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Formation of large-scale structures in electron temperature gradient turbulence: zonal flows or streamers

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Abstract: The generation of large-scale structures including zonal flows and streamers in electron temperature gradient (ETG) turbulence is investigated based on a gyrofluid model. It is found that spectral anisotropy of ETG turbulence due to the role of magnetic shear seems to govern the formation of different structures, namely, pattern selection, in electrostatic slab geometry. In toroidal ETG turbulence, streamers are locally formed in linearly stable region of ETG mode along the field line and enhance electron transport.

I. Introduction

Recently, the importance of large-scale structures in anomalous transport has been recognized in fusion plasmas. Specifically, toroidally and poloidally axisymmetrical zonal flows can efficiently suppress turbulent heat transport through the shearing decorrelation of turbulence, while radially elongated streamers may enhance the transport by increasing radial correlation length. [1] Both of such different patterns have been observed numerically in ETG turbulence under the tokamak configuration.[2-5] Due to the opposed roles in plasma transport, a crucial issue is to understand whether the zonal flows or streamers are preferentially generated in ETG fluctuations. Another interesting question is what key parameter may determine the formation of zonal flows or streamers in ETG turbulence, then, the electron transport may be controlled. This work will present a theoretical derivation of general secondary instability and numerical simulations of ETG turbulence, which show that the magnetic shear may play a key role in the pattern selection, at least, in slab ETG turbulence. The streamer dynamics in toroidal ETG turbulence is investigated based on 3D gyrofluid simulations in a curved slab domain.

II. Gyrofluid modeling equations of ETG turbulence

Toroidal electromagnetic ETG turbulence is described by following normalized three-moment (i.e., potential, ϕ, parallel vector potential, A, and electron pressure, p) nonlinear gyrofluid equations in a curved slab geometry $\vec{B} = B[\vec{z} + (x - x_0)\vec{y} / L_s]$ with adiabatic ion response $\tilde{n}_i = -\phi$ [5],

$$(1-\nabla_\perp^2)\partial_t\phi - (1-2\varepsilon_n + K\nabla_\perp^2)\partial_y\phi - 2\varepsilon_n\partial_y p - \nabla_{//}(\nabla_\perp^2 A) = [\phi, \nabla_\perp^2\phi] - \tfrac{\beta_e}{2}[A, \nabla_\perp^2 A] + D_\perp\nabla_\perp^4\phi \quad , \tag{1}$$

$$(\nabla_\perp^2 - \tfrac{\beta_e}{2})\partial_t A - \nabla_{//}(\phi - p) - \tfrac{\beta_e}{2}K\partial_y A + 4\varepsilon_n\partial_y\nabla_\perp^2 A = -[\phi, \nabla_\perp^2 A] + \beta_e[\phi, A] + \tfrac{\beta_e}{2}[A, p] - \mu_\perp\nabla_\perp^4 A \quad , \tag{2}$$

$$\partial_t p + K\partial_y\phi + 4\Gamma\varepsilon_n\partial_y p + (\Gamma - 1)\sqrt{\tfrac{8}{\pi}}|k_{//}|(p + \phi) + \Gamma\nabla_{//}(\nabla_\perp^2 A) = -[\phi, p] + \tfrac{3\beta_e}{2}[A, \nabla_\perp^2 A] + \chi_\perp\nabla_\perp^2 p \quad , \tag{3}$$

with $K = 1 + \eta_e$, $\varepsilon_n = L_n / R$, $\beta_e = 8\pi n_0 T_{e0} / B^2$, $\Gamma = 5/3$. Poisson brackets express the $\vec{E}\times\vec{B}$ convective nonlinearity and the $\vec{B}\cdot\nabla$ bending of the magnetic field lines due to the magnetic perturbations, i.e. $\tilde{\nabla}_{//} = ik_{//} = \overline{\nabla}_{//} - \vec{V}_{A_{//}}\cdot\nabla$. Here, $\eta_e = d\ln T_e / d\ln n$, $L_n = (d\ln n_e / dx)^{-1}$, $\overline{\nabla}_{//} = \partial_z + \hat{s}x\partial_y$ with $\hat{s} = L_n / L_s$, and R is the major radius of a tokamak plasma. Cross-field viscosities and thermal conductivity are employed to absorb the energy cascaded to higher $|k|$ region. In simulations, the toroidal coupling terms are expressed as

$$2\varepsilon_n \partial_y \tilde{f}_{m,n} \sim \varepsilon_n [\partial_y (\tilde{f}_{m+1,n} + \tilde{f}_{m-1,n}) + i\partial_x (\tilde{f}_{m+1,n} - \tilde{f}_{m-1,n})] \quad , \tag{4}$$

with *m* and *n* corresponding to the poloidal and toroidal numbers in a tokamak plasma, respectively.

III. Modulation analysis on the excitation of secondary fluctuations

The generation of large-scale structures including zonal flows, streamers and generalized Kelvin-Helmholtz (GKH) fluctuation can be investigated through a modulational analysis. In an ETG turbulence environment, the dispersion relation of secondary instability can be generally derived based on a 2D inviscid Hasegawa-Mima (HM) turbulence modelling, which is the simplest version of Eqs. (1-3) in the electrostatic slab limit, i.e.,

$$\omega_q (1 + k_q^2) + k_{yq} = -\frac{2 k_q^2 \Lambda_-^2 (k_0^2 - k_q^2)[\omega_q (\Lambda_0 - 4\Lambda_+^2 / k_q^2) + k_{yq}]}{(2\omega_0 \Lambda_+ + k_{yq} + \Lambda_0 \omega_q)^2 - (\omega_0 k_q^2 + 2\Lambda_+ \omega_q)^2} |\phi_0|^2 \quad , \tag{5}$$

with $\Lambda_0 = 1 + k_0^2 + k_q^2$, $\Lambda_+ = k_{xq} k_{x0} + k_{yq} k_{y0}$, $\Lambda_- = k_{xq} k_{y0} - k_{yq} k_{x0}$, $\omega_0 = -k_{y0} / (1 + k_0^2)$. Here, the monochromatic pumping wave and general secondary fluctuation are assumed with the *ansatz* $\tilde{\phi}_p = \phi_0 e^{i\vec{k}_0 \cdot \vec{x} - i\omega_0 t} + c.c.$ and $\tilde{\phi}_q = \phi_q e^{i\vec{k}_q \cdot \vec{x} - i\omega_q t} + c.c.$, respectively. The complete three-wave coupling including the sidebands is taken into account without the scale separation assumption between the pumping mode and secondary fluctuations. When $k_{yq} = 0$, Eq. (5) is reduced to the dispersion relation of zonal flows. [5] On the contrary, $k_{xq} = 0$ corresponds to the streamer case. Fig. 1 illustrates the growth rates of large-scale zonal flows ($k_{xq} = 0.1$) and streamers ($k_{yq} = 0.1$) for given pumping waves. It shows some characteristics: (1) There exist pumping amplitude thresholds for the excitation of large-scale structures; (2) The generation of large-scale zonal flows and streamers in ETG turbulence is slightly asymmetrical against the corresponding pump structures due to the propagation direction of ETG fluctuation; (3) Most importantly, formula (5) reveals a basic nature of secondary excitation as shown in Fig.2: radially longer and poloidally shorter pump waves tend to generate a zonal flow instability. Contrarily, poloidally shorter and radially longer pump modes favor the generation of streamer structures. This may provide a guideline to control the formation of different large-scale structures in ETG turbulence by adjusting the spectral distribution of turbulent fluctuations. Fig.2 also shows that the zonal flow and streamer are only two extreme-value components of most unstable secondary fluctuations. They should include the corresponding global spectral structures. Furthermore, it can be seen from Fig.2(b) that for isotropic pumping waves, the streamer component may be slightly stronger than the zonal flow. However, the streamers undergo Landau damping in the realistic ETG turbulence so that they might not be preferentially generated in the homogenous ETG turbulence.

IV Pattern selection in slab ETG turbulence

The finding that the pattern selection is closely related to the spectral anisotropy of turbulent background fluctuations may involve some parametric dependence, such as the magnetic shear. Note that the eigen structure of slab ETG mode becomes wider as the magnetic shear decreases, which corresponds to a shrinking k_x spectrum. Such shear dependence is favorable for the zonal flow instability.[3,5] On the contrary, the streamers may be expected in ETG turbulence with stronger magnetic shear under the weak turbulence theory. To confirm this idea, the nonlinear evolution equations, (1-3), are numerically solved by employing an initial value code in the electrostatic slab limit. Simulations are performed by increasing the magnetic shear from $\hat{s} = 0.1$ to $\hat{s} = 1.6$ with fixed parameter setting: $\eta_e = 6$, $D_\perp = \mu_\perp = \chi_\perp = 0.5$. It is found that in the weak shear case, zonal flows are enhanced and efficiently suppress the turbulent electron heat transport. Turbulent ETG structures are strongly regulated by zonal flows and a low-frequency long wavelength KH fluctuation may be excited to limit the flow. [5] As the magnetic shear increases, the zonal flow level tends to decrease and the anomalous electron transport increases. In plasmas with higher shears, zonal flow component becomes almost ignorable and streamer structures are observed clearly, but the electron transport is lower. The reason for low turbulent fluctuations is probably due to the stabilizing role of magnetic shear. On the other hand, the streamer amplitude is relatively weaker in turbulent fluctuations compared with the zonal flow counterpart in the weak shear case. It may result from the Landau damping. Spatial spectral analyses of ETG turbulence, as shown in Fig.3, clearly display the condensation tendency of turbulent fluctuations to the zonal flow component ($k_y \to 0$) in weak shear plasmas and to the streamer structures ($k_x \to 0$) for higher magnetic shears.

V Streamers in toroidal ETG turbulence

In a toroidal plasma, poloidal harmonics of ETG fluctuations can couple through the toroidal curvature effect so that radial stream-like structures can be linearly formed in the bad curvature region, namely, ballooning structure. These linear vortices are broken at the saturation of ETG fluctuations with lower transport. ETG turbulence is characterized by almost isotropic spectra in this phase. However, some large-scale streamers, which are dominated by a few modes, are locally excited in linearly stable region of ETG mode along the flux tube after initial ETG saturation, as shown in Fig.4. Quasi-steady streamers are only formed in toroidal ETG turbulence with higher magnetic shear $\hat{s} > 0.4$, which is similar to the observation in gyro-kinetic calculation. [2] However, Fig.5 illustrates that the averaged electron transport increases only by 3~4 times compared to the initial saturation level with around gyro-Bohm value. Simulations show that the streamer dynamics seems not to sensitively depend on the electromagnetic effect, but on the toroidicity.

VI Conclusion and summary

The formation of large-scale structures in ETG turbulence is investigated analytically and numerically. It is found that the excitation of zonal flows or streamers is governed by the spectral anisotropy of turbulent fluctuations. Magnetic shear seems to be a key controllable parameter for pattern selection, at least in a slab geometry. In toroidal ETG turbulence, streamers are locally excited in linearly stable region of ETG mode along the flux tube after initial ETG saturation, which does not depend on the electromagnetic effects.

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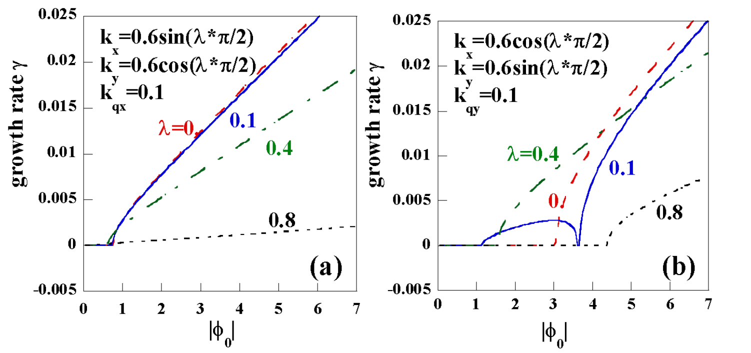

Fig.1 Growth rates of zonal flows (a) and streamers (b) for given pumping wave. λ 's label different spectral distributions of assumed pumping modes.

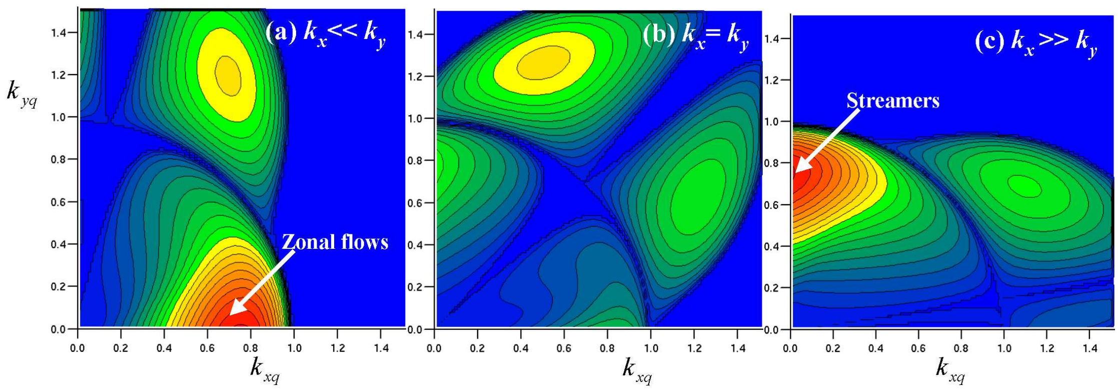

Fig.2 Contours of growth rate of secondary fluctuations including zonal flows and streamers for assumed spectral structures of pumping waves with $k_0 = 1.$ and $|\phi_0| = 4$.

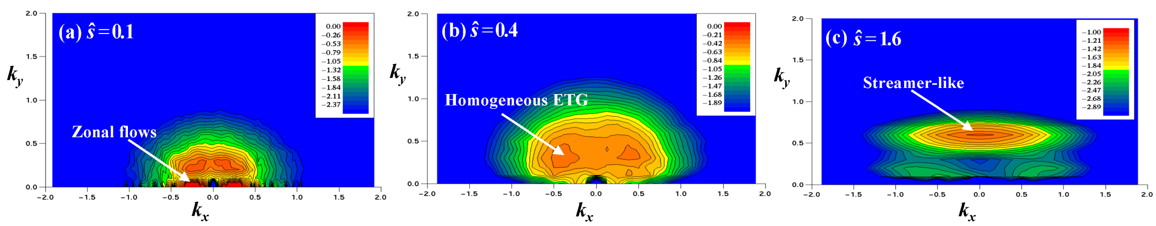

Fig.3 Spectral distributions of slab ETG fluctuations in $k_x - k_y$ plane for different magnetic shears. (a) fluctuation condensation to zonal flows; (b) homogeneous ETG ; (c) energy condensation to streamers.

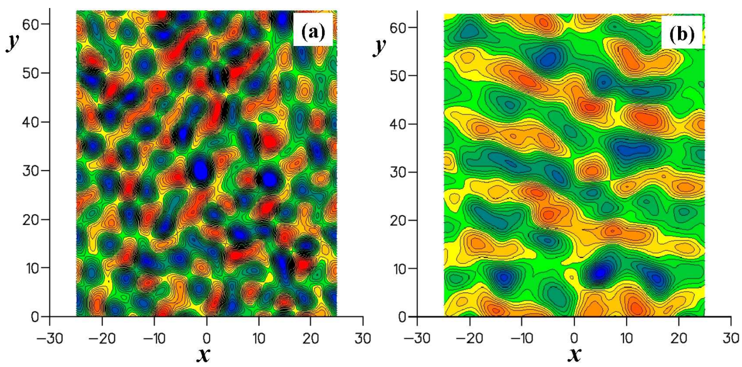

Fig. 4 Contours of electrostatic potential in toroidal ETG simulation in the quasi-steady state. It shows the turbulent region (a) and streamer-dominated region (b) along the flux tube. $\hat{s} = 0.6$, $\eta_e = 3.2$, $\varepsilon_n = 0.45$.

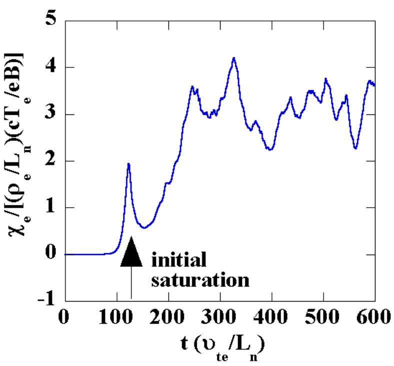

Fig. 5 Evolution of heat conductivity $\chi_e(t) = -(\frac{\rho_e}{L_n}\frac{cT_e}{eB})\langle p\partial_y\phi\rangle K^{-1}$. Parameters are the same as in Fig.4.