§1. Toroidal Rotation Properties without External Torque Input in LHD

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Spontaneous toroidal rotation attracts much attention because toroidal rotation has a potential to control MHD stabilities in high beta plasmas. An empirical scaling law was obtained for H-mode plasmas of tokamaks. However, spontaneous rotations in L-mode plasmas depend on plasma parameters in a complicated way, and is considered to be determined by turbulence [1]. In helical plasmas, an anomalous perpendicular viscosity due to turbulence and a parallel viscosity play an main role to determine toroidal rotation in the core and periphery, respectively. The spontaneous rotations were also observed to correlate with ion temperature gradient and radial electric field, so far [2, 3, 4].

In order to investigate the basic property of spontaneous toroidal rotation in 3-dimensional helical plasmas, the toroidal rotation without net torque input has been observed in a wide parameter regime in LHD. The plasma was heated by perpendicular (radial) neutral beam injection (NBI) or combination of perpendicular NBIs and balanced tangential NBIs. The residual torque generated by unbalance NBI power, orbit asymmetry between co- and counter-directed fast ions corresponds to toroidal rotation with the velocity of 2km/s, which is less than uncertainty of measurement and negligible in this experiment. Figure 1 show the summary of the experimentally observed toroidal rotation measured at $r_{\rm eff}/a_{99} = 0.6$, where $r_{\rm eff}$ and a_{99} are averaged minor radius and plasma size which encompasses 99% of the electron stored energy, respectively. Both co- and counter-rotation were observed with the magnetic configurations of $R_{\rm ax} = 3.60$m and $R_{\rm ax} = 3.75$m. No clear correlation of spontaneous rotation with density gradient was observed in LHD. The toroidal rotation can be separated to two regions depending on collisionality. In the low collisionality regime, spontaneous rotation is co-direction, and in the high collisionality regime, that is counter-direction. The toroidal rotation profile was compared between co- and counter-rotating plasmas, and the change of rotation shear was observed near the edge region ($r_{\rm eff} > 0.4$) with nested magnetic flux surface. The change of density fluctuation was also observed there [5].

1) J. Rice et al., Nucl. Fusion **51**, (2011) 083005.

2) M. Yoshinuma, et al., Nucl. Fusion **49**, (2009) 075036.

3) K. Nagaoka, et al., Nucl. Fusion **51**, (2011) 083022.

4) K. Ida, et al., Nuclear Fusion **50**, (2010) 064007.

5) K. Nagaoka, et al., Phys. Plasmas **20**, (2013) 056116.

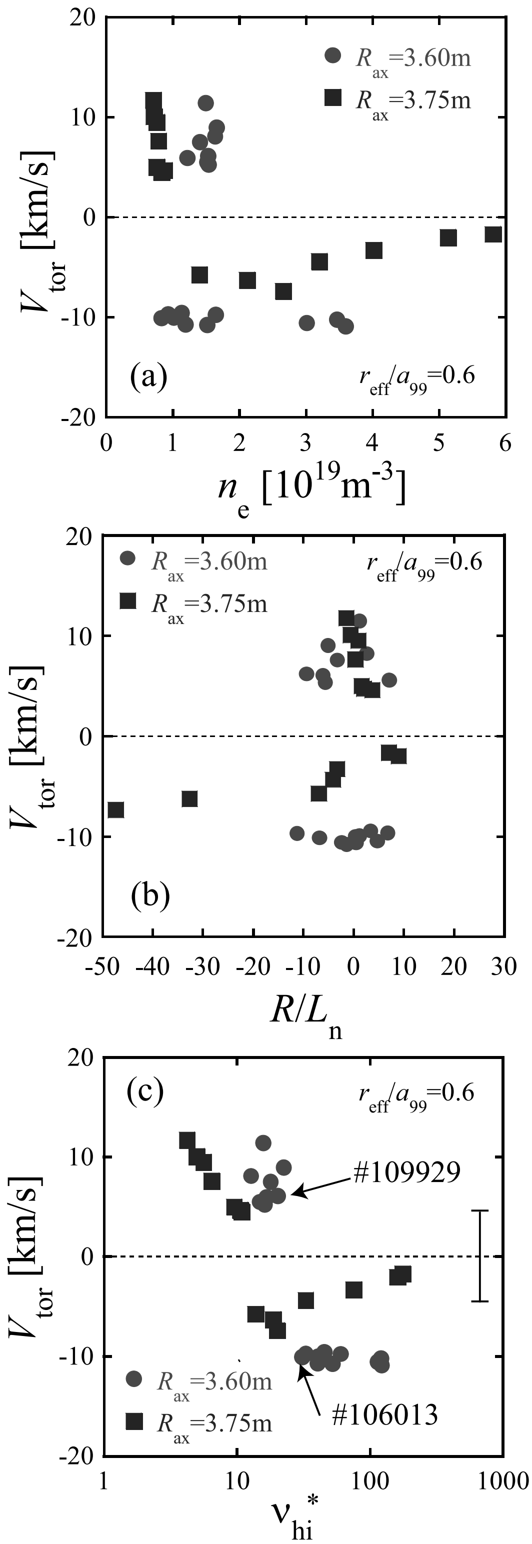

Fig. 1: Toroidal rotation velocity measured at $r_{\rm eff}/a_{99} = 0.6$ without external torque input as functions of (a) the local electron density, (b) normalized density gradient and (c) collisionality.