The relation between divertor conditions and the L-H threshold on JET

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INTRODUCTION

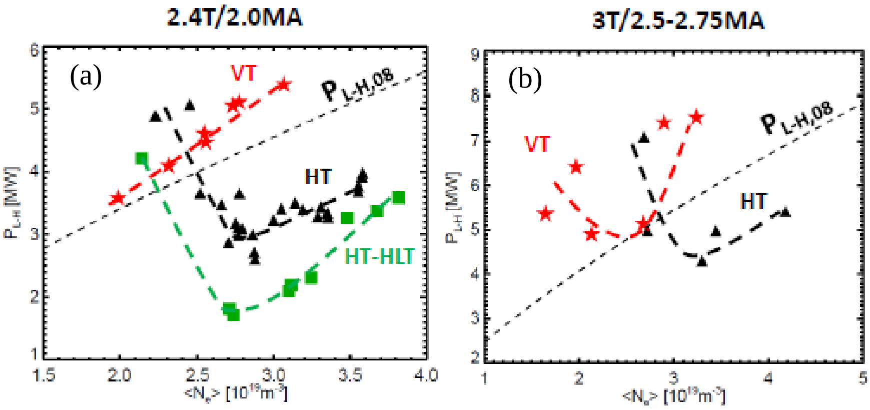
H-mode access will be required from the early stages of ITER operation onwards to develop plasma scenarios and test control techniques (ELM mitigation, H-mode exit). Knowledge of the L-H threshold power (P_{L-H}) is therefore inherent to the planning of the experimental timeline and availability of systems. The anticipated threshold power on ITER (52MW at a density of 5 $10^{19}m^{-3}$ in deuterium) is extrapolated from a multi-machine scaling [1], based on density, magnetic field and machine size. Many other ‘hidden parameters’ are known to affect the threshold. This induces considerable uncertainty in the extrapolation. Because the available heating power on ITER (73MW max.) is only marginally above the expected threshold, there is an ongoing effort to understand the physics behind these additional dependencies and to evaluate if any could be used to lower the power threshold on ITER.

EXPERIMENTS

Experiments on several machines have reported a strong effect of the divertor configuration and conditions on P_{L-H} (e.g. JET-C [2], C-Mod [3], DIII-D [4]). Dedicated experiments using slow power ramps (1MW/s) have been carried out on JET-ILW in 2013/14 to investigate this effect with the Be/W wall [5]. A strong increase of P_{L-H} in the high density branch is found for discharges with the outer strike point (OSP) on the vertical target (VT) compared to discharges in the horizontal target configuration (HT) [6,7]. The threshold decreases further in the HT configuration if the lower triangularity is increased (HT-HLT), moving the inner strike point higher onto the vertical target [5]. Fig. 1a shows P_{L-H} for the different divertor configurations at 2.4T. No minimum in P_{L-H} as function of density is observed at 2.4T for the VT configuration. At increased toroidal field (3T) the minimum that is observed in P_{L-H} for the HT configuration shifts to higher density (see fig. 1b) [5] and is now also observed for the VT configuration, but at lower density than for the HT configuration.

INTERPRETATION

The currently accepted view is that the L-H transition is caused by the suppression of turbulence by E_rxB shear and that the radial electric field well is sustained by the ion diamagnetic term in the force balance equation [8]. Therefore we have investigated if the change in P_{L-H} could be explained by changes in the edge density and temperature profiles when the divertor configuration is changed [6]. Edge density profiles (Li-beam, reflectometry, Thomson scattering) and temperature profiles (ECE, Thomson scattering, edge



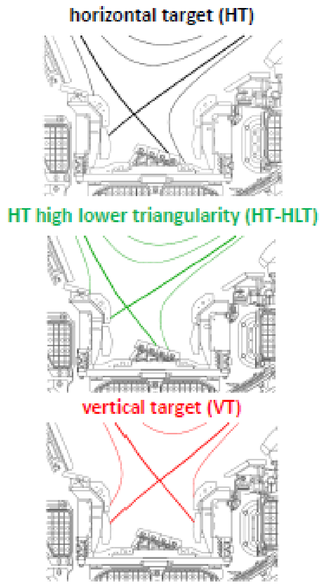


Fig. 1: Thermal loss power at the L-H transition at 2.4T/2MA (a) and at 3T/2.5-2.75MA (b) as function of line averaged density. The dashed line is the scaling law [1].

CXRS) measured in the L-mode phase before the transition have been fitted. For all discharges with edge CXRS data, T_e was observed to be equal to T_i in both the high and low density branch. The diamagnetic radial electric field has been derived from the fitted profiles. The density dependence of the threshold shows reasonable agreement with the existence of a critical depth of the diamagnetic E_r well before the transition for each of the divertor configurations but cannot explain the differences between them as the discharges with higher threshold also exhibit higher edge temperatures and a concomitant deeper E_r well before the transition [6,7].

The strong variation in threshold power due to relatively small changes in the divertor configuration hints towards changes in the scrape off layer (SOL) directly affecting the transition, rather than indirectly through changes in the upstream kinetic profiles. The shear in the outer part of the E_r well, where the pedestal forms, is determined not only by the E_r structure in the plasma edge but also by the radial electric field in the near SOL. We have no direct measurements of the radial electric field structure in the SOL between divertor configurations for these discharges, but we present indications that (1) E_r in the SOL depends on the divertor configuration and that (2) the SOL E_r plays a role in the transition.

SOL E_r IN HORIZONTAL AND VERTICAL TARGET CONFIGURATION

The potential in the SOL relates to the target T_e profiles through the potential difference over the Debye and magnetic pre-sheath, leading to $E_r \approx -3\mathrm{grad}(T_e)/e$ in the SOL [9]. This neglects contributions from radial gradients in the parallel current and pressure gradients, which is a better approximation at the outer than inner strike point. Discharges with the outer strike point (OSP) on the horizontal target have a strongly peaked target T_e profile, as derived from Langmuir probe data (fig. 2a). This corresponds to a strong positive E_r in the near SOL. Discharges with the OSP on the vertical target have a much broader target T_e profile (fig. 2b), leading to a flatter E_r. To corroborate this interpretation, EDGE2D-EIRENE [10,11] simulations including drifts and parallel currents have been carried out on two pulses, one in HT and one in VT configuration, using identical transport coefficients ($D_\perp$=1m^{2}s^{-1}, $\chi_{e,i}$=2m^{2}s^{-1}), input power (2.6MW) and similar separatrix density (N_{sep}=1.0 10^{19} m^{-3} (VT) and 1.2 10^{19} m^{-3} (HT)). The code results qualitatively reproduce the observed target T_e profiles (fig. 2ab) and indeed predict a very strong positive E_r close to the separatrix for the HT configuration, whereas for the VT configuration only a mildly positive E_r is reached in the outer SOL (see fig. 2c). The strong difference between the two configurations in the code is attributed to the difference in neutral recycling. In VT configuration, the neutrals recycling of the outer divertor target plate are scattered towards the outer divertor leg, broadening the target T_e profiles, whereas the neutrals in the HT configuration are recycled away from the

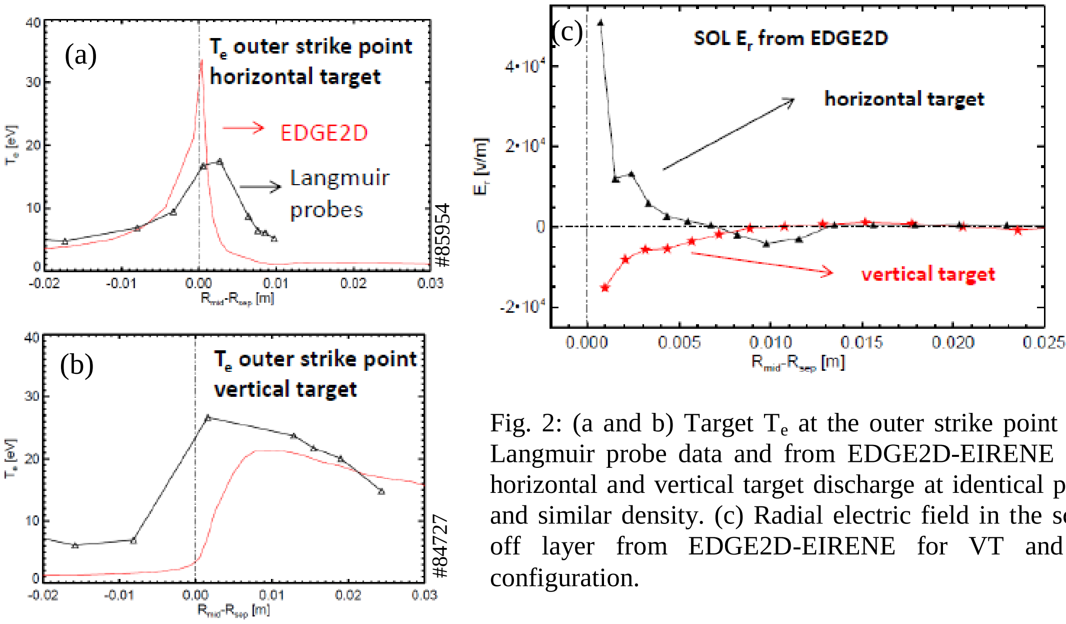


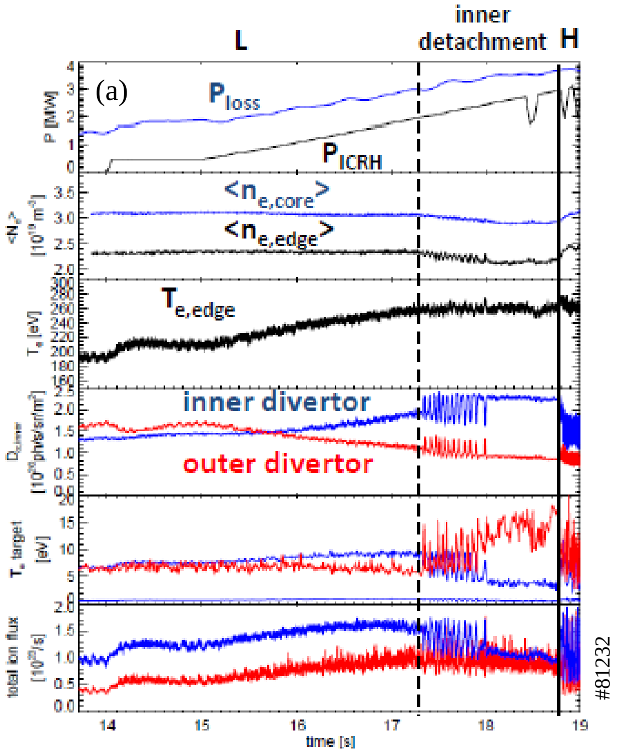
Fig. 2: (a and b) Target T_e at the outer strike point from Langmuir probe data and from EDGE2D-EIRENE for a horizontal and vertical target discharge at identical power and similar density. (c) Radial electric field in the scrape off layer from EDGE2D-EIRENE for VT and HT configuration.

outer divertor leg. These results were proven to be robust against small variations in assumed input power and separatix density in the code.

The difference in observed target temperature profiles indicates a more positive E_r in the SOL for the HT configuration, creating a higher shear in the outer part of the E_r well, and the EDGE2D-EIRENE modelling supports these observations due to a difference in the recycling pattern of neutrals between HT and VT configuration.

CORRELATION BETWEEN DIVERTOR RECYCLING ASYMMETRY AND $P_{L\text{-}H}$

The presence of a strong E_r in the SOL is also consistent with the effects the E×B drifts have on distributing the particle and heat fluxes between the inner and outer divertor targets. For B×grad(B) directed towards the divertor, the E×B drift in the main SOL is directed from the inner towards the outer divertor and from the outer to the inner in the private flux region and along the divertor legs. The combined effect of these drifts is an increase in the inner divertor density compared to a situation with no drifts [12]. This asymmetry between inner and outer targets is already observed at power levels well below the H-mode threshold and is most pronounced in the divertor D_α emission. Fig. 3a shows the evolution of the divertor emission, target temperature and ion fluxes as the power is ramped up in L-mode for a HT configuration discharge. A gradually increasing inner-outer asymmetric recycling pattern is observed, consistent with an increasing E_r×B drift effect in the SOL and divertor. This is observed for both HT and VT discharges. For HT discharges, for which we expect a stronger SOL E_r, a sudden drop of the inner strike point temperature and ion saturation current and a large increase of the D_α emission in front of the entire inner target is observed. The ratio D_δ/D_α increases by a factor 2-3, indicating inner target detachment. This sudden transition is labelled 'inner detachment' in fig. 3. These sudden changes in the divertor conditions are usually modulated by the heat fluxes from sawtooth crashes and are therefore referred to as 'divertor oscillations' [13]. No change to the upstream profiles is observed during the divertor oscillations in JET-ILW. Remarkably, a sudden increase in the target temperature peaking at the outer strike point is observed, which implies a sudden increase in E_r in the SOL, as the inner divertor detaches. The critical power at which this occurs always precedes the L-H transition in the high density branch, as illustrated in fig. 3b. At the highest densities in the L-H threshold density scans, the detachment of the inner divertor will immediately trigger an L-H transition, which demonstrates that this state, associated with a higher SOL E_r, is beneficial for H-mode access.



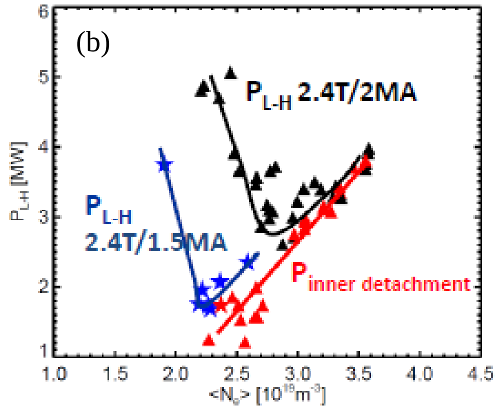


Fig. 3: (a) Evolution of deuterium emission and target temperature and ion flux as the power is ramped up at constant density in L-mode. (b) L-H threshold power and power threshold for detachment of the inner divertor leg.

Dithering L-H transitions (~130Hz), which are only observed in the high density branch, could also be understood through dynamics involving the divertor and SOL conditions. Dithering L-H transitions show very similar oscillations in the deuterium emission pattern as divertor oscillations, except for a short H-mode phase that is triggered from the state with the detached inner divertor leg, associated with the higher SOL E_r. The H-mode transition itself triggers the re-attachment of the inner divertor and the more symmetric recycling pattern associated with the lower SOL E_r leading to the H-L back transition.

OUTLOOK

An increase in edge $E_r \times B$ shear through the SOL E_r is proposed as a mechanism to explain the divertor configuration effect on the L-H threshold. Observations on JET-ILW indicate that configurations with a strong inner/outer asymmetry in the divertor recycling pattern are beneficial for H-mode access at reduced power. A better understanding of the physics behind this mechanism could open up prospects of lowering the L-H threshold on ITER through influencing the divertor and SOL conditions.

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