H-mode access with different X-point height in TCV

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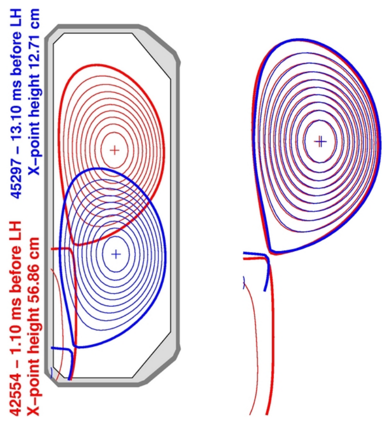
Introduction Present day tokamaks high performance scenarios rely on the possibility to access the high confinement mode (H-mode). Transition from the standard confinement mode (L-mode) to the H-mode is typically achieved when the power flowing across the last closed flux surface, neglecting radiation losses, $P_L = P_{ohm} + P_{aux} - dW/dt$ exceeds a certain threshold $P_{L,LH}$ (where P_{ohm} is the Ohmic input power, P_{aux} the auxiliary heating power and dW/dt is the plasma internal energy variation). This power threshold is found to strongly depend on plasma density, toroidal magnetic field and plasma size and can be characterized by a general power-law scaling, $P_{thresh} = 0.0488\,\langle n_e\rangle_l^{0.72} B_t^{0.80} S^{0.940}$ where $\langle n_e\rangle_l$ is the plasma line-average density (10^{20} m^{-3}), B_t is the vacuum toroidal field at the magnetic-axis (T) and S is the plasma boundary surface area (m^2)[1]. Predictions for ITER reveal that the foreseen auxiliary power could be marginal to achieve the H-mode at high density. Improving the empirical scalings can reduce the uncertainty of the prediction to ITER and possibly reveal means to facilitate H-mode access in ITER. Many experiments have shown that the H-mode power threshold also depends on plasma shape and X-point geometry. In particular, a favorable decrease of $P_{L,LH}$ while decreasing the X-point height has been observed in JET[2]. Recent experiments were performed on TCV to investigate this influence. A variation up to 30% in $P_{L,LH}$ has been observed moving the X-point towards the bottom of the plasma vessel.

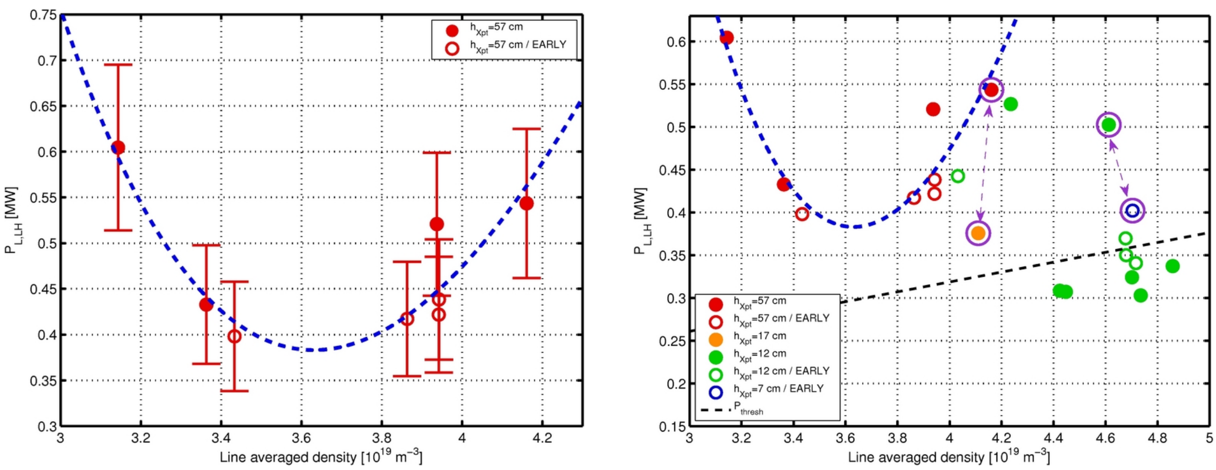


(a) (b)

Figure 1: Equilibria comparison. (a) Two discharges with different X-point height. (b) The previous equilibria shifted vertically.

Experimental procedure Dedicated experiments were performed using the TCV standard divertor configuration: a horizontal divertor leg going to high field side and a vertical one. The separatrix legs lay on C-tiles for all plasma positions. Using the high TCV shaping capabilities, the outer divertor leg length was reduced by more than a factor of 6 without significant variation of the plasma shape, Figure 1. All plasmas were configured with the ion ∇B drift in the favorable direction. The target plasma parameters were:

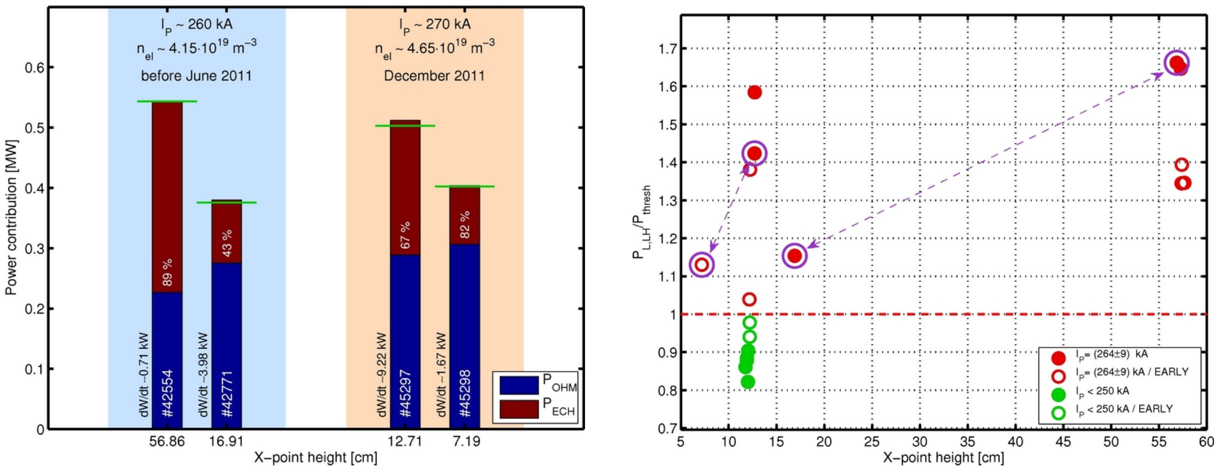
$I_p \sim$260±9 kA, $B_T \sim$1.4±0.005 T, $q_{95} \sim$3±0.09, $\kappa \sim$1.7±0.01 and $S \sim$11±0.05 m^2, reported with their standard deviation. The H-mode power threshold, $P_{L,LH}$, has been measured in a shot-to-shot scan for different plasma vertical position. In each shot a slow ramp of electron cyclotron resonance heating (ECRH) power triggers the L-H transition during the plasma current flat-top phase. The ECH launcher system is capable of depositing the ECH power at the same plasma radius ($\rho = 0.6 \div 0.8$) for all the investigated plasma vertical positions. 8 reference shots has been performed at different line averaged density $\langle n_e \rangle_l$, with the X-point almost 57 cm above the bottom of the vessel, Figure 2(a). The non-monotonic density dependence of $P_{L,LH}$ already established in many machines[3, 4] is reproduced. The $P_{L,LH}$ minimum can be approximately located at $\langle n_e \rangle_l^{min} \sim 3.6 \cdot 10^{19}\mathrm{m}^{-3}$. In Figure 2(a), the error bars are an overall estimate of the



(a) (b)

Figure 2: Power threshold versus line averaged density. Open symbols mark L-H transitions that occur within 50ms from the ECH turn on. (a) Reference shots performed with X-point height fixed to 57 cm. A representative trend is fitted. (b) The complete database. The multi-machine scaling[1] is reported for comparison.

uncertainty which was evaluated to be of the order of 15%. The greatest contribution to this uncertainty is given by the extreme sensitivity of the first pass absorption of the electron cyclotron (EC) wave to the density profile details. ECRH power absorption was evaluated using the ray-tracing code TORAY[5]. Kinetic and current profiles adjust to ECRH conditions in approximately 50 ms from the ECRH system turn on. The open symbols mark shots where the transition to H-mode occurs during this time lag. In these cases $P_{L,LH}$ is probably overestimated given that the minimum power injected by the launchers is approximately 200 kW. This symbol convention will be used throughout the whole paper. The scaling law, P_{thresh}, does not take into account the non-monotonic density dependence of $P_{L,LH}$, so comparison between experimental measurements and P_{thresh} are meaningful only for density value greater than $\langle n_e \rangle_l^{min}$. Assuming this minimum would not have changed while varying the plasma position, all the subsequent discharges were performed at density greater than $\langle n_e \rangle_l^{min}$. Moving the plasma towards the bottom of the vessel a particular attention was paid to keep the inner and outer gaps greater than 2 cm without changing the plasma shape. All the other plasma parameters were kept as fixed as possible, apart from density and current. At the low X-point position, the minimum power delivered by the ECRH system (200 kW) was high enough to trigger the L-H transition immediately after the ECRH turn on. In order to avoid early L-H transitions due to the unavoidable initial step in ECH power, the only solution consisted in reducing the ohmic contribution to total power loss via a reduction of the plasma current down to 180 kA. The vertical position was changed in order to obtain 4 different X-point height: 57, 17, 12 and 7 cm above the vessel bottom. In Figure 1 the comparison between two plasma equilibria at different plasma position with the same plasma shape and plasma current is reported. The complete set of discharges is depicted in Figure 2(b).



(a) (b)

Figure 3: X-point height influence on normalized power threshold. (a) A detailed comparison between pairs of shots with similar plasma parameters (x axis is not in scale to enhance the pair comparison). Contribution to the power loss is reported. Red bar: ohmic contribution, Blue bar: ECRH contribution, internal energy variation reported aside each bar. Green lines indicate the measured value of the power loss at the transition, $P_{L,LH}$. The white percentage on ECRH contribution is the calculated first path absorption. The pairs correspond to the points linked by purple arrows in Figure 2(b) and Figure 3(b). (b) Normalized power threshold for shots with $\langle n_e \rangle_l > 3.6 \cdot 10^{19} \mathrm{m}^{-3}$. Different colors account for the different plasma current values.

X-point height influence Before entering the discussion about the whole dataset, it is convenient to focus the attention on two pairs of shots: those marked in purple and linked by arrows in Figure 2(b). These are almost equal in terms of density, current and plasma shape, so the difference in the measured power threshold can be attributed a to reduced number of quantities, including the X-point height variation. A detailed comparison of the different contribution to the power loss is reported in Figure 3(a). Difference in $P_{L,LH}$ is completely due to a variation in the ECRH contribution, while the Ohmic one remains almost unchanged. The influence of the X-point height is evident and the variation in $P_{L,LH}$ is larger when the X-point is closer to the bottom of the vessel. The first pair of shots shows a decrease of $P_{L,LH}$ value approximately by 30% moving the X-point 40 cm down from the upper position, while in the second case a downward shift of 5.5 cm turns in a 20% decrease of $P_{L,LH}$.

This picture becomes more intricate when the whole dataset is taken into account, see Figure 2(b). The average decrease in power threshold at lower plasma position is still valid, even if a large scatter affects the measurements. This scatter becomes more evident looking at Figure 3(b) where the normalized power threshold measurement is reported against the X-point height for all the shots performed at $\langle n_e \rangle_l > 3.6 \cdot 10^{19}\text{m}^{-3}$. This variability can be due to different reasons. The change in current does not only imply a decrease in the Ohmic input power, but also carries a variation of more than 50% in q_{95} value. Moreover, different I_p and different ECRH can result in a decoupling of ion and electron heat flux. This, in turn, can influence the H-mode transition at low density, as speculated in [6]. Even comparing shots at the same current, density and X-point height different values of $P_{L,LH}$ were measured. In fact shots performed before June 2011 show noticeable lower $P_{L,LH}$ if compared to shots performed in December 2011, see Figure 3(a). Between the two campaigns the discharges seem to be characterized by different wall conditions. In fact a change in Z_{eff} is observed, approximately 50% higher for shots performed in December. In [7] $P_{L,LH}$ is reported to grow as $(Z_{eff}/2)^{0.7}$, so an increase by 50% in Z_{eff} turns in a 30% increase of $P_{L,LH}$ which would be enough to compensate the difference between the two campaigns. No marked differences in the D_α from the divertor region is observed between the two campaigns. So, wall conditions seem to play a role in determining the H-mode power threshold, but further investigations are requested to assess how important is its contribution.

Conclusions A recent series of TCV experiments have been dedicated to investigate the influence of X-point height on H-mode power threshold. Sets of similar plasma discharges show singnificant variations in $P_{L,LH}$ due to a reduction of the divertor leg length, in agreement with the scaling observed at JET. Moreover, the well-established non-monotonic density dependence of $P_{L,LH}$ has been documented.

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