Experimental Investigations of the H-mode Access in Mixed Hydrogen-Deuterium Plasmas at ASDEX Upgrade

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In each stage of operation, ITER envisages H-mode access in plasmas of different hydrogen isotope mixtures. In order to reliably predict the H-mode access for ITER, it is of high importance to study the conditions for the transition from L- to H-mode in present day devices. Theoretical and experimental efforts have been undertaken in recent years to understand the underlying mechanisms which lead to the L-H transition. However, these mechanisms as well as the various dependencies of the H-mode power threshold (P_{LH}) have not yet been clarified unambiguously. For example, the dependence of P_{LH} on the main ion composition is not fully understood.

It has been observed in early isotope experiments that the H-mode power threshold scales inversely with the mass of the hydrogen isotope [1]. P_{LH} is increased by about a factor of 2 in pure hydrogen (H) compared to pure deuterium (D) plasmas. Experimental investigations, together with gyro-kinetic simulations, have shown that this is connected to increased turbulent edge transport in hydrogen compared to deuterium L-modes [2, 3]. Recent L- to H-mode transition experiments in mixed H-D plasmas at JET and AUG have shown that P_{LH} increases non-linearly with the relative hydrogen content ($n_{\mathrm{H}}/(n_{\mathrm{H}}+n_{\mathrm{D}})$) [4, 5]. This would not be expected intuitively from the simple mass scaling established in [1].

It is well known that the formation of the H-mode is connected to the presence of strong gradients in the edge ion and electron kinetic profiles. One of the most prominent paradigms leading to the L-H transition is the suppression of edge turbulence by $E \times B$ shear flows [6], which are present due to strong gradients in the edge radial electric field (E_r). In this contribution we investigate experimentally these different edge quantities at the L-H and H-L back transition in mixed H-D plasmas ($0 < n_{\mathrm{H}}/(n_{\mathrm{H}}+n_{\mathrm{D}}) < 1$) at AUG. For this, state-of-the-art diagnostics are employed, giving information about the ion and electron temperature, the electron density and the edge radial

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electric field. For more details on the different diagnostics used in this study the reader is referred to [7–13].

Several discharges featuring both L-H and H-L back transitions were performed, all with small step ECRH or NBI power ramps (up- and downwards) to pinpoint P_{LH} or P_{HL}, respectively. All discharges were in lower-single null *favourable* drift configuration (i.e. ion $\nabla B \times B$-drift points *towards* active X-point), had a plasma current of 0.8 MA, a toroidal magnetic field of -2.5 T at the geometric axis and $q_{95} \approx -5$. The discharges were fuelled feed-forward with different mixtures of D and H gas. The relative hydrogen content was monitored with a mass spectrometer, which delivers edge localized neutral particle fluxes for H and D [14]. Two series of discharges were performed targeting different L-mode density ranges: one around the density minimum of P_{LH}, which is at $\bar{n}_e \approx 4.0 \times 10^{19}\,\mathrm{m}^{-3}$ at AUG [15], and the other at $\bar{n}_e \approx 2.5 \times 10^{19}\,\mathrm{m}^{-3}$, which is in the low-density branch.

The transition into H-mode as well as the back transition were determined from the evolution of the edge plasma density and stored thermal energy as well as from magnetic and shunt current measurements. In this work P_{LH} (P_{HL}) is defined as the net input power, P_{net}, at the L-H transition (H-L back transition), where P_{net} is the sum of the total auxiliary heating power, accounting for the respective losses of its contributions and the Ohmic power minus corrections for changes in the stored thermal energy. Main chamber radiation was neglected, since it was found to be small and showed little variation among the different discharges. These definitions for the transition time point and power are consistent with previous work on L-H transitions described in [5, 15, 16]. The edge kinetic and E_r profiles were taken from stable L-mode phases, averaged over about 100 ms, directly before the L-H transition, while at the H-L back transition the dynamics were found to be faster, where time windows of about 5 ms length were investigated.

L-H and H-L Back Transitions at Density Minimum A comparison of P_{LH} in pure D and H plasmas could confirm that P_{LH} is about two times larger in H compared to D for the same plasma density (see Fig. 1). For the E_r-well at the plasma edge it was found that both the negative and positive E_r gradients were about the same strength in both D and H plasmas at the L-H transition, i.e. at different P_{LH}. Furthermore, the same minimum value ($E_{r,\mathrm{min}}$) and width of the E_r-well was found in both, H and D plasmas, confirming previous E_r measurements at AUG [16]. From the new measurements in pure D and H plasmas it was concluded that in these type of L-H transition plasmas at medium density the $E_{r,\mathrm{min}}$ value can be used as a proxy for its gradients [17].

As shown in Fig. 1, both P_{LH} and P_{HL} exhibit the same non-linear dependence on $n_{\mathrm{H}}/(n_{\mathrm{H}} + n_{\mathrm{D}})$ and start to increase towards the hydrogen level only for $n_{\mathrm{H}}/(n_{\mathrm{H}} + n_{\mathrm{D}}) > 0.6$. Although a hysteresis between P_{LH} and P_{HL} is absent if plotted against $n_{\mathrm{H}}/(n_{\mathrm{H}} + n_{\mathrm{D}})$, the H-L back transition always occurs at slightly higher plasma density compared to the respective L-H transition. Also the main chamber radiation is found to be slightly higher at the H-L compared to the L-H transition. If these two quantities were taken into account, then a small hysteresis would be visible.

Power balance calculations with ASTRA [18] and RABBIT [19] show that the total edge ion heat flux ($Q_{i,\mathrm{edge}}$) at the L-H transition follows the same non-linear behaviour with $n_\mathrm{H}/(n_\mathrm{H}+n_\mathrm{D})$ as P_LH (see Fig. 1b). On the other hand, $E_{r,\mathrm{min}}$ is found to be constant, at about $-11\,\mathrm{kV/m}$, independent of $n_\mathrm{H}/(n_\mathrm{H}+n_\mathrm{D})$ (see Fig. 1c). Thus, the measurements indicate that similar E_r gradients are reached for different H-D mixtures. Further analysis of a sub-set of L-H transition discharges with constant plasma density (n_e) revealed that the edge ion temperature gradient (∇T_i) is approximately the same at the L-H transition for different $n_\mathrm{H}/(n_\mathrm{H}+n_\mathrm{D})$. From these edge measurements together with the ion heat flux calculations, it could be concluded that the ion heat diffusivity $\chi_i = -Q_i/\chi_i n_i \nabla T_i$ must also increase non-linearly with $n_\mathrm{H}/(n_\mathrm{H}+n_\mathrm{D})$. For pure H and D plasmas this implies that $\chi_i(\mathrm{H}) \approx 2\chi_i(\mathrm{D})$, which is consistent with recent theoretical work [2, 3]. The increase of the L-mode edge transport with increasing H fraction could also explain the increase of P_LH with $n_\mathrm{H}/(n_\mathrm{H}+n_\mathrm{D})$.

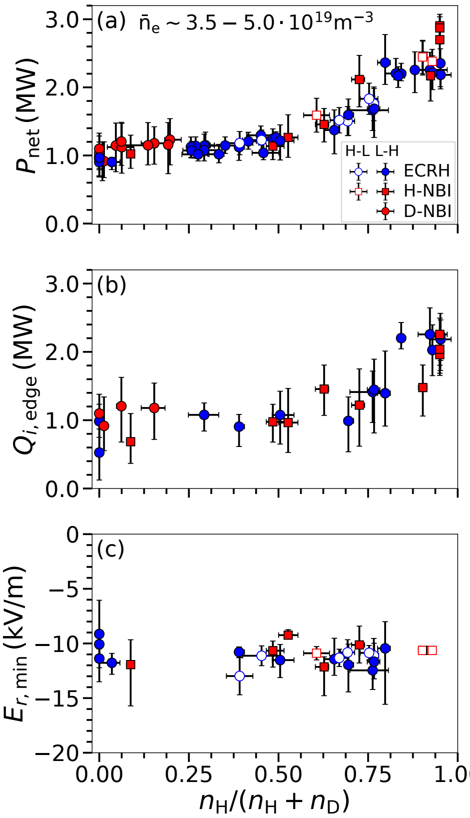

Figure 1: *(a) H-mode power threshold, (b) total edge ion heat flux and (c) minimum of the edge radial electric field plotted against the relative hydrogen content at the L-H (filled symbols) and the H-L back (open symbols) transition.*

Comparisons of edge profile measurements at the L-H and the H-L transition show that in the edge electron quantities there is no hysteresis present, in line with previous observations at AUG [20]. Also the $E_{r,\mathrm{min}}$ value is found to be the same directly before the H-L transition as it is before the L-H transition (see also Fig. 1c). This indicates that the same boundary conditions set both the L-H and the H-L back transition.

Low Density Branch In low density plasmas with $n_\mathrm{H}/(n_\mathrm{H}+n_\mathrm{D}) > 0.6$ no H-mode could be achieved, although the auxiliary ECRH power was increased up to 4 MW. However, in these plasmas in favourable drift configuration an I-mode-like confinement regime was discovered, which exhibits improved energy, but L-mode-like particle confinement. A similar regime has been observed previously at AUG in low density pure H plasmas [21]. An example of this I-mode-like regime is shown in Fig. 2. As can be seen in Fig. 2a-c both the electron and the ion edge temperature increase with increasing ECRH power, leading to an edge temperature pedestal, whereas the increase in edge density with ECRH power is only weak.

Also a weakly coherent mode (WCM) is observed, visible e.g. in density fluctuation measurements (see Fig. 2d). The frequency range of this WCM agrees with the one of WCMs observed in pure hydrogen I-modes in unfav. drift configuration [22].

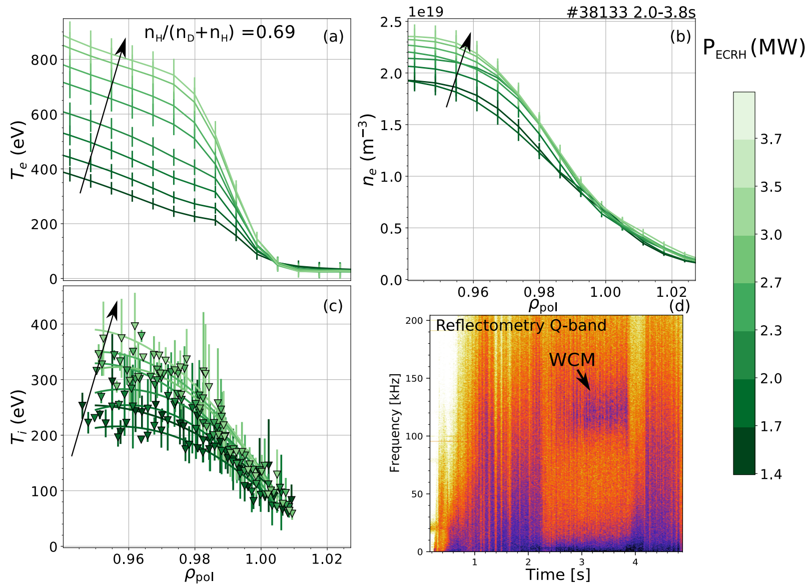

Figure 2: *Evolution of the edge (a) electron temperature (b) electron density (c) ion temperature and plotted against the normalized poloidal flux* ρ_{pol}*, with increasing ECRH power. (d) Evolution of the weakly coherent mode (WCM) within the I-mode regime.*

The existence of this regime in favourable drift configuration indicates that I-mode can exist as soon as access to H-mode is hindered, i.e. P_{LH} is high, and not only if the plasma is in unfavourable drift configuration. The observation of this regime in these specific conditions could help to guide theoretical work in order to understand under which circumstances a decoupling of energy and particle edge transport is possible.

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