§14. Analysis Method to Study Dynamics of Turbulence-driven Transport in LHD

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For more than 20 years, dynamic behavior of magnetized plasma has indicated limitations of a local diffusive picture of transport in which the transport flux is expressed in terms of mean parameters and their spatial derivatives at the same location and achieved wide recognition during recent years [1]. More recently, a new spatiotemporal analysis of a dynamic response of plasma has been developed and new global hysteresis in the gradient-flux relation was discovered [2]. The heat flux is a multiple-valued function of gradient, so that the dynamics in the temperature perturbation is far from a simple diffusive response. This issue has a critical impact on the predictive capability of temporal evolution of future burning plasmas and thus should be clarified. We applied this analysis technique extensively to LHD experiments and the results made establish a research method of plasma turbulence transport.

We developed research methods of plasma turbulence transport associated with the non-local features. We observed the higher harmonics of the temperature perturbation induced by modulated electron cyclotron heating (MECH) on the LHD. The ECH modulation ($f_{\rm mod}$ = 25 Hz) is imposed on a low-density (n_0 = 1.35×10^{19} m^{-3}) NBI heated plasma (balanced injection of 2 MW) confined in LHD ($R_{\rm ax}$ = 3.6 m and $B_{\rm ax}$ = 2.75 T). The ECH power of 2 MW is absorbed in the central core $r_{\rm eff}/a_{99} \sim 0.2$, here $r_{\rm eff}$ is the effective minor radius and a_{99} is the minor radius in which 99% of the total stored energy is confined. We have applied the conditional averaging technique. In this procedure, the time of ECH-turn-off is detected in each period, and temporal evolutions of $T_{\rm e}$ for each time intervals are extracted and averaged. Figure 1 shows the conditional-averaged periodic modulation of $T_{\rm e}$. There are two distinct time scales. First is the very short time scale: The change of time derivative of $T_{\rm e}$ at the time of switch-off/on of ECH power propagates in radius very rapidly (white dash lines), approximately the radial propagation velocity of change in the long-range modes [3]. Second is much longer time scale: The propagation of $T_{\rm e}$ perturbation follows the slow propagation (a contour line of $\delta T_{\rm e}(r_{\rm eff},t)/\delta T_{\rm e,max}(r_{\rm eff})$ = 0.5 is chosen as a reference and shown as black dash lines), of the order of the global energy confinement time scale. One of conventional method estimates heat transport coefficients ($\chi_{\rm hp}$) from the response of the fundamental harmonics of the perturbation. However, it is found to be powerless because the conventional method does not consider "the two time scales" (i.e. hysteresis). The nonlinear feature associated with the hysteresis in gradient-flux relation should appear in the response of extremely-higher harmonics. The conditional averaging technique is a very powerful tool to observe the extremely-higher harmonics. After conditional averaging, the noise level is significantly decreased and thus the higher harmonics up to 10th harmonics are unambiguously observed. The heat wave is fitted to $\delta T \approx \Sigma \exp(-im\omega_0 t+ik_m r_{\rm eff})$, here m is the number of harmonics and $k_m = k_{m\rm r}+ik_{m\rm i}$. The real and imaginary parts of radial wavelength ($k_{\rm r}$, $k_{\rm i}$) of heat wave are estimated from radial dependence of the phase (θ) and amplitude (A), respectively ($k_{\rm r}=\partial\theta/\partial r_{\rm eff}$, $k_{\rm i}=\partial \ln A/\partial r_{\rm eff}$). Figure 2 shows that the dependence of $k_{\rm r}$ (and also $k_{\rm i}$) on the number of harmonics is qualitatively different from prediction by the diffusive model. The smaller $k_{\rm r}$ indicates the very fast radial propagation shown in Fig. 1 and this temporal response of temperature perturbation is owing to the hysteresis in the gradient-flux relation. This analysis method could be very useful to detect non-diffusive and non-local transport easily in many experimental devices.

1) S. Inagaki et. al., Phys. Rev. Lett. **107** , 115001 (2011)
2) S. Inagaki, et. al., Nucl. Fusion **53** , 113006 (2013).
3) S.-I. Itoh, K. Itoh, Sci. Rep. **2** , 860 (2012)

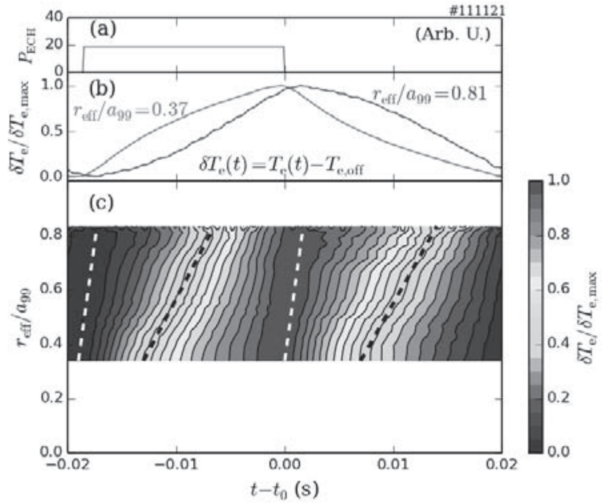

Fig. 1 Time evolution of ECH power (a), the temperature perturbation ($\delta T_{\rm e}/\delta T_{\rm e,max}$) at $r_{\rm eff}/a_{99}$ = 0.51 (b) and spatiotemporal evolution of $\delta T_{\rm e}$ (c)

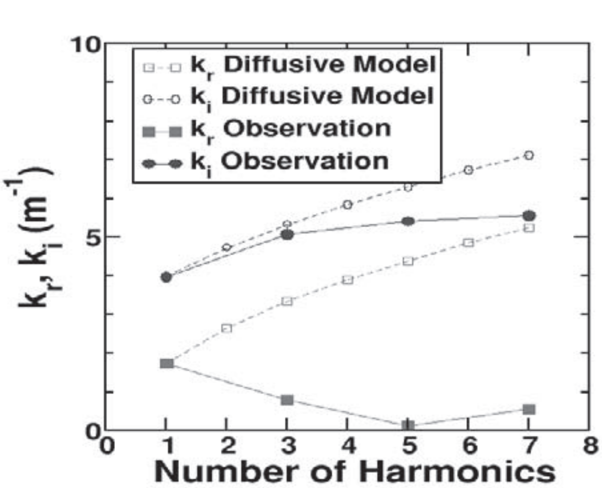

Fig. 2 Real and imaginary part of radial wave number of the heat wave.