

Relation among ITG Turbulence, Zonal Flows, and Transport in Helical Plasmas^{*)}

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Relation among the ion temperature gradient (ITG) turbulence, zonal flows, and the transport in helical plasmas is investigated by nonlinear gyrokinetic simulations. Local gyrokinetic simulations for helical field configurations are carried out employing various parameters such as the density and temperature gradients and local shears. From the simulation results, we construct a simple model function to represent ion heat diffusivity in terms of the turbulent fluctuations and zonal flow amplitude in helical plasmas.

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Turbulent transport has been considered to be one of the most critical issues in the magnetically confined fusion plasma research. For the study of plasma confinement properties, it is very important to evaluate the transport level associated with turbulence caused by micro-instabilities such as the ion temperature gradient (ITG) mode. To date, a large number of gyrokinetic simulation studies have been made for clarifying the turbulent transport physics [1]. Owing to recent great progress in the development of computational resources, direct comparisons of numerical simulation with experimental data are possible. However, only a few validations of the gyrokinetic simulations in helical systems such as the Large Helical Device (LHD) [2] have been performed, in contrast to the case for tokamaks in which studies against the experiments have been extensively promoted [3]. This is because gyrokinetic simulations for non-axisymmetric systems require a higher spatial resolution than those for tokamaks. In addition to the physical clarification and validation, it is also necessary to construct a reduced transport model for integrated simulations [4]. Therefore, we should clarify the intermediate relation bridging the turbulence simulation and transport modeling.

In our previous paper [5], nonlinear local flux-tube gyrokinetic Vlasov simulations of ITG turbulent transport were carried out by using the GKV-X code [6] for the high ion temperature (high- T_i) LHD plasma in shot number 88343 [7]. The simulation results reproduced the turbulent ion heat transport level and the wavenumber spectra of the density fluctuations observed in the experiment. Figure 1 shows that the simulation results are in reasonable agreement with the experimental values of turbulent ion heat

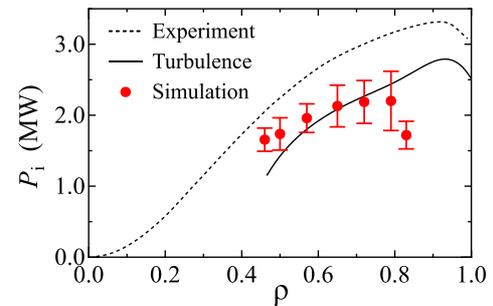


Fig. 1 Radial profiles of ion heat flux P_i in the high- T_i LHD plasma #88343 obtained from the experiment (dotted curve) and the simulations (red symbols). Solid curve shows the turbulent contribution of the experimental result obtained by subtracting neoclassical contribution from the observation.

flux obtained by subtracting the neoclassical contribution from the observation. The turbulent transport level is determined through the interactions of turbulent fluctuations and zonal flows [8]. In the present study, in order to quantitatively clarify the effects of turbulence and zonal flows on the transport level in helical plasmas, we define two nonlinear quantities, the squared turbulent potential fluctuation $\mathcal{T} \equiv (1/2) \sum_{k_x, k_y \neq 0} \langle |\tilde{\phi}_{k_x, k_y}|^2 \rangle$, and the squared amplitude of zonal flow potential $\mathcal{Z} \equiv (1/2) \sum_{k_x} \langle |\tilde{\phi}_{k_x, k_y=0}|^2 \rangle$. Here $\tilde{\phi}$ is the electrostatic potential fluctuation normalized by $T_i \rho_{ti} / e R_0$ with the ion thermal gyro radius ρ_{ti} , and the major radius of the field R_0 . The flux-surface average is denoted by $\langle \dots \rangle$, and (k_x, k_y) represent wavenumbers in radial and poloidal directions, respectively.

Figure 2 shows the time evolutions of \mathcal{T} , \mathcal{Z} and the ion heat transport coefficient in the gyro-Bohm unit $\chi_i / \chi_i^{\text{GB}}$ for two cases, where $\chi_i^{\text{GB}} = \rho_{ti}^2 v_{ti} / R_0$ and $v_{ti} = \sqrt{T_i / m_i}$.

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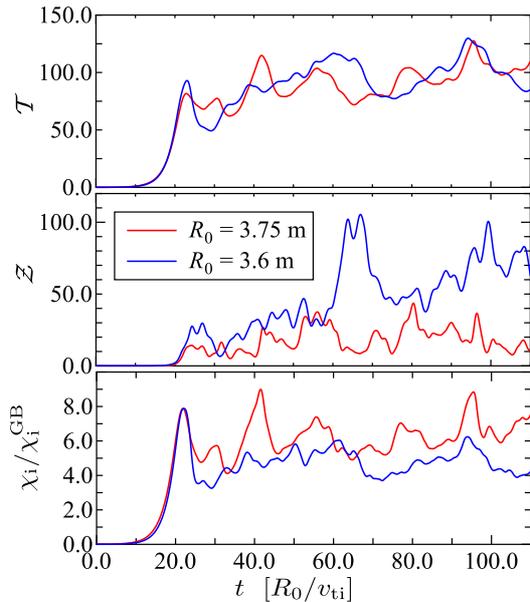


Fig. 2 Time evolutions of \mathcal{T} , \mathcal{Z} and $\chi_i/\chi_i^{\text{GB}}$ resulting from the gyrokinetic simulations. Red curves correspond to the case for $R_0 = 3.75$ m, and blue curves for the vacuum magnetic configuration with $R_0 = 3.6$ m.

One of the simulation results indicated by red curves in Fig. 2 corresponds to the point for $\rho = 0.65$ in Fig. 1 using the magnetic configuration obtained from the MHD equilibrium calculation for the high- T_i LHD plasma #88343, in which the magnetic axis is at $R_0 = 3.75$ m. Here, $T_i = 2.16$ keV and $\rho_{ti} = 1.8 \times 10^{-3}$ m at $\rho = 0.65$. For the other results indicated by blue curves in Fig. 2, the temperature and density gradients are the same as in the case mentioned above, although we use the vacuum magnetic configuration without finite β effects such as the Shafranov shift and the magnetic axis is located at $R_0 = 3.6$ m. In the latter case, the radial drift velocities of helical ripple trapped particles decrease, consequently, the neoclassical transport is reduced [9] while the zonal flow response is enhanced [10]. The squared turbulent fluctuations \mathcal{T} for the two cases are comparable, which corresponds to the fact that the maximum linear growth rates of ITG modes are almost the same, $\gamma_{\text{max}} = 0.246 v_{ti}/R_0$ for the configuration with $R_0 = 3.75$ m and $0.252 v_{ti}/R_0$ for $R_0 = 3.6$ m. On the other hand, the squared zonal flow amplitude \mathcal{Z} for $R_0 = 3.6$ m is greater than that for $R_0 = 3.75$ m. Consequently, the transport level is reduced by the enhanced zonal flow generation for $R_0 = 3.6$ m.

To investigate the dependence of χ_i on $(\mathcal{T}, \mathcal{Z})$, we have performed 17 nonlinear ITG turbulent transport simulations making use of GKV-X for helical plasmas with changing values of various parameters such as the temperature gradient ($7.5 < R_0/L_{Ti} < 23.9$), radial position ($0.46 < \rho < 0.83$), and safety factor ($1.1 < q < 2.2$). Then, it is found that the simulation data at a wide range of the parameters are well represented by the following the model

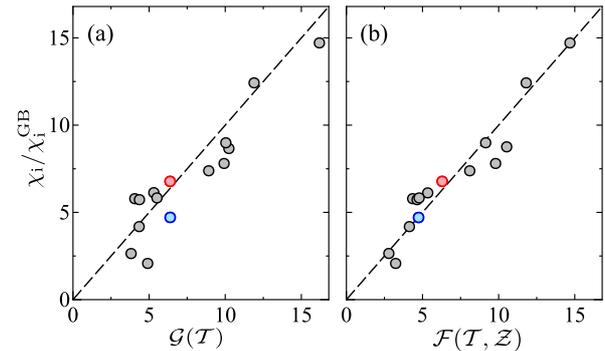


Fig. 3 Comparisons of $\chi_i/\chi_i^{\text{GB}}$ obtained from the simulations and the functions $\mathcal{G}(\mathcal{T})$ and $\mathcal{F}(\mathcal{T}, \mathcal{Z})$. Here, the relative errors are given by $\sigma_{\mathcal{G}} = 0.377$ and $\sigma_{\mathcal{F}} = 0.198$, where σ 's are defined as the root mean square of $[\chi_i/\chi_i^{\text{Model}} - 1]$ with $\chi_i^{\text{Model}}/\chi_i^{\text{GB}} = \mathcal{G}$ and \mathcal{F} . Red and blue symbols represent the results shown in Fig. 2 for $R_0 = 3.75$ m and $R_0 = 3.6$ m cases, respectively.

function

$$\frac{\chi_i}{\chi_i^{\text{GB}}} = \frac{C_1 \mathcal{T}^\alpha}{C_2 + \mathcal{Z}^{1/2}/\mathcal{T}} \equiv \mathcal{F}(\mathcal{T}, \mathcal{Z}), \quad (1)$$

where $\alpha = 0.55$, $C_1 = 0.055$, and $C_2 = 0.063$. In the definition of $\mathcal{F}(\mathcal{T}, \mathcal{Z})$ given by Eq. (1), the numerator $C_1 \mathcal{T}^\alpha$ indicates the enhancement of χ_i with increasing the turbulent fluctuations while $\mathcal{Z}^{1/2}$ in the denominator represents the regulation of χ_i due to zonal flows as shown in Fig. 2. Comparisons between $\chi_i/\chi_i^{\text{GB}}$ obtained from the simulations and the functions are done. In Fig. 3, $\mathcal{F}(\mathcal{T}, \mathcal{Z})$ agrees with the simulation results better than another function $\mathcal{G}(\mathcal{T}) \equiv C_0 \mathcal{T}^\delta$ with $C_0 = 0.26$ and $\delta = 0.69$.

The relation in Eq. (1) will contribute to constructing a reduced transport model for the ITG turbulence in helical plasmas that can be applied to an integrated transport code such as TASK3D [4]. Indeed, the squared turbulent fluctuation \mathcal{T} is strongly correlated with the linear growth rates of the ITG mode, and the squared zonal flow amplitude \mathcal{Z} can be related to the linear zonal flow responses. To construct the model, we should clarify the relations between the results of the nonlinear simulations and linear analyses, which will be reported elsewhere. Because the number of samples used here may still not be sufficient to evaluate the validity of the formula in Eq. (1), we should perform more nonlinear simulations and investigate the dependencies on other parameters, such as collisionality and T_i/T_e which are not considered in this paper. Extension of the physical model to include trapped electrons and electromagnetic effects should also be pursued in future study.

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