## §14. Effects of Equilibrium Radial Electric Fields on Zonal Flows

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Zonal flows driven by ion temperature gradient (ITG) turbulence in helical systems have been studied based on gyrokinetic theory and simulation in our previous works [1-3] where equilibrium electric fields are neglected. In this work [4], we investigate how the residual zonal-flow level is influenced by the equilibrium radial electric field, which can be produced by the neoclassical ambipolar condition in asymmetric toroids. The radial electric field $\mathbf{E} = E_r \nabla r$ drives the equilibrium $\mathbf{E} \times \mathbf{B}$ drift velocity $\mathbf{v}_E \equiv (c/B) E_r \nabla r \times \mathbf{b}$ in the direction tangential to the flux surface. Here, for simplicity, we consider radially local region in which $E_r$ is assumed to be constant and has no shear. For the zonal-flow component with the wave number vector $\mathbf{k}_\perp = k_r \nabla r$, at first, the equilibrium electric field does not seem to influence the zonal-flow response because $\mathbf{k}_\perp \cdot \mathbf{v}_E = 0$. However, when treating helical configurations, we find subtle points about the above argument with respect to the zonal-flow response. In the ballooning representation and the local flux tube model, only the neighborhood of a single field line labeled by $\alpha \equiv \zeta - q(r)\theta$ is considered. For helical systems, the field line label $\alpha$ explicitly appears in the gyrokinetic equation in contrast to tokamak cases. Even if the zonal-flow potential $\phi$ is independent of $\alpha$, the explicit appearance of $\alpha$ in the magnetic drift terms of the gyrokinetic equation causes the perturbed gyrocenter distribution function $\delta f$ to depend on $\alpha$. Therefore, in helical configurations, we generally have $\mathbf{v}_E \cdot \nabla \delta f \neq 0$ so that the zonal-flow response can be affected by the existence of the equilibrium electric field.

Compared with passing and toroidally trapped particles, helical-ripple-trapped particles will have their orbits changed more greatly by the equilibrium radial electric field $E_r$. The radial displacements of helical-ripple-trapped particles are significantly reduced when the $\mathbf{E} \times \mathbf{B}$ drift due to $E_r$ generates their rapid poloidal rotations as shown in Fig. 1. For such cases, neoclassical ripple transport is reduced and, in addition, higher zonal-flow responses are expected because the shielding of the zonal-flow potential by the helically-trapped particles is weakened. This scenario was first presented by Mynick and Boozer [5], who employed the action-angle formalism and pointed out the analogy between the mechanisms of zonal-flow shielding and neoclassical transport.

Taking account of the dependence of the perturbed distribution function on the field line label $\alpha$, our formulation of zonal-flow response is extended to derive detailed expressions for the $E_r$ effects on the zonal-flow response. We now assume the bounce centers of helically-trapped particles to draw poloidally-closed orbits with the poloidal angular velocity $\omega_\theta \equiv -cE_r/(rB_0)$. Furthermore, considering the helical configuration with the single-helicity component $\epsilon_h$ in the Fourier spectrum of magnetic field strength $B$, we find that, for $t \gg 1/\omega_\theta$, the collisionless long-time limit of the zonal-flow response kernel, which represents the residual zonal flow level, is given by

$$\mathcal{K}_{Er} = [1 + G + \mathcal{E}_{Er}/(k_r \rho_{ti})^2]^{-1} = \left[1 + G + \frac{15}{8\pi}(2\epsilon_h)^{1/2} \left(\frac{\epsilon_t v_{ti}}{r\omega_\theta}\right)^2 \left(1 + \frac{T_e}{T_i}\right)\right]^{-1} \quad (1)$$

where $G$ is the ratio of the neoclassical polarization due to toroidally trapped ions to the classical polarization and $\mathcal{E}_{Er}$ represents the shielding term due to the helically-trapped particles (see Refs. 2 and 4 for their detailed definitions). We see that, as $E_r$ increases, $\mathcal{K}_{Er}$ increases and approaches the value $1/(1+G)$ because $\mathcal{E}_{Er}$ is inversely proportional to the square of $E_r$. It is noted that $\mathcal{E}_{Er}/k_r^2$ given in Eq. (1) corresponds to the product of the helically-trapped-particles' fraction ($\sim \epsilon_h^{1/2}$) and the square of the radial orbit width $\Delta_E (\propto 1/\omega_\theta \propto 1/E_r)$ of helically-trapped-particles' poloidal rotation (see Fig. 1), which agrees with Mynick and Boozer [5]. In helical configurations such as the inward-shifted LHD case, which are optimized for reduction of neoclassical transport, the enhancement of zonal-flow response due to $E_r$ is expected to work more effectively than in the standard configuration because the neoclassical optimization reduces radial displacements $\Delta_E$ of helically-trapped particles during their poloidal $\mathbf{E} \times \mathbf{B}$ rotation.

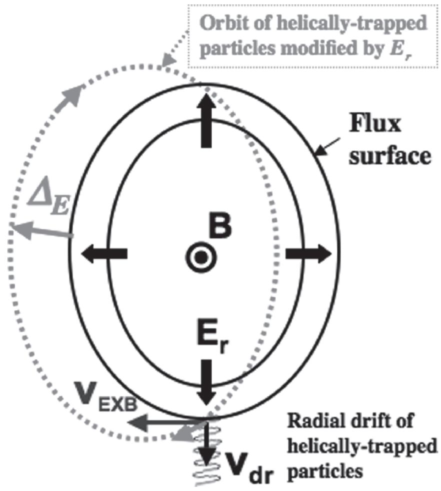


Fig.1. Orbit of bounce-center motion of helical-ripple-trapped particles modified by the radial electric field $E_r$. Here, $\Delta_E$ represents the radial displacement of the orbit.


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4) H. Sugama, T.-H. Watanabe, and S. Ferrando-Margalet, ITC17/ISHW2007 (Toki, Japan, 2007), PI-08.
5) H. E. Mynick and A. H. Boozer, Phys. Plasmas **14**, 072507 (2007).