EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–PR(05)28

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** See annex of J. Pamela et al, "Overview of JET Results ", (Proc.20 th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004).*

Preprint of Paper to be submitted for publication in
Plasma Physics and Controlled Fusion

ABSTRACT

H-mode access studies under conditions of very low plasma density provide valuable information on the physics of the edge transport barrier formation and are an important part of operational scenario development for the next step fusion device, ITER. JET operation with a very low edge electron density, $\bar{n}_e$= 0.8-1.4 x10^{19} m^{-3}, with the MkII Gas Box Septum divertor was found to have a significant effect on the power threshold for the L-H transition, P_{th}. A sharp turning point below which P_{th} increases with decreasing is found $\bar{n}_e$ for I_p/B_t values of 2.5MA/2.7T, 2.5MA/2.6T, 2.5MA/2.4T and 2.2MA/2.4T. The pedestal electron temperature demonstrates a very similar dependence on the edge $\bar{n}_e$ as P_{th}. Shots with the divertor septum present are compared with an identical $\bar{n}_e$scan, run with the MkII GB Septum Replacement Plate divertor at 2.5MA/2.7T and 2.5MA/2.6T. The results from this investigation indicate that removal of the septum may have lowered the $\bar{n}_e$ turning point for P_{th}.

1. INTRODUCTION

In all tokamaks the power threshold for H-mode access, P_{th}, is observed to increase approximately linearly with electron density, n_e [1]. However, a minimum P_{th} as a function of n_e has been demonstrated on several machines including COMPASS-D [2,3], ALCATOR C-Mod [4] and DIII-D [5]. With 75MW of additional heating power available on ITER [6], it is planned to access the H-mode at the relatively low line averaged electron density of $\bar{n}_e \cong 0.5\text{x}10^{20}$ m^{-3} for which the predicted power threshold is 35MW < P_{th} < 46 MW [1,7]. Hysteresis between the L-H and the H-L transitions is expected to maintain the H-mode during the density rise to the ELMy H-mode operating density of $\bar{n}_e \cong 1 \text{ x } 10^{20}$ m^{-3} [6,8]. Consequently, it is very important to fully characterise and possibly scale H-mode access in present-day tokamaks under conditions of very low plasma density.

Ohmic H-modes exhibited a clear low density threshold on COMPASS-D at $n_e \sim 2.5 \text{ x } 10^{19}$ m^{-3} [2,3]. At densities below this value P_{th} was observed to increase sharply as n_e was decreased, with substantial additional Electron Cyclotron Resonance Heating (ECRH) power required to produce H-modes at values of $n_e < 0.5 \text{ x}10^{19}$ m^{-3}. It was concluded that the sharpness of the increase in the COMPASS-D P_{th} at the lowest densities, together with the very low relative levels of impurity radiation, suggests that impurities were not the primary contributing factor to the low density P_{th} behaviour.

Density and power scans carried out by Hubbard et al. [4] demonstrated that P_{th} varies non-linearly with n_e on Alcator C-mod, P_{th} increased at both at the highest and lowest values of n_e near the low density limit. In contrast, the edge T_e was found to remain close to 120 eV at the L-H transition independent of density. These results strongly suggest a necessary condition in T_e or a closely related parameter for accessing the H-mode.

Experiments performed on DIII-D [5] demonstrated that higher input powers were needed to access H-mode at both high and low plasma densities and that a minimum threshold power exists at moderate densities. The increased power required for the L-H transition at the very lowest plasma densities were attributed to the requirement of additional NBI during the initial I_p ramp-up phase of those shots, in order to avoid locked modes. When an error field correcting coil was used to reduce the locked mode density limit, the additional heating during the I_p ramp-up phase was no longer needed and the increase in P_{th} was essentially eliminated.

An experimental campaign was carried out on JT-60U to investigate the low density L-H transition limit [9] and these results demonstrated a clear minimum in P_{th} at an average electron density of $n_e = 1.2 \times 10^{19}$ m^{-3}. A substantial increase in P_{th} in the range $n_e < 1.2 \times 10^{-19}$ m^{-3} and a more moderate rise in P_{th} for $n_e > 1.5 \times 10^{19}$ m^{-3} was observed. The n_e dependence of P_{th} at low density is attributed in [9] to the variation of the ratio of edge neutral density to edge n_e.

The departure of P_{th} on JET from the ITER n_e scaling at very low densities was first reported by Horton et al. [10], Righi et al. [11] and Sartori et al. [12]. Low density H-mode threshold data from COMPASS-D, JT-60U and JET have also been compared with Alfv n Drift Instability theory by Igitkhanov et al. in [13]. This earlier JET work is extended in this paper with the presentation of results from n_e, B_t and I_p scans under conditions of low plasma density both with and without the divertor septum in place. The experimental details and diagnostic measurements of the relevant parameters for the study are described in section 2. The results from the experiments are presented and discussed in section 3 and the paper concludes with a summary of the main points in section 4.

2. H-MODE THRESHOLD EXPERIMENTS

A series of density scans were performed on JET with the MKIIGB Septum divertor shown in figure 1(a), at I_p/B_t values of 2.5 MA/2.7 T, 2.5 MA/2.6 T, 2.5 MA/2.4 T and 2.2 MA/2.4 T. The density scans at 2.5 MA/2.7 T and 2.5 MA/2.6 T were then repeated with the MkIIGB Septum Replacement Plate (SRP) divertor, shown in figure 1(b), to study the effect of the divertor septum on H-mode access under conditions of low density. All the plasmas presented in this paper had a lower single null configuration with the ion $\nabla\mathbf{B}$ drift towards the X-point. Both inner and outer strike points were on the vertical targets of both divertors and the plasmas were fuelled with deuterium gas.

The L-mode target density was held constant using active feedback control, while the additional heating was slowly ramped up at rate of ~1 MW/s using both Neutral Beam Injection (NBI) and Ion Cyclotron Resonance Heating (ICRH) methods. The NBI power ramp was achieved with fast modulation of the beam ion source with a modulation period much shorter than the fast ion slowing down time. The total NBI input power, P_{in}, has been corrected for shine through losses. The threshold power for H-mode access is defined in this study as, $P_{th} = P_{in} + P_{OH} - dW_{dia}/dt$, where P_{in} is the total additional heating power from either NBI or ICRH, P_{OH} is the ohmic power and dW_{dia}/dt is the rate of change of the diamagnetic energy. The dW_{dia}/dt is typically less than 15 % of the total input power. The analysis presented in this paper also uses the power crossing the separatrix into the scrape-off layer, $P_{SEP} = P_{th} - P_{rad}^{bulk}$, where P_{rad}^{bulk} is the total power radiated in the bulk plasma, measured using tomographic reconstruction [14].

At the very lowest plasma densities accessed in the scans it was not possible to use NBI auxilliary heating due to increased shine through. Therefore, at the extreme low end of the density scans, H-modes were achieved using ICRH additional heating only. Reference pulses were run at similar edge $\bar{n}_e$ with either NBI only or ICRH only, to examine the influence of the method of additional heating on the measured P_{th} for H-mode access. No significant difference was observed in P_{th} between the two methods of heating, as illustrated by the example in figure 2. The two shots compared in figure 2 have the same edge density, $\bar{n}_e = 1.25 \times 10^{19}\ m^{-3}$, at the L-H transition. The power threshold at the transition was measured to be, P_{th} = 5.3MW with ICRH only heating (black solid trace) and P_{th} = 5.6MW for NBI only heating (blue dashed trace). The similarity of P_{th} for ICRH and NBI additional heating is in agreement with the findings by ITPA H-mode Power Threshold Database Working Group [1].

3. DENSITY DEPENDENCE OF THE H-MODE POWER THRESHOLD

3.1 MKIIGB SEPTUM

The pedestal electron temperature, T_e^{ped}, in these shots has been measured with multichannel ECE radiometer with a time resolution of 1 ms. The top of the pedestal had been identified by the discontinuity in the gradient as defined in [15] and as used in previous JET studies [16,17]. The T_e^{ped} at the L-H transition is obtained by applying the pedestal position identified at the first clear H-mode T_e pedestal, to the T_e profile at the time of the transition. The line integrated edge n_e is measured with an interferometer along a single chord at the mid-plane radius of R_{mid} = 3.74 m for these shots. The line average edge $\bar{n}_e$ has been calculated by dividing the measured edge line integrated n_e by the chord length in the plasma.

The general plasma parameters for two shots at 2.5 MA/2.6 T scan are shown in figure 3(a) shot # 53181 with MkIIGB Septum divertor and (b) #56748 with the MkIIGB SRP divertor. The L-H transition can be clearly seen for both examples, shot #53181 is characterised by a sharp drop in the divertor D_α signal, while Pulse No: 56748 s divertor D_α D_α signal has an abrupt transition to high frequency ELMs. The transition to H-mode is also characterised by a sharp rise in the edge $\bar{n}_e$, stored diamagnetic energy W_{dia} and confinement factor H_{89} for both plasmas. The L-H transition for both shots are also clearly identifiable in the spectrograms and integrated spectra of the high frequency turbulence (100-300 kHz) for shot #53181 and the full frequency range for shot #56748, all measured using reflectometry [18] and shown in figure 3 (c) and (d). These two example shots are characteristic of the well defined L-H transitions seen in the plasmas from the scans. However, for the lowest density plasmas the L-H transition was less sharp with the divertor D_α light, $\bar{n}_e$, T_e^{ped}, W_{dia} and H_{89} demonstrating more gradual transitions to H-mode. It was still possible to clearly identify a transition time for the lowest density shots from these three parameters as shown by the example in figure 4 from the 2.2 MA/2.4 T electron density scan. In this example the time of the L-H transition is determined as the first transition after which the plasma remains in H-mode, which is identifiable in this example from the D_α and T_e^{ped} parameters.

The values of P_{th} and T_e^{ped} for all I_p/B_t scans carried out with MKIIGB Septum divertor are shown in figure 5(a) and (b) as a function of edge density. All the data show a clear minimum in P_{th} and that the power threshold deviates from the linear ITER $\bar{n}_e$ scaling at the lowest densities explored. In addition, T_e^{ped} demonstrates a very similar $\bar{n}_e$ dependence to P_{th}, with the highest values of T_e^{ped} measured at the lowest plasma densities. However, the minima in P_{th} and T_e^{ped} do not occur at the same edge density. This can be seen in figure 5(b) where the minimum in T_e^{ped} lies outside the shaded region which represents the P_{th} minimum.

It has been speculated that the increase in P_{th} at the lowest densities is due to a corresponding increase in plasma Z_{eff}. To investigate this further on JET the power flowing across the separatrix in to the SOL, P_{SEP}, and Z_{eff} are plotted as a function of edge $\bar{n}_e$ in figure 6(a) and (b) respectively. The dependence of P_{SEP} on the edge $\bar{n}_e$ is very similar to the P_{th} dependence, even though Z_{eff} decreases monotonically with increasing edge density, with no evidence of a sharp turning point corresponding to that seen in P_{th} or P_{SEP}.

Since it was not necessary on JET to use additional NBI heating during any phase of the lowest density ICRH only heated plasmas in order to avoid locked modes, the elevated P_{th} values cannot be attributed to this. However, analysis of the low density shots shows that they are indeed very close to the locked mode density limit at the L-H transition. It is impossible to determine if the P_{th} behaviour at low edge density is a direct result of proximity to the locked mode threshold from this data.

Finally, it is also interesting to note that P_{th} for these MkIIGB SRP divertor shots appears to be influenced by changes in I_p at constant B_t, at the lowest values of edge $\bar{n}_e$. In the comparison shown in figure 5(a) it can be seen that P_{th} is very similar for I_p/B_t = 2.5 MA/2.4 T (blue symbols) and 2.2 MA/2.4 T (green symbols) at edge $\bar{n}_e$= 1.8 x 10^{19} m^{-3}. However, at edge $\bar{n}_e$< 1.8 x 10^{19} m^{-3}, P_{th} is 1.5 MW to 2 MW higher at I_p/B_t = 2.5 MA/2.4 T than at 2.2 MA/2.4 T. This result may indicate that under low plasma density conditions, any global parameter scaling expression for P_{th} on ITER may need to include an I_p or q_{95} term.

3.2 MKIIGB SEPTUM REPLACEMENT PLATE

The electron density scan carried out at 2.5 MA/2.7 T and 2.5 MA/2.6 T with the MkIIGB Septum divertor was repeated with the MKIIGB SRP divertor and the results from this scan are compared in figure 7(a) and (b) for P_{th} and T_e^{ped} respectively. Despite lowering the SRP plasma edge density to $\bar{n}_e$ = 1.1 x 10^{19} m^{-3}, no evidence of departure of P_{th} from the linear ITER scaling with $\bar{n}_e$ is observed. The minimum accessible edge $\bar{n}_e$ with the MkII SRP divertor was $\bar{n}_e$= 1.1 x 10^{19} m^{-3}, due to insufficient ICRH antennae conditioning. If a minimum P_{th} point exists at around or below $\bar{n}_e$ = 1.1 x 10^{19} m^{-3} with the SRP divertor, it would only be possible to identify it if the electron density scan could be extended to even lower densities. Comparison of T_e^{ped} in figure7(b) demonstrates this parameter to be very similar for both divertors over the edge density range considered, indicating that the pedestal does not appear to be significantly influenced by the removal of the divertor septum.

SUMMARY AND CONCLUSIONS

Density scans carried out on JET with the MkII GB Septum divertor have shown that at very low densities a minimum P_{th} for H-mode access exists. The increase in P_{th} does not appear to be dependent on the increase in Z_{eff} with decreasing edge electron density. Following subtraction of the bulk plasma radiated power, P_{SEP} has a very similar dependence to P_{th} on $\bar{n}_e$. In the low edge density region, T_e^{ped} for these shots is also found to increase with decreasing edge electron density. This indicates that additional factors other than a threshold T_e^{ped} are involved in the transition from L to H-mode. These scans also provide some evidence that at the densities below the minimum in P_{th}, a sensitivity to I_p at fixed B_t appears, the decrease in I_p from 2.5 MA to 2.2 MA at B_t = 2.4T reduces P_{th} by 1.5 - 2MW. This result could provide an indication of the importance of an I_p or q_{95} term in the scaling of P_{th} for ITER in the low density regime.

A comparison of the effect of the divertor septum on H-mode access under conditions of low edge density was carried out by repeating reference density scans with the divertor Septum Replacement Plate. No evidence of departure of P_{th} from the standard ITER scaling was found for the edge density range covered. It was not possible to access even lower plasma densities with the MKII GB SRP divertors due to outgassing from the ICRH antenna during operation. The size of any deviations from the normal linear density scaling for densities above or below those observed in the septum experiments cannot be assessed. The pedestal electron temperature was found to be very similar for the two sets of divertor data across the edge density range scanned, indicating that removal of the septum had minimal effect on the pedestal parameters.

ACKNOWLEDGEMENT

This work was funded jointly by the United Kingdom Engineering and Physical Sciences Research Council and by the European Communities under the contract of Association between EURATOM and UKAEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work has been carried out within the framework of the European Fusion Development Agreement. The authors wish to thank R. Groebner for valuable discussions and his encouragement in the preparation of this work.

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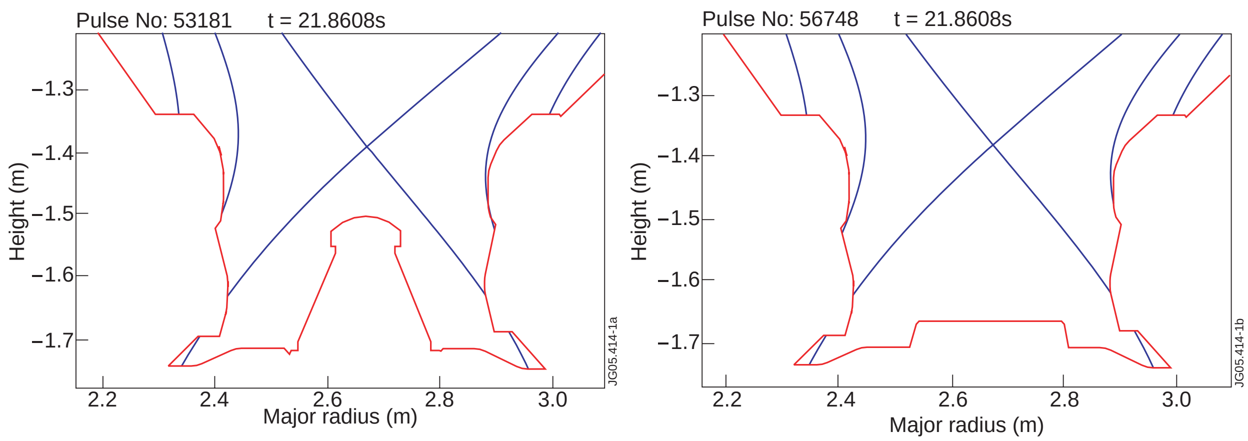

Figure 1: JET's (a) MkII Gas Box (GB) Septum divertor and (b) MkII GB Septum Replacement Plate (SRP) divertor.

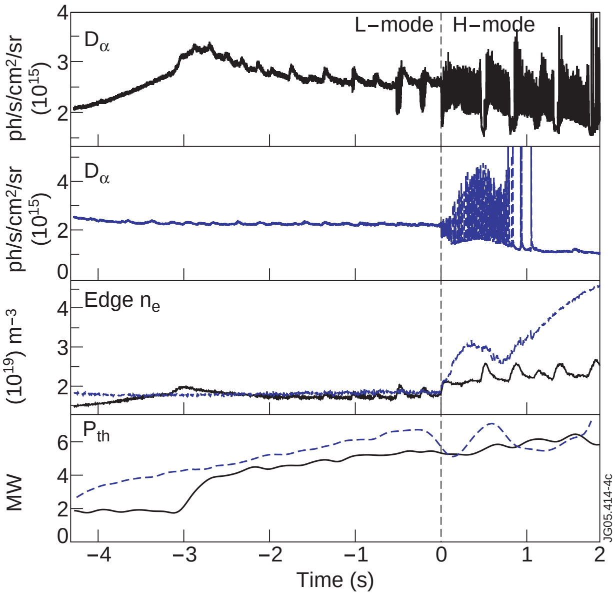

Figure 2: Comparison of the power threshold for H-mode access using two types of additional heating, ICRH only (Pulse No: 47762, solid trace) and NBI only (Pulse No: 53178, dotted trace) for a pair of shots with an edge line average electron density of $\bar{n}_e = 1.25 \times 10^{19}$ m^{-3}. The time-base has been shifted such that the L-H transition occurs at time, t = 0s for both shots.

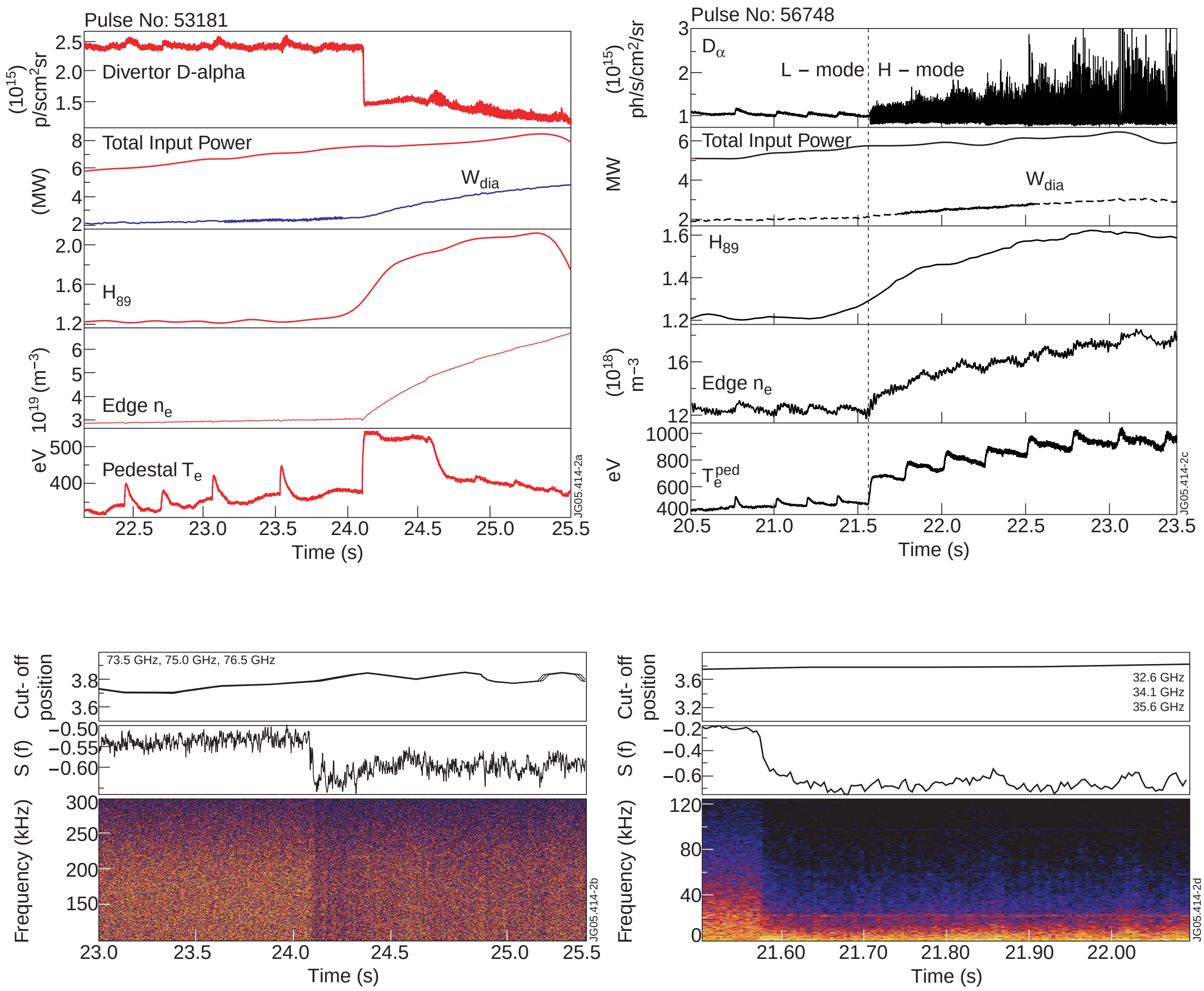

Figure 3: General plasma parameters for shots from the density scans at 2.5MA/2.6T with (a) the MkIIGB Septum divertor (Pulse No: 53181) and (b) with the MkIIGB SRP divertor (Pulse No: 56748). Reflectometry measurements of radial position of the cut-off layer, integrated spectrogram and a sliding FFT spectrogram of the reflected signal are shown from the top box down for (c) Pulse No's: 53181 and (d) 56748.

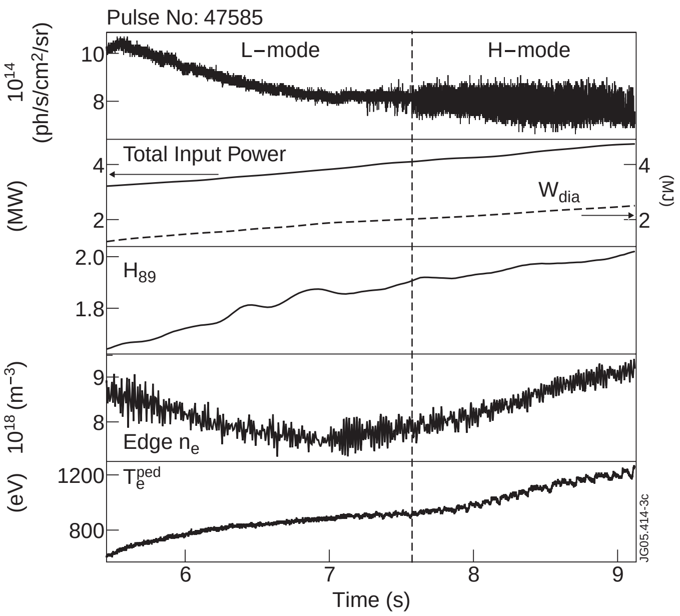

Figure 4: General plasma parameters for the low density Pulse No: 47585 from the density scan at 2.2MA/2.4T with the MkIIGB Septum divertor.

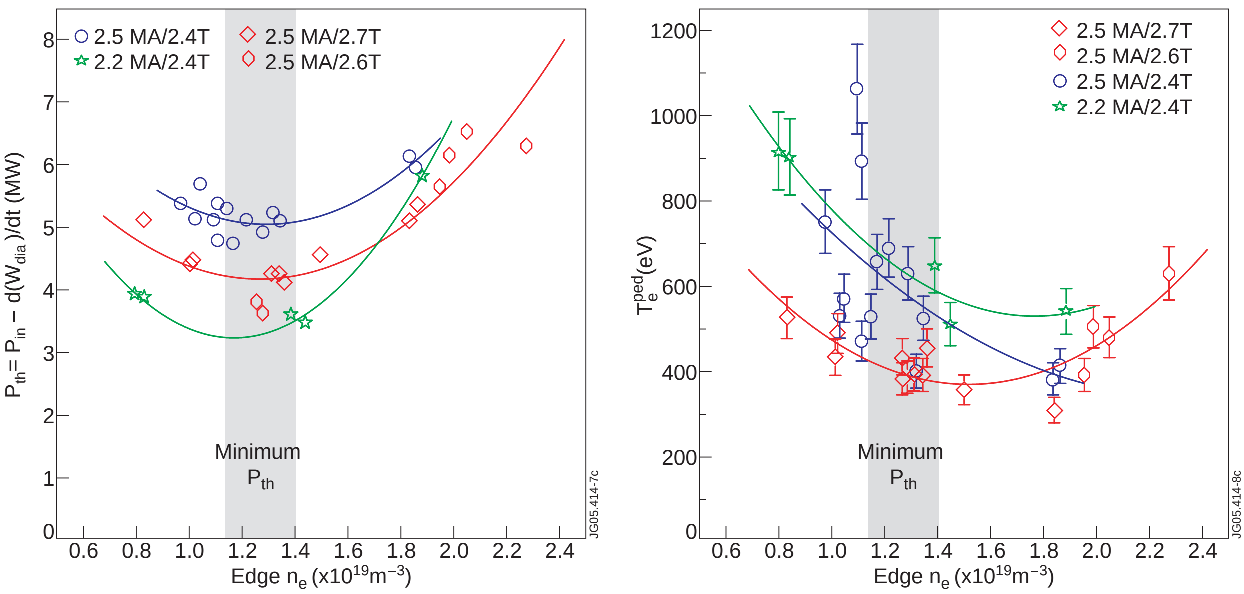

Figure 5: (a) Power threshold, P_{th}, and (b) pedestal electron temperature, T_e^{ped}, at the L-H transition plotted as a function of edge $\bar{n}_e$ for the MkIIGB Septum divertor density scans. The solid lines represent fits to the data.

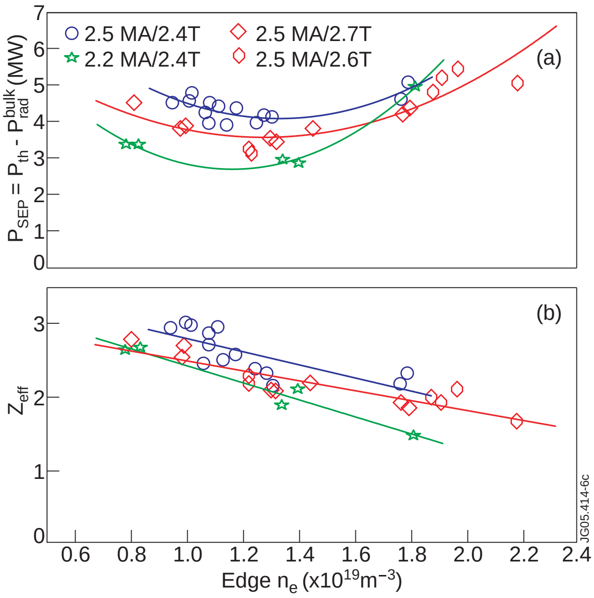

Figure 6: (a) Power into the SOL and (b) Z_{eff} plotted as a function of edge $\bar{n}_e$. The solid lines represent fits to the data.

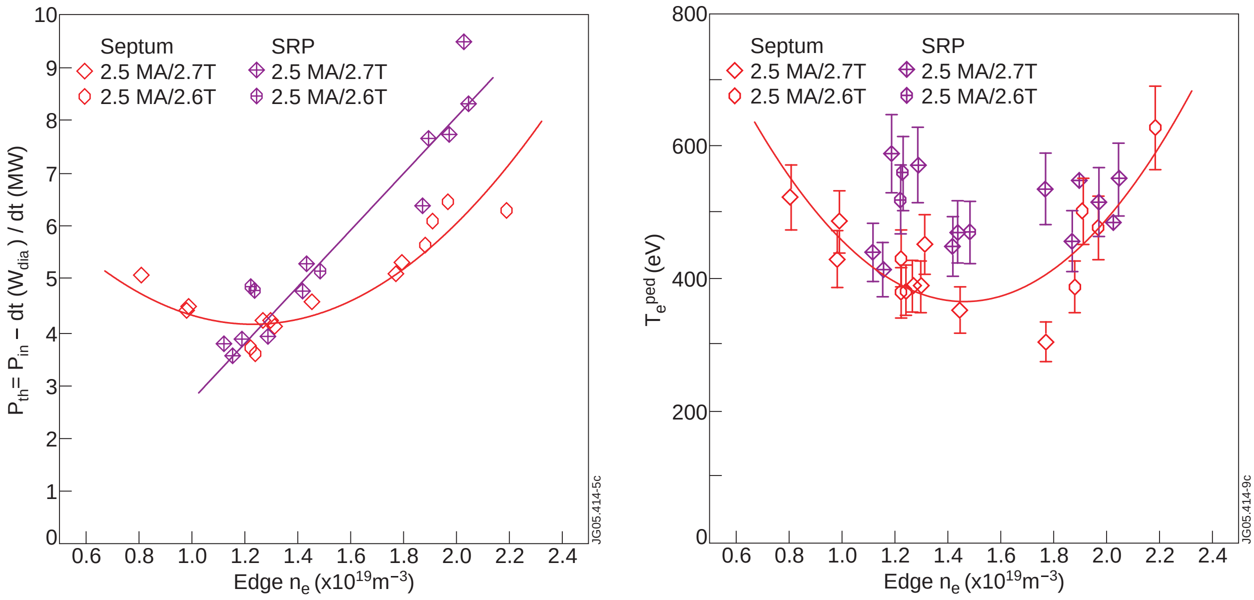

Figure 7: (a) P_{th} and (b) T_e^{ped} for the MkIIGB Septum and SRP divertors plotted as a function of edge $\bar{n}_e$. The solid lines represent fits to the data.