H-Mode confinement properties close to the power threshold in ASDEX Upgrade

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Abstract. Confinement properties close to the H-mode power threshold are studied in the ASDEX Upgrade tokamak. The results show that good confinement can be obtained close to the threshold with Type-I ELMs. The existence of Type-I ELMs does not necessarily require the heating power to be higher than the H-Mode power threshold, but it requires collisionality to be low enough. At higher collisionality Type-III ELMs replace the Type-I ELMs and confinement time is reduced by about 20%.

1. Introduction

The confinement time predictions for the ITER standard scenario, the ELMy H-mode, are based on scaling laws deduced from the ITPA multi-machine H-mode confinement database. The most widely used expression at present is the ITER98Y2 [1], from which one deduces the H-Mode factor $H_{98Y2}/\tau_{\text{ITER98Y2}}$, where $\tau_{\text{th}}$ is the thermal confinement time, i.e. without fast ion contribution. A new public version of this database has been recently released and its main properties are reported in [2].

It is well-known that the H-Mode is reached above a certain power threshold $P_{\text{thr}}$ which is, in particular, studied using the ITPA multi-machine power threshold database [3, 4]. These studies yielded several scaling expressions for $P_{\text{thr}}$, the most recent one, recommended for ITER, is discussed in a companion paper at this conference [5]. It yields $P_{\text{thr}}$ in MW and reads:

$$P_{\text{thr}} = 1.97B_T^{0.77}n_{\text{20}}^{0.78}a^{-0.98}R^{1.0}$$

where $B_T$, $n_{\text{20}}$, $R$ and $a$ are respectively the magnetic field, line averaged density, minor and major radii, with the following units: T, $10^{20}$ m$^{-3}$, m. The heating power to be compared to $P_{\text{thr}}$ is the usual net loss thermal power, $P_{\text{LTH}}$, also used in the ITPA databases and written as:

$$P_{\text{LTH}} = P_{\text{Ohm}} + P_{\text{heat}} - P_{\text{losses}} - dW/dt$$

Here $P_{\text{Ohm}}$ is the residual Ohmic heating power, $P_{\text{heat}}$ the auxiliary heating power, whereas $P_{\text{losses}}$ accounts for all losses, which are prompt fast ion losses in the case of NBI and RF absorption in the case of ICRF. $W$ is the plasma energy content. In several present-day tokamaks the net heating power $P_{\text{LTH}}$ can exceed $P_{\text{thr}}$ by a large factor. Indeed, this is confirmed by the examination of the ITPA confinement database for the divertor tokamaks with ITER like shape, such as ASDEX Upgrade, Alcator C-Mod, DIII-D, JET and JT-60U for deuterium operation, as discussed in [5]. Except in Alcator C-Mod for which $P_{\text{LTH}}/P_{\text{thr}}$ does not exceed 1.3, in the other devices this ratio can be high. In contrast to the general present situation, one expects $P_{\text{LTH}}$ to be rather close to $P_{\text{thr}}$ in ITER due to the limitation on the auxiliary heating power. It is therefore of great interest for predictions to investigate in detail the behaviour of confinement in H-Modes for heating powers close to the threshold power. This is the aim of this paper which deals with ASDEX Upgrade confinement data.
2. ASDEX Upgrade data-set

ASDEX Upgrade is a divertor tokamak (R = 1.65m, a = 0.5m , \(\kappa \approx 1.6\)) from which about 1500 time slices are recorded in the ITPA confinement database. The device is equipped with NBI heating (8 beams, 2.5 MW each), delivering up to 20 MW for deuterium, and with ICRF power up to 6 MW, the scheme being here (H)D. Both methods have been used, either separately or combined, in the discharges included in the data-set analyzed here. For the present work we selected from the ASDEX Upgrade contribution to the ITPA database time slices fulfilling the condition \(P_{\text{LTH}}/P_{\text{thr}} \leq 1.6\). This builds a data subset of about 270 records, to which we added data from other ASDEX Upgrade shots chosen on purpose for the present work. This yields finally a data-set of 360 time slices. These discharges were all run in the magnetic configuration in which the ion VB drift was directed towards the active X-point which provides the lowest LH power threshold. In addition, plasma and beam gases were deuterium and no time slice with high radiation losses has been included. The choice of the restriction \(P_{\text{LTH}}/P_{\text{thr}} \leq 1.6\) is arbitrary and has been dictated by the wish to investigate the confinement behaviour close enough to the threshold while providing an amount of data which is, on one hand, sufficient to be representative and on the other hand limited enough to allow the assessment of the individual time points if necessary. The time slices have been chosen such that they are not taken during (3,2) or (2,1) NTM modes. They were chosen in quasi steady-state phases, in time intervals taken late enough after the last change of the heating power, such that the \(dW/dt\) contribution to \(P_{\text{LTH}}\) is negligible. The length of the time interval over which the data are taken and averaged is also long enough to guarantee reliable and representative values. This data-set contains data for time intervals with Type-I and Type-III ELMs, as well as intermediate cases for which Type-I and Type-III ELMs are mixed within the selected time interval. One can distinguish two types of “mixed ELMs”: (i) regular Type-I ELMs each of them being followed by a train of 3-4 Type-III ELMs, often named compound ELMs, (ii) cases in which Type-I and Type-III ELMs occur independently and without any regular pattern. In the following we do not distinguish between these 2 cases which are both categorized as “mixed” and labeled Type-I/III. The database contains 218 time slices categorized as Type-I ELMs, 80 Type-I/III and 62 Type-III. Type-I ELMs are thought to be caused by an ideal MHD instability whereas Type-III ELMs are most probably linked with a resistive phenomenon [6, 7]. The ELM type can be determined from the time evolution of the discharges, in particular, the variation of the ELM frequency when power is varied is a precious indication of the ELM type. The ELM frequency increases with power for Type-I ELMs, but it decreases with power for Type-III ELMs [6]. The ELM type may be difficult to determine when the density is strongly increased at constant heating power and some uncertainty might exist in such cases.

![Figure 1](image-url)

**Figure 1.** Ranges of the ASDEX Upgrade data-set used in this work. The 3 different ELM types are indicated by the symbols. Left plot: \(q_{95}\) versus plasma current. Right plot: line-averaged density versus plasma current, the Greenwald limit is indicated by the dashed line.

The ranges covered by the main control parameters are given in figures 1 and 2. They all correspond
The left plot of figure 2 shows the ratio $P_{\text{LTH}}/P_{\text{thr}}$ versus net heating power. The range in $P_{\text{LTH}}$ is limited to values below about 5 MW by the restriction $P_{\text{LTH}}/P_{\text{thr}} \leq 1.6$ and remains well below the machine possibility of 20 MW. The large number of points at $P_{\text{LTH}} \approx 2.5$ MW and $P_{\text{LTH}} \approx 5$ MW correspond respectively to one and two NBI beams. The points in-between correspond either to the use of ICRF power, or to reduced NBI power by modulation or reduced acceleration voltage. The values of $P_{\text{LTH}}/P_{\text{thr}}$ range between $\approx 0.7$ and 1.6, the imposed upper limit. The lower boundary of $P_{\text{LTH}}/P_{\text{thr}}$ is determined by the H-to-L transition. The existence of H-Mode points for $P_{\text{LTH}}/P_{\text{thr}} < 1$ is due to the fact that the scaling of $P_{\text{thr}}$ represents the L-to-H transition which is in general higher than the back transition due to the good confinement provided by the H-Mode, a phenomenon often called H-Mode hysteresis. At $P_{\text{LTH}} \approx 2.5$ MW the ratio $P_{\text{LTH}}/P_{\text{thr}}$ varies by a factor of about 2, which is due to the variation of $P_{\text{thr}}$ induced by different $B_T$ and $n_e$ values. For $P_{\text{LTH}} \approx 5$ MW, there are no points for $P_{\text{LTH}}/P_{\text{thr}} < 1.2$ which suggests that $P_{\text{thr}}$ cannot not be pushed to extremely high values by increasing magnetic field or density. This is in agreement with previous studies in ASDEX Upgrade which indicated that, when approaching $n_{\text{GW}}$, a very high heating power is required to sustain the H-Mode and $P_{\text{LTH}}/P_{\text{thr}}$ must be much larger than 1 [9, 10]. As $P_{\text{thr}}$ depends on $B_T$ and $n_e$ we show the ranges covered by these two quantities in the right plot of figure 2. There is a factor of 2 range in $B_T$ and the density has been explored over a significant range at each value of $B_T$, providing a rather balanced data-set. The larger number of points at 2 T corresponds to the discharges at 1 MA and $q_{95} \approx 3.5$. In this plot we also added lines which correspond to the values of $B_T$ and $n_e$ corresponding to the threshold scaling of equation 1 for three fixed values of $P_{\text{thr}}$: 1.5 MW, 2.5 MW and 4 MW. One sees that the lower points in this plot correspond to $P_{\text{thr}} \approx 1.5$ MW, whereas the higher points almost reach 4 MW. Therefore, in our data-set $P_{\text{thr}}$ varies by a factor of about 2.5. The points with the highest values of $P_{\text{thr}}$ in this plot correspond to the upper right corner of the left plot, $P_{\text{LTH}} \approx 5$ MW and $P_{\text{LTH}}/P_{\text{thr}} > 1.3$. They correspond, in particular, to the highest density values which can be reached, limited by $n_{\text{GW}}$. Triangularity, $\delta$, has also been varied over the whole $I_p$ range between 0.2 and 0.45. The analysis
of our data-set shows that, as well-known [11, 12, 13], higher $\delta$ helps sustaining the H-mode with good confinement at high density. However, this parameter does not play a crucial role in the results presented here and we will not discuss its influence in detail.

3. Power threshold
Before investigating the confinement properties, it is important to verify that the scaling used for $P_{th}$ reproduces well the ASDEX Upgrade data. This is expected because the contribution of the ASDEX Upgrade data to the threshold database is significant and also because it is close to the center of gravity of the ITPA database and is therefore well fitted.

Figure 3. Two examples of the time evolution of H-Mode discharges at low heating power, both at $I_p = 1$ MA, $B_T = 2$ T. The different signals are indicated in the corresponding boxes. Left plot: power ramp, no gas puffing. Right plot: heating power in one step, gas puffing to increase density.

Figure 3 shows a selection of time traces for two representative discharges, both at $I_p = 1$ MA, $B_T = 2$ T, $q_{95} \approx 3.5$. The first example (left plot) has a slow heating power ramp obtained by NBI modulation with varying duty-cycle, as preferred for accurate threshold studies. The L-H transition occurs at about 1.77 s, as indicated by the vertical line. At this time point, the ratio $P_{LTH}/P_{th}$ is very close to 1 as revealed by the corresponding curve. This corresponds to $P_{LTH} \approx 1.6$ MW. After the L-H transition, as usual, plasma energy and therefore confinement time, represented by $\tau_{th}$ and $H98Y2$, increase by about a factor of 2. Density also starts to increase after the L-H transition. Note that $P_{LTH}$ first quickly decreases after the L-H transition due to the $dW/dt$ term. It should be underlined that the hysteresis allows this behaviour. As the power ramp continues up to 2.5 MW, $P_{LTH}$ increases again, leading to a decrease of $\tau_{th}$, whereas $H98Y2$ remains constant. The first Type-I ELM occurs at about 2.05 s followed at regular intervals by further ELMs. The ELM frequency is low, about 8 Hz, which is due to the low heating power. There was no gas puffing in this discharges but the low ELM frequency leads to a rather slow but large increase of density up to $810^{19}$ m$^{-3}$. Consequently, $P_{th}$ increases and $P_{LTH}/P_{th}$ remains very close to 1.
The other discharge illustrated in the right plot is quite different. There is no power ramp, but 1 NBI beam is turned on, leading quickly to the L-H transition. Here also, $P_{LTH}/P_{thr}$ is very close to 1 at the L-H transition. Gas puffing is applied to increase density, which indeed reaches $10^{20} \text{m}^{-3}$ later in the discharge. Due to this gas puffing, the discharge oscillates 2 times between ELM-free H-mode and L-mode in the time interval 1.5 - 1.9 s to finally remain in the H-mode with rather high frequency Type-III ELMs and a transition to slower Type-I ELMs at about 2.4 s. In this case the ratio $P_{LTH}/P_{thr}$ is also close to one and confinement is good, as shown by $H98Y2 \approx 1$.

The good agreement of $P_{LTH}$ with $P_{thr}$ at the L-H transition illustrated by these cases is general for the data used here. This is also confirmed by previous L-H threshold power studies for ASDEX Upgrade data only, which yield a scaling very close to that used here [3].

4. Confinement behaviour

An overview of the confinement behaviour, given in figure 4, shows the H-Mode enhancement factor, H98Y2, as a function of $P_{LTH}/P_{thr}$. The question is often asked whether it is possible to define a minimum value of $P_{LTH}/P_{thr}$ above which confinement is good, i.e. $H98Y2 \approx 1$. Figure 4 indicates that obviously good confinement can be achieved with high probability as soon as $P_{LTH}/P_{thr} \geq 1$.

The symbols for the different ELM types indicate that Type-III ELMs have systematically a somewhat lower confinement than the two other types. This is quantified by the statistical distribution plots for each ELM type in the right part of figure 4. For Type-I ELMs, H98Y2 is very close to unity whereas it is around 0.8 for Type-III ELMs. This is in agreement with the usual expectation that, in devices of the size of ASDEX Upgrade at least, the confinement of H-Modes with Type-III ELMs is somewhat lower than that of Type-I ELMs. This difference can be attributed to a lower pedestal pressure for Type-III ELMs, see e.g. [11]. Therefore good confinement is determined by the ELM type and not directly by the value of $P_{LTH}/P_{thr}$. In the scatter plot of figure 4 we added linear fits of $H98Y2$ versus $P_{LTH}/P_{thr}$ for each ELM type. For Type-I ELMs the line is, as expected, very close to 1 and exhibits almost no dependence upon $P_{LTH}/P_{thr}$. For Type-III ELMs, the line is clearly below 1 but shows a significant increase with increasing $P_{LTH}/P_{thr}$. This might be caused by an increase of pedestal pressure and/or pressure gradient for Type-III, linked with the improved stability of these ELMs as collisionality decreases. The fit for Type-I/III ELMs lies in-between. In addition, we have verified that the ability to achieve good confinement at rather low values of $P_{LTH}/P_{thr}$ is not restricted to specific values of control parameters such as $I_p$, $B_T$ or $q_{95}$.

The left plot of figure 5 shows the relation between normalized $\beta$, $\beta_N$, and confinement factor. They are here closely related: The rather distinct two groups of points which built two parallel patterns increasing with $H98Y2$ are due to the discretisation of the NBI input power either 2.5 MW (1 beam)
or 5 MW (2 beams). The excursion in $H98Y2$ is due to the fact that the confinement scaling cannot reproduce all dependencies with a very high accuracy. In particular, machine conditioning plays an important role through its influence on pedestal pressure, as investigated for ASDEX Upgrade in [14]. Triangularity also contributes to this variation, as discussed in [11, 12] for ASDEX Upgrade. This plot shows that $\beta_N \approx 2.4$ can be reached, despite the restriction in power imposed in the present study. The right plot indicates that reaching $\beta_N \approx 2$ only requires $P_{LT/H}/P_{thr} \geq 1.2$. This is an important result for ITER for which the standard scenario does not require $\beta_N$ above 2. It should be possible to reach this value with $H98Y2 \approx 1$ and for $P_{LT/H}/P_{thr}$ not significantly above 1. Moreover, it should be underlined that high values of $\beta_N$ can be obtained with Type-III ELMs, most of them corresponding here to high density cases.

The question of the minimum value of $P_{LT/H}/P_{thr}$ required to get a certain type of ELM, in particular Type-I, is often asked. Elements for the answer are provided by figure 6 in which $P_{LT/H}/P_{thr}$ is plotted versus line-averaged density or normalized density. The possible relation with physics quantities, such as resistivity or collisionality, is discussed below. Clearly, the ELM type is not fully dictated by $P_{LT/H}/P_{thr}$ but also, in particular by density if we consider control parameters. At medium densities there is a clear trend for Type-III ELMs to only occur at values of $P_{LT/H}/P_{thr}$ below 1, whereas at high density Type-III ELMs also occur frequently for $P_{LT/H}/P_{thr}$ values clearly above 1. This behavior does
not seem to be more clearly related with \( f_{GW} \) than with \( \bar{n}_e \). This is partly due to the fact that many of the high density points with \( f_{GW} \) close to 1 were obtained at the same plasma current of 1 MA in this data-set. There are a few Type-III ELM points, at rather low density and \( P_{LTH}/P_{thr} > 1 \) which seem to be in disagreement with the rest of the figure. These “low density outliers” have been verified carefully and are indeed Type-III ELMs. This might be attributed to the increase of \( P_{thr} \) towards low density, which is not taken into account in the scaling. However this would be somewhat unexpected at this density of about \( 5 \times 10^{19} m^{-3} \) which is large compared to the minimum threshold density \( \approx 2.5 \times 10^{19} m^{-3} \) in ASDEX Upgrade [3]. This could also be due to machine conditions, but we have not found any concrete indication for this hypothesis. Apart from these few points, overall the two plots of figure 6 suggest that resistivity or collisionality may play a role. This would be in agreement with the hypothesis that Type-I and Type-III ELMs are respectively ideal or resistive MHD events. While resistivity, in general, formally separates ideal and resistive MHD, in the case of ELMs, collisionality also plays a role, due to the fact that at the plasma edge, the bootstrap current contribution, \( j_{BS} \), to the local current is important, see e.g. [15, 16, 17, 18]. As \( j_{BS} \) strongly depends on normalized collisionality \( \nu^*/A^{3/2} \), [19], these quantities should also be considered when discussing ELM types. Indeed, \( \nu^*/A^{3/2} \) has been shown to unify the dependence of ELM losses between devices and is widely used in studies dealing with ELMs. We show here diagrams for the ELM types in figure 7 using Spitzer resistivity \( \eta_{Spitzer} \) and \( \nu^*/A^{3/2} \).

These plots indeed show that Type-III ELMs are concentrated at higher values of \( \eta_{Spitzer} \) or \( \nu^*/A^{3/2} \), whereas Type-I ELMs are rare in this region and populate in majority the low values. The difference between the two representations does not allow to state whether one or the other better reflects reality. It should be noted that, as both quantities depend on electron temperature, they are strongly correlated. There is one Type-III point at very low value of \( \eta_{Spitzer} \) and \( \nu^*/A^{3/2} \). This is one of the low density outliers mentioned above and the only remaining outsider in the plots of figure 7. Indeed, the other few outliers have rather poor confinement and, despite low density, higher values of \( \eta_{Spitzer} \) and \( \nu^*/A^{3/2} \). They are therefore in the bulk of the other Type-III points in figure 7. The reason for the poorer confinement of these points could not be identified.

Confinement reflected by \( H_{98}/Y_{2} \) is provided in the plots of figure 8 which shows a confinement degradation with increasing \( \eta_{Spitzer} \) and \( \nu^*/A^{3/2} \), in concert with the occurrence of Type-III ELMs. It should be noted, that this figure is not plotted at constant \( \rho^* \) and \( \beta \) and cannot be interpreted as a general result on the dependence of confinement upon collisionality. It should be underlined that plotting \( H_{98}/Y_{2} \) versus density (not shown) does not exhibit a clear degradation for this data-set and does not order at all the ELM types.

5. Discussion and conclusion

The results presented here indicate that good confinement, \( H_{98}/Y_{2} \geq 1 \), can be achieved at heating powers very close to the H-mode power threshold. This requires, however, H-Modes plasmas with
Type-I ELMs, probably not acceptable in ITER because of their high power load in the divertor. Type-III ELMs, which are more favorable from the point of view of divertor power load, exhibit values of $H98Y^2$ which are 10 to 20% lower than the Type-I ELM cases. In addition, our results indicate that values of $\beta_N$ above 2 can be reached at low heating power and even with Type-III ELMs.

The confinement degradation linked with Type-III ELMs is a general behavior in tokamaks. It occurs in particular at high density and is caused by a reduction of the pedestal height which propagates to the core by profile stiffness, see for instance Alcator C-Mod [20], ASDEX Upgrade [21], DIII-D [22], JET [13]. In some cases this degradation can be partly compensated by density peaking, as reported in ASDEX Upgrade [23, 12] and DIII-D [24]. However, high density peaking has deleterious effects on impurity transport and NTM stability. To avoid these different difficulties, several types of plasma scenarios with small ELMs, generally at high density, have been developed, see for instance review [25]. Their properties and ability to be extrapolated to ITER are still under assessment.

The majority of the Type-III ELMs included in the present work have been obtained at high density and rather low temperature. As a result, the occurrence of Type-I or Type-III ELMs is clearly linked with collisionality or resistivity. Figure 7 shows that, within our data, it is not possible to conclude whether one or the other quantity is more important to separate the ELM types. This is due to the fact that both strongly depend on temperature and possibly also because collisionality plays an important role in the ELM mechanism through the edge bootstrap current. Whether resistivity can play a major role in the ELM type may be clarified in the future in dedicated experiments in which density and temperature are varied adequately. Most of the recent analyses on the occurrence of Type-III ELMs, carried out in other devices, were focused, so far, on the effect of collisionality. In agreement with our observations, they also indicated that Type-III ELMs are obtained as density is sufficiently increased [26, 27, 28, 17]. However, high density or collisionality is not always required for Type-III ELMs which have also been observed at low collisionality in DIII-D [28] and JET [27]. Indeed, two branches for Type-III ELMs seem to exist: one at high density, with $v_e^* > 1.0$, where the ELMs seem to exist only below a critical temperature, independently of density, and a second one at low density, approximatively in the region $v_e^* < 0.3$ in which the Type-III ELM boundary seems to be linked with $\beta_N$ [28, 17, 27]. Whether resistivity plays a key role in such cases remains to be investigated. Our Type-III outlier at low $v_e^*$ in figure 7 could be such a low density case. These must be very rare in ASDEX Upgrade, because the lowest density in the H-mode is in general higher than that achieved in JET and DIII-D. This should be investigated in future ASDEX Upgrade experiments.

In ITER, the predicted values of $v_e^*$ at the pedestal lies between 0.03 and 0.07 [29, 30]. This shows that achieving high density Type-III ELMs comparable to those occurring in present devices with $v_e^* > 1.0$ would required a strong decrease of $v_e^*$ at the very edge by radiative cooling or other control method. This is a difficult task and this indicates that the low density Type-III ELMs seem to be a possible way for ITER which should be further explored.
In ASDEX Upgrade, Type-I ELMs do not necessarily require $P_{\text{LTH}}/P_{\text{th}}$ above unity. This is interpreted as being provided by the H-Mode hysteresis linked with the transport reduction in the H-Mode. In JET, the situation seems to be a bit different: Type-I ELMs require $P_{\text{LTH}}/P_{\text{th}}$ to be larger than 1.3 to 2.5, depending on the conditions [27]. This is somewhat surprising as $v^*_e$ in JET is expected to be in general lower than in ASDEX Upgrade which should favor the Type-I ELMs. In both devices, as power is increased, Type-III ELMs appear just above the threshold. However, once in the Type-I ELM regime with $P_{\text{LTH}}$ significantly above $P_{\text{th}}$, JET plasmas seem to be more sensitive to a fall-back into Type-III ELMs than in ASDEX Upgrade. This could be linked with the associated density decrease in such JET cases and to the existence of the low density Type-III ELMs in JET. It should also be underlined that no physics reason links the ELM type to threshold power itself. Indeed, the L-H transition depends on edge parameters in the L-Mode just prior to the H-Mode, whereas ELMs are dictated by collisionality, pressure gradient and MHD stability in the pedestal region, when the H-Mode has developed. This is illustrated, for instance in ASDEX Upgrade, by plasmas in which the ion $\nabla B$ drift is directed away from the X-point, which is well-known to lead to a high power threshold. In this configuration, Type-III ELMs do not seem to exist. Another argument is provided by the fact that Type-III are the most usual ELMs in devices smaller than ASDEX Upgrade, for instance ASDEX [6], even when the heating power is well above the threshold. Thus, this observation is also in agreement with the fact that collisionality seems to play a key role for the ELM type. In view of ITER, these questions are being addressed in comparative studies between devices and will certainly improve our future understanding.

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