# A critical edge ion heat flux for L-H transition from combined analysis using Alcator C-Mod and ASDEX Upgrade tokamaks

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Experimental studies of the transition from L-mode to H-mode confinement (L-H) on Alcator C-Mod and ASDEX Upgrade (AUG) strengthen the basis for projecting power requirements for future fusion devices. Energy confinement at H-mode levels is generally a requirement for the success of burning plasma experiments such as ITER, yet existing devices need a minimum level of input power to access H-mode. Typically, projections for H-mode power threshold $P_{th}$ arise from empirical scaling laws derived from multi-machine databases. The commonly used 2008 ITPA scaling [1] for the power threshold in MW is $P_{th} = 0.049\bar{n}^{0.72}B_T^{0.80}S^{0.94}$, where $\bar{n}$ is the line averaged density ($10^{20}$m$^{-3}$), $B_T$ is the toroidal field (T) and $S$ is the plasma surface area (m$^2$). This expression gives $P_{th} = 53$ MW for ITER baseline parameters in D plasmas, with some uncertainty. On C-Mod, we have now compared L-H experiments at $B_T$ of 4.0—7.8T to the ITPA scaling law [2,3]. Figure 1 shows the most recent evaluation of $P_{th}$ at 7.8T. $P_{th}$ is in rough quantitative agreement with this power law, but, as on AUG and other devices, the expression does not capture the experimental reversal of the $P_{th}$ density dependence at low normalized density $\bar{n}/n_G$

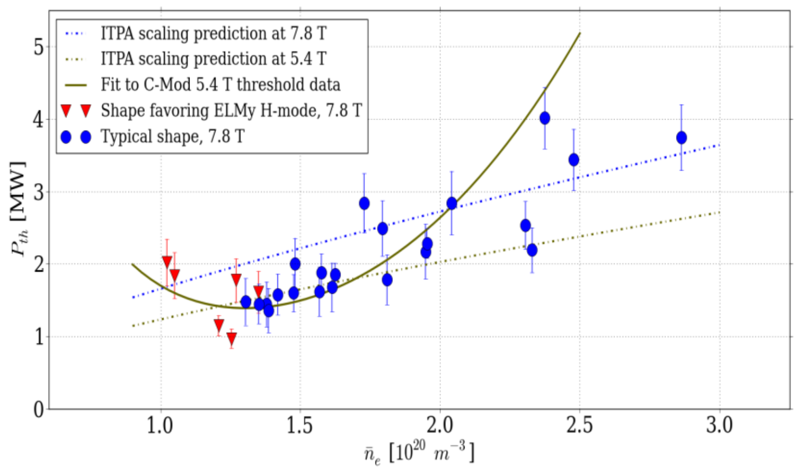


*Figure 1: $P_{th}$ dependence on density in C-Mod discharges at 7.8T (symbols); ITPA scaling law at 7.8T (blue dash-dot) and 5.4T (brown dash-dot). The solid curve is a non-monotonic fit to separate C-Mod L-H data set at 5.4T, which captures the low-density branch behavior [2]. (adapted from [3].)*

[2]. Furthermore, at moderate to high line averaged density $\bar{n}$, the inferred experimental $P_{th}$ on C-Mod does not scale as strongly with $B_T$ as the scaling law indicates [2,3]. Many of the 7.8T data in Fig. 1 agree reasonably well with the empirical 5.4T curve.

We can partially resolve these discrepancies by performing transport and power balance analysis of C-Mod plasmas just prior to L-H transitions, at densities where the experimental $P_{th}$

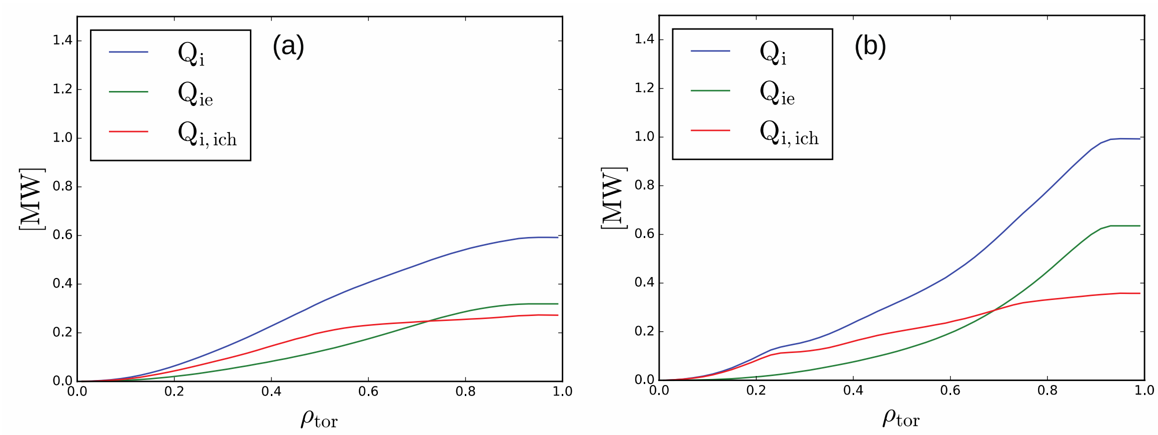


*Figure 2: Profiles of the surface integrated ion heat flux ($Q_i$), as well as its components, ICH deposition ($Q_{i,ICH}$) and heat transfer from electrons ($Q_{ie}$) at the L-H transition for discharges with (a) density $n_e$ = 0.94 x $10^{20}$ $m^{-3}$ and (b) $n_e$ = 1.36 x $10^{20}$ $m^{-3}$. Both discharges have $B_T$ = 5.4T and $I_P$ = 0.9MA. (From [4].)*

is relatively insensitive to density [4]. The TRANSP code is used to calculate deposition rates of power onto both electrons and main ion species, along with the radially dependent heat transfer rate between electrons and ions. In most discharges, input power is deposited predominately on electrons. Because energy transfer between species weakens at lower density, the amount of power flowing in the ion channel decreases at low density as well. Figure 2 compares the calculation of the surface-integrated ion heat flux $Q_i$ for two distinct density values. The total injected power in these cases is similar.

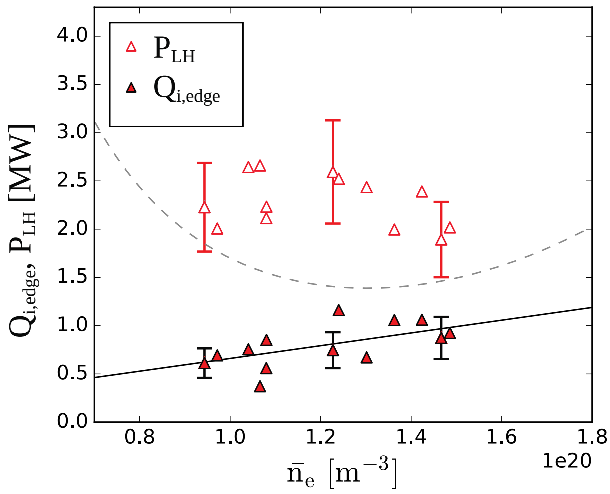


*Figure 3: Surface-integrated ion heat flux $Q_{i,edge}$ and total loss power $P_{LH}$ versus density just before the L-H-transition, for $B_T$ = 5.4T and $I_P$ = 0.9MA. The solid black line is the fit through the $Q_{i,edge}$ points, forced through the origin. The dashed curve is the fit to $P_{LH}$ from [2]. (From [4].)*

Analysis of several discharges at 5.4T confirms and extends a key result found on AUG: a critical value of surface-integrated ion heat flux per particle $Q_i/\bar{n}$ is necessary to enable the transition from L-mode to H-mode [5].

This is readily seen in Fig. 3. In this region of density space approaching the "low-density branch" of the power threshold, a linear dependence of $Q_i$ on density is evident, despite $P_{th}$ being flat or even decreasing with $\bar{n}$. This result agrees qualitatively with the AUG findings [5], and the trend may even be compared quantitatively, by considering the ion heat flux $q_i \equiv Q_i/S$. We find that the ratio of the value $q_i/\bar{n}$ evaluated on C-Mod and AUG is exactly the ratio of the magnetic field strength of the devices: 5.4T / 2.35T. This is highly suggestive of a toroidal field term which might be identifiable on a scan in a single device.

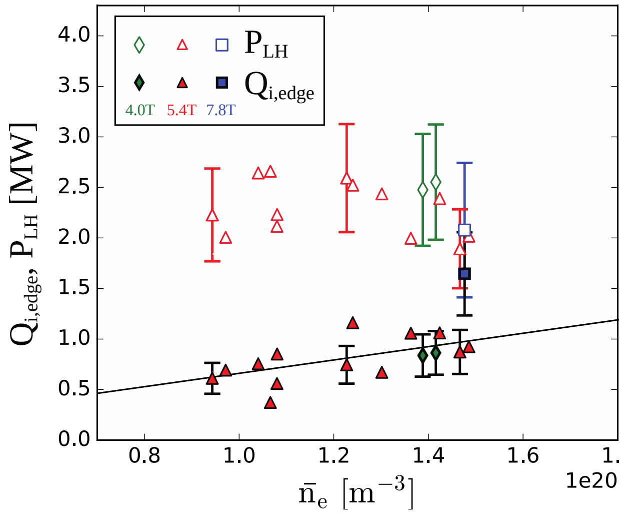


*Figure 4: $Q_{i,edge}$ and $P_{LH}$ versus density just before the L-H-transition. Black line reproduces the fit through the 5.4T cases as shown in Figure 3. (From [4].)*

Figure 4 adds data from discharges at 4.0T and 7.8T, for which TRANSP power balance analysis was possible, to the 5.4T data shown in Fig 3. Because the error bars are considerable, the 4.0T data neither confirm nor refute the hypothesized trend of $Q_i \propto B_T$, but the 7.8T case is consistent with such a scaling. TRANSP analysis further indicates a difference in the absorption of auxiliary ion cyclotron heating when going from discharges in the 5.4T range (minority H damping) to the 8T range (minority $^3$He damping). The ratio of power delivered to the ions vs. electrons is considerably higher at 7.8T. We believe this may explain the overall similar values of total threshold power $P_{th}$ obtained at 5.4T and 7.8T (*e.g.* as in Fig 1).

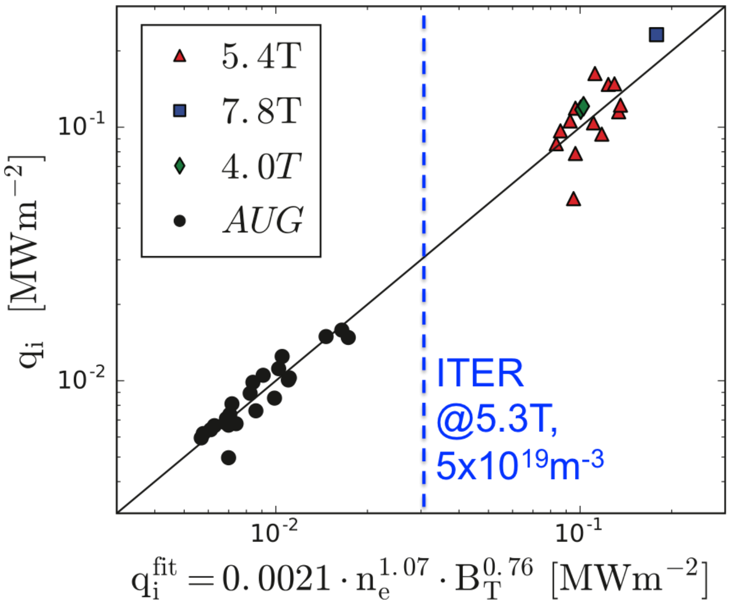


*Figure 5: Experimental edge ion heat flux at L-H versus an expression fit to the data set from ASDEX Upgrade and Alcator C-Mod. A projection to ITER is indicated in blue. (Adapted from [4].)*

In short, the analysis of C-Mod data suggests that $Q_i$ at the L-H transition not only increases linearly with $\bar{n}$ but also with $B_T$. The $\bar{n}$, $B_T$ scalings are not necessarily reflected in the experimental total L-H power because of changing balance of edge electron and ion heat fluxes, which depends in turn on the auxiliary heating scheme and the strength of electron-ion equilibration. Combining data from C-Mod and AUG yields a general expression for the edge ion heat flux at the L-H transition, $Q_i/S \propto \bar{n}^{1.07} {B_T}^{0.76}$, where $S$ is the plasma surface area. Because of the expected link between heat flux per particle and edge ion temperature gradient, and the dominance of $\nabla T_i$ in the neoclassical expression for radial electric field [6], our result is consistent with a critical shear in edge $E \times B$ being necessary for H-mode access, and provides a physics interpretation of the similar dependencies on $\bar{n}$, $B_T$, and $S$ found in the $P_{th}$ scaling law. Note that this interpretation does not shed light on detailed dynamics of transport barrier formation, in particular the flow generation and rapid suppression of edge turbulence that is often observed [7]. Nonetheless we may assert that a minimum ion heat flux is a necessary condition for initiating the L-H transition. Figure 5 illustrates the match of the expression above to experimental data from C-Mod and AUG, and also shows where ITER lies with respect to the two machines. Satisfyingly, the projection to ITER represents an interpolation on this data set, not an extrapolation. The derived $Q_i$ expression may prove useful for ITER predictions constrained by transport models.

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