Radial heat propagation studies using the Transfer Entropy in TJ-II and W7-X

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In this work, we study the outward propagation of electron temperature perturbations, generated in Electron Cyclotron Resonance Heated (ECRH) discharges in the TJ-II [1] and W7-X stellarators. For this purpose, we apply an advanced analysis technique, the Transfer Entropy [2], to radially distributed local Electron Cyclotron Emission (ECE) measurements. The Transfer Entropy (TE) is directional and capable of distinguishing outward from inward propagating perturbations, thus affording greater clarity of results than common techniques, such as the correlation.

The location of the magnetic surfaces is known with a high precision in both TJ-II and W7-X due to excellent external control of the magnetic field, thus allowing the study of the interaction of heat transport with the magnetic surfaces.

TJ-II - Fig. 1 shows the outward propagation of a spontaneous T_e fluctuation, originating in the core ECRH power deposition region. In principle, such propagating pulses allow extracting information about heat transport, and the new TE technique greatly facilitates exploiting this phenomenon.

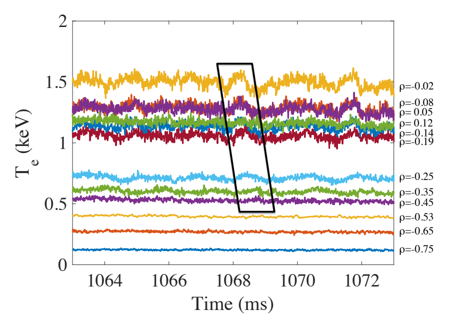

Fig. 1 - Propagation of spontaneous heat pulse

To study the impact of the magnetic configuration on heat transport, a iota scan was performed, cf. Fig. 2. In every configuration, a number of shots were made, analyzed using the TE, and results were averaged to obtain statistically significant results [1]. Fig. 3 shows just a few illustrative cases. The TE was calculated between a reference channel near ρ = 0 and the

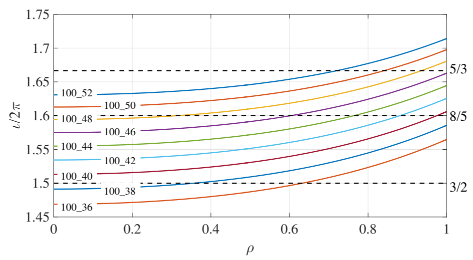

Fig. 2 - Rotational transform profiles

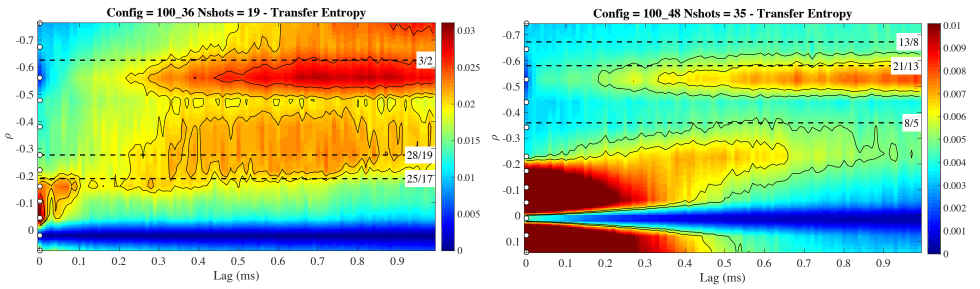

Fig. 3 - Transfer Entropy for two magnetic configurations. Horizontal lines indicate the location of rational surfaces. White dots indicate the location of ECE channels.

other channels. It therefore shows the outward propagation of the causal effect of fluctuations originating there. An outward 'plume' is visible, such that positions further outward tend to respond later than positions nearer to the core. However, propagation is not continuous: it tends to be delayed near specific radial locations (leading to long horizontal 'tails'), possibly associated with rational surfaces, and to 'jump over' other radial locations. Both effects seem difficult to reconcile with diffusive propagation.

Modulated discharges were also studied. Fig. 4 shows an example, comparing the results from a traditional Fourier analysis (showing the phase delay with respect to the

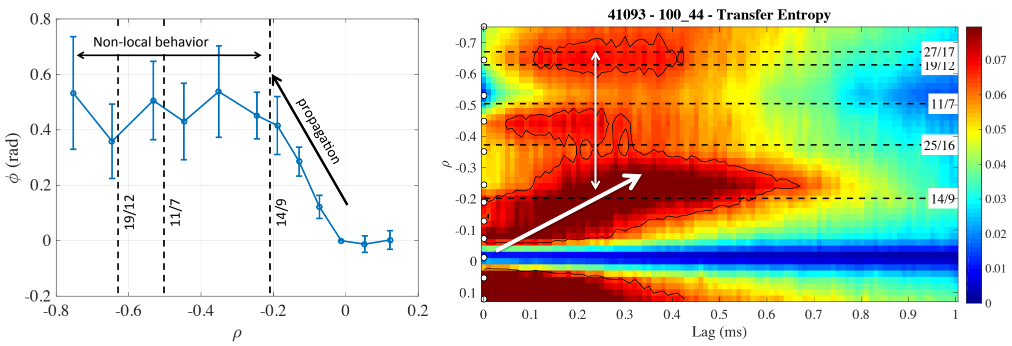

Fig. 4 - Analysis of modulated discharge. Left: Fourier technique; Right: TE

reference channel at the modulation frequency) to the TE. Results are similar in the sense that one both observes a region with outward propagation and a region with apparently non-local behavior.

In order to gain some insight into the interpretation of these observations, we performed simulations using a resistive MHD model, using parameters matching the experimental situation [1]. Once steady state was achieved, a heat pulse was introduced and its propagation observed, cf. Fig. 5. The heat pulse does not propagate in a continuous fashion but is detained near shear flow maxima (corresponding to mini-transport barriers), associated with rational surfaces. The TE also reflects this effect and in addition shows the non-local

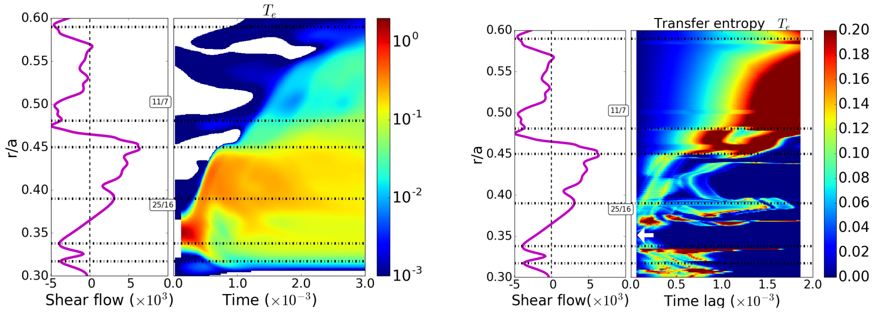

Fig. 5 - Simulation of a heat pulse in a resistive MHD model. Left: Heat pulse; Right: TE. The purple line shows the shear flow.

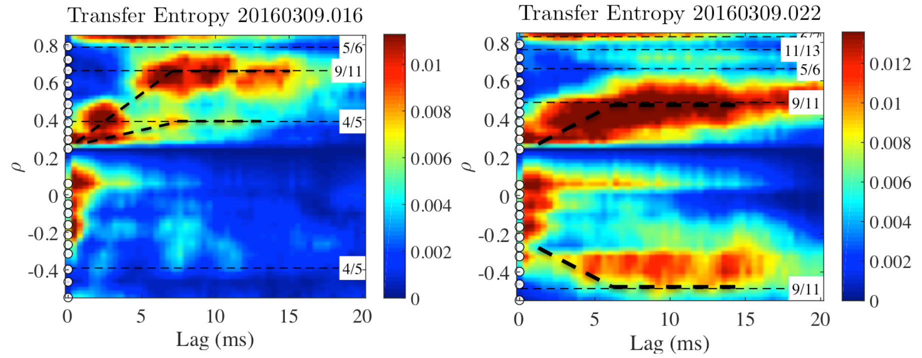

Fig. 6 - Transfer Entropy for two magnetic configurations. Horizontal lines indicate the location of rational surfaces. White dots indicate the location of ECE channels.

'jumping' effect also seen in the experimental results, understood to reflect MHD mode coupling effects.

W7-X - Similar studies were performed in W7-X. Fig. 6 shows the TE calculated for centrally ECR heated discharges with different magnetic configurations. The reference channel was taken close to ρ = 0.2 (immediately outside the power deposition region). A similar picture as in TJ-II emerges: one observes an outward propagating 'plume' that tends to be delayed near rational surfaces. Multiple such 'mini-transport barriers' are observed to exist simultaneously, and propagation is not smooth and continuous.

Again, a comparison was made with the traditional Fourier analysis of modulated discharges, cf. Fig. 7. Propagation was found to be stepwise and a possible relation to the location of the rational surfaces can be observed. In the off-axis heating case, the accumulation of TE near ρ = 0.6 may account for the 'bump' seen in the Fourier amplitude.

Simulations using the resistive MHD model with W7-X parameters, similar to those presented above for TJ-II, are in progress.

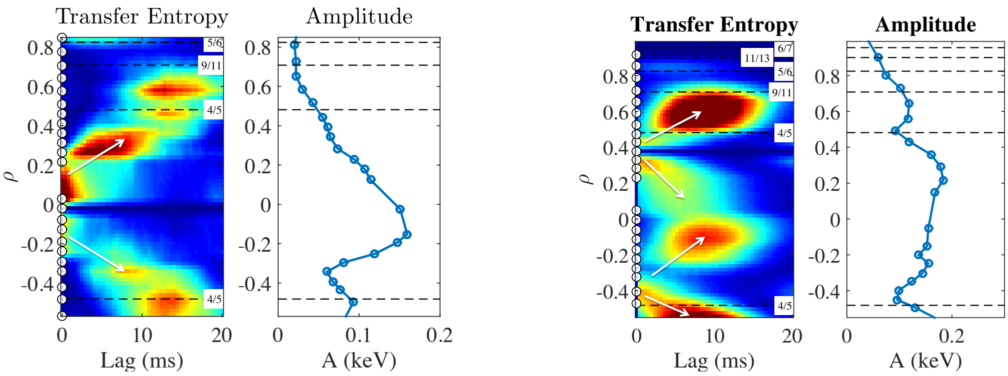

Fig. 7 - Transfer Entropy and Fourier analysis for modulated discharges. Left: central modulation. Right: off-axis modulation.

Conclusions - In this work, we have used the Transfer Entropy to study the propagation of heat pulses in both the TJ-II and W7-X stellarators. Transport does not appear to be smooth and continuous but occurs in a step-wise fashion. In the vicinity of major rational surfaces, 'trapping zones' tend to form where radial transport is slowed down (mini-transport barriers). In-between such trapping zones, transport tends to be faster than what would be expected from global estimates of the heat diffusivity, and we observe a 'jumping effect' by which locations further outward respond before intermediate locations do. Based on simulations using a resistive MHD code, we associate the 'trapping zones' with local flow shear maxima, while we ascribe the rapid radial transport (reminiscent of avalanches) to mode coupling effects.

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