NOVEL EFFECTS OF EDGE-LOCALISED RMPS AND PLASMA DENSITY ON THE L-H TRANSITIONS AND TURBULENCE

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Understanding the low-to-high confinement mode (L-H) transitions is crucial for achieving H-mode access in ITER and advanced scenarios. Despite over 40 years of research, several significant questions remain unanswered, particularly regarding the roles of hidden variables and magnetic fluctuations [1-5]. This paper presents findings from the 2024 KSTAR experiments in the newly upgraded tungsten lower divertor to investigate density scans and edge-localized magnetic perturbations (ERMPs) [3,5]. Here, ELMPs have a preferential impact on edge localized modes (ELMs) in the edge plasmas, with the advantage of maintaining high core confinement [6], unlike conventional RMPs that can lead to instabilities like lock modes and core confinement degradation.

The experiments were done with the toroidal magnetic field B_T=1.9T, plasma current Ip=0.6MA, and neutral beam for the main plasma heating. Low single null (LSN) tungsten and upper single null (USN) carbon divertors respectively have favourable and unfavourable magnetic drifts.

The summary of the key findings are as follows. In LSN divertor, L-H transitions are temporally more variable with repeated L-H and H-L transitions compared with those in the previous carbon LSN diverter, likely due to enhanced impurities in the tungsten divertor. We identify the rollover density at which the power threshold takes the minimum value and elucidate the dual role of magnetic fluctuations in the L-H transitions and transport, depending on the plasma density. Furthermore, different power ramping scenarios lead to the scatters in the L-H transition power threshold, acting as a hidden variable, in agreement with the theoretical prediction [4].

In USN, ERMPs delay the L-H transition, suppress ELMs and coherent modes, and trigger the H-L transitions. However, when ERMPs are applied for a short duration in L-mode, they result in a more unstable H-mode compared with the H-mode achieved from plasma discharges without ERMPs in L-mode. Thus, ERMPs can induce hysteresis in plasma turbulence, making the plasma more unstable.

Density effects on the L-H transition power threshold and transport: Fig. 1 shows the power threshold P_{net} by using $P_{net} = P_{ohm} + P_{NBI} - \frac{dW}{dt} - P_{rad}$ where P_{ohm}, P_{NBI}, W, and P_{rad}, respectively, represent the Ohmic power, NBI power, plasma energy, and radiation loss power. The black and blue upper triangles, respectively, represent the power threshold for the L-H and H-L transitions in USN; the red and yellow lower triangles, respectively, represent the power threshold for the L-H and H-L transitions in LSN. Fig. 1 includes the three shots (in sky blue) that did not transition to the H-mode.

There are the four black upper triangles around $n_e \sim 2 \times 10^{19}$ m^{-3} from the USN discharges (#35638, #35640, #35641, #35643) which used different NBI power ramping scenarios including one or more stepwise increases and linear NBI power ramping at different ramping rates (0.3MW/sec, 0.45MW/sec). The highest power threshold was obtained with a large power step-up (#35638). In comparison, the smallest power threshold was obtained for #35643 with the smallest linear ramping rate of 0.3MW/sec. These results suggest that power ramping rates contribute to the uncertainty in the power threshold, acting as a hidden variable [4]. It is clearly seen that the power threshold is larger in USN compared with LSN. Furthermore, around $n_e \sim 2 \times 10^{19}$ m^{-3}, ERMP pre-emptive discharge #37404 has a slightly larger P_{net} than the conventional ERMP discharge #35641.

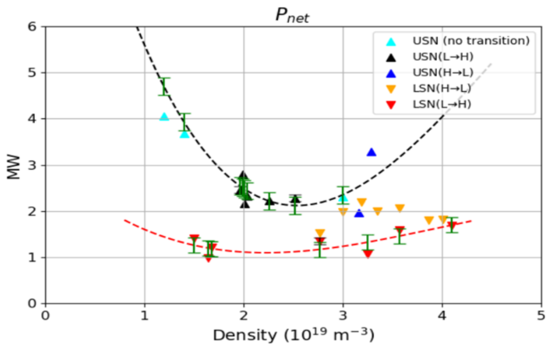

Fig. 1 Power threshold P_{net} for L-H and H-L transition at different densities in USN and LSN discharges.

Notably, magnetic fluctuations appear to play different roles depending on the density. In particular, in the low-density plasmas $n_e \lesssim 2 \times 10^{19}$ m^{-3}, broadband magnetic fluctuations are suppressed at the L-H transition while in the high-density plasmas $n_e > 2 \times 10^{19}$ m^{-3}, they are increased in the H-mode, correlated with the increasing density. It suggests that magnetic fluctuations play a passive role at the low density, suppressed by presumably ExB shear flows. In contrast, they play an active role at high density, increasing in the H-mode. Associated with this, at low density, toroidal angular momentum transport is efficient in the core plasmas with quite flat radial-profiles of toroidal rotation velocity. In comparison, toroidal shear varies over the L-H transition at high density. This could be due to the angular momentum transport reduction due to magnetic fluctuations (e.g., through the Maxwell stress) as well as high collisionality. In addition, coherent magnetic fluctuations tend to suppress instabilities like sawteeth or ELMs.

Effects of ERMPs in the USN plasmas: We conducted two experiments with the pre-emptive ERMPs (#37404) and conventional ERMPs (#35641) in USN where n=1 ERMP are applied in the L-mode and H-mode, respectively. For #37404, n=1 ERMP was on at time t=[5,6] secs while for #35641, ERMPs were on t=[10,12] secs in the H-mode. The left panel in Fig. 2 shows the time traces of Wmhd, Pnbi, Pohm, and density (from top to bottom) in black for 35641 and in red for 37404. These two discharges have similar plasma parameters up to t= 5 secs when the ERMP was turned on in #37404. ERMPs prevented #37404 from transitioning to H-mode while ERMP-free discharge #35641 underwent the L-H transition at t=5.2 secs. Shortly after the switch-off of ERMPs at t=6 secs, #37404 transitions to the H-mode at t=6.17 secs, followed by the H-L and L-H transitions.

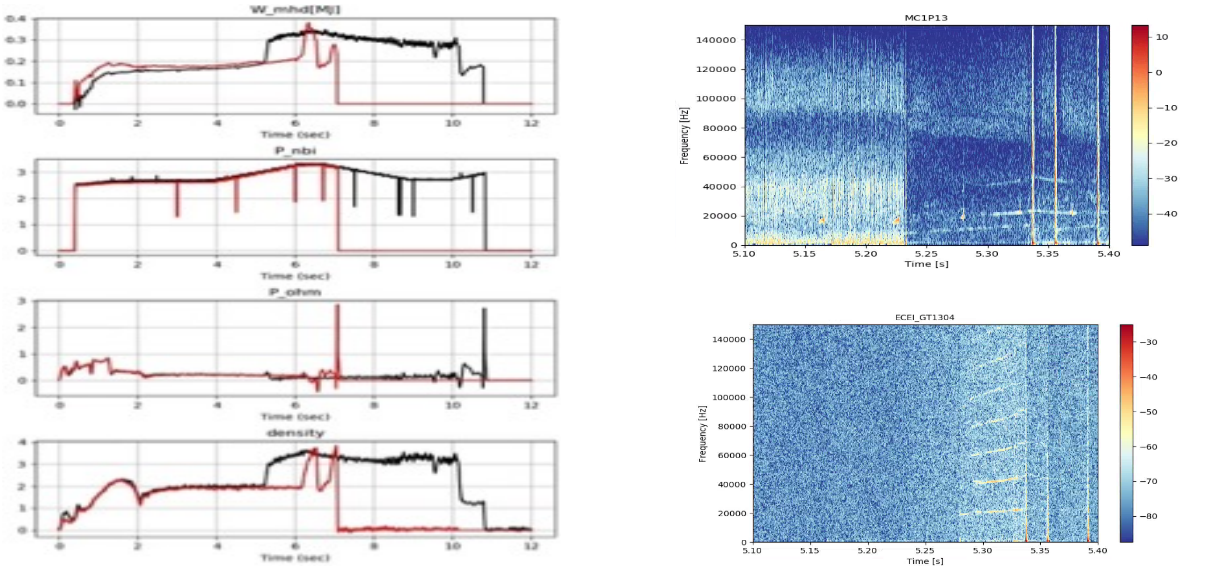

Fig. 2. (Left) Time-traces of plasma energy W, NBI power Pnbi, and Ohmic power Pohm in MWs and density for #35641 (black) and #37404 (red); (Right) Spectrograms of magnetic fluctuations (top) and electron temperature fluctuations (bottom).

In comparison, the conventional discharge #35641 maintains the H-mode for over 5 secs and transitions back to the L-mode shortly after the ERMP switch-on at 10 secs. Therefore, the pre-empt ERMP led to a more unstable H-mode, with larger ELMs killing off plasmas after the second L-H transition. Furthermore, Spectrograms of magnetic fluctuations and electron temperature fluctuations shows coherent modes at time t=[5.27, 5.33] secs in the H-mode for #35641 as shown in the right panel of Fig. 2. These coherent modes are suppressed by ERMPs. Thus, although the #35641 discharge did not have ERMPs at the time of the L-H transition at t= 6.12 secs, it ends up in a different H-mode state compared with #35641. Nevertheless, the maximum values of plasma energy and density are higher in this pre-empt ERMP discharge, suggesting high performance [7] even for a short time.
In summary, this paper highlights the importance of hidden variables (e.g., impurity, power ramping) and magnetic fluctuations in understanding the L-H/H-L transition. Also, our results reveal novel hysteresis and instabilities induced by ERMPs whose effects are multi-faceted and sometimes contradictory.

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