§1. Turbulence-driven Zonal Flows in Helical Systems with Radial Electric Fields

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Collisionless long-time responses of the zonal-flow potential to the initial condition and turbulence source in helical systems having radial electric fields are derived theoretically [1–2]. All classes of particles in passing, toroidally-trapped, and helical-ripple-trapped states are considered. The transitions between the toroidally-trapped and helical-ripple-trapped states are taken into account while solving the gyrokinetic equation analytically by taking its average along the particle orbits. When the radial displacements of helical-ripple-trapped particles are reduced either by neoclassical optimization of the helical geometry lowering the radial drift or by strengthening the radial electric field E_r to boost the poloidal rotation, enhanced zonal-flow responses are obtained. Under the identical conditions on the magnitude of E_r and the magnetic geometry, using ions with a heavier mass gives rise to a higher zonal-flow response, and therefore the turbulent transport is expected to show a more favorable ion-mass dependence than the conventional gyro-Bohm scaling.

The collisionless long-time behavior of the zonal-flow potential is described by

$$\frac{e\phi_{\mathbf{k}_\perp}(t)}{T_i} = \frac{\langle I(t)\rangle}{\mathcal{D}}, \tag{1}$$

$\langle\cdots\rangle$ denotes the flux-surface average. For the wave-number region relevant to the ITG turbulence, where $k_\perp \rho_i < 1$, the shielding term $\mathcal{D}$ on the right-hand side of Eq.(1) is written as

$$\begin{aligned}\mathcal{D} &= n_0\left\langle k_\perp^2 \rho_{ti}^2\right\rangle \\ &\quad + \sum_{a=i,e}\frac{T_i}{T_a}\left\langle \int d^3v\, F_{a0} k_r^2 \left\{\langle \Delta_{ar}^2\rangle_{\rm po} - \langle \Delta_{ar}\rangle_{\rm po}^2\right\}\right\rangle \\ &= n_0\left\langle k_\perp^2 \rho_{ti}^2\right\rangle \big[1 + G_p + G_t \\ &\quad + M_p^{-2}(G_{ht} + G_h)(1 + T_e/T_i)\big], \end{aligned} \tag{2}$$

and $\langle I(t)\rangle$ is given by

$$\begin{aligned}\langle I(t)\rangle &= \left\langle \int d^3v\, \left[1 + ik_r\left\{\Delta_{ir} - \langle\Delta_{ir}\rangle_{\rm po}\right\}\right] \right. \\ &\quad \left. \times \overline{[\delta f_{i\mathbf{k}_\perp}^{(g)}(0) + F_{i0} R_{i\mathbf{k}_\perp}(t)]}\right\rangle, \end{aligned} \tag{3}$$

which includes the initial conditions and nonlinear sources. If we assume that the initial perturbed ion gyrocenter distribution function takes the Maxwellian form, the relation of the residual zonal-flow potential at time t to its initial value is derived from Eqs.(1)–(3) as

$$\phi(t) = \frac{\phi(0)}{1 + G_p + G_t + M_p^{-2}(G_{ht} + G_h)(1 + T_e/T_i)}, \tag{4}$$

where the contributions of the nonlinear source are dropped. Details of the notations used here are found in Ref.2. The dimensionless geometrical factors G_p and G_t are related to passing and toroidally-trapped particle orbits, respectively, while the other geometrical factors G_h and G_{ht} originate from the poloidally-closed and unclosed orbits of helical-ripple-trapped particles, respectively. The probability of the transition from the toroidally-trapped to helical-ripple-trapped is taken into account for evaluating G_{ht}. Figure 1 shows toroidally-trapped and helically-trapped orbits, between which transitions can occur.

The radial displacements Δ_r of helical-ripple-trapped particles giving the main contributions to the shield of the zonal-flow potential are proportional to the radial drift velocities $\overline{v}_{dr}$ of those particles, and are inversely proportional to the equilibrium radial electric field E_r. In helical configurations optimized for reducing neoclassical transport, helical-ripple-trapped particles have small v_{dr}; therefore, G_{ht} and G_h have small values, and the zonal-flow potential exhibits a good response to the turbulence source. The effects of E_r on the zonal-flow response appear in Eqs.(2) and (4) through the poloidal Mach number $M_p \equiv |(cE_r/B_0 r_0)(R_0 q/v_{ti})|$. The shield of the zonal-flow potential is weakened by strengthening the radial electric field E_r, and increasing M_p. For the same value of E_r, M_p can be also increased also by using ions with a heavier mass, which is expected to produce zonal flows more efficiently and establish a more favorable ion-mass dependence of the ITG turbulent transport than the conventional gyro-Bohm scaling.

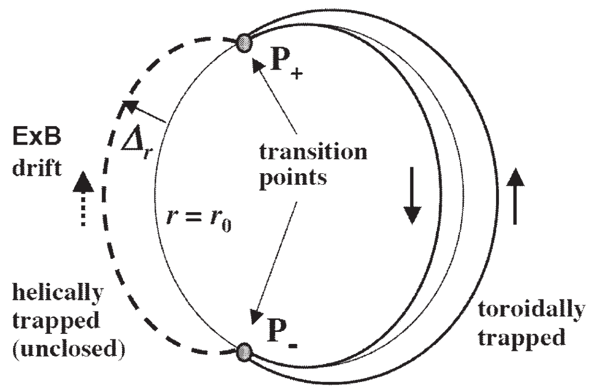

Fig.1. Poloidal cross sections of toroidally-trapped and helically-trapped orbits, between which transitions can occur at P_+ and P_-. A dashed curve represents a bounce-center $\mathbf{E}\times\mathbf{B}$-drift motion of a helically-trapped particle.

1) H. Sugama, Bull. Am. Phys. Soc. **53**, 322 (2008).
2) H. Sugama and T.-H. Watanabe, Phys. Plasmas **16**, 056101 (2009).