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Confinement and Pedestal and Edge Physics

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Assessment of the H-mode Power Threshold Requirements for ITER

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Abstract. This paper contains a multi-machine assessment on accessing H-mode plasmas for the non-nuclear operational phase in ITER with H and/or He plasmas. Experiments have been performed to determine the H-mode power threshold, P_{TH}, in ASDEX Upgrade, C-Mod, DIII-D, JET, NSTX, and MAST. The ratio of $P_{TH}(H)/P_{TH}(D)$ appears to be relatively consistent at about a value of 2. However, for helium there is a large variation in $P_{TH}(He)/P_{TH}(D)$ from 1.0–1.8. On devices that show a difference, the ratio of $P_{TH}(He)/P_{TH}(D)$ decreases towards unity with increasing L-mode (or target) electron density, which is a favorable trend for ITER for operation at higher densities. The application of resonant magnetic perturbation fields can lead to significant increases in the H-mode power threshold as has been determined in ASDEX Upgrade, DIII-D, MAST and NSTX.

1. Introduction

This paper reports on results from multiple magnetic fusion devices on the dependence of the H-mode threshold power, P_{TH}, on the main ion species and on applied 3D fields. The scientific results are due to the combined activities of the ITPA Topical Groups on Transport and Confinement (T&C) and Pedestal and Edge Physics (PEP). In particular, this paper reports on P_{TH} for H and He plasmas (as well as D plasmas) in preparation for the first phase of plasma operations in ITER, which will be performed with H and/or He plasmas to avoid activation of the vessel during tests and commissioning of the device hardware and control systems. Accessing H-mode plasmas in this operational phase is important in order to assess the capabilities of control systems in H-mode e.g. for edge localized mode (ELM) control. These experiments are also important to understand the operational limits of H and He plasma scenarios in ITER [1,2]. In the case of D plasmas, the assessment of the H-mode power threshold has been extensively investigated over several decades culminating in the latest version of the parametric scaling of the threshold power with global variables given by [3]

$$P_{TH,\,scal08}(D) = 0.049\ B_T^{0.80} n_e^{0.72} S^{0.94} \quad , \tag{1}$$

where B_T is the toroidal magnetic field (T), n_e is the line-averaged electron density in L-mode (10^{20} m^{-3}) and S is the plasma surface area (m^2). For the isotopes of hydrogen, the P_{TH} has been shown to roughly scale as A^{-1} with respect to the above scaling, where A is the isotopic mass [4]. Presently, there is no explicit scaling expression for P_{TH} for helium, but only a relative determination with respect to D plasmas. Therefore, in order to assess P_{TH} in the non-nuclear operational phase for ITER with H and/or He plasmas, experiments have recently been performed in ASDEX Upgrade (AUG), Alcator C-Mod, DIII-D, JET, NSTX, and MAST with particular attention to the density dependence of P_{TH}. Note that all references to helium plasmas and helium neutral beam injection (NBI) in this paper refer to the helium-4 (^{4}He) isotope unless otherwise mentioned.

The use of magnetic perturbations, through the application of 3D fields, has led to ELM mitigation or suppression in several devices [5,6]. However, the application of these 3D fields may also affect the H-mode power threshold, which is an important consideration for the application of 3D fields in ITER and this paper reports on the latest results in this area.

2. H-mode Threshold Power Dependence on Main Ion Species

Experiments on ASDEX Upgrade (mostly at I_p=1.0 MA, B_T=2.4 T, R=1.65 m, a=0.5 m, κ=1.6) on the H-mode threshold power dependence on the main ion species have been performed over the course of several years during which the plasma facing components (PFCs) were changed, from mostly carbon (in 2003) to mostly tungsten by 2008. Before 2008, the P_{TH} in H and He were roughly 1.8 and 1.4 times that in D plasmas, respectively. In 2008, with the full tungsten wall, a series of dedicated experiments were performed to determine the density dependence of P_{TH} in both deuterium and helium. [7]. In these discharges, it was determined that P_{TH} is the same for D and He [Fig. 1(a)] and exhibits a non-monotonic dependence upon density, with a minimum around 4x10^{19} m^{-3}. These experiments were performed with different auxiliary heating methods: electron cyclotron heating (ECH), D-[neutral beam injection(NBI)] and H-NBI. Note that ECH or H-NBI into helium plasmas would be the heating methods that would be used in the non-nuclear phase of ITER operations. The use of H-NBI resulted in an increase in the H concentration and, consequently, an increase in the power threshold as the ^{4}He purity decreased [7]. The experimental results in 2008 also revealed that P_{TH} in D was about 25% lower than the previous studies in D, which has been confirmed in further systematic studies from 2008 to 2012 [8]. The fact that P_{TH} is the same in D and He in the 2008 study (with the full tungsten wall) is in sharp contrast to the results before 2008 (with the carbon wall) in which the P_{TH} in He was about 1.4 higher than in D and the reason for this is as yet unknown. In the case of hydrogen, the threshold power was a factor of 1.8 higher than in D with the carbon PFCs and this ratio also holds for the tungsten wall in which P_{TH} in H (as in D) is also decreased by about 25%.

In C-Mod, experiments were performed to compare the P_{TH} in D and He plasmas using ion cyclotron radio frequency (ICRF) heating on the H minority ions with PFCs consisting of bulk molybdenum tiles with varying degrees of boron coatings. Note that

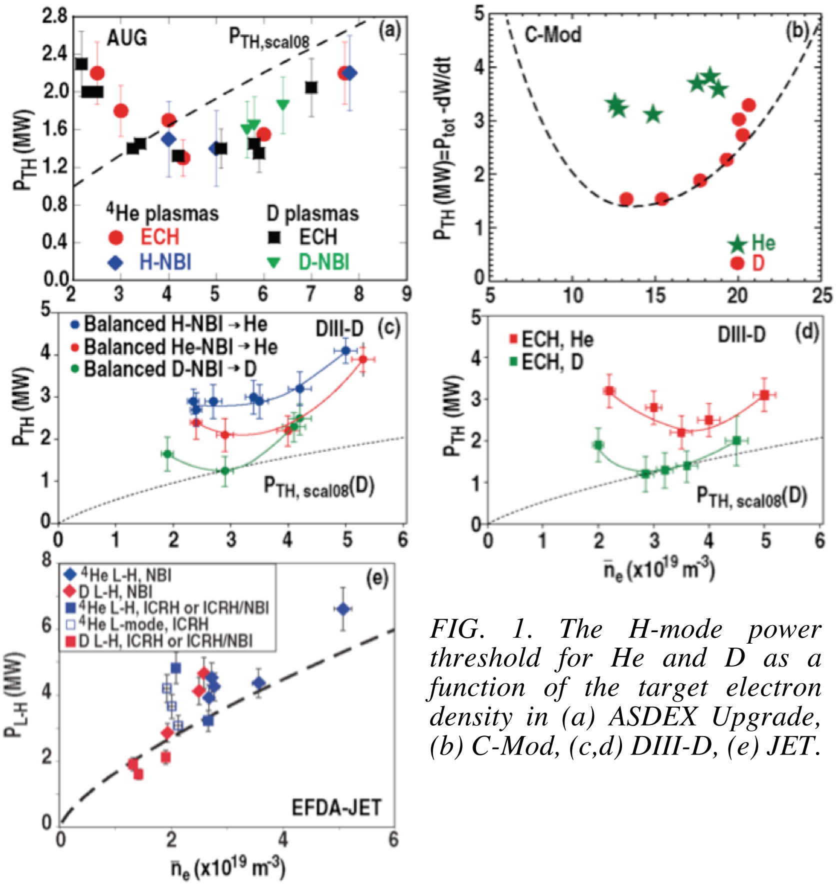

FIG. 1. The H-mode power threshold for He and D as a function of the target electron density in (a) ASDEX Upgrade, (b) C-Mod, (c,d) DIII-D, (e) JET.

C-Mod employs a closed divertor configuration very similar to that designed into ITER. A series of He plasma discharges with (I_p=1.0 MA, B_T= 5.4 T, R=0.67 m, a=0.22 m, κ=1.6) were first performed to evaluate P_{TH} as a function of density between 1.2–1.9x10^{20} m^{-3} [9]. This was followed by the determination of P_{TH} in a series of D plasmas with the density decreasing from 2.1 to 1.3x10^{20} m^{-3}. The measured power thresholds are shown in Fig. 1(b), alongside the dashed curve corresponding to the fit with pure D plasmas (as determined from a large database of D plasma discharges). The D discharges were generally in good agreement with the database trend, while the He discharges had power thresholds roughly a factor of 2 higher. The initial D majority discharges with $\overline{n}_e$ >2x10^{20} m^{-3} likely had substantial concentrations of residual He, which could be responsible for a slightly more elevated P_{TH} than the fit with pure D plasmas. In separate experiments, P_{TH} was found to be reduced in D plasmas by placing the outer strike point more deeply in the divertor [10], but it is not yet known whether this effect persists in He plasmas.

On DIII-D, H-mode power threshold experiments have been performed on H, He and D plasmas (mostly at I_p=1.0 MA, B_T=1.65–2.0 T, R=1.7 m, a=0.7 m, κ=1.7) using auxiliary heating with ECH, H-NBI, D-NBI and He-NBI with carbon PFCs. High levels of main ion purity were maintained in these plasmas by using the corresponding gas species for the NBI system (i.e. He-NBI into He plasmas, H-NBI into H plasmas, D-NBI into D plasmas). For H plasmas with H-NBI, the P_{TH} is a factor of 2–2.5 greater than that for D plasmas [11]. Figure 1(c,d) shows the density dependence of P_{TH} for D and He plasmas for balanced (i.e., zero input torque) NBI and ECH discharges. Figure 1(c) shows the density dependence for D-NBI into D plasmas, He-NBI into He plasmas and H-NBI into He plasmas. The lowest power threshold at the lower target densities (n_e<3x10^{19} m^{-3}) is observed for D plasmas followed by significantly higher power thresholds for He plasmas. However, at higher densities (~4x10^{19} m^{-3}) the threshold powers for D and He plasmas are about the same, indicating that the difference in the power threshold between D and He plasmas is very density dependent similar to the results in C-Mod [Fig. 1(b)]. The power threshold for discharges with H-NBI into He plasmas is substantially higher than the above cases at all densities. This is to be expected given that the power threshold for H is higher than that for He [12] and there is some dilution of the He plasmas due to fueling by the H-beams. One non-nuclear operational scenario for ITER is to use H-NBI into He plasmas and this may lead to an increase in P_{TH} in these plasmas. However, the degree of beam fueling is expected to be lower on ITER than in present day devices and so should lead to a lower level of hydrogen dilution and the expected increase in P_{TH} may be small. For the case of ECH into D and He plasmas [Fig. 1(d)], a variation in the ratio of P_{TH}(He)/P_{TH}(D) with density is also observed with the ratio becoming smaller at higher densities. For the He plasmas, the minima in the density dependence of P_{TH} occurs at a slightly higher density than for deuterium, which partly explains the similarity in power thresholds at higher densities as a result of shifting of the minima.

The DIII-D experiments also showed a strong dependence of P_{TH} on the height of the X-point location above the divertor surface for all three ion species (H, D and He) and this is suspected to be caused by changes in edge recycling as the X-point is changed [13]. This effect changes the absolute value of P_{TH} for all three species, with the P_{TH} decreasing with decreasing X-point height. This is an important effect that needs to be considered for any extrapolations and predictions for ITER.

Experiments on JET have been performed over a span of several years on H, D and He plasmas with H-NBI, D-NBI, He-NBI and ion cyclotron resonance heating (ICRH) and predominantly carbon PFCs. Early studies showed that P_{TH}(H)/P_{TH}(D) was ≈2 [4]. Later studies with He plasmas showed that P_{TH}(He)/P_{TH}(D) was about 1.4 [14]. More recent studies show that the ratio of P_{TH}(He) to that of P_{TH}(D) varies with the line-averaged electron density [15] with P_{TH}(He)/P_{TH}(D) tending towards to unity at higher densities (i.e. n_e=2.5–2.8x10^{19} m^{-3}) as shown in Fig. 1(e), which is similar to the results at higher densities in C-Mod and DIII-D. At lower densities (n_e~2.1x10^{19} m^{-3}), the ratio of P_{TH}(He)/P_{TH}(D) is around 1.3, which is consistent with the 2004 results, which were also performed at low n_e=1.0–1.5x10^{19} m^{-3}. Edge T_e measurements at the pedestal at the time of the L-H transition indicate a fairly weak dependence on density for both He and D plasmas with T_e being slightly higher in D plasmas.

Experiments on MAST have compared P_{TH} in D plasmas with D-NBI to P_{TH} in He plasmas with D-NBI. With a ratio of He to D concentrations of 0.5/0.15, the ratio of P_{TH}(He)/P_{TH}(D) was determined to be 1.4 at a line averaged density of ~2.4x10^{19} m^{-3} [16]. With the same excess power P_{loss}-P_{TH}~0.3 MW. The edge n_e and T_e were similar in both D and He plasmas, with the core temperature being slightly higher in the He plasmas. No systematic dependence of P_{TH} in He plasmas with density was performed and no measurements of P_{TH} were made with H plasmas. As observed in DIII-D and JET, the vertical position of the X-point location was observed to significantly change P_{TH} (in this case in both single and double null configurations).

Experiments on NSTX compared P_{TH} in relatively pure D and He plasmas with auxiliary power input using high harmonic fast wave (HHFW) heating, with a wavenumber of k_ϕ=-8 m^{-1} [17,18]. The experiments were performed over a small range of line-averaged electron density from 1.8–2.2x10^{19} m^{-3} and it was not possible to determine the density for the minimum in P_{TH} for either D or He. The results are shown in Fig. 2, which shows the threshold power normalized by the line-averaged density. Overall, P_{TH} for He is about 1.0–1.4 greater than that for D. Examination of the T_e profiles indicated no obvious or consistent presence of a critical edge T_e at the L-H transition for the D and He plasmas. Further L-H transition studies indicated that P_{TH} decreases with increasing radius of the X-point location, which was explained with the lowered toroidal field at the increased radius and the scaling of P_{TH} with the toroidal field.

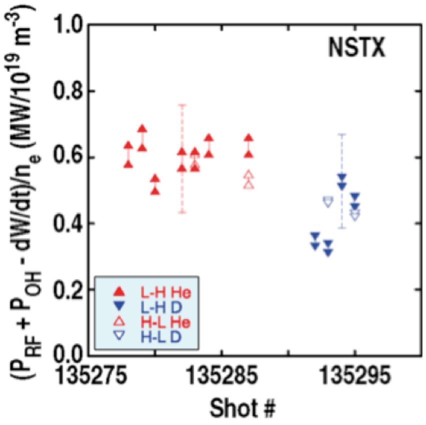

FIG. 2. Threshold powers normalized by line-averaged density for a sequence of discharges in NSTX. There are two symbols for each discharge, indicating the value using the average overall heating efficiency and the heating efficiency for that particular species.

The results from all the above experiments for H and He plasmas compared to D plasmas are summarized in Table 1, which shows the variation in the ratio of the power thresholds for the respective species in these devices (not the absolute power thresholds).

For hydrogen, the ratio of P_{TH}(H)/P_{TH}(D) appears to be relatively consistent at about a value of 2. However, for helium there is a large variation in P_{TH}(He)/P_{TH}(D) ranging from 1.0–1.8. These results will be discussed in Sec. 4.

Table 1. The ratio of P_{TH}(H)/P_{TH} (D) and P_{TH} (He)/P_{TH} (D) determined in several devices using different auxiliary heating methods

Device	AUG	C-Mod	DIII-D	JET	MAST	NSTX
P_{TH}(H)/P_{TH}(D)	~1.8		~2	~2		
P_{TH}(He)/P_{TH}(D)	~1.0	1.2-1.8	1.0-1.6	1.0-1.3	1.4	1.0-1.4
Auxiliary heating	H-NBI, D-NBI, ECH	ICRH	H-NBI, He-NBI, D-NBI, ECH	H-NBI, He-NBI, D-NBI, ICRH	D-NBI	HHFW

3. H-mode Power Threshold Dependence on 3D Fields

In ASDEX Upgrade, ELM mitigation by 3D magnetic perturbations (MPs) is achieved above a certain density, which corresponds to about 0.6 n_{GW} [6]. Correspondingly, the effect on the

L-H transition by these magnetic perturbations has been investigated in AUG for the case of n=2 MPs in D plasmas [19]. The experiments were conducted with a constant level of magnetic perturbations and the L-H transition obtained during heating power ramps at various densities for 1 MA discharges. A clear change of the L-H threshold power above a certain density has been found, which is similar to the behaviour with the density dependence for ELM mitigation. The results are summarized in Fig. 3, which shows the increase in P_{TH} in the presence of n=2 MPs compared to the cases without MPs ($P_{TH,ref}$) as well as the discharges that remain in L-mode despite significantly higher heating powers ($P_{L\text{-mode}}$, open circles) with n=2 MPs at higher densities. At low density ($n_e \leq 0.4\ n_{GW}$) the MPs, at maximum available field strength, have no effect on the L-H transition, P_{TH} is the same with and without MPs and the L-H transition is followed by the appearance of type-I ELMs. However, at high densities ($n_e > 0.6\ n_{GW}$) the L-H transition cannot be produced even with a level of heating power, which is 2 times greater than the value without MPs. For intermediate densities ($0.4\ n_{GW} \leq n_e \leq 0.6\ n_{GW}$), the power required to produce the L-H transition increases with increasing density above the P_{TH} without MPs. In these cases, the L-H transition is immediately followed by small type-III ELMs, which in turn are fully mitigated by the increase in the natural density which follows the L-H transition.

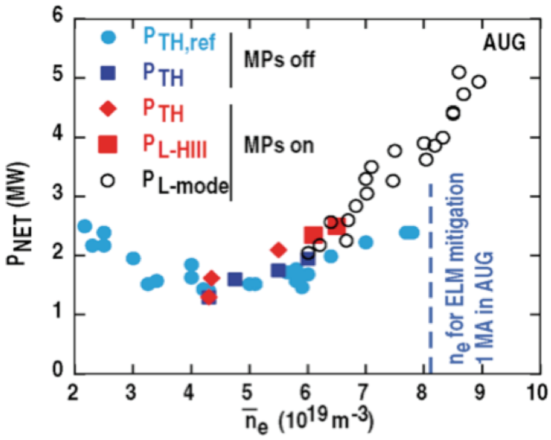

FIG. 3. Net heating power versus line averaged density in AUG showing the L-H power threshold with and without MPs n=2 (I_p=1 MA).

In DIII-D, the application of n=3 RMP fields leads to significant increases in the H-mode power threshold. The effect on the L-H transition has been investigated in D plasmas heated by ECH and balanced D-NBI and in He plasmas heated by ECH and balanced H-NBI [13]. The n=3 fields are produced by internal, off-midplane magnetic coils (I-coils) for specific values of q_{95} in order to optimize the resonance of the applied fields. The H-mode power threshold was determined for different I-coil currents and the results for D plasmas are shown in Fig. 4 as a function of $\delta B/B_T$. Here $\delta B/B_T$ is the normalized radial component of the n=3 vacuum RMP field integrated along the closed magnetic lines on a rational magnetic surface, as determined by the SURFMN code [20]. The solid blue circles correspond to the NBI heated discharges at q_{95}=3.4, which were resonant with the RMP field and that transitioned to H-mode. The discharge with the highest I-coil current of 5.3 kA did not transition to H-mode at that applied NBI power. The open blue circles correspond to NBI heated discharges with off resonant components (i.e. at q_{95}=4.0) that also transitioned to H-mode. For ECH discharges, the P_{TH} for resonant q_{95} values are depicted by the red solid squares and for off resonant values by the open red squares. The ECH discharge at $\delta B/B_T \sim 3.5\text{x}10^{-4}$ denoted by a red solid triangle did not transition to H-mode with the available ECH power. Overall, for strong resonant components in the RMP

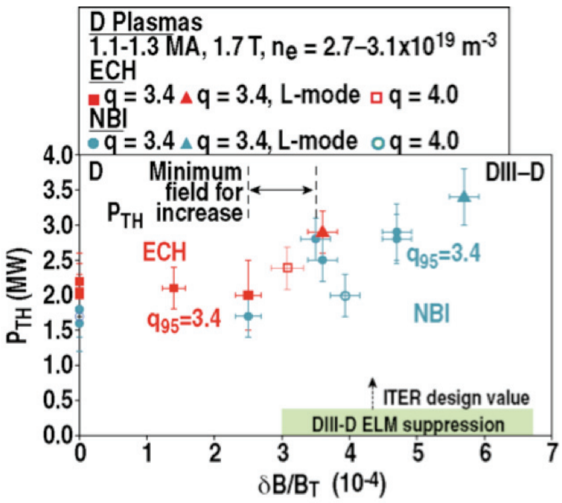

FIG. 4. The H-mode threshold power as function of RMP field strength in DIII–D for different values of the edge safety factor and for ECH and NBI for D plasmas.

spectrum, there is a significant increase in P_{TH} for RMP fields above a critical threshold field (i.e. for $\delta B/B_T$ above ~$3x10^{-4}$), whereas no clear increase in P_{TH} is observed below this field level (in contrast to He plasmas, where there is no critical threshold in the perturbing field). For off resonant fields, there is a much smaller increase in P_{TH} with the applied field. For reference, $\delta B/B_T$ values between 3–$7x10^{-4}$ are normally required for ELM suppression in DIII-D [5]. Also, shown is the nominal design value for the perturbing field required for ELM suppression in ITER. The implications of these results in helium and deuterium plasmas for any fusion device in which the available auxiliary heating power may be marginal over the H-mode threshold power, such as in ITER, is that careful timing of full activation of the ELM control coils is required whereby the coils are energized after the H-mode transition, but before the first type 1 ELM.

In the case of He plasmas, for both ECH and H-NBI cases, there is a clear increase in P_{TH} with increasing perturbing field strength at resonant values of q_{95} i.e. q_{95}=3.4–3.5. In He plasmas, there appears to be no discernible minimum in the perturbing field at which this effect occurs, i.e. the effect is noticeable at even low values of $\delta B/B_T$. For strong off resonant fields i.e. for discharges with q_{95}~4.0, P_{TH} exhibits only a weak increase with $\delta B/B_T$. This indicates that the increase in P_{TH} is not a pure linear dependence on just $\delta B/B_T$, but is more dependent on the degree of resonance with the spectral components of the perturbing field.

Experiments were performed in JET to examine the effect of edge n=2 magnetic perturbations, produced by external Error Field Correction Coils (EFCCs), on the L-H transition power threshold in D plasmas [21]. In this case, a reduction of ~20% in P_{TH} was observed for magnetic perturbations with I_{EFCC} > 32 kAt when compared with the unperturbed reference pulse. The reasons for the observed decrease in P_{TH} are not yet fully understood, but may be due to factors related with the 3D modification of the plasma shape caused by the EFCCs. A detailed analysis of equilibrium reconstructions using magnetic sensors located in different octants of the tokamak have shown that the plasma shape is perturbed with the application of the EFCCs, causing (amongst other effects) the X-point to lower by at least 2 cm in two of the octants. This observation is consistent with results obtained in previous JET experiments [22,23], where a reduction in P_{TH} was obtained by lowering the X-point height, making it plausible that the change in divertor geometry is responsible of the decrease in the power threshold. Further experiments are required to study these results.

Studies on MAST [24] have shown that if RMPs in an n=1,2 or 3 configuration are applied with sufficient strength, they can suppress the L-H transition in D plasmas with D-NBI. The heating power had to be increased by ~80% (over that for discharges without RMPs) in order to produce the L-H transition at the same time in the discharges. In contrast, it has been found that the n=4 and n=6 configurations have little effect on the L-H transition characteristics and can still manage to mitigate the first ELM [25]. Figure 5 shows a set of LSN discharges on MAST with RMPs with different toroidal mode numbers. Figure 5(b) shows the time-trace of the discharge with the L-H transition produced without RMPs. The n=2

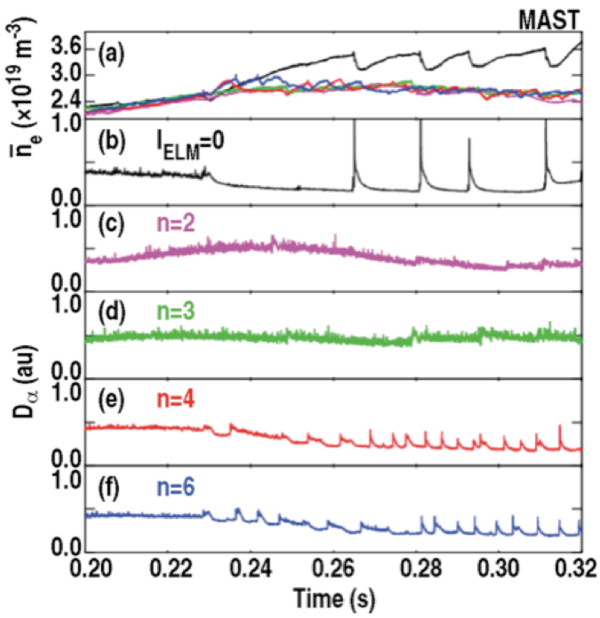

FIG. 5. Time traces from MAST of (a) line average density ($\bar{n}_e$) and the target D_α intensity for a lower SND shot with the RMPs having (b) I_{ELM}= 0 kAt, (c) I_{EFCC}=6.0 kAt in n=2, (d) I_{ELM}= 4.0 kAt in n=3, (e) I_{ELM}=5.6 kAt in n=4 and (f) I_{ELM}= 5.6 kAt in n=6 configuration.

configuration was produced using the external EFCC described in Ref. [26], while the other configurations were produced using the lower row of the ELM coils. The necessary coil current required to suppress the L-H transition was 6 kAt for the *n*=2 configuration [Fig. 5(c)] and 4 kAt for the *n*=3 configuration [Fig. 5(d)]. Figure 5(e,f) shows the D_α traces for cases where the *n*=4 and *n*=6 configurations of the RMPs in which the maximum applied current of 5.6 kAt was not sufficient to suppress the L-H transition. The L-H transition time is similar to the shot without RMPs [Fig. 5(b)] and, furthermore, the first ELM is also mitigated. From an empirical basis, the effect on the L-H transition appears to be decreased at higher *n*, which may be favorable for devices such as ITER, which, for example, will operate in an *n*=4 configuration.

The dependence of the H-mode power threshold on edge magnetic perturbations in D plasmas was investigated on NSTX using external coils normally used for error field corrections. The application of *n*=3 fields (coil currents ~0.6 kA) at the plasma edge in similar D-NBI heated D plasmas resulted in an increase of the H-mode power threshold by over 50%.

4. Discussion and Conclusions

Detailed examination of the results on the main ion species (as described in Table 1) from the many devices, reveals that the ratio of P_{TH}(He)/P_{TH}(D) varies with the L-mode (or target) electron density. For example, in DIII-D, the ratio of P_{TH}(He)/P_{TH}(D) is about 1.6 at electron densities of 2.5×10^{19} m^{-3}, but moves towards unity as the target density increases to 4.5×10^{19} m^{-3}. Similarly, in JET, the H-mode power threshold for He is much higher than D at low densities of 2×10^{19} m^{-3}, but appears to be comparable as the target density increases towards 3×10^{19} m^{-3}. Similar variations are observed in C-Mod, in which the ratio of P_{TH}(He)/P_{TH}(D) becomes smaller as the target density is increased. The density dependence is not yet understood and requires further investigation. The variation of P_{TH}(He)/P_{TH}(D) ratio with target electron density appears to be favorable for ITER operational scenarios at relatively higher target densities. However, in AUG, the ratio of P_{TH}(He)/P_{TH}(D) appears to remain constant at a factor of 1 over a large range of target densities. The reason the AUG results are different from the other devices (or even the earlier pre-2008 AUG results) is not yet known and needs further investigation. There appears to be no significant variation in P_{TH} between the use of ECH or NBI as the main heating scheme for either He or D plasmas.

The quantitative predictions for ITER using the P_{TH} scaling expression with global parameters [Eq. (1)] gives the H-mode threshold power for D at a L-mode (target) electron density of 5×10^{19} m^{-3} at 30 MW and 52 MW for half-field (2.65 T) and full-field (5.3 T) baseline scenario operation, respectively (note: for a plasma surface area of 680 m^2). This would also be close to the expected P_{TH} for He plasmas given that P_{TH}(He)/P_{TH}(D) ratio tends towards unity at higher electron densities in several devices and from the AUG result for all electron densities. However, assuming the more pessimistic P_{TH}(He)/P_{TH}(D) ratio of 1.4, this gives 42 and 73 MW at half-field and full-field, respectively. For hydrogen, assuming P_{TH}(He)/P_{TH}(D)~2, the P_{TH} at the same density would be 60 and 104 MW at half-field and full-field, respectively. However, these values are obtained from a global scaling expression, which does not take in to account the strong influence (by a factor of 2) of the plasma topography in the vicinity of the divertor, as shown by the dependence of the X-point location with respect to the divertor surfaces. One working hypothesis for this effect is that changes in the recycling and the divertor neutral density as a result of changing the X-point location can affect the H-mode threshold power. If the closed divertor configuration in ITER can be shown (through modeling) to affect the recycling in a way similar to what is obtained in lowering the X-point in open-divertor devices, then it may be possible to expect a lower P_{TH} in ITER than the global scaling predictions and, for very favorable conditions, maybe even make possible the use of hydrogen plasmas. Since this effect is so strong, it requires a detailed investigation in order to effectively make accurate predictions for ITER and to also reduce the level of uncertainty in these predictions.

The application of resonant magnetic perturbations can lead to clear changes in the H-mode power threshold. Power-scan studies in AUG, DIII-D, MAST and NSTX show increases in $P_{TH,}$ by up to a factor of 2 above the non-RMP threshold power, with clear thresholds in the RMP field strength (DIII-D, MAST, NSTX) or the target density (AUG). The implication for ITER is that careful timing of full activation of the ELM control coils is required whereby the coils are energized after the H-mode transition, but before the first type 1 ELM. The results from AUG also suggest that the L-mode density may have to be maintained below a certain level to avoid any increases in P_{TH} depending on the strength of the applied 3D field.

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