EXPERIMENTAL IDENTIFICATION OF COEXISTING LOCAL AND NON-LOCAL TURBULENCE

[1,2]N. KENMOCHI, [1,2]K. IDA, [1]Y. MIZUNO, [1,2]T. TOKUZAWA, [1]R. YASUHARA, [1]H. FUNABA, [1,2]H. UEHARA, [3]D.J. DEN HARTOG, [1,2]I. YAMADA, [1,2]M. YOSHINUMA, [1,2]Y. TAKEMURA, [1,2]H. IGAMI, [1]R. YANAI, [1]T. TAKEUCHI

[1]National Institute for Fusion Science, Toki, Gifu 509-5292, Japan.
[2]The Graduate University for Advanced Studies, SOKENDAI, Toki, Gifu 509-5292, Japan.
[3]Wisconsin Plasma Physics Laboratory, University of Wisconsin-Madison, Madison, WI 53706, USA.

Email: kenmochi.naoki@nifs.ac.jp

This study identifies the coexistence and distinct roles of local and non-local turbulence, providing novel insights into plasma transport: (i) Non-local turbulence acts as a mediator, enabling rapid spatial propagation of perturbations throughout the plasma, while local turbulence accompanies temperature gradient. (ii) The observed power-law relationship between heat pulse velocity and pulse duration highlights the critical role of deviations from equilibrium in driving non-local transport. These findings deepen our understanding of the interplay between turbulence and transport, illustrate how local perturbations (i.e. edge-localized modes (ELM)) can rapidly affect the entire plasma, and guide improvements in control strategies.

Understanding turbulent transport remains a fundamental challenge in magnetic fusion plasma research. Plasma transport cannot be fully explained by local diffusion models alone, as non-local transport involves rapid and extensive energy and particle flows that defy traditional approaches. Insights from simulations and theory have highlighted key mechanisms such as turbulent self-diffusion, avalanche processes driven by turbulence-gradient interactions, and multiscale coupling of turbulent structures facilitated by mediators. As these phenomena occur simultaneously on multiple spatial and temporal scales, detailed multiscale observations and analyzes are required to achieve a comprehensive understanding.

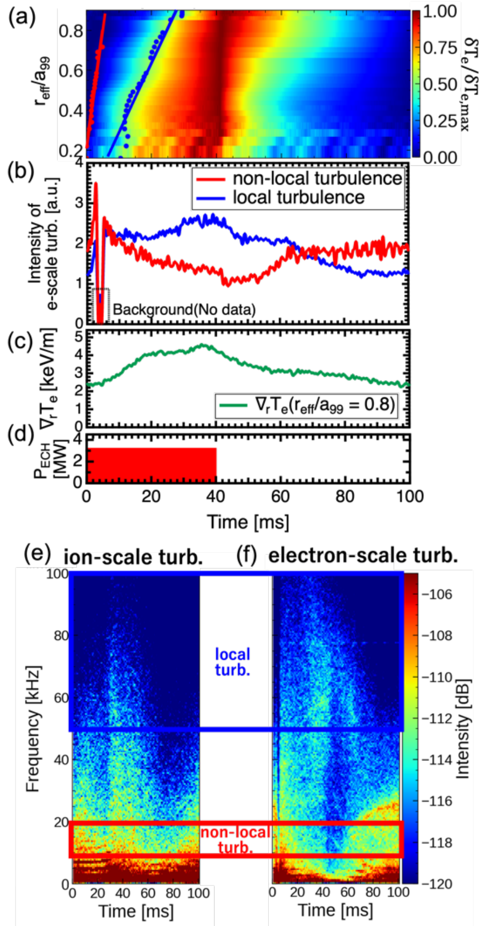

Figure 1. (a)Time evolution of the T_e profiles measured by the electron cyclotron emission with the variation normalized between 0 and 1. Time evolution of (b) non-local turbulence(red), local turbulence(blue) of electron scale turbulence measured by back-scattering, and (c)radial gradient of electron temperature(T_e) at the same measurement position r_{eff}/a_{99}=0.8, respectively. Note that no electron-scale turbulence data were detected during the t = 2.5-5 msec, as the measurement beam was not injected for background measurement. (d)Time evolution of ECH injection power. The non-local turbulence is excited immediately after the start of heating, while the local turbulence synchronized with the T_e gradient.

Time evolution of frequency spectrum for (e) ion-scale turbulence and (f) electron-scale turbulence measured by the reflectometer and the back-scattering measurement, respectively.

The existence of local and non-local turbulence can be seen in both ion and electron scale turbulence.

The modulated electron cyclotron heating (MECH) experiments systematically investigated the relationship between heat pulse propagation and turbulence dynamics by varying the duration of the electron cyclotron heating (ECH)[1]. The results revealed that shorter heat pulses propagate faster and exhibit non-local transport characteristics, whereas longer pulses propagate more slowly at velocities comparable to the local transport. Fig. 1(a) shows the time evolution of the normalized electron temperature profile ($\delta T_e/\delta T_{e,max} := (T_e - T_{e,min})/(T_{e,max} - T_{e,min})$) obtained by the electron cyclotron emission (ECE) measurement with the variation normalized between 0 and 1 using the conditional averaging technique with the duration of ECH as 40 ms. Herein, $T_{e,min}$ and $T_{e,max}$ are the minimum temperature and the maximum temperature in time at each location, respectively. Here, the electron cyclotron wave is absorbed around the magnetic axis of $r_{eff}/a_{99} = 0$, and the heat propagates from near the magnetic axis to the peripheral region. Fig. 1(a) includes a linear fit of $\delta T_e/\delta T_{e,max}$= 0.03(red) immediately after heating and that of $\delta T_e/\delta T_{e,max}$ = 0.5(blue) at half the temperature rise, indicating the presence of a component with non-local transport properties that propagates at high speed immediately after heating. Figs. 1(e) and 1(f) display the time evolution of the frequency spectrum of turbulence intensity on the ion-scale observed using a reflectometer and electron-scale observed using a back-scatter measurement, respectively. Figs. 1(b) and 1(c) show the time evolution of electron-scale turbulence intensity and radial T_e gradient at the same measurement position r_{eff}/a_{99}=0.8, respectively. As the heating time increases, two distinct turbulence components with different propagation characteristics are observed. These turbulence components shown in Fig. 1(b) are measured using a 90 GHz W-band millimeter-wave back-scattering measurement, and mainly includes the turbulent component of the electron scale. These two components exhibited different frequency ranges. The first was in the low-frequency range (10 - 20 kHz) and was excited immediately after heating begun, whereas the second was in the high-frequency range (50 - 100 kHz) and synchronized with the T_e gradient. Here, the low-frequency component of turbulence is called 'non-local turbulence', and the high-frequency component is called 'local turbulence' in this study. As shown in Figs. 1(e) and 1(f), both the ion-scale and the electron-scale turbulence measurements showed that non-local turbulence was observed in the low-frequency range, and local turbulence was observed in the high-frequency range. Fig. 2 shows the peak timings of the T_e gradient (green), the local-turbulence (blue), and the non-local turbulence (red) measured using the back-scattering measurement at each measurement position. The T_e gradient and the local turbulence propagated from the core to the peripheral region over a time period of about 10 ms. On the other hand, the non-local turbulence was excited almost simultaneously in the whole plasma region within 1 ms by spatial coupling. Based on the results of these experiments, we speculate that that ion-scale turbulence, characterized by lower wavenumbers, contributes to spatial coupling, while electron-scale turbulence rides on the ion-scale turbulence acting as a mediator.

The deviation from the equilibrium state is crucial in understanding the pulse propagation. By modulating radial heat fluxes through continuous pellet injection experiments in the LHD, robust transport results in a deeper transport potential, as the plasma rapidly returns to its original transport curve after perturbation. Studies across various plasma devices (JET, ISTTOK, TJ-II) highlighted the critical role of self-regulating mechanisms between plasma transport and density gradients. Recovery to equilibrium can be inferred from the speed at which the T_e gradient returns to normal, i.e., the propagation velocity of the heat pulse. The relationship of the timescale of heat pulses to the radial propagation velocity is investigated. Here, the timescale is defined as the interval from the pulse's initial rise to the peak of the pulse. The velocities of thermal pulses during the collapse of the electron internal transport barrier (e-ITB) obtained in the LHD [2] are also included in the investigation. The propagation velocity of the heat pulse (v) on a timescale of 1 ms to 100 ms shows a relationship of $v \propto s^{-1.06\pm0.05}$ with respect to its timescale (s). The smaller the timescale of heat pulses, the faster the velocity, which has an approximate power-law relationship. In this study, the propagation of short pulses considered out of equilibrium shows faster propagation compared to the transport scale. In contrast, the long pulses are close to the perturbation of the equilibrium state and shows slow propagation velocities at near transport speeds. These results suggest that non-local turbulence acting as a mediator in the plasma could mediate the rapid propagation of locally generated heat pulse owing to an increase in displacement from the equilibrium state.

By identifying the dual nature of turbulence and its rapid spatial coupling, these results shed light on why local perturbations can rapidly propagate and alter global behavior. Non-local turbulence enables near-instantaneous communication of perturbations between different regions, affecting overall plasma performance. Understanding this process provides a powerful guideline for controlling fusion plasmas, as deeper insight into non-local turbulence can significantly improve predictive capability and control in future devices.

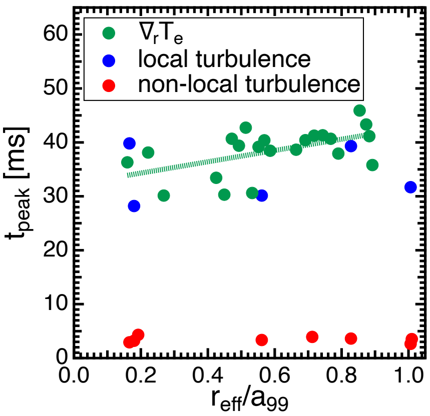

Figure 2. Peak timings of the temperature gradient (green), local turbulence (blue), and the non-local turbulence (red) measured using the back-scattering measurements at each measurement position. The T_e gradient and the local turbulence propagate from the core to the peripheral region over a time period of about 10 ms, while the non-local turbulence is excited almost simultaneously in the whole plasma region within 1 ms.

REFERENCES

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