EXPERIMENTAL IDENTIFICATION OF COEXISTING LOCAL AND NON-LOCAL TURBULENCE

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Abstract

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, observed in the low-frequency range, enabling rapid spatial propagation of perturbations throughout the plasma, while local turbulence, dominant in the high-frequency range, accompanies temperature gradient. (ii) The observed power-law relationship between heat pulse velocity and pulse duration highlights the critical role of deviations from steady state 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.

1. INTRODUCTION

A comprehensive understanding of turbulent transport remains a fundamental challenge in magnetic fusion plasma research, as numerous experimental processes cannot be fully accounted for by the local closure assumption, which often posits a simple proportionality between the heat flux (or turbulence amplitude) and temperature gradient. In many instances, the rapid and extensive flows of energy or particles extend beyond the scope of local diffusion models. These deviations are collectively referred to as "non-local transport" [1–4], which includes phenomena such as multiple flux-gradient relations (i.e., hysteresis of flux-gradient relation[2, 5]) and significant turbulence below the critical gradient leading to radial turbulence propagation (i.e., turbulence spreading[6–13]). Notably, experiments in the TEXT tokamak [14] and the Large Helical Device (LHD) [15] have shown that peripheral cooling can trigger a rise in the central temperature—an outcome difficult to explain using local transport models alone. Moreover, non-local transport can only be identified in the transient phase of perturbation experiments and not in the steady state.

Simulations and theory have shown that turbulent transport processes, including turbulent self-diffusion and avalanche-like events driven by turbulence-gradient interactions, occur at multiple spatial and temporal scales[5, 16–20]. These multiscale behaviors are often facilitated by "mediators," which link turbulent structures over extended regions[21–26]. The candidate mediators are macro/mesoscale turbulence[21, 24, 27–30], MHD[22] and zonal flows[4, 31–38]. In nuclear fusion research, recognizing and characterizing these dynamics are crucial for achieving stable, high-performance plasmas. For instance, boundary-region events, such as edge cooling or edge-localized modes (ELMs)[39, 40],can significantly influence transport and stability in the core, highlighting the need to consider broader scales and more complex interactions than those captured by purely local models. Consequently, deeper insights into non-local transport may reveal aspects of plasma dynamics that remain obscure within conventional local transport models, offering new strategies for plasma control, including optimal operational scenarios and enhanced confinement regimes.

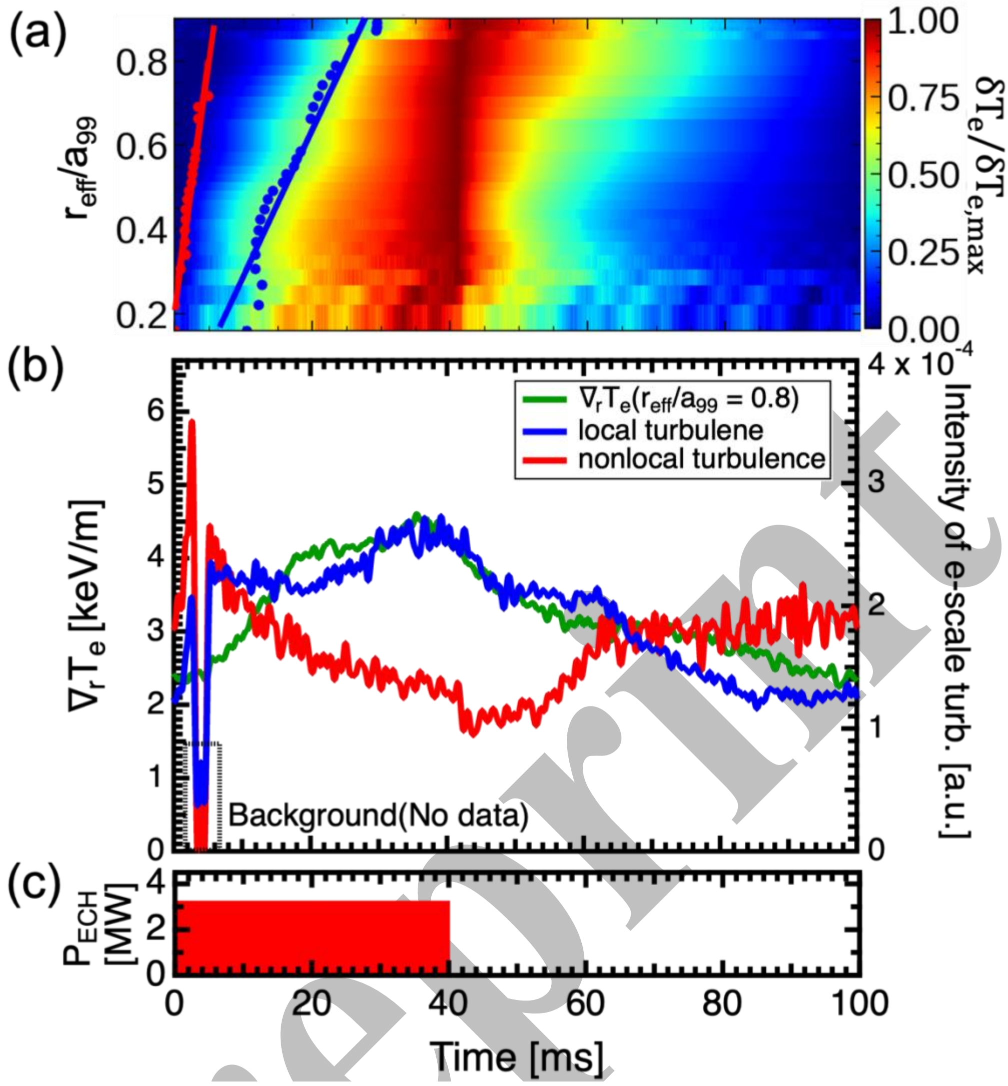

FIG. 1. (a)Time evolution of the T_e profiles measured by the electron cyclotron emission with the variation normalized between 0 and 1. Time evolution of (b) non-local turbulence(red), local turbulence(blue) of electron scale turbulence measured by backscattering, and radial gradient of electron temperature(T_e)(green) 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. (c)Time evolution of ECH injection power.

Despite the recognized significance of non-local transport, most existing studies have focused on observing or visualizing these phenomena, while neglecting the specific turbulence types involved and their interrelation with temperature and density gradients. In this study, we define local turbulence as turbulence primarily driven by the local temperature (and/or density) gradient, whereas non-local turbulence does not solely depend on these gradients and may propagate or couple across extended spatial scales. Although distinguishing between these two forms of turbulence is critical, the experimental and theoretical tools required for such a nuanced classification remain underdeveloped. Consequently, this study integrates dedicated diagnostic methods and analytical frameworks to define local and non-local turbulence separately and clarify the mechanisms and dominant factors driving non-local transport. We highlight the coexistence of local and non-local turbulence and clarify their distinct roles in plasma transport, providing valuable insights into the interplay between turbulence and transport.

2. RESULTS

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) in the LHD[41, 42]. 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)

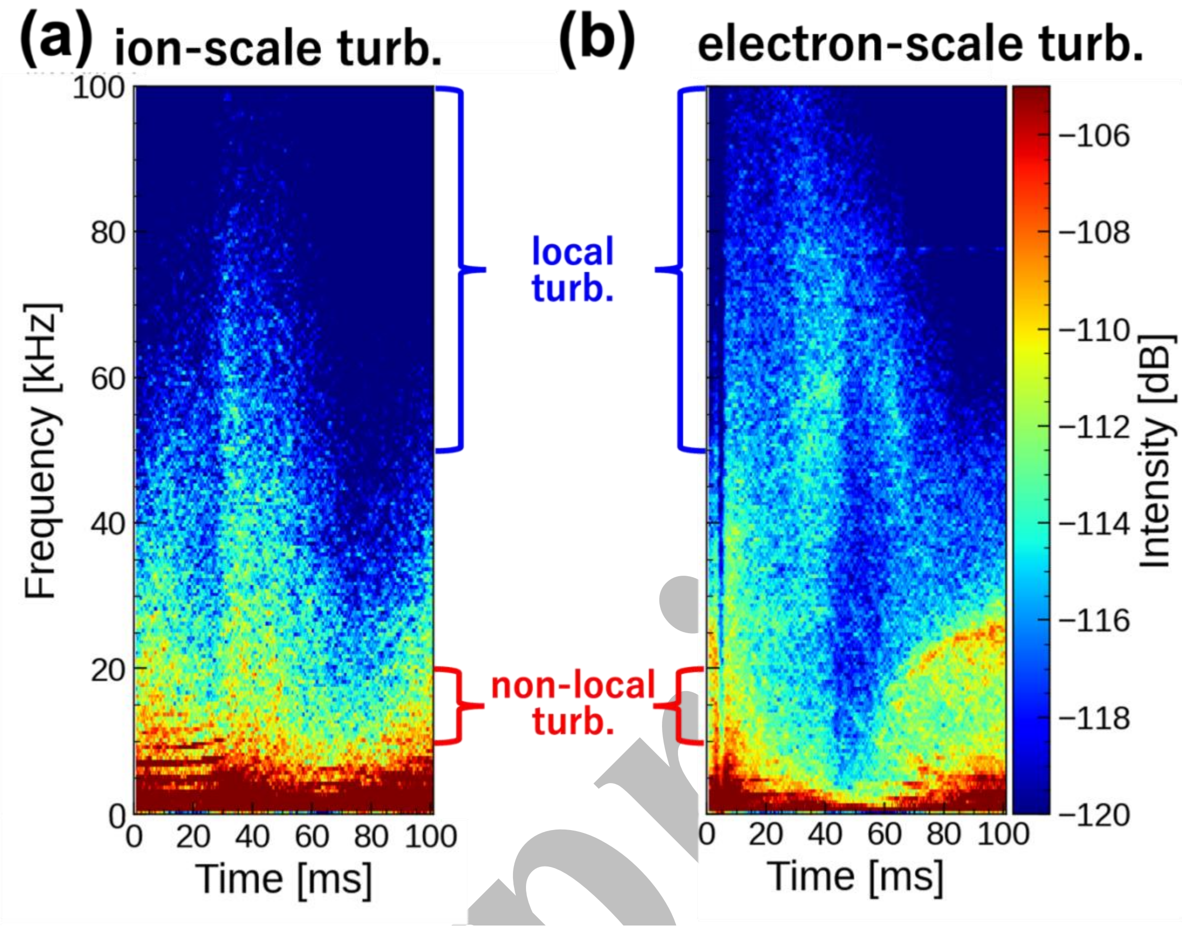

FIG. 2. Time evolution of frequency spectrum for (a) ion-scale turbulence and (b) electron-scale turbulence measured by the reflectometer and the backscattering measurement, respectively.

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. 2(a) and 2(b) 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 backscattering measurement, respectively. Figs. 1(b) shows the time evolution of electron-scale turbulence intensity and radial T_e gradient at the same measurement position r_{eff}/a_{99}=0.8. 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 backscattering 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. 2(a) and 2(b), 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. 3 shows the peak timings of the T_e gradient (green), the local-turbulence (blue), and the non-local turbulence (red) measured using the backscattering 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 low-frequency non-local turbulence facilitates spatial coupling and acts as a mediator.

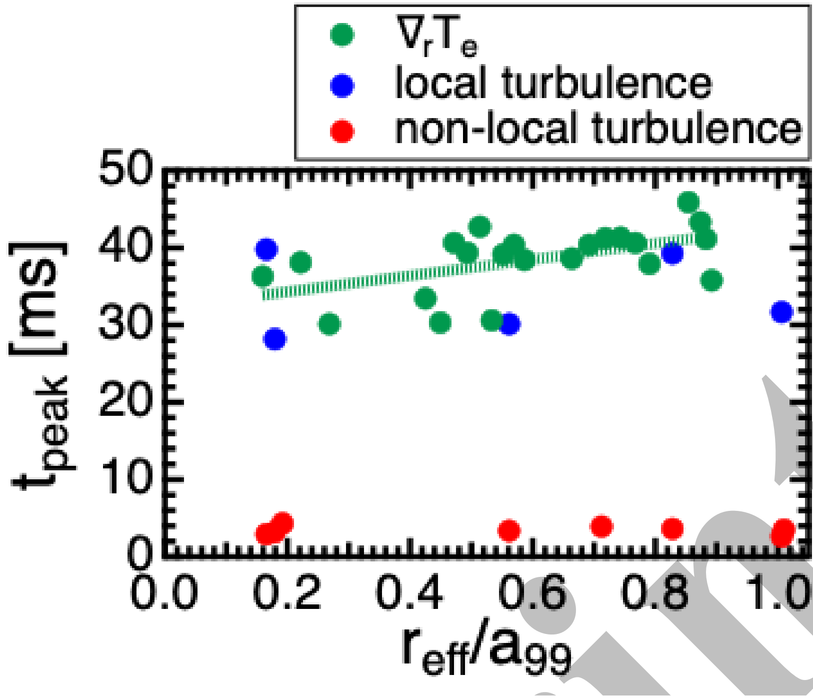

FIG. 3. Peak timings of the temperature gradient (green), local turbulence (blue), and the non-local turbulence (red) measured using the backscattering measurements at each measurement position.

3. DISCUSSIONS

The deviation from the steady 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 [43]. Studies across various plasma devices (JET, ISTTOK, TJ-II) highlighted the critical role of self-regulating mechanisms between plasma transport and density gradients [44]. Recovery to steady state can be inferred from the speed at which the T_e gradient returns to normal, i.e., the propagation velocity of the heat pulse. Fig. 4 shows the relationship of the time scale of heat pulses to the radial propagation velocity. 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 [45] 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 steady state shows faster propagation compared to the transport scale. In contrast, the long pulses are close to the perturbation of the steady 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 steady state.

4. SUMMARY

We experimentally identify that turbulence plays two coexisting, distinct roles—non-local (mediator) and local (gradient-following)—clarifying how it governs heat transport. In modulated ECH experiments on LHD using coordinated ECE, reflectometry, and backscattering diagnostics, we observed a low-frequency response that emerges quasi-simultaneously across radius within ~1 ms (non-local role) and a high-frequency response that tracks the evolving temperature gradient and propagates outward over ~10 ms (local role). Systematic variation of pulse duration revealed an approximate power-law between heat-pulse velocity and pulse timescale,
$v \propto s^{-1.06\pm0.05}$: short, out-of-steady-state pulses propagate faster and express the non-local role more strongly, whereas long pulses travel at speeds consistent with local transport.

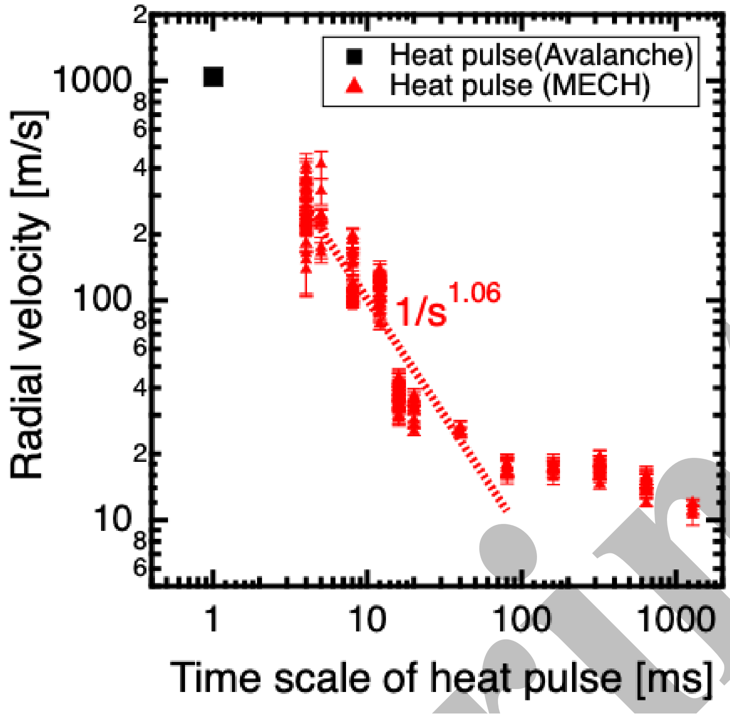

FIG. 4. The relationship of the time scale of heat pulses to the radial propagation velocity. The solid line shows the fitting results from t = 4 ms to 100 ms, and the dotted line shows the extrapolation of this straight line to 1 ms.

These findings explain how nominally local perturbations (e.g., ELM-like edge events) can rapidly reshape global behavior, motivate transport models that combine local closure with mediator-enabled coupling, and suggest a practical control handle: shaping pulse duration to regulate propagation speed. Applying these insights across regimes and devices should improve predictive capability and inform real-time strategies for sustaining high-performance confinement.

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