Characteristics of viscosity and intrinsic rotation in ion internal transport barrier plasmas on the Large Helical Device

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Momentum transport and intrinsic/spontaneous rotation attract much attention in fusion research field, and have been strongly investigated experimentally and theoretically, because a toroidal rotation could affect the confinement and stabilities of tokamak plasmas. The viscosity (diffusive transport of momentum) is experimentally estimated in many tokamak experiments and compared with thermal diffusivity (Prandtl number) [1-2]. The inter-device comparison of the spontaneous rotation has been investigated and a scaling law was obtained for H-mode plasmas [3]. In helical plasmas, neoclassical viscosity is significant near the edge region, where the rotation is determined by toroidal and poloidal viscosity and the beam driven rotation damps strongly [4]. On the other hand, the neoclassical viscosity is negligibly small in the core region. The driving force due to tangential neutral beam injection (NBI) is much larger than damping force due to neoclassical viscosity in the core plasmas. The toroidal rotation in the core of helical plasmas is determined by the balance between external driving force and radial momentum transport.

Intrinsic rotations in the peripheral region were observed to depend on radial electric field and on the ion temperature gradient in the Large Helical Device (LHD) [5]. Recently, ion internal transport barrier (ion ITB) with strongly peaked toroidal rotation in the co-direction was observed in LHD, and the viscosity in the core plasma reduces with the reduction of ion thermal diffusivity [6]. The spontaneous rotation was also observed in the ion ITB plasma [6-7]. In this paper, the momentum transport in the core region of ion ITB helical plasmas are qualitatively evaluated and the dependence of intrinsic momentum flux on the ion temperature gradient is discussed.

The experimental stage is LHD which is the world’s largest superconducting magnetic confinement device employing a heliotron concept. The magnetic field of up to 3 T is provided

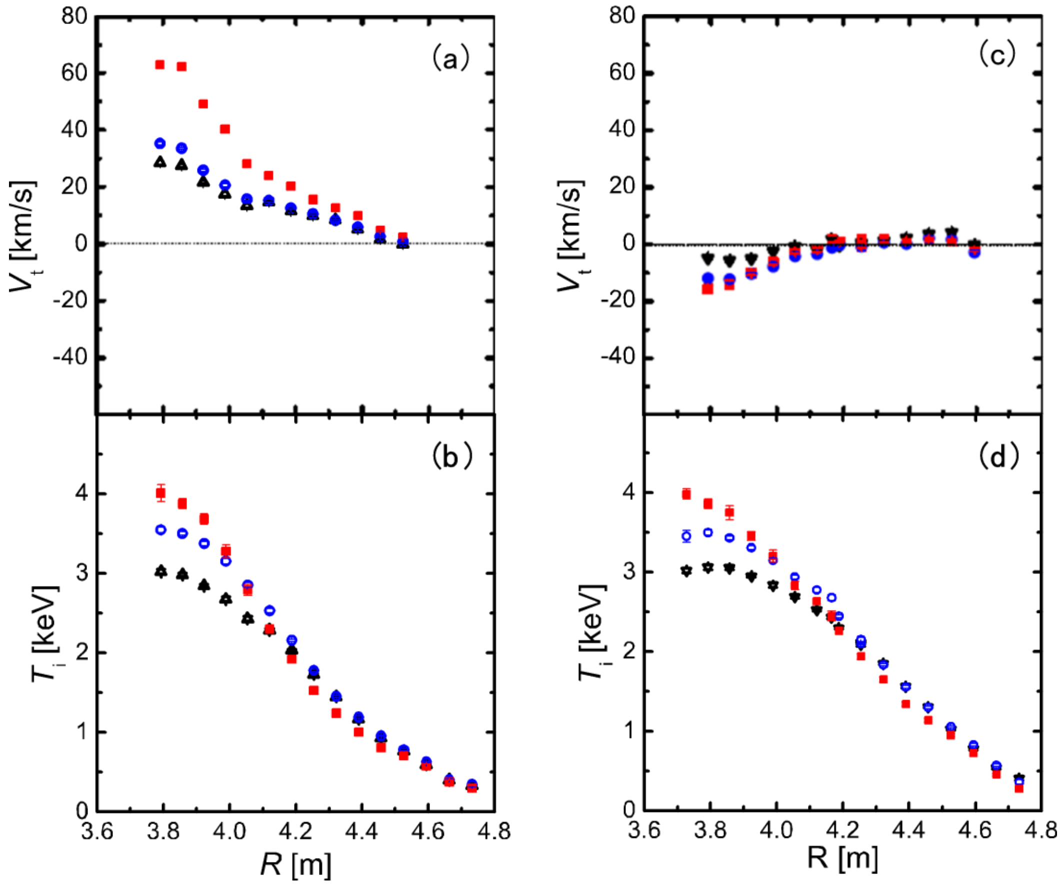

Fig.1 (a) Toroidal rotation and (b) ion temperature profiles with different ion temperature with co-directed NBI dominated. (c) Toroidal rotation and (d) ion temperature profiles with ctr-dominated NBI.

steadily. The toroidal and poloidal periods are m = 10 and l = 2, respectively. The major and averaged minor radii of plasmas in this experiment are 3.6 and 0.6 m, respectively. The NBI system has three tangential NBIs with the beam energy of 180 keV and total port-through power of 16 MW (BL1 and BL3, ctr-directional; BL2, co-directional) [8]. Two perpendicular NBIs are also operated with the total port-through power of 13 MW. In the present experiment, all NBI were operated to form ion ITB and the coil current producing the confinement magnetic field was reversed to change the direction of external torque input.

For the quantitative analysis of momentum transport in helical plasmas, the parallel viscosity should be taken into account in the calculation of momentum flux;

$$\Gamma_M = \frac{1}{r}\int r dr \left[F_{\mathrm{ext}} - \frac{\partial}{\partial t}(m_{\mathrm{i}} n_{\mathrm{i}} V_{\mathrm{T}}) - \mu_{||} m_{\mathrm{i}} n_{\mathrm{i}} V_{\mathrm{T}}\right] \quad (1)$$

where F_{ext} and $\mu_{||}$ are external force due to tangential NBI and parallel viscosity coefficient, respectively. The parallel viscosity coefficient is calculated with neoclassical theory. The second term corresponds the time evolution of momentum profile. Here, we consider two type of radial momentum transport, one is diffusive transport and the other is non-diffusive transport;

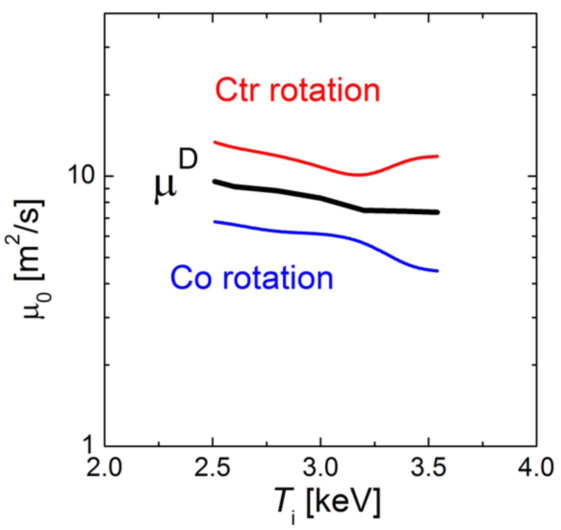

Fig. 2. The viscosity of co- (blue) and ctr-rotating plasmas (red) at the r_{eff}/a_{99} = 0.30 as a function of the ion temperature.

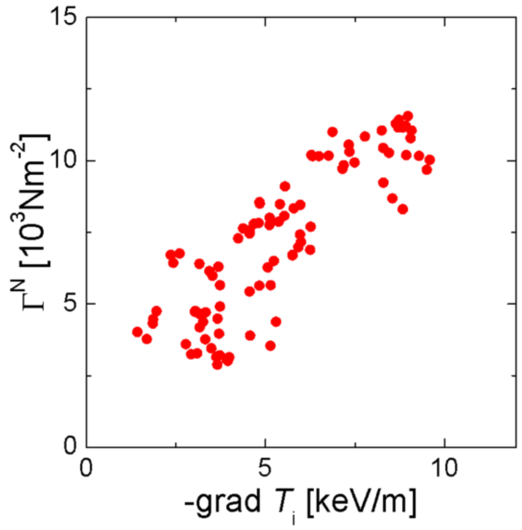

Fig. 3 The non-diffusive momentum flux at r_{eff}/a_{99} = 0.30 as a function of ion temperature gradient.

$$\Gamma_M = -\mu \frac{\partial}{\partial r}(m_i n_i V_T) + \Gamma^{ND} \quad (2)$$

where μ is viscosity. The first term coresponds diffusive transport and the senond non-diffusive transport. In the present experiment, the viscosity and non-diffusive momentum flux are estimated by balance between eq.1 and eq.2.

The toroidal rotation profiles with different ion temperatures are shown in Fig.1. The significant asymmetry between co- and ctr-rotations indicates the existence of spontaneous rotation. The rotation velocity increases with ion temperature, and this dependence is more significant in the core region than periphery. When the non-diffusive term is not taken into account, Γ^{ND}=0, the viscosity of the co-rotating plasma is smaller than that of the ctr-rotating plasma, which are shown in Fig. 2. Here, we assume that the viscosity is same between co- and ctr-rotating plasmas, then we can distinguish the viscosity as averaged one and the non-diffusive transport effect as a difference from the diffusive transport. The viscosity decreases with increment of ion temperature and decreases with ion thermal diffusivity. The Prandtl number is from 1 to 3, which is almost identical to that obtained in tokamak experiments [1-2,9]. The non-diffusive momentum fluxes are estimated and clearly increases with ion temperature gradient, which is shown in Fig. 3. This indicates that the non-diffusive momentum transport drives co-directed rotation in proportion to ion temperature gradient. The characteristics of non-diffusive momentum transport/spontaneous rotation are consistent both with that driven by neoclassical toroidal viscosity and with that driven turbulence such as ion temperature gradient mode, because these effects has same dependence on ion temperature gradient. Thus it is very important to compare between observed spontaneous rotation in experiments and predicted one from neoclassical theory for distinguishing of each contribution. The neoclassical theory for momentum transport in helical plasmas, however, is not applicable to the rotating plasma driven by external momentum input such as tangential NBI [10]. Therefore the heating power scan experiment (ion temperature scan) without external torque input is planned to compare the spontaneous rotation with predicted rotation from neoclassical theory. The magnitude of non-diffusive momentum transport is up to 30% of diffusive transport for the co-rotating plasma and up to 70% for the ctr-rotating plasma. The non-diffusive momentum transport is not so small and not a second order correction of diffusive transport.

In the analysis presented above, the symmetry of diffusive transport is assumed. However it does not seem to be guaranteed, because the hidden source of momentum transport can break the symmetry. However the assumption seems to be appropriate for a first order analysis. Further detailed analysis is necessary to discuss the accuracy of symmetry of diffusive transport.

In summary, the diffusive and non-diffusive momentum transports in the core region of helical plasmas were quantitatively estimated from asymmetry of toroidal rotation properties between co- and ctr-rotating plasmas. The viscosity correlates with ion thermal diffusivity and the Prandtl number is form 1 to 3, which is almost identical to that obtained in tokamak plasmas. The non-diffusive transport is proportional to ion temperature gradient, in other words, spontaneous rotation observed in the core of the helical plasma is mainly driven by ion temperature gradient. The comparison of observed spontaneous rotation and prediction of neoclassical theory is next step of this research.

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