## §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, $[\partial P_{heat} / \partial p] a^2/\chi_N$, 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 $\chi_N$ is the turbulent thermal diffusivity. The turbulent transport increases when the heating power is switched on, if $\partial P_{heat} / \partial p > 0$.

The 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 $f = f_0 + \tilde{f}$. The source in the phase space $S$ naturally contains the component, which is coherent to the fluctuation of interest,

$$S\left[f; \boldsymbol{x}, \boldsymbol{v}, t\right] = \dot{S}\left[f_0; \boldsymbol{x}, \boldsymbol{v}, t\right] + \frac{\delta S\left[f_0; \boldsymbol{x}, \boldsymbol{v}, t\right]}{\delta f_0} \tilde{f} + \cdots$$

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, $P_{\mathrm{heat}}(x,t)$, is expanded as $P_{\mathrm{heat}}(x,t) = P_{\mathrm{heat}}(x,t) + \tilde{p}\, \partial P_{\mathrm{heat}} / \partial p + \cdots$. The amplitude of the long-range fluctuations, which are linearly-stable, is given as

$$\langle \varphi_1 \varphi_1 \rangle = \frac{1}{1 - F \chi_N^{-1} k_\perp^{-2}} \langle \varphi_1 \varphi_1 \rangle_0 ,$$

where $F \equiv \partial P_{\mathrm{heat}} / \partial p$ and $\langle \varphi_1 \varphi_1 \rangle_0$ 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 tem $\gamma_h$ is given as $\gamma_h(t) = \gamma_{h0} H(t - t_0)$, where $H(t - t_0)$ is a Heviside function. The statistical average of fluctuation intensity is given as

$$\langle \varphi_1 \varphi_1 \rangle = \exp\left(-\left(\chi_0 k_\perp^2 - \gamma_{h0}\right)(t - t_0)\right) \langle \varphi_1 \varphi_1 \rangle_0 + \frac{1 - \exp\left(-\left(\chi_0 k_\perp^2 - \gamma_{h0}\right)(t - t_0)\right)}{1 - \gamma_{h0} \chi_0^{-1} k_\perp^{-2}} \langle \varphi_1 \varphi_1 \rangle_0 .$$

When the heating is turned-off at $t = t_0$, $\gamma_h$ is given as $\gamma_h(t) = \gamma_{h0} H(t_0 - t)$, and the evolution is given as

$$\langle \varphi_1 \varphi_1 \rangle = \frac{\exp\left(-\chi_0 k_\perp^2 (t - t_0)\right)}{1 - \gamma_{h0} \chi_0^{-1} k_\perp^{-2}} \langle \varphi_1 \varphi_1 \rangle_0 + \left(1 - \exp\left(-\chi_0 k_\perp^2 (t - t_0)\right)\right) \langle \varphi_1 \varphi_1 \rangle_0 .$$

The characteristic time $\tau$ for the access to the new state is $\tau^{-1} = \chi_0 k_\perp^2 - \gamma_{h0}$ at the onset of heating, while it is given as $\tau^{-1} = \chi_0 k_\perp^2$ 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.

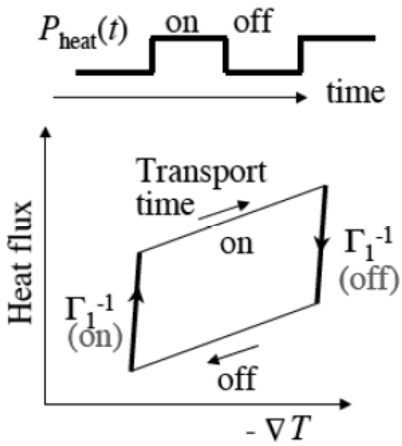


**Fig.1**: Immediate response of fluctuations at on/off of heating induces hysteresis in the gradient-flux relation.

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[2] Itoh, S. -I. & Itoh, K., Sci. Rep. **2** (2012) 860.
[3] Itoh, S.-I. & Itoh, K., Nucl. Fusion **53** (2013) 073035.