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JET Helium-4 ELMy H-mode Studies

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ABSTRACT.

This paper reports H-mode plasma results from the 2009 JET ^4He campaign which, as part of a wider ITPA study, have extended the physics basis to enable improved predictions of ^4He , H-modes in ITER. L-H threshold experiments included the first ever dedicated study of the effect of concentration on the L-H threshold. ^4He concentration, as measured by edge visible spectroscopy, was varied from 1 to 87% and was found to have little impact on the power threshold. This is in line with recent ASDEX Upgrade studies, but in contrast to JET 2001 results, which found that ^4He plasmas have a 40% higher threshold than D equivalents. A study of the density dependence of the L-H threshold power in ^4He and D found very different behaviour which may, in part, explain the differences between the JET 2001 and 2009 studies which were performed at different densities. The 2009 studies included the first experiment to measure the threshold required for Type I ELMs in ^4He plasmas. A series of ^4He and D plasmas with matched field (1.8T), current (1.7MA), shape (triangularity of 0.4) and divertor configuration were performed with different input powers. Similar Type I ELM power thresholds were found for the D (6.7-9.3MW) and ^4He (7.5-9.3MW) plasmas. By normalising to a standard L-H threshold scaling, these results can be extrapolated to the ITER, ^4He , half-field, baseline conditions (2.65T, 7.5MA and density of 85% of the Greenwald limit) where they predict a required input power of 42-48MW, or 23-86MW for an appropriately chosen 95% confidence interval. These intervals are largely consistent with the design auxiliary heating capacity of ITER. Confinement and ETB studies show that energy confinement times in ^4He plasmas were approximately 60% of those for reference D ones, in line with previous studies on several machines. The relative impact of the core transport and ETB on this difference is assessed. IR camera measurements during ^4He , Type I ELMs show that the heat load is deposited over significantly longer periods than for D equivalents. The impact of magnetic perturbations on Type I ELMs in ^4He is also studied.

1. INTRODUCTION

During its low activation phase, ITER must operate with hydrogen (H) or helium-4 (^4He) plasmas [1]. To assess ELM loads and study and demonstrate ELM mitigation prior to the active deuterium (D) and deuterium-tritium (D-T) phases, it is required that part of this operation be in ELMy H modes. The high L-H power threshold ($P_{\text{L-H}}$) in H, $P_{\text{L-H}}(\text{H}) \approx 2P_{\text{L-H}}(\text{D})$ [2,3], appears to preclude hydrogen H-modes on ITER. Instead ^4He plasmas are seen as the most likely for ELMy H-mode operation in the low activation phase [4,5]. 2001 JET studies [4] found ^4He plasmas had $P_{\text{L-H}} \approx 1.4$ times that of deuterium (D) equivalents and the resulting ELMy H-modes had confinement times (τ_{E}) ≈ 0.7 times D equivalents. At the transition, the ^4He plasmas had a purity ($f_{\text{He}} = n_{\text{He}} / (n_{\text{D}} + n_{\text{He}})$) of 84-94%, as measured by edge visible spectroscopy. 2008 ASDEX Upgrade studies [5] ($f_{\text{He}} \approx 50-80\%$) found similar confinement time behaviour but no change in L-H power threshold between D and ^4He plasmas. 2009 DIII-D studies ($f_{\text{He}} > 90\%$) found ^4He plasmas had $P_{\text{L-H}} \approx 1.3-1.5$ times that of deuterium (D) equivalents [6]. This paper presents results from the 2009 JET ^4He campaign which, as part of ITPA joint experiments, aimed to strengthen the ^4He physics basis by: (i) studying the

impact of ^4He concentration, electron density (n_e), and heating scheme on the L-H threshold power; (ii) measuring the power threshold for Type I ELMs; (iii) identify the roles of core transport, the edge transport barrier (ETB) on global confinement; and (iv) assessing ELM heat loads and their mitigation.

2. EXPERIMENT SETUP

To ensure ITER equivalent ^4He concentrations, the JET ^4He campaign was run with ^4He Neutral Beam Injection (NBI) sources. Argon frosted cryopumps in both the NBI sources and the divertor were used to enable density control. The resulting ^4He purity was 80-95%. Density control was limited with edge recycling tending to rise throughout ^4He discharges. Ion Cyclotron Resonant Heating (ICRH) was also used, mainly at the fundamental hydrogen resonance [7].

A series of ^4He , H-mode plasmas were produced along with a set of D references. Figure 1 shows timetraces for a typical pair. As the input power is raised, both plasmas undergo a transition to H-mode. The D plasma undergoes a sharp transition with the presence of low frequency ELMs ($\approx 20\text{Hz}$), a rapid rise in density and energy along with the formation of a clear edge pedestal. By contrast, the transition in ^4He plasmas was more gradual with high frequency ELMs ($\approx 2\text{kHz}$), a very small rise in density and energy and, initially, no clear pedestal. The frequency of these high frequency ELMs was found to negatively correlate with the input power and the ELMs were identified as Type III [8,9]. If the input power to ^4He plasmas was raised sufficiently high, a transition to Type I ELMs occurred and a clear edge pedestal was observed. As can be seen from the base level of the He-I divertor light, the edge recycling continues to rise throughout the ^4He discharge.

3. L-H THRESHOLD

A study of the impact of ^4He concentration on $P_{\text{L-H}}$ varied f_{He} from 1 to 87% at fixed configuration, shape ($\delta = 0.25$), core line average density ($\bar{n}_e = 2.3\text{-}2.8 \times 10^{19} \text{ m}^{-3}$), field ($B = 1.8\text{T}$) and current ($I = 1.7\text{MA}$) [10]. This scan was performed with ^4He NBI sources, except for the lowest ^4He concentration discharges ($f_{\text{He}} < 2\%$) where D NBI sources were used. The L-H threshold is defined as the loss power, $P_{\text{loss}} = P_{\text{aux}} + P_{\text{Ohmic}} - dW_{\text{th}}/dt$, immediately prior to the L-H transition. Here, P_{aux} is the auxiliary absorbed power, P_{Ohmic} is the Ohmic heating power and W_{th} is the total thermal energy. The L-H threshold power varied only weakly across the scan, figure 2, lying in the range of $\approx 1.2\text{-}1.4$ times the Martin08 scaling [11], the ITPA recommended scaling for the L-H threshold in D. The Martin08 scaling is defined as

$$P_{\text{Martin 08}} = 0.00488e^{\pm 0.057} n_{e,20}^{0.717 \pm 0.035} B^{0.803 \pm 0.032} S^{0.941 \pm 0.019}$$

where P_{Martin08} is the power in MW, $n_{e,20}$ is the core line average electron density in 10^{20} m^{-3} , B is in T, and S is the plasma surface area in m^2 . This result is similar to that reported on ASDEX Upgrade [5], but differs from that for the 2001 JET ^4He study, which found that L-H threshold

power in helium was ≈ 1.4 times that of D equivalents [4].

The impact of \bar{n}_e on P_{L-H} was studied by measuring P_{L-H} in ^4He (80-95% pure) and D plasmas at a range of \bar{n}_e with the same configuration, shape, B and I as for the above concentration scan, figure 3. The ^4He and D plasmas had similar P_{L-H} at $\bar{n}_e = 2.5\text{-}2.8 \times 10^{19} \text{ m}^{-3}$, but P_{L-H} was significantly (>60%) higher for ^4He plasmas than for D plasmas at lower $\bar{n}_e = 2.1 \times 10^{19} \text{ m}^{-3}$. This differing \bar{n}_e dependence is consistent with the fact that the 2001 studies ($\bar{n}_e = 1.0\text{-}1.5 \times 10^{19} \text{ m}^{-3}$) found $P_{L-H}(^4\text{He}) > P_{L-H}(\text{D})$ whereas the 2009 concentration scan ($\bar{n}_e = 2.0\text{-}2.7 \times 10^{19} \text{ m}^{-3}$) found $P_{L-H}(^4\text{He}) \approx P_{L-H}(\text{D})$. In contrast, ASDEX Upgrade found that the $e n$ dependence of the L-H power threshold in D and ^4He was identical.

The top window of figure 4 shows the same data as figure 3 plotted against the average edge density measured by interferometry. The same trend in the L-H threshold power with central line average density is observed. ^4He and D data from the JET 2001 studies has been added taken from plasmas with a similar shape ($\delta = 0.25$), B = 1.8T and I = 1.8MA, but with a different divertor configuration. The 2001 experiments were also performed with the more closed, septum divertor [12]. Whilst the 2001 D data lies broadly within the trend of the 2009 D data, the 2001 ^4He data lies somewhat below. The edge electron temperature, at the radial position equivalent to the eventual edge pedestal top, for the same 2009 discharges shows a fairly weak dependence on density for both ^4He and D. This is in line with previous JET studies [13]. The edge temperatures at the D, L-H transitions lie systematically above those of the ^4He , L-H transitions. The 2001 data is also shown and indicate that the transitions at lower densities have significantly higher edge electron temperatures, with any differences between ^4He and D plasmas lying within the much greater uncertainties on these measurements.

Whilst there is no agreed first principles model for the L-H transition [14], a model based on the generation of a critical electric field, E_{crit} , by neoclassical ion orbit losses has been found to well describe the dependence of the JET L-H transition on density, field and hydrogenic isotope mass [15]. A comparison of this model with the JET 2001 ^4He data was inconclusive due to the high level of uncertainty in the available edge data [16]. Significantly better edge data in 2009 enabled the studies to be performed, for a ^4He discharge and D reference, with matched configuration, shape ($\delta = 0.25$), B = 1.8T, I = 1.7MA and $\bar{n}_e = 2.6 \times 10^{19} \text{ m}^{-3}$. The ASCOT code [17] was used to model the neoclassical orbit losses and to compute the resulting electric field profiles. The results are shown in figure 5. The model predicts that both transitions would occur at the same E_{crit} , so the considerably higher electric field computed for the D discharge than the ^4He discharge clearly contradicts the model. However, it should be noted that a sensitivity analysis indicates that this result depends strongly on the shape of the edge density and temperature profiles.

4. TYPE I-III THRESHOLD

For the first time in ^4He , the threshold in P_{loss} required for Type I ELMy H-modes, P_{I-III} , was studied. Following previous studies [18], this was measured by performing power scans at fixed shape,

$B = 1.8\text{T}$ and $I = 1.7\text{MA}$ in ^4He plasmas and D references – figure 6. ELM behaviour can be seen to vary between the two scans, with ^4He ELMs constantly evolving. This is believed to be due to the increasing neutral particle flux at the edge which results from the poor pumping of ^4He plasmas. However, the ^4He can be seen to have erratic ELMs with 7.5MW of input power and Type I ELMs with 9.1MW of input power, so $P_{\text{I-III}}$ is identified as being in the range 7.5-9.3MW. Relative to the preferred ITER L-H threshold scaling, P_{Martin08} , [11] this becomes $P_{\text{I-III}}/P_{\text{Martin08}} = 1.4-1.6$. A similar range is observed for the D references: $P_{\text{III}} = 6.7-9.3\text{MW}$, equivalent to $P_{\text{I-III}}/P_{\text{Martin08}} = 1.2-1.8$.

5. H-MODE PHYSICS

In the 2009 studies, a set of Type I ELMy H-mode plasmas were produced in ^4He , with purities of $f_{\text{He}} = 0.65-0.8$, along with D references. Across the dataset, the energy confinement time normalised to the IPB98(y,2) scaling law [19] was found to be around 60-80% of the D equivalents. This implies that similar D and ^4He plasmas would have confinement times in the relation $\tau_{\text{E}}(^4\text{He}) \approx 0.6\tau_{\text{E}}(\text{D})$ in line with the 2001 JET and the 2008 ASDEX Upgrade studies [5]. Due to the low efficiency of pumping ^4He , all of the ^4He discharges had high edge recycling which has been shown to reduce confinement [20]. Impurity accumulation, which can reduce confinement, was also observed on some ^4He discharges. If edge recycling and impurity accumulation could be mitigated, $\tau_{\text{E}}(^4\text{He}) > 0.6\tau_{\text{E}}(\text{D})$ may be achievable. Improvements in JET diagnostics meant that the electron density, temperature and pressure profiles, figure 7, of the ETB could be resolved in these studies. For the two plasmas Pulse No's: 79193 and 79745 (time traces in figure 6) the thermal energies were in the ratio $W_{\text{th}}(^4\text{He})/W_{\text{th}}(\text{D}) = 0.71 \pm 0.09$ and the electron pedestal pressures in the ratio $p_{\text{e,ped}}(^4\text{He})/p_{\text{e,ped}}(\text{D}) = 0.69 \pm 0.05$, showing that the lower confinement observed in ^4He plasmas is associated with a lower pedestal pressure. This is in line with the strong correlation between pedestal total thermal energy confinement observed in ASDEX Upgrade [5] and in hydrogenic plasmas in JET [21]. The ratio of total pedestal pressures $p_{\text{ped}}(^4\text{He})/p_{\text{ped}}(\text{D})$ was not measured, but would be expected to be below that for electrons, due to ion dilution.

No evidence of a change in pedestal width was found, with the width of the electron thermal pedestal ($\delta_{\text{Te,ped}}$) being similar for the two discharges: $\delta_{\text{Te,ped}}(^4\text{He}) = 2.1 \pm 0.5\text{cm}$ and $\delta_{\text{Te,ped}}(\text{D}) = 2.5 \pm 0.5\text{cm}$.

Heat load studies of Type I ELMy H-modes, using a divertor IR camera, find that ^4He inter-ELM and time averaged profiles were moderately broader ($\approx 50\%$) in ^4He compared with D plasmas, with an associated reduction in peak heat load, figure 8. [22]. ^4He and D ELM heat load profiles have similar radial widths, but with ^4He ELMs having a much longer power arrival time scale. The application of Resonant Magnetic Perturbations did not mitigate ELM heat loads in the ^4He plasmas studied.

It is believed that this is a consequence of the high recycling in the ^4He plasmas [23].

6. EXTRAPOLATION TO ITER

Due to the absence of α -heating and the predicted high threshold powers for H and ^4He plasmas, ELMy H-mode operation in the low activation (H and ^4He) phase of ITER is expected to focus on the half-field baseline: $B = 2.65\text{T}$, $I = 7.5\text{MA}$ [1]. The transition to H-mode would be at relatively low density ($\bar{n}_e \approx 2.5 \times 10^{19} \text{ m}^{-3}$), with Type I ELMy H-mode operation at higher density ($\bar{n}_e \approx 5 \times 10^{19} \text{ m}^{-3}$) equivalent to 85% of n_{Gr} , the Greenwald density limit [24] - NB: the density limit in ^4He plasmas has been found to be well described by the Greenwald density limit [25]. Based on the existing physics basis, the predictions for the thresholds in H and ^4He are given in Table I. $P_{\text{L-H}}(^4\text{He})$ is taken in the range from P_{Martin08} , consistent with the $P_{\text{L-H}}(^4\text{He}) \approx P_{\text{L-H}}(\text{D})$ of the ASDEX Upgrade results [5] and the JET concentration scan study above, to $1.4 P_{\text{Martin08}}$, consistent with the $P_{\text{L-H}}(^4\text{He}) \approx 1.4 P_{\text{L-H}}(\text{D})$ of the JET 2001 results [4] and the $P_{\text{L-H}}(^4\text{He}) > P_{\text{L-H}}(\text{D})$ seen at $n_e \approx 2 \times 10^{19} \text{ m}^{-3}$ here and in the DIII-D studies [6]. $P_{\text{LH}}(\text{H}) \approx 2 P_{\text{Martin08}}$ has been taken from the results of previous hydrogenic species studies [2,3]. $P_{\text{I-III}}/P_{\text{Martin08}} = 1.4-1.6$ is taken directly from the results here. The 95% confidence interval for the Martin08 scaling has been calculated as $\pm 80\%$ of the central estimate [11] and this range has been taken for all of the threshold estimates. Given the design input power of ITER (73MW), both H and ^4He plasmas would be expected to access H-mode at low density, but H plasmas would be marginal at the higher field. ^4He plasmas are also predicted to be able to access the high confinement, Type I ELMy H-mode regime. There is no agreed scaling for the Type I-III threshold in H plasmas, but it is expected to be significantly (50-100%) above the L-H threshold, meaning that hydrogen, Type I ELMy H-mode would be largely precluded. This result is compounded by the fact that, on JET, ICRH power (20MW in the ITER design) is observed to be well coupled in the ITER ^4He plasma ICRH schemes, whereas coupling is observed to be problematical in the ITER H plasma ICRH schemes [26].

Figure 9. shows the predicted parameter space for volume averaged electron density ($\langle n_e \rangle$) and temperature ($\langle T_e \rangle$) for ^4He operation in the half-field ITER baseline scenario calculated with the GTBURN code [27]: assuming $H_{98(y,2)} = 0.7$, $P_{\text{LH}} = P_{\text{Martin08}}$ and $P_{\text{I-III}} = 1.4 P_{\text{Martin08}}$. A significant operational space exists, with, for $\langle n_e \rangle \approx 4-6 \times 10^{19} \text{ m}^{-3}$, temperatures in the range $\langle T_e \rangle \approx 5-8 \text{keV}$. However, the achievable pressures would be fairly low with $\beta_N < 1.3$, significantly below the $\beta_N = 1.8$ of the $Q = 10$ baseline point in D.

CONCLUSION

The 2009 JET ^4He campaign has strengthened the physics basis in the areas of L-H and Type I-III threshold, ETB, core transport, confinement and ELM heat loads. The results in these areas will be discussed and brought together with those from other machines, including ASDEX Upgrade and DIII-D. Extrapolations indicate that the L-H and Type I power thresholds can be achieved in ^4He plasmas in ITER. These plasmas are expected to have lower confinement than their D equivalents, but their study should provide important insight into core H-mode physics and the impact of ELM heat loads on plasma facing components prior to the high activation phase of ITER.

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REFERENCES

- [1]. B.J. Green, *Plasma Physics and Controlled Fusion* **45** (2003) 687
- [2]. K. Lackner, et al., *Plasma Physics and Controlled Fusion* **36** (1994) B79
- [3]. E. Righi, *Nuclear Fusion* **39** (1999) 309
- [4]. D.C. McDonald, et al., *Plasma Physics and Controlled Fusion* **46** (2004) 519
- [5]. F. Ryter, et al., *Nucl. Fusion* **49** (2009) 062003
- [6]. P. Gohil, et al., *Nucl. Fusion* **50** (2010) 064011
- [7]. M.J. Mantsinen, et al., "ICRF heating scenarios in JET with emphasis on 4He plasmas for the non-activated phase of ITER," in *Radio-Frequency Power in Plasmas (Proc. 14th Topical Conference on Radio Frequency Power in Plasmas 7-9th May, 2001, Oxnard, CA, USA)*, AIP, New York, p. 59-66
- [8]. E.J. Doyle et al., *Physics of Fluids B* **3** (1991) 2300
- [9]. H. Zohm, *Plasma Physics and Controlled Fusion* **38** (1996) 105
- [10]. G. Calabrò et al., "H-mode threshold studies in helium-4 JET plasmas", presented at the, 37th EPS Conference on Plasma Phys., Dublin, 21-25 June 2010, P-O5.127
- [11]. Y. Martin, et al., *J. Phys.: Conf. Ser.* **123** (2008) 012033
- [12]. M. Keilhacker for THE JET TEAM, *Nuclear Fusion*, **41** (2001) 1925
- [13]. Y. Andrew, et al., *Plasma Physics and Controlled Fusion* **46** (2004) 337
- [14]. J. W. Connor and H. R. Wilson, *Plasma Physics and Controlled Fusion* **42** (2000) R1
- [15]. T. Kiviniemi, et al., *Plasma Physics and Controlled Fusion* **43** (2001) 1103
- [16]. T. P. Kiviniemi, et al., "L-H transition threshold temperature for helium discharges in JET", *Proc. 30th EPS Conference on Contr. Fusion and Plasma Phys., St. Petersburg, 7-11 July 2003* ECA Vol. 27A, P-1.162
- [17]. J. A. Heikkinen, et al., *J. Comput. Phys.* **173** (2001) 527
- [18]. R. Sartori, et al., *Plasma Physics and Controlled Fusion* **46** (2004) 723
- [19]. ITER Physics Basis: Chapter 2, *Nucl. Fusion* **39** (1999) 2175
- [20]. G. Saibene, et al., *Plasma Physics and Controlled Fusion*, **44** (2002) 1769
- [21]. G. Saibene, et al., *Nuclear Fusion*, **39** (1999) 1133
- [22]. W. Fundamenski, et al., "Effect of ion mass and charge on divertor heat load profiles on JET", paper EXD/P3-11, this conference

- [23]. E. de la Luna, et al., “Effect of ELM mitigation on confinement and divertor heat loads in JET”, paper EXC/8-4, this conference
- [24]. M. Greenwald, et al., Nuclear Fusion, **28** (1988) 2199
- [25]. J. Rapp, et al., Journal of Nuclear Materials **313-316** (2003) 524
- [26]. E. Lerche, “Potential of the ICRH schemes in H-(^3He) plasmas proposed for ITER’s half-field non-activated phase”, paper THW/P2-03, this conference
- [27]. J. Mandrekas and W.M. Stacey, Fusion Technology **19** (1991) 57

Transition	$\langle n_e \rangle$ (10^{20}m^{-3})	f_{Gr}	Threshold power			
			^4He plasma		H plasma	
			simple (MW)	95% interval (MW)	simple (MW)	95% interval (MW)
L-H	0.25	0.42	18-25	12-40	37	20-66
L-H	0.5	0.85	30-42	20-65	60	33-108
Type I-III	0.5	0.85	42-48	23-86	-	

Table 1: Predicted power thresholds for the ITER half-field baseline in H and ^4He plasmas based on the present studies

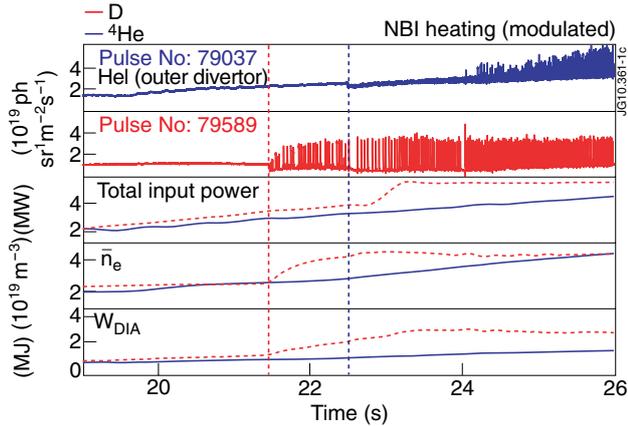


Figure 1: Time traces for a typical ^4He plasma (blue) and D reference (red), both with the same configuration, shape ($\delta = 0.25$), field (1.8T) and current (1.7MA). The dashed lines mark the times of the L-H transitions.

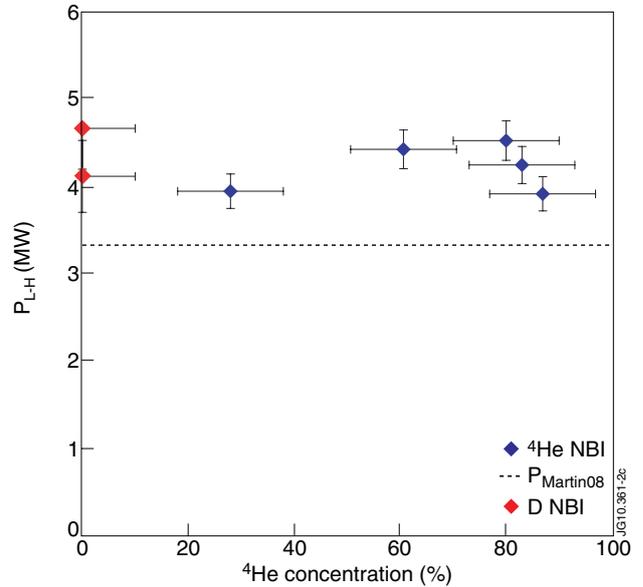


Figure 2: L-H threshold power versus ^4He concentration for JET discharges at matched shape ($\delta=0.25$), field (1.8T), current (1.7MA) and density ($\bar{n}_e = 2.5-2.8 \times 10^{19} \text{m}^{-3}$). Plasmas were heated by D (red) and ^4He (blue) NBI. Dashed line shows the Martin08 scaling [11].

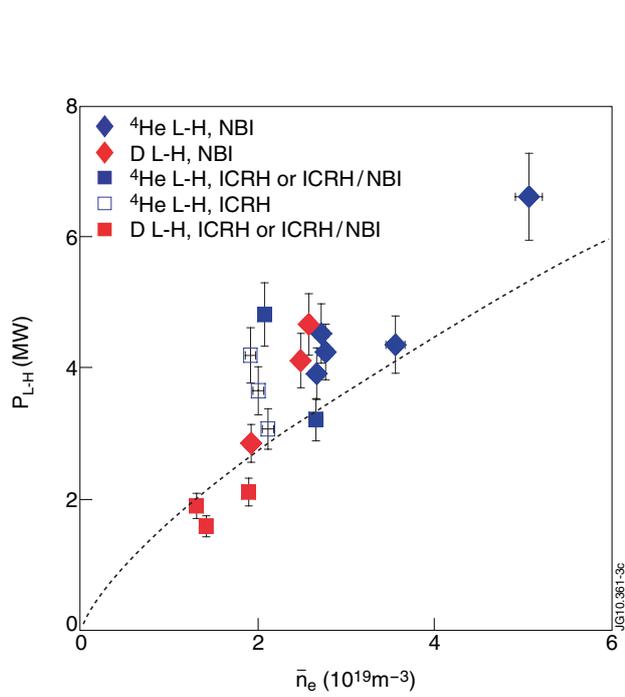


Figure 3: L-H threshold power versus line average electron density for ^4He discharges from the JET 2009 studies (blue) and their D references (red). Open symbols denote L-modes. Dashed line shows the Martin08 scaling [11].

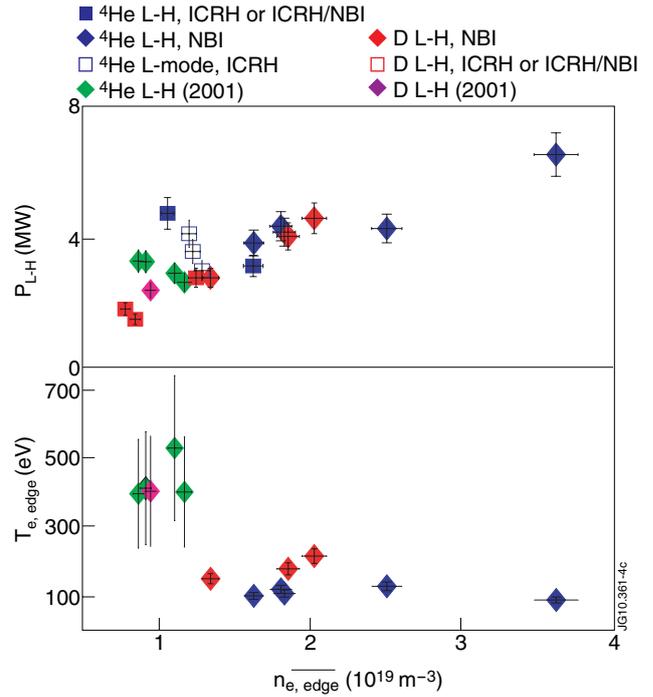


Figure 4: Loss power (top) and edge electron temperature versus edge electron density for ^4He discharges from the JET 2009 studies (blue) and their D references (red). Plasmas are both NBI (diamonds) and ICR (squares) heated. Open symbols denote Lmodes. All discharges have the same configuration, shape ($\delta = 0.25$), field (1.8T) and current (1.7MA). Also included are 2001 ^4He (green) and D (magenta) discharges in a different configuration with similar shape ($\delta = 0.2$) field (1.8T) and current (1.8MA).

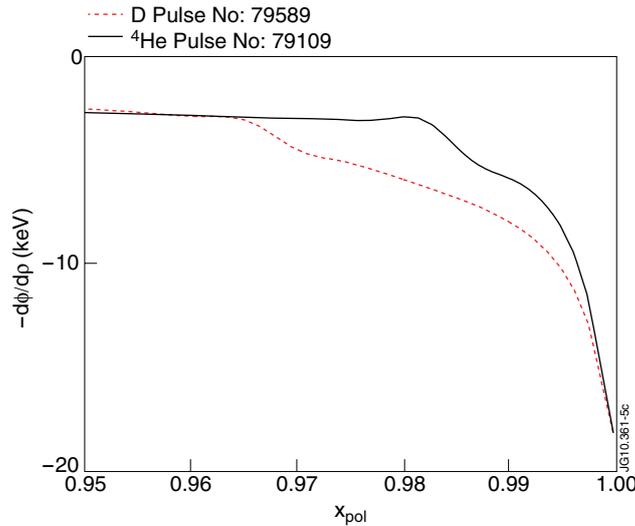


Figure 5: Profile of the radial gradient of the electric potential calculated by the ASCOT code [17] immediately prior to the L-H transition for a ^4He discharge (blue) and a D equivalent (red).

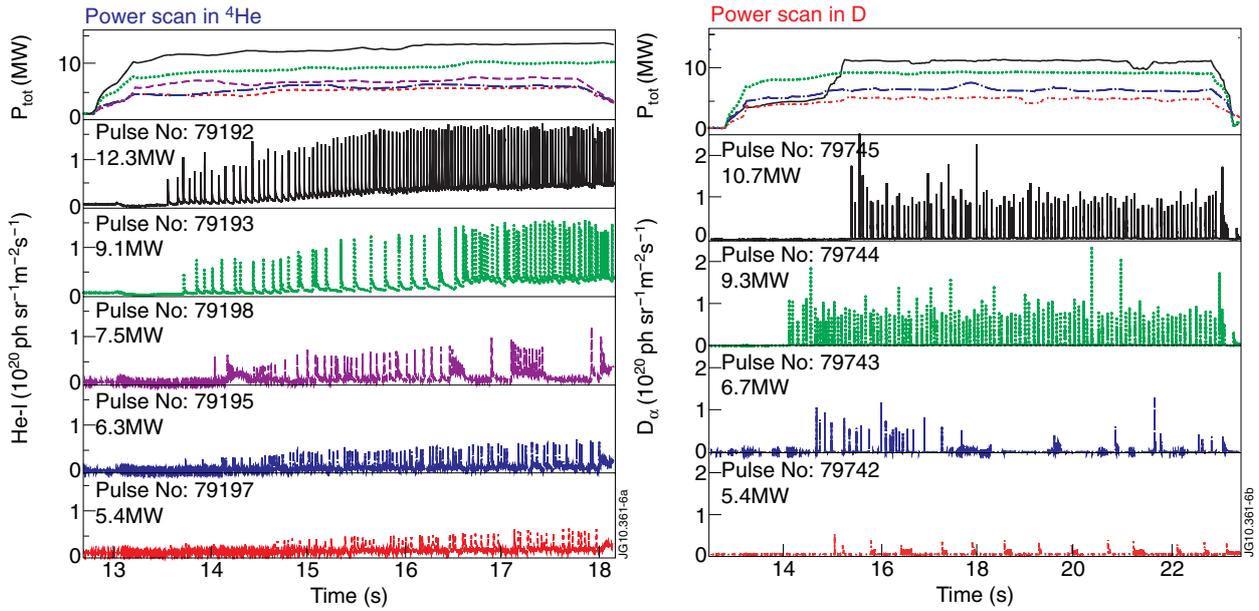


Figure 6: Time traces of input power and divertor light emission for discharges in power scans to determine the Type I-III threshold in ^4He (LHS) and D (RHS) plasmas. Both scans were performed in the same configuration, shape ($\delta = 0.4$), field (1.8T) and current (1.7MA).

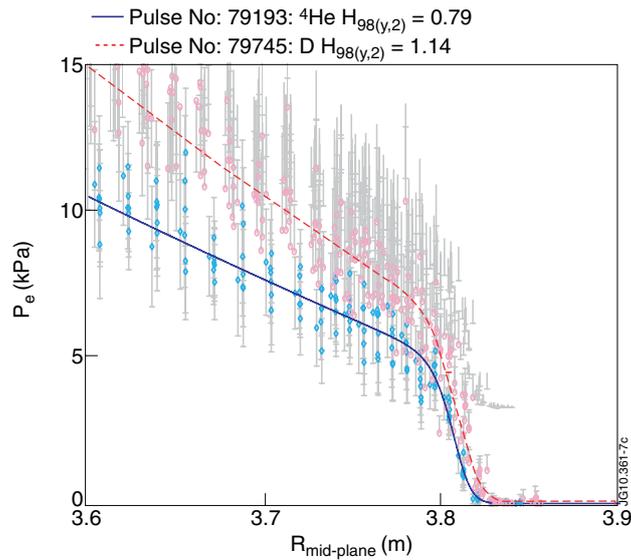


Figure 7: Plasma electron pressure profile from Thomson scattering for a 1.7MA/1.8T, high shape ($\delta = 0.4$) ^4He discharge (blue) from the JET 2009 studies and a D reference (red) at same B, I, power and shape. Solid lines represent the fitted profiles.

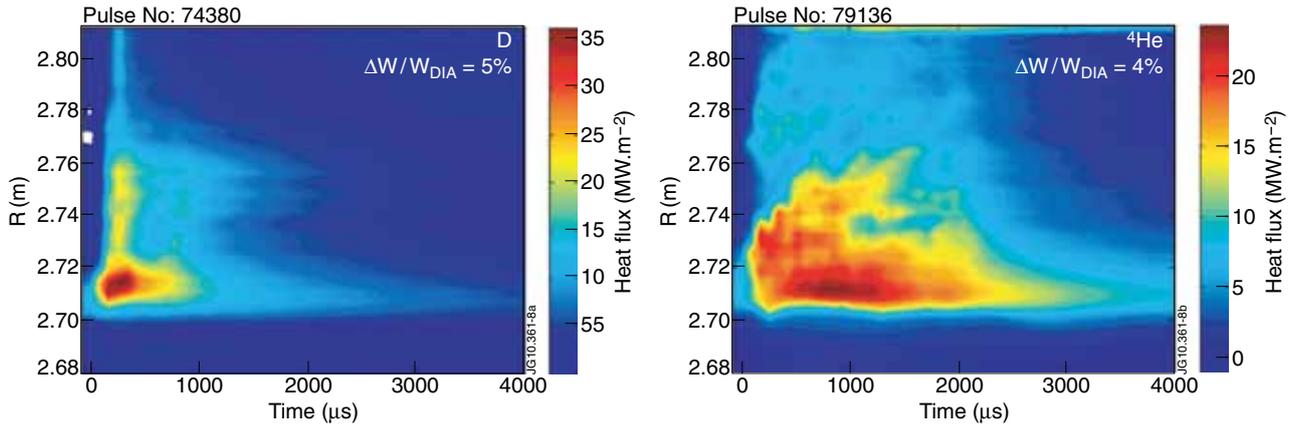


Figure 8: Temporal evolution of the heat load profiles during a typical, medium size ($\Delta W/W \sim 4-5\%$) ELM on the outer divertor target in comparable D and He plasmas.

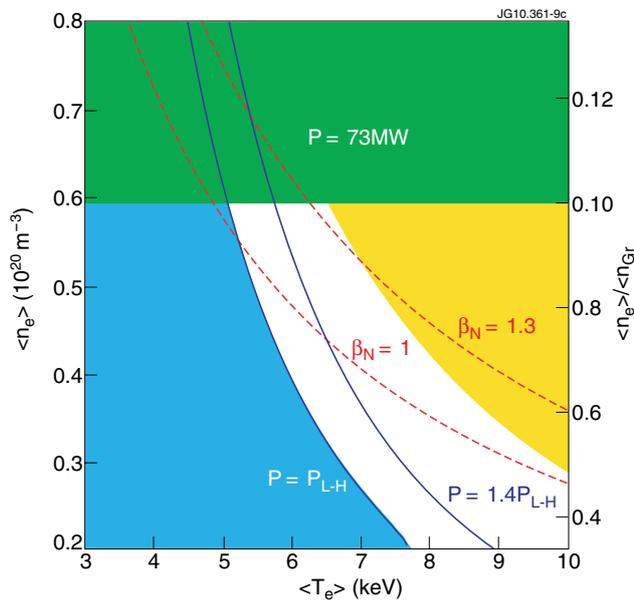


Figure 9: Predicted volume average density versus volume average temperature predicted for ITER He4, half-field baseline scenario: 7.5MA/2.65T. Central white region denotes that accessible for Hmode operation, bounded by L-H threshold power (blue), Greenwald density limit (green) and maximum input power (yellow/black). Also shown are contours of constant beta-normalised (red).