The causal impact of magnetic fluctuations in slow and fast L–H transitions at TJ-II

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A statistical analysis of a large number of discharges with L-H transitions at the TJ-II stellarator shows that the presence of a low order rational in the plasma edge (gradient) region lowers the threshold density for H-mode access, cf. Fig. 1.

In this work, we will mainly focus on two magnetic configurations: (a) In configuration 100_35_61 ($\iota(\rho = 2/3) = 1.493$), the radial position of the $\iota = 3/2$ rational is located at $\rho \simeq 0.73$. This configuration is characterized by a 'slow' transition. The transition is not straight into the H phase, but rather into an I phase, characterized by Limit Cycle Oscillations (LCOs), as reported elsewhere [1, 2] and similar to LCOs reported at other devices [3]. (b) In configuration 101_42_64 ($\iota(\rho = 2/3) = 1.568$), the radial position of the $\iota = 8/5$ rational is located at $\rho \simeq 0.86$. In this case, the transition is 'fast' and enters directly into the H phase.

It is observed that low frequency MHD activity is systematically suppressed before or at the confinement transition, cf. Fig. 2. In the case of the 'slow' transitions, one observes a gradual decrease of MHD activity prior to the L–H transition, the decay starting some ten ms beforehand. In the case of the 'fast' transitions, the drop of RMS is rather sharp and lasts only a few ms, although one could still argue that the decay starts before the transition time. These results imply that the magnetic configuration and MHD activity interact with the L-H tran-
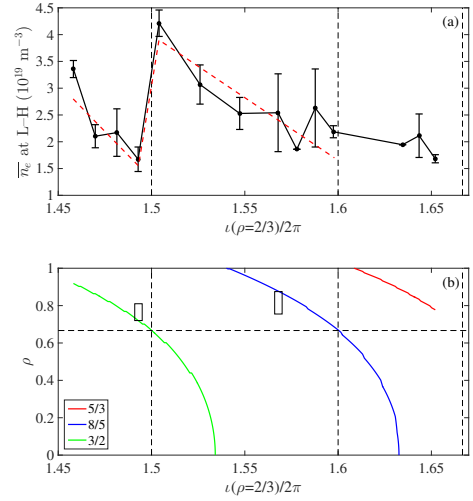

Figure 1: *Magnetic configuration scan (configurations identified via $\iota(\rho = 2/3)$). (a) Line average density at L–H transition. The red dashed line is provided to guide the eye. The bars indicate the shot to shot variation (not the measurement error). (b) Position of the main low order rational surfaces in vacuum. The horizontal dashed line indicates $\rho = 2/3$. The vertical dashed lines correspond to $\iota(\rho = 2/3) = 3/2, 8/5,$ and $5/3$. The two small rectangles indicate the approximate measurement locations of Doppler Reflectometry, as discussed in the text.*
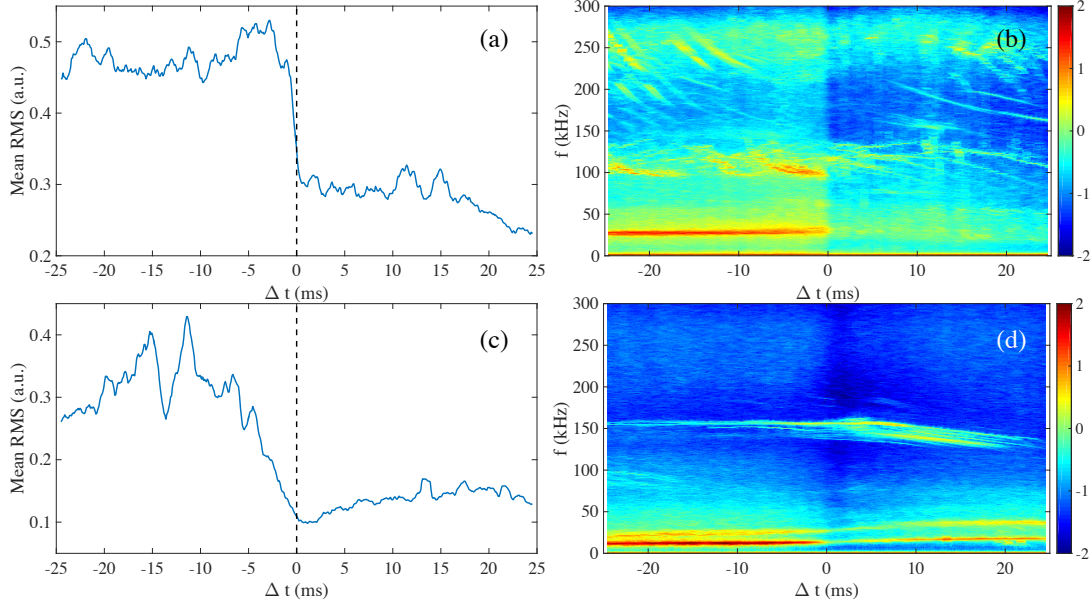
Figure 2: *Mean evolution of magnetic activity across confinement transitions. (a,b): Fast transitions, 90 discharges. (c,d): Slow transitions, 36 discharges. (a,c): mean RMS amplitude of a Mirnov coil. (b,d): mean spectrogram of a Mirnov coil.*

sition dynamics.

To clarify the direction of this interaction, we turn to a causality detection technique, the Transfer Entropy [4, 5]. The Transfer Entropy between signals Y and X quantifies the number of bits by which the prediction of a signal X can be improved by using the time history of not only the signal X itself, but also that of signal Y (Wiener's 'quantifiable causality'), and thus measures a directional 'information flow' from signal Y to signal X.

The interaction between magnetic fluctuations and Zonal Flows is probed using the signal from a magnetic poloidal field pick-up coil ($\dot{B}$) and the perpendicular rotation, $v_\perp$, measured by Doppler reflectometry.

Fig. 3 (left, a) shows the Transfer Entropy $T_{v_\perp \rightarrow \sigma(|\tilde{n}|)}$, reflecting the interaction between the perpendicular flow velocity and the density fluctuation amplitude, $\sigma(|\tilde{n}|)$, both measured by the reflectometer. The radii shown correspond to the I phase. The figure shows that the perpendicular velocity mainly has a causal impact on the density fluctuations in a period of about 30 ms after the L–I transition, in a specific radial range. In vacuum, the radial position of the $\iota = 3/2$ rational is located at $\rho \simeq 0.73$. Probably, the rational surface is shifted outward somewhat in the presence of the plasma with a small negative net current, and possibly coincides with the radial position at which the Transfer Entropy is showing a strong response ($\rho \simeq 0.74 - 0.79$). We note

that the locations and times of high Transfer Entropy coincide with the observation of LCOs in these same discharges [1], i.e., mainly after the L–I transition.

Fig. 3(left, b) shows the Transfer Entropy $T_{v_\perp \to \dot{B}}$, to study the interaction between the perpendicular flow velocity and the magnetic fluctuations, measured by a pickup coil. The Transfer Entropy is now only large in a time period of about 25 ms preceding the transition time. Thus, one may presume that the interaction between $v_\perp$ and $\dot{B}$ plays a role in gradually reducing RMS($\dot{B}$) prior to the 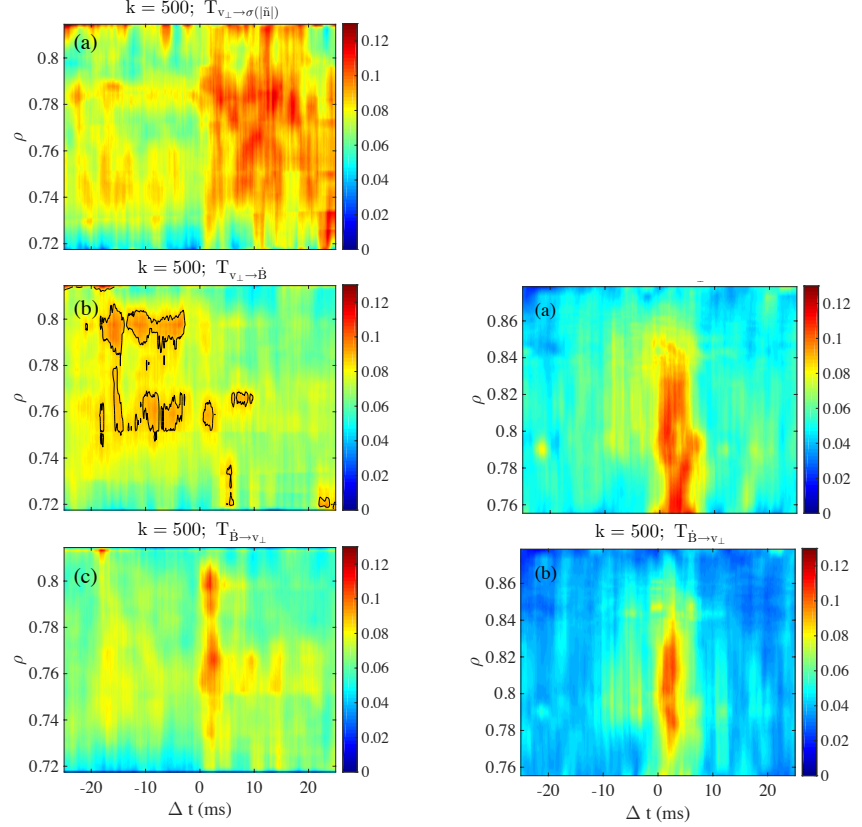transition, as shown in Fig. 2. There seem to be two predominant zones of interaction: one at $\rho \simeq 0.76$ and one at $\rho \simeq 0.8$. It should be noted that the radii in the L phase ($\Delta t < 0$) are somewhat smaller than indicated on the ordinate axes of the graphs (valid for the I phase, $\Delta t > 0$), so the actual radii are, respectively, $\rho_L \simeq 0.69$ and 0.76, bracketing the theoretical vacuum position of the rational surface (0.73). Thus, the Transfer Entropy suggests that the perpendicular flow affects the magnetic fluctuations at two radial positions, somewhat inside and outside of the $\ell = 8/5$ rational surface.

Figure 3: *Transfer Entropy. Left: Slow transitions ($\ell(\rho = 2/3) = 1.493$). (a) $T_{v_\perp \to \sigma(|\tilde{n}|)}$. (b) $T_{v_\perp \to \dot{B}}$. (c) $T_{\dot{B} \to v_\perp}$. Right: Fast transitions ($\ell(\rho = 2/3) = 1.568$). (a) $T_{v_\perp \to \dot{B}}$. (b) $T_{\dot{B} \to v_\perp}$.*

Further evidence of the interaction between velocity oscillations and magnetic fluctuations is shown in Fig. 3(left,c), showing $T_{\dot{B} \to v_\perp}$. The Transfer Entropy exhibits a short burst at the L–I transition time, at the same two radial locations as in Fig. 3(left,b). We note that the direction of the causality is reversed; here, the magnetic fluctuations are influencing the perpendicular

velocity fluctuations, precisely at the transition.

Similar observations were made for the fast transitions, cf. Fig. 3 (right). However, in this case the Transfer Entropy is sharply concentrated at the L–H transition. The temporal sharpness of the interaction between perpendicular velocity and magnetic fluctuations is likely related to the sharp decay of RMS($\dot{B}$) shown in Fig. 2 for this configuration. Probably, the rational surface is shifted inward somewhat in the presence of the plasma with a small positive net current, and possibly coincides with the radial position at which the Transfer Entropy is showing a response ($\rho \simeq 0.76 - 0.84$).

Thus, it is shown that magnetic oscillations associated with rational surfaces play an important and active role in confinement transitions, as they interact in significant ways with the perpendicular flow velocity (taken as a proxy for Zonal Flows). It is still unclear why the rational 8/5 leads to a 'fast' transition and the rational 3/2 to a 'slow' one, although the position and width of the islands associated with the corresponding rational and the local density gradient may play a role. This question is left to future work.

Acknowledgements

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