Interaction between Small-Scale Zonal Flows and Large-Scale Turbulence: A Theory for Ion Transport Intermittency in Tokamak Plasmas

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Interaction between small-scale zonal flows and large-scale turbulence is investigated. The key mechanism is identified as radially nonlocal mode coupling. Fluctuating energy can be nonlocally transferred from the unstable longer to the stable or damped shorter wavelength region, so that the turbulence spectrum is seriously deformed and deviates from the nonlinear power law structure. Three-dimensional gyrofluid ion-temperature gradient (ITG) turbulence simulations show that an ion transport bursting behavior is consistently linked to the spectral deformity with the causal role of ITG-generated zonal flows in tokamak plasmas.

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Introduction.—Interactions among turbulence and flows are of importance in plasmas and fluids. Sheared $\vec{E} \times \vec{B}$ or turbulence self-generated zonal flows have been shown to play an efficient role in regulating the turbulence structure and suppressing the heat transport in magnetized plasmas [1]. Over the past years, a remarkable theoretical progress on this topic is the recognition of flow shear-induced decorrelation in drift-wave turbulence [2,3]. When the effective shearing rate of sheared flows exceeds the turbulence decorrelation rate, which is usually approximated by the linear growth rate, turbulence eddies are broken and the turbulent transport can be reduced. Previous studies on the dynamics of sheared flows in transport suppression were dominantly focused on the sheared or zonal flows with radial scale larger or similar to fluctuations, such as ion-temperature gradient (ITG) turbulence, namely, $k_x^{(zf)} \leq k_x^{(ITG)}$, which are subject to the above suppression mechanism. [In this Letter, the wave number k_x is measured by the ion gyroradius.] For the opposite case with $k_x^{(zf)} > k_x^{(ITG)}$, a proposal was recently presented [4], where a linear gyrokinetic particle code calculation showed strong stabilizing effects of electron temperature gradient (ETG) turbulence-driven zonal flows on the ITG mode. This topic involves the interaction between small-scale sheared flows, for example, with a spatial scale on the electron gyroradius or the collisionless skin depth, and the large-scale turbulence. The interaction mechanism, nonlinear dynamics, and/or turbulent transport affected by such small-scale flows are open issues. It may exploit a new role of zonal flows in regulating different spatiotemporal scale turbulence and the relevant transport and, further, aim at studying the interaction between the turbulence with different spatiotemporal scale lengths [5].

In this Letter, we identify a key physical mechanism that small-scale sheared flows interact with large-scale fluctuations through a radially nonlocal mode coupling. It can deform the nonlinear spectral structure of large-scale turbulence, then modulate the turbulent transport. This mechanism is different from the usual shearing decorrelation of ITG turbulence by sheared $\vec{E} \times \vec{B}$ flows with $k_x^{(zf)} \leq k_x^{(ITG)}$ [2,3]. The latter can break turbulence eddy structure. On the other hand, it is also distinct from the local step-by-step energy cascade process [6], which usually leads to a typical power law spectrum, such as the Kolmogorov-type one. Our three-dimensional (3D) nonlinear gyrofluid simulations show an intermittent or bursting behavior of turbulent ion heat transport in ITG turbulence in the presence of small-scale zonal flows. Except for many observations in edge plasmas [7], intermittent density fluctuations have been clearly observed in TFTR core plasma. The turbulence phase becomes completely chaotic at bursting peaks [8]. We find that, during bursts, ITG turbulence is characterized by a pronounced spectral alternation between nonlinear power law and linear deformed structure. The occurrence of intermittency is attributed to both the stabilizing effects of small-scale zonal flows on ITG fluctuations and the casual role of ITG-generated zonal flows, rather than the damping role of collisionality in zonal flows [9].

Interaction mechanism.—In the strong drift-wave turbulence, the self-generated zonal flow may be sustained at a higher quasisteady level because it cannot be damped out by linear collisionless processes [10]. The generation of zonal flows in different scale length turbulence seems to be a ubiquitous phenomenon. Large zonal flow potentials such as the Mach number being about 0.5% with a long-lived coherent structure with $k_x^{(zf)}\rho_e$ being about 0.1–0.3 and a very peaked low-frequency spectrum (e.g., $\Delta\omega/\omega_{*e} < 0.01$ with electron scaling normalization) have been observed in the local gyrofluid normal-sheared ETG simulation [11] and the global gyrokinetic negative-sheared ETG simulation [4], as well as in 3D Braginskii turbulence simulation in the core/edge transitional region of tokamak plasmas [12]. Those zonal flows driven by quickly developed turbulence with a small spatiotemporal scale, such as ETG, may be regarded as quasisteady sheared fluid flows for ITG fluctuations. They can interact with large-scale turbulence on a gyrophase averaged and velocity space averaged level from the view of fluid. Note that there exists no directly mutual interaction between the turbulence self-generated zonal flows and external small-scale flows. Ignoring the weak time dependence, the coherent structure of the small-scale zonal flows are typically modeled by a circular function (sine or cosine) as follows:

$$v_{\perp p}(x) \propto d\phi_{ex}(x)/dx = A(k_{ex})\cos(k_{ex}x), \qquad (1)$$

when they are externally embedded in ITG fluctuations. Here, k_{ex} is the normalized wave number of small-scale flows, which is generally larger than 1. It is assumed that the factor $A(k_{ex})$ has included both gyrophase and velocity space averaged effects for the convenience of fluid treatment, in which k_{ex} dependence should be involved in Bessel functions. Note that there exists no difference for large-scale ITG fluctuations if the cosine or sine function is assumed in Eq. (1).

Analyses and simulations are based on a simplified gyrofluid model for the dynamics of electrostatic slab ITG [or $\eta_i = d\ln T_i/d\ln n$] turbulence [13,14], which includes the small-scale flows as an external source by adding $\partial_x\phi_{ex}\partial_y\tilde{f}$ term to the corresponding moment equations, the correct adiabatic electron response to the ITG-generated zonal flows [15] and the kinetic Landau damping physics [16].

In a general fluid model, sheared flows interplay with the ITG mode through the Doppler shift effect. For usual sheared $\vec{E}\times\vec{B}$ or ITG-driven zonal flows with $k_x^{(\mathrm{zf})} \leq k_x^{(\mathrm{ITG})}$, the Doppler shift dominantly leads to local shearing modification of fluctuating potential structures. However, a different interaction mechanism for small-scale zonal flows can be advisably revealed by a perturbation analysis [17]. Keeping the lowest order effects of a small amplitude flow and Fourier transforming the perturbed eigenmode equation from real space to wave number k space, i.e., $\phi(x) = \sum_k \phi_k e^{-ikx}$, it can formally yield

$$(\mathcal{L} + U_k)\phi_k = A\vartheta(\Lambda - \mathcal{L})(\phi_{k+k_{ex}} + \phi_{k-k_{ex}}). \qquad (2)$$

Here $\mathcal{L} \equiv d^2/dk^2$, $U_k = (L_s\Omega/L_n)^2[k_y^2 - (1-\Omega)/(\Omega + K) + k^2]$, $\Lambda = L_s^2\Omega^3(1+K)/2L_n^2(\Omega+K)^2$, $\vartheta = L_n/\Omega$ with $\Omega = \omega/\omega_{*e}$ and $K = 1 + \eta_i$. This is a coupling equation system of different radial components k, $k + k_{ex}$, and $k - k_{ex}$. It shows that small-scale sheared flows can produce radial mode coupling of different harmonics, which is formally similar to the well-known poloidal coupling of drift wave in a toroidal magnetic configuration [18]. However, the new feature of this model is that the coupling is nonlocal in the radial spectral space due to $k_{ex} > 1$, generally. It may directly transfer the fluctuating free energy from the longer wavelength region, in which the ITG mode is generally unstable, to stable or damped components at shorter wavelengths. Then, the ITG mode is stabilized. This nonlocal coupling sensitively depends on two factors: the intensity of small-scale flows including gyrophase averaged effects, which may strongly reduce the coupling intensity due to the dependence of k_{ex} in Bessel functions, i.e., $A(k_{ex}) \sim A_0\Gamma_0^{1/2}$, $\Gamma_0 = I_0(k_{ex}^2)e^{-k_{ex}^2}$ [15], and the spectral structure of ITG fluctuations between different radial modes k, $k + k_{ex}$, and $k - k_{ex}$. The latter means that the smaller the decay rate of ITG turbulence spectrum is in the inertial range, the stronger the coupling is for a given k_{ex}. It can be expected that the zonal flows generated by the mesoscale turbulence on the collisionless skin depth size may more effectively interact with ITG turbulence. The ETG-driven zonal flow is only an example of small-scale zonal flows taken in this Letter. In addition, the coupling to wider spectral space, such as $k + 2k_{ex}$, $k - 2k_{ex}$, and so on, may also occur.

Nonlinear evolution equations have been numerically solved by using an initial value code [14]. The typical parameters are $\eta_i = 2.5$, $\hat{s} = L_n/L_s = 0.2$, $\mu_\perp = \eta_\perp = \chi_\perp = 0.5$, $L_x = 50\rho_i$, $L_y = 10\pi\rho_i$, $L_z = 2\pi L_n$, $m \leq 15$. Nonlinear simulations have been performed by initially including small-scale flows for different flow intensities or wave numbers k_{ex}. Two typical results for the cases without and with small-scale zonal flows are illustrated for comparison. Figure 1 shows the time evolution of the space averaged potential energylike quantity $\langle\phi^2\rangle/2$ in the earlier linear phase and the corresponding instantaneous radial spectra. An initial slowdown of the time evolution of the potential fluctuations is observed because of the stabilization role of small-scale flows, as shown in Fig. 1(a). Note that these external flows do not seem to affect the saturation level, which may be determined by the $\vec{E}\times\vec{B}$ convective nonlinear coupling and the ITG self-generated zonal flows. Most importantly, a spectral prominence with width $\Delta k_x \sim 2$ clearly appears near $k_x = k_{ex}$, as well as another one near $k_x = 2k_{ex}$, as shown in Fig. 1(b). The monotonic decay spectrum is broken down at shorter wavelengths due to the radially nonlocal mode coupling. The width of the spectral prominence mirrors the fact that the unstable ITG mode stands in the range $k_x \leq 1$. For the stronger flows, the spectral prominence becomes more peaked, until the ITG fluctuation is completely suppressed. Similar results have been also observed for different k_{ex} values. Therefore, we conclude that small-scale zonal flows interact with large-scale ITG modes dominantly through the radially nonlocal mode coupling rather than the usual shearing decorrelation. Furthermore, the spectral prominences are observed to disappear at saturation. It may also involve the complex nonlinear energy transfers such as cascade and inverse cascade, which are discussed in the following nonlinear simulations.

Ion transport intermittency.—Our nonlinear simulations are designed to explore the role of small-scale zonal

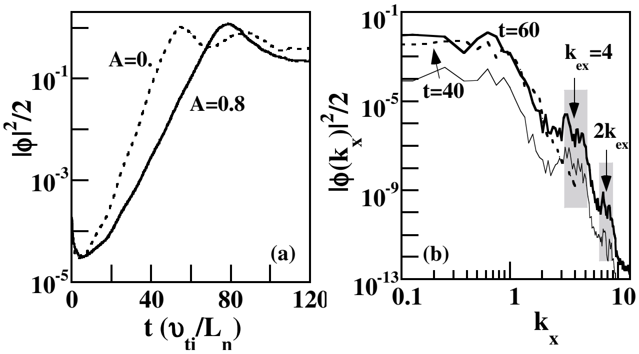

FIG. 1. The time history of $\langle\phi^2\rangle/2$ (a) and the instantaneous radial spectra (b) without (dashed line) and with (solid line) small-scale flows.

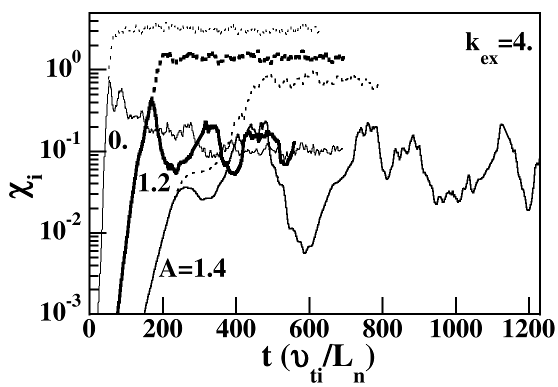

FIG. 2. The time history of χ_i for different small-scale flows. Dashed curves correspond to their counterparts artificially excluding ITG-generated zonal flows.

flows in ITG turbulence saturation and turbulent ion heat transport. Note that the development of turbulence generally depends on their temporal scales. As a basic scheme of numerical experiments, we performed simulations by initially including ETG-driven zonal flows. This case corresponds to the plasma state that ETG turbulence may be first developed. For a strong ITG turbulence drive, for example, $\eta_i \geq 4$, simulations show that even for the strongest small-scale zonal flows, which may be possibly observed in our strong ETG turbulence simulations [11], the small-scale zonal flows add less effects to the saturation level and the nonlinear evolution of ITG turbulence except for a negligible slowdown of the fluctuation evolution in the linear phase. It is well known that ITG turbulence is strongly regulated and suppressed by self-generated zonal flows through random shearing. The ITG-generated zonal flows dominate the turbulence structure and the nonlinear evolution. Hence, it may be understood that the stabilizing effect of the small-scale zonal flows due to the nonlocal mode coupling is too weak compared with the strong nonlinear dynamics of ITG-generated zonal flows, so that it is submerged by strong nonlinear coupling interactions in the quasisteady state.

As the turbulence drive is reduced, such as to $\eta_i \leq 2.5$, the corresponding levels of turbulent ITG fluctuations and self-generated zonal flows decrease much. It is characterized by the relatively weak turbulence. Meanwhile, a remarkable intermittent or bursting behavior of ion heat transport appears, accompanied by the intermittent ITG-generated zonal flows with a time lag. It is also observed that the turbulence intensity $\langle\phi^2\rangle/2$ and ion heat conductivity χ_i $[= -(\rho_i/L_n)(cT_i/eB)\langle p\partial\phi/\partial y\rangle/(1+\eta_i)]$ are in phase during bursts [9]. The bursting period becomes longer, even infinite (it means no linearly unstable ITG modes) as the ETG-driven flows increase, as shown by solid curves in Fig. 2. The time-averaged transport becomes decreasing for stronger flows. We next performed simulations by artificially excluding ITG-driven zonal flow components in order to find the related factors for the intermittency occurrence. The transport levels become about 1 order higher than their counterparts above. No bursts are observed except for the quasisteady levels of ITG fluctuations decreasing as the flow intensity increasing, as shown by the dashed curves in Fig. 2. It is clear that the ITG-driven zonal flow dynamics still dominates the ITG turbulent transport in the relatively weak turbulence, but the turbulence can be remarkably modulated by small-scale flows. The emergence of ion transport intermittency requires the simultaneous presence of both small-scale flows and ITG-driven zonal flows.

The causal relation between the turbulent transport and ITG-generated zonal flows during bursts is plotted in Fig. 3(a) for the case with $A(k_{ex}) = 1.4$ in Fig. 2. The bursting process can practically last a long time (we have calculated to $t = 3000$). How these small-scale zonal flows lead to an intermittent behavior in ITG turbulence is a key question. Note that the turbulent fluctuations seem to roughly exponentially go up and down during bursts, as shown in Fig. 2. The growth rates are approximately the same for all bursts but slightly smaller than that in the initial linear phase. Performing spectral analyses for ITG turbulence, we found that at bursting peaks, k_x spectra are characterized by a monotonic decay structure with an approximate power law, which is a typical nonlinear Kolmogorov-type scaling determined mainly by energy cascade and inverse energy cascade processes. However, the spectral structures near $k_x = k_{ex}$ and $k_x = 2k_{ex}$ are gradually deformed after the bursts, actually degenerated to the linear spectral shape at valleys, as shown in Fig. 3(b), which is dominated by the linear nonlocal mode coupling. The bursts emerge in the recovery phases of nonlinear saturation spectra. It seems to be in agreement with the experimental characters for fluctuation structure [8]. The physical mechanism of the intermittency may be understood. The exponentially growing ITG fluctuations can be slowed down in the initial linear phase by small-scale zonal flows through the nonlocal mode coupling. As the perturbation linearly grows, the ITG fluctuation is dominantly saturated by self-generated

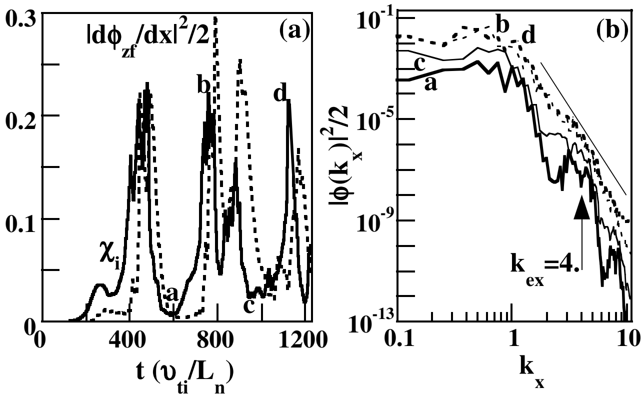

FIG. 3. The causal relation between transport and ITG-generated zonal flows (a) and the radial spectra at peaks and valleys of bursts (b).

zonal flows, as well as the nonlinear coupling. Afterwards, the stabilization role of the nonlocal mode coupling can lead to ITG fluctuations decreasing due to the competition between the linear nonlocal coupling and the nonlinear mode coupling. ITG-generated zonal flows follow the turbulence decreasing with a time lag behind due to the nonlinear drive decreasing. During this phase, the nonlinear turbulence spectrum is alternated to a linear deformed structure. When the effective shearing rate of ITG-generated zonal flows becomes lower than the turbulence decorrelation rate, the ITG fluctuations linearly grow again and then lead to a burst. Note that the level of residual self-generated zonal flows in this growing phase may remain higher than that in the initial linear phase, so that the smaller growth rate of ITG fluctuation than the initial linear one was consistently observed. As a matter of fact, the intermittency is a very important issue in fluid turbulence accompanied by spectral deviations from the Kolmogorov scaling in the inertial range [6]. One might be tempted to speculate that the spectral deviation from the nonlinear power law due to some mechanisms, such as the nonlocal mode coupling in this Letter, is consistently linked to the occurrence of intermittency. This work may reveal a practical illustration of such evidence.

The emergence of ion transport intermittency does not seem to depend on ITG turbulence states when the small-scale zonal flows are included, provided the causal role of ITG-generated zonal flows can approximately remain. We performed the simulations by starting ETG-driven zonal flows in fully developed ITG turbulence with self-generated zonal flows. This case corresponds to the state that the excitation of ETG turbulence lags behind ITG fluctuations. The same bursting process was observed by properly controlling intensities of ETG-driven zonal flows. It requires that the properties of ITG-driven zonal flows can keep basically unchanged. If the stabilization role of small-scale flows in the ITG turbulence is too strong, ITG fluctuations can be sharply suppressed.

Conclusion.—We have established a theoretic model on the interaction between small-scale sheared flows and large-scale turbulence in magnetized plasmas by sampling ETG-driven zonal flows and ITG turbulence. The key physical mechanism has been identified as a radially nonlocal mode coupling between unstable and stable or damped components, rather than the shearing decorrelation of zonal flows in drift-wave turbulence [2,3]. It can deform the nonlinear monotonic decay spectrum of large-scale ITG turbulence in the inertial range and lead to an intermittent or bursting behavior of turbulent ion transport. The onset mechanism of bursts is found to originate from both the stabilization role of small-scale sheared flows to ITG fluctuations and the causal role of ITG-generated zonal flows. This theory may suggest a way to study turbulence interactions in different spatiotemporal scales through the zonal flows.

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