§26. A Parameter that Denotes Non-equilibrium Property for Turbulent Plasmas

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In employing the terminology 'far non-equilibrium', one naively assumes that the 'distance' from thermal equilibrium may be definable. The distance from thermal equilibrium, if it is quantified, is one of the essential parameters that specify the turbulent plasmas.

The turbulence and transport can change much faster than global parameters, after an abrupt change of heating power [1]. A new theory, showing that the heating power directly influences the turbulence, has been proposed [2, 3]. In this theory, the new control parameter, $[\partial P_{heat} / \partial p] a^2 / \chi_{\mathrm{N}}$, i.e., the rate of change in *velocity* space, quantifies the thermodynamical force. Here, P_{heat} is the heating power density, p is the plasma pressure, a is the plasma radius (characteristic scale length of spatial gradient), and χ_{N} is the turbulent thermal diffusivity. The turbulent transport increases when the heating power is switched on, if $\partial P_{heat} / \partial p > 0$. The newly introduced controlled parameter, , does illustrate the additional distance of departure from thermal equilibrium.

The direct influence of the plasma heating on the nonlinearly-excited long-range fluctuations as [2]

$$I = \frac{1}{1 - \Gamma_h} I_0 \quad , \qquad (1)$$

where I is the normalized density of fluctuation energy of interests, and the control parameter

$$\Gamma_h = \frac{\gamma_h}{\chi_N k_\perp^2} = \frac{\delta P}{\delta p} \frac{1}{\chi_N k_\perp^2} \qquad (2)$$

is the counter part of the parameter (9) in the fluid modelling, and I_0 is the mean intensity in the absence of the heating effect. Note that the normalizing time $\chi_N^{-1} k_\perp^{-2}$ depends on the correlation length of the fluctuation of the interest. This dependence causes the additional timescale mixing through cross-scale nonlinear interactions. The control parameter and Γ_{heat} is proportional to the heating power (if other parameters are common). Before the changes of pressure and its gradient happen, the turbulent intensity increases after the onset of heating if near $\gamma_{\mathrm{h}} > 0$.

The relation (2) shows that the impact on fluctuation intensity becomes stronger as the heating power increases. Experimental observation has also shown that the increment of fluctuation intensity and jump in the hysteresis increase more rapidly than the increment of heating power [1]. Equation (2) is in qualitative agreement with experimental observation. However, Eq.(2) shows a singularity at $\gamma_h \sim \chi_N k_\perp^2$, although the singularity does not appear in experimental observations.

This singularity is resolved by considering the nonlinear damping of the excited mode. Following the Kadomtsev's argument in [4], the evolution of the fluctuation intensity follows the equation

$$\frac{\partial}{\partial t} I = -\left(\gamma_{damp} - \gamma_h\right) I - \omega_2 I^2 + \varepsilon \qquad (3)$$

where $\gamma_{damp} = \chi_N k_\perp^2$ is the damping rate of the fluctuation (in the absence of heating effect), the term $\omega_2 I^2$ denotes the damping rate by self-nonlinear effect, and ε is the spontaneous excitation as was deduced in [3]. The mean energy density and the spontaneous emission term is related as $\varepsilon = \gamma_{damp} I_0$, which gives the stationary solution Eq.(2) in the limit of small fluctuation amplitude. Equation (3) gives the stationary solution as [5]

$$I = \frac{\Gamma_h - 1 + \sqrt{\left(\Gamma_h - 1\right)^2 + 4 I_0 \omega_2 \chi_N^{-1} k_\perp^{-2}}}{2 \omega_2 \chi_N^{-1} k_\perp^{-2}} \; . \qquad (4)$$

In the limit of small Γ_{h}, Eq.(2) is recovered. In the limit of stronger heating, $\Gamma_{\mathrm{h}} \gg 1$, one has

$$I \sim \gamma_h / \omega_2 \; . \qquad (5)$$

This result resolves the singularity in Eq.(2). The transition from Eq.(2) to Eq.(5) takes place near $\Gamma_{\mathrm{h}} \sim 1$.

The phenomena of hysteresis in gradient-flux relation are important in understanding experimental observations [1]. In addition, the hysteresis in transport relation will introduce rapid response in burning plasmas. More emphasis on study of the phase space dynamics is necessary for the understanding of turbulent plasmas.

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[1] Inagaki, S., et al.: Nucl. Fusion **53** (2013) 113006.
[2] Itoh, S. -I. and Itoh, K.: Sci. Rep. **2** (2012) 860.
[3] Itoh, S.-I. and Itoh, K.: Nucl. Fusion **53** (2013) 073035.
[4] Kadomtsev, B. B.: Plasma Turbulence (Academic Pres, New York, 1965)
[5] Itoh, K. and Itoh, S.-I.: Plasma Fusion Research (2015) in press.