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H-mode Access in the low density regime on JET

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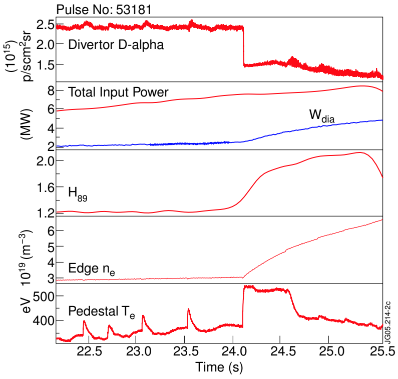
1. Introduction In all tokamaks the power threshold for H-mode access, P_{th}, is observed to increase approximately linearly with density [1]. However, a minimum P_{th} as a function of n_e has been demonstrated on several tokamaks including COMPASS-D [2, 3], ALCATOR C-Mod [4] and DIII-D [5]. The P_{th} for the ITER ELMy H-mode may exceed the available heating power except at densities appreciably lower than the desired operating condition of $\sim 10^{20} m^{-3}$. An operating scenario under consideration for ITER starts with the transition into H-mode at low n_e followed by an increase in n_e to the required operating condition. Hysteresis between the L-H and the H-L transitions is expected to maintain the H-mode during the n_e rise. Therefore, it is important to characterise H-mode access in present day tokamaks under conditions of very low density.

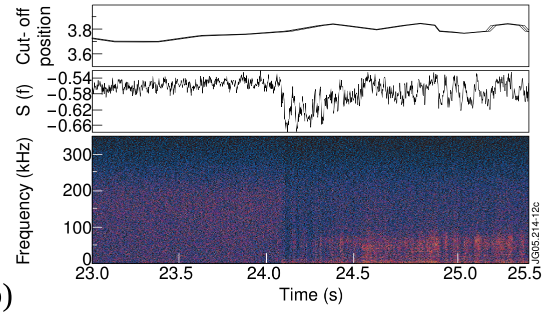
The departure of P_{th} on JET from the ITER n_e scaling at very low densities was first reported by Horton et al in [6], Righi et al. in [7] and Sartori et al. in [8]. Low density data from COMPASS-D, JT-60U and JET have also been compared with Alfven Drift Instability theory by Igitkhanov et al. in [9]. This earlier JET work is extended here with experimental results from n_e, B_t and q_{95} scans under conditions of low plasma density both with the Septum and the Septum Replacement Plate (SRP) in the MkII Gas Box (MkIIGB) divertor configurations.

2. Low Density L-H Transition Experiments Density scans were performed with the MKIIGB Septum divertor at I_p/B_t values of 2.5 MA/2.7(2.6) T, 2.5 MA/2.4 T and 2.2 MA/2.4 T. The L-mode target density was held constant, while the additional heating was slowly ramped up at a rate of 1 MW/s, as illustrated by an example shot in figure 1. The L-H transition for this shot is clearly seen as a sharp drop in the divertor D_α signal and corresponds to a reduction in turbulence as measured by reflectometry shown in figure 1(b). Generally, NBI heating was used for the higher density plasmas, but for the lowest densities it was necessary to use ICRH additional heating power only, due to operating constraints. All the plasmas examined used a lower single null configuration, with both inner and outer strike points on the vertical

*See Appendix of J Pamela et al., Fusion Energy 2004, (Proc. 20^{th} Int. Conf. Vilamoura, 2004) IAEA Vienna (2004)



(a)



(b)

Figure 1: *(a)General plasma parameters for an example MkIIGB Septum shot (53181) part of the density scan at 2.5 MA/2.6 T and (b) from top to bottom, reflectometry measurements of radial position of the cut-off layer, integrated spectrogram and a sliding FFT spectrogram of the reflected signal for shot 53181.*

targets of the MkIIGB divertor and had deuterium fuelling. The pedestal electron temperature, T_e^{ped}, in these shots has been measured with a multichannel ECE radiometer with a time resolution of 1 ms, while the the line average edge n_e is the interferometer measured line integrated $\bar{n}_e$ divided by the chord length in the plasma.

The values of P_{th} and T_e^{ped} at the L-H transition for the three sets of I_p/B_t scans with the MkIIGB Septum divertor are shown in figure 2 as a function of edge density. P_{th} is defined as the total input power less shine through power losses for NBI, less the rate of change of stored magnetic energy. All three sets of data show a minimum in P_{th} as a function of density and clearly demonstrate that P_{th} deviates from the ITER n_e scaling for the lowest density plasmas. T_e^{ped} also has a dependence on n_e in the low density regime, with the highest T_e values in the scans at the lowest values of n_e, which indicate that T_e cannot be the controlling parameter for H-mode access under the low density regime.

The effect of plasma Z_{eff} on P_{th} has been investigated by subtracting the bulk radiated power from P_{th} to give P_{SEP} i.e. the power flowing across the separatrix in to the SOL. P_{SEP} and Z_{eff} are plotted in the top and bottom graphs respectively, in figure 3 as a function of edge n_e. The edge n_e dependence of P_{SEP} is very similar to that of P_{th} and Z_{eff} decreases monotonically with increasing n_e, showing no evidence of a sharp turning point.

On DIII-D increased values of P_{th} at low density were attributed to NBI heating required during the initial current ramp up phase to avoid locked modes [5]. When an error field correcting coil was used on DIII-D to reduce the locked mode density limit, the increase in P_{th} at low density was eliminated. Since it was not necessary on JET to use additional NBI heating during any phase of these ICRH only heated plasmas to avoid locked modes, the higher values of P_{th} at low n_e cannot be attributed to surplus power. However, analysis of the JET low-density shots shows that they are indeed very close to the locked mode density limit at the L-H transition.

It is also interesting to note that P_{th} is influenced by a change in I_p at constant B_t at the lowest values of n_e. In figure 2 at n_e = 1.8x10$^{19}m^{-3}$, P_{th} is very similar for I_p/B_t = 2.5 MA/2.4 T and 2.2 MA/2.4 T. However, at n_e = 1.3x10$^{19}m^{-3}$ and 0.8x10$^{19}m^{-3}$, P_{th} is 1.5-2 MW higher at I_p/B_t

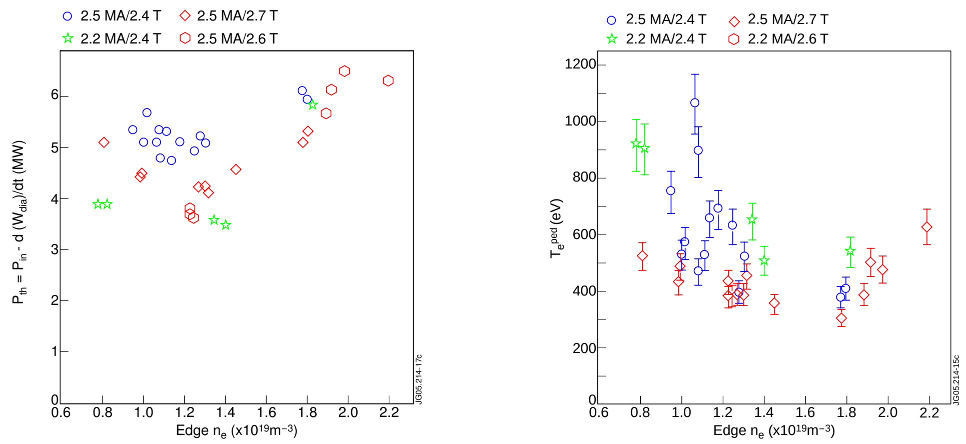


Figure 2: P_{th} *and corresponding pedestal* T_e^{ped} *values plotted as a function of the edge* n_e *for MkIIGB Septum divertor.*

of 2.5 MA/2.4 T than at 2.2 MA/2.4 T. On the other hand, in a separate I_p ramp experiment at B_t = 2.4 T, I_p was varied from 2.5 MA to 3 MA at the L-H transition. The edge edge n_e was held constant at 1.3x$10^{19}m^{-3}$ and P_{th} demonstrated no dependence on I_p in the range scanned. The contrast between these two results may be due to the difference in the I_p range explored.

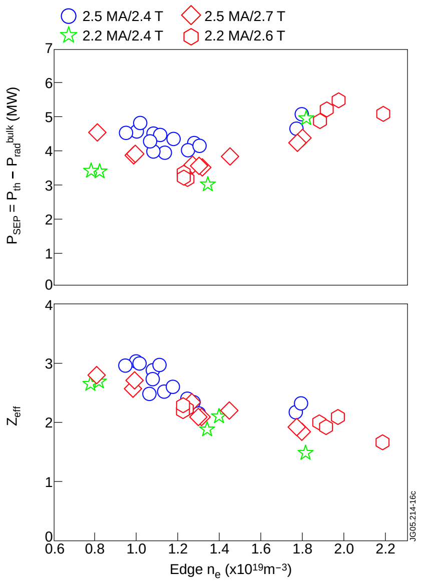
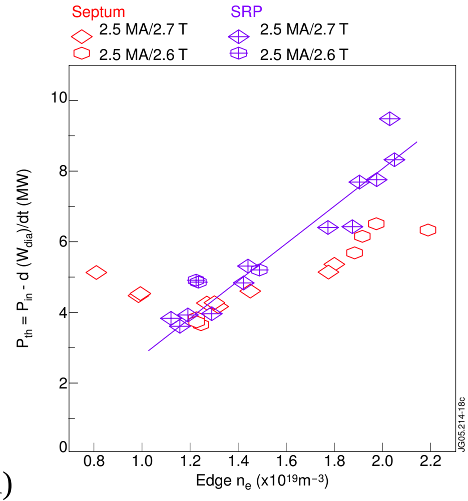


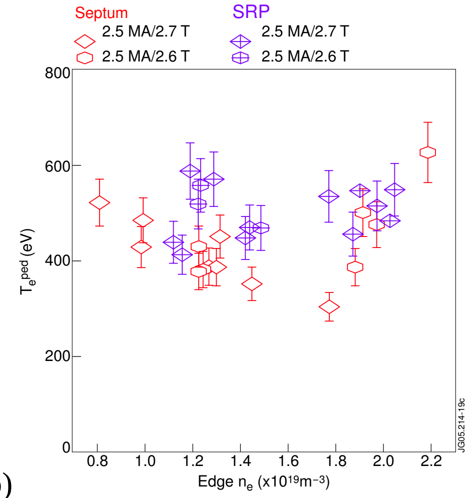
Figure 3: P_{SEP} *and* Z_{eff} *values plotted as a function of the edge* n_e *for MkIIGB Septum divertor.*

The n_e scan carried out at 2.5 MA/2.7(2.6) T was repeated with the MKIIGB SRP divertor and the values of P_{th} and T_e^{ped} from this scan are compared in figure 4(a) and (b). Despite lowering the SRP plasma density to n_e = 1.1x$10^{19}m^{-3}$, no evidence of a departure of P_{th} from the ITER scaling is observed. Therefore, if a minimum P_{th} exists with the SRP it is lower than that with the divertor septum in place (n_e = 1.2 x$10^{19}m^{-3}$). It is also interesting to note that removal of the septum made little difference to the T_e^{ped}.

3. Conclusions Density scans carried out on JET with the MkII GB septum divertor have shown that at very low plasma densities a minimum in P_{th} exists. The increase in P_{th} does not appear to be dependent on increasing Z_{eff} at the lowest densities, with subtraction of the bulk radiated power making no significant difference to the n_e dependence. There is a sensitivity of P_{th} to q_{95} at fixed B_t at the lowest densities, with a decrease in I_p from 2.5 MA to 2.2. MA reduces P_{th} by 1.5 - 2 MW. The effect of the divertor septum on H-mode access in the low density regime was examined by repeating reference density scans with the SRP, but no evidence of departure of P_{th} from the standard ITER scaling was found for lowest densities



(a)



(b)

Figure 4: *(a)P_{th} and (b) T_e^{ped} at the L-H transition plotted as a function of edge n_e at 2.5 MA/2.7 T for the MkIIGB Septum and the MkIIGB SRP divertors*

explored. If a minimum P_{th} exists it has been shifted to an even lower value of n_e with the removal of the septum. Finally, T_e^{ped} was found to be very similar for the two sets of divertor data.

Acknowledgement

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