H-Mode Threshold and Confinement in Helium and Deuterium in ASDEX Upgrade

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Abstract. In 2008, experiments have been carried out in ASDEX Upgrade to compare H-mode power threshold and confinement time in helium and deuterium. A scan in magnetic field and a wide density variation indicate that the threshold power in the two gases is very similar. The density dependence of the threshold exhibits a clear minimum. Confinement in helium is about 30% lower than in deuterium, mainly due to the reduction of the ion density caused by Z=2 in helium.

1. Introduction

The H-Mode is at present the baseline scenario foreseen for ITER and its threshold power (P_{thr}) predicted by the scaling deduced from the ITPA database is about 50 MW in deuterium at a density of $5 \times 10^{19} \mathrm{m}^{-3}$ [1]. It has been emphasized recently that achieving the H-mode during the non-nuclear phase of ITER in hydrogen or helium plasmas is highly desirable to assess several physical and technical issues. However, it is well established that P_{thr} in hydrogen is about 2 times larger than in deuterium, [2, 3, 4, 5]. In contrast, it has been shown in JET that P_{thr} in helium is only about 40% higher than in D, [6]. This motivated in April 2008 the ITPA Transport and Confinement Topical Group to initiate Joint Experiments (proposal TC-4 *H-Mode transition and confinement dependence on ionic species*), including ASDEX Upgrade, DIII-D and JET, to better assess H-mode threshold and confinement dependencies on ion species. To this aim, dedicated experiments in ASDEX Upgrade have been performed between May and October 2008. Moreover, the existence of a minimum threshold ($P_{thr,min}$) at a density n_{min} was observed in several tokamaks [7, 8, 9, 1]. Results from Alcator C-Mod suggesting that n_{min} increases with magnetic field, [10], are a concern for ITER at $B_T \approx 5$ T. This issue is addressed in the ITPA proposal TC-3 (*Scaling of the low density limit of the H-Mode threshold*), for which experiments in ASDEX Upgrade have also been carried out in 2008. In this Letter we present the ASDEX Upgrade contributions to both TC-3 and TC-4.

2. Previous results in H, D and ^{4}He

Besides the well-documented deuterium results on threshold and confinement contributed to the ITPA data bases for about 15 years, a rather complete hydrogen data set was available from ASDEX Upgrade before 2008, but only sparse results from non-systematic experiments in ^{4}He existed. In Fig. 1, the threshold results for the three gases are compared using the ITPA scaling expression [1], only valid above n_{min} and which reads for D, in MW:

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

where $B_T[T], n_{20} [10^{20} \mathrm{m}^{-3}]$ and $S [\mathrm{m}^2]$ are respectively the magnetic field, line-averaged density and plasma surface area. The values for P_{thr} are provided by the usual net heating power just prior to the LH transition and defined as

$$P_{net} = P_{Ohm} + P_{heat} - dW/dt \tag{2}$$

where P_{Ohm} is the residual Ohmic power, P_{heat} the absorbed auxiliary heating power and W is the plasma energy content. As usually done for such studies and for the scaling as well, the radiation losses are not subtracted. It should be underlined that the radiated power from the main plasma corresponds to about 30% of the input power in the discharges studied here and is very similar in deuterium and helium.
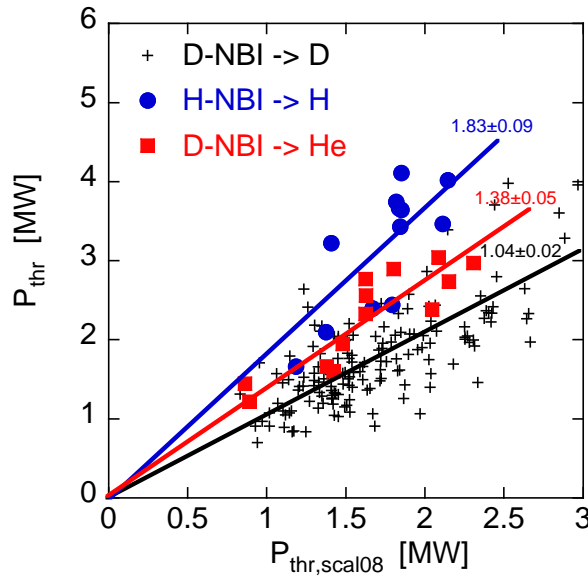

Figure 1. *Power threshold results in ASDEX Upgrade in D, H and He before 2008. Experimental power threshold versus scaling assuming deuterium. The lines are linear fits forced through the origin.*

Figure 1 indicates that the deuterium data are in good agreement with the scaling as shown by the slope of the fit which is very close to 1. The ranges in our dataset are 1.5 - 2.8 T for B_T, 0.5 - 1.0 m^{-3} for n_{20} and 42 - 45 m^2 for S. The threshold for H is about 1.8 higher than in D, whereas that of ^{4}He plasmas only by about 1.4. The D and H confinement data (not

shown here) agree with the usual confinement scaling ITERH98y2, [11], including the mass dependence $M^{0.19}$. The ^{4}He confinement data are about 30% lower than in D and very close to those in H. These previous threshold and confinement results are in agreement with those from JET, [6].

3. New threshold and confinement results in ^{4}He and D

3.1. Experimental conditions

The new helium studies have been carried out in July 2008. Electron Cyclotron Heating and Hydrogen Neutral Beam Injection were used to heat the plasmas. Since 2008, the ECH system delivers up to 2.2 MW absorbed in the plasma, which allows to explore H-mode threshold over a wide density window. In particular, the low density branch of P_{thr} could be extensively investigated. The choice of hydrogen for NBI has been governed by the fact that this species will be used in ITER at the beginning and that ASDEX Upgrade ^{4}He data with D-NBI already existed. As adding hydrogen into helium plasmas is expected to increase P_{thr} and reduce confinement, this is a conservative approach for extrapolating to ITER in which the NBI fueling will be much lower than in ASDEX Upgrade. Figure 2 shows the helium purity, measured by spectroscopy in the divertor region and assessed by active charge exchange spectroscopy in the main plasma for some of the points.
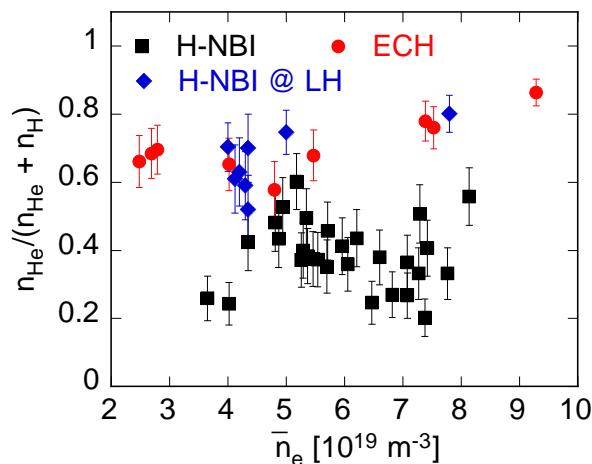

Figure 2. *Purity of ^{4}He versus density, for ECH any time during discharge, for H-NBI at LH transition or any time in discharge.*

The helium purity was around 75% for ECH-heated plasmas with a trend to increase with density, attributed to gas puffing. For plasmas heated with H-NBI, the helium purity is lower and varies strongly. It should be noted that in general with H-NBI, the ^{4}He concentration decreases with time during a discharge, while in counterpart the H concentration increases. This is the cause for the large scatter of the H-NBI data taken at any time during the discharges, with different values of heating power (black squares in Fig. 2). In contrast, the H-NBI points

at the LH transition have a rather high helium purity because they are early in the discharges and with rather low NBI power.

3.2. Power threshold in D and ^{4}He

The B_T dependence of P_{thr} in ^{4}He has been studied using H-NBI at $\bar{n}_e \approx 4 \times 10^{19} \text{m}^{-3}$. As shown in Fig. 3, the B_T dependence of P_{thr} in ^{4}He follows that of the scaling. On average, the 2008 points are somewhat below the scaling, as discussed later. For comparison, we also plotted data points from previous deuterium plasmas in the same density range.
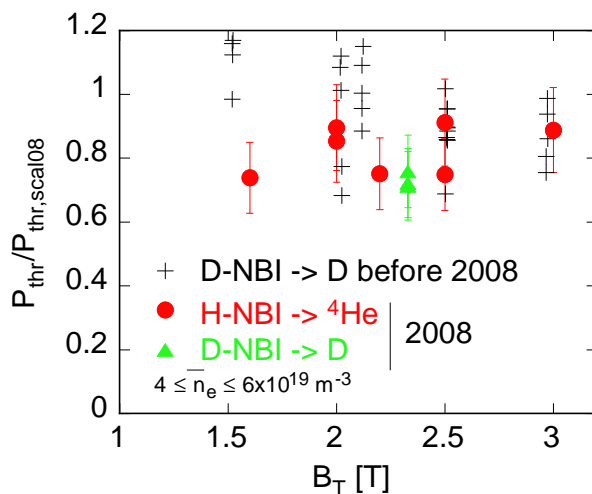

Figure 3. *Power threshold normalized to scaling assuming deuterium, versus magnetic field for a narrow density range indicated in the plot. The effect of the density variation is corrected by the scaling.*

The density dependence of P_{thr} has been investigated in 2008 with ECH in both D and ^{4}He discharges with the same plasma parameters ($I_p = 1.0$ MA, $B_T = 2.3$, T $q_{95} \approx 4.5$). For comparison between heating methods, points for P_{thr} have also been obtained with NBI.

The results for the density dependence, Fig. 4, clearly exhibit a minimum of P_{thr} at $n_{min} \approx 4.5 \times 10^{19} \text{m}^{-3}$. The minimum is very similar for the two gases. The fact that also the values of P_{thr} are the same over the whole density range is in contrast to our previous results (Sect. 2) and to the JET results. The deuterium points with ECH have mainly been obtained in May 2008. Motivated by the unexpected lack of difference between P_{thr} in D and ^{4}He, in October, we performed further experiments in D with ECH and with D-NBI, which confirmed the results. There is so far no explanation for the discrepancy between the previous and the new results. As possible influence, it should be underlined that the 2008 experiments have been carried out with the full tungsten wall instead of graphite for the previous data. Also, a somewhat different plasma shape has been used which better fits the divertor geometry. The line plotted in Fig. 4 shows that both the deuterium and helium points obtained in these new series are about 20% below the scaling in its region of validity ($\bar{n}_e \geq 4 \times 10^{19} \text{m}^{-3}$). In fact, a comparison with our previous data in deuterium indicates that the 2008 points are just at
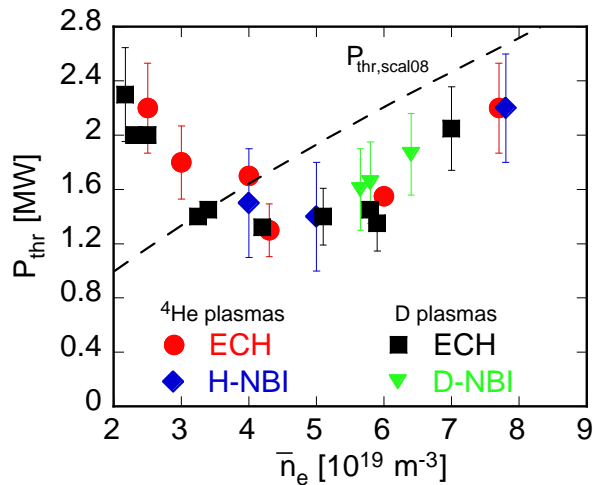
Figure 4. *Power threshold versus density for D and ^{4}He, all points from 2008. The dashed line is $P_{thr,scal08}$ for the corresponding plasma conditions.*

the lower boundary of all the previous P_{thr} values. Finally, it is also worth-noting that no measurable difference can be detected between ECH and NBI.

We collected a complete set of edge data at the LH transition. The first analyses suggest that the edge electron pressure at the LH transition is independent of density and gas [12]. A complete analysis of this aspect will be published elsewhere.

3.3. New confinement data in ^{4}He

To compare the experimental confinement time in helium, we use the usual ITERH98y2 scaling expression, assuming deuterium. The fast ions corrections required to estimate the experimental thermal confinement time were assumed to be the same as in deuterium, which introduces additional uncertainties up to 10%. Our normalized confinement data, $\tau_E/\tau_{ITERH98y2}$, in helium for H-NBI, D-NBI and ECH are summarized in Fig. 5 versus density. For the three datasets, $\tau_E/\tau_{ITERH98y2}$ decreases with density, with different strengths characterized by a power law indicated in the figure for comparison with $\propto n_e^{0.41}$ of *ITERH*98y2. This property of the density dependence is not specific to helium plasmas and is also generally observed in deuterium plasmas, see e.g. [13], indicating that the actual density dependence is weaker than that of the scaling. The significant difference between D-NBI and H-NBI may be attributed to the influence of helium purity. This is supported by the fact that the ECH points lie in-between and that all datasets converge at high density. It should be pointed out that the uncertainties on the corrections for the fast ions effects mentioned above might also play a role.

During the 2008 campaign we performed D and ^{4}He H-mode discharges, heated by D-NBI and H-NBI respectively, with the same shape, at $I_p = 1$ MA, $q_{95} \approx 4.5$ and with a heating power of 3.4 MW. The ELM frequency in D was about 50 Hz whereas it was about 300 Hz in ^{4}He. This led to a higher density in D compared to that in ^{4}He. In these discharges, the
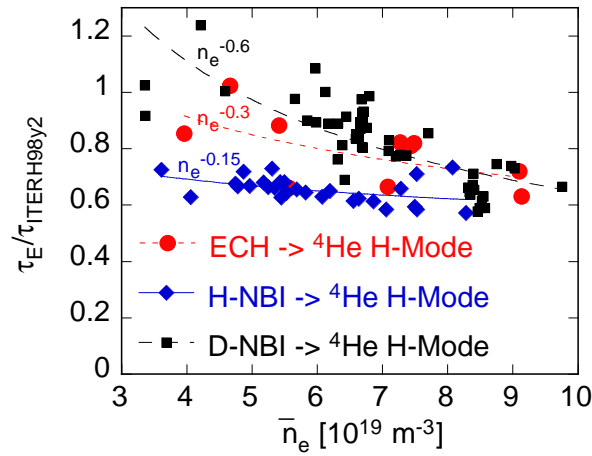
Figure 5. *Density dependence of the helium confinement data. The circles and diamonds are from 2008, the squares from previous data. The lines are power fits.*

temperature profiles were very similar for both gases with $T_e \approx T_i$. Taking into account a rough estimate of Z_{eff} and impurity content, the ion density can be deduced and the total pressure calculated, see Fig. 6. The pressure in ^{4}He is lower than that in D by about 30%, as also shown in Fig. 6 by the ratio of the pressure in the two gases. This effect is mainly due to Z=2 of the helium ions with an additional contribution to the difference arising from the lower pedestal pressure in helium, likely linked with the ELM behaviour. This is consistent with the different τ_E values in the two gases, $\tau_E/\tau_{ITERH98y2}$ being ≈ 1 in D and ≈ 0.65 in ^{4}He, as also indicated by Fig. 5.
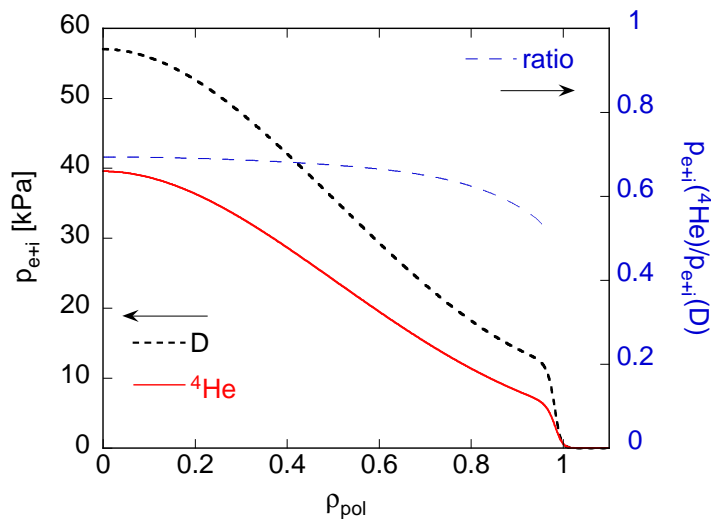

Figure 6. *Plasma pressure in D and ^{4}He: total pressure profiles in the two gases and their ratio.*

The different confinement times in ^{4}He and D have a completely different origin than the well-known isotope effect between H and D. In the case of hydrogen, the temperature profiles

are lower than in D due to a higher heat transport as investigated in ASDEX Upgrade, [14].

4. Conclusion

As a prompt response to requests for ITPA Joint Experiments, H-mode power threshold and confinement studies have been carried out in ASDEX Upgrade in both helium and deuterium plasmas. The new results indicate that the power threshold in the two gases is very similar, in contrast to previous data from ASDEX Upgrade and JET. The reason for this difference remains to be understood in further experiments in 2009. In any case, the power threshold in helium is clearly lower than in hydrogen which is favorable for ITER. It should be underlined that a metallic inner wall, tungsten in our case, has no deleterious effect on the power threshold.

In agreement with previous data from ASDEX Upgrade and JET, the global confinement time in helium is about 30% lower than in deuterium, mainly caused by Z=2 in helium. From the point of view of power threshold and confinement, helium appears to be a better choice than hydrogen for the non-nuclear phase of ITER. However, it should be underlined that the expected higher ELM frequency might not allow to test ELM control methods.

It must be underlined that the factor of 2 between electron and ion pressure in helium is an interesting situation to extend H-mode transition and pedestal physics studies. It could help sorting out the respective role of ions and electrons and may widen the understanding of the ELM physics, for instance in comparison with impurity seeding experiments. Therefore, comparison between deuterium and helium plasmas, which is of great interest for future tokamak operation and physics understanding, should be intensified.

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