Dynamics of Large-Scale Structure and Electron Transport in Tokamak Microturbulence Simulations

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Abstract: An important issue whether the zonal flow or streamer is preferentially formed in plasma turbulence with electron gyro-radius scale is studied. It is found that the generation of different large-scale structures is determined by the spectral anisotropy of turbulent fluctuation. 3D gyrofluid simulations show that the magnetic shear governs the pattern selection in slab electron temperature gradient (ETG) driven turbulence. Weak shear favors the enhancement of zonal flows so that the electron transport is strongly suppressed. Contrarily, radially elongated streamers are formed in stronger shear ETG turbulence. In a toroidal plasma, streamers are excited in linearly stable region along the field (i.e., good curvature region) after the initial saturation of ETG modes, and higher electron transport is dominated by the fluctuations with peaked poloidal spectrum. Further, we show that the enhanced zonal flows in weak shear ETG turbulence may be damped by a Kelvin-Helmholtz (KH) instability. Also, results on the complicated mutual interaction among ETG turbulence, zonal flows and KH mode in finite-Beta toroidal ETG turbulence will be addressed.

1. Introduction

Microturbulence driven by ion/electron temperature gradient (ITG/ETG) is believed to be plausibly responsible for the anomalous ion/electron transport in magnetic confinement plasmas. It is recently recognized that large-scale structures in microturbulence can play an essential role in plasma transport. These nonlinearly generated secondary fluctuations include the poloidally and toroidally axisymmetric zonal flows/fields, radially elongated streamers, long wavelength (generalized) Kelvin-Helmholtz (KH or/and GKH) modes [1,2]. They are usually of coherence. Further, ITG mode with ion gyro-radius scale may be also regarded as a large-scale fluctuation in the multi-scale (mixed) ITG and ETG turbulence. It may interact with small-scale ETG fluctuation through some mechanisms such as flow shearing, potential/field trap, or zonal flow/streamer generation as a medium [3-5]. Hence, issues on the interaction among different scale fluctuations, the dynamics of large-scale structures and their roles in plasma transport are of great importance in the study of plasma transport.

While ion transport, as well as ion internal transport barriers (ITBs), in magnetic confinement devices seems to be gradually understood based on ITG turbulence theory and simulations with flow dynamics, the electron transport is still very unclear. The conventional ETG modeling predicts lower transport than the experimental observation. On the other hand, an unanswered question is what mechanism may be experimentally relevant to the electron ITB formation, among the ETG mode, trapped electron mode and/or some MHD activities. Under assuming the ETG turbulence modeling, some simulations based on gyrokinetic [6, 7] or gyrofluid [8] codes have recently been performed with an emphasis on the dynamics of large-scale structures. However, different patterns, streamers [6] and enhanced zonal flows [7,8] have been observed, which are closely related to the electron transport level. A crucial, extensively concerned question is whether the zonal flow or streamer is preferentially generated in ETG fluctuations [9,10]. Another interesting question is what physical parameters may determine the pattern selection in ETG turbulence, then, the electron transport may be controlled. In this work, we describe the achieved progress based on a gyrofluid ETG turbulence model [8]. Our attention is primarily focused on exploring the underlying mechanisms on the dynamics of large-scale structures in ETG turbulence and electron transport.

2. Generation of large-scale structures via modulation instability

It is known that zonal flows can suppress transport through the flow shearing decorrelation in turbulence and the streamers may enhance the transport through the longer radial correlation length. These two types of large-scale structures can be nonlinearly generated through a modulation instability under assuming the turbulent fluctuation as a pump source. Without loss of generality, our analyses are carried out for the generation of GKH modes [1]. In a background with ETG potential $\tilde{\phi}$, the excitation process of secondary fluctuations can be described based on a 2D Hasegawa-Mima(HM) model, which is the reduced version of gyrofluid (or fluid) slab ETG turbulence at the lowest order under the assumption of adiabatic ion response, i.e. [8],

$$(1-\nabla_\perp^2)\partial_t\tilde{\phi} = \partial_y\tilde{\phi} + [\tilde{\phi}, \nabla_\perp^2\tilde{\phi}] \quad . \tag{1}$$

Assuming a monochromatic wave packet with 2D spectral structure as the pumping mode $\tilde{\phi}_p = \phi_0 e^{i\vec{k}_0\cdot\vec{x} - i\omega_0 t} + c.c.$, the eigen-frequency is subject to the drift wave dispersion relation $\omega_0 = -k_{y0}/(1+k_0^2)$. A small perturbation $\tilde{\phi}_q = \phi_q e^{i\vec{k}_q\cdot\vec{x} - i\omega_q t} + c.c.$, which is regarded as the secondary mode, is nonlinearly interacted with the pump through the production of the sidebands $\tilde{\phi}_\pm = \phi_\pm e^{i\vec{k}_\pm\cdot\vec{x} - i\omega_\pm t} + c.c.$ with frequency and wave-number matches $\omega_\pm = \omega_0 \pm \omega_q$ and $\vec{k}_\pm = \vec{k}_0 \pm \vec{k}_q$. The three-wave modulation interactions give out the perturbed quantities as

$$\left[\omega_\pm\left(1+k_\pm^2\right) + k_{y\pm}\right]\phi_\pm = i\Lambda_-(k_0^2 - k_q^2)\phi_{0\pm}\phi_q \quad , \tag{2}$$

$$\left[\omega_q\left(1+k_q^2\right) + k_{yq}\right]\phi_q = i\Lambda_-(2\Lambda_+ + k_q^2)\phi_+\phi_{0-} + i\Lambda_-(2\Lambda_+ - k_q^2)\phi_-\phi_{0+} \quad , \tag{3}$$

with $\Lambda_+ = k_{xq}k_{x0} + k_{yq}k_{y0}$, $\Lambda_- = k_{xq}k_{y0} - k_{yq}k_{x0}$, $\phi_{0+} = \phi_0$ and $\phi_{0-} = \phi_0^*$. Then, a dispersion relation of the secondary instability can be obtained, i.e.,

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

where $\Lambda_0 = 1 + k_0^2 + k_q^2$. Here $\vec{x}$ and $\vec{y}$ correspond to the radial and poloidal directions in a tokamak geometry, respectively. Note that the derivation of this formula does not require the scale separation assumption so that it is also suitable for the excitation of general higher wave-number secondary fluctuations.

When $k_{yq} = 0$, Eq. (4) is reduced to the dispersion relation of zonal flow instability[8]. On the contrary, $k_{xq} = 0$ corresponds to the streamer case. Calculations of the eigenvalues in Eq. (4) exhibit some basic characteristics of the GKH mode generation as shown in Fig.1: (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 homogeneous pump waves due to the propagation direction of ETG fluctuation; (3) The isotropic large-scale GKH mode can be excited by anisotropic fluctuations although its role in turbulence and transport is not much clear. (4) Most importantly, formula (4) reveals a basic nature of secondary excitation as shown in Fig.2: radially longer and poloidally shorter pump waves tend to excite a zonal flow instability. Contrarily, poloidally longer and radially shorter pump modes favor the formation of streamer structures. Further, the zonal flow and streamer components are of maximal growth rates in the $k_{xq} - k_{yq}$ spectral space. They are only two special components in GKH modes. This may be helpful to understand why the zonal flow or streamer is more robust in plasma turbulence. Actually, they are included in a global k_{yq} (for zonal flow) or k_{xq} (for streamer) spectral structure. This feature will be described in 3D simulations of next section. On the other hand, it is noticed that the zonal flow is a secondary fluctuation with almost zero frequency, but the streamer component has a finite one as illustrated in Fig.2(e-f). This may infer that the suppression role of zonal flow in turbulent transport is more efficient than the enhancement of streamer dynamics [11,12]. In addition, the streamer also suffers from the Landau damping so that the zonal flow dynamics may be more competitive in the realistic plasmas.

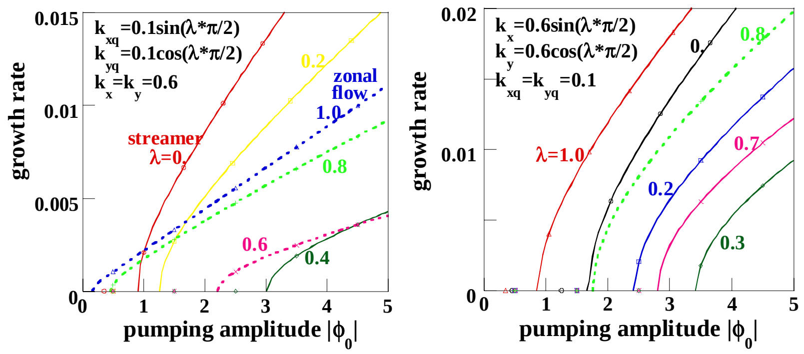

FIG.1 (a) Growth rates of secondary GKH fluctuations for given isotropic pump wave; (b) growth rates of isotropic GKH for given anisotropic pump waves. Parameter λ labels the spectral anisotropy of both GKH mode and pump waves.

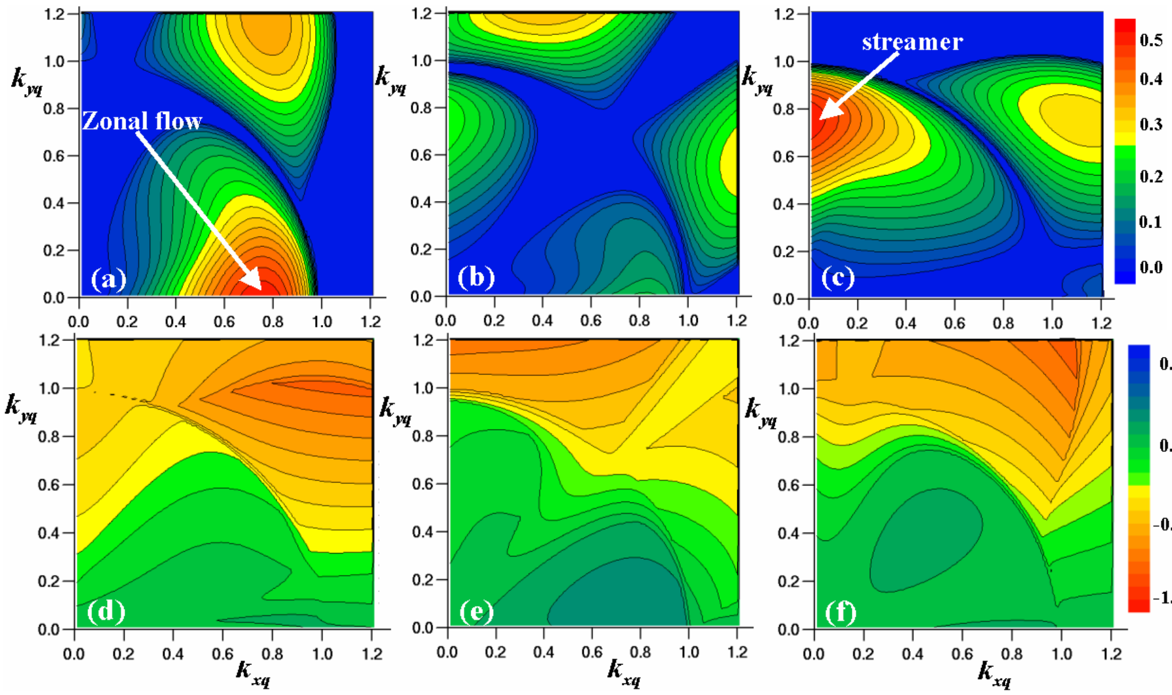

FIG.2 Contours of the growth rate (a-c) and corresponding real frequency (d-f) of secondary fluctuations including zonal flows and streamers for assumed anisotropic pump waves with $k_0 = 1$. and $|\phi_0|^2 = 4$. $k_{x0} << k_{y0}$ (a,d); $k_{x0} = k_{y0}$ (b,e); $k_{x0} >> k_{y0}$ (c,f).

The modulation analysis based on a simple model reveals a key feature: the pattern selection in an ETG background is determined by the spectral anisotropy of turbulent fluctuation. This result may provide a guideline to form different large-scale structures in tokamak plasmas. The drift wave theory shows that the spatial structure of ETG mode is governed by some physical parameters, typically like the magnetic shear. The radial mode width increases as decreasing the shear. Under the weak turbulence assumption, these eigen modes are super-positioned into the turbulent fluctuations so that the secondary excitation can be influenced by some key physical factors. In the following, we will perform gyrofluid ETG simulations to prove the role of magnetic shear in pattern selection, accompanying with the dynamics of large-scale structures in electron transport.

3. Dynamics of zonal flows and electron transport suppression

In this section, the dynamics of zonal flows is studied in ETG turbulence with weak magnetic shears. By applying an initial value code, 3D simulations of electrostatic slab ETG turbulence with radially periodic boundary condition were performed [8]. The parameter setting is $\eta_e = 6$, $\hat{s} = 0.1$, $L_x = 200\rho_e$, $L_y = 20\pi\rho_e$, $L_z = 2\pi L_n$, $\Delta k_y = k_y^{\mathrm{Min}} = 0.1$ and $k_y^{\mathrm{Max}} = 2.4$. The artificial damp coefficients are taken as $\mu_\perp = \eta_\perp = \chi_\perp = 0.5$. A higher electron energy confinement state was predicted. An enhanced zonal flow was observed, which greatly reduces the electron transport [4,13]. These results are very consistent with above modulation stability analysis on the zonal flow generation. Here, we report on the saturation of enhanced zonal flows, global k_y spectrum in higher resolution simulation, as well as the electromagnetic (EM) and toroidal effects. Our gyrofluid ETG model and simulation have been extended to the toroidal EM version [13].

3.1 Saturation and global spectrum of zonal flows in weak shear ETG simulations.

Zonal flows can be damped by different mechanisms in turbulence. Here we demonstrate that a weekly unstable KH mode is the primary one to limit the enhanced zonal flows in weak shear ETG turbulence. Besides the stability of KH mode in the observed flow is examined, the evolution of spatio-temporal spectra of turbulent ETG fluctuations in 3D simulations are analyzed in details. Comparing the spatial Fourier spectra ($k_x - k_y$) and time-frequency wavelet energy spectra ($t - \omega$) in the simulations with and without (artificially set zero flow in time) zonal flows, it shows that: (1) In the case with zonal flows, the turbulent k_y spectrum shrinks to the long wavelength fluctuations with k_y =0.2~0.3, which corresponds to the spectral peak of linear KH mode, except for much turbulent ETG energy condensing to the zonal flows. This is different from the isotropic spectral structures in both longer and shorter wavelength regions in the case without flows; (2) As the exponential growth of zonal flows is slowed down, a low-frequency long wavelength fluctuation is excited in time, which corresponds to the KH mode as shown in Fig. 3. (Here the frequency of KH mode is analyzed by simulating linear KH instability driven by an observed zonal flow in 3D simulation.) These analyses may suggest that there exists a possibility of turbulence transition from the ETG-dominated one to the KH-dominated one due to the enhanced zonal flow dynamics.

To further examine the KH mode excitation in ETG turbulence with enhanced zonal flows and study the global k_{yq} spectral structure of zonal flows, a higher resolution 3D simulation is performed by doubling the simulation domains along y and z directions. Here, $L_x = 200\rho_e$, $L_y = 40\pi\rho_e$, $L_z = 4\pi L_n$, $\Delta k_y = k_y^{\mathrm{Min}}$ =0.05 and $k_y^{\mathrm{Max}} = 2$. Fig.4 shows the time evolution of zonal flows and turbulent fluctuation energy $\int dxdydz(\phi^2 + |\nabla_\perp \phi|^2)/2$, as well as the turbulent electron transport. The dynamics of zonal flows behave qualitatively the same as the counterparts in lower resolution case above, except that the flow level is lowered a little and the transport increases slightly. This is in agreement with the KH mode dynamics because the KH instability is characterized by a peaked growth rate at $k_y \approx 0.25$, which was missed in the lower resolution simulation. On the other hand, during the linear evolution of ETG modes, the low k_y components grow up more quickly in some phase so that a peaked low k_y spectral distribution is formed as shown in Fig.5. It corresponds to the nonlinearly generated GKH spectrum observed in the modeling analysis in Sec.2. (Note that Fig.5 shows the power spectra of potential but not the growth rate like in Fig.2. The low zonal flow component is only due to the zero initial value and the lack of linear drive.) Approaching the ETG saturation, this peaked long wavelength spectral distribution is flattened by complex nonlinear processes like inverse energy cascade. This feature is further clearly confirmed by a 2D simulation with very high resolution $\Delta k_y = k_y^{\mathrm{Min}}$ =0.0125.

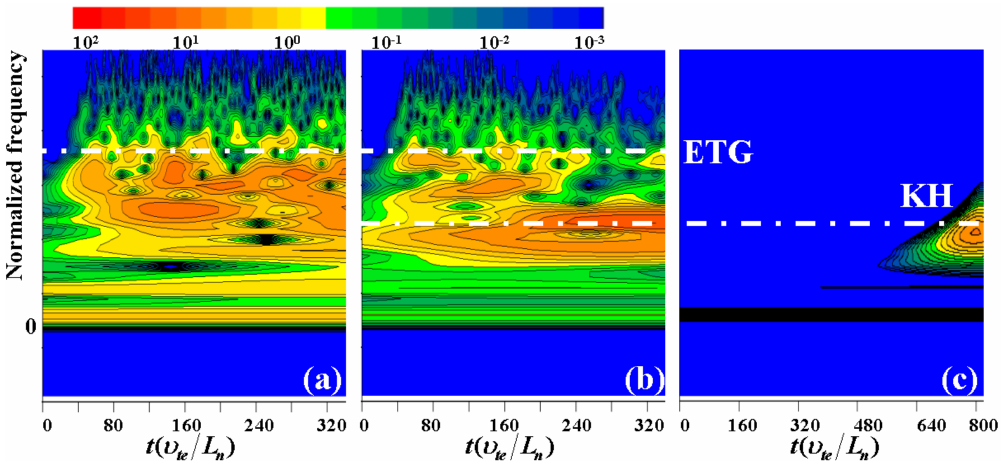

FIG.3 Contours of time-frequency wavelet spectra with $k_y = 0.3$ in 3D ETG simulations without (a) and with (b) zonal flows and in linear KH mode calculation(c). The growth of zonal flows is slowed at around t=160~200 in (b).

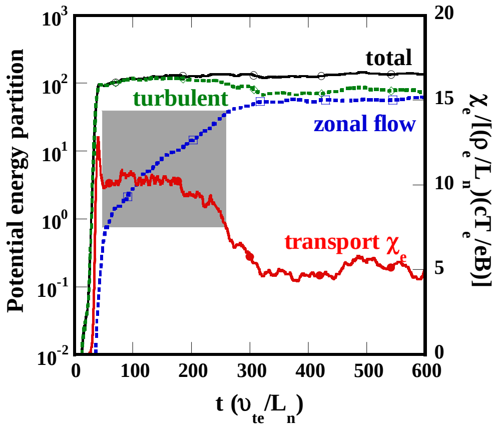

FIG.4 Time evolution of the zonal and turbulent potential, and the electron heat conductivity in high resolution 3D simulation with $\hat{s} = 0.1$ and $\eta_e = 6$. The shaded part marks the growing phase of zonal flows, which clearly shows a zonal flow instability.

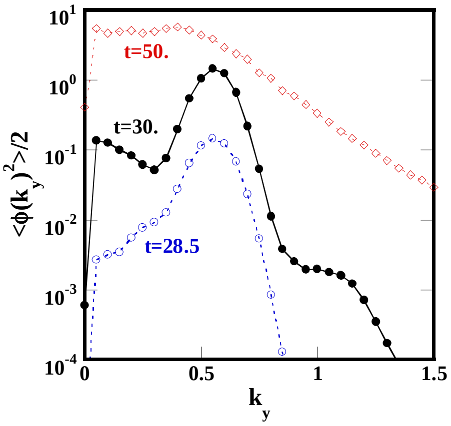

FIG.5 k_y spectra of electrostatic potential before ETG saturation in the simulation of Fig.4. It shows a pecked spectrum at longer wavelengths, which corresponds to the global k_y one of zonal flows in Fig.2.

3.2 Electromagnetic effects in weak shear ETG turbulence.

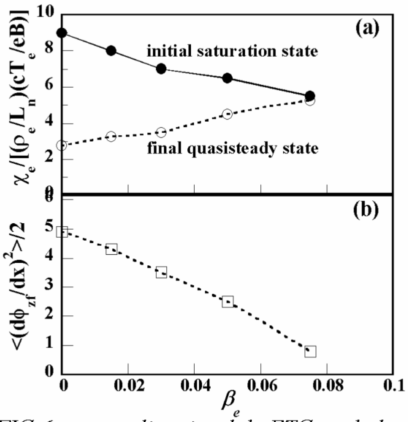

FIG.6 β_e *scaling in slab ETG turbulence with weak shear* $\hat{s}=0.1$. $\eta_e=6$, $L_x=200\rho_e$, $L_y=20\pi\rho_e$ *and* $L_z=2\pi L_n$.

It is commonly believed that the electron transport may be influenced by EM turbulence. On the one hand, direct EM heat flux is due to the magnetic flutter. On the other hand, the most important EM property may be ascribed to the formation of some large or meso-scale structures. The meso-scale mode with the collisionless skin depth size may be excited in the EM ETG fluctuation with higher β_e, which might be responsible for the core electron transport in tokamaks. Here we show that when 3D ETG simulations with moderate shears can reproduce the conventional Ohkawa's scaling, $\chi_e \propto 1/\beta_e$, of electron transport, the zonal flow dynamics may reverse this dependence in weak shear ETG turbulence. Fig.6(a) illustrates different β_e scaling of χ_e in two nonlinear phases. In the initial saturation state of ETG turbulence, the zonal flow level is low for all β_e's, and the Ohkawa scaling is observed. However, in the final quasi-steady state, the level of enhanced zonal flows decreases with increasing β_e as shown in Fig.7(b) so that the electron heat transport becomes to be proportional to β_e. This mainly results from the reduction of the flow generation by the Maxwell stress in EM ETG turbulence.

4. Streamer dynamics and electron transport in ETG turbulence

The opposed anisotropic large-scale structure to the zonal flow is the streamer, which may enhance plasma transport. In this section, we first demonstrate the pattern selection, zonal flow or streamer, in 3D slab ETG turbulence can be controlled by the magnetic shear. Then, the streamer dynamics in toroidal ETG simulations will be presented.

4.1 Pattern selection in slab ETG turbulence

Motivated by the results from modulation analysis in Sec.2, it is expected to form the streamer structure in strong shear ETG fluctuations based on the weak turbulence theory of drift wave and the confirmation of enhanced zonal flows in weak shear ETG turbulence. Hence, our simulations are designed by increasing the magnetic shear with other parameters fixed, as in Sec.3. In the calculations, the radial domain is decreased as increasing shear for saving the CPU time. It is found that as the magnetic shear increases, the zonal flow level tends to decrease and the anomalous electron transport slowly increases. In plasmas with higher shears, the 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 effects of the streamer. Spatial spectral analyses of ETG turbulence with different magnetic shears clearly reveal the parametric dependence of structure formation as shown in Fig. 7: turbulent ETG fluctuations condense 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. In the moderate shear case, ETG fluctuations behave with homogeneous turbulent structures. It is shown that the pattern selection in ETG turbulence can be controlled by some key parameters such as the magnetic shear. Fig.7(a) also shows that besides the zonal flows, turbulent ETG fluctuating energy shrinks to the spectra with $k_y = 0.2 \sim 0.3$, which correspond to the KH mode. In Fig.7(c), the streamers are located at $k_y = 0.5 \sim 0.6$, which approaches the linear spectrum. The inverse energy cascade seems to be ineffective.

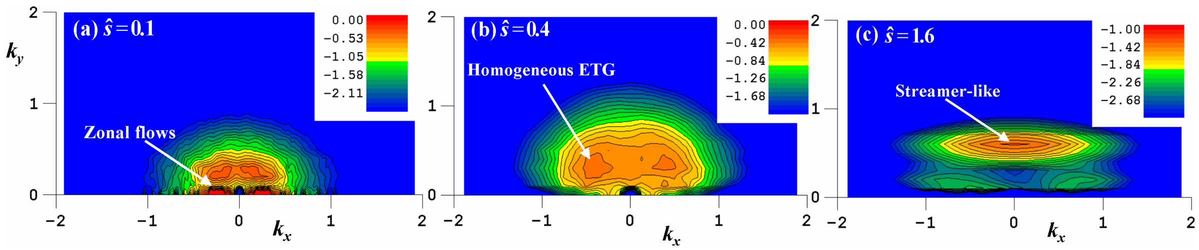

FIG.7 Spectral distributions of slab ETG turbulence in $k_x - k_y$ plane for different magnetic shears. (a) fluctuation condensation to zonal flows; (b) homogeneous ETG ; (c) energy condensation to streamers. These show that pattern selection can be controlled by a key parameter: magnetic shear.

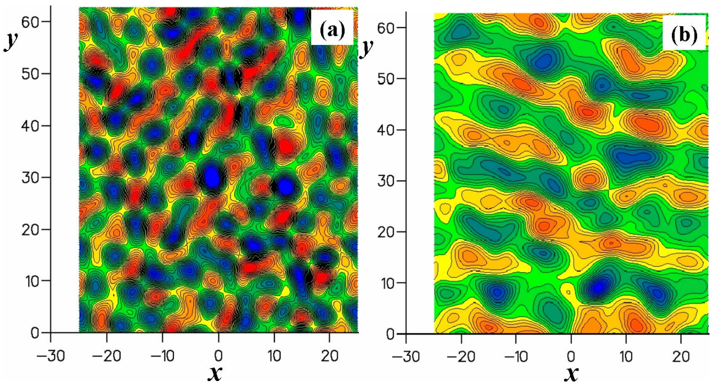

FIG.8 Contours of quasi-steady electrostatic potential in turbulent (a) and streamer-dominated (b) regions in toroidal ETG simulation. $\hat{s} = 0.6$, $\eta_e = 3.2$, $\varepsilon_n = 0.45$, $\beta_e = 0$..

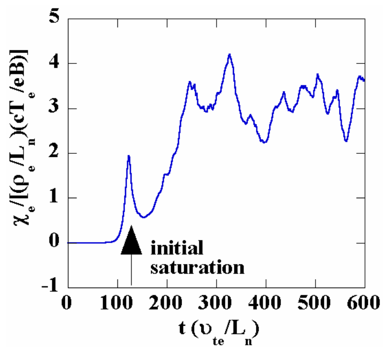

FIG. 9 Evolution of turbulent electron heat conductivity in the simulation as in Fig.8.

4.2 Streamer formation in toroidal ETG turbulence

In a toroidal plasma, poloidal harmonics of ETG fluctuations can couple through the toroidal curvature effect so that radially elongated vortices can be linearly formed in the bad curvature region, namely, ballooning structure. These linear modes are broken at the saturation of ETG fluctuations with lower transport. ETG turbulence is characterized by almost isotropic spectra in this initial saturated phase. However, some large-scale streamers, which are dominated by fluctuations with peaked k_y spectral distribution, are locally excited in linearly stable region of ETG mode along the field after initial ETG saturation, as shown in Fig.8. Quasi-steady streamers are formed in toroidal ETG turbulence with moderate magnetic shear $\hat{s} \geq 0.5$, which is similar to the observation in gyro-kinetic calculation.[6] However, Fig.9 illustrates that the averaged electron transport $\chi_e(t) = -(\frac{\rho_e}{L_n}\frac{cT_e}{eB})\langle p\partial_y\phi\rangle K^{-1}$ increases only by 3~4 times compared to the initial saturation level with around gyro-Bohm level. Simulations show that the streamer dynamics seems not to sensitively depend on the EM effect, but on the toroidicity. As the magnetic shear increases, ETG fluctuations and the electron transport on average decrease due to the shear stabilization. Interestingly, they show a bursty character when $\hat{s} \geq 0.7$. It is observed that the intermittency results from the alternative emergency of linearly elongated vortices (ballooning structure) in bad curvature region and the nonlinear streamers at around good curvature region along the magnetic field. It needs to perform more simulations with higher shears to investigate the dependence of toroidal streamer dynamics on the magnetic shear although ETG turbulence is strongly stabilized by high shears.

5. Summary and conclusions

In conclusion, the generation of large-scale structures such as zonal flows or streamers in ETG turbulence, namely, pattern selection, is determined by the spectral anisotropy of turbulent fluctuations. Radially elongated fluctuation favors the excitation of zonal flows and poloidally elongated vortices enhance the streamers. The magnetic shear is a key parameter in pattern selection in slab ETG turbulence except for its stabilization role. In weak shear ETG turbulence, fluctuating energy condenses to the enhanced zonal flows, which is identified to be limited by a KH instability. The electron transport is dramatically reduced. In this case, EM effects may reverse the conventional Okawa-scaling of electron transport. For strong shears, slab streamer structures are formed with weaker intensity compared with the zonal flow counterpart. ETG fluctuations and turbulent electron transport are still weak due to the shear stabilization.

In a toroidal geometry with moderate magnetic shears $\hat{s} \geq 0.5$, quasi-steady streamer structures are excited in linearly stable region of ETG modes after initial ETG saturation. Turbulent electron transport is enhanced by 3~4 times of the initial saturated Gyro-Bohm level. As the magnetic shear increases, toroidal ETG fluctuations and electron transport become to be characterized by intermittent bursts. It results from the alternative emergency of linearly elongated structures in bad curvature region and the nonlinear streamers at good curvature region. The understanding of the complex nonlinear interaction process is in progress.

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