§10. Gyrokinetic Simulation of ITG Turbulence in Helical Plasma with Equilibrium-scale $E \times B$ Flow

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In recent years, one of the main issues in theoretical studies on turbulent transport and zonal flows in helical systems, such as the Large Helical Device (LHD), is the zonal flow response enhancement by improvement of collisionless orbits of helical ripple trapped particles. It has been pointed out that the long-time response function of zonal flows is amplified by an equilibrium scale radial electric field[1)], $\overline{E}_r$, which is spontaneously generated by the ambipolar particle diffusion of the neoclassical transport and drives a poloidal $\boldsymbol{E} \times \boldsymbol{B}$ rotation. The zonal flow enhancement by the radial electric field is confirmed by the gyrokinetic simulation[2)] which is extended so as to incorporate field-line-label dependence of the confinement field strength. Application of the poloidally global model to the ITG turbulence, however, causes a difficulty associated with mixture of different scale lengths for equilibrium and turbulence. To overcome this issue, we have devised a multi-scale simulation model, named "*flux-tube bundle*" model, for turbulence and zonal flows in helical plasmas with the poloidal $\boldsymbol{E} \times \boldsymbol{B}$ rotation[3)].

The zonal flow response to a given source term is calculated by means of the linear gyrokinetic simulation using the flux-tube bundle model. Time-history of the zonal flow potential is plotted in Fig. 1, where M_p means the poloidal Mach number, $M_p = |\omega_\theta| R_0 q_0 / v_{ti} = (R_0 q_0 / r_0) |c \overline{E}_r / B_0 v_{ti}|$. Eight flux tubes are set in the flux-tube bundle model for a range of $-\pi/M \leq \alpha \leq +\pi/M$ with $M = 10$ for the LHD configuration, where α means the field line label $\alpha = \zeta - q\theta$ and q is the safety factor. The residual zonal flow level after the initial damping of the geodesic acoustic mode (GAM) is enhanced by $\overline{E}_r$, which is consistent with the previous simulaitons[2)]. As the finite collision term is introduced here, the residual zonal flow level decays in a longer time.

Nonlinear simulations of the ITG turbulence using the flux-tube bundle model have also been carried out where the eight flux tubes are employed. In case without the poloidal rotation ($M_p = 0$), turbulence and zonal flows in each flux tube develop independently. The total average of the heat flux agrees with that of the single flux tube case, because the ITG mode in LHD plasma has little dependence on the field line label α. In case with the poloidal rotation, a collective phenomenon among flux tubes arises when zonal flows developed in the ITG turbulence. Because of the zonal flow response enhancement by $\overline{E}_r$, the zonal flow amplitudes in the flux tubes continue to grow after the initial saturation of the instability growth as seen in Fig. 2. For $M_p = 0.3$, the power of zonal flow potential averaged over flux tubes is about two times higher than that for $M_p = 0$.

Multi-scale simulations for turbulence and zonal flows in poloidally-rotating helical plasmas have demonstrated strong zonal flow generation by turbulence, which implies that turbulent transport processes in non-axisymmetric systems are coupled to the neoclassical transport through the macroscopic $\boldsymbol{E} \times \boldsymbol{B}$ flows determined by the ambipolarty condition for neoclassical particle fluxes.

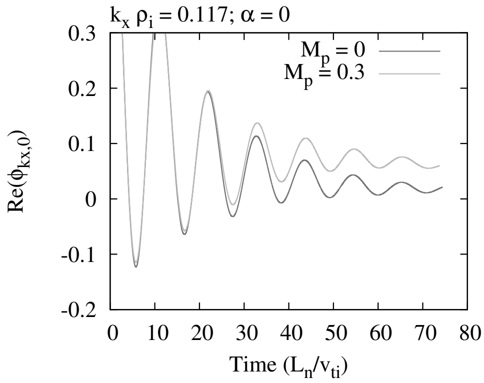

Fig. 1: Zonal flow response calculated by means of the flux-tube bundle model with and without poloidal rotation, where M_p denotes the poloidal Mach number of the $\boldsymbol{E} \times \boldsymbol{B}$ flow[4)].

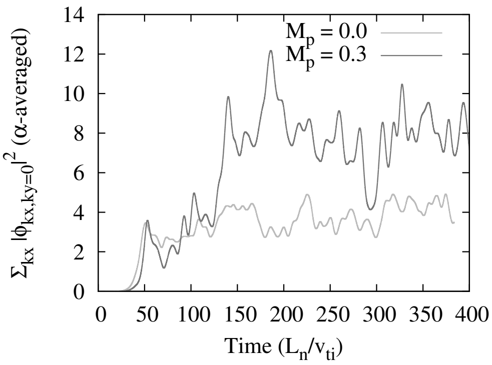

Fig. 2: Time-history of zonal flow potential driven by the ITG turbulence in a helical system with and without the poloidal $\boldsymbol{E} \times \boldsymbol{B}$ rotation[4)].

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2) Watanabe, T.-H., Sugama, H., and Nunami, M.: Nucl. Fusion **51** (2011) 123003.

3) Watanabe, T.-H., Sugama, H., Nunami, M., and Nakata, M.: J. Phys.: Conf. Ser. bf 399 (2012) 012020.

4) Watanabe, T.-H. et al.: 24th IAEA Fusion Energy Conference 2012, San Diego, USA (IAEA, Vienna, 2012) TH/8-1.