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In this contribution, the role of neutrals on the confinement of JET hybrid scenarios is examined in the carbon wall and in the ITER-like wall. There have been evidence both in ASDEX Upgrade and JET [1, 2] that neutrals can impact directly the confinement suggesting that the density is not a relevant engineering parameter for confinement scaling laws.

In the carbon wall, JET-C had carried out in 2008 dedicated power scans (β_N~2 to ~3) experiments at constant density in both low ($\delta = 0.2$) and high shape ($\delta = 0.4$) with the initial objective to determine the role played by the pedestal in the observed H-factor increase (H = 1 to 1.4) in the hybrid scenario [1]. These two power scans, have been revisited recently using the important property that the plasma average densities are constant within +/–10% across the power scan in addition to the plasma current Ip, the toroidal shape BT and the plasma shape (i.e. q_{95} as well). As a consequence, the variation of the dimensionless parameters ρ^* ($\sim T^{1/2}/B$, n^* ($\sim n/T^2$) and β ($\sim nT/B^2$) across the power scan can be written solely as function of the temperature T variation and therefore the power P variation as:

$$d\nu^*/\nu^* = -2(1+\alpha)\ dP/P \quad (1)$$

$$d\rho^*/\rho^* = (1+\alpha)/2\ dP/P \quad (2)$$

$$d\beta/\beta = (1+\alpha)\ dP/P \quad (3)$$

assuming $T\sim P^{(1+\alpha)}$. $Ip{\cdot}n^{-0.5}$from the notional scaling law $\tau = W/P = n^{0.5}$. $Ip{\cdot}P^{\alpha}$ and a the power dependence coefficient of the confinement. The volume average kinetic data (n_e, T_e, T_i) are collected from Thomson scattering and charge exchange diagnostics, averaged over ~0.5s outside of any significant MHD impacting on confinement and sometimes occurring in hybrid scenarios such as 3/2 or 4/3 tearing modes. The pedestal heights are inferred from the T_e and n_e profile by using hyperbolic tangent fits.

For the low triangularity shape ($\delta = 0.2$), the root mean square analysis show that the dimensionless parameters expressions (equations 1 to 3) are verified experimentally with an exponent $\alpha = 0.385$ +/–5%. Therefore, the confinement time variation with power can be described by a scaling $\tau\sim P^{-0.385}$ and consistently in terms of the dimensionless core parameters ρ^* and ν^* and β. Note that this power dependence of the confinement is much less than the variation present in the standard H_{98y2} scaling [2]. However, it should be stressed here that there may exist hidden co-linearities: in this power scan Ti/Te increases from 1.1 to 1.4 and Mach number from 0.7 to 0.95. Both quantities are known to play a role in the transport processes.

For the high triangularity shape ($\delta = 0.4$), the root mean square analysis cannot find experimentally a unique value of a for the dimensionless parameters expressed in equation 1 to 3. The confinement time varies this time like $\tau\sim P^{-0.77}$. In addition, both Mach number and T_i/T_e are hardly varying across the power scan (by typically less than +/–10%). This suggest the confinement variation with power cannot be described by ρ^*, ν^*, β, Mach number or T_i/T_e only. A different parameter is impacting on the global confinement and the confinement scaling cannot capture the effect of power on the confinement.

The high shape pulses at the highest (16MW) and lowest (6MW) input power, have been simulated using the CRONOS suite of codes and TGLF to predict the heat transport. The density was taken from the data as well as the pedestal as boundary condition. The results are showing that the model underestimates slightly heat transport in the core for the low power case, but not for the high power case. Therefore, the power dependence of the confinement predicted by the simulation should be higher than measured by the power scan experiment.

We are now examining experimentally the hypothesis that the edge recycling flux from neutrals is playing a role in these different observations on confinement dependence with power between the two plasma shapes. This is investigated using the H_α light from visible spectroscopy in the main chamber and the neutral pressure from the main chamber gauges. In addition, the D_α light monitored by the visible camera is used to identify where the strongest recycling area are in the main chamber: top (i.e. where the change of shape is the largest) or in the mid-plane.

Pressure gauges measurements in the main chamber and the Ha light from visible spectroscopy are both showing evidence an increase of the neutral pressure in the main chamber with the input power in the high triangularity case (Fig.2). All these measurements are correlated with a decrease of the energy content in the pedestal (WPED) when the input power is the strongest (~16MW). The neutral pressure increases by more than 1.5 and the recycling flux from the main chamber by a factor of 3. In addition, the analysis of the D_α light data ($\lambda = 580$–770nm) in the area of the secondary X-point (top of the vessel) and in the main chamber (midplane) are showing increases of recycling flux of the same order with power for the high shape.

This is a strong indication that the pedestal confinement is correlated with the increase of recycling flux.

This analysis strongly suggests that core confinement in the high shape case could be affected by the edge neutrals. Therefore neglecting the effect of recycling neutrals could produce an inconsistent result when a making a confinement scaling using only core dimensionless parameters (which is the case of all the standard scaling laws).

The impact of neutral on confinement in hybrid discharges in the carbon wall has been further evidenced by comparing 2 different high shape hybrid discharges with different wall clearance but operated with matched: $Ip = 1.4MA$, $B_T = 1.7T$, and $\beta_N = 2.8$ and showing significant different confinement not captured by the standard confinement scaling: the high clearance shot has ~15% higher τ_E. Visible spectroscopy is also showing a significant difference (by factor ~2) of the recycling flux in the mid-plane. For these two discharges computation with the SOLEDGE2D-EIRENE code is in addition predicting a large difference in neutral pressure, $n_{eSOL}(77802) < n_{eSOL}(77793)$ and $\lambda_{SOL}(77802) < \lambda_{SOL}(77793)$ in the main chamber close to the secondary X-point. These calculations are consistent with the Ha light analysis on the top of the vessel using the visible camera and showing a higher level of recycling flux (by ~x4) for the pulse with the lowest clearance. This observation could provide an explanation for the difference in confinement between the hybrid scenario ($\beta_N = 2.8$, $H = 1.1$) run in the 2003–6 JET campaigns [3] and the same type of scenarios carried out in 2008 with a larger clearance in the area of the secondary X-point but reaching H>1.3 for similar β_N [4]. From the above experimental evidence, one concludes that the enhanced neutral flux (both by the increased loss power in the SOL and the clearance) from the wall to the plasma could affect the pedestal temperature and density and impact on the pedestal confinement. For a full recycling model, ne at the SOL scales in detached conditions as the square root of wall flux, and so this result is consistent with previous observations that energy confinement correlates negatively with $n_{e,SOL}$ as observed in JET and ASDEX Upgrade [5, 6].

More recently, an identical power scan has been carried out in the JET ITER-like wall (JET-ILW) for the hybrid scenario at high triangularity for identical magnetic field and plasma current than in the carbon wall (JET-C). This time, the pedestal energy content rises continuously with power in the JET-ILW and shows a smaller dependence of the confinement time with power ($\tau \sim P^{-0.39}$) than in the JET-C high shape but almost identical to the JET-C low shape case. Also, the root mean square analysis shows that the confinement can be described by the standard core dimensionless variables (ρ^*, ν^* and β). In addition, the recycling flux in in the mid-plane from visible spectroscopy stays constant across the whole power scan in the JET-ILW. In relative terms the neutral pressure from pressure gauges in the main chamber also hardly increases. However it cannot be compared in absolute terms to the JET-C because of calibrations issues. It should be stressed that the ELM frequency between the two sets of data in each JET-C and JET-ILW is comparable which could suggest that the pedestal stability is not necessarily affected by the neutrals influx. On the other hand, there is a strong difference in Z_{eff} (~2.3 in the JET-C and 1.2 in the JET-ILW respectively).

The change of the wall composition is most likely at the origin these differences [7]. Be and W plasma facing components do not have the same affinity to deuterium molecules and neutrals than carbon, giving more ground to the interpretation that neutrals at the edge play a non-negligible role in the confinement of hybrid discharges. These observations also indicate that the neutrals are impacting on the confinement in a different way than they did in the carbon wall. At high power, it can be observed that the pedestal energy is about the same than in the JET-C possibly because neutrals are mitigating the pedestal height in the JET-C and not in the JET-ILW. On the other hand at low power ($\beta_N \sim 2$) there is a large difference in the energy content of the pedestal which apparently cannot be accounted for by the recycling of neutrals.

The above observations, illustrating the impact that neutrals have on the pedestal, suggest that unless recycling flux (or neutral pressure in the mid-plane) is kept constant in the main chamber across a given confinement database, the attempts to infer a confinement scaling are unlikely to succeed if core dimensionless parameters (ρ^*, ν^* and β) are only considered. In the case where neutrals are believed to play a role, the scaling should envisage an additional dependence in confinement scaling engineering expression such as the n_{eSOL} a $\Gamma D_\alpha^{1/2}$ as additional variable (where GDα is the total recycling flux in the chamber). At constant density (as it is the case in the above experiment) the confinement dependence would be of the order of $\tau_E \sim P^{-0.38}$. $n_{eSOL}{}^{-2}$ which is a much stronger dependence neSOL with than in previous studies [6].

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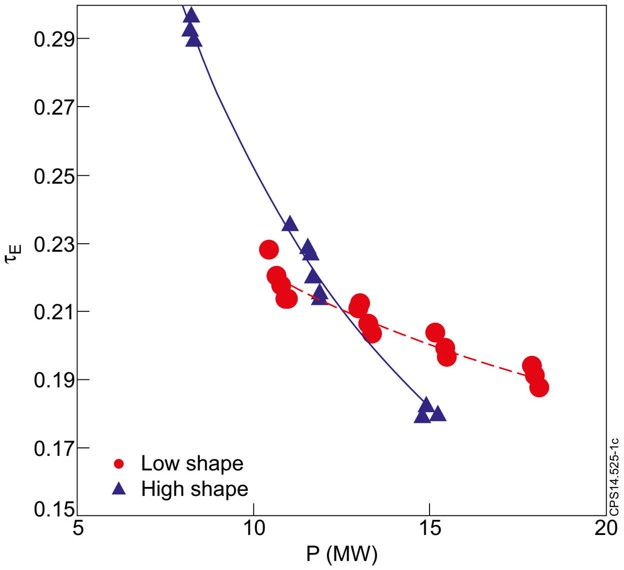

Figure 1: Confinement decay with power for the low shape (red dots) and high shape (blue triangles) triangles.

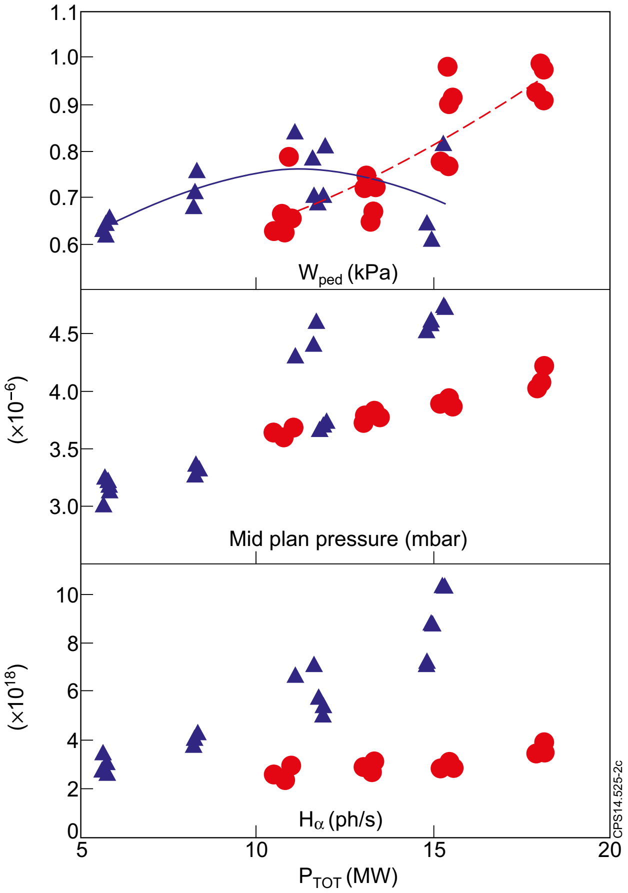

Figure 2: From top to bottom: i) energy content in the pedestal, ii) neutral, pressure in the main chamber, iii) Ha light from visible spectroscopy for high pulses (triangles) and low (dots) triangularity pulses of the power scan in JET-C.

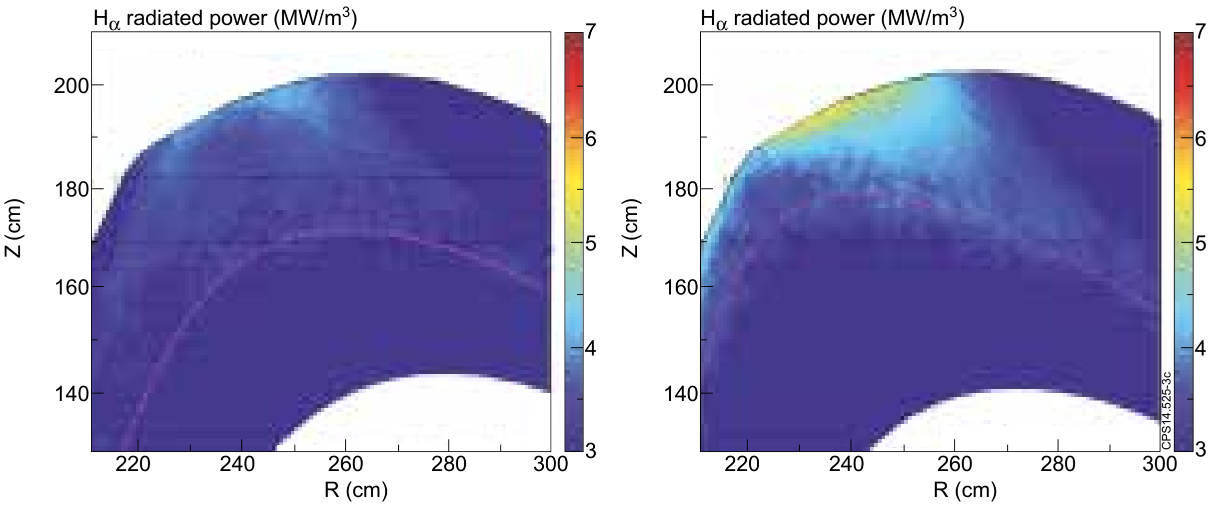

Figure 3: SOLEDGE2D EIRENE calculation for 2 hybrid discharges ith different top clearance. The black rectangle represents the area of integration used in the measurement with the visible camera.

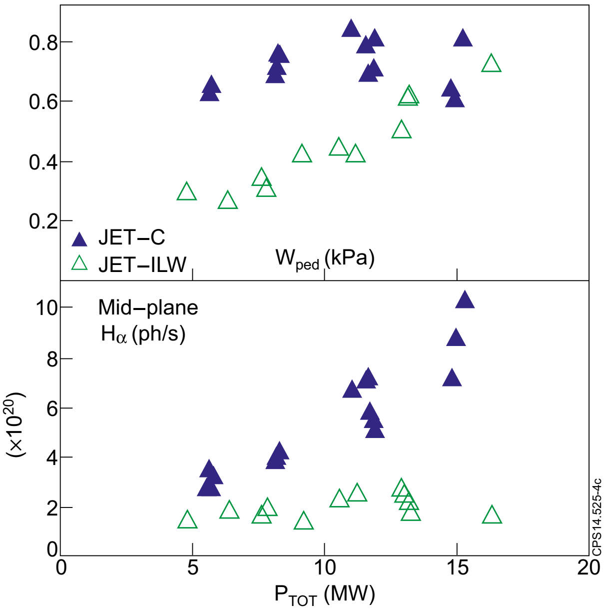

Figure 4: Comparison of i) pedestal energy and mid-plane recycling flux, for the power scan in the JET-C (blue triangles) and JET-ILW (green open triangle) for high triangularity.