§16. Immediate Influence of Heating
Power on Turbulent Plasma Transport

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Recently, it has been discovered that the turbulence and transport change much faster than global parameters, after an abrupt change of heating power [1]. A new theory of plasma turbulence has been proposed, showing that the heating power directly influences the turbulence [2]. New mechanism, that an external source couples with plasma fluctuations in phase space so as to affect turbulence, was pointed out. In this theory, the new control parameter, \([\partial P_{\text{heat}}/\partial p]a^2/\chi_N\), i.e., the rate of change in velocity space, quantifies the thermodynamical force. Here, \(P_{\text{heat}}\) is the heating power density, \(p\) is the plasma pressure, \(a\) is the plasma radius (characteristic scale length of spatial gradient), and \(\chi_N\) is the turbulent thermal diffusivity. The turbulent transport increases when the heating power is switched on, if \(\partial P_{\text{heat}}/\partial p > 0\).

The essence of the new mechanism that affects turbulence and turbulent transport in plasmas is illustrated. The distribution function is separated into the mean and perturbation as \(f = f_0 + \delta f\). The source in the phase space \(S\) naturally contains the component, which is coherent to the fluctuation of interest,

\[
S[f, x, v] = S[f_0, x, v] + \frac{\delta S[f_0, x, v]}{\delta f_0} \delta f + \cdots
\]

This new term represents the change rate of distribution function by heating, and it directly couples with and affects the fluctuations. This term jumps at the on/off of heating, so that the on/off of heating can immediately influence the fluctuation dynamics, without waiting the slower change of the mean \(f_0\).

In order to examine this new effect, we employ fluid-like equations in describing the turbulence in magnetically-confined inhomogeneous plasmas [3]. The external heating source, \(P_{\text{heat}}(x, t)\), is expanded as \(P_{\text{heat}}(x, t) = P_{\text{heat}}(x, 0) + \int_0^t \partial P_{\text{heat}}/\partial p \delta f + \cdots\). The amplitude of the long-range fluctuations, which are linearly-stable, is given as

\[
\left\{\psi_1, \psi_1\right\} = \frac{1}{1 - F\chi_N k_x^2} \left\{\psi_0, \psi_0\right\}_0
\]

where \(F = \partial P_{\text{heat}}/\partial p\) and \(\left\{\psi_0, \psi_0\right\}_0\) is the intensity in the absence of the effect of the heating.

The response of long-range fluctuations after the onset of heating power is analyzed [3]. Consider the case that the strong heating is turned on at \(t = t_0\), and the term \(\gamma_0\) is given as \(\gamma_0 = \gamma_{10} H\left(t - t_0\right)\), where \(H\left(t - t_0\right)\) is a Heviside function. The statistical average of fluctuation intensity is given as

\[
\left\{\psi_1, \psi_1\right\} = \exp\left\{-\frac{\chi_0 k_x^2}{1 - \gamma_{10}\chi_N} \gamma_0 (t - t_0)\right\} \left\{\psi_0, \psi_0\right\}_0
\]

\[
+ \frac{1 - \exp\left\{-\frac{\chi_0 k_x^2}{1 - \gamma_{10}\chi_N} \gamma_0 (t - t_0)\right\}}{1 - \gamma_{10}\chi_N k_x^2} \left\{\psi_0, \psi_0\right\}_0
\]

When the heating is turned-off at \(t = t_0\), \(\gamma_0\) is given as \(\gamma_0 = \gamma_{10} H\left(t_0 - t\right)\), and the evolution is given as

\[
\left\{\psi_1, \psi_1\right\} = \exp\left\{-\frac{\chi_0 k_x^2}{1 - \gamma_{10}\chi_N} \gamma_0 (t - t_0)\right\} \left\{\psi_0, \psi_0\right\}_0
\]

\[
+ \left(1 - \exp\left\{-\frac{\chi_0 k_x^2}{1 - \gamma_{10}\chi_N} \gamma_0 (t - t_0)\right\}\right) \left\{\psi_0, \psi_0\right\}_0
\]

The characteristic time \(\tau\) for the access to the new state is \(\tau^{-1} = \chi_0 k_x^2 - \gamma_{10}\) at the onset of heating, while it is given as \(\tau^{-1} = \chi_0 k_x^2\) after switching-off the heating. The latter is shorter than the former. The difference of the relaxation times at on/off of the heating is predicted to be observed. Figure 1 illustrates the evolution of turbulent transport in the heating power modulation experiment. There are two distinct time scales, i.e., that of the immediate response at the on/off of heating and that of the gradual evolution of global parameters. Hysteresis of flux-gradient relation appears owing to the direct and immediate influence of heating on the pressure-gradient driven turbulence.

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**Fig. 1: Immediate response of fluctuations at on/off of heating induces hysteresis in the gradient-flux relation.**

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