§9. Gyrokinetic Simulation of Zonal-Flow Response in Helical System with Equilibrium-Scale Radial Electric Field

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For understanding anomalous transport mechanism and predicting transport levels in magnetically confined fusion plasmas, we have conducted gyrokinetic simulations of drift-wave turbulence by means of the GKV code, where the gyrokinetic equations for the perturbed one-body distribution function is numerically solved on the five-dimensional phase-space. Extensive GKV simulation studies of ion temperature gradient (ITG) turbulence and zonal flows in helical systems manifest transport reduction with enhanced zonal-flow generation in the neoclassically optimized helical configuration. In the inward-shifted LHD plasma, the ITG turbulent transport is more effectively regulated by the stronger zonal flows than those in the standard configuration[1]. This is attributed to the higher zonal-flow response in the former than that in the latter, and is also consistent to our theoretical prediction that the zonal-flow is enhanced in helical configurations with slower radial drift motions of helical-ripple-trapped particles[2),3)]. The inward-shifted LHD plasma is, thus, expected to show better confinement than that with the standard magnetic axis position, which is also consistent with the experiments.

The gyrokinetic theory on zonal flows in helical systems suggests further enhancement of zonal flows, when the equilibrium radial electric field E_r producing the poloidal ***E*x*B*** rotation is included[4),5)]. This is because radial displacement of helical-ripple-trapped particles is reduced by the ***E*x*B*** rotation. In order to verify the theoretical prediction, we have newly extended the GKV code to a poloidally global model[6)], where the poloidally rotating ***E*x*B*** drift particles are taken into account, while the local flux-tube model around a single field line was employed in previous studies with no equilibrium radial electric field.

The gyrokinetic equation describing the collisionless damping of zonal flows with E_r in the helical configuration is given by

$$\left[\frac{\partial}{\partial t} + v_\parallel \hat{\mathbf{b}}\cdot\nabla + i\mathbf{k}_r\cdot\mathbf{v}_d - \mu\left(\hat{\mathbf{b}}\cdot\nabla\Omega\right)\frac{\partial}{\partial v_\parallel} + \omega_\theta\frac{\partial}{\partial\alpha}\right]\delta f$$

$$= -i\mathbf{k}_r\cdot\mathbf{v}_d\frac{e\langle\psi\rangle}{T_i}F_M .$$

where the field-aligned coordinates of $x = r - r_0$, $y = r_0[\theta - \zeta/q]$, and $z = \zeta$, are used with the field-line label $\alpha = \theta - \zeta/q$. We choose α so that $\mathbf{B} = \nabla\Psi_t \times \nabla\alpha$, where Ψ_t denotes the toroidal flux and $\omega_\theta = -cE_r/r_0 B_0$.

The zonal-flow component of the electrostatic potential is defined by its flux-surface-average, $\langle\phi\rangle$, so that unstable ITG modes are decoupled from zonal flows in the linear regime, where

$$\langle A\rangle \equiv \iint d\alpha d\zeta \frac{A(\alpha,\zeta)}{B(\alpha,\zeta)} \Big/ \iint d\alpha d\zeta \frac{1}{B(\alpha,\zeta)} .$$

For simplicity, we assume the quasi-neutrality in a low electron temperature limit,

$$\frac{e}{T_i}\langle\phi\rangle = \frac{\langle n_i\rangle}{n_0\left[1-\Gamma_0(k_r^2)\right]} .$$

Numerical simulations of the zonal-flow response are performed for the radial wavenumber $k_r\rho_i$=0.131 and the poloidal Mach number M_p=0, 0.1, 0.2, and 0.3. Time-histories of real part of the zonal flow potential are plotted in Fig.1. It is clearly found that the zonal-flow response is enhanced by introducing the radial electric field. For M_p=0.3, the residual level is about 3 times higher than that for M_p=0. The new GKV simulation results of zonal-flow response with E_r support the theoretical prediction[4),5)]. Under the same conditions on E_r and the magnetic geometry, use of ions with a heavier mass leads to a higher zonal-flow response, and thus, the turbulent transport is expected to show a more favorable ion-mass dependence than the conventional gyro-Bohm scaling.

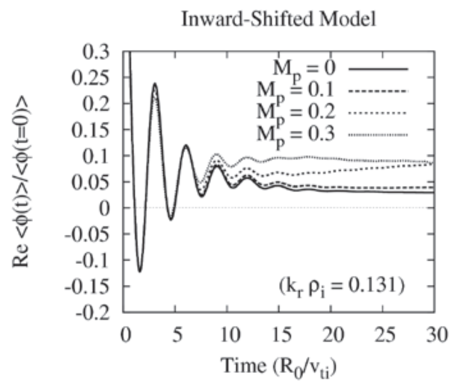

Fig. 1. Zonal-flow response of a model configuration for the inward-shifted LHD plasma with the equilibrium radial electric field. Here, M_p stands for the poloidal Mach number.

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