

## JET Helium-4 ELMy H-mode studies

D. C. McDonald 1), G. Calabrò 2), M. Beurskens 1), I. Day 1), E. de la Luna 3,4), T. Eich 5), N. Fedorczak 6), O. Ford 7), W. Fundamenski 1), C. Giroud 1), P. Gohil 8), M. Lennholm 9,4), J. Lonroth 10), P. J. Lomas 1), G. P. Maddison 1), C. F. Maggi 5), I. Nunes 11,4), G. Saibene 12), R. Sartori 12), W. Studholme 1), E. Surrey 1), I. Voitsekhovitch 1), K-D. Zastrow 1) and JET-EFDA contributors\*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

1) Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK

2) Italy Associazione Euratom-ENEA, Via Enrico Ferri 46, 0044 Frascati, Italy

3) Laboratorio Nacional de Fusión, Asociación EURATOM-CIEMAT, Madrid, Spain

4) EFDA-JET CSU, Culham Science Centre, Abingdon, OX14 3DB, UK

5) Max-Planck-Institut für Plasmaphysik, Boltzmannstrasse 2, 85748 Garching, Germany

6) Euratom-CEA, CEA/DSM/DRFC, CEA Cadarache, Saint-Paul lez Durance, France

7) Blackett Laboratory, Imperial College, London SW7 2BZ, UK

8) General Atomics, PO Box 85608, San Diego, CA 92186, USA

9) European Commission, B-1049 Brussels, Belgium

10) Association Euratom-Tekes, Aalto University, Finland

11) EURATOM/IST Fusion Association, IPFN, Av. Rovisco Pais 1049-001 Lisbon Portugal

12) Fusion for Energy Joint Undertaking, 08019 Barcelona, Spain

Email contact of main author: Darren.McDonald@ccfe.ac.uk

**Abstract.** This paper reports H-mode plasma results from the 2009 JET  $^4\text{He}$  campaign which, as part of a wider ITPA study, have extended the physics basis to enable improved predictions of  $^4\text{He}$ , H-modes in ITER. L-H threshold experiments included the first ever dedicated study of the effect of concentration on the L-H threshold.  $^4\text{He}$  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  $^4\text{He}$  plasmas have a 40% higher threshold than D equivalents. A study of the density dependence of the L-H threshold power in  $^4\text{He}$  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  $^4\text{He}$  plasmas. A series of  $^4\text{He}$  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  $^4\text{He}$  (7.5-9.3MW) plasmas. By normalising to a standard L-H threshold scaling, these results can be extrapolated to the ITER,  $^4\text{He}$ , 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  $^4\text{He}$  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  $^4\text{He}$ , 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  $^4\text{He}$  is also studied.

### 1. Introduction

During its low activation phase, ITER must operate with hydrogen (H) or helium-4 ( $^4\text{He}$ ) 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 ( $P_{L-H}$ ) in H,  $P_{L-H}(H) \approx 2P_{L-H}(D)$  [2,3], appears to preclude hydrogen H-modes on ITER. Instead  $^4\text{He}$  plasmas are seen as the most likely for ELMy H-mode operation in the low activation phase [4,5]. 2001 JET studies [4] found  $^4\text{He}$  plasmas had  $P_{L-H} \approx 1.4$  times that of deuterium (D) equivalents and the resulting

\* See the Appendix of F. Romanelli et al., paper OV/1-3, this conference

ELMy H-modes had confinement times ( $\tau_E$ )  $\approx 0.7$  times D equivalents. At the transition, the  $^4\text{He}$  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] ( $f_{\text{He}} \approx 50\text{-}80\%$ ) found similar confinement time behaviour but no change in L-H power threshold between D and  $^4\text{He}$  plasmas. 2009 DIII-D studies ( $f_{\text{He}} > 90\%$ ) found  $^4\text{He}$  plasmas had  $P_{\text{L-H}} \approx 1.3\text{-}1.5$  times that of deuterium (D) equivalents [6]. This paper presents results from the 2009 JET  $^4\text{He}$  campaign which, as part of ITPA joint experiments, aimed to strengthen the  $^4\text{He}$  physics basis by: (i) studying the impact of  $^4\text{He}$  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  $^4\text{He}$  concentrations, the JET  $^4\text{He}$  campaign was run with  $^4\text{He}$  Neutral Beam Injection (NBI) sources. Argon frosted cryopumps in both the NBI sources and the divertor were used to enable density control. The resulting  $^4\text{He}$  purity was 80-95%. Density control was limited with edge recycling tending to rise throughout  $^4\text{He}$  discharges. Ion Cyclotron Resonant Heating (ICRH) was also used, mainly at the fundamental hydrogen resonance [7].

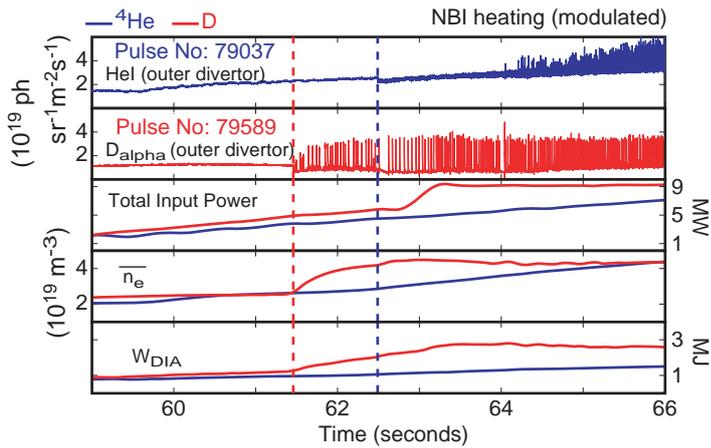


FIG. 1. Time traces for a typical  $^4\text{He}$  plasma (blue) and a D reference (red), both with the same configuration, shape ( $\delta=0.25$ ), field (1.8T) and current (1.7MA). The dashed lines mark the times of the L-H transitions. Density shown is the core line average density.

A series of  $^4\text{He}$ , H-mode plasmas were produced along with a set of D references. FIG. 1. shows time traces 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  $^4\text{He}$  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  $^4\text{He}$  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  $^4\text{He}$  discharge.

## 3. L-H threshold

A study of the impact of  $^4\text{He}$  concentration on  $P_{\text{L-H}}$  varied  $f_{\text{He}}$  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  $^4\text{He}$  NBI sources, except for the lowest  $^4\text{He}$  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, FIG. 2., lying in the range of  $\approx 1.2$ -1.4 times the Martin08 scaling [11], the ITPA recommended scaling for the L-H threshold in D. The Martin08 scaling is defined as

$$P_{Martin08} = 0.0488e^{\pm 0.057} n_{e,20}^{0.717 \pm 0.035} B^{0.803 \pm 0.032} S^{0.941 \pm 0.019},$$

where  $P_{Martin08}$  is the power in MW,  $n_{e,20}$  is the core line average electron density in  $10^{20} \text{m}^{-3}$ ,  $B$  is in T, and  $S$  is the plasma surface area in  $\text{m}^2$ . This result is similar to that reported on ASDEX Upgrade [5], but differs from that for the 2001 JET  $^4\text{He}$  study, which found that L-H threshold power in helium was  $\approx 1.4$  times that of D equivalents [4].

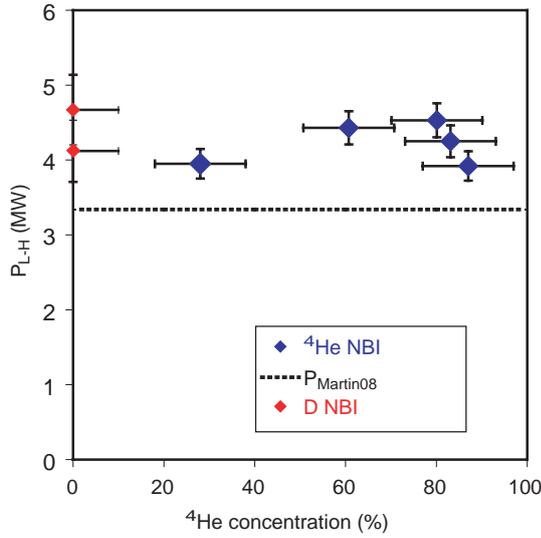


FIG. 2. L-H threshold power versus  $^4\text{He}$  concentration for JET discharges at matched shape ( $\delta=0.25$ ), field (1.8T), current (1.7MA) and density ( $\bar{n}_e=2.5$ - $2.8 \times 10^{19} \text{m}^{-3}$ ). Plasmas were heated by D (red) and  $^4\text{He}$  (blue) NBI. Dashed line shows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

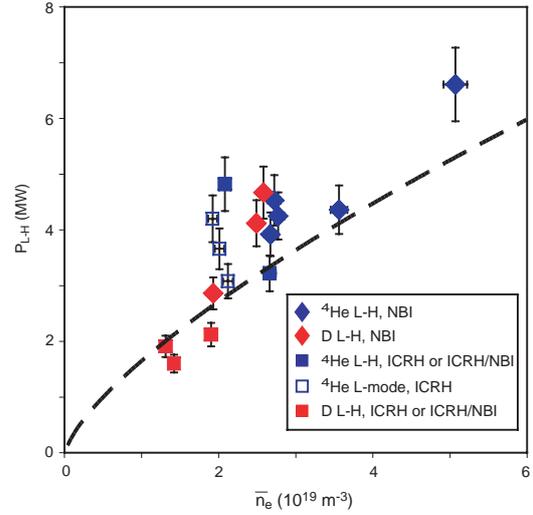


FIG. 3. L-H threshold power versus line average electron density for  $^4\text{He}$  discharges from the JET 2009 studies (blue) and their D references (red). Open symbols denote L-modes. Dashed line shows the Martin08 scaling [11].

The impact of  $\bar{n}_e$  on  $P_{L-H}$  was studied by measuring  $P_{L-H}$  in  $^4\text{He}$  (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, FIG. 3. The  $^4\text{He}$  and D plasmas had similar  $P_{L-H}$  at  $\bar{n}_e=2.5$ - $2.8 \times 10^{19} \text{m}^{-3}$ , but  $P_{L-H}$  was significantly ( $>60\%$ ) higher for  $^4\text{He}$  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 ( $\bar{n}_e=1.0$ - $1.5 \times 10^{19} \text{m}^{-3}$ ) found  $P_{L-H}(^4\text{He}) > P_{L-H}(\text{D})$  whereas the 2009 concentration scan ( $\bar{n}_e=2.0$ - $2.7 \times 10^{19} \text{m}^{-3}$ ) found  $P_{L-H}(^4\text{He}) \approx P_{L-H}(\text{D})$ . In contrast, ASDEX Upgrade found that the  $\bar{n}_e$  dependence of the L-H power threshold in D and  $^4\text{He}$  was identical.

The top window of FIG. 4. shows the same data as FIG. 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.  $^4\text{He}$  and D data from the JET 2001 studies has been added taken from plasmas with a similar shape ( $\delta=0.25$ ),  $B=1.8\text{T}$  and  $I=1.8\text{MA}$ , 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  $^4\text{He}$  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  $^4\text{He}$  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  $^4\text{He}$ , 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  $^4\text{He}$  and D plasmas lying within the much greater uncertainties on these measurements.

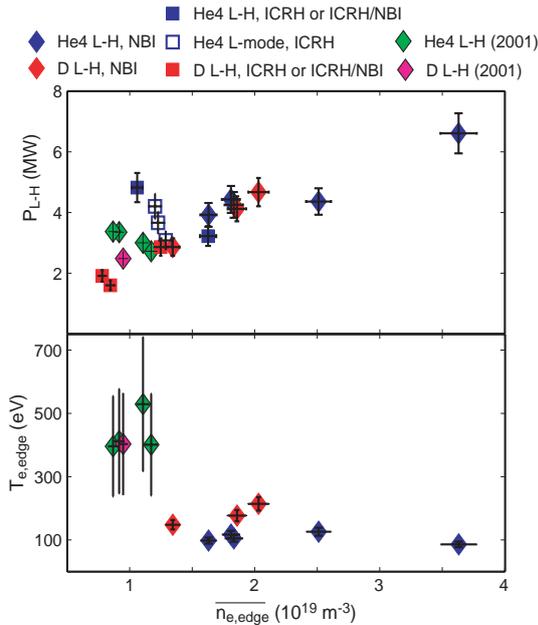


FIG. 4. Loss power (top) and edge electron temperature versus edge electron density for  $^4\text{He}$  discharges from the JET 2009 studies (blue) and their D references (red). Plasmas are both NBI (diamonds) and ICR (squares) heated. Open symbols denote L-modes. All discharges have the same configuration,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

neoclassical orbit losses and to compute the resulting electric field profiles. The results are shown in FIG. 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  $^4\text{He}$  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.

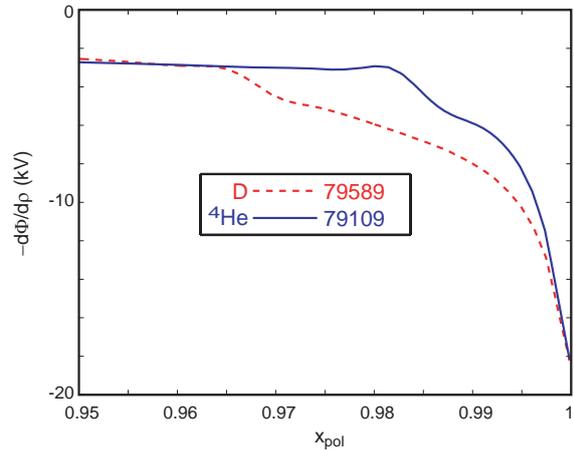


FIG 5. Profile of the radial gradient of the electric potential calculated by the ASCOT code [17] immediately prior to the L-H transition for a  $^4\text{He}$  discharge (blue) and a D equivalent (red).

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  $^4\text{He}$  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  $^4\text{He}$  discharge and D reference, with matched configuration, shape ( $\delta=0.25$ ),  $B=1.8\text{T}$ ,  $I=1.7\text{MA}$  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 FIG. 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  $^4\text{He}$  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  $^4\text{He}$ , the threshold in  $P_{\text{loss}}$  required for Type I ELMy H-modes,  $P_{\text{I-III}}$ , 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  $^4\text{He}$  plasmas and D references – FIG. 6. ELM behaviour can be seen to vary between the two scans, with  $^4\text{He}$  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  $^4\text{He}$  plasmas. However, the  $^4\text{He}$  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,  $P_{\text{Martin08}}$ , [11] this becomes  $P_{\text{I-III}}/P_{\text{Martin08}}=1.4-1.6$ . A similar range is observed for the D references:  $P_{\text{I-III}}=6.7-9.3\text{MW}$ , equivalent to  $P_{\text{I-III}}/P_{\text{Martin08}}=1.2-1.8$ .

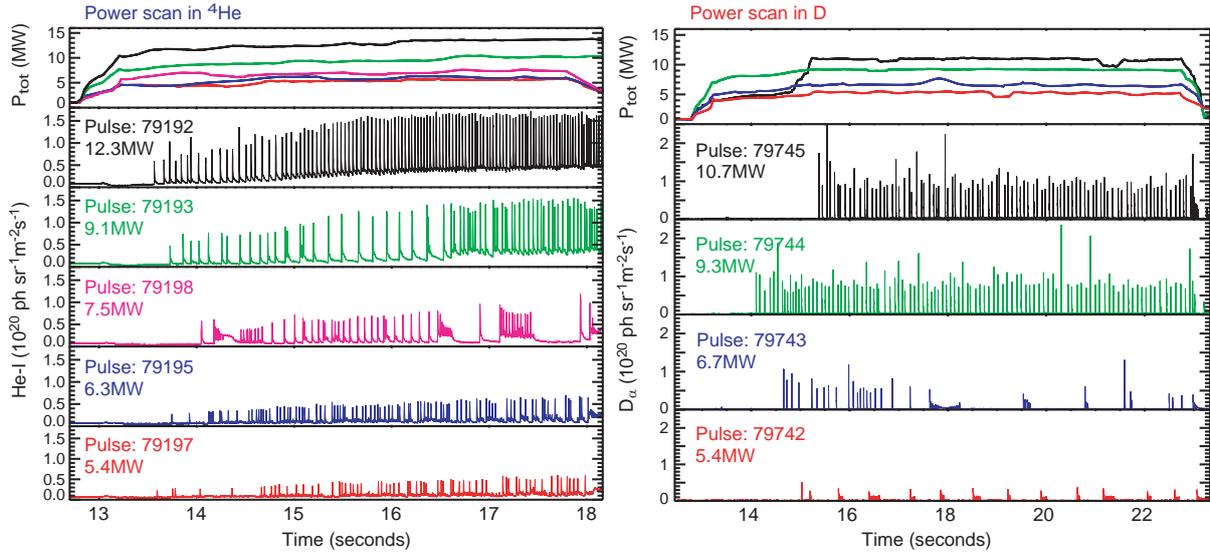


FIG. 6. Time traces of input power and divertor light emission for discharges in power scans to determine the Type I-III threshold in  $^4\text{He}$  (LHS) and D (RHS) plasmas. Both scans were performed in the same configuration, shape ( $\delta=0.4$ ), field (1.8T) and current (1.7MA).

#### 5. H-mode physics

In the 2009 studies, a set of Type I ELMy H-mode plasmas were produced in  $^4\text{He}$ , 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  $^4\text{He}$  plasmas would have confinement times in the relation  $\tau_E(^4\text{He})/\tau_E(\text{D})=0.5-0.7$  in line with the 2001 JET and the 2008 ASDEX Upgrade studies [5]. Due to the low efficiency of pumping  $^4\text{He}$ , all of the  $^4\text{He}$  discharges had high edge recycling which has been shown to reduce confinement [20]. Impurity accumulation, which can reduce confinement, was also observed on some  $^4\text{He}$  discharges. Thus, the lower  $\tau_E$  observed for  $^4\text{He}$  plasmas is not purely due to isotope effects and, if edge recycling and impurity accumulation could be mitigated, higher  $\tau_E(^4\text{He})/\tau_E(\text{D})$  may be achievable. Improvements in JET diagnostics meant that the electron density, temperature and pressure profiles, FIG. 7., of the ETB could be resolved in these studies. For the two plasmas #79193 and #79745 (time traces in FIG. 6) the thermal energies were in the ratio  $W_{\text{th}}(^4\text{He})/W_{\text{th}}(\text{D})=0.6-0.8$  and the electron pedestal pressures in the ratio  $p_{e,\text{ped}}(^4\text{He})/p_{e,\text{ped}}(\text{D})=0.6-0.8$ , showing that the lower confinement observed in  $^4\text{He}$  plasmas is associated with a lower pedestal pressure. This is in line with the strong correlation between pedestal energy and 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.

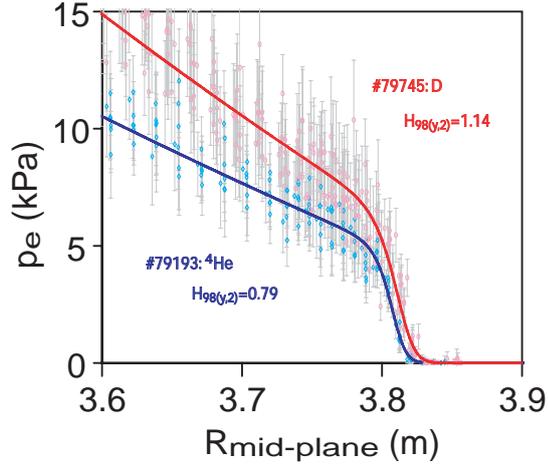


FIG. 7. Plasma electron pressure profile from Thomson scattering for a 1.7MA/1.8T, high shape ( $\delta=0.4$ )  $^4\text{He}$  discharge (blue) from the JET 2009 studies and a D reference (red) at same B, I, power and shape. Solid lines represent the fitted profiles

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  $^4\text{He}$  inter-ELM and time averaged profiles were moderately broader ( $\approx 50\%$ ) in  $^4\text{He}$  compared with D plasmas, with an associated reduction in peak heat load, FIG. 8. [22].  $^4\text{He}$  and D ELM heat load profiles have similar radial widths, but with  $^4\text{He}$  ELMs having a much longer power arrival time scale. The application of Resonant Magnetic Perturbations did not mitigate ELM heat loads in the  $^4\text{He}$  plasmas studied. It is believed that this is a consequence of

the high recycling in the  $^4\text{He}$  plasmas [23].

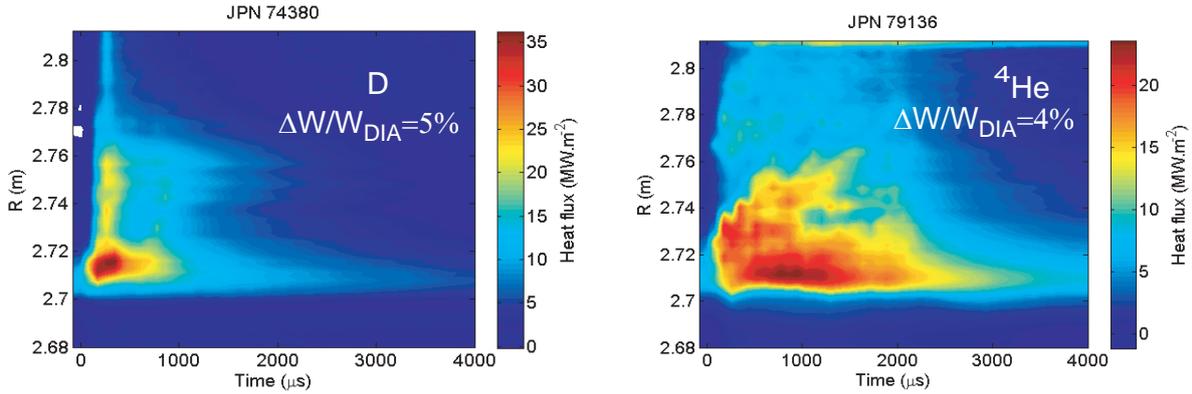


FIG. 8. Temporal evolution of the heat load profiles during a typical, medium size ( $\Delta W/W \sim 4\text{-}5\%$ ) ELM on the outer divertor target in comparable D and He plasmas.

## 6. Extrapolation to ITER

TABLE I. PREDICTED POWER THRESHOLDS FOR THE ITER HALF-FIELD BASELINE IN H AND  $^4\text{He}$  PLASMAS BASED ON THE PRESENT STUDIES

Transition	$\langle n_e \rangle$ ( $10^{20}\text{m}^{-3}$ )	$f_{\text{Gr}}$	Threshold power			
			$^4\text{He}$ 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	-	

Due to the absence of  $\alpha$ -heating and the predicted high threshold powers for H and  $^4\text{He}$  plasmas, ELMy H-mode operation in the low activation (H and  $^4\text{He}$ ) 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  $n_{\text{Gr}}$ , the Greenwald density limit [24] - NB: the density limit in  $^4\text{He}$  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  $^4\text{He}$  are given in Table I.  $P_{\text{L-H}}(^4\text{He})$  is taken in the range from  $P_{\text{Martin08}}$ , 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  $\bar{n}_e \approx 2 \times 10^{19} \text{ m}^{-3}$  here and in the DIII-D studies [6].  $P_{\text{H}}(\text{H}) \approx 2 P_{\text{Martin08}}$  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  $^4\text{He}$  plasmas would be expected to access H-mode at low density, but H plasmas would be marginal at the higher field.  $^4\text{He}$  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  $^4\text{He}$  plasma ICRH schemes, whereas coupling is observed to be problematical in the ITER H plasma ICRH schemes [26].

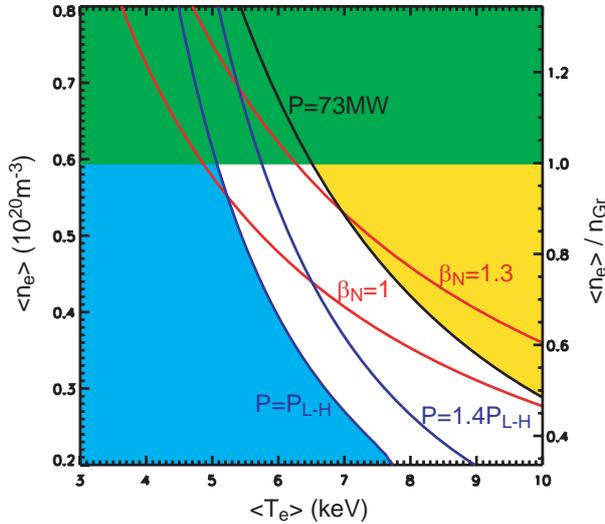


FIG. 9. Predicted volume average density versus volume average temperature predicted for ITER  $^4\text{He}$ , half-field baseline scenario: 7.5MA/2.65T. Central white region denotes that accessible for H-mode operation, bounded by L-H threshold power (blue), Greenwald density limit (green) and maximum input power (yellow/black). Also shown are contours of constant beta-normalised (red).

Upgrade and DIII-D. Extrapolations indicate that the L-H and Type I power thresholds can be achieved in  $^4\text{He}$  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

FIG. 9. shows the predicted parameter space for volume averaged electron density ( $\langle n_e \rangle$ ) and temperature ( $\langle T_e \rangle$ ) for  $^4\text{He}$  operation in the half-field ITER baseline scenario calculated with the GTBURN code [27]: assuming  $H_{98(y,2)}=0.7$ ,  $P_{\text{L-H}}=P_{\text{Martin08}}$  and  $P_{\text{I-III}}=1.4P_{\text{Martin08}}$ . 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.

## 7. Conclusion

The 2009 JET  $^4\text{He}$  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

physics and the impact of ELM heat loads on plasma facing components prior to the high activation phase of ITER.

### Acknowledgements

*This work, part-funded by the European Communities under the contract of Association between EURATOM and CCFE, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was also part-funded by the RCUK Energy Programme under grant EP/G003955. Part of this work is implemented under the International Energy Agency's cooperation agreement on Large Tokamak Facilities established between JAEA, US DOE, and EURATOM.*

### References

- [1] B. J. Green, Plasma Phys. Control. Fusion **45** (2003) 687
- [2] K. Lackner, et al., Plasma Phys. Control. Fusion **36** (1994) B79
- [3] E. Righi, Nucl. Fusion **39** (1999) 309
- [4] D. C. McDonald, et al., Plasma Phys. Contr. 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 <sup>4</sup>He 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., Phys. Fluids B **3** (1991) 2300
- [9] H. Zohm, Plasma Phys. Cont. 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, Nucl. Fusion, **41** (2001) 1925
- [13] Y. Andrew, et al., Plasma Phys. Control. Fusion **46** (2004) 337
- [14] J. W. Connor and H. R. Wilson, Plasma Phys. Control. Fusion **42** (2000) R1
- [15] T. Kiviniemi, et al., Plasma Phys. Contr. 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 Phys. Control. Fusion **46** (2004) 723
- [19] ITER Physics Basis: Chapter 2, Nucl. Fusion **39** (1999) 2175
- [20] G. Saibene, et al., Plasma Phys. Control. Fusion, **44** (2002) 1769
- [21] G. Saibene, et al., Nucl. 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., Nucl. Fusion, **28** (1988) 2199
- [25] J. Rapp, et al., J. Nucl. 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