L-H transition studies in hydrogen and mixed ion species plasmas in JET

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Introduction – H-mode operation is the scenario envisaged for future burning plasmas, but significant uncertainties remain for extrapolating the required power threshold to reach the L-H transition. Due to these uncertainties and the staged implementation of auxiliary heating in ITER the prognosis for accessing H-mode during non-active phases of operation remains unknown. By setting a minimum for the power crossing the separatrix, the L-H threshold is also directly linked to the impact of power exhaust requirements on the design for DEMO. Reducing the uncertainties for extrapolating the threshold is therefore critical for the design and success of future burning plasma experiments. Burning plasmas will operate with a deuterium-tritium fuel mixture, but there has been relatively little work in the area of mixed main ion species plasmas. We present results on the L-H transition threshold including a database covering L-H transitions in JET with an ITER-like wall (JET-ILW), where the threshold power was measured experimentally by slowly ramping the input power; results from dedicated scans of hydrogen-deuterium and hydrogen-helium mixtures; and comparisons between transitions in pure hydrogen and deuterium plasmas.

JET-ILW L-H Transition Database – A database composed of 192 L-H transitions in JET has been compiled including hydrogen (H), deuterium (D), and mixed ion species plasmas; nitrogen, neon, and helium seeding; B_t=1.8-3.4 T, I_p=1.7-3.2 MA, $\langle n_e \rangle \sim$1.5-5.0 $\times 10^{19}$ m^{-3};

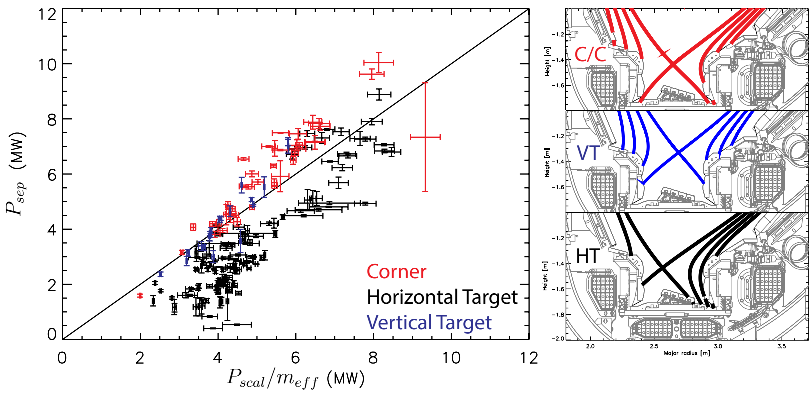

Figure 1: *Database of 192 L-H transitions in JET-ILW, plotted against scaling law prediction [1] modified to include mass dependence and colored by divertor configuration, pictured at right.*

several plasma magnetic configurations; and with ICRH and/or NBI heating. Figure 1 shows the result plotting the power crossing the separatrix against the predicted threshold for each case and the different divertor configurations. The scaling prediction is taken from Ref. [1], adding also an assumed $1/m_i$ dependence using measurements of the ratio between hydrogen and deuterium in the plasma such that $m_{eff} = 1$ for pure deuterium and 0.5 for hydrogen. The power across the separatrix is $P_{sep} = P_L - P_{rad}$. For, P_L, the thermal loss power, the time change in stored energy and estimated fast particle losses are subtracted from the sum of the ohmic and auxiliary input power. The radiated power, P_{rad} from within the separatrix is estimated from a bolometry array. Tomographic reconstructions have been performed for a subset of the data and the estimate for P_{rad} scales consistently with the available reconstructions, in some cases with a constant offset (<1 MW) depending on divertor configuration. While the radiated power was not subtracted from the database used in Ref. [1], it is necessary here due to correlation of P_{rad} with other parameters, such as ICRH input power. The data in Fig. 1 are colored according to the location of the outer strike point, whether on the horizontal target (HT), vertical target (VT), or in the 'corner' (C/C) near the pump throat. It is notable that VT and C/C have about the same threshold, which is roughly a factor of two larger than HT. VT and C/C have very different pumping characteristics and different X-point height, which are thought to cause changes in threshold on other experiments. There is more variation in the HT data set, since due to lower threshold value there has been more scope to vary parameters in experiments.

Dependence on heating method – Figure 2 shows results, all in fixed horizontal target outer strike point configuration, of the isotope effect and impact of heating method. In D, N=1 hydrogen minority heating was used for ICRH and N=2 majority was used in hydrogen. Considering only the ICRH data, the H and D data are roughly consistent with the $1/m_i$ scaling observed in many experiments, with the 50/50 mixtures about halfway in between. For JET-ILW we observed that the isotope dependence is stronger in the low density branch than the high density branch, unlike ASDEX-Upgrade where it was observed to be the same [2]. This results in the minimum of the dependence on density moving to higher values, from deuterium to 50/50 to hydrogen. There are also comparisons of NBI vs. ICRH heating for both pure D and H plasmas. For deuterium, there is little difference, but there is a larger difference, particularly in the low density branch, for hydrogen. Similar results were observed before in DIII-D [3]. The difference in threshold for NBI-heated plasmas can be as much as a factor for 4 between deuterium and hydrogen. Work is on-going to assess the role of edge rotation as in Ref. [3] and the partition between ion and electron energy fluxes, as in Ref. [4]. The ICRH scheme used for hydrogen was 2^{nd} harmonic majority hydrogen heating, which PION [5] simulations predict predominantly heats the ions. NBI heating calculations show that for a case at $\langle n_e \rangle \sim 3.3 \times 10^{19}$ cm^{-1}, close to the minimum threshold for NBI-heated hydrogen cases, that the power deposition was approximately equal between ion and electrons. Further transport analysis to clarify the explanatory role of the ion heat flux in these results is on-going.

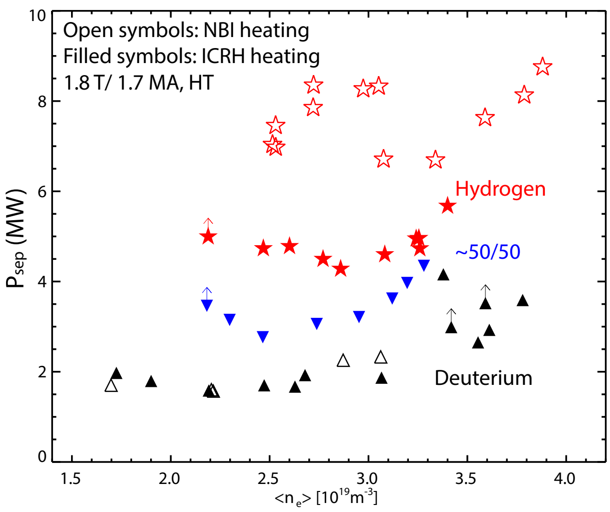

Figure 2: *L-H transition threshold in hydrogen, deuterium, and 50/50 mixtures. Filled symbols use ICRH heating only and open symbols use NBI heating only. Upwards arrows indicate L-mode pulses serving as lower bounds.*

Mixed ion species plasmas – Figure 3 shows the results of scans in concentration ratio in mixed hydrogen-deuterium and hydrogen-helium plasmas, all in fixed horizontal target magnetic configuration. The line-averaged density spans $3.1 - 3.8 \times 10^{19}$ m^{-3}, which is either in the high density branch or close to the minimum; due to the variation in density the data is normalized to the Martin scaling law. Some of the variation near 50/50 may be due to deviations in JET-ILW from the density dependence in the scaling law. We observe most change occurs either $H/(H+D) < 0.2$ or $H/(H+D) > 0.8$, while there is little change in between. This non-linear behavior differs from a simple $1/m_{eff}$ dependence. The strong variation at small concentration levels may indicate a role for ion-ion collisions between hydrogen and deuterium in mixed species plasmas, where the product of the isotope densities gives a parabolic dependence for the collision rate. PION simulations at the time of the transition have been performed for the H/(H+D) scan, which predict a non-monotonic dependence of the electron heat deposition, peaking at $H/(H+D) \sim 0.1-0.2$ and a monotonic increase in ion heating as the hydrogen fraction rises. Further transport analysis is on-going to clarify whether energy exchange can clearly dominate over the power deposition in all cases for these conditions, as is expected in the high density branch.

Based on the H/(H+D) scan, experiments were also performed with helium seeding into hydrogen plasmas. Similar to the H/D results, a large change in the threshold power was observed for small concentration values. The results are shown in Fig. 3. Due to operational concerns NBI heating was used instead of ICRH for the H/He plasmas, which is why there is a higher threshold even for the pure hydrogen cases. Helium-4 was used for the seeding gas, but there may have been $\sim 1\%$ helium-3 leftover from a previous experiment. Although there are only results from a limited number of pulses, the strong reduction of threshold power with helium seeding is very promising and could offer an avenue for lowering the power threshold during the non-active phase of ITER while maintaining a predominantly hydrogen plasma.

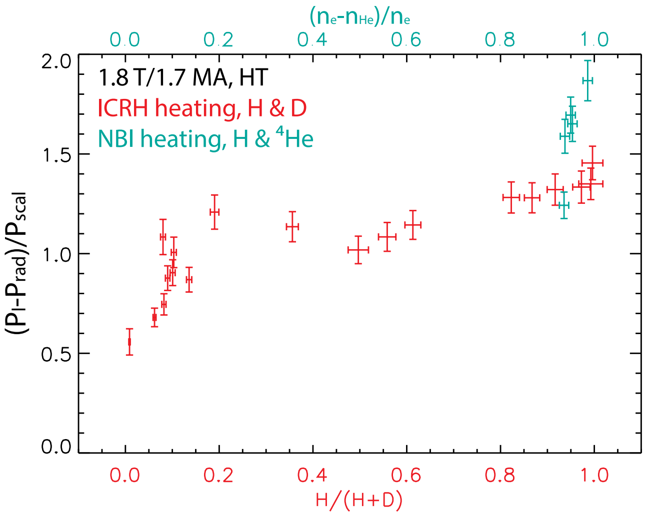

Figure 3: *Dependence of L-H transition power threshold in mixed ion species plasmas. All data 1.8 T/ 1.7 MA in horizontal target divertor configuration.*

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