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INTRODUCTION.

Experiments in JET with the ITER-like Be wall and W MkII-HD divertor (JET-ILW) have highlighted a sensitivity of L-H transitions to low-Z plasma impurity composition: reduced effective charge, Z_{eff}, from JET-C (line averaged $Z_{eff} \sim 1.6–2.0$, C as main intrinsic impurity) to JET-ILW ($Z_{eff} \sim 1.0–1.2$, Be as main intrinsic impurity) and concomitant reduction in L-H power threshold, P_{L-H}, in the high density branch by 30–40% [1]. The transition to H-mode also occurs at lower edge temperature than in JET-C. P_{L-H} denotes here the net power across the separatrix, $P_{sep} = P_{loss}-P_{rad,bulk}$. In addition, a minimum in P_{L-H} vs density is observed in divertor configurations with the outer strike point on the horizontal target (V5 configuration) [1], whereas matched discharges in JET-C show P_{L-H} monotonically increasing with density, thus following the 2008 ITPA L-H scaling law [2]. The reduction in P_{L-H} in JET-ILW projects favourably to ITER, however the underlying physics mechanism is not yet understood. Moreover, the density of minimum P_{L-H}, $n_{e,min}$, increases with $B_T^{4/5}$ in JET-ILW (at ~ constant $q_{95} = 3.3–3.7$ and I_P varying from 1.7 to 2.75MA). In JET-C a minimum in P_{L-H} with n_e had been previously observed with the more closed MkII-GB divertor geometry. All these findings show that divertor/SOL physics are strong players. A recent, physics based scaling for $n_{e,min}$, proposed in [3] (based on the ion energy channel being the important one for the L-H transition) is not compatible with the full set of JET observations described above.

In this study we explore two mechanisms that could explain an increase in P_{L-H} with low-Z impurity concentration (or Z_{eff} as its proxy): i) the effect of impurities on the stability of the background edge turbulence and ii) changes in radiated power distributions from JET-C to JET-ILW, which may affect the edge temperature/heat fluxes regulating the L-H transition.

1. TEST OF H-MODE POWER THRESHOLD SCALING LAW INCLUDING Z_{eff} ON JET L-H DATA.

Figure 1 compares P_{L-H} for the JET MkII-HD L-H data sets collected in the last 5 years (JET-C and JET-ILW, but excluding the recent JET-ILW L-H transitions with both strike points on the vertical target, discussed in [4]) with the 2008 ITPA L-H scaling law [2]. We note that this scaling law was derived for the loss power, P_{loss}, from discharges with radiated power fraction $P_{rad}/P_{loss} < 50\%$ and applies to the high density branch only. The JET L-H data set includes: i) impact of wall change-over from C to Be/W, ii) impact of divertor configuration in JET-ILW at fixed $B_T/I_P = 2.4T/2.0MA$ (see [4] for most recent results on vertical target configuration, not included here), iii) B_T variation: 1.8T, 2.4T and 3.0T at $q_{95} = 3.3–3.7$, iv) JET-ILW L-H transitions with and w/o N_2 injection (see Section 4). An earlier scaling law (ITPA 2004 database) gives a similar dependence on n_e, B_T and plasma surface area S, but includes a Z_{eff} dependence [5]: $P_{L-H} \sim B_{0.7}\, n_e^{0.7}\, (Z_{eff}/2)^{0.7} S^{0.9}$. The JET L-H data set is compared to this scaling law in Figure 2, where we choose P_{sep} rather than P_{loss} to separate dependencies on Z_{eff} from those of radiated power. Although neither scaling law accurately describes the JET MkII-HD L-H data set, it is evident that including Z_{eff} brings the data points much closer together. It is also interesting to note that the large spread in P_{L-H} in the 2.4T JET-ILW data set of Figure 1 (the divertor configuration scan discussed in [1]) is greatly reduced in Figure 2.

2. EFFECT OF LOW-Z IMPURITIES ON STABILITY OF BACKGROUND EDGE TURBULENCE.

JET-ILW edge kinetic profiles at the L-H transitions have been investigated with linear gyro-kinetic calculations with GENE (the input profiles are from the 1.8T/1.7MA data set). It is found that in the high density branch the primary instability is of resistive nature and thus can be stabilized by increased temperature, hence power [6]. The unstable modes are identified as being resistive ballooning modes (RBMs) and their growth rates decrease with temperature. As the temperature is increased further, ITG-TEM modes take over. This competition between RBM stabilization and ITG-TEM destabilization leads to a growth rate that is minimum at a given temperature (Figure 2 in [6]), whose value is of the order of the experimentally measured edge temperature at the L-H transition. The RBM growth rates increase with Z_{eff}, while for ITGs an increase in Z_{eff} is stabilizing. When Z_{eff} is increased in the calculations, from typical JET-ILW values of 1.0-1.3 to a representative JET-C Z_{eff} of 2.0, the minimum in density of the threshold temperature, T_{th}, is shifted towards lower values and T_{th} is larger in the high density branch (Figure 2 in [6]), in qualitative agreement with the changes in P_{L-H} observed between JET-ILW and JET-C [1]. In this model, a mean E×B shear is required to suppress the edge turbulence and thus lead to the L-H transition. For the L-H data set under investigation, we find that the experimental ω_{ExB} shearing rates, derived using the radial force balance equation for E_r, are indeed of order of the minimum growth rates of the unstable modes in the GENE calculations, $\gamma_{LGK} \sim 2 \times 10_4\ s_{-1}$, as shown in Figure 3. We note that ω_{ExB} (and the depth of the negative E_r well) is essentially constant across the density scan, at the given B_T and divertor configuration (for this dataset the JET divertor configuration is V5, see e.g. [1]).

Further tests of the thesis proposed in [6] require measurement of the local Z_{eff} profile at the plasma edge (being addressed by forward modelling of the continuum emission using Bayesian methods - in progress), verification of the linear GK results with non-linear GK calculations (in progress) and experimental discrimination of the nature of the background fluctuations (future experiments). In the meantime we have obtained further evidence of the role of low Z impurities (Z_{eff}) in JET L-H transitions by recreating in JET-ILW Z_{eff} values and radiation conditions typical of JET-C. In order to achieve this we have exploited N_2 injection, due to the well known similarity of C and N as divertor radiators.

3. L-H TRANSITIONS WITH NITROGEN INJECTION.

New experiments were carried out in the almost C-free JET-ILW, in which N_2 was injected into the divertor private flux region prior to the L- H transition to achieve radiated power distributions and Z_{eff} values similar to those of JET-C. Because N_2 injection raises the target density at the low power levels typical of 1.8T/1.7MA L-mode plasmas, the low density branch of P_{L-H} could not be accessed in this first set of experiments. A second set of experiments with N_2 injection is planned at higher I_P/B_T, where access to the low density branch is favoured in JET-ILW [1]. Figures 4 and 5 show that P_{L-H} increases with N_2 injection level at densities close to $n_{e,min}$ and approaches JET-C values at N_2

levels corresponding to an increase in $\Delta Z_{eff} \geq 1$. At lower N_2 levels ($\Delta Z_{eff} \sim 0.2$–0.5) little change in $P_{L\text{-}H}$ is observed, suggesting threshold type behaviour with edge impurity concentration. Analysis of the effect of N_2 injection on the local parameters indicates that both the edge temperature and the edge radial electric field at the L-H transition react to increased N_2 rates (Z_{eff}). T_{edge} approaches JET-C values at high N_2 rates (Figure 6). The diamagnetic component of the neoclassical E_r has been found to be a good proxy for the total equilibrium radial electric field at low rotation in AUG [6], $E_r \sim \quad p_i/(e\, n_i)$. Given that for JET-ILW L-H transitions $T_{i,edge} \sim T_{e,edge}$ [1], the ion quantities can be approximated by the electron quantities. This has been verified against discharges where good quality edge CXRS data on C^{+6} are available and for which the measured poloidal velocity is found to be consistent with the neoclassical value. Figure 7 shows that the depth of the negative E_r well, which is found to be constant across the density scan without N_2 injection, is unchanged at low N_2 flow rates, but increases in magnitude at higher rates, corresponding to $\Delta Z_{eff} \geq 1$, thus mirroring the increase in P_{sep} with ΔZ_{eff}.

With increasing N_2 injection level (and total radiated power) both divertor legs become detached and the radiation progressively moves to the X-point and above. The radiated power fraction, $f_{RAD} = P_{rad,tot}/P_{loss}$ is capped at ~ 62% , with a progressive relative increase in bulk radiation over divertor + SOL radiation. As in previous work [1], the bulk radiation is the total radiated power from bolometry integrated over volume to the 98% flux surface. With this definition P_{sep} has been proven to be robust against different tests of $P_{rad,bulk}$ calculations and also against N_2 injection, as in this case the strong localization of the radiation near the X- point makes consistent evaluations imperative. In the JET-C comparison discharges, similar radiation distributions are observed, with f_{RAD} reaching maximum values of 50%. In the JET- ILW L-H data set w/o N_2 injection, f_{RAD} can reach ~ 75% in the ICRH heated discharges, with ¾ of the total radiation being radiated in the bulk (low density branch, high P_{rad} from W and Ni with ICRH [1]). If P_{sep} is evaluated by subtracting from P_{loss} the *total* P_{rad} rather than the *bulk* P_{rad}, the effect of N_2 injection on P_{sep} is suppressed, bringing the JET-ILW data with and w/o N_2 close together. The separation between JET-C and JET-ILW $P_{L\text{-}H}$ is instead preserved, indicating that the spatial distribution of P_{rad} in JET-ILW + N_2 appears to be more biased towards divertor + SOL than in JET-C. However, the observation that the local parameters T_{edge} and E_r are affected by N_2 injection makes us exclude this definition of P_{sep} as being the relevant one.

4. CONCLUSIONS AND OUTLOOK.

In JET, L-H transitions are sensitive to low Z impurity concentration as shown by the change-over of PFCs from JET-C to JET-ILW. This effect has been confirmed both by global (P_{sep}) and local (T, E_r) measurements in recent L-H experiments in JET-ILW with N_2 injection, which approximated Z_{eff} values and radiated power distributions similar to those of JET-C. However, the physics mechanism that drives this effect is not yet identified unambiguously. Results from linear gyro-kinetic calculations are qualitatively consistent with the experimental evidence and support the thesis of Z_{eff} affecting the stability of the background edge turbulence possibly connected with the L-H trigger.

Work on non-linear simulations is in progress, to verify the linear results. On the experimental side, edge Z_{eff} profiles are needed – rather than the line averaged parameter accessible so far - (here work is in progress with forward modelling of the continuum emission using Bayesian methods), as well as higher quality edge CXRS data during N_2 injection for local heat flux analysis and edge turbulence measurements (both can be acquired during the 2nd set of experiments planned at higher B_T). In parallel, lacking a complete physics picture with predictive capabilities, it is always useful to continue working on global, H-mode power threshold scaling laws. For the JET MkII-HD L-H data set, the 2004 ITPA scaling law including a $Z_{eff}^{0.7}$ dependence fits the measured $P_{L\text{-}H}$ better than the commonly used 2008 ITPA scaling law.

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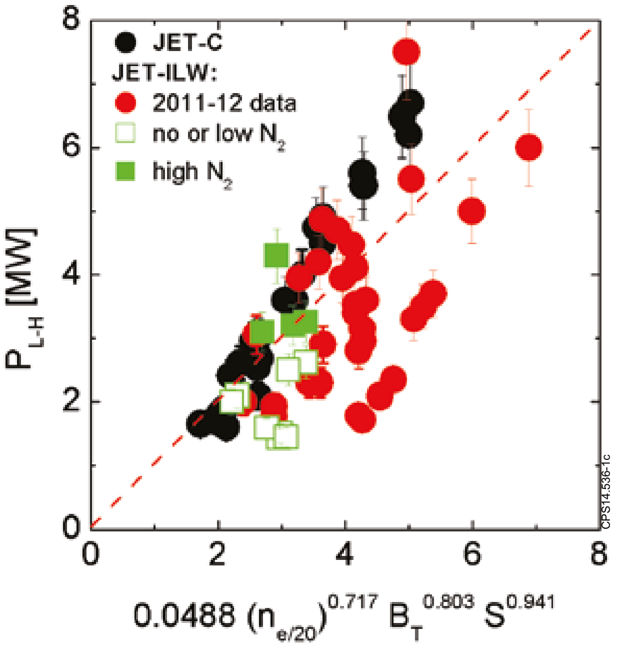

Figure 1: $P_{L\text{-}H}$ (= P_{loss} here) vs ITPA 2008 H-mode threshold scaling law [2].

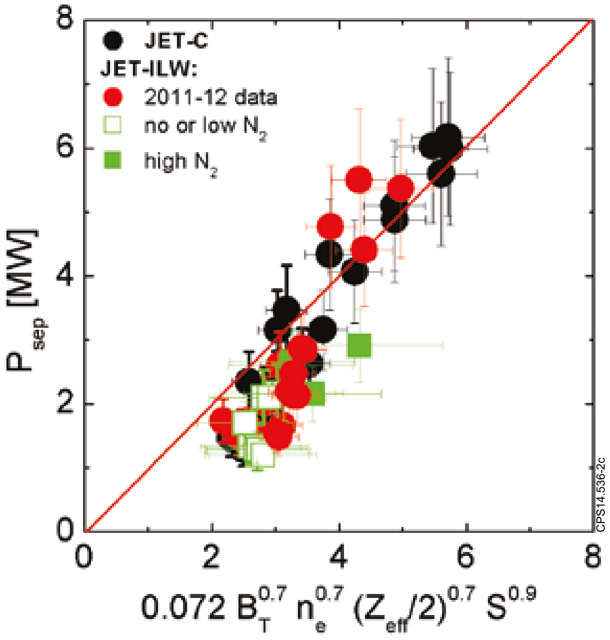

Figure 2: P_{sep} versus ITPA 2004 scaling law including Z_{eff} [5] for JET MkII-HD divertor data.

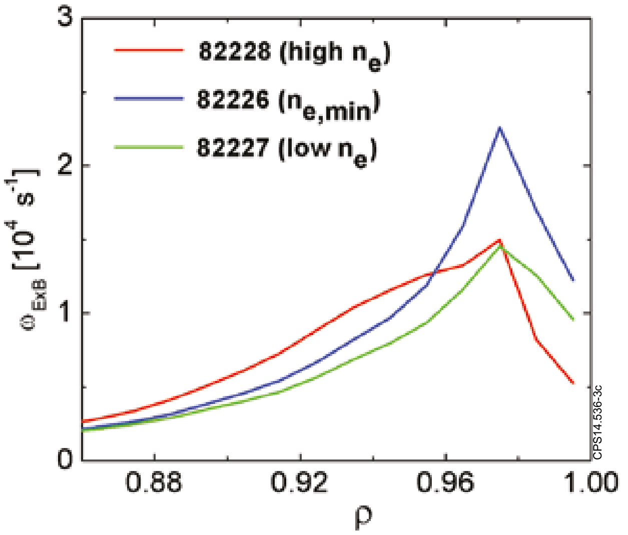

Figure 3: ω_{EXB} at L-H from radial force balance for JET-ILW n_e scan at 1.8T/1.7MA.

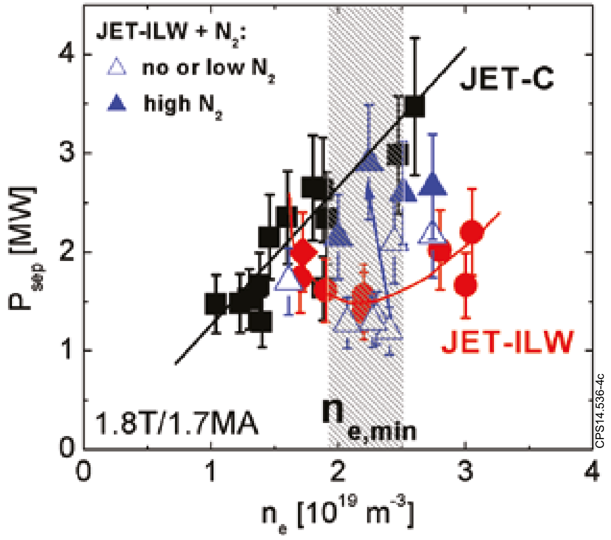

Figure 4: P_{sep} versus n_e for the 1.8T/1.7MA JET MkII-HD L-H transitions in JET-C (black), JET-ILW (red) and JET-ILW with N_2 injection (blue).

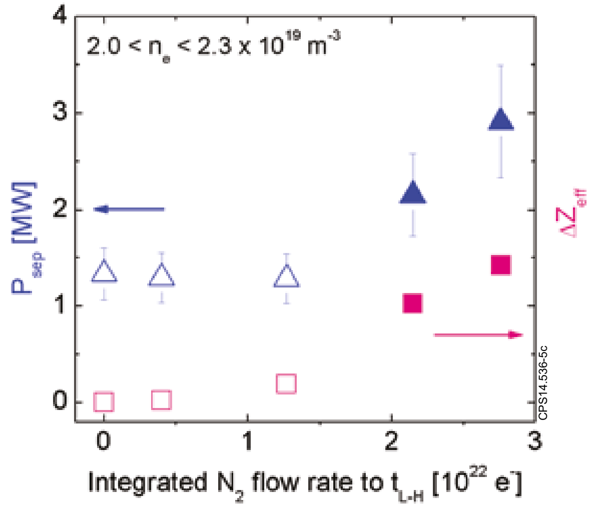

Figure 5: P_{sep} (left) and ΔZ_{eff} (right) versus N_2 flow rate in L-mode phase integrated to the time of the L-H transition, t_{L-H}, in JET-ILW at $n_e \sim n_{e,min}$.

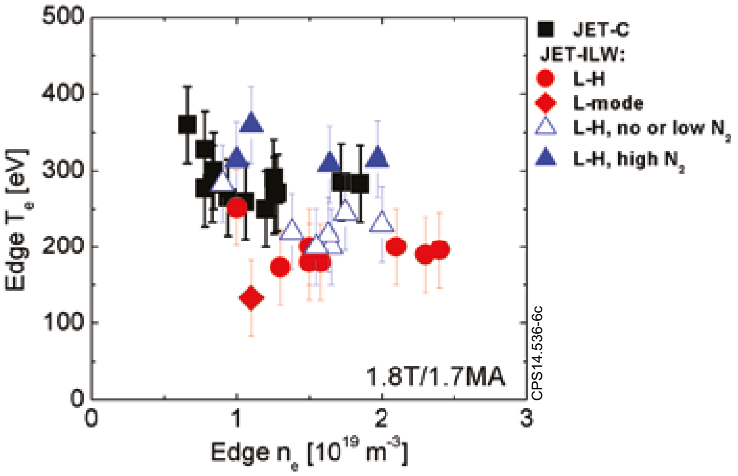

Figure 6: *Edge Te versus edge* n_e *for the 1.8T/1.7MA JET MkII-HD L-H transitions in JET-C (black), JET- ILW (red) and JET-ILW with* N_2 *injection (blue).*

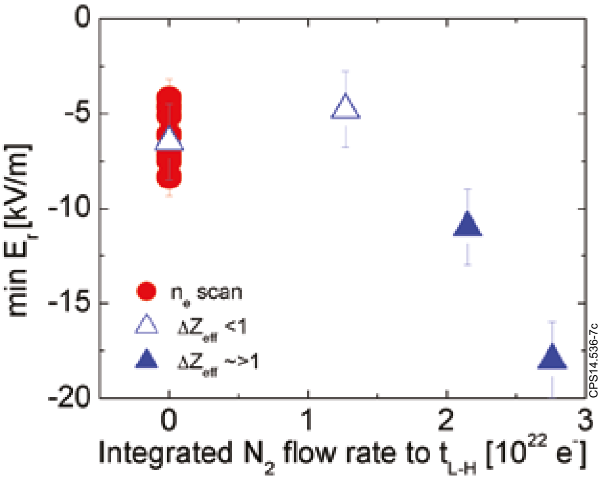

Figure 7: *Minimum* E_r *in JET-ILW 1.8T/1.7MA L-H transitions (V5 configuration). Red:* n_e *scan w/o* N_2*; blue:* N_2 *injection scan at* $n_e \sim n_{e,min}$.