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Transition in multiple-scale-lengths turbulence in plasmas

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Abstract

Statistical theory of strong turbulence in inhomogeneous plasmas is extended to the state where fluctuations with different scale lengths, micro and semi-micro modes, coexist. Their nonlinear interactions give several states of turbulence: in one state, the micro mode is excited while the semi-micro mode is quenched; in another state, the latter is excited while the micro mode is suppressed. A new turbulence transition with a hard bifurcation was obtained. A phase diagram was obtained. A new insight is given for the physics of internal transport barrier.

Keywords: plasma turbulence, multiple scale lengths, turbulence transition, internal transport barrier, extended fluctuation-dissipation theorem, cusp type catastrophe, phase diagram, radial electric field

High temperature plasmas are often in the state far from thermal equilibrium, and the development of statistical theory for strongly turbulent plasma has been one of the main subject of plasma physics theory. A characteristic feature of strong plasma turbulence is that it is driven by spatial inhomogeneities of plasma parameters and fields [1,2], and that varieties of modes with different scale lengths appear. Importance of interactions between the modes with different scale lengths is recognized recently. For instance, the dynamics of meso-scale structure of radial electric field cause varieties in the dynamics of microscopic fluctuations; Examples include the electric field domain interface [3, 4], zonal flow [5] and streamer [6], and an effort to develop a statistical theory for zonal flow is reported [7]. (See also [1] .) Observations on ITB (internal transport barriers) have shown that the anomalous electron transport remains large even after the sudden reduction of ion transport happens [8]. This suggests multiple kinds of modes, nonlinearly interacting, exist in plasma.

In this article, we extend the statistical theory framework [9] to include two different collective modes with different scale lengths. The nonlinear interactions between micro-mode (being represented by, e.g., current-diffusive interchange mode (CDIM) [2] of the scale length $\sim \delta$, the skin depth, or by the electron temperature gradient (ETG) mode [1]) and semi-micro mode (e.g., drift mode or ion temperature-gradient (ITG) mode of $\sim \rho_i$, the ion gyroradius [1]) are taken into account for the case of $\delta < \rho_i$. Their interplay (nonlinear dynamics) determines both the fluctuation levels and the associated cross-field turbulent transport. The nonlinear interactions of two collective modes of fluctuations are treated as follows. The hierarchical structure is adopted. The micro-turbulence of smaller size affects the semi-micro one through the renormalized drag and the micro-noise. The effect of semi-micro turbulence is included in the dynamical equation of the micro-mode as a kind of a driving or damping force. Nonlinear self-interactions in one class of fluctuation are divided into the coherent drag and the self-noise as has been done in refs. [9, 10]. The combined Langevin equations are to be formulated. A set of equations of the fluctuation level and decorrelation rate for the micro and semi-micro fluctuations is obtained. A case where driving mechanisms by global inhomogeneities exist (for both micro and semi-micro modes) is investigated. It is found that there are several states of fluctuations: in one state, the micro mode is excited and the semi-micro mode is quenched; in the other state, the semi-micro mode is excited, and the micro mode remains at finite but suppressed level. New type of turbulence transition is obtained, and a cusp type catastrophe is revealed. A new insight in the confinement improvement in ITB is given.

We study a slab plasma, the pressure of which is inhomogeneous in the x -direction, in a sheared magnetic field $\boldsymbol{B} = \left(0,\, sx,\, 1\right)\bar{B}_0$. Magnitude of the magnetic field is also inhomogeneous in the x-direction $\bar{B}_0 = \left(1 + \Omega' x + \cdots\right)B_0$. A reduced set of equations for the variables $f = \left(\phi, A_{\|}, V_{\|}, p_e, p_i\right)^{\mathrm{T}}$ is employed for the study of instabilities with multiple scale lengths. In the presence of global driving parameters (ion temperature gradient $\mathrm{d}T_{i0} / \mathrm{d}x$, pressure gradient $\mathrm{d}p_{i0} / \mathrm{d}x$, magnetic field gradient Ω' , and the inhomogeneous global radial electric field $\mathrm{d}E_{r0} / \mathrm{d}x$) the system describes turbulence caused by the ITG mode and CDIM. The global parameters, $\mathrm{d}p_0/\mathrm{d}x$, Ω' , and $\mathrm{d}E_{r0} / \mathrm{d}x$ are fixed constant. In other words, we assume that the time for the evolution of global parameters is longer than the autocorrelation times of the semi-micro and micro modes.

The dynamical equations of fluctuation fields are given symbolically as

$$\frac{\partial}{\partial t} f + \mathcal{L}^{(0)} f = \mathcal{N}(f, f) \ . \tag{1}$$

$\mathcal{L}^{(0)}$ denotes the linear operator which describes the linear ITG mode and CDIM [11], and $\mathcal{N}(f, f) = -\left(\nabla_\perp^{-2}\left[\tilde{\phi}, \nabla_\perp^2\tilde{\phi}\right], \left(1 - \delta^{-2}\nabla_\perp^{-2}\right)^{-1}\left[\phi, \tilde{J}_{\|}\right], \left[\tilde{\phi}, \tilde{V}_{\|}\right], \left[\tilde{\phi}, \tilde{P}_e\right], \left[\tilde{\phi}, \tilde{p}_i\right]\right)^{\mathrm{T}}$ is the Lagrangean nonlinearities. The bracket $[f, g]$ denotes the Poisson bracket, $[f, g] = (\nabla f \times \nabla g)\cdot \boldsymbol{b}$, and $\boldsymbol{b} = \boldsymbol{B}_0/B_0$. Explicit form and normalization are given in, e.g., [12]. Transport coefficients by the collisional process as well as thermodynamical noise can affect the turbulence level quantitatively; however, they are neglected here because the strong turbulence limit is interested in. The spatially-inhomogeneous part of the Doppler shift by global electric field, $\omega_E = k_y x \omega_{E1}$ and $\omega_{E1} = B^{-1} dE_r/dx$, contributes to the suppression of the turbulence [13, 14].

We consider the situation where two kinds of fluctuations are simultaneously excited. Scale separation is introduced. Their scale lengths are assumed to be different, and the semi-micro component and micro one are denoted by symbols l (low) and h (high), respectively. Lagrangean nonlinearity term $\mathcal{N}(f, f)$ gives three effects on a test mode f_k. The coherent part causes the turbulent drag to this test mode. This part is written as $-\Gamma_k f_k$. The second is the effective modification of the driving term. This part is symbolically written $\mathcal{D}_k f_k$. (A symbol 'D' stands for 'drive'.) Other incoherent part is considered as a random self noise $\tilde{S}_k$. Symbolically, we write $\mathcal{N}^l(f, f) = -\left(\Gamma^l_{(l)} + \Gamma^l_{(h)}\right) f^l + \tilde{S}^l_{(l)} + \tilde{S}^l_{(h)}$ and $\mathcal{N}^h(f, f) = -\Gamma^h_{(h)} f^h + \mathcal{D}^h_{(l)} f^h + \tilde{S}^h_{(h)}$, respectively. In this expression, the subscripts (l) and (h) denote the contributions from semi-micro and micro modes, respectively. A Langevin equation is derived as

$$\frac{\partial}{\partial t} f + \mathcal{L} f = \tilde{S} \ . \tag{2}$$

For semi-micro elements, one has $\mathcal{L} = \mathcal{L}^{(0)} + \Gamma^{l}_{(l)} + \Gamma^{l}_{(h)}$, and $\tilde{S} = \tilde{S}^{l}_{(l)} + \tilde{S}^{l}_{(h)}$. For micro elements, one has $\mathcal{L} = \mathcal{L}^{(0)} + \Gamma^{h}_{(h)} - \mathcal{D}^{h}_{(l)}$ and $\tilde{S} = \tilde{S}^{h}_{(h)}$. Modelling of the drag $-\Gamma_k f_k$ and noise $\tilde{S}$ has been discussed in literature [9, 10, 15] and is not repeated here. An essential contribution in $\mathcal{D}^{h}_{(l)}$ is the stretching of the micro mode via the $E \times B$ convection of the semi-micro mode. For this process we have $\left(\mathcal{D}^{h}_{(l)}\right)_{j\,j} = i\,\omega_{E(l)}$ with $\omega_{E(l)} = k_y \frac{\partial}{\partial x}\tilde{\phi}^{l} - k_x \frac{\partial}{\partial y}\tilde{\phi}^{l}$ ($j = 1 - 5$) where $\omega_{E(l)}$ is the Doppler shift owing to the $E \times B$ velocity caused by the semi-micro mode. The local pressure steepening occurs and one has $\left(\mathcal{D}^{h}_{(l)}\right)_{1\,j} = i\,\omega_{j\,(l)}$ with $\omega_{j(l)} = -k_y \frac{\partial}{\partial x}\tilde{f}^{l}_{j} + k_x \frac{\partial}{\partial y}\tilde{f}^{l}_{j}$ ($j = 2 - 5$).

Solving Eq.(2), the statistical average of fluctuation level has been given as

$$\left\langle f_1^{(1)*} f_1^{(1)} \right\rangle = \frac{1}{2\Re e(\lambda_1)} \left| A_{11}^{(1)} \right|^2 \left\langle \mathcal{S}^{(1)*} \mathcal{S}^{(1)} \right\rangle . \tag{3}$$

Details of the analysis will be presented elsewhere [16]. In this equation, the operator $\boldsymbol{A}^{(m)}$ for spectral decomposition ($m = 1 - 5$) is introduced as $\exp\left[-\mathcal{L}(t-\tau)\right] = \sum_{m=1}^{5} \boldsymbol{A}^{(m)} \exp\left(-\lambda_m (t-\tau)\right)$, $\mathcal{S}^{(1)}(\tau) = \boldsymbol{V}_R^{(1)} \cdot \tilde{\boldsymbol{S}}(\tau)$ is the projected noise amplitude with $\boldsymbol{A}^{(m)} = \boldsymbol{V}_L^{(m)}\, \boldsymbol{V}_R^{(m)\mathrm{T}}$, and $-\lambda_m$ ($m = 1 - 5$) satisfies the nonlinear dispersion relation

$$\det(\lambda \boldsymbol{I} + \mathcal{L}) = 0 \tag{4}$$

$\boldsymbol{I}$ is a unit tensor. $-\lambda_1$ corresponds to the least stable branch, i.e., CDIM and ITG for micro and semi-micro modes, respectively. (Decomposition of $\boldsymbol{A}^{(m)}$ in terms of $\boldsymbol{V}_L^{(m)}$ and $\boldsymbol{V}_R^{(m)}$ is discussed in [9].) For the transparency of the argument, one takes the limit where the amplitude of highly damped branches is neglected, $\left\langle f_i^{(m)*} f_i^{(m)} \right\rangle \to 0$ for $m = 2 - 5$. The superscript (m) is suppressed in the following.

A diagonalization approximation is used and the noise source is estimated by use of amplitude for the potential fluctuations $I_k^{h,\,l} = \left\langle f_{1,k}^{h,\,l\,*} f_{1,k}^{h,\,l} \right\rangle$ as $\left| A_{11}^{(1)} \right|^2 \left\langle \mathcal{S}_k^{h\,*} \mathcal{S}_k^{h} \right\rangle = C_0^h \gamma_v^h I_k^h$ for micro mode and $\left| A_{11}^{(1)} \right|^2 \left\langle \mathcal{S}_k^{l\,*} \mathcal{S}_k^{l} \right\rangle = C_0^l \gamma_v^l I_k^l + \hat{C}_0^h \gamma_v^h k^2 \left(k_0^h\right)^{-4} I^h$ for semi-micro mode, respectively. Here, $I^{h,\,l} = \sum_k I_k^{h,\,l}$ is the total fluctuation , and k_0^h is a typical mode number of the micro mode. γ_v is the eddy damping rate of vorticity, $\gamma_v = \Re e\left(\gamma_1\right)$. C_0^h , C_0^l and $\hat{C}_0^h$ are numerical coefficients representing the spectrum average and given in [9]. These estimates of noise sources are combined with Eq.(3), and one has

$$I^h = \frac{C_0^h \gamma_v^h}{2\Re e\left(\lambda_1^h\right)} I^h \,, \qquad \text{(micro)} \qquad (5a)$$

$$I^l = \frac{1}{2\Re e\left(\lambda_1^l\right)} \left(C_0^l \gamma_v^l I^l + \hat{C}_0^h \gamma_v^h \left(k_0^l / k_0^h\right)^4 I^h \right) . \qquad \text{(semi-micro)} \qquad (5b)$$

The eddy damping rates γ_v^h and γ_v^l are related with fluctuation levels through the renormalization relation. They are evaluated as $\gamma_v^{l\,2} \simeq \left(k_0^l\right)^4 I^l + \left(k_0^l\right)^2 \left(k_0^h\right)^2 \left(\gamma_v^l / \gamma_v^h\right) I^h$, (semi-micro) and $\gamma_v^{h\,2} \simeq \left(k_0^h\right)^4 I^h$ (micro), respectively.

The solution of nonlinear eigenvalue equation (4) is obtained. The eigenvalue of the ITG mode for the long wave length region, which is most influential in the cross-field transport, was given as $\gamma_0^l = \frac{r}{qR} s \left(1 + \eta_i\right) \left|\omega_{*,l}\right|$. The instability is suppressed by the $E \times B$ flow shear, the criterion for which is given as $\omega_{E1} = \omega_{Ec}^l \equiv \left(2/\sqrt{1+\eta_i}\right) \gamma_0^l$ [17]. We use a Lorentzian fit as $\Re e\lambda^l = -\left(1 + \left(\omega_{E1}/\omega_{Ec}^l\right)^2\right)^{-1} \gamma_0^l + \gamma_v^l$. The nonlinear growth rate of CDIM is given as $\gamma_0^h = \sqrt{G_0}\, v_A / qR$. The critical $E \times B$ -shearing rate for suppression has been obtained as $\omega_{Ec}^h \simeq s\, v_{thi} / \sqrt{aR}$ [18]. For the micro mode, the shearing by the $E \times B$ flow of the semi-micro mode is effective for suppression. The rate of shearing by the semi-micro mode is evaluated as $\left|\omega_{E(l)}\right| = \left(k^l\right)^2 \sqrt{I_1^l}$. Taking this fact into account, the nonlinear eigenvalue for the micro mode is given as $\Re e\, \lambda^h = -\frac{\gamma_0^h \sqrt{1 + \left|k_0^{l\,2} / 2\gamma_v^l\right| \sqrt{I_1^l}}}{1 + \left(\omega_{E1}/\omega_{Ec}^h\right)^2 + \left(k^l\right)^4 \left(\omega_{Ec}^h\right)^{-2} I^l} + \gamma_v^h$. The enhancement factor in the numerator represents the local pressure steepening by the semi-micro mode. Substituting $\lambda^{h,l}$ into Eq.(5), we have a closed set of equations for $\gamma_v^{h,l}$ and $I^{h,l}$ as

$$\frac{\gamma_v^{l\,2}}{k_0^{l\,4}} \simeq I^l + \frac{\gamma_v^l}{k_0^{l\,2}} \sqrt{I^h} \,. \qquad (6a)$$

$$\frac{\gamma_v^l}{k_0^{l\,2}} I^l = D^l I^l + \varepsilon \left(I^h\right)^{3/2} \qquad (6b)$$

where $D^l = 2\left(2 - C_0^l\right)^{-1} \left(1 + \left(\omega_E / \omega_{Ec}^l\right)^2\right)^{-1} \gamma_0^l k_0^{l\,-2}$ and $\varepsilon = \hat{C}_0^h \left(2 - C_0^l\right)^{-1} \left(k_0^l / k_0^h\right)^2$ for semi-micro mode, and

$$\gamma_v^h \simeq k_0^{h2} \sqrt{I_i^h} \qquad (7a)$$

$$I^h = \left(D^h\right)^2 \frac{1 + \left|k_0^{l\,2}/2\gamma_v^l\right|\sqrt{I^l}}{\left(1 + I_{eff}^{-1}\, I^l\right)^2} \tag{7b}$$

where $D^h = 2\left(2 - C_0^h\right)^{-1}\left(1 + \left(\omega_{E1}/\omega_{Ec}^h\right)^2\right)^{-1}\gamma_0^h\, k_0^{h-2}$, and $I_{eff} \equiv \left(1 + \left(\omega_E/\omega_{Ec}^h\right)^2\right)\left(\omega_{Ec}^h\right)^2\left(k^l\right)^{-4}$ for micro mode. Here, D^l and D^h denote the magnitude of driving power by the global inhomogeneity and represent the characteristic level of diffusivity of semi-micro mode and that of micro mode, respectively. In the absence of mutual nonlinear interactions, we have $I^l \simeq \left(D^l\right)^2$ and $I^h \simeq \left(D^h\right)^2$. I_{eff} represents the level of semi-micro mode which is enough to suppress the micro mode by velocity shear.

Equations (6) and (7) have multiple solutions and show a hard bifurcation. Figure 1 illustrates the fluctuation amplitude as a function of D^l for the fixed value of D^h . When the drive for the semi-micro mode is weak, $D^l < D^h$, the micro mode is excited, but the semi-micro mode is quenched. The solution is given as

$$I^h \simeq \left(D^h\right)^2 \text{ and } I^l \simeq \varepsilon\, I^h\ . \tag{8}$$

Although the drive for the semi-micro mode is finite, instabilities do not grow, but is only excited through the noise pumping by the micro mode. When the drive D^l becomes large, $D^l > D^h$, the other type of solution appears. In the large D^l limit, one has

$$I^l \simeq D^{l2} \text{ and } I^h \simeq \left(D^h\right)^2 I_{eff}^2\, D^{l-4}\ . \tag{9}$$

The semi-micro mode is strongly excited and the micro mode is suppressed by the $E \times B$ shear of the semi-micro mode. Owing to the coexistence of two solutions, a hysteresis appears in the relation between the gradient and fluctuation level. At the critical point, the transition between these solutions takes place.

There appears a cusp type catastrophe in the phase diagram of the turbulence. Global plasma parameters are represented by the two parameters D^l and D^h . The threshold condition for the micro mode solution to exist is $D^l < D^h$. The condition for the other solution is estimated as $D^h < \left(4\, D^l\, I_{eff}\right)^{-1}\left(D^{l2} + I_{eff}\right)^2$. One sees that the two solutions can appear in the cusp region $D^l < D^h < \left(4\, D^l\, I_{eff}\right)^{-1}\left(D^{l2} + I_{eff}\right)^2$. The critical point of the cusp is given as $D^l = D^h = \sqrt{I_{eff}}$.

A new dynamical transition is induced by the global radial electric field shear. When the nonlinear interactions between different fluctuations are neglected, the inhomogeneous radial electric field suppresses the fluctuations as $D^l \propto \left(1 + \omega_{E1}^2\, \omega_{Ec}^{l\ -2}\right)^{-1}$ and $D^h \propto \left(1 + \omega_{E1}^2\, \omega_{Ec}^{h\ -2}\right)^{-1}$. In the presence of their nonlinear interactions between fluctuations, different types of bifurcation appear depending on the ratio $\omega_{Ec}^l/\omega_{Ec}^h$. The suppression by flow shear is usually stronger for the semi-micro mode, $\omega_{Ec}^l \le \omega_{Ec}^h$. (For the case of ITG and CDBM/CDIM, one has $\omega_{Ec}^l \sim s v_{th}/qR$ and $\omega_{Ec}^h \sim s v_{th}/\sqrt{aR}$, satisfying the condition $\omega_{Ec}^l \le \omega_{Ec}^h$.) If the condition $\omega_{Ec}^l \le \omega_{Ec}^h$ holds, $D^l\left(\omega_{E1}\right)$ decreases faster than $D^h\left(\omega_{E1}\right)$ as ω_{E1} increases. When ω_{E1} is increased from zero, the semi-micro mode starts to be suppressed by the global electric field shear. The micro mode is, however, first enhanced, because the suppression by the semi-micro mode is reduced. The reduction of suppression of semi-micro mode is stronger than the reduction of the drive for the micro mode $D^h\left(\omega_{E1}\right)$ by the global electric field shear. When the trajectory $\left(D^l, D^h\right)$ crosses the phase boundary, $D^h = \left(4\, D^l\, I_{eff}\right)^{-1} \left(D^{l2} + I_{eff}\right)^2$, the phase transition of turbulence takes place. The semi-micro mode is quenched, and the level of micro fluctuations jumps up with an enhanced dissipation. The electric field shear suppresses the micro mode, and the level starts to decrease. Figure 2 illustrates the fluctuation amplitude $\sqrt{I^l}$ and $\sqrt{I^h}$ as a function of the global shear of radial electric field. A hard type bifurcation is observed.

The induced transition of the semi-micro fluctuations sheds a light on the ITB formation. It is widely conjectured that the steep gradient of global radial electric field plays a role in reducing the anomalous thermal conductivity. In many cases, the electron thermal transport remains to be large (in the level of L-mode) although the thermal barrier for the ion energy is established . The ITB for electron thermal transport can also be formed when the ITB for ion energy is prominent. This problem of two types of ITB could be solved by considering the transition of the semi-micro and micro turbulence. As is shown in Fig.2, at the transition, the semi-micro mode is almost completely quenched, but the micro mode can jump up to a large amplitude. The turbulent thermal conductivity by the micro mode could appear dominantly for electrons, χ_e^h . (E.g., the case of CDBM [19]. So is the case of ETG.) Above the threshold value, the semi-micro mode is quenched and the ion thermal conductivity decreases strongly. The micro mode fluctuation is enhanced, so that the electron thermal transport coefficient does not decrease much. When the global electric field shear is strong enough, the electron thermal transport is also reduced.

In summary, the statistical theory of strong turbulence in inhomogeneous plasmas was extended to analyzing the nonlinear interactions when fluctuations with different scale lengths coexist. Several states of fluctuations are found: in one state, the micro mode is excited and the semi-micro mode is quenched; in another state, the latter is excited, and the former is suppressed. A new turbulence transition was obtained, being associated with a hard bifurcation. A phase diagram was obtained. The result clearly shows that the nonlinear interplay is essential in the dynamics of the strong turbulence in inhomogeneous plasmas.

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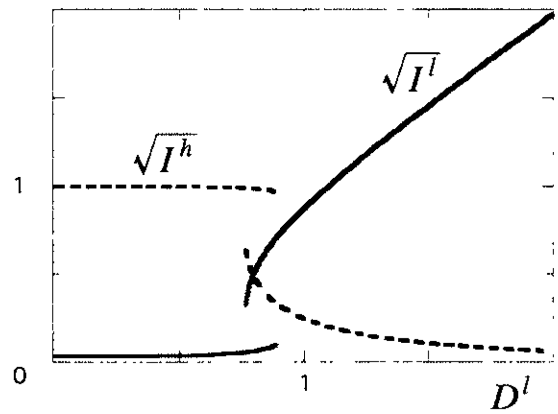

Fig.1 Fluctuation level for semi-micro mode I_1^l (solid line) and that for micro mode I_1^h (dashed line) as a function of the driving rate of the semi-micro mode D^l. ($\sqrt{I_{eff}} = 0.5\, D^h$.) The driving rate for the micro mode D^h is fixed. For the intermediate value of D^l, multiple solutions are allowed and hard transition takes place at critical values of D^l.

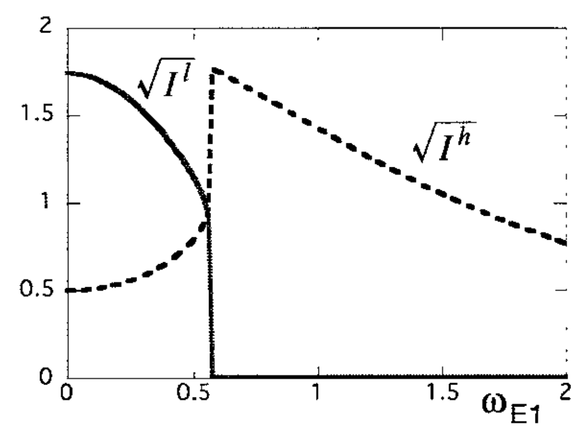

Fig.2 Fluctuation amplitude $\sqrt{I^l}$ (solid line) and $\sqrt{I^h}$ (dashed line) as a function of the shear of global $E \times B$ velocity. Quantities are normalized to $\sqrt{I_{eff}}$. (Parameters are: $D^l(0) = D^h(0) = 2\sqrt{I_{eff}}$ and $\omega_{Ec}^l = \sqrt{0.4}\ \omega_{Ec}^h$)

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