Gyrofluid Simulation of Slab ITG Turbulence in Plasmas Including Pressure Profile Corrugation*)

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Ion temperature gradient driven drift wave instability and turbulence are investigated based on a gyrofluid slab model in the presence of a pressure gradient corrugation (PPC). It is shown that the PPC cannot only stabilize or destabilize the ITG mode through local flattening or steepening of the radial pressure gradient, but most importantly also play a stabilizing role due to the global effect of the wave-type corrugation. The latter effect dominates in the highly corrugated cases and is identified to result from a nonlocal mode coupling in radial wave-number space, which scatters the spectra from unstable modes to high dissipation region. While the local stabilization/destabilization is stronger than the global stabilization in the cases with less corrugation, the global stabilization effect dominates the highly corrugated cases. Interestingly, it is found that the global stabilization of the PPC causes ion heat intermittency, which closely connects to the zonal flow dynamics.

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1. Introduction

Coherent large-scale flows and structures such as the mean and zonal flows (ZFs) in drift wave turbulence play an important role not only in suppressing the ambient turbulence to form the transport barriers but also in arising various dynamic transport processes such as intermittency in fusion plasmas [1]. Particularly, the ZFs produced by the turbulence at given scale may affect the turbulent fluctuations and transport property at different scales. For example, it was found that small-scale ZF generated by electron temperature gradient (ETG) driven turbulence can stabilize the ion temperature gradient (ITG) turbulence through a nonlocal mode coupling in radial wave-number space and further induce an intermittency of ion heat transport [2]. On the other hand, the zonal pressure (ZP) component is also simultaneously generated with the ZFs, which can modify the driving force of the ambient turbulence, typically, such as the well-known quasi-linear flattening effect. The ZP with higher radial wave-number components may corrugate the pressure profile so that the driving force is altered by the local modification of the pressure gradient and also by the global feature of the wave-type corrugation.

Recently, the pressure profile corrugation (PPC) is revealed in gyrokinetic simulations based on DIII-D experimental database [3, 4], which may result from the interaction between electromagnetic fluctuations and the rational surfaces. As a result, a time-stationary flattening of the temperature profiles around the lowest-order rational surfaces is observed so that the temperature gradient profile is characterized by an approximate wave-type radial dependence. The PPC may be produced nonlinearly by different scale turbulence through the ZP generation, which corresponds to the radial short wave-length components, or result from the formation of transport barriers due to complex nonlinear self-organization processes relevant to the rational surfaces. It has been understood that the local modification of the pressure gradient can directly influence the drift wave instability versus the change of the driving force. However, the global effect of the corrugated wave-type pressure profile on the micro-instability and turbulence associated with the ZF dynamics is still an unclear problem. In this work, we investigate the PPC effects on the slab ITG turbulence and the ion transport property based on gyrofluid simulation. While the local and global stabilization of the PPC is analyzed by 2-dimensional (2D) linear simulations along a single rational surface, we mainly focus on 2D and 3D turbulence simulations to understand the global effects of the PPC on the ion transport property. A bursty ion transport behavior is observed in the presence of the highly corrugated pressure profile. Spectral analyses show that the underlying mechanism results from a nonlocal mode coupling due to the wave-type feature of the corrugation.

The remainder of this paper is organized as follows: in Sec. II we give a description of the ITG turbulence model with an imposed PPC as an external modification of the equilibrium profile. In Sec. III, we perform linear ITG stability analyses to distinguish the local and global effects of the PPC on the micro-instability. Both 2D and 3D nonlin-

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ear simulations are carried out in Sec. IV to understand the ion transport characteristics. Finally, we give a brief summary of achieved results in Sec. V.

2. Physical Model and Numerical Approach

The PPC is characterized by a wave-type pressure profile modification, which can be modeled by an additional pressure gradient component with a single wave number, namely,

$$\nabla p_{\mathrm{ext}}(x) = -\delta\eta_{\mathrm{i}} \cos(k_{\mathrm{p}} x + \theta), \tag{1}$$

where $k_{\mathrm{p}} = 2\pi L_{\mathrm{p}}/L_x$ represents the global feature of the corrugation, which does not only include the so-called profile shearing, namely, the curvature of the pressure profile [5], but is also characterized by a wave behavior. $\delta\eta_{\mathrm{i}}$ is the maximal local temperature gradient modification. Here L_{p} is the mode-number of the PPC and L_x is the domain size in the radial direction. As a typical character of the wave-type flows such as in [2], the global effect should not depend on the type of sine or cosine function. However, here the PPC can directly modify the local driving force of the turbulent fluctuations near the resonant surface so that the deviation between the location with maximal ∇p_{ext} and the rational surface corresponds to different local driving force. Hence a phase factor θ is introduced to characterize this local effect of the PPC. In the following simulations and analyses, the PPC is imposed in the turbulent environment as an additional component of the equilibrium pressure profile.

The ITG turbulence is governed by a set of normalized 3-field nonlinear gyrofluid equations in slab geometry with $\boldsymbol{B} = B\left[\hat{\boldsymbol{z}} + (x - x_0)\hat{\boldsymbol{y}}/L_s\right]$ for simplicity as follows [6]

$$\left(1 - \delta - \nabla_\perp^2\right)\partial_t\phi = -\left[1 + (K + \nabla p_{\mathrm{ext}})\nabla_\perp^2\right]\partial_y\phi - \nabla_{/\!/} v_{/\!/} + \left[\phi, \nabla_\perp^2\phi\right] - \partial_x\bar{\phi}\partial_y\phi - \mu_\perp\nabla_\perp^4\phi, \tag{2}$$

$$\partial_t v_{/\!/} = -\nabla_{/\!/}(\phi + p) - [\phi, v_{/\!/}] + \eta_\perp\nabla_\perp^2 v_{/\!/}, \tag{3}$$

$$\partial_t p = -(K + \nabla p_{\mathrm{ext}})\partial_y\phi - (\Gamma - 1)\sqrt{8/\pi}\left|k_{/\!/}\right|(p - \phi) - [\phi, p] - \Gamma\nabla_{/\!/} v_{/\!/} + \chi_\perp\nabla_\perp^2 p. \tag{4}$$

Here the term with $\partial_x\bar{\phi}$ in Eq. (2) is from the correct adiabatic electron response to the ITG self-generated ZFs. $\delta = 1$ is for ZF component and $\delta = 0$ for fluctuations. The Poisson brackets

$$[f, g] = \hat{\boldsymbol{z}} \cdot \nabla_\perp f \times \nabla_\perp g = \partial_x f \partial_y g - \partial_y f \partial_x g, \tag{5}$$

indicate the $\boldsymbol{E} \times \boldsymbol{B}$ convective nonlinear terms. The kinetic Landau damping physics is represented by Hammett and Perkins closure model [7]. The cross-field dissipation terms are included to absorb the energy transferred to very short wavelength region, as the usual way in fluid model. The definitions and the normalization of other quantities are conventional [6].

The equations (2)-(4) are numerically solved by using an initial value code [6], in which Fourier transformations in y and z directions for any perturbed quantity f is employed as

$$f(x, y, z, t) \sim \sum_{m,n} f_{m,n}(x, t)\exp(i2\pi my/L_y - i2\pi nz/L_z), \tag{6}$$

with wave numbers $k_y = 2\pi m/L_y$, $k_z = 2\pi n/L_z$ and $k_{/\!/} = 2\pi n/L_z - 2\pi m\hat{s}x/L_y$. Here $\hat{s} = L_n/L_s$ is the magnetic shear. A finite difference scheme for x variable is used. The periodic boundary conditions for all perturbed physical quantities in y and z directions are automatically satisfied in domain sizes L_y and L_z. In the radial direction, fixed boundary condition is assumed in 2D simulations with single rational surface and twisting periodicity with the simulation domain $x = \pm L_x/2$ is applied for 3D simulations with finite magnetic shear. A second (or fourth) order implicit Runge-Kutta method is employed for the time advance. The small random noise is chosen for the initial perturbation of all potential harmonics. In the following simulations, the typical parameters are $\eta_{\mathrm{i}} = 1.5$, $\hat{s} = 0.2$, $\mu_\perp = \eta_\perp = \chi_\perp = 0.1$, $L_x = 50\rho_{\mathrm{i}}$, $L_y = 20\pi\rho_{\mathrm{i}}$, $m \leq 30$ for in 2D simulations and $L_y = 10\pi\rho_{\mathrm{i}}$, $L_z = 2\pi L_n$, $m \leq 15$ in 3D simulations and enough n number is chosen so that the rational surfaces can be fully distributed in the whole simulation box. For the PPC, $\delta\eta_{\mathrm{i}} = 0.5\eta_{\mathrm{i}}$ is chosen and the mode-number and the phase factor are changeable.

3. Linear Stability Analysis

The characteristics of the PPC are sensitive to the linear instability of drift wave since the PPC can directly modify the driving force of the instability. As shown in Eq. (1) that when L_{p} is small, the global effect of the PPC is much weakened and it may behave as a quasilinear flattening or steepening effect determined by the phase factor θ. Hence, the ITG instability in the cases with small L_{p} may sensitively depend on the phase factor θ as a local effect. As L_{p} increases, the corrugation effect is enhanced as a wave-type feature. As a result, the ITG mode may be influenced through a mode coupling caused by the corrugation. To examine such physical processes, we first simulate the linear evolution of ITG fluctuation along one rational surface, namely 2D simulation, in the presence of the PPC.

Fig. 1 (a) plots k_y spectra of the ITG growth rate versus L_{p} for the cases with $\theta = 0$ (solid curves) and $\theta = \pi$ (dashed curves), which correspond to the local flattening and steepening of the pressure profile around the rational surface, respectively. For smaller L_{p}, the PPC can stabilize or destabilize the ITG mode, obviously showing local effects due to the change of pressure gradient. However, the stabilizing effect is stronger than the destabilization for the same $\delta\eta_{\mathrm{i}}$ even if the phase factor is just reversed from $\theta = 0$ to $\theta = \pi$. This asymmetry results from the PPC stabilization due to wave-type feature, showing that the global effect always stabilizes the ITG mode with increasing L_{p}. Fig. 1 (b) plots the dependence of the growth rate of the

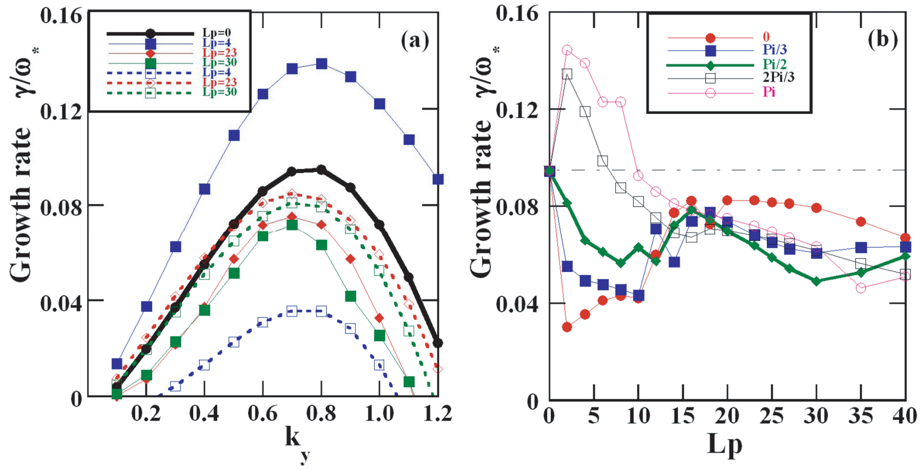

Fig. 1 (a) k_y spectra of ITG growth rate versus mode-number of the PPC for phase factor $\theta = 0$ (solid) and $\theta = \pi$ (dashed). (b) Dependence of ITG growth rate on the mode-number of the PPC for different phase factor.

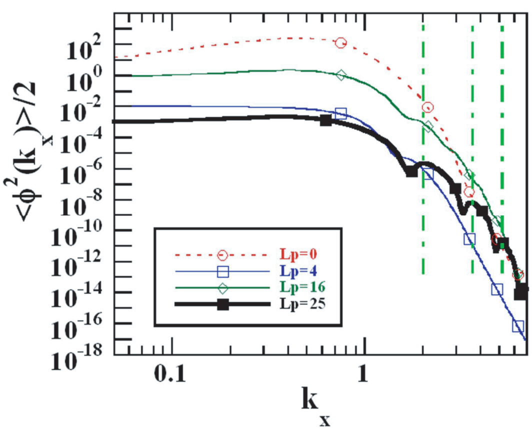

Fig. 2 k_x spectra of linear ITG mode for different mode-number of the PPC. $\theta = \pi/2$. The vertical dotted reference lines correspond to wave-number matching condition $k_x^{\mathrm{hump}} = lk_{\mathrm{p}} \pm k_x^{\mathrm{ITG}}$. Parameters are the same as in Fig. 1 (b).

most unstable component $k_y = 0.8$ on L_{p} versus different phase factors. It is noticeable that local strong stabilizing or destabilizing effect dominated for small L_{p} is weakened as L_{p} increases. Whereas the global stabilization is robust for larger L_{p}. The balanced point may be located around $L_{\mathrm{p}} \sim 18$. Furthermore, the global effect of the wave-type feature can be more apparently shown by the case with $\theta = \pi/2$, in which the local stabilizing and destabilizing effects are averagely cancelled out near the rational surface. The residual stabilization mainly originates from the global feature.

The mechanism of the global stabilization effect of the PPC is different from the local profile flattening but originates from a nonlocal mode coupling [2, 6] caused by the wave-type feature of the PPC. Such mode coupling is similar to the toroidal coupling in tokamak plasma produced by a curved magnetic configuration. However, sparse radial spectra are linked here under the wave-number matching condition $k_x^{\mathrm{hump}} = lk_{\mathrm{p}} \pm k_x^{\mathrm{ITG}}$ due to $L_{\mathrm{p}} \gg 1$, resulting in evident spectral humps at short wavelength, as shown in Fig. 2. Here l is an integer. The role of the nonlocal mode coupling can be analyzed similarly in [2, 6], in which the fluctuation energy of the most unstable ITG mode is transferred to the dissipation range through the nonlocal mode coupling so that the ITG mode is stabilized. However, different from the effect of the micro-scale ZFs that the stabilization is independent of the phase factor θ [2], the PPC here directly modifies the driving force of the ITG instability so that the local stabilizing or destabilizing effects are prominent. The resultant stabilization corresponds to the competition result between the local and global effects of the PPC.

4. Nonlinear Simulation and Transport Intermittency

Nonlinear ITG turbulence simulations with the PPC are performed for both 2D and 3D cases. The setting of numerical calculations in the former case is the same as in above linear analyses, in which one rational surface is assumed so that the dependence of the phase factor is likely kept. However, the effect of the phase factor should averagely disappear in the 3D simulations. This is because multiple rational surfaces uniformly distribute in the radial domain so that the local stabilizing and destabilizing effects for different phase factors along different rational surfaces are averaged by the nonlinear mode coupling. Hence, the global effect of the PPC due to the nonlocal mode coupling may be prominently displayed.

First, we perform 2D simulations for different mode-number L_{p} and the phase factor of the PPC for given $\delta\eta_{\mathrm{i}}$. As L_{p} increases, the linear stabilizing effect is weakened in the case with $\theta = 0$. Most interestingly, a bursty behavior of the ion heat transport is observed after the turbulence saturation so that the ITG turbulence is characterized by a dynamic quasi-steady state, as shown in Fig. 3. This behavior is quite similar to the observation in the ITG turbulence with a micro-scale ZF [2, 6]. The transport intermittency tends to be enhanced for weaker ITG turbulence, i.e., smaller η_i. Spectral analyses show that corresponding to the valleys of the intermittency, some spectral humps appear at short wavelengths of k_x, as shown in Fig. 4 (a), similar to the k_x spectra in the linear phase. Whereas, Fig. 4 (b) shows that there are no short wavelength spectral humps at the peaks of the intermittency. These observations indicate that the ion transport intermittency may originate from the nonlocal mode coupling due to the global stabilizing effect of the PPC.

To understand the underlying mechanism of the ion heat transport intermittency in the presence of the PPC, the comparison of the simulations with and without the ZF dynamics is carried out as shown in Fig.5. The intermittency disappears when the ZF is artificially turned off, showing that the PPC effect cannot individually lead to a dynamic change of the ITG fluctuation without ZF dynamics. The ZFs play an essential role in the intermittent processes. The causal relation between the ZF level and the ITG turbulence suppression is well revealed during the bursty circles, in which the peaks of the ZFs emerge after the ITG turbulence. The bursty behavior is similar to the collisional damp effect of the ZFs in the ITG turbulence [8] but the physical process here is different. The PPC effect stabilizes the ITG mode itself at lower level of fluctuations mainly through producing a nonlocal mode coupling, similar to the effect of the micro-scale ZFs [2, 6]. When the ITG fluctuations is strong, the smoothly decayed spectrum is dominated by the nonlinear mode coupling, which may cover the nonlocal mode coupling due to PPC so that it becomes relatively ignorable. However, when the ITG turbulence is suppressed by growing ZFs, the PPC stabilization versus the nonlocal mode coupling tends to be effective, evidenced by the spectral humps. The ZFs decreases following the reduced ITG fluctuations. Afterwards the suppression of the ITG turbulence by the ZFs decreases so that the ITG fluctuation then grows again. This mechanism is consistent with the observation that the local flattening ef-

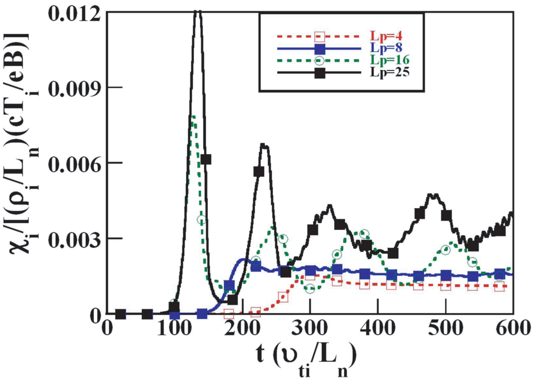

Fig. 3 Time history of the ion heat conductivity for different mode-number L_p of the PPC. $\theta = 0$.

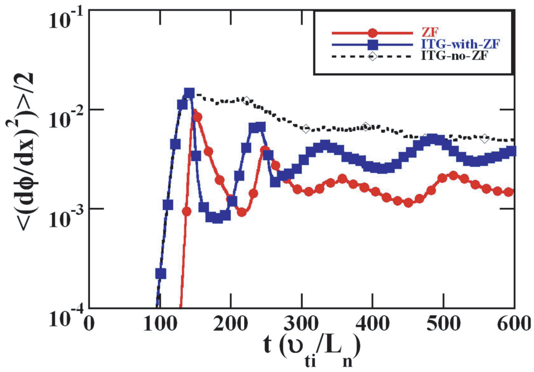

Fig. 5 Causal relation between the intermittent turbulence and the ZF dynamics in 2D simulation. $\theta = 0$. $L_p = 25$. Parameters are same as in Fig. 3.

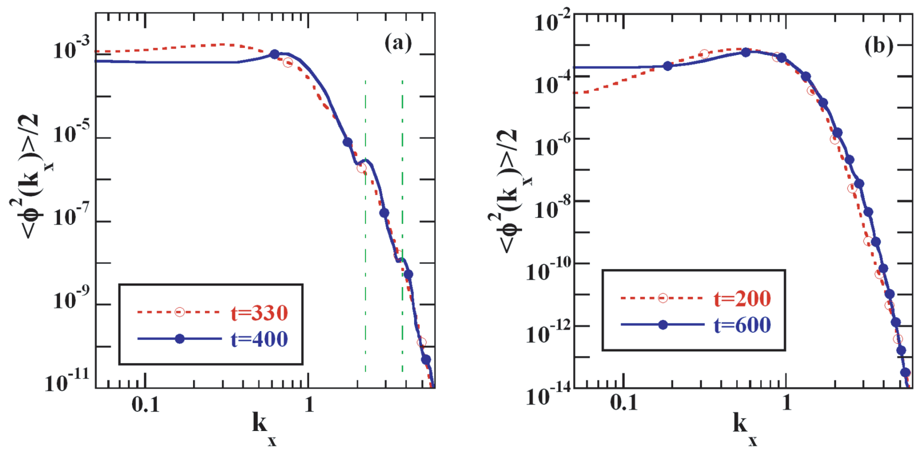

Fig. 4 k_x spectra of 2D ITG turbulence excluding ZF component for different mode-number L_p of the PPC. $\theta = 0$. (a) $L_p = 25$, (b) $L_p = 4$. The vertical dotted reference lines correspond to wave-number matching condition $k_x^{\mathrm{hump}} = lk_p \pm k_x^{\mathrm{ITG}}$. The time evolution of the simulation is shown in Fig. 3.

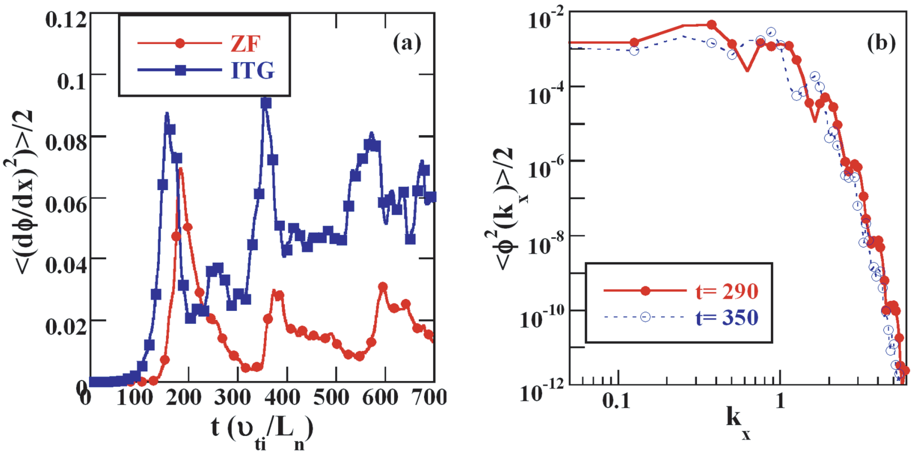

Fig. 6 (a) Causal relation between the intermittent turbulence and the ZF dynamics in 3D simulation. (b) k_x spectra of 3D ITG turbulence excluding ZF component at the valley (t = 290) and the peak (t = 350) of the intermittency.

fects of the PPC do not cause the ion heat transport intermittency.

Second, 3D simulations are carried out to examine the global effects of the PPC in ITG turbulence. Here the turbulence generated ZP component is turned artificially off in time to manifest the PPC effect, otherwise, the PPC may be partially cancelled by the ZP. When the PPC with smaller L_p is applied, the ITG turbulence saturation amplitude tends to decrease, showing the stabilizing effect of the PPC on average. On the other hand, when a PPC with larger L_p is imposed in the simulation, an ion heat transport intermittency is also revealed. Fig. 6 (a) exhibits the causal relation of the intermittent ITG turbulence with the dynamic ZF level, which is similar to the 2D case in Fig. 5. The spectral analyses also show evident spectral humps in k_x as plotted in Fig. 6 (b), which mainly appear around the valleys of the intermittency. 3D simulations further demonstrate the stabilizing effect of the PPC on the ITG mode and the important role in leading to ion heat transport. Note that intermittent turbulent transport has been observed in experiments [9] and simulations with fixed flux source [10], which was identified to relate to radial propagation of pressure corrugations or avalanche fronts. Such propagation generally occurs in the so-called global simulations involving consistent profile effects. However, we actually performed a local simulation but including a fixed corrugated pressure gradient component here so that the radial propagation of the pressure fluctuation may be difficult to occur even if the ZP component is allowed. It may be understood that the pressure profile is partially sustained by this fixed corrugation.

5. Summary

In this work, the PPC effects on the slab ITG instability and turbulence as well as the ion heat transport are investigated based on gyrofluid simulation. A corrugated pressure profile modification is imposed. The results show that in the less corrugated case, the PPC can stabilize or destabilize the ITG mode through the local flattening or steepening of the pressure profile, depending on the phase factor. However, the PPC stabilizes the ITG mode through the global effect as a wave-type feature in the highly corrugated case. It is identified that the PPC can produce a nonlocal mode coupling in the radial wave-number space to scatter the fluctuation energy to the dissipation region. As a result, an ion heat transport intermittency is produced with the causal connection of the ZF dynamics.

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