow has spiral structure due to the helical symmetry and the toroidal flow can be anti-parallel to the $<E_r \times B_\theta>$ drift direction depending on the direction of pitch of spiral structure.

In conclusion, the spontaneous poloidal and toroidal flow are observed in tokamak and helical plasmas associated with the large positive or negative radial electric field near the transport barrier. The understanding of the mechanism to drive the spontaneous poloidal and toroidal flow will be the key issue in the research of confinement improvement of high temperature toroidal plasmas.

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