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Statistical characteristics of turbulent plasmas dominated by zonal flows

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Abstract. In order to better understand the feature of turbulent transport in tokamak plasmas dominated by zonal flows and nonlinearly excited tertiary (Kelvin–Helmholtz-like) waves, the radial dependency of the turbulent structure in the back of steady-state zonal flows was analyzed based on gyrofluid simulation of the electron temperature gradient turbulence in a sheared-slab configuration. The zonal flows change the characteristics of plasma turbulence from homogeneous to inhomogeneous. Thus, it is found that turbulent vortices are regulated by a radially alternative potential pattern where the spatiotemporal characteristic scales with respect to local fluctuations change radially. From the cross spectrum analysis between the poloidal electric field and the pressure perturbation, it was found that, in plasmas dominated by zonal flows, the restriction of heat flux is conducted by two mechanisms, i.e. the reduction of coherence and the phase synchronization.

1. Introduction

In recent years, it is widely recognized that various transport dynamics such as irregular intermittency, blowout event and suppressed transport with a transport barrier, may tightly link to the structure of turbulence. Large-scale convective cells nonlinearly generated from the maternal turbulence such as zonal flows, radially elongated streamers, and long wavelength generalized Kelvin–Helmholtz (KH) modes (tertiary waves), are found to play an essential role in plasma transport [1,2].

In this research, in order to gain a better understanding of the turbulent dynamics in tokamak plasmas dominated by zonal flows and nonlinearly excited tertiary (KH-like) waves, the statistical characteristics at the back of steady-state zonal flows are investigated from gyrofluid tokamak simulation [3] of the electron temperature gradient (ETG) turbulence in a sheared-slab configuration. The zonal flows change the characteristics of plasma turbulence from homogeneous to inhomogeneous, in which it is found that turbulent vortices are regulated by a radially alternative potential pattern. The spatial and temporal scales with respect to local fluctuations change radially. From the viewpoint of production of net heat flux, the coherency and phase difference from the cross spectrum analysis between

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the poloidal electric field E_y and the pressure fluctuation p are investigated for turbulent plasmas and plasmas dominated by zonal flows.

This paper is organized as follows. In Sec. 2, we describe our method of simulation, which is based on a gyrofluid model. In Sec. 3, the radial dependency of the spatiotemporal characteristics of the fluctuations produced by ETG turbulence dominated by the zonal flows is exhibited. In Sec. 4, the coherence and phase difference between E_y and p are discussed. Finally, a summary is given in Sec. 5.

2. Simulation model

In this research, ETG turbulence is modeled based on the following gyrofluid equation in a sheared-slab geometry including Landau damping effect with Hammett–Perkins closure [4] and choosing a proper ion adiabatic response.

$$(1-\hat{\nabla}_\perp^2)\frac{\partial\hat{\phi}}{\partial\hat{t}} = [1+(1+\eta_e)\hat{\nabla}_\perp^2]\frac{\partial\hat{\phi}}{\partial\hat{y}} + [\hat{\phi},\hat{\nabla}_\perp^2\hat{\phi}] + \hat{\nabla}_\parallel\hat{v}_{e\parallel} - \mu_{e\perp}\hat{\nabla}_\perp^4\hat{\phi},$$

$$\frac{\partial\hat{v}_{e\parallel}}{\partial\hat{t}} = \hat{\nabla}_{e\parallel}\hat{\phi} - \hat{\nabla}_\parallel\hat{p}_e - [\hat{\phi},\hat{v}_{e\parallel}] + \eta_{e\perp}\hat{\nabla}_\perp^2\hat{v}_{e\parallel},$$

$$\frac{\partial\hat{p}_e}{\partial\hat{t}} = -(1+\eta_e)\frac{\partial\hat{\phi}}{\partial\hat{y}} - [\hat{\phi},\hat{p}_e] - \Gamma\hat{\nabla}_\parallel\hat{v}_{e\parallel} - (\Gamma-1)\sqrt{8/\pi}\mid k_\parallel\mid(\hat{p}_e+\hat{\phi}) + \chi_{e\perp}\hat{\nabla}_\perp^2\hat{p}_e.$$

Here, $\Gamma = \frac{5}{3}$, $\eta_e = d\ln T_e/d\ln n$, and coordinates are normalized to characteristic scales as $\hat{x}=x/\rho_e$, $\hat{y}=y/\rho_e$, $\hat{z}=z/L_n$ and $\hat{t}=v_{te}t/L_n$. The perturbed quantities, the electrostatic potential, the electron parallel velocity and the electron pressure, are normalized as $\hat{\phi}=(L_n/\rho_e)(e\tilde{\phi}/T_e)$, $\hat{v}_{e\parallel}=(L_n/\rho_e)(v_{e\parallel}/v_{te})$ and $\hat{p}_e=(L_n/\rho_e)(\tilde{p}/p_0)$, with $L_n=(d\ln n/dx)^{-1}$, where ρ_e is the electron Larmor radius, v_{te} is the electron thermal velocity, T_e is the electron temperature, $v_{e\parallel}$ is the electron parallel velocity and n is the electron density. Here, $\hat{p}_e$ includes the zonal component. The magnetic shear parameter $\hat{s}$ is defined as $\hat{s}=L_n/L_s$, where $L_s=B_0/(dB_y/dx)$ and B_0 is the longitudinal magnetic field.

The dynamics of fluid are computed in a three-dimensional rectangular box with the Cartesian coordinates (x,y,z). A periodic boundary condition is adopted in the y and z directions. The twisting periodicity condition [5] is employed in the x direction. The system sizes are mainly set as $L_x=100\rho_e$, $L_y=10\pi\rho_e$, $L_z=2\pi L_n$. For numerically stable and efficient calculation, the viscosity terms are introduced in each equation as a damping effect for the instabilities with wavelength smaller than electron Larmor radius, which does not change the linear growth rate of ETG turbulence. Then, $\mu_{e\perp}$, $\eta_{e\perp}$ and $\chi_{e\perp}$ are assumed to be 0.5. The details of the computation are described in [3].

In our simulations, a quasi-steady state is achieved until $t\sim 1000(L_n/V_{te})$ in each case. Thus, the time series data regarding fluctuations from $t=1000$ to 2000 will be used for the cross spectrum analysis of fluctuations.

3. Radial dependency of fluctuations

In ETG turbulent plasmas, a variety of fluctuations are generated through the dynamics of fluctuations with various temporal and spatial scales, and statistical characteristics become uniform in space [6]. On the other hand, in the presence

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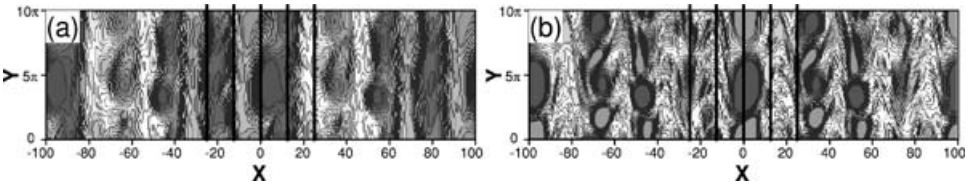


Figure 1. Contours of the electrostatic potential $\hat{\phi}$ (at $t = 1000 L_n/V_{te}$) for zonal flow-dominated plasma ($\hat{s} = 0.1$, $\eta_e = 6$): (a) with the zonal flow component; and (b) without the zonal flow component.

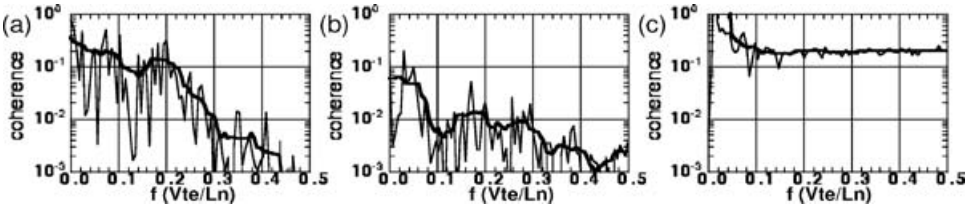


Figure 2. Coherence between E_y and p: (a) in turbulent plasma ($\hat{s} = 0.1$, $\eta_e = 3$); (b) at the ETG-like mode region ($x = -12.5$) in zonal flow dominated plasma ($\hat{s} = 0.1$, $\eta_e = 6$); and (c) at the KH-like mode region ($x = 0.0$) in zonal flow dominated plasma ($\hat{s} = 0.1$, $\eta_e = 6$).

of zonal flows, which are obtained in weak magnetic shear and large temperature gradient regime [2], the turbulence is radially restricted by coherent poloidal flows due to the radial electric field. Thus, plasmas dominated by zonal flows can exhibit different characteristics radially at the scale length of the Larmor radius. Figure 1(a) shows the electrostatic potential contours at for $\hat{s} = 0.1$ and $\eta_e = 6$, in which the zonal flow component is dominant, and a coherent structure of a radially striped pattern is maintained.

However, behind the zonal flows, it is found that large vortices moving in the $-y$ direction are generated by the KH-like instabilities due to the coupling of background ETG fluctuations and the zonal flows (i.e. $x = -25.0$ and 0, where the zonal flows are large in the $-y$ direction), as shown in Fig. 1(b). On the other hand, in the zones in which the KH-like instabilities are weak (i.e. $x = -12.5$ and $+12.5$, where the zonal flows are large in the $+y$ direction), many small vortices moving in the $+y$ direction are observed. In addition to the radial dependence of characteristic length, the characteristic time of turbulent fluctuations such as E_y was also found to vary radially by the Doppler shift of the electron drift frequency [7].

4. Coherence and phase difference

From the cross spectrum analysis between E_y and p in turbulent plasma and in plasmas dominated by zonal flows, we have clarified their correlation relation generating the net heat flux. Figure 2(a) shows that a relatively high coherency in broad frequency region is observed at $x = 0$ in the turbulent plasma, in which such high coherency may be homogeneously observed.

However, in the plasma dominated by zonal flows, the cross spectrum analysis shows radially dependent results proceeding from different spatiotemporal characteristic scales. At the zone ($x = -12.5$) in which background ETG-like modes induce

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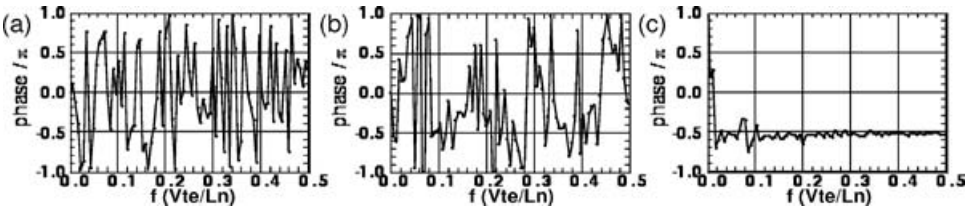


Figure 3. Phase difference between E_y and p. The parameters are the same as in Fig. 2.

small vortices, it is found that the reduction of coherence in wide spectrum range, as shown in Fig. 2(b). Such a reduction of coherence is considered to correspond to the restriction of net heat flux.

On the other hand, at the zone ($x = 0.0$) in which KH-Like modes induce large vortices, it is found that the coherence between E_y and p is rather enhanced. Alternatively, the phase difference between E_y and p is found to be considerably regulated by zonal flows, as shown in Fig. 3(c). In wide spectrum range, the phase difference becomes approximately $\pi/2$, which gives almost no net heat flux.

5. Discussion

In order to gain a better understanding of the turbulent dynamics in tokamak plasmas dominated by zonal flows and KH-like modes, the ETG turbulence has been simulated with a gyrofluid model in a sheared-slab configuration. In plasma dominated by zonal flows, it is found that the spatiotemporal characteristic scales with respect to local turbulent fluctuations are regulated by the alternative existence of two kinds of zone with large vortices induced by KH-like modes and small vortices induced by background ETG-like modes.

From the cross spectrum analysis between E_y and p, a relatively high coherency in broad frequency regime is observed in turbulent plasmas, which manifests the production of net heat flux. However, in plasmas dominated by zonal flows and KH-like modes, it was found that the cross spectrum analysis shows radially different results. At the zone in which background ETG-like modes induce small vortices, it is found that the reduction of coherence in wide spectrum range. On the other hand, at the zone in which KH-Like modes induce large vortices, the phase difference becomes approximately $\pi/2$. Thus, we considered that, in ETG turbulent plasmas dominated by zonal flows, the restriction of heat flux is conducted by two mechanisms, i.e. the reduction of coherence and the phase synchronization between E_y and p. As a result, the heat flux becomes radially inhomogeneous.

The transport dynamics in the ion temperature gradient turbulent plasma dominated by zonal flows is also important. This issue will be addressed in future study.

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References

[1] Diamond, P. H. et al. 2005 *Plasma Phys. Control. Fusion* **47**, R35.
[2] Li, J. and Kishimoto, Y. 2004 *Phys. Plasmas* **11**, 1493.
[3] Li, J. and Kishimoto, Y. 2002 *Phys. Plasmas* **9**, 1241.
[4] Hammett, G. W. and Perkins, F. W. 1990 *Phys. Rev. Lett.* **64**, 3019.
[5] Beer, M. A., Cowley, S. C. and Hammett, G. W. 1995 *Phys. Plasmas* **2**, 2687.
[6] Matsumoto, T., Kishimoto, Y. and Li, J. 2004 *J. Plasma Fusion Res. SERIES* **6**, 585.
[7] Matsumoto, T., Kishimoto, Y. and Li, J. 2006 *Proc. 21st IAEA-FEC*, Chengdu.

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