H-mode threshold studies in helium-4 JET plasmas

G Calabrò[1], D C McDonald [2], M Beurskens[2], C F Maggi[5], I Day[2], E de la Luna[3,4], T Eich[5], N Fedorczak[6], D Frigione[1], O Ford[2], E Giovannozzi[1], C Giroud[2], P Gohil[7], T.P. Kiviniemi[8], M Lennholm[4,9], P J Lomas[2], J Lonnroth[8], G P Maddison[2], I Nunes[2,10], V Pericoli Ridolfini[1], F Ryter[5], G Saibene[11], R Sartori[11], W. Studholme[2], E Surrey[2], I Voitsekhovitch[2], K-D Zastrow[2] and JET-EFDA Contributors*

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

[1]*Associazione Euratom-ENEA, Via Enrico Fermi 46, 0044 Frascati, Italy*
[2]*Culham Centre for Fusion Energy, Abingdon, Oxon OX14 3DB, UK*
[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 fur Plasmaphysik Euratom Association, D-85740 Garching, Germany*
[6]*Association Euratom-CEA, CEA Cadarache, F-13108, St Paul lez Durance, France*
[7]*General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA*
[8]*Association EURATOM-Tekes, Helsinki University of Technology, Finland*
[9]*European Commission, B-1049 Brussels, Belgium*
[10]*EURATOM/IST Fusion Association, IPFN, Av. Rovisco Pais 1049-001 Lisbon Portugal*
[11] *Fusion for Energy Joint Undertaking, 08019 Barcelona, Spain*

1. Introduction

During its low activation phase, ITER must operate with H or He plasmas [1]. To assess ELM loads and commission some systems, it is desirable that part of this operation be in ELMy H-modes. The high L-H power threshold (P_{thr}) in hydrogen (H) appears to preclude H H-modes on ITER and instead He is seen as the most likely choice [2,3]. 2001 JET studies found He plasmas had P_{thr}(He) ≈ 1.4 times that of D [2]. At the transition the He plasmas had helium purity (f_{He}) of 84-94%. 2008 ASDEX Upgrade (AUG) studies (f_{He} ≈50-80%) found no change in P_{thr} between D and He plasma [3]. It should be underlined that previous AUG results showed P_{thr}(He) ≈ 1.4 times that of D. Finally, 2009 DIII-D studies (f_{He} ≈95%) found He plasmas had P_{thr} ≈ 1.3-1.5 times that of D [4].

This paper presents results from the 2009 JET He campaign aimed to better assess He H-mode threshold by studying the impact of f_{He} and electron density (n_e) on P_{thr}.

2. Experimental setup

To ensure ITER-like He concentrations the JET 2009 campaign was run with He NBI sources and argon frosted cryopumps in both the NBI sources and the divertor. The resulting He purity was 80-95%. 2009 L-H threshold experiments were performed operating with the MarkII-HD divertor (in 2001 JET operated with MarkII-GB divertor). The pumping speed of He+D in 2009 was lower than in 2001 (by 50% typically). The He purity was measured by spectroscopy in the divertor region. The relative errors in He concentration measurements have been estimated as having a standard deviation of 20% of the true value [2]. The f_{He} and n_e dependence of P_{thr} has been investigated in He and D

* See the Appendix of F. Romanelli et al., Proceedings of the 22nd IAEA Fusion Energy Conference 2008, Geneva, Switzerland

references discharges with the same plasma parameters (I_P = 1.7 MA, B_T = 1.8T, $q_{95} \approx 3.6$). The configurations all had the same low, $\delta \approx 0.25$, shape. The L-H power threshold was measured using a NBI (with or only ICRH heating at low densities) linear power slow ramp (about 1.3-1.4 MW s^{-1}) from the Ohmic level to a value above the transition to H mode. In all cases, power ramp with NBI were obtained through fast modulation of beam ion source. The standard deviation of the relative errors for the correction for shine-through losses lie in the range 8-11% [2]. All the data used in the present analysis have been averaged over 50 ms in the L-mode phase just before the L-H transition. The values for the power threshold P_{thr} are provided in the normal way as the loss power though the separatrix, $P_{LOSS}=P_{OHM}+P_{AUX}-dW_{DIA}/dt$, where P_{OHM} is the ohmic power dissipated in the plasma, P_{AUX} is the absorbed auxiliary heating and dW_{DIA}/dt is the rate of change of the diamagnetic energy W_{DIA}. The threshold results for He and D will be compared using the ITPA 2008 scaling [5], which predicts for D, in MW:

$$P_{thr,scal08} = 0.049 B_T^{0.80} n_{20}^{0.72} S^{0.94}, \qquad (1)$$

where B_T [T], n_{20} [$10^{20}m^{-3}$] and S [m^2] are respectively the magnetic field, line-averaged density, plasma surface area. The dependence of the threshold power on the ion mass number M is given by $P_{thr} \propto 1/M$ [6].

3. L-H transition in He plasmas

With the experimental setup described in Section 1, the dependence of P_{L-H} on the f_{He} and density has been studied. The He purity dependence of P_{thr} has been studied using He NBI during the D to He changeover with f_{He} varied from 1–87% and density variations 2.3-2.8 x $10^{19}m^{-3}$. In Fig.1 two identical discharges obtained at 1.7MA/1.8T using D and He (f_{He}~83%) are shown. The L-H transition in D plasma is clearly defined with a sharp discontinuity in the main plasma parameters as the D_α light, n_e and W_{DIA}. On the contrary the L-H in He is observed as a slow transition. In the present analysis n_e is the interferometer measured line integrated divided by the central chord length in the plasma. Errors in density are estimated as ±4%.

The nature of the He L-H transition has been studied through a detailed analysis of the spectroscopic measurements of He I line emission from outer and inner part of the divertor. L-H in He was observed as a transition a metastable plasma state where high frequency pseudo-periodic oscillations (~2kHz) are seen in the divertor spectroscopic measurements, then followed by type I ELMs. Fig. 2 shows the scalogram of the He I line outer divertor signal for the same He shot considered in Fig.1. A mode around 2kHz starts and slowly evolves in frequency while the input power is increasing. In addition, at the L-H transition, the correlation between the inner and outer divertor signals starts to increase above the noise level and stays at high level (~0.7) whilst the time shift between the two signals reaches a constant values as well (~300µs from outer to inner divertor plates). Together with the front like shape of the oscillations (sharp increase and slower relaxation), these oscillations are identified as type III ELMs, labelling the L-H transition.

The influence that the f_{He} has on the transition to H-mode is summarized in Fig.3, where the P_{thr} is plotted against the He concentration. The D based scaling $P_{thr,scal08}$, given in eq. (1), is also shown, for a toroidal field of B_T=1.8T and a plasma surface area of S=150m^2. Although all the shots lie above the ITPA 2008 scaling, the results show a weak trend with concentration and $P_{thr}(He) \approx P_{thr}$ (D), even weaker if the radiated power is removed. This trend agrees with AUG 2008 results [3].

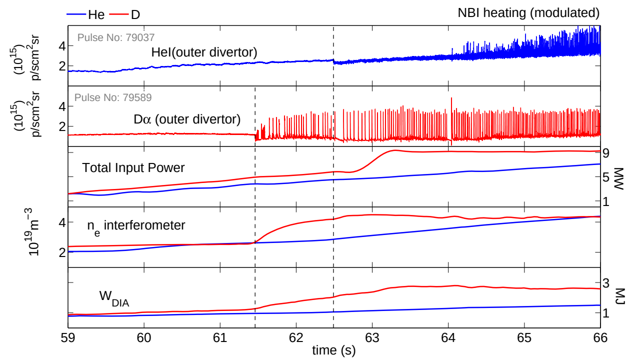

Figure 1: Time evolution of the main plasma parameters for two identical discharges obtained at 1.7MA/1.8T and δ=0.25 using He and D. The total input power showed is the sum of the ohmic power dissipated in the plasma and the absorbed auxiliary heating power.

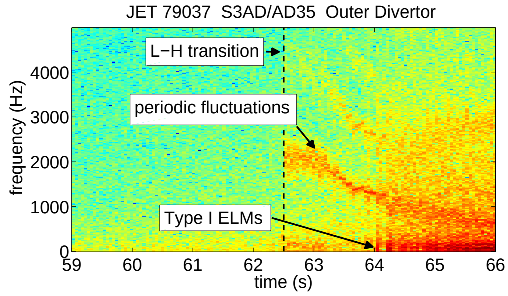

Figure 2: The frequency scalogram for the outer divertor spectroscopic measurement (given for the He discharge) .

The n_e dependence of P_{thr} showed a marked difference in the He and D data (Fig. 4). The He and D plasmas had similar P_{thr} at n_e=2.3-2.8 x 10^{19}m^{-3}, but P_{thr} was significantly higher for He plasmas than for D plasmas at lower n_e=2.1 10^{19}m^{-3}. This differing n_e dependence is consistent with the fact that the 2001 studies (n_e=1-1.6 x 10^{19}m^{-3}) found P_{thr}(He)>P_{thr}(D) [2]. At $n_e \approx$ 2.0 x 10^{19}m^{-3}, it was found that P_{thr}(He)>P_{thr} (D) for ICRH heated plasmas. By normalising to the standard L-H threshold scaling, described in eq. (1), these results can be extrapolated to the ITER, He, half-field, baseline conditions (2.65T, 7.5MA, 678m^2 and density of 50% of the Greenwald limit), by giving a prediction of 42-52MW of injected power would be required to achieve an H-mode transition, consistent with the design auxiliary heating capacity of ITER (73MW).

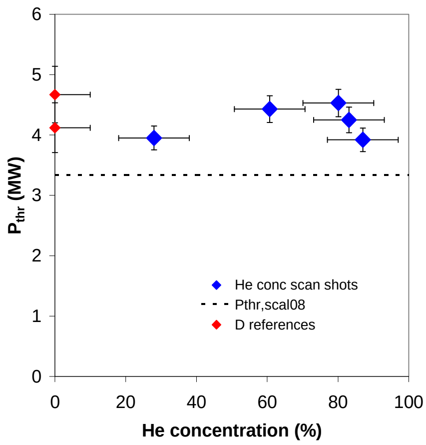

Figure 3: P_{thr} obtained with NBI as function of f_{He} for both He and D reference discharges at 1.7MA/1.8T. The configurations all had the same low δ≈0.25 shape, and densities variations 2.3-2.8 x 10^{19}m^{-3}.

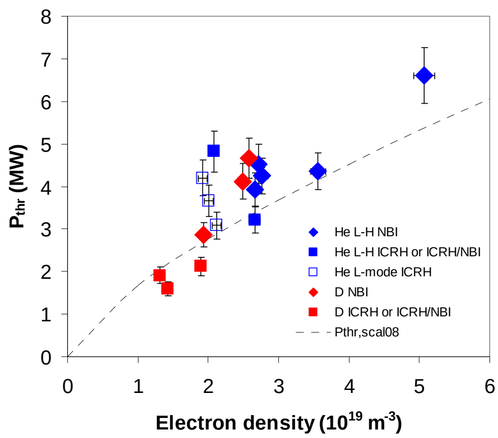

Figure 4: P_{thr} as function of n_e for both He and D reference discharges at 1.7MA/1.8T. The configurations all had the same low δ≈0.25 shape, and densities variations 1.3-5.01 x 10^{19}m^{-3}.

A set of High Resolution Thomson Scattering (HRTS) edge data at the LH transition for D and He discharges has been collected. L-H in He is observed, in Fig. 5, as a transition with a smaller ETB than in D. In addition, at similar $n_{e,edge}$, a transition at lower $T_{e,edge}$ is observed in He. This result is not consistent with the L-H transition model based on a critical E_r x B shear flow stabilization of edge turbulence, resulting from neoclassical transport in the collisonal regime [7]. Here, Er is the radial electric field and B is the magnetic field. Simulations for D and He, with matched density and temperature profile and charge neutrality assumed, were reported in the same paper. The shear was observed much lower for helium. As discussed in ref [7], assuming that the critical shear is similar in D and He and shear increases as a function of the temperature, this implies that the threshold temperature for L-H transition is expected to be higher for He than for D. Further studies are needed.

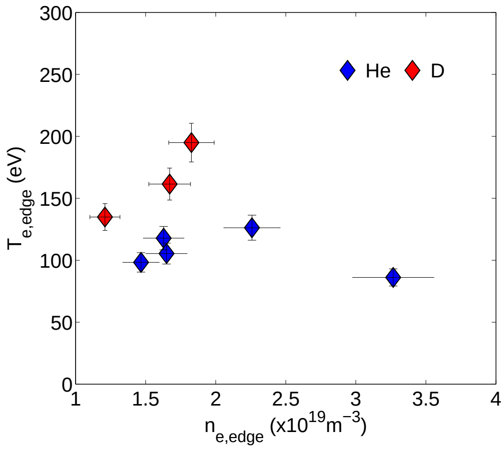

Figure 5. Edge electron temperature values plotted as a function of the edge density for He and D discharges. Errors in HRTS edge data are estimated as ±8-10%.

4. Conclusions

2009 JET He campaign has given an important contribution to the multi-machine L-H threshold studies. L-H in He has been observed as a transition to Type III ELMs with a small confinement improvement and small ETB. He concentration 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 predicted that He plasmas have a 40% higher threshold than D equivalents. A study of the density dependence of the L-H threshold power in 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 results seem to justify in making the $P_{thr}(He)/P_{thr}(D) \approx 1\text{-}1.5$ assumption where density seems to an important driver in determining the low or high end of the range. Although physics understanding remains to be improved and further experiments have to be intensified, helium remains the favorable choice than hydrogen for the non-nuclear phase of ITER.

Acknowledgments

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