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INTRODUCTION

To achieve the goals in ITER [1] operation in the high confinement H-mode regime is crucial. H-mode is accessible above a threshold heating power, P_{thr}, marked by the formation of an edge transport barrier. Regression of data from todays tokamaks provides an empirical scaling of the form: $P_{thr}^{Martin'08} = 0.049 n_{e20}^{0.72} B_T^{0.80} S^{0.94}$ [2]. Here n_{e20} is the line averaged density in 10^{20} m^{-3}, B_T the magnetic field at the geometric axis in T and S the plasma surface area in m^2. This scaling law, however, is only applicable above a certain minimum density, ne;min, since a U shaped dependence of P_{thr} as function of density is commonly observed [3–5]. According to a detailed analysis of the heat flux through the plasma edge on ASDEX Upgrade the density at the minimum P_{thr} scales like $n_e^{min} \approx 0.71 I_p^{0.34} B_T^{0.62} a^{-0.95} (R/a)^{0.4}$ [6] and is determined by the collisional coupling between electrons and ions. Other explanations involve the parallel heat transport regime of the scrape-off layer (SOL) [7], although in this work the closure of the equations and the assumption of a constant SOL collisionality leading to the observed U shape is technically wrong. However, this can be rectified by using the equally valid radial density decay length in the SOL as substitution for the unknown heat-flux decay length rather than the temperature decay length.

The impact of divertor and SOL geometry on H-mode access has long been known [8] and is an active area of research on many devices [5, 9–12]. Whilst the good agreement of the scaling of n_e^{min} with the measurements in several devices presented in [6] is a strong support for the role of the energy exchange term, the differences of P_{thr} as function of density measured on JET with C as plasma facing components (JET-C) compared to the ITER like W/Be wall (JET-ILW) in the same divertor geometry (MKII-HD) points towards the role of the SOL [5]. The JET-ILW data shows U shaped density dependence of P_{thr} and a reduction of about 30% in the high density branch compared to JET-C (MKII-HD), where in the same density range $P_{thr} \propto n_{e20}^{0.7}$. However, a minimum of P_{thr} with n_{e20} had been observed in JET-C previously with the more closed MKII-GB divertor [8]. In this paper we compare recent results from JET-ILW with both strike points on the vertical targets (VT) to the JET-ILW data discussed in [5] giving further evidence on the importance of the SOL for the L-H transition.

EXPERIMENT

Using slow power ramps ($dP_{NBI}/dt \approx 1MW/s$) L-H transitions at $0.14 \leq n_{e20} \leq 0.31$ were investigated in VT. Figure 1 shows the new (black solid) VT configuration in comparison with the old (blue dash) V5 and (red dash-dot) V5L divertor configuration. Clearly, the lower triangularity is different in the three shapes with $\delta_l^{VT} = 0.22$ in VT, $\delta_l^{VT} = 0.32$ in V5 and $\delta_l^{V5L1} = 0.39$ in V5L. The upper triangularity $\delta_u \approx 0.18$ and plasma surface area $S \approx 145m^2$ is similar in all shapes. The elongation $\kappa^{VT} \approx 1.68$ in the VT configuration is slightly higher than $\kappa^{V5,V5L} \approx 1.63$ in the V5 and V5L configurations. In addition to the matching density scan in VT at $B_T = 2.4T$ and $I_p = 2.0MA$ ($q_{95} = 3.5$), also discharges in V5 with lower $I_p = 1.5MA$ ($q_{95} = 5.1$) and low density were performed. Furthermore, a set of V5 discharges at constant n_{e20} with different three different gas fuelling locations (top, outer mid-plane, inner divertor) and VT discharges with dominant shallow pellet fuelling from the low field side (LFS) are used to investigate the effect of the particle source

POWER THRESHOLD

The loss power $P_{loss} = P_{abs} + P_{\Omega} - dW_p/dt$ (P_{abs}: absorbed auxiliary heating power, P_{Ω}: Ohmic heating power and Wp stored energy) as function of line averaged density is shown in Fig.2 at (black triangles) the L to H transition and (green diamonds) the H to L transition. The data show no clear minimum of P_{loss} with density and apart from the lowest density point the data at both transitions compares well to the (red line) Martin'08 scaling. There is also no indication for a hysteresis between L-H and L-H transitions. It should be noted that here the radiated power in the core, P_{rad}^{core}, is not subtracted. The Martin'08 scaling has been derived for P_{loss}, since P_{rad}^{core} is difficult to determine in many devices. Here, we define P_{rad}^{core} to be the power radiated within the 98% flux surface (ψ_N = 0.98) from a tomographic reconstruction of the bolometer data. If to compare the power flowing over the separatrix into the SOL $P_{sep} = P_{loss} - P_{rad}^{core}$ the back transition would happen at a slightly lower power, since the core radiated power at the H-L back transition is in average by $P_{rad}^{H-L} - P_{rad}^{H-L}$ = (0.3±0.14) MW higher than for the L-H transition due to the higher temperature and higher impurity influx in H-mode. This may be interpreted as a small hysteresis, but though consistent is well with the estimated error bars for P_{loss} of 10% and 15% for the L-H and H-L transition respectively.

In Fig.3 the comparison of P_{sep} at the L-H transition between the different data sets is shown. In the range where the data in (blue circles) V5 and (red squares) V5L shows a clear minimum the data in (black triangles) VT shows only the high density behaviour $P_{thr} \propto n_{e20}^{0.7}$ with P_{thr} at densities above $n_e^{min} \approx 2.7\times10^{19}\,m^{-3}$ 2 or 2.5 time higher than in V5 and V5L respectively. The data with LFS pellet fuelling align well with gas fuelled data in VT, whilst changing the fuelling location (dark blue open circles) seems give small changes in P_{thr}. In particular, the data breaks the correlation of $P_{thr} \propto p_{div}$ (p_{div}: sub divertor pressure) previously observed [5]. A phase of oscillations in the range of ~150Hz in the edge emitters (D_{α}, BeI) are commonly observed in the V5 configuration, but are absent in VT. Here, a particle barrier seems to form first and the plasma oscillates between a lower confinement (high emission) and a higher confinement (low emission) state with corresponding oscillations in the edge density and temperature. During this phase the core and edge densities rise whilst the gas puff rate decreases. The duration of the phase depends on the fuelling location and lasts for 0.41s, 0.15s and 0.04s for top, mid-plane and divertor fuelling respectively. The physics of these oscillations is still under investigation and we take the L-H transition at the end of this phase. The lower I_p data (green circles in Fig.3) show a reduction by a factor of two for an I_p change by 25% from 2.0MA to 1.5MA, whereas at high density , if at all, only a small dependence is present [5]. A similar behaviour has recently been reported from ASDEX Upgrade [6]. The $I_p^{0.34}$ dependence of $n_{e,min}$ however would predict $n_{e,min}^{1.5MA} \approx 2{:}4\times10^{19}\,m^{-3}$.

EDGE PARAMETERS

Figure 4 shows the comparison of the edge temperature at the L-H transition in (black triangles) the VT, (blue circles) the V5 and (red squares) the V5L configuration. The data is taken at the position where the in H-mode the pedestal forms. In all three configurations the data are more or less constant over the full density range, though there may be a slight increase towards the lowest densities. In V5 and V5L $T_e^{V5} \approx (0.16\pm0.02)$ keV and $T_e^{V5} \approx (0.20\pm0.02)$ keV respectively, more or less independent of magnetic field [5]. Interestingly, the data in the VT configuration are with $T_e^{VT} \approx (0.37\pm0.04)$ keV almost twice as high. In the edge of the JET plasma generally $T_e \approx T_i$ is observed this holds also true in the VT, even at low edge densities, as can be seen from the black triangels with a grey fill in Fig.4. Further analysis is ongoing to see if this is due to the strong coupling of the electrons and ions or because of the heating of both species by NBI. The data at lower $I_p = 1.5$MA align well with the higher I_p data despite the much lower P_{thr}.

The common picture for the formation of the edge transport barrier is that of turbulence suppression by a sheared E×B flow. Here, the role of turbulence driven flows in contrast to the equilibrium flows is still uncertain. On the one hand, evidence for the turbulence driven flows to be the trigger for the L-H transition is mounting [13]. On the other hand, studies on ASDEX Upgrade point towards a strong link to the equilibrium flows with the radial electric field, E_r, close to the neoclassical field [4, 6]. For the equilibrium field the quantity $E_r^{neo} \approx \nabla p_i/(en_i)$ has been found to be a good proxy at low rotation [4]. On JET-ILW $T_i \approx T_e$ in the edge region and the ion quantities can be approximated by the electron quantities and typical E_r^{neo} profiles from fits to T_e and n_e are shown in Fig.5 for (black) VT and (blue) V5. The available profile data averaged over 0.4s before the L-H transition was fitted using a modified tanh fit to Thomson Scattering (HRTS) and Li-beam data for the density and HRTS and ECE data for the temperature. The approximated E_r^{neo} at $\rho_{pol} = \sqrt{\psi_N} = 0.97$ as function of edge density is shown in Fig.6. As on ASDEX Upgrade E_r^{neo} is constant as function of density, but the values in the VT configuration are much more negative than in V5 and V5L configurations, due to the higher T_i. Hence, the shear in the equilibrium E_r^{neo} is unlikely to be the trigger for the transition itself, but may well be required to sustain the barrier.

CONCLUSIONS

The change of the outer strike point from the horizontal target (V5/V5L) to the vertical target (VT) leads to a qualitatively different behaviour of the density dependence of P_{thr} on JET. In addition, whilst the edge temperature and the equilibrium radial electric field shear, ∇E_r^{neo}, remain constant with a shift of the strike point on the horizontal target twice as high values are required to access H-mode in VT. However, in a given configuration Eneor is independent of density. This shows that SOL/divertor conditions play a key role in the L-H transition physics. ∇E_r^{neo} does not set a universal access condition for the L-H transition, but a certain minimum shear may be necessary to sustain the H-mode triggered by i.e. turbulence driven flow shear. The strongly reduced P_{thr} at low density and low I_p with constant B_T is favourable for the ITER ramp-up that requires H-mode access during the current ramp.

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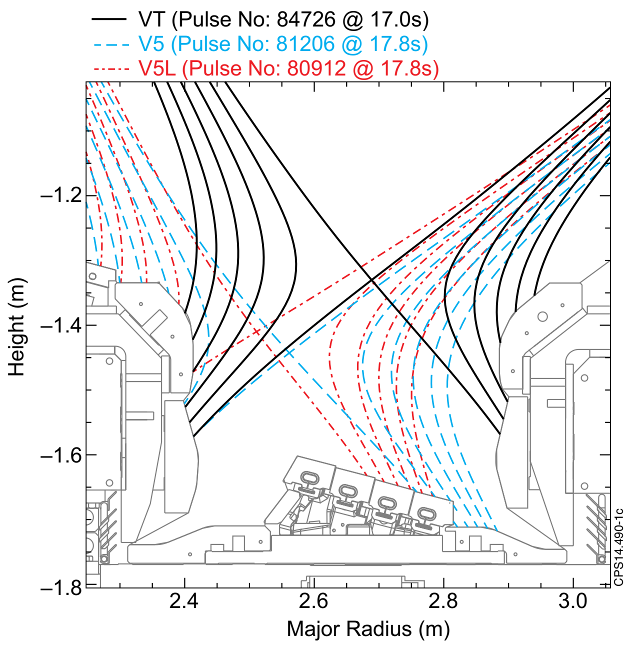

Figure 1: Different magnetic configurations in the JET-ILW divertor used in the study, (black solid) VT, (blue dash) V5 and (red dash-dot) V5L.

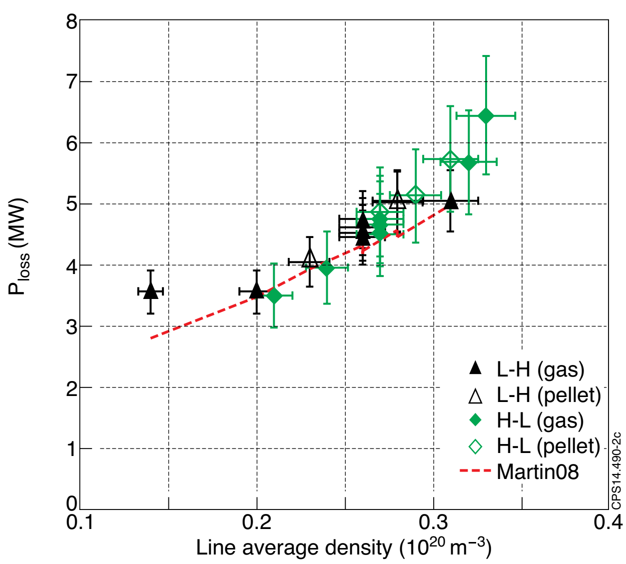

Figure 2: P_{loss} versus n_{e20} in VT at (black triangles) the L-H and (green diamonds) the H-L transition in comparison with (red line) the Martin'08 scaling. Discharges with dominant pellet fuelling are marked with open symbols.

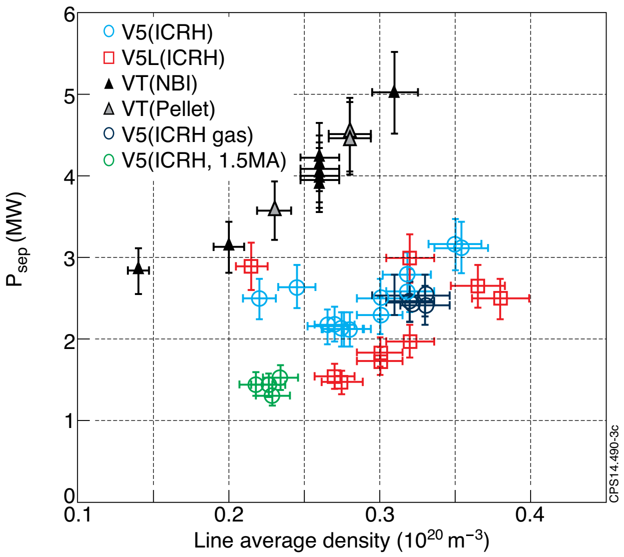

Figure 3: Comparison of P_{sep} as function of line averaged density between (black triangles) the VT, (blue circles) the V5, (green circles) the V5 at 2.4T/1.5MA and (red squares) the V5L configuration. NBI heated discharges are filled symbols and ICRH heated discharges open symbols. Discharges with dominant pellet injection in VT are marked with a gray fill and discharges from a variation of the fuelling location in V5 are shown in dark blue

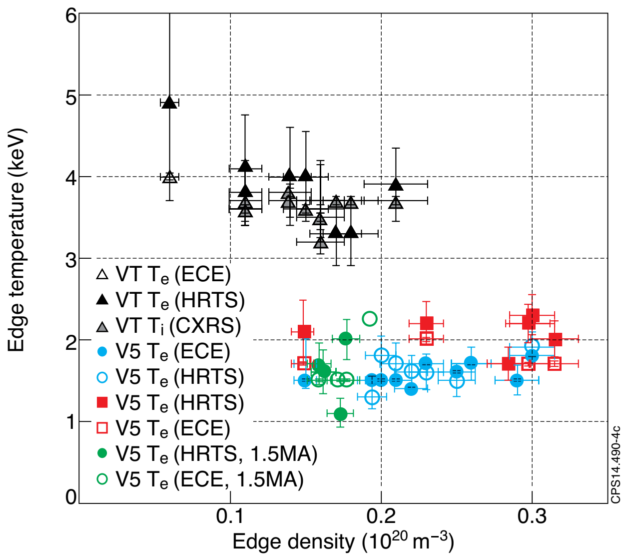

Figure 4: Comparison of edge temperature as function of edge density between (black triangles) the VT, (blue circles) the V5 configuration and (green circles) V5 at 2.4T/1.5MA. Open symbols mark ECE Temeasurements, filled symbols T_e from HRTS and the gray filled symbols Ti from edge CXRS.

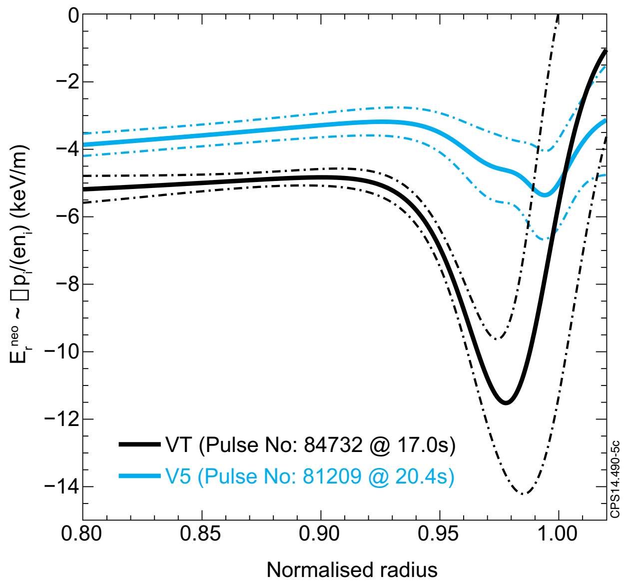

Figure 5: Profile of approximate L-mode neocl. E_r for (black) the VT configuration and (blue) the V5 configuration at $n_e^{ped} \approx 0.15\times10^{20}\ m^{-3}$.

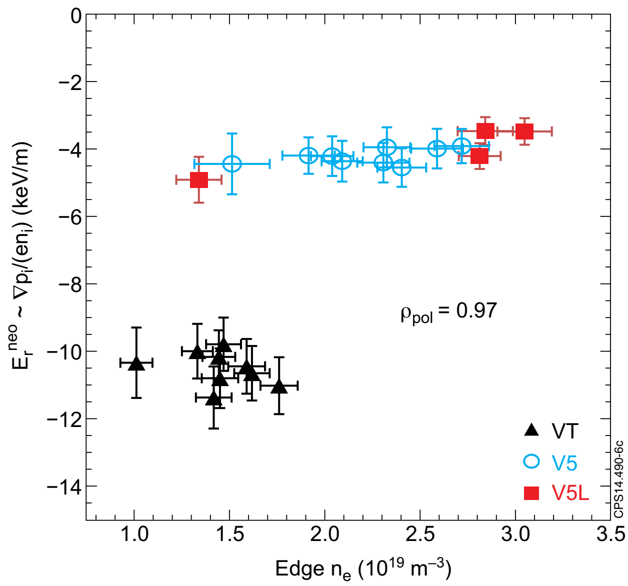

Figure 6: Approximation for the neocl. radial electric field at $\rho_{pol} = 0.97$ versus edge density for the different divertor configurations as in Fig.2.