§9. Flux-tube Bundle Model for Gyrokinetic Turbulence Simulation in Helical Systems

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Because of helical ripples, gyrokinetic simulation generally requires higher resolution of the phase space for helical systems than for tokamaks. Especially, nonlinear gyrokinetic simulation for the shell region over the whole flux surface in helical systems needs much more computational memory and time than for a single flux-tube domain. Here, we propose a flux-tube bundle model [1] as a new method for multiscale gyrokinetic simulation which treats the macroscopic $\mathbf{E} \times \mathbf{B}$ rotation and the microscopic zonal flows with a smaller computational burden than direct simulation for the whole shell region. Based on the scale separation concept, we use the macroscopic (or large scale length) coordinates (r, α, z) and the microscopic (or small scale length) coordinates (x, y). Here, r, $\alpha \equiv \theta - \zeta/q(r)$, and $z \equiv \theta$ represent the radial coordinate, the field-line label, and the poloidal angle, respectively, which are included in the equilibrium (or background) variables; for example, the equilibrium magnetic field strength is written as $B = B(r, \alpha, z)$. The (x, y) coordinates represent the same as (r, α) although (x, y) are used to describe microscopic scale variation of turbulent variables on the plane perpendicular to the magnetic field. For example, the fluctuating potential is written as $\phi = \phi(x, y, z; r, \alpha)$ where (x, y) and (r, α) are treated as independent pairs of coordinates to separately represent microscopic and macroscopic variations.

Figure 1 shows a bundle of flux tubes distributed over a given flux surface labeled by the macroscopic radial coordinate r. Each flux tube is specified by assigning certain constant values to r and α. We note that $z \equiv \theta$ is regarded as the coordinate along the magnetic field line because the direction parallel to the magnetic field is given by changing z with all other coordinates fixed. When microscopic fluctuations are considered for each flux tube, unstable modes such as the ITG instability need to have finite wave numbers $k_y \neq 0$ in the y-direction. For $k_y = 0$, fluctuations give linearly stable modes such as zonal flows. The gyrokinetic equation for the zonal ($k_y = 0$) component of the perturbed ion gyrocenter distribution function $\delta f_i(x, z, E, \mu; r, \alpha)$ is written as

$$\left[\frac{\partial}{\partial t} + \frac{v_\parallel}{qR}\frac{\partial}{\partial z} + v_{dr}\frac{\partial}{\partial x} + \omega_{E\times B}\frac{\partial}{\partial \alpha} - C_i\right]\delta f_i(x, z, E, \mu; r, \alpha)$$
$$= -\frac{e}{T_i} f_{iM}\left(\frac{v_\parallel}{qR}\frac{\partial}{\partial z} + v_{dr}\frac{\partial}{\partial x}\right)\overline{\phi}(x, z; r, \alpha) + \mathcal{N}(\overline{\phi}, \delta f_i), \quad (1)$$

where $\mathcal{N}(\overline{\phi}, \delta f_i)$ denotes the $k_y = 0$ component of the nonlinear $\mathbf{E} \times \mathbf{B}$ convection term that is regarded as a source of zonal flows. The effect of the equilibrium radial electric field E_r on the zonal flow generation appears from the $\mathbf{E} \times \mathbf{B}$ rotation term $\omega_{E\times B}\partial\delta f_i/\partial\alpha$ on the left-hand side of Eq. (1). This term causes the interaction between the zonal ($k_y = 0$) modes distributed over the bundle of flux tubes with different values of α and thus influences zonal flow generation and turbulent transport. When different flux-tube regions are coupled through the background $\mathbf{E} \times \mathbf{B}$ rotation in the flux-tube bundle model, the perturbed distribution function is considered to show poloidally-global structures reflecting poloidal excursions of helical-ripple-trapped particles which cannot be grasped by conventional single-flux-tube simulations. We expect from this coupling that the turbulent transport processes are necessarily linked to the neoclassical transport because the ambipolar neoclassical particle fluxes determine the $\mathbf{E} \times \mathbf{B}$ rotation which can, in turn, enhance zonal-flow generation and accordingly regulate the turbulent transport. Gyrokinetic turbulence simulation using the flux-tube bundle model described above is in progress to confirm the E_r effect on the zonal flows and the ITG turbulent transport [2,3].

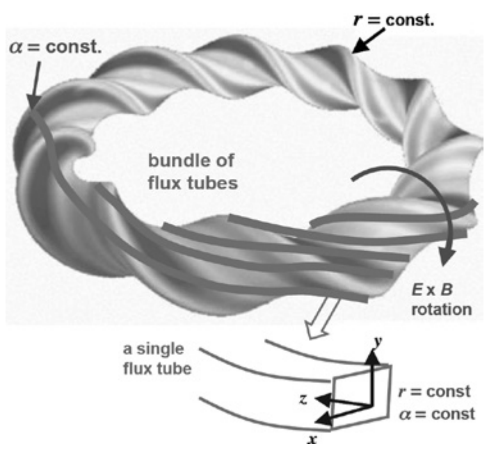

Figure 1: The flux-tube bundle model. A bundle of flux tubes used for simulation domains are shown in red color.

1) H. Sugama, T.-H. Watanabe, M. Nunami, S. Satake, S. Matsuoka, K. Tanaka, Plasma Fusion Res. **7**, 2403094 (2012).
2) T.-H. Watanabe, *et al.*, 24th IAEA Fusion Energy Conference 2012, San Diego, USA (IAEA, Vienna, 2012) TH/8-1.
3) T.-H. Watanabe, H. Sugama, M. Nunami, M. Nakata, J. Phys.: Conf. Ser. **399**, 012020 (2012).