Dynamic method to study turbulence and turbulence transport

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Conventional method has serious difficulty

\[ \chi_{hp} = -\frac{\partial q_e}{n_e \nabla T_e} \neq -\frac{q_e}{n_e \nabla T_e} = \chi_{pb} \]

Pulse Propagation

Lopes Cardozo PPCF 1995

Periodic power modulation

Discovery of the New Transport Relation on LHD

Conventional Approach

Single-Valued Function

One time-scale

Multiple-Valued Function (\(\rightarrow\) hysteresis)

Two time-scales
Contents

Method to study turbulence transport

- Assessment of conventional method (What is $\chi_{hp}$?).
- A simplified new approach to understand the transport with multiple-valued flux (hysteresis, barrier formation)

Method to observe multi-scale couplings of turbulence

- Observation of coupling of micro-fluctuations at distant locations
Exp. Set-up and Conditional Averaging

- Target plasma (NBI+MECH)
- Modulations of $T_e$, $\nabla T_e$ and fluctuation are observed simultaneously

![Graph showing $T_e$ vs. $n_e$ with no ITB, no ETB and no evidence of high-energy tail.]

![Diagram showing periodic temporal evolution of signals are precisely extracted.]

Periodic temporal evolution of signals are precisely extracted.
Precise spatiotemporal structure of heat pulse

The conventional $\chi_{hp}$ is flawed since it neglects two time scales in transient response.
Higher harmonics in the heat pulse propagation

The two-time scale feature should appear in the response of extremely-higher harmonics

(Conditional Averaged)

More-than 10th harmonics are observed even far away from source
Features of Higher harmonics

Weaker decay in amplitude
Faster propagation

Diffusion

\[ \frac{1}{A} \frac{A}{r} \sim \frac{\mu}{r} \sqrt{m} \]

Observations far from diffusive nature
Higher harmonics in the heat pulse propagation

Fundamental mode cannot catch the response around turn-on/off of ECH power where $q_e$ changes discontinuously.

To describe a discontinuous function, higher harmonics is essential.

Higher harmonics should be more routinely checked to clarify the transport with multiple-valued flux.
Heat pulse propagation during ITB transition

- ECH modulation experiment near the ITB transition
- The ITB foot shifts back and forth during ECH modulation

Delayed rises and simultaneous drops are observed

Similar to K. Ida NF 2009
Mixed time-scale phenomena

- Three or four dynamics combined
- Fast propagation, Displacement of ITB front, Global (non-local) response in $V T_e$

(Conditional Averaged)

ITB transition is involved with multi-mechanisms
Method to observe multi-scale couplings of turbulence

Non-locality of turbulence is one of the important keys to understand the multiple-valued flux (hysteresis and two time-scale response)
Cross Bi-Coherence of Fluctuations at Distant Locations

\[ b_{nl}^2 (f_1, f_2) = \frac{\langle \Phi^*(f_3, \rho_A) \Phi(f_1, \rho_B) \Phi(f_2, \rho_B) \rangle^2}{\langle |\Phi^*(f_3, \rho_A)|^2 \rangle \langle |\Phi(f_1, \rho_B) \Phi(f_2, \rho_B)|^2 \rangle} \]

\( \Phi(f_1, \rho_B), \Phi(f_2, \rho_B) \): Fluctuations at \( \rho_B \)

\( \Phi(f_3, \rho_A) \): Fluctuations at \( \rho_A \)

\( \rho_B - \rho_A \gg \) correlation length of micro-modes
Non-Local Micro-Global Coupling

- Summed bi-coherence shows a peak at 2.75 kHz
- The summed bi-coherence converges to 0.2 (~1/10 of the local summed bi-coherence)

$150 \text{ kHz} < f_1 < 250 \text{ kHz} \text{ at } \rho = 0.88$

Global fluctuation (2.75 kHz) at $\rho_A = 0.63$ non-locally couples with micro-fluctuations (150-250 kHz) at $\rho_B = 0.88$
Tri-Coherence analysis is just started

4-Wave coupling between distant locations

\[ f_1 + f_2 = f_3 + f_4 \]

Micro-Turbulence

Long-range modes

\[ \gamma_{\text{tri}}^2 > 0.1 \]

Tri-coherence at two distant locations is calculated
Summary

This study established methods for analyzing (i) heat transport dynamics beyond Fick’s law and (ii) ‘non-local’ coupling of micro-fluctuations.

- Conditional averaging technique is very useful to understand the transport with multiple-valued flux

  Hysteresis in transport = two-time scale response
  = Slow decay and fast propagation of the higher harmonics

  Identification of three or four time-scale responses in the ITB plasma

- Non-local bi-/tri-spectrum analysis allows us to study the non-local coupling between micro-fluctuations

These results are beneficial for understanding of the plasma dynamics in future fusion reactors.
Non-Local Micro-Micro Coupling

Tri-coherence suggests:
- Micro-fluctuations (>50 kHz) at two different locations are coupled
- Global-fluctuations (<10 kHz) are involved

Like-scale couplings e.g. 102 kHz + 101 kHz → 99 kHz + 103 kHz