ID: 2697

Experimental identification of coexisting local and non-local turbulence

N. Kenmochi[1,2], K. Ida[1], T. Tokuzawa[1,2], Y. Mizuno[1], R. Yasuhara[1,2], H. Funaba[1], H. Uehara[1,2], D. J. Den Hartog[3], I. Yamada[1], M. Yoshinuma[1,2], Y. Takemura[1,2], H. Igami[1], R. Yanai[1] and T. Takeuchi[1]

[1]National Institute for Fusion Science, [2]The Graduate University for Advanced Studies, SOKENDAI,
[3]Wisconsin Plasma Physics Laboratory, University of Wisconsin-Madison

Email: kenmochi.naoki@nifs.ac.jp

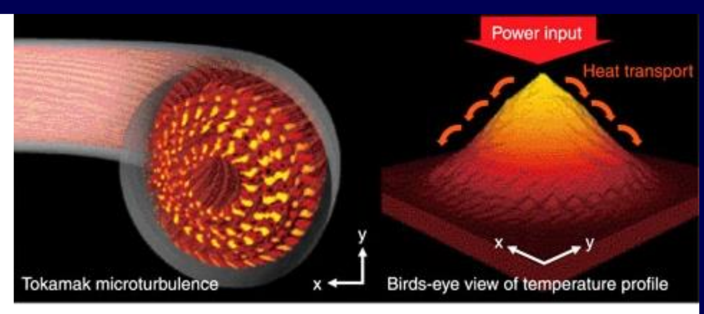
30th IAEA Fusion Energy Conference, 13-18 October 2025, Chengdu, People's Republic of China

ABSTRACT

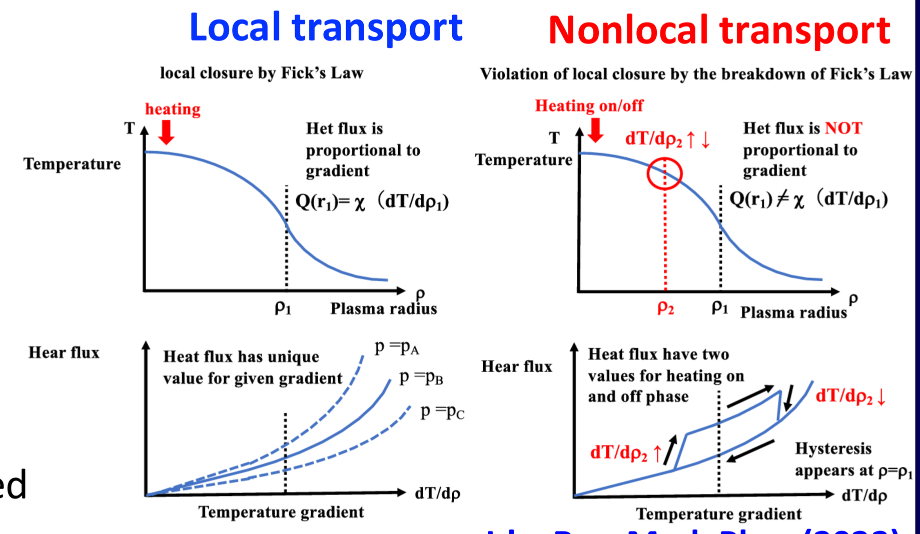
- ✓ This study identifies the coexistence and distinct roles of local and nonlocal turbulence, providing novel insights into plasma transport:
  - i. Nonlocal turbulence acts as a mediator, observed in the low-frequency range, enabling rapid spatial propagation of perturbations throughout the plasma, while local turbulence, dominant in the high-frequency range, accompanies temperature gradient.
  - ii. the propagation velocity and the intensity ratio of the nonlocal to local turbulence increase correspondingly, demonstrating the critical role of deviations from steady state in driving nonlocal 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.

BACKGROUND

- ✓ Understanding turbulent transport remains a fundamental challenge in magnetic fusion plasma research.
- ✓ Plasma transport cannot be fully explained by local diffusion models alone, as nonlocal 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.

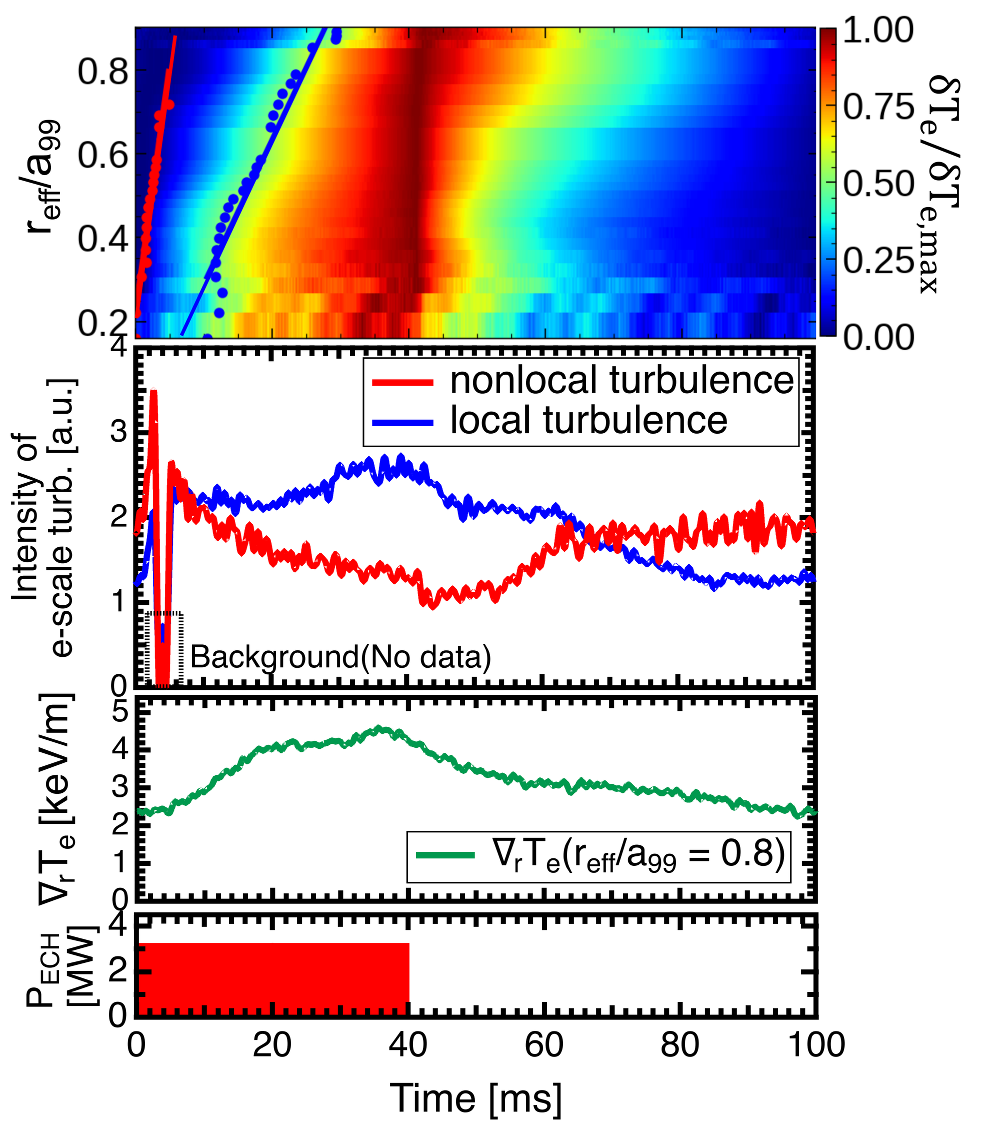


https://rdreview.jaea.go.jp/review_en/2011/e2011_3_10.html



Ida, Rev. Mod. Phys.(2022)

Observation of two turbulence components

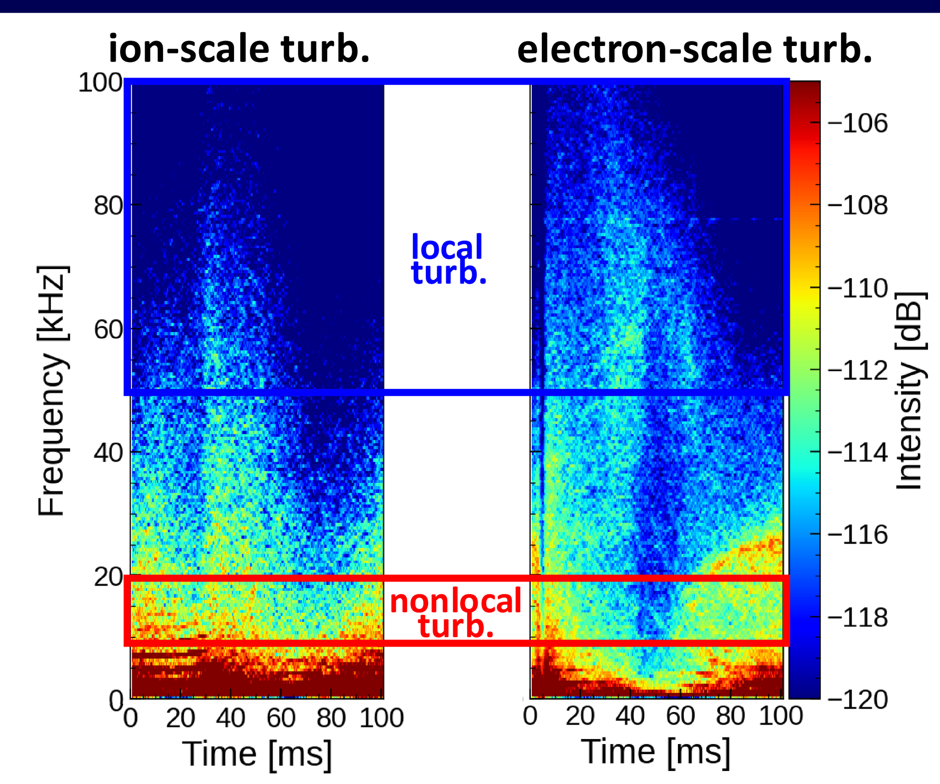


To systematically investigate **the effects of the time scale of turbulence and heat pulse on their propagation velocity**, the modulation ECH (**MECH**) **experiments were performed** in the LHD.

The time evolution of the electron temperature profile obtained by the ECE measurement with the variation normalized between 0 and 1 using the conditional averaging technique.

N. Kenmochi+Scientific Reports2024

Two components of turbulence with different frequency ranges

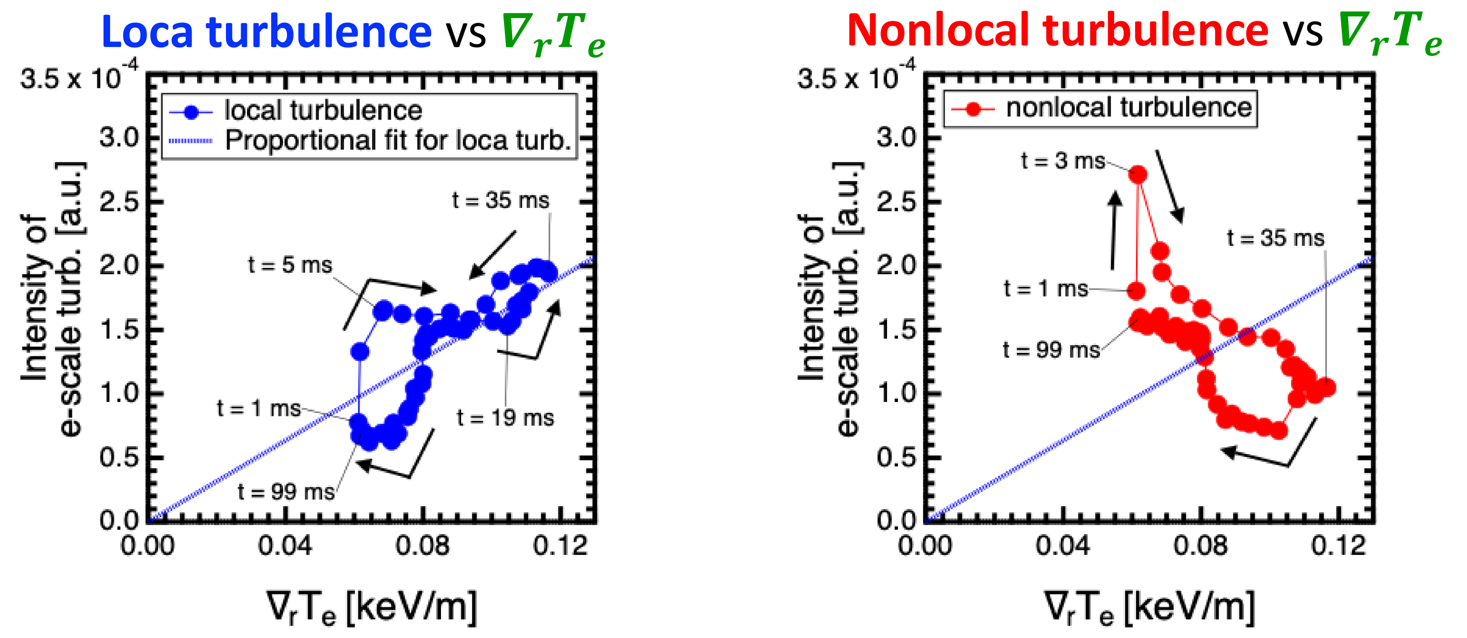


- ✓ **Local turbulence:** Exists in the high-frequency range (50 - 100 kHz) and propagates with **temperature gradients**.
- ✓ **Nonlocal turbulence:** Exists in the low-frequency range (10 - 20 kHz) and is excited immediately after heating begins. The turbulence designated nonlocal occupies a mesoscale frequency band comparable to that of the geodesic acoustic mode (GAM), consistent with mediator candidates proposed in prior studies.

CONCLUSION

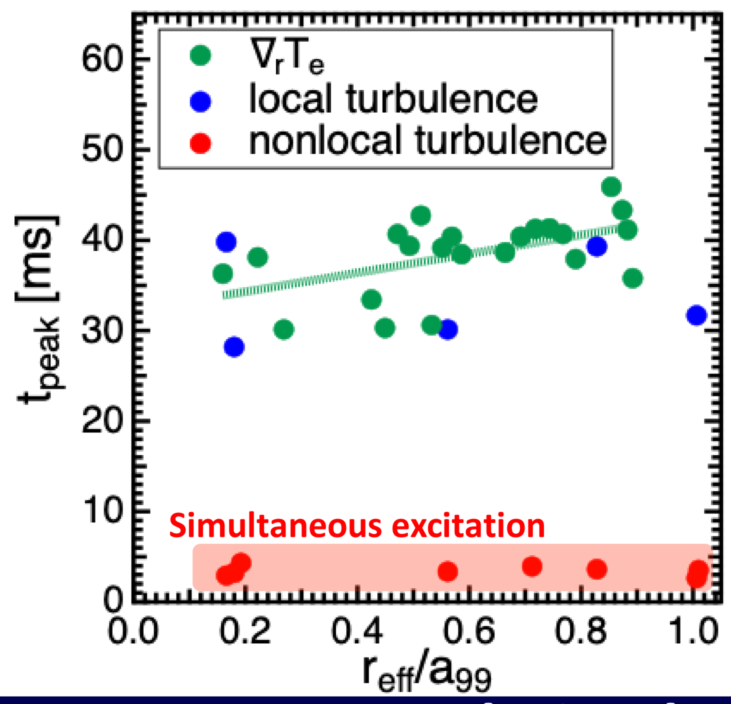
- ✓ High-frequency turbulence scaled with the temperature gradient, while low-frequency turbulence appeared independent of the gradient immediately after departure from steady state.
- ✓ By distinguishing gradient-driven local turbulence from gradient-independent nonlocal turbulence, we identified their coexistence and coupled roles in heat transport: local turbulence set the heat flux, whereas nonlocal turbulence mediated rapid spatial coupling.
- ✓ The heat pulse speed and duration followed $v \propto s^{-1.06}$, indicating that greater departures from steady state enhance nonlocal transport.
- ✓ Shorter pulses increased the nonlocal-to-local intensity ratio, with disturbances first carried by a fast nonlocal component and then by a slower local component.

Gradient scaling for turbulence intensity



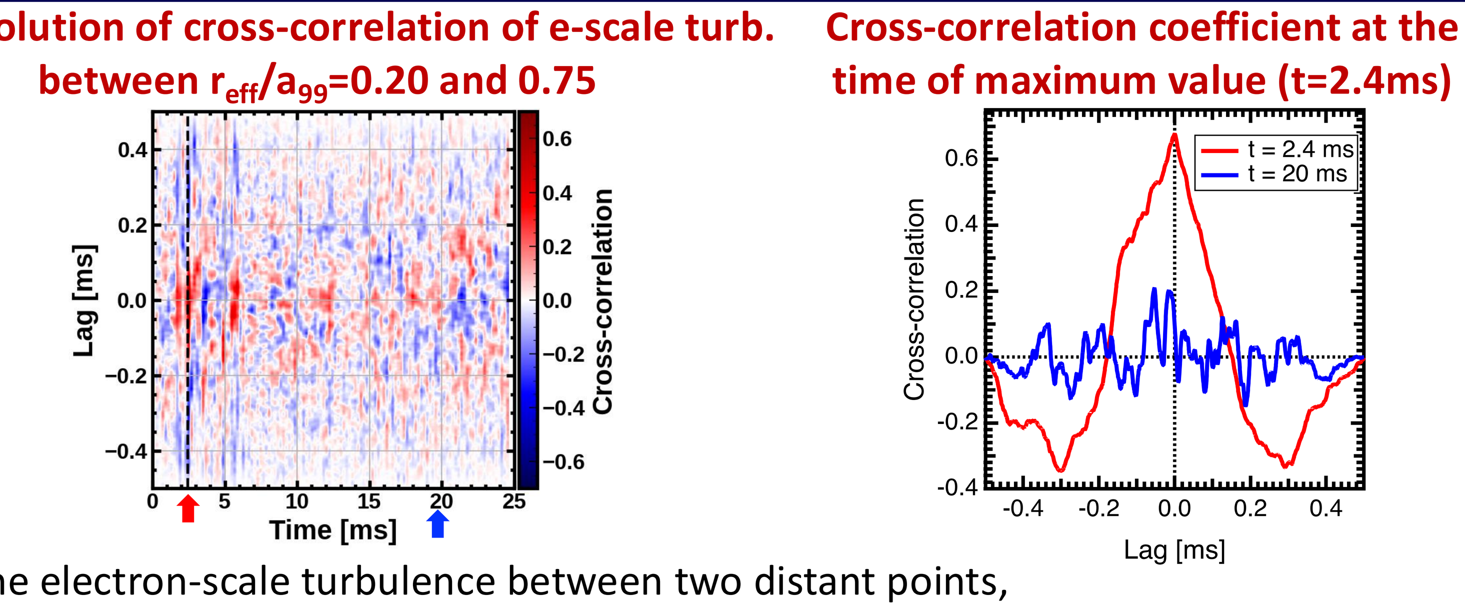
- ✓ Local turbulence exhibits a positive, approximately proportional correlation with the magnitude of the temperature gradient, whereas nonlocal turbulence shows no such positive correlation.
- ✓ This supports that local turbulence responds in concert with the temperature gradient.

Propagation characteristics of heat and two turbulence components



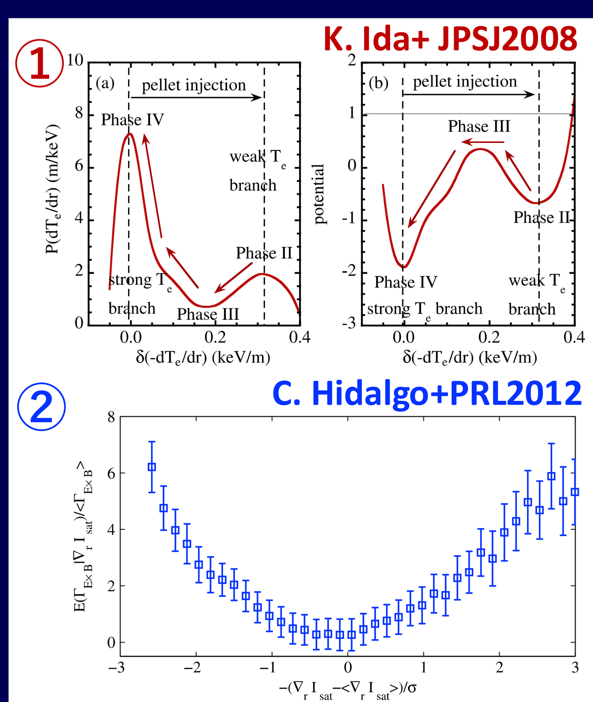
- ✓ $\nabla_r T_e$ and Local turbulence propagate from the core to the peripheral region over a time period of about 10 ms.
- ✓ The nonlocal turbulence is excited almost simultaneously in the whole plasma region within ~ 1 ms.
- ✓ It is suggested that nonlocal turbulence in the low-frequency range contributes to **spatial coupling** and **acts as a mediator**.

Strong cross-correlation between the e-scale turb. at two points immediately after heating begins



- ✓ In the electron-scale turbulence between two distant points, a strong correlation is observed immediately after heating begins.
- ✓ The time lag (which varies from event to event) is within 100 us.
- ✓ It is suggested that nonlocal turbulence acts as a mediator by interacting instantaneously in space immediately after heating begins.

Discussion: Deviation from the steady state

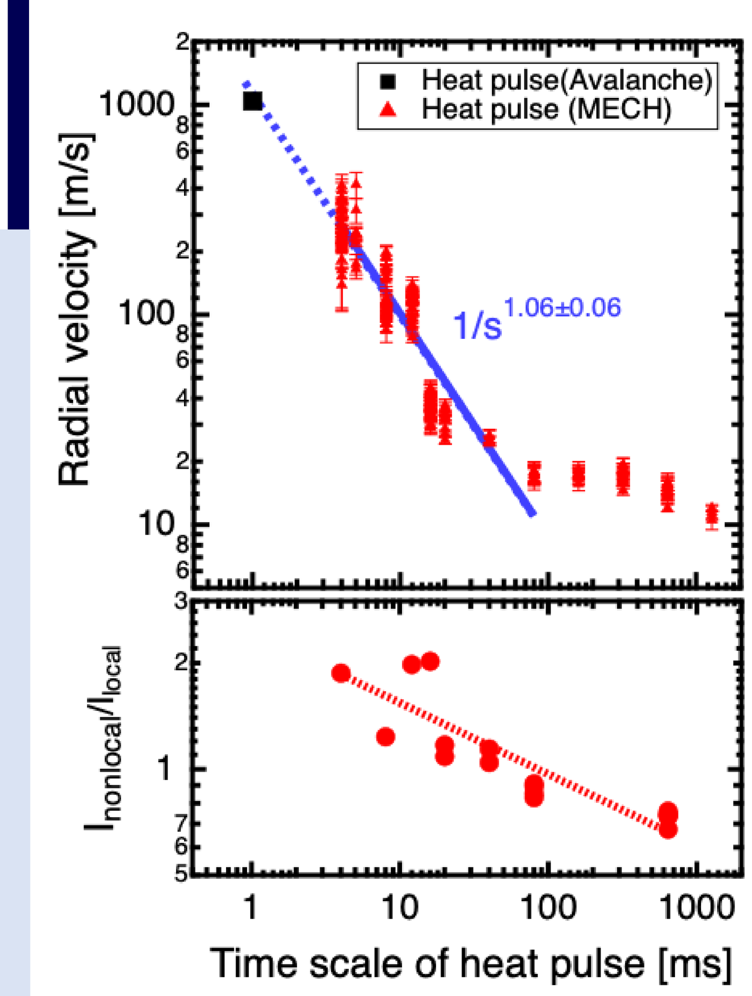


The deviation from the steady state is crucial in understanding the propagation of pulses.

① By modulation of radial heat fluxes by continuous pellet injection experiments in the LHD, when the transport is robust, the transport potential becomes deep because the plasma goes back to the original transport curve quickly after the perturbation.

② In the investigation of the dynamical coupling between density gradients and particle transport for the different tokamaks (JET, ISTTOK) and stellarator (TJ-II), the importance of a self-regulating mechanism between plasma transport and gradient in fusion devices has been pointed out.

Pulse Duration Controls Nonlocal Heat Transport & Turbulence Balance



- ✓ The heat pulse speed (v) and the pulse duration (s) obeyed $v \propto s^{-1.06}$, showing that the degree of departure from steady state controls nonlocal transport.
- ✓ The ratio of nonlocal to local turbulence intensity ($I_{nonlocal}/I_{local}$) increases as the pulse becomes shorter.
- ✓ Shorter pulses represent larger departures from steady state and coincide with a higher nonlocal contribution.
- ✓ Local and nonlocal turbulence coexist. Immediately after heating an early nonlocal component carries the pulse, and a later local component follows on the transport timescale.
- ✓ Reducing the heating duration shifts the balance toward the nonlocal component.
- ✓ Mediator structures in the plasma likely enable rapid spread of locally generated heat when the system is driven further from steady state.