Impact of divertor geometry on ITER scenarios performance in the JET metallic wall


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Abstract
Recent experiments with the ITER-like wall have demonstrated that changes in divertor strike point position are correlated with strong modification of the global energy confinement. The impact on energy confinement is observable both on the pedestal confinement and core normalised gradients. The corner configuration shows an increased core density gradient length and ion pressure indicating a better ion confinement. The study of neutral re-circulation indicates the neutral pressure in the main chamber varies inversely with the energy confinement and a correlation between the pedestal total pressure and the neutral pressure in the main chamber can be established. It does not appear that charge exchange losses nor momentum losses could explain this effect, but it may be that changes in edge electric potential are playing a role. This study emphasizes the importance of pumping in the main chamber of a metallic wall device.

1- Introduction
The transition in JET from a fully carbon wall to the ITER-like wall (ILW) with tungsten (W) plasma facing components (PFCs) in the divertor and primarily beryllium PFCs in the main chamber has been an essential step in 2011 for demonstrating the compatibility of ITER scenario with a metallic environment [1]. The initial experiments have shown that the operational domain at H98y2=1 is significantly reduced with the JET ITER-like wall (JET-ILW) mainly because of the need to inject large amount of gas (above 10^{22} D/s) to control core radiation mostly due to W. These first results have stressed the importance of the edge plasma and plasma-wall interaction physics in determining the core plasma performance [2]. The change in the impurity mix or the recycling flux of the main gas could play a role in the physics of core and pedestal confinement. The importance of the particle source as a key control parameter is confirmed by the degradation of the confinement obtained when puffing gas in order to limit impurity accumulation in the plasma. Maximisation of confinement, control of metallic impurity sources and heat loads are the main challenges facing the further development of the ITER scenarios in JET.

For this reason, specific exploration of the effect of divertor geometries on confinement have been conducted in JET in 2013 and 2014 to identify the divertor conditions leading to the optimum confinement and thermal neutron rate. This was explored for both the baseline (βN=2) and hybrid scenario (βN=3) with low shape magnetic configuration (δ=0.2) with the objective to investigate the possible influence of neutral recycling on the plasma confinement based on experimental analyses and modelling.
2- Experimental set-up and confinement observations

A series of type I ELMy H-mode discharges have been developed for JET with different divertor magnetic topology in order to isolate the effect of divertor recycling. The three equilibria/configurations have identical bulk plasma volume but the position of the strike-points is positioned differently with respect to the inner and outer pumping ducts. All three plasma shapes have a low upper triangularity ($\delta=0.2$) so as to minimize recycling from the possible interaction of the plasma with the main chamber. Figure 1a shows the magnetic equilibria as reconstructed by EFIT [3]. The 3 cases will be referred to as the horizontal, corner and vertical targets in remainder of the paper. With these three topologies, baseline scenario type [2] has been run with $I_p=2.5MA$ and $B_T=2.7T$ ($q_{95}=3.2$) at two different input power (15 and 23MW, i.e. $\beta_N\sim 1.5$ and \sim 2). In addition, hybrid scenario [2] with $I_p=2.0MA$ and $B_T=2.35T$ ($q_{95}=3.8$, $\beta_N\sim 3$) has also been compared in the horizontal and corner configurations. In both scenario cases, different level of deuterium gas injection rate have been employed from the inner private flux region except for a few cases where the gas was injected from the main chamber at the outboard mid-plane for comparison. Also in the case of the baseline scenario, one of the two JET cryogenic pumps (pumping speed of ~50m$^3$/s each) has been switched off for a few discharges during the experiment to separate the effect of neutral pumping and recycling on confinement.

It is observed (Fig 1b) that for identical fuelling rates and input power, the discharges on horizontal and the vertical target configurations have similar $H_{98y2}\sim 0.7$, while the corner configuration exhibits a confinement factor reaching 0.9 close to the level of confinement for identical discharges with the carbon wall (JET-C). This trend is general and for comparable fuelling rates and pumping, corner configuration shows confinement factors larger than those observed in the horizontal and vertical configurations. Several contributions in the past have reported that deuterium puffing (from the main chamber or the divertor) impacts negatively on the confinement for both the JET-C [4] and the JET-ILW [2]. In the present cases, it appears that the variation in divertor geometry and therefore in neutral recycling and pumping also impact confinements.

Although not in stationary phase, this effect on the energy confinement is also observed for the
hybrid scenario (fig 2). An increased normalised energy confinement factor of $H_{98y2} \approx 1.4$ is observed for the corner configuration, whereas this is in general not achievable on the horizontal target for the identical gas rate. Given that the pedestal is playing a strong role in this improved confinement [2] this suggests that pedestal confinement is strongly affected by the change of divertor configuration.

Since the changes imposed on the plasma bulk geometry are very small (~2\% in elongation and minor radius), fig 1b indicates that the IPBy2 confinement scaling law [5] does not capture the change in confinement resulting from the divertor geometry modifications. It is therefore likely that the edge and scrape-off (SOL) conditions (recycling neutral and/or pumping are contributing to the confinement of these discharges. Also, it should be noted that the distance of the separatrix to the main chamber wall does not vary significantly with respect to the SOL width, excluding a large influence on the confinement.

### 3- Core and pedestal transport analysis

The observed changes in energy confinement are consistent with the changes in core plasma density, temperature and pressure profiles (fig 3). The corner case is characterized by ion and electron kinetic pressures substantially higher than the two other cases, the difference reaching almost 50\% at the centre of the plasma. Interestingly, this gain in plasma pressure is achieved due to changes in either the core temperature or density profiles. The horizontal and corner configuration discharges present about the same density level, but the electron and ion temperatures are 50\% larger in the corner case. On the contrary, the vertical configuration discharge exhibits much lower density than the other two, but the electron temperature is similar to that of the corner case and the ion temperature profile is intermediate between the horizontal and corner cases. This suggests that the mechanisms explaining the degradation of the confinement in the horizontal and vertical configurations with respect to the corner may not be identical.

The higher measured neutron rate for the corner configuration is consistent with higher Ti for otherwise identical neutral source rate from the neutral beam power.

Differences in the profiles are both due to variations in the pedestal (Pe is 50\% larger at the top of the pedestal in the corner configuration) and to changes in the core gradients. It can be also be observed that the temperature gradient length $R/L_{T_e}$ changes by about 20\% (fig 4) with the radial position of the outer strike point. On the other hand, the density gradient length $R/L_{n_e}$ is 2 times larger in the corner configuration than on the horizontal target suggesting that the particle channel transport is the most affected. TRANSP [6] has been run for all three cases. The results

![Fig 3: Density, temperature (from Thomson scattering) and ion temperature (from charge exchange diagnostic) for the three divertor geometry cases.](attachment:image.png)

![Fig 4: Total pedestal pressure ($o$) (see also figure 5) and core energy confinement factor at 0.4$\leq r \leq 0.7$ (-). Density gradient length ($\Delta$) varies like the pedestal pressure ($o$) by almost a factor of 2.](attachment:image.png)
show a lower ion thermal transport coefficient for the corner case than the other two by typically a factor of 2 in the confinement region (0.4<r/a<0.7). The horizontal and vertical targets transport coefficients are consistent with the observations of global energy confinement.

The profiles observations suggest that the edge or divertor conditions affect the pedestal properties and then core transport. Pedestal confinement has been studied experimentally using edge charge exchange (for ion temperature and rotation), high resolution Thomson scattering (HRTS) for electron density end temperature [7] and reflectometry (for the edge electron density). The analysis has been made both by ELM averaging (over typically 0.5 to 1s of steady state phase) and by averaging the pre-ELM values for several ELMs of the same time window. Both analyses give very similar results. In figure 5, pedestal top data averaged over ELMs are shown for the 3 different divertor geometries at different input power and gas rate. The highest pedestal density is found for the horizontal target (where the divertor recycling also dominates, see next section). But the highest ion pedestal pressure is observed for the corner configuration which is consistent with the core ion temperature shown in figure 3, whereas the pedestal electron temperature does not show the same trend. The most striking difference comes from the toroidal velocity which is much higher for the corner configuration. The toroidal velocity could play a key role in the edge rotational shear and therefore in the transport quality of the edge barrier. This observation will be further commented in the discussion section. The analyses have also attempted to determine the pedestal characteristics (width and height). There are consistent indications between the HRTS and the edge reflectometry that the density gradient is the strongest for the corner configuration. However, the error bars are quite large on these quantities and more statistical work would be needed.

The ELM behaviour is also markedly different for each of the divertor configuration [7]. In the corner configuration, regular ELMs typically occur with a frequency of 35Hz. The vertical configuration exhibits an irregular ELM frequency varying from 10 to 100Hz whilst the horizontal configuration has in general high frequency ELMs above 50Hz. The different pedestal conditions suggest that the peeling-balloonning stability is different for all three configurations. Preliminary stability calculations made with the MISHKA [8] and ELITE [9] codes show consistently that the vertical configuration has the highest ballooning stability limit. However the irregular ELM frequency observed in the vertical and horizontal target indicates that the stability limit is probably varying [10]. The corner configuration has the lowest boundary limits.

4- Characterisation of the neutral recirculation in the divertor and main chamber.

A detailed experimental analysis of the divertor particle recirculation [11] is presented in this section with the objective to identify the link with the confinement and transport observations for all three divertor geometries.

Figure 6a and 6b respectively show the inner and outer divertor D\(\alpha\) emission as a function of the strike-point position for the different fuelling and pumping rates used in the experiment. As expected, the D\(\alpha\) emission increases with the fuelling rate whilst pumping decreased by 50%
leads to emission levels (Dα) equivalent to twice the gas fuelling rate with full pumping. Also, changing injection location has little influence on the recycling level [12]. These observations indicate that the divertor particle source is determined by the balance of neutral recycling from surfaces (source) and neutrals pumped (sink). The amplitude of Dα light emission is found to depend on the strike-points locations, with a drop of a factor of 3 at similar gas injection rate between the horizontal on one hand and the corner and vertical configurations on the other hand, independent of the amount of the input power. The higher pedestal density observed for the horizontal target (fig 5) may also be associated with this high level of recycling.

Visible spectroscopy observations are confirmed by the neutral pressure measurements in the sub-divertor which increase by 50% when moving from the horizontal to the vertical configuration. Since the pumped particle flux is proportional to the sub-divertor pressure, more particles are pumped in the vertical configuration leading to a reduction of the effective recycling of particles and possibly to the lower pedestal density observed in this divertor configuration. This also could be helped by the proximity of the inner strike to the inner corner which could participate to the effective pumping. It should be pointed out that the minimum radiation observed for the corner configuration may be due to vignette line of sight into the corner strike point region. Thus one cannot draw firm conclusions as to the significance of this minimum.

The data of Fig 6 is consistent with Langmuir probes measurements. While there is an absence of probes in the outer divertor corner, it can be estimated that the particle flux reaching the target is about 60% lower (peak and integral value) at the outer-strike point in the vertical configuration compared with the horizontal one. Bolometry reconstruction of the divertor area for all three divertor configurations also show decreasing radiation intensity (by typically a factor of 3) in the X-point area with increasing major radius of the outer strike point. This supports again the observation made with visible spectroscopy that neutral recirculation in the divertor is the lowest for the vertical configuration. Given all the above observations, it appears that there is not an obvious correlation between the neutral recycling or divertor radiation in the divertor with global energy confinement.

However, in JET, the divertor area neutral pressure and density are strongly correlated with the main chamber values, and neutral recirculation in the divertor may impact directly to the main chamber neutral pressure [13]. By changing the divertor geometry, the leakage of neutrals towards the main chamber could change and modify the neutral pressure in the main chamber.

Looking at the variation of the main chamber neutral pressure for the 3 divertor configurations (Fig 7a), it can be observed that the corner configuration has the lowest pressure in comparison to the horizontal and vertical ones. Doubling the gas rate (in the divertor) typically increases the pressure by the same amount which indicates that a strong connection between the

![Fig 6a](image1.png)  ![Fig 6b](image2.png)

**Fig 6a:** variation of the recycling emission in the inner divertor for the three configurations for different gas injection rate and with ½ of the cryo.

**Fig 6b:** variation of the recycling emission in the outer divertor for the three configurations for different gas injection rate and with ½ of the cryo.
neutral pressure in the divertor and in the main chamber does exist. It is also interesting to note
that increasing the input power has the effect of increasing the neutral pressure in the main
chamber whilst preserving the same trend. This effect could be associated with the increased Be
erosion at higher power as described in [14]. The levels of neutral pressure shown in 7a are also
consistent with Dα emission level monitored in the main chamber. Figure 7b presents the total
pedestal pressure from kinetic measurements versus the main chamber pressure for the same
database of pulses. At a given gas injection and input power, an anti-correlation of the pedestal
pressure with the main chamber pressure is observed indicating a possible physical link between
the main chamber neutrals and the loss of confinement.

Past experiment with the carbon wall had also reported the impact of neutral in the main
chamber on the confinement. With the JET-C, it was pointed out that the separatrix density could
be the source of the confinement degradation [15]. Also, more recently, the loss of confinement
in high triangularity hybrid scenario in JET-C has been correlated with an increase of the neutral
pressure and recycling in the main chamber [16, 17]. Although the causality between main
chamber and confinement is not formally demonstrated here, the new ILW data evidence points
towards the same neutral effect on energy confinement as for the previous experiments with the
C-wall.

5- Discussion on the role of neutrals on confinement in JET with the ILW

In this section, a few physics mechanisms are reviewed with the attempt to identify the
physics mechanism which could explain the role of neutrals in the loss of pedestal energy
confinement by neutrals.

Modelling of the discharges with different divertor configuration has been carried
out using the EDGE2D-EIREINE [18] and SOLEDGE-EIREINE [19] codes with the
objective to investigate the interaction of the neutrals with the pedestals. In general, these
calculations have used the equilibrium and the input power as input with no impurities thus
concentrating on the deuterium specie. Inside the separatrix, the cross-field heat and particle
transport is adjusted to reproduce the measured pedestal density and temperature. The first
possible loss channel that has been examined is the ion energy losses on edge neutrals through
charge exchange processes. In the two extreme configuration (horizontal and vertical outer divertor strike point), the last closed flux surface comes close to the divertor baffles (see fig 1). In addition, in the main chamber, the proximity to the wall may also induce charge exchange losses through higher level of neutral. The calculations with SOLEDGE (fig 9) [11] are showing that in all cases the order of magnitude of the energy loss channel is too small to explain the observed fall in energy confinement in the experiment. The divertor geometry does lead to a variation of the losses compatible with the confinement variation (there is a minimum loss for the corner configuration) but the losses do not exceed 1MW out of 15MW crossing the separatrix. This is confirmed by EDGE2D-EIREINE simulations [20] showing that pedestal charge exchange losses are typically less than 5% of the power crossing the separatrix (Psep). Consequently, the neutral power losses inside the confined region of the plasma are generally small and unlikely to explain the observed reduction in energy confinement. This is suggesting that the responsible mechanism is probably implicit and may be related to a modified radial transport in the pedestal due to changes in the divertor and SOL.

Another possible loss channel resides in the observation that the corner configuration shows a much higher toroidal velocity (fig 5) than the other two configurations. Here, we examine the hypothesis that neutral recycling modifies the ion flow in the vicinity of the edge barrier layer (ETB) and degrades the ETB as a result. The force balance equation for the main ion can be written as:

\[ E_r = \frac{T}{en_i} \frac{\partial n_i}{\partial r} + (1 - \kappa) \frac{\partial T}{\partial r} + V_r B_p, \]

where the poloidal velocity has been replaced by its neoclassical value, \( \kappa \sim 0.5-1.5 \) depending on the collisionality regime and \( B_p \) the local poloidal field. From figure 3, the gradient of the ETB can be inferred and one comes to the conclusion that the density gradient terms (first term) dominate \( E_r \) by a factor 2 to 5 over the last two terms of the equation above. This suggests that edge particle transport could have a strong impact on the rotation at the edge and may impact on the strength of the ETB. Experimentally at JET [21], it has been observed in the JET-C that the angular momentum can be considerably affected with a significant lowering of the thermal Mach number at the edge when the neutral pressure is increased. Therefore neutral may potentially participate to the momentum loss by friction with the ions and change the ETB strength.

To test this, an external force inside the separatrix has been adjusted in the momentum balance in EDGE2D-EIREINE such that flow velocities would be close to the sound speed. The neutral friction is calculated inside the separatrix and indicates much lower amplitude than the momentum transport to the SOL. This indicates that the viscous transport of momentum would be the dominant mechanism acting on the rotation. This would therefore confirm the hypothesis that neutral pressure could play a role on the edge rotation. This effect has been examined theoretically [22] and it was suggested that if neutrals are not affecting the ion flow they could, on the other hand, strongly modify the electrostatic potential at the edge.

SOL conditions may also be altered with the increase of the neutral pressure. So far, only the upstream density could be measured using the Lithium beam and the reflectometer diagnostics. But no temperature measurements could be made. It is therefore challenging to fully characterise the changes at the foot of the ETB. Tungsten impurities eroded from the divertor could also modify the SOL characteristics by atomic physics processes as shown in [23]. Tungsten spectroscopy is showing a lower level of W at high gas injection rate and with 1/2 pumping. However, these measurements can be reliably made only for the horizontal divertor configuration. For the other divertor configurations the diagnostic viewing lines does not cover the area where the outer strike point is located making any comparison difficult to interpret.

6- Conclusions

H-mode experiments at JET with the ITER-like wall have demonstrated that changes in divertor strike point position are correlated with strong modification of the global energy confinement. Typically the normalised energy confinement factor can vary from 0.7 to 0.95 and is a maximum when the outer strike is close to (or inside) the pumping throat. The IPB98y2
confinement scaling law predicts an identical confinement time for all three configuration in contradiction with these observations.

The impact on energy confinement is observable both on the pedestal confinement and core normalised gradients. The vertical divertor configuration shows a much lower pedestal density and pressure. The corner configuration shows an increased core density gradient length and ion pressure indicating a better ion confinement than the two other divertor configurations.

Pedestal ion pressure and toroidal velocity is also stronger than in the other configuration and there are indications that the density gradient of the ETB is also larger. This suggests that the corner configuration has a smaller pedestal transport than the other two configurations.

The study of neutral re-circulation indicates that the neutral recycling in the divertor is not correlated with the confinement. On the other hand, the neutral pressure in the main chamber varies inversely with the energy confinement and a correlation between the pedestal total pressure and the neutral pressure in the main chamber can be established although formally the causal link has not yet been demonstrated.

So far, it does not appear that the energy losses induced in the pedestal by charge exchange can explain the loss of pedestal confinement. Computed charge exchange losses with edge codes amounts to less than 5% of the power going through the separatrix over both the divertor and main chamber area. Momentum losses are another potential candidate but preliminary calculation does not seem to confirm this hypothesis despite contradicting past experimental results in the JET-C. However, it may be that the neutrals are also affecting directly the edge electric potential as suggested in [22]. More experimental and modelling work is necessary here to infirm or confirm this hypothesis.

The performance achieved in both baseline and hybrid scenario described in this paper emphasizes the operational importance of pumping in the main chamber with the JET-ILW. Even though these experiments are not representative of the divertor conditions expected in ITER (i.e. semi-detachment), since ITER has very limited pumping capabilities (~150m³/s for a volume of ~1000m³), it is essential to understand the underlying physics that governs the interaction between the neutrals in the main chamber and the pedestal leading to changes in pedestal and core energy confinement with a metallic wall environment.

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