L-H threshold at low density and low momentum input in the JET tokamak

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1. Introduction. Previous measurements in JET, as well as in other tokamaks, have found a minimum value of plasma density (n_e), $n_{th,min}$, below which the H-mode power threshold, P_{thr}, increases with decreasing n_e [1],[2]. On the other hand, the multi-machine H-mode threshold scaling law, $P_{thr,08}$ [3], is roughly linear with n_e and the physics mechanisms underlying the 'roll-over' of P_{thr} at low n_e are unexplained. It is of relevance to ITER, which foresees H-mode access at high B_T (5.3T) and low n_e, whether $n_{th,min}$ scales with B_T and machine size. This paper reports on recent L-H threshold studies carried out in JET with the MkII-HD divertor at low density and two values of B_T to provide additional input to these issues.

Over the years, L-H threshold experiments at low n_e in JET have shown similar P_{thr} in plasmas with either neutral beam (NB) or ion cyclotron resonance (ICRH) heating. In ASDEX-Upgrade, similar P_{thr} has been reported for NBI and ECH heated plasmas over a wide range of n_e [4]. In JET, P_{thr} is not affected by variations in toroidal rotation due to TF ripple [5]. On the other hand, in DIII-D P_{thr} is found to increase with injected torque and edge toroidal rotation in experiments that vary input power and torque independently by means of co- and ctr- NBI [6]. New JET discharges with varying momentum input are analysed in this paper to investigate the influence of NB torque on P_{thr}.

It is likely that the H-mode transition is linked to achieving critical edge conditions. The second part of this paper therefore focuses on the analysis of the edge parameters at the L-H transition, in order to provide input to the physics of edge transport barrier formation.

2. Global H-mode power threshold analysis. New low n_e experiments were carried out in JET with the MkII-HD divertor at B_T = 1.8 and 3.0T and down to the lowest achievable n_e values (similar to those obtained in previous JET low density scans). No evidence of a 'roll-over' of P_{thr} and edge T_e at low n_e was found (Figure 1), in contrast to earlier findings with the MkII-GB divertor (B_T = 2.4-2.7 T) and consistent with more recent experiments with the MkII-GB SRP (=divertor septum removed) [2]. This indicates that removing the divertor septum had an impact on P_{thr} and may have lowered its density turning point [2] or even eliminated it, although there is no physics explanation to date of why this may be the case. Thus, the new data only provide an upper bound for $n_{th,min}$ in JET MkII-HD. Overall, the old and new JET L-H datasets at low n_e show a weaker than linear increase of $n_{th,min}$ with B_T in the range 1.2-3.0T, as indicated in the analysis of [3].

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* See the Appendix of F. Romanelli et al., Proceedings of the 23rd IAEA FEC 2010, Daejeon, Korea

A plasma current (I_P) scan from 1.7 to 2.75 MA was carried out in JET MkII-HD at fixed B_T=3T and n_e~ $2x10^{19}$ m^{-3}. P_{thr} was found to vary weakly with I_P (or q_{95}), consistent with previous results with MkII-GB at similar values of n_e ($P_{hr} \sim I_P^{\alpha}$, $|\alpha| <0.2$, B_T=2.4T) [1] and with the absence of an I_P dependence in $P_{thr,08}$. The weak dependence of P_{thr} on I_P is robust against variations in divertor geometry in JET.

The influence of NB torque on P_{thr} in JET was assessed quantitatively with a variation in momentum input, achieved by modifying the NBI/ICRH ratio, in a subset of the MkII-HD discharges shown in Figure 1. A further selection of the data is performed in order to eliminate the known dependencies of P_{thr} with respect to n_e, B_T and X-point to outer strike point distance. After normalization to $P_{thr,08}$, a residual increase of P_{thr} with torque of at most 20-30% is found when the injected NB torque increases from 0 (ICRH only) to 6 Nm (Figure 2). This is a small, but systematic deviation from the scaling law, which can be employed to test physics-based models of the H-mode transition. In this study, the NB torque is the average NB torque injected into the plasma, without ion orbit effects, as computed by PENCIL [7]. More refined calculations of the NB torque, accounting for ion orbit effects, are planned.

3. Analysis of the edge profiles at the L-H transition. Composite profiles are collected in the quasi-stationary L-mode phase (~100-200 ms) prior to the H-mode transition. n_e profiles are obtained by combining HRTS [8] and Li-beam [9] data, T_e profiles from HRTS and ECE [10] and T_i, v_ϕ, v_θ from edge CXRS on C^{+6} [11]. As shown in Figure 3, no edge pedestal is observed in T_e and T_i before the L-H transition, while n_e exhibits a pedestal shape, consistent with a SOL source. In H-mode, a steepening of the edge gradients is observed in all profiles. The JET MkII-HD dataset is characterized by edge $T_i \sim$ edge T_e at the L-H transition, weakly varying with n_e^{PED}.

Using the composite profiles, the edge radial electric field, E_r, is calculated from the C^{+6} impurity force balance equation, $E_r = \nabla p_I/(Z_I\, e\, n_I) - v_{\theta,I}\, B_\phi + v_{\phi,I}\, B_\theta$, assuming constant Z_{eff} and C as the dominant impurity. With this assumption, necessary due to lack of direct n_I measurements, n_I is proportional to n_e. Due to the weak edge n_e and T_i gradients at the L-H transition, the diamagnetic component, E_{dia}, is the weakest contribution to E_r and its gradient (Figure 4). The v_θ profile is flat and of order 0-5 km/s in the ion diamagnetic direction, consistent with earlier measurements in JET [12], and $E_{v\phi}$ increases with increasing momentum input. In H-mode, all E_r components increase substantially, leading to a more pronounced E_r well (see Figure 4) and a spin-up of v_θ up to 10 km/s in the e- diamagnetic direction is observed in the steep edge gradient region. Due to uncertainties in the EFIT magnetic reconstructions, alignment of the edge profiles with respect to the separatrix position is inaccurate to at least 2cm when projected at the torus outer midplane. Thus, at present, the radial locations of the E_r minima cannot be determined with sufficient accuracy. Work is on going, so as to reduce such uncertainties, both improving the EFIT reconstructions and refining the relative alignment of the edge profiles by invoking power balance along the magnetic field lines.

The EXB shearing rate, $\omega_{EXB} = (R\, B_\theta)^2/B\, \partial/\partial\psi\, (E_r/R\, B_\theta)$, is considered by theory to be responsible for the suppression of edge turbulence and the formation of the edge transport barrier. The new JET MkII-HD dataset is used to study the relation of ω_{EXB} with density, B_T

and NB torque, assuming that a critical ω_{EXB} value is required to achieve the L-H transition. Note that in this study the neoclassical v_θ, calculated by NCLASS [13] is used in the derivation of E_r, rather than the measured one, which is often too noisy at the L-H transition. This is justified by the observation that $v_\theta \sim n_{\theta,neo}$ within a factor of 2 (i.e. inside the uncertainty of the measurements). In order to eliminate correlations between n_e and NB torque, the data are selected at fixed torque/density when studying a variation of ω_{EXB} with density/torque. The maximum value of ω_{EXB} at the L-H transition is found to be independent of n_e^{PED} and B_T at fixed torque. This could be explained with the assumption of a critical ω_{EXB} value at the L-H transition and more power required to achieve the critical ω_{EXB} at higher B_T and n_e (consistent with $P_{thr,08}$). At fixed n_e, a modest increase of ω_{EXB} with NB torque, related to the increase of $E_{v\phi}$ with torque, is not excluded by the data. This can be confirmed/disproved by reducing the scatter in ω_{EXB} and extending the variation in torque in the experiments at 3T. The analysis will also be extended to the TF ripple experiment, where a significant variation in edge v_ϕ was observed, with no effect on P_{thr} [5].

4. Conclusions and next steps. In contrast to earlier results with MkII-GB, no minimum in P_{thr} and edge T_e versus n_e was found in JET MkII-HD, suggesting that removal of the divertor septum may have lowered or even removed the n_e turning point of P_{thr}. P_{thr} varies weakly with I_P (or q_{95}) and shows a residual increase with NB torque of at most 20-30% with respect to $P_{thr,08}$. Analysis of the edge profiles at the L-H transition shows lack of T_e and T_i pedestals and the presence of a weak pedestal in n_e. A weak E_r gradient is observed at the L-H transition, dominated by the $E_{v\phi}$ and $E_{v\theta}$ components. The maximum value of ω_{EXB} at the L-H transition is independent of n_e^{PED} and B_T at fixed torque, which could be explained under the assumption of a critical ω_{EXB} at the L-H transition. A modest increase of ω_{EXB} with torque cannot be excluded by the present data. Reducing the uncertainties in the E_r gradients and extending the variation in NB torque in the experiment will elucidate the relation between ω_{EXB}, torque and P_{thr} and thus enable testing whether a critical ω_{EXB} is required to achieve the L-H transition.

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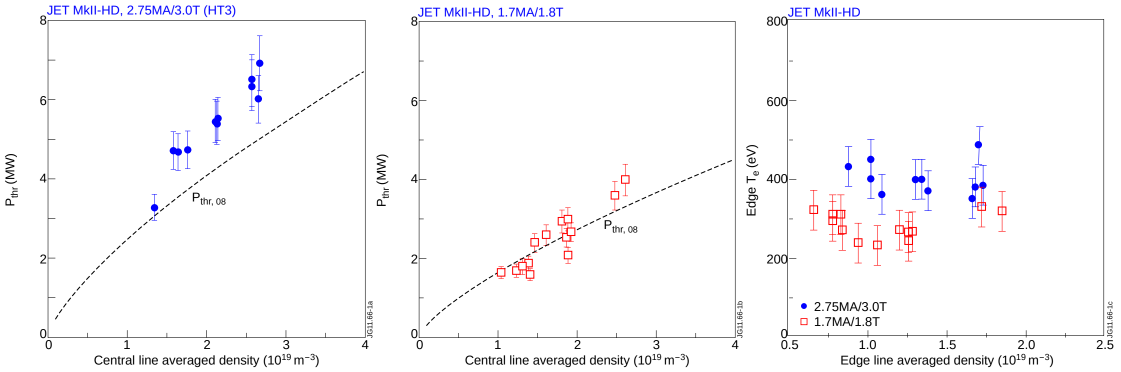

Figure 1. From left to right : P_{thr} vs central line averaged density at $B_T = 3.0$ and 1.8 T in JET MkII-HD and edge T_e vs edge line averaged density.

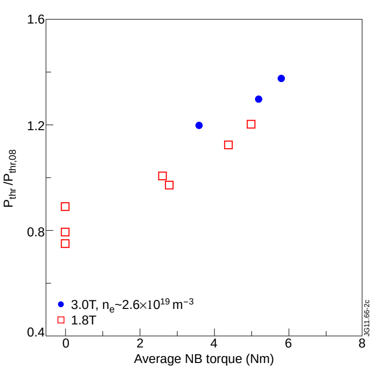

Figure 2. Residual variation of P_{thr}, compared to $P_{thr,08}$, with average injected NB torque. Selection of data from Figure 1 (see text).

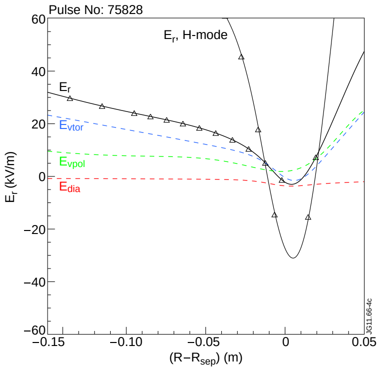

Figure 4. Edge radial electric field at the L-H transition and comparison with H-mode.

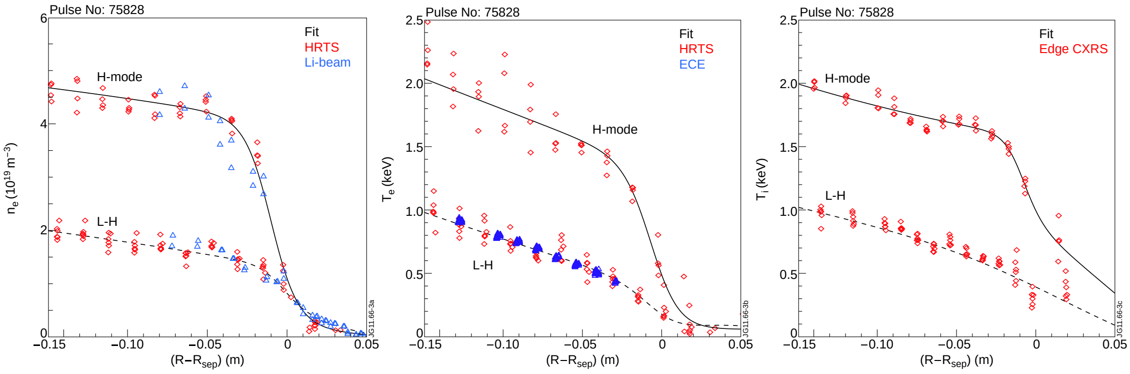

Figure 3. n_e, T_e and T_i profiles in JET at the L-H transition and comparison with H-mode.

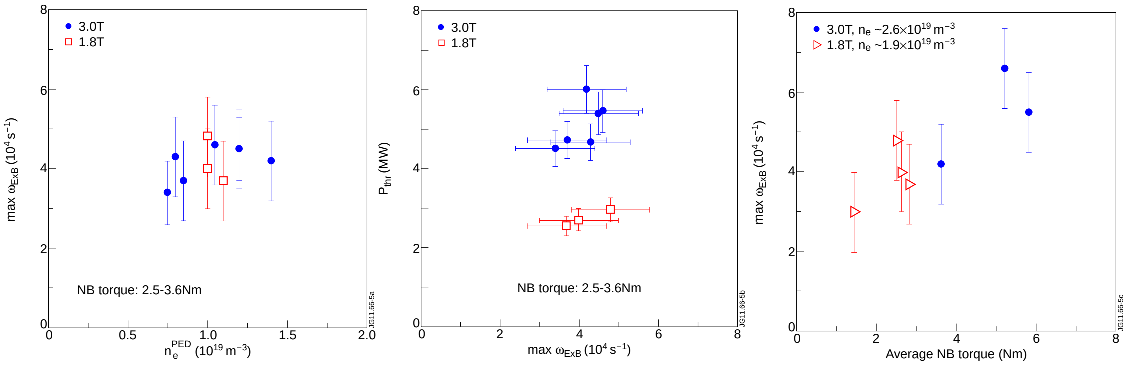

Figure 5. From left to right : variation of max ω_{EXB} at the L-H transtion with n_e^{PED}, P_{thr} and torque.