§7. Observation of Flow Reversal in the Plasma with Neoclassical Internal Transport Barrier in CHS

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The reversal of toroidal flow is observed when the 2 nd ECH pulse is applied to the NBI plasma with low electron density below 0.7 x $10^{19}m^{-3}$[1]. The direction of the toroidal flow is anti-parallel to the direction of $<E_r \times B_\theta>$ drift. This is in contrast to the fact 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 in tokamaks. As seen in the contour plot of magnetic field strength in Fig.1(a), the minimum grad B direction is roughly parallel to the pitch angle of helical coils of $\theta/\phi = 4$, where θ and ϕ are poloidal and toroidal angles, respectively. On the other hand, the averaged pitch of magnetic field is only 0.7. The arrows in the figure represent the direction of flow measured. The flow reversal in the plasma with 2nd ECH shows that the plasma tends to flow along the minimum grad B direction rather than the direction of $<E_r \times B_\theta>$ drift.

Since the viscosity favors flow in the direction of the minimum grad B, the viscous stress proportional to the poloidal velocity is introduced as $\mu_{\phi\theta}V_\theta(r)$. We introduce here the toroidal-poloidal viscous coefficient, $\mu_{\phi\theta}$, and its values are experimentally determined. When there is an external force due to the neutral beam injection and the anomalous perpendicular viscosity, the toroidal flow velocity is determined with the diffusion equations of momentum as $F_{nbi}(r)/\{m_i n_i(r)\} = \mu_\phi V_\phi(r) + \mu_{\phi\theta}V_\theta(r) - \mu_\perp \nabla^2 V_\phi(r)$, where F_{nbi} is a driving force due to NBI and μ_ϕ is a toroidal parallel viscosity coefficient, which determines a magnitude of damping term of toroidal flow and $\mu_\perp$ is a perpendicular viscosity coefficient for the diffusion process. The poloidal flow is mainly determined by the ambipolar condition of radial flux of ions and electrons. Even there is no driving force from NBI, the finite toroidal flow exists in the plasma when there is a poloidal flow driven by non ambipolar flux or turbulence [$V_\phi(r) = -(\mu_{\phi\theta}/\mu_\phi)V_\theta(r)$, if $\mu_\perp=0$]. Therefore the $\mu_{\phi\theta}V_\theta(r)$ term is not a simple damping term, but represents the coupling between toroidal and poloidal flows. Figure 1 (b) shows the radial profiles of the toroidal viscous stress and toroidal force due to the NBI for various values of $\mu_{\phi\theta}$. The calculated beam torque shows a drop by a factor of 2 in the 2nd ECH pulse case. This is due to the decrease of ionization of the neutral beam and the longer slowing down time at lower electron density and higher electron temperature. In the plasma without neoclassical ITB, the toroidal viscous stress is much smaller than the force due to the NBI and it is almost negligible at $\rho < 0.5$ regardless of the magnitude of $\mu_{\phi\theta}$, because the poloidal flow velocity is almost zero. On the other hand, the toroidal viscous stress exceeds the toroidal force due to the NBI and becomes bigger as the toroidal-poloidal viscous coefficient, $\mu_{\phi\theta}$ is increased in the plasma with neoclassical ITB. By solving the diffusion equations of toroidal momentum described above, the radial profiles of toroidal flow velocity are calculated with the different values of $\mu_{\phi\theta}$. As seen in Fig1(c), the toroidal-poloidal viscous coefficient, $\mu_{\phi\theta}$ of 40 1/ms gives relatively good agreement of toroidal flow velocity with the measured values both in the plasmas with and without neoclassical ITB.

[1] K.Ida, et . al., Phys. Rev. Lett. 86 (2001) 3040.

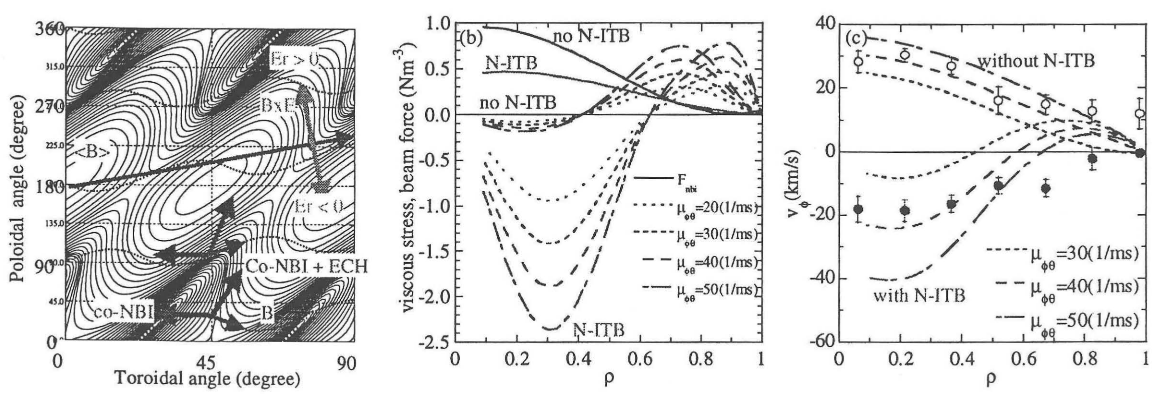

Fig.1. (a)Contour of magnetic field strength on the magnetic flux surface at $\rho=0.3$, (b) the toroidal force due to the NBI and the toroidal viscous stress with various magnitude of viscous coefficient, $\mu_{\phi\theta}$, of 20, 30, 40, 50 1/ms and (c) calculated toroidal flow velocity with $\mu_{\phi\theta}=30$, 40, 50 1/ms and measured toroidal flow velocity for the plasma without neoclassical ITB (without 2nd ECH) and with neoclassical ITB (with 2nd ECH) plasmas.