§13. Comparison between Theory and Simulation of Residual Zonal Flows in Helical Systems with Radial Electric Fields

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Zonal flows are now recognized as one of key mechanisms to regulate turbulent transport in magnetically confined plasmas and they are intensively investigated from the viewpoint of improving confinement of fusion plasmas. We have been studying zonal flows in helical systems based on gyrokinetic theory and simulation [1-5]. In helical systems, the equilibrium radial electric field E_r determined from the ambipolar particle flux condition generates the macroscopic $\mathbf{E} \times \mathbf{B}$ rotation which is distinguished from the microscopic sheared $\mathbf{E} \times \mathbf{B}$ zonal flows. In our previous work [4], the formulas for collisionless zonal-flow responses were derived by taking account of transitions between toroidally-trapped particles and helical-ripple-trapped particles, the latter of which show the poloidal $\mathbf{E} \times \mathbf{B}$ rotation. Since the E_r effects appear through the poloidal Mach number $M_p \equiv (c|E_r|/B_0 r_0)(R_0 q/v_{ti})$, higher zonal-flow responses are predicted by using ions with a heavier mass, which increases M_p, and accordingly the resultant turbulent transport is expected to show a more favorable ion-mass dependence than the conventional gyro-Bohm scaling.

In our new work [5], the collisionless zonal-flow response in helical systems with E_r is theoretically described with a modified expression for the probability of the transition from the toroidally-trapped orbit to the helical-ripple-trapped orbit. In order to investigate effects of the $\mathbf{E} \times \mathbf{B}$ rotation on the residual zonal flow, the theoretical predictions about enhancement of the residual zonal-flow level due to E_r are compared with the linear gyrokinetic Vlasov simulation over the poloidally global domain [3]. Figure 1 shows the magnetic field strength along the field line for the magnetic configuration model used in the simulation, which corresponds to the inward-shifted LHD plasma. In Fig. 2, the normalized residual zonal-flow potential $\langle\phi_{\mathbf{k}_\perp}(t=\infty)\rangle/\langle\phi_{\mathbf{k}_\perp}(0)\rangle$ obtained by the simulation is plotted by symbols with error bars as a function of the normalized radial wave number $k_r\rho_{ti}$ for $M_p = 0$ and $M_p = 0.3$. Here, the initial ion gyrocenter distribution function is given by the Maxwellian form. Solid lines in Fig. 2 represent theoretical predictions. The accuracy of the theoretical formulas used here is not good enough for $k_r\rho_{ti} > 0.15$, where the theoretical curves are not plotted. Different radial-wave-number dependences of the residual zonal-flow potential in the small $k_r\rho_{ti}$ limit for $M_p = 0$ and $M_p = 0.3$ are confirmed in Fig. 2 as theoretically predicted. In contrast to the case of $E_r = 0$ ($M_p = 0$), the residual zonal-flow potential takes a finite value in the limit of $k_r\rho_{ti} \to 0$ for $E_r \neq 0$. Thus, in the presence of the radial electric field which significantly reduces the radial displacement of the helical-ripple-trapped particles, enhancement of the zonal-flow generation due to the turbulence is expected.

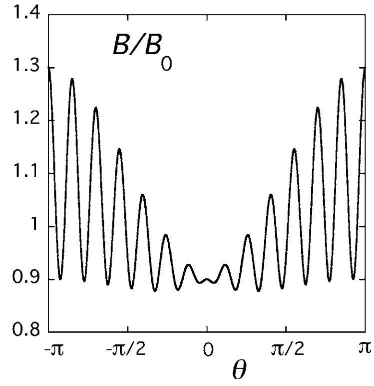

Fig.1. The profile of the field strength along the field line $\zeta = q\theta$ in a model magnetic geometry corresponding to the inward-shifted LHD configuration.

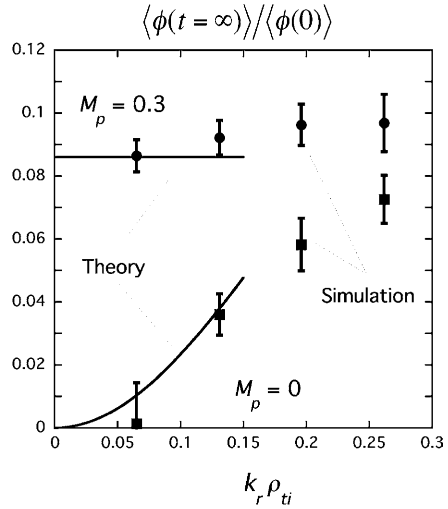

Fig.2. The normalized residual zonal-flow potential $\langle\phi_{\mathbf{k}_\perp}(t=\infty)\rangle/\langle\phi_{\mathbf{k}_\perp}(0)\rangle$ as a function of the normalized radial wave number $k_r\rho_{ti}$ for $M_p = 0$ and $M_p = 0.3$. Symbols with error bars and solid lines represent simulation results and theoretical predictions, respectively.

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3) T.-H. Watanabe, H. Sugama, and S. Ferrando-Margalet, 22nd IAEA Fusion Energy Conference 2008, Geneva, Switzerland (IAEA, Vienna, 2008) TH/P8-20.
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