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H-mode power threshold and transition in ASDEX Upgrade

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Abstract. Global and local H-mode threshold analyses are presented and discussed. The density window was extended up to the density limit towards which the power threshold exhibits a dramatic increase. First results with the new divertor are compared to the previous threshold scaling. Local edge measurements at the L–H transition show that the temperature decreases slightly with density and increases with magnetic field, and that the ion collisionality at the plasma edge is always clearly above unity, between 5 and 15. Experiments at high power threshold exhibit improved L-mode confinement and suggest that two mechanisms are required for the L–H transition.

1. Introduction

Despite great efforts invested during the past years in individual devices and with the ITER threshold database [1], the prediction of the threshold power in ITER is still uncertain [2]. Therefore, further studies are necessary to characterize the H-mode transition, with both global and local parameters. The analyses with global parameters, which can be performed on a larger number of discharges, eventually including data from different tokamaks, are expected to yield an extrapolation of the power threshold for future devices. The more dedicated studies with local parameters, taken at the plasma edge where the L–H transition occurs, allow one to investigate transition physics and comparisons with theoretical models. Global and local analyses are complementary and should yield consistent results.

In this paper we present and discuss results from the ASDEX Upgrade tokamak on L–H power threshold and transition. The device was operated with the original divertor (DV-I) until August 1996 and with the 'Lyra DV-II' from April 1997. The DV-II divertor has a smaller chamber volume, and is deeper and better baffled than DV-I and a higher retention of neutrals is expected. Most of the data used in this paper were acquired with DV-I, but the first results from DV-II (May–August 1997) are presented.

2. Analyses with global parameters

Previous analyses of the H-mode power threshold, P_{thres}, showed, in ASDEX Upgrade as in other tokamaks, $P_{\mathrm{thres}} \sim \bar{n}_{\mathrm{e}} B_{\mathrm{T}}$ in the middle-range densities, [3]. We use here for P_{thres} the loss power, $P_{\mathrm{Loss}} = P_{\mathrm{heat}} - \dot{W}$, where P_{heat} is the injected NBI power minus fast ion losses.

The density range of threshold studies has recently been extended to density values up to the density limit [4]. In the region above $\approx$ 70% of the Greenwald density limit ($\bar{n}_{e,GW}$), the power threshold increases dramatically and the H-mode can be neither achieved nor even sustained just below $\bar{n}_{e,GW}$. This is shown in figure 1 which represents an existence diagram in the P_{Loss}/B_T versus $\bar{n}_e/n_{e,GW}$ plane. This figure is only slightly modified when the radiation power inside the separatrix is subtracted from P_{Loss}.

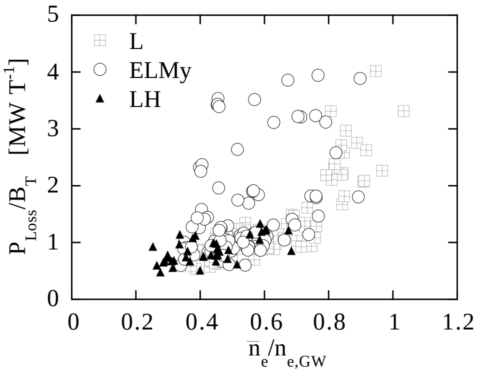

Figure 1. Regime existence diagram: P_{Loss}/B_T versus $\bar{n}_e/n_{e,GW}$; L–H points taken in the L-mode immediately prior to L–H transition.

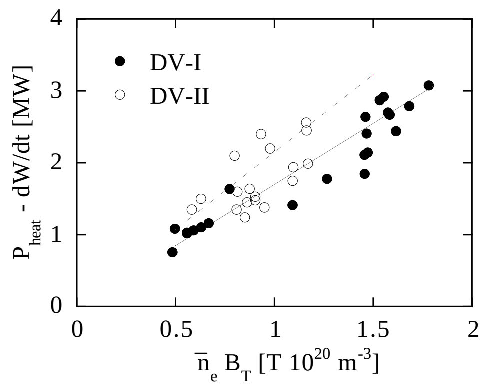

Figure 2. Power threshold of L–H transition. The solid and dashed lines indicate the threshold in DV-I ($1.7\bar{n}_e B_T$) and DV-II ($2.15\bar{n}_e \times B_T$) respectively.

These studies also indicated that in the high-density region the L–H and H–L thresholds are very similar: the power hysteresis disappeared. This is attributed to the confinement degradation of the H-mode at high density with gas puffing. This is of course an important issue for ITER and the physical reasons for this behaviour can be investigated with the edge measurements, [5].

The first threshold results with Lyra DV-II show a moderate but statistically significant (slightly above one standard deviation) increase of P_{thres} by $\approx$ 25%, compared to DV-I, (figure 2). The cause of this effect is not yet clarified and can be attributed, in addition to a possible genuine effect of the divertor geometry, to changes in neutral distribution in the plasma edge and divertor and/or to the insufficient conditioning of protection limiters and target plates during the limited duration of the experimental period with DV-II. These questions are expected to be answered during the next experimental campaign.

A further question related to power threshold is the following: what power in excess of the threshold is necessary to reach good confinement? This issue was addressed for ASDEX Upgrade in two dedicated scenarios to achieve the H-mode: (i) with constant power just above ($\approx$ 10%) the threshold power; (ii) with a rather short initial heating pulse and, taking advantage of the hysteresis, subsequently with a power reduced to a level below the initial threshold. The analysis, using in addition data from conventional H-mode discharges with type-I or type-III ELMs, without radiative edge, at constant power, shows that the thermal confinement time normalized to the ELMy H-mode scaling ITERH92PY is centred around 1 and is independent of P_{Loss}/P_{thres} in the range $0.8 \leqslant P_{Loss}/P_{thres} \leqslant 6$, investigated here. This result is valid for both type-I and type-III ELMs.

3. Local analyses

In this section, the results obtained in ASDEX Upgrade with local parameters are summarized and compared with the global analyses. More details on the local studies can be found in [5]. The edge electron temperature ($T_{\mathrm{e,edge}}$) and density ($n_{\mathrm{e,edge}}$) were measured at a position 2 cm inside the separatrix, in the equatorial plane. This position corresponds to $\rho_{\mathrm{pol}} \approx 0.97$, where ρ_{pol} is the normalized radius deduced from the poloidal flux. The edge ion temperature was also measured in some of the discharges and was shown to be somewhat higher (factor of 1.5–2.0) than $T_{\mathrm{e,edge}}$ at low density and close to $T_{\mathrm{e,edge}}$ at high density.

The edge temperature at the L–H transition is given by the expression $T_{\mathrm{e,edge}} \sim n_{\mathrm{e,edge}}^{-0.3} B_{\mathrm{T}}^{0.8} I_{\mathrm{p}}^{0.5}$. Even in the high-density regime where P_{thres} increases as shown in figure 1, the edge transition temperature does not increase with density. It must be underlined that the scalings for $T_{\mathrm{e,edge}}$ and P_{thres} are consistent, within the uncertainties, as obvious for the magnetic field. For $n_{\mathrm{e,edge}}$ and I_{p} the relationship between global and local results is consistent because $T_{\mathrm{e,edge}}$ is determined by power balance and by the value of $n_{\mathrm{e,edge}}$. In fact, the linear dependence of P_{thres} on $\bar{n}_{\mathrm{e}}$ would imply no dependence of $T_{\mathrm{e,edge}}$ on $n_{\mathrm{e,edge}}$ if profile and power balance were independent of density. This is not the case because the density profiles becomes broader at high density (with gas puffing) and the edge losses increase with density, whereas transport probably does not vary much in the L-mode. P_{thres} does not depend on I_{p} because the positive dependence of $T_{\mathrm{e,edge}}$ on I_{p} is automatically provided by the well-known confinement improvement with I_{p}.

Assuming $T_{\mathrm{i,edge}} = T_{\mathrm{e,edge}}$ and $Z_{\mathrm{eff}} = 2$, the edge data yield the ion collisionality at the L–H transition which is found to vary between 5 and 15, as shown in figure 3. This seems, on one hand, to be in contradiction with L–H transition models based on ions losses for which the L–H transition occurs when collisionality is as low as unity. On the other hand, the positive $T_{\mathrm{e,edge}}$ dependence on I_{p} may be related to the ion poloidal gyro-radius.

Interesting observations were made in ASDEX Upgrade for cases of high power threshold occurring: (i) in deuterium with unfavourable ion ∇B drift (away from X-point); (ii) in hydrogen plasma with the favourable drift. In these discharges we increased the heating power in steps up to the L–H transition, identified according to the well known H-mode signatures, the drop in the $D\alpha$ light in the divertor and in the density fluctuation level. Accordingly, we refer to L-mode before this transition and to H-mode after it. In case (i) the L–H transition is abrupt, without dithering; otherwise, observed in ASDEX Upgrade, in case (ii) it is smoother. In both cases the power at the L–H transition is approximately a factor of two higher than in the corresponding low-threshold case. Consequently, the edge temperature is also higher. In both cases, the confinement of the L-regime, before the L–H transition, shows almost no power degradation and is therefore good (80% of the H-mode) immediately before the L–H transition.

The time evolution of this improving L-mode confinement extends over 3–5 energy confinement times, at constant power, and is accompanied by macroscopic fluctuations at the plasma edge, observed on several diagnostics (T_{e}, Dα, magnetics), but not yet identified. During the time of the improving L-mode the temperature and density profiles become broader and a pedestal develops. Immediately prior to the L–H transition the electron temperature profile is similar to that of the H-mode, as shown in figure 4. This figure represents the evolution of the temperature profile for two discharges with opposite ion ∇B drift, the other main parameters being the same. The profile behaviour suggests the development of an edge transport barrier during the improved L-mode. In such discharges a radial electric field develops at the edge as reported and discussed in [6]. It must be

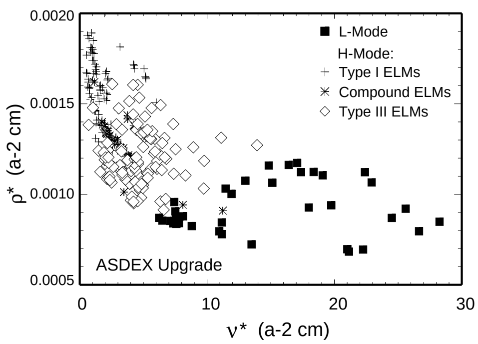

Figure 3. Ion collisionality at the plasma edge (2 cm inside separatrix) versus normalized gyro-radius.

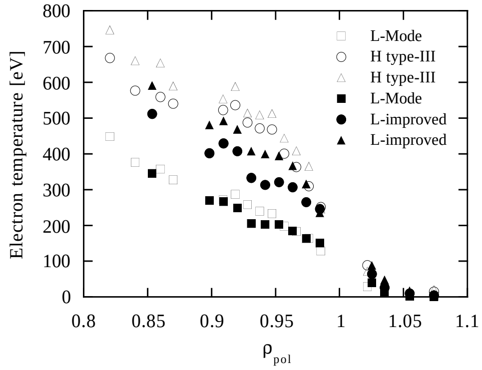

Figure 4. Edge temperature profile evolution for two discharges: closed symbols = low threshold, open = high threshold.

underlined again that this improvement is not accompanied by the two typical H-mode signatures, the reduction of the $D\alpha$ light in divertor and of the fluctuation level. Thus, reduced transport, in particular at the edge, is established with high power fluxes through the edge, although the usual H-mode is not achieved. This does not follow from the standard L–H transition models e.g. ion orbit losses, Reynolds stress, Stringer spin-up, pressure gradient. It is however not clear whether it really excludes any of them. Our results show improvement of confinement in a region of the n_e, T_e diagram, independently of the mode (L or H). They suggest that two steps contribute to the usual H-mode, which are separated in these experiments. Following [7] and by virtue of the effect of $E \times B$ on turbulence, one can imagine that the improved L-mode corresponds to a decorrelation of turbulence, whereas the classical H-mode requires its suppression, which occurs at the L–H transition in the discharges described here. Another possibility is that the improved L-mode is caused by a reduction of the conductive transport and the L–H transition at the end of the improved L-mode period corresponds to a reduction of the particle transport (strong $D\alpha$ drop and density increase) and therefore of the convective contribution to the energy transport.

Summary and conclusion

The H-mode threshold studies with global parameters in ASDEX Upgrade show that the H-mode cannot be achieved or sustained close to the Greenwald density limit in gas puffing operation. The reasons for this are not yet identified. This is an important issue for ITER and a only better physical understanding and modelling in the plasma edge may allow us to address the question of the extrapolation to ITER.

The edge measurements yield an expression for temperature dependence at the L–H transition which is in agreement with the global scaling. No hysteresis of the edge temperature is observed, suggesting that the hysteresis in power is due to confinement. As a consequence, at least two possibilities emerge: (i) the temperature is not the driving parameter of the L–H transition; (ii) the L–H transition is not a bifurcation, because this implies an hysteresis of the driving parameter.

The local edge measurements also show that the ion edge collisionality is between 5 and 15 in ASDEX Upgrade, in disagreement with H-mode models based on ion orbit losses.

Under conditions of high H-mode power threshold, the L–H transition exhibits an unusual behaviour: on a slow timescale before the L–H transition, identified by the usual signatures, a gradual confinement improvement occurs, in correlation with a steepening of edge profiles similar to those observed in the H-mode. This observation is not explained by the current L–H transition models, however it is not clear that it excludes any of them.

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