33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-4.123 (2006)

Investigation of Toroidal Rotation as a Result of Reduction of Toroidal Magnetic Field Ripple by Installing Ferritic Steel in JT-60U

M. Yoshida[1], Y. Koide, H. Takenaga, H. Urano, N. Oyama, K. Kamiya,
Y. Sakamoto, Y. Kamada and the JT-60 Team
Japan Atomic Energy Agency, Naka, Ibaraki-ken, 311-0193 Japan

1. Introduction

Plasma rotation profiles play one of the most critical roles for plasma transport and MHD stability. Therefore, it is important to understand the driving mechanism of plasma rotation and momentum transport. The radial electric field (E_r) in the toroidal plasma is balanced by the pressure gradient and Lorentz force due to plasma rotation as,

$$E_r = \nabla p_i / Z_i e n_i - V_p B_t + V_t B_p \qquad (1)$$

where e is the charge number, Z_i, p_i, and n_i are the ion charge, pressure, and density, B_t and B_p are toroidal and poloidal magnetic fields, V_p and V_t are poloidal and toroidal rotation velocities. In JT-60U, near-perpendicular (PERP) neutral beam (NB) heated plasmas exhibit a toroidal rotation in the direction antiparallel to the plasma current, i.e. the counter (CTR) direction. The injection angle of near-perpendicular NBI is 75 degree with respect to the magnetic axis. An inward electric field induced by a ripple loss of fast ions was considered as a candidate for the CTR rotation in the peripheral region [1]. In JT-60U, in order to reduce the toroidal magnetic field ripple for the reduction of the fast ions losses and improvement of rotation controllability, the ferritic steel tile (FST) is installed in the vacuum vessel. In this report, effects of the ripple loss of fast ions on the toroidal rotation are investigated by using data with and without FST.

2. Toroidal Rotation without FST

In the case with large ripple loss condition, CTR rotation is observed with near-perpendicular NBIs. Figure 1 shows the response of V_t to near-perpendicular NBI before inserting FST. Main plasma parameters for this L-mode discharge are plasma current I_P=1.15 MA, B_T=2.6 T, the safety factor at 95% flux surface q_{95}~4.1, and the plasma volume Vol.~65 m^3. The maximum ripple ratio for this plasma is about 1% in the peripheral region. A near-perpendicular NB is injected with constant power, and a short pulse of another near-perpendicular NB is injected as shown in Fig. 1(a). This short pulse of NB is used for the charge exchange recombination spectroscopy measurement of ion temperature and velocity of the fully stripped carbon impurity ions. When the diagnostic NB is injected, the magnitude of CTR rotation increases in the edge region [Figs. 1(b) and 1(c)]. The ion temperature (T_i) profile, which is connected with pressure gradient, does not vary with NBI power in the edge region [Fig. 1(d)].

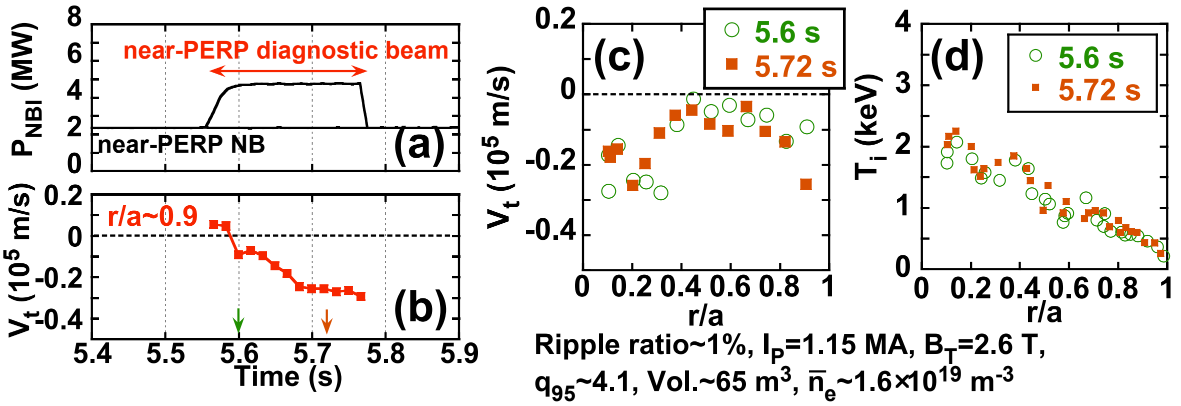

Fig. 1 Waveforms of (a) neutral beam injection power (P_{NBI}), and (b) the toroidal rotation velocity (V_t) at r/a~0.9 before inserting ferritic steel tile (FST) in L-mode plasma. Profiles of (c) V_t, and (d) the ion temperature (T_i) at t=5.6 s and 5.72 s, respectively.

3. Reduction in CTR rotation with FST

The reduction in ripple losses by inserting FST brings about a change in V_t. In Figs. 2(a)-(c), profiles of V_t, T_i, and the density (n_e) in L-mode plasmas (I_p=1.15 MA, B_T=2.6 T, q_{95}~4.1, Vol.~65 m^3) are shown, where solid circles show the data in the case with FST and open squares are the data in the case without FST. The toroidal rotation is shifted to the CO direction by inserting FST. In these plasmas, only near-perpendicular NBs are injected (the absorbed power P_{ABS}~1.4-1.8 MW). The profiles of T_i and n_e in the case with FST are similar to each profile in the case without FST in the peripheral region, therefore, pressure gradients, which is described the first term on right-hand side of equation (1), in the case with and without FST are similar. From these data, the difference in CTR rotation between the two discharges is not due to an increase in pressure gradient, which can enhance the inward electric field. The relation between V_t in the peripheral region (r/a~0.9) and the ripple loss power is investigated by NB power and the toroidal field ripple (with and without FST) scans, as shown in Fig. 2(d). The ripple loss power is calculated by orbit following Monte Carlo (OFMC) code. In this data set, I_P, B_T, Vol. and the line averaged electron density ($\bar{n}_e$) are kept almost constant and the

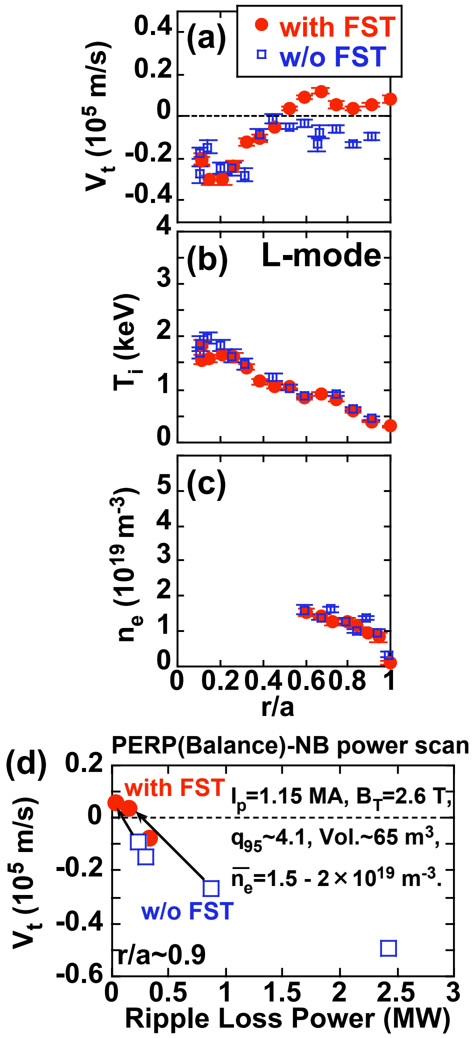

Fig. 2 Profiles of (a) V_t, (b) T_i and (c) the electron density (n_e) with and without FST in L-mode plasmas. (d) V_t dependence on the ripple loss power in the peripheral region with NB power and the toroidal field ripple scans.

pressure gradient does not largely affect CTR rotation ($\nabla p_i / Z_i e n_i$ is about 1/5 of $V_t B_p$ at ripple loss power ~0.9 MW in Fig. 2(d)). The magnitude of CTR rotation reduces with FST as a consequence of the reduction in the ripple loss power.

4. Driving source of CTR rotation

In this section, the location of the driving source of CTR rotation is investigated. The steady V_t profile in an L-mode plasma with FST is shown in Fig. 3(a). In this experiment, the plasma with low I_P (I_P ~0.87 MA, q_{95}~8.2) and large volume (Vol.~72 m^3) was selected in order to enhance ripple losses, therefore, CTR rotation is observed. In order to investigate the driving source due to the ripple loss of fast ions, we have evaluated the radial profile of the ripple loss of fast ions by the use of OFMC code. The radial profiles of fast ions at birth and after the prompt loss (~4 ms after NBI) are shown in Fig. 3(b). The time-scale of ripple losses is much faster than slowing down time (τ_S~0.4 s), therefore, the hatched region indicates the region where ripple losses mainly take place. In order to confirm the location of the driving source of CTR rotation, beam perturbation techniques [1] are applied in the L-mode plasma. In order that the central region is free from direct external momentum input, off-axis PERP-NBs (P_{IN}~3.9 MW) are injected with a square wave modulation at 2 Hz into a discharge similar to one shown in Fig. 3(a). The radial profiles of the amplitude of the modulated part of V_t ($\tilde{V}_t$) and of the phase delay of $\tilde{V}_t$ ($\Delta\phi$) are shown in Figs. 3(c) and 3(d), respectively. The phase delay is taken from the start of NB injection. Large amplitude and small $\Delta\phi$ are recognized in the peripheral region (0.7<r/a<0.9), and this region agrees with the location at which fast ion losses take place. These results indicate that fast ion losses, which can induce CTR rotation through the formation of inward electric field, mainly occur close to the edge region.

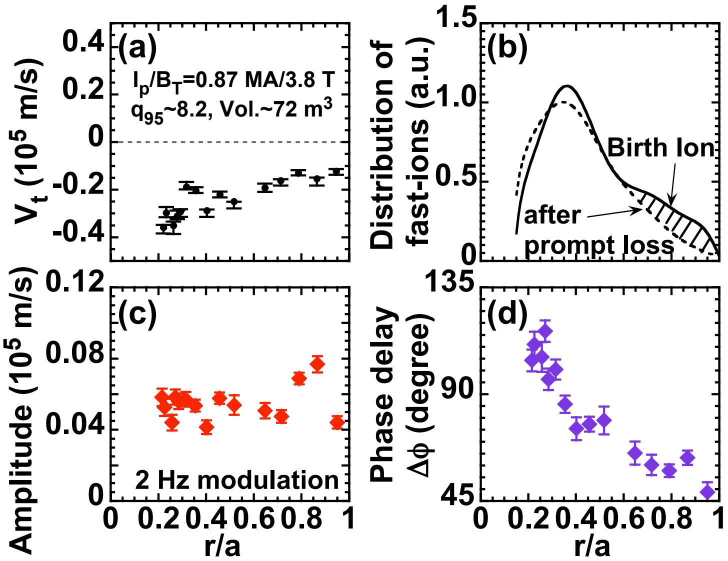

Fig.3 Profiles of (a) the steady V_t during off-axis PERP-NBIs, (b) fast ion at birth and after the prompt loss. The hatched region indicates the region where ripple losses mainly take place. Profiles of (b) modulated amplitude, (c) phase delay ($\Delta\phi$) from PERP-NB perturbation techniques.

5. Momentum transport

In the previous sections, it is found that the driving source of CTR rotation is localized near the peripheral region, and the phase delay of modulated part of the V_t becomes larger in the inner region. In this section, V_t profiles in the core region are discussed from the viewpoint of a moment transport using $\tilde{V}_t$ and $\Delta\phi$ profiles in Figs. 3(c) and 3(d). The toroidal momentum flux is expressed as

$$M = -m_i n_i \chi_\phi \partial V_t / \partial r - m_i n_i V_{conv} V_t \qquad (2)$$

where M, m_i, χ_ϕ and V_{conv} are the toroidal momentum flux, the ion mass, the toroidal momentum diffusivity and the convection velocity. Figs. 4(a) and 4(b) show χ_ϕ and V_{conv} as evaluated from modulation analysis [2] (i.e. $\tilde{V}_t$ and $\Delta\phi$ profiles in Figs. 3(c) and 3(d)) assuming the momentum source in the core region (0.2<r/a<0.65) to be negligible. As is shown in Fig. 4(a), χ_ϕ is comparable to the ion thermal diffusivity (χ_i) at r/a~0.5 in this plasma. Experimental data (solid circles), which is the same data in Fig. 3(a), is shown in Fig. 4(c) again. The solid lines show V_t profiles calculated from equation (2) using transport coefficients in Figs. 4(a) and 4(b) with the boundary condition at r/a~0.65. As is shown in Fig. 4(c), V_t profile in the core region can be explained by momentum transport considering χ_ϕ and V_{conv} with PERP-NBIs. Thus, the toroidal rotation in the core region is dominated by the momentum transport in this L-mode plasma.

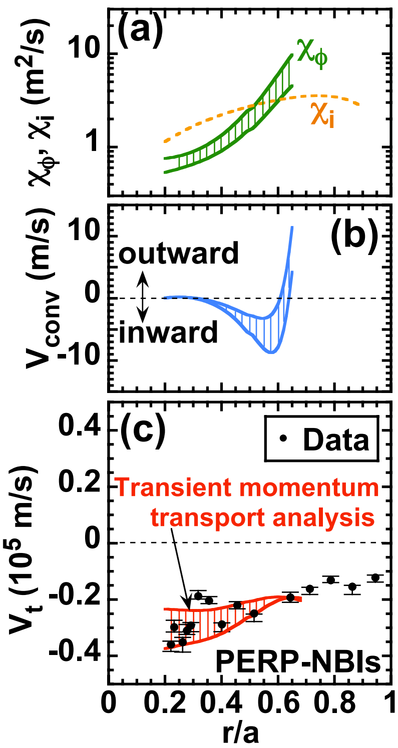

Fig.4 Profiles of (a) the toroidal momentum diffusivity (χ_ϕ) and (b) the convection velocity (V_{conv}) obtained from beam perturbation techniques in Fig. 3. (c). Experimental data (solid circles) in L-mode plasma with PERP-NBIs.

6. Conclusion

The magnitude of CTR rotation with near-perpendicular NBs reduces by installing FST as a consequence of the reduction in the ripple losses. Location of the driving source of CTR rotation agrees with the region where fast ion losses mainly take place. In an L-mode plasma, V_t profile in the core region can be explained by momentum transport considering χ_ϕ and V_{conv} estimated from transient momentum transport analysis.

Acknowledgments

This work was partly supported by JSPS, Grant-in-Aid for Young Scientists (B) No 17740374.

References

[1] Koide Y *et al* 1993 *Plasma Phys. Control. Nucl. Fusion Research* **1** 777

[2] Nagashima K *et al* 1994 *Nucl. Fusion* **34** 449