§22. Transport Analysis with the Effect of Zonal Flows about Electron Internal Transport Barriers in Toroidal Helical Plasmas

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The turbulence-driven transport and the transport barriers is the key issue in fusion research. One thread of thoughts to explain transport barriers is the structural transition of the profile of radial electric field E_r and suppression of turbulence by its gradient. The bifurcation of the radial electric field in helical plasmas is influenced by the neoclassical ripple transport, and the resultant electric field interface (by which the radial domains with positive E_r and negative E_r are separated) was predicted to induce the internal transport barrier due to the shear of the radial electric field in the helical plasmas. The E_r -interface was found on the Compact Helical System (CHS), and the improvement of confinement was found inside of the interface for E_r. The appearance and location of the E_r-interface were analyzed. Surprisingly, the transport coefficient of electron energy was found to be suppressed not only near the interface but also in the whole region of the strong positive E_r in the electron transport barriers (e-ITB) plasma. Away from the transition radius, the gradient dE_r/dr is not strong enough to suppress turbulent transport. Fundamental problem has remained unresolved, and is explained here

We use the system of one-dimensional transport equations for plasma parameters and the mean radial electric field here. The improvement of the confinement was predicted in two ways: the turbulent transport is suppressed by dE_r/dr near the interface, and the neoclassical transport is strongly suppressed inside of the electric field interface. These are insufficient to explain the reduction in the entire core plasma ($\rho < \rho_{int}$), where $\rho = r/a$ and ρ_{int} is the location of E_r interface. The zonal flows (ZFs) (at nearly zero frequency) are generated by the fluctuations and influence the turbulent transport strongly. The damping rate of ZFs, ν_{damp}, controls the turbulent transport. The damping of ZFs is caused by the collisional process and the self-nonlinearity of zonal flows. In the toroidal helical plasmas, the collisional process remains important in the regime of $\nu_* < 1$ ($\nu_* = \nu_i qR/(\varepsilon v_{thi})$). Whether the zonal flows are excited or not is determined by the competition between the excitation by micro turbulence and the damping of ZFs. Including the effect of ZFs, a formula of turbulent transport coefficient has been derived: $\chi_T = \sqrt{\chi_{T0}}\,\min(\sqrt{\chi_{T0}}, \sqrt{\chi_{damp}})$. In this equation, χ_{T0} is the turbulent transport coefficient given in the absence of ZFs. When ν_{damp} is small and $\chi_{damp} < \chi_{T0}$ is satisfied, ZFs are excited. The damping rate of ZFs is given by the neoclassical ripple transport as $\nu_{damp} = (\partial J_r^{NEO}/\partial E_r)/\varepsilon_\perp$, where superscript NEO stands for the neoclassical ripple transport and $\varepsilon_\perp$ is the perpendicular dielectric coefficient. The turbulent transport coefficient becomes smaller when the strong positive radial electric field is established in e-ITB. The bifurcation of E_r itself induces the transition of turbulent transport in the bulk of the plasma column as well as at the interface of the electric field. The one-dimensional transport analysis for LHD-like plasma has been performed and the mean profile of E_r, T_e, T_i and n were solved. In this analysis, thermal diffusivity is given as the sum of χ_T and neoclassical transport. In this calculation, χ_{T0} is given based on the nonlinear current-diffusive interchange mode which was found relevant in preceding analysis. An example is taken from the low density plasma which is sustained by electron cyclotron resonance (ECR) heating. Profile of total diffusivity with the zonal flow effect (solid line) is shown in Figure 1. In this case, the E_r-interface is established at $\rho_{int} = 0.3$, and E_r is strongly positive for $\rho < \rho_{int}$. The clear reduction of the total diffusivity is shown in the region $\rho < \rho_{int}$ compared with that in the region $\rho > \rho_{int}$ in the case with the effect of the zonal flows. The total thermal diffusivity of electrons χ_e^{total} represents the sum of the turbulent part and neoclassical part. It is found that the condition $\chi_{damp} < \chi_{T0}$ is satisfied in the core of e-ITB due to the strong E_r. Zonal flows are excited and χ_T is reduced there (thin broken line), due to the smaller damping of zonal flows. The simulation using bare fluctuations without the effects of zonal flows χ_{T0}, thermal diffusivity has a dip near the interface, but does not show the noticeable reduction for $\rho < \rho_{int}$ (dashed line); χ_{T0} increases in the core owing to the higher temperature (thin dotted line). The screened transport coefficient is close to what has been reported from LHD experiments. Experimental confirmation is given on CHS. It is reported that the energy of fluctuations is transferred into zonal flows when the damping rate ν_{damp} becomes weak in the e-ITB.

Reference
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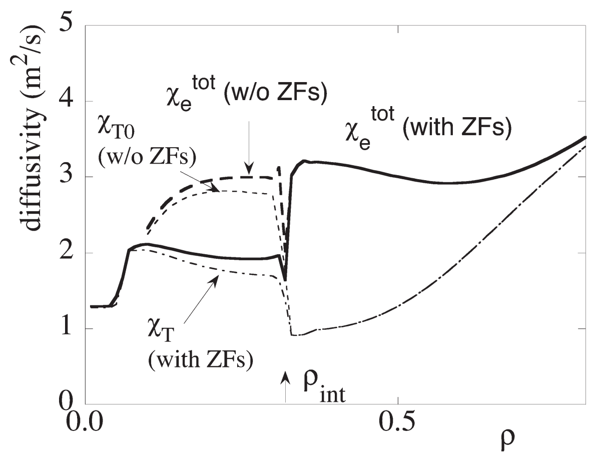

Figure 1 Transport analysis of LHD-like plasma with the e-ITB