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The isotope effect on divertor conditions and neutral pumping in horizontal and corner divertor configurations in JET-ILW Ohmic plasmas

J. Uljanovs[1] , M. Groth[1] , A.E. Jaervinen[1] , D. Moulton[2] , M. Brix[2] , G. Corrigan[2] , P. Drewelow[3] , C. Guillemaut[5] , D. Harting[2] , J. Simpson[2] , A. Huber[4] , S. Jachmich[6] , U. Kruezi[2] , K.D. Lawson[2] , A.G. Meigs[2], A.C.C. Sips[7] , M.F. Stamp[2] , S. Wiesen[4] , and the JET contributors*

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK.
[1]Aalto University, Espoo, Finland.
[2]Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, UK.
[3]Max-Planck-Institut für Plasma Physics, Greifswald, Germany.
[4]Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung - Plasmaphysik, 52425 Jülich, Germany.
[5] IPFN, Lisbon, Portugal.
[6]Ecole Royale Militaire, Brussels, Belgium.
[7]EUROfusion Programme Management Unit, Abingdon, UK.

Abstract

Understanding the impact of isotope mass and divertor configuration on the divertor conditions and neutral pressures is critical for predicting the performance of the ITER divertor in DT operation. To address this need, ohmically heated hydrogen and deuterium plasma experiments were conducted in JET with the ITER-like wall in varying divertor configurations. In this study, these plasmas are simulated with EDGE2D-EIRENE [1-2] outfitted with a sub-divertor model [3], to predict the neutral pressures in the plenum with similar fashion to the experiments. EDGE2D-EIRENE predictions show that the increased isotope mass results in up to a 25% increase in peak electron densities and 15% increase in peak ion saturation current at the outer target in deuterium when compared to hydrogen for all horizontal divertor configurations. This observation is consistent with [4] indicating a change from hydrogen to deuterium as main fuel decreases the neutral mean free path leading to higher neutral density in the divertor. Consequently, this mechanism also leads to higher neutral pressures in the sub-divertor. The experimental data provided by the hydrogen and deuterium ohmic discharges shows that closer proximity of the outer strike point to the pumping plenum results in a higher neutral pressure in the sub-divertor [5]. The baratron pressure measurements show that a two to three-fold increase in sub-divertor pressure was achieved in the corner and nearby horizontal configurations compared to the far-horizontal configurations, likely due to ballistic transport of the neutrals into the sub-divertor. The corner divertor configuration also indicates that a neutral expansion occurs during detachment, resulting in a sub-divertor neutral density plateau as a function of upstream density at the outer-mid plane.

Keywords: Nuclear Fusion, Divertor Physics, Neutral Transport, Pumping, JET

∗ See App. of F. Romanelli et al., Proc. of the 25th IAEA Fusion Energy Conf. 2014, St. Petersburg, Russia.

1. INTRODUCTION

The neutral dynamics within the divertor region of the tokamak play a key role in both detachment and fuel exhaust. The study of the factors that influence the neutral dynamics is crucial for future, reactor-relevant fusion devices. [9] The magnetic configuration of the divertor plasma, and the physical shape of the divertor have a significant impact on the neutral dynamics in the divertor region largely due to the geometric effects. [7] In JET, as well as in other tokamaks, divertor plasma configurations with the strike points close to the pumping plena are of particular interest, as they permit the highest pumping and thus a more efficient particle content control. In turn, the corner configuration shows the best plasma performance at JET [17]. In these configurations the pumping is strongly determined by ballistic transport of neutrals from the divertor strike zone into the sub-divertor and towards the pumps.

In this study a comparison is made between the sub-divertor pressures in the corner and horizontal magnetic configurations in JET ohmically heated plasmas. In addition, to elucidate possible isotope effects on the neutral dynamics and divertor conditions a comparison is made between hydrogen and deuterium fuel in the horizontal configurations, in order to determine the isotope effect on neutral dynamics and divertor conditions. The isotope effect is studied, as next-step fusion reactors are planned to run on DT fuel, thus understanding the effect of increasing fuel mass on the plasma-edge is paramount.

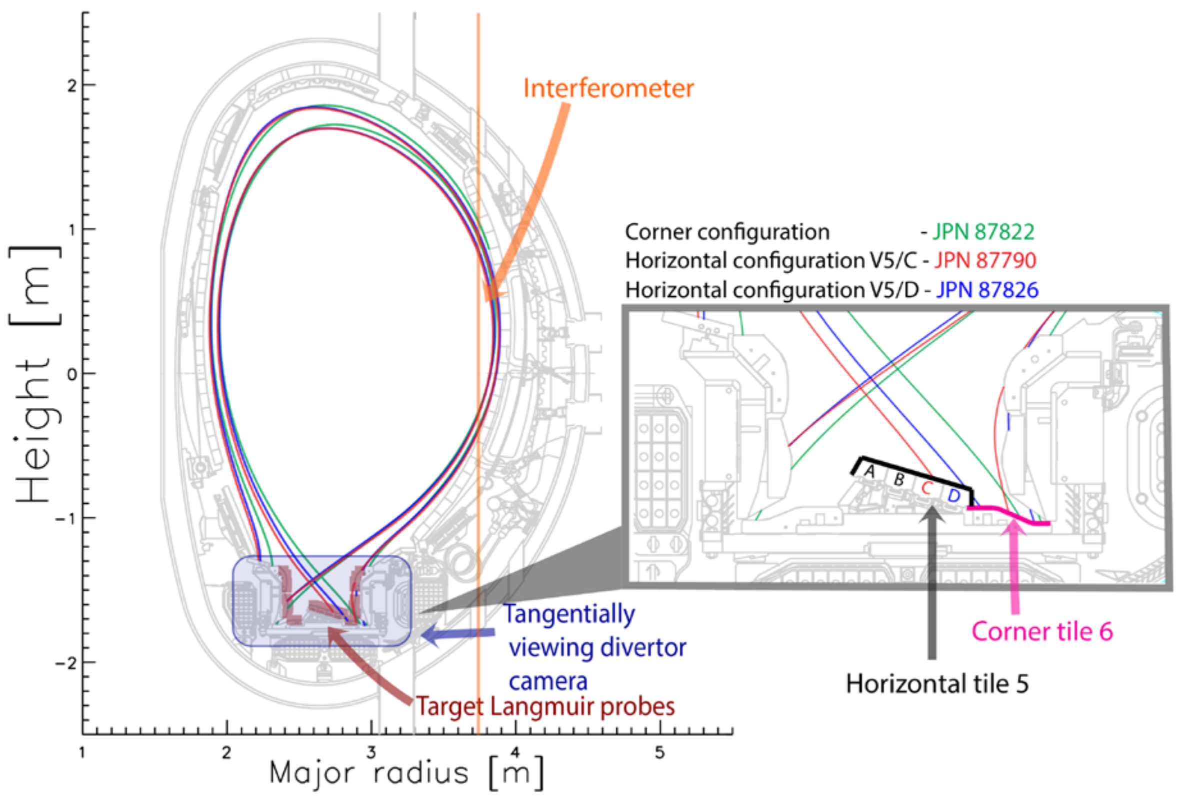

Figure 1: Diagnostic set-up for the experiment along with the three magnetic configurations employed in the hydrogen experiments.

In an experiment during the 2014 JET hydrogen campaign, the proximity to the pumping plenum was systematically increased up to the point where the plasma target location is in the corner configuration (Fig. 1). A number of critical upstream and downstream parameters are considered here to characterise the Scrape-Off Layer (SOL) and neutral dynamics. These include the sub-divertor pressures as measured by the baratron pressure gauge [11] within the sub-divertor, target ion current to the low field side (LFS) divertor target measured by Langmuir probes [12], two-dimensional spectroscopic imaging of the divertor region via tangentially viewing, filtered cameras [14], and the electron densities at the LFS mid-plane [12] using interferometry [18], high-resolution Thompson scattering [19] and lithium beam diagnostics [20]. The magnetic configurations explored in these studies are two LFS horizontal configurations, for which the separatrix is incident on the divertor horizontal tile 5, toroidal rows C and D and a corner configuration with the LFS strike point on JET divertor tile 6 (the reader is referred to Figure 1 for tile locations). Throughout these experiments the HFS (High Field Side) strike point remained on the vertical plate in approximately the same location (Fig. 1).

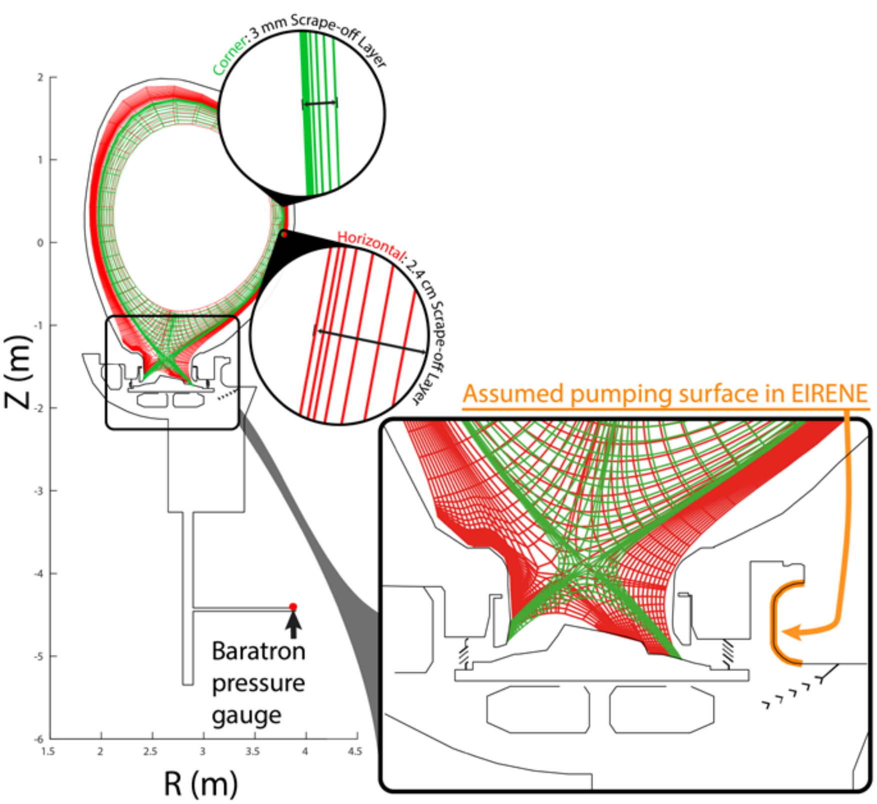

Figure 2: Simulated EIRENE sub-structure and comparison of 3 mm slim corner and 2.4 cm wide horizontal simulation grids.

In the hydrogen experiment, JET was operated at I_p= *2.0 MA* and B_t= *2.0 T*, this resulted in an edge safety factor of *q95 =3.4.* The core, and thus SOL plasma density was increased via increasing the rate of injected deuterium or hydrogen from the top and mid-plane of the main chamber via four gas injections modules. The sub-divertor cryogenic pump [13] was kept at liquid nitrogen temperature enabling hydrogen and deuterium pumping. The line averaged edge density was controlled via feedback using the gas injection modules and cryogenic pump. To obtain the divertor profiles along the LFS target, controlled density steps with strike point sweeps were also performed, in addition to fuelling ramp with fixed strike point positions. For a detailed description of the plasma conditions in the deuterium experiments, the reader is referred to [6].

The SOL conditions of these plasmas are simulated using the coupled plasma fluid/Monte-Carlo neutral edge simulation code EDGE2D-EIRENE [1][2]. The deuterium plasmas were previously simulated in [6], with similar settings used in this study. The deuterium fuel injection was set to emanate from the private flux region, while the pump was at a surface emulating the experimental pump region (Fig. 2), the surface was set-up with a predefined albedo as described in [3]. A total of *2.2 MW* heating power (split evenly between ions and electrons) was applied. A boundary condition was imposed on the SOL such that $D_\perp = 1\ m^2s^{-1}$ in the core and pedestal region, $D_\perp = 0.5\ m^2s^{-1}$ across the separatrix, and 1 m^2s^{-1} in the mid and far SOL regions. The electron and ion thermal diffusivity constant, $\chi_{i,e} = 1\ m^2s^{-1}$ in the core and pedestal region and drops to $\chi_{i,e} = 0.5\ m^2s^{-1}$ across the separatrix, continuing at this value all the way through the mid and far SOL regions [21].

Further, an additional module was employed [3] to simulate the full sub-divertor sub-structure and the neutral particle transport therein. This addition allowed for study of the neutral particle transport in and out of the sub-divertor, and gave a direct metric of comparison with the experiments by allowing for simulation of the baratron pressures. To limit the increased computational time, by the extension of the neutral model into the sub-divertor; impurities, neutral-neutral collisions and cross-field drifts were not yet simulated. Figure 2 shows the full simulated domain used for this study. The upstream density at the LFS mid-plane was controlled in these simulations to achieve densities similar to that of experiment.

The adopted numerical grids used for the horizontal configuration were obtained from previous experimental magnetic equilibria used in the deuterium experiments discussed in this paper, as there was no significant difference in the plasma shape between the two. However, a dedicated grid was required to simulate the corner configuration. Due to a limitation of EDGE2D-EIRENE, it was not possible for magnetic field lines of a grid to pass through objects in the main chamber (i.e. limiter configurations), the generated grid was constrained to a SOL thickness of only *3 mm* as opposed to the thickness of *2.3 cm* (see Figure 2) obtained for the horizontal configuration. Thus far this grid produced unphysical results and was excluded from analysis in this paper while further work is carried out.

2. JET EXPERIMENTAL RESULTS

As the strike point was relocated closer to the pumping plenum, the pressures in the sub-divertor increase approximately linearly with upstream density at the OMP, as a result of a wider angle of direct incidence for the neutral particles into the sub-divertor [7]. The repositioning from the horizontal C to the horizontal D divertor plate leads to a 3-fold sub-divertor pressure increase in deuterium and 2-fold increase in hydrogen plasmas with a further 2-fold increase in the corner configuration (Fig. 3). From these data it appears that the sub-divertor pressure in deuterium plasmas is more sensitive to the target location than it is in hydrogen plasmas. Further investigation is required to determine if this effect persists to the same degree in the corner configuration of deuterium plasmas.

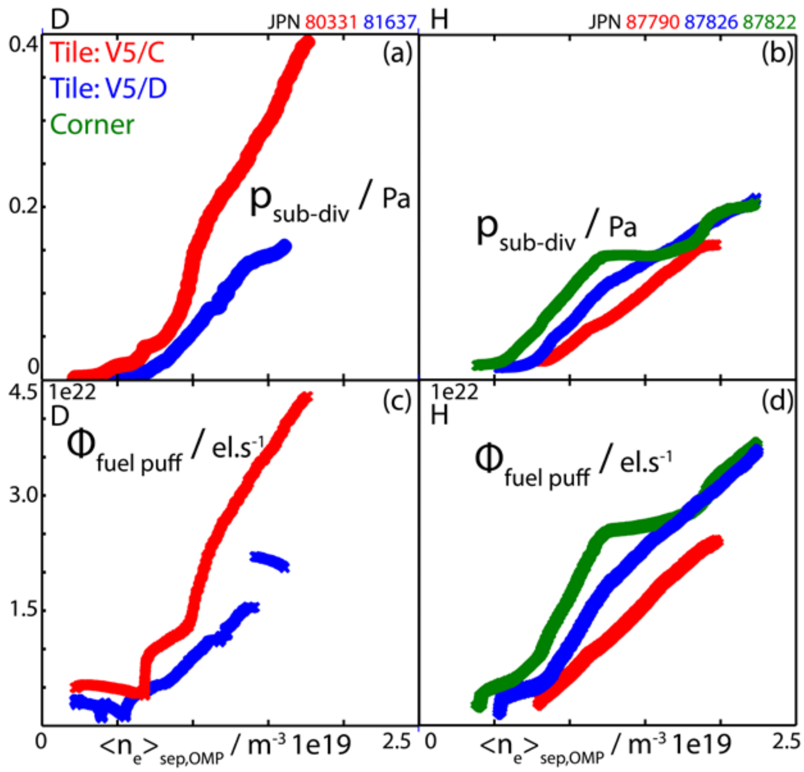

Figure 3: Experimental fuelling rate and sub-divertor pressure comparisons at different strike point locations in deuterium (a,c) and hydrogen (b,d) plasmas.

Similarly, the main fuel has a significant effect on the sub-divertor pressures. Deuterium plasmas have up to three-fold higher sub-divertor pressures than hydrogen plasmas at similar upstream densities, while the puff rate differs by less than *50%.* This is an unexpected result considering that the shorter mean-free path (MFP) of deuterium should be detrimental to neutral transport into the sub-divertor [4]. An evaluation of the pumped flux for the pressure readings seen in Figure 3 has indicated that the pumped flux is a function of the sub-divertor pressure and is not a constant. [22]

In the corner configuration for hydrogenic plasmas, an increase in sub-divertor pressures with proximity to the pumping plenum was observed, continuing the trend of the horizontal C and D target locations. At an upstream density of $1.8 \times 10^{19} m^{-3}$, in the corner configuration, the sub-divertor pressure saturates as the upstream density increases through additional gas pumping (Fig. 3b). While at an upstream density of approximately $1.8 \times 10^{19} m^{-3}$, the $p_{sub\text{-}div}$ resumes increasing at approximately linear rate with upstream density.

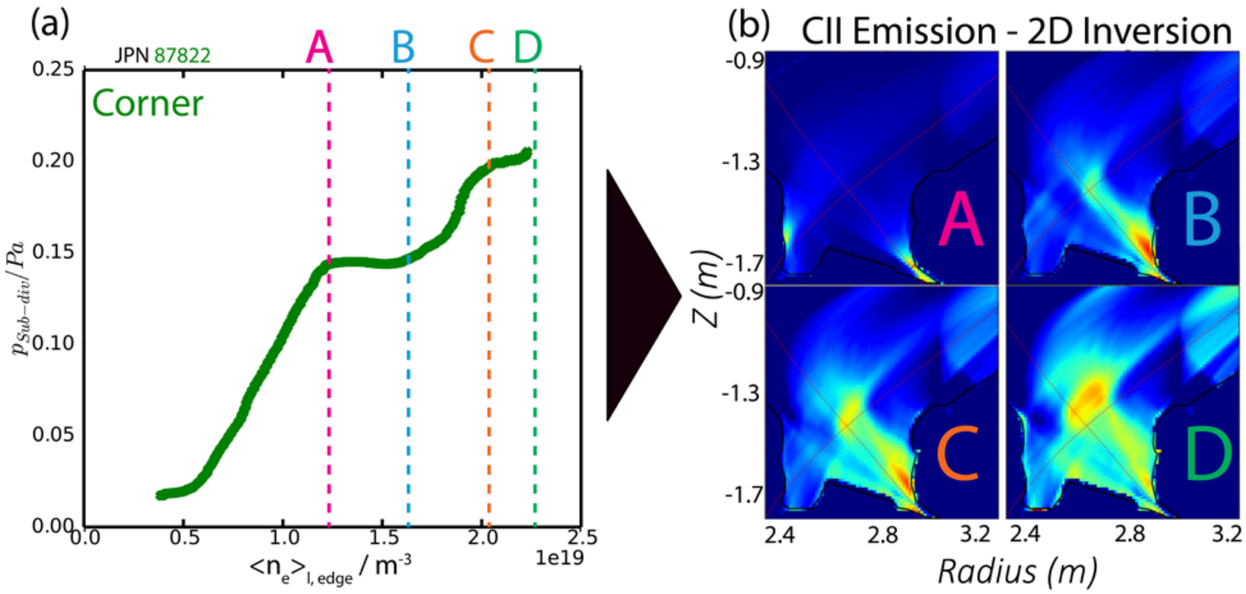

Figure 4: CII emissivity (b) during different stages of the pressure plateau (a) in the corner configuration. Prior to detachment (A) and during different stages of detachment (B-D)

Imagining of the CII emission, as a proxy for the location of the ionization front, shows that at the onset of the pressure plateau the peak emission is situated on the corner tile 6 (Fig. 4b - A). As the upstream OMP density is further ramped up the CII emission zone moves off the divertor target toward the LFS X-point region, while the outer strike-point remains in the same position (Fig. 4b - B). When the density is sufficiently high for the ionization-front to move out completely from LFS corner, the linear relationship between the $p_{sub\text{-}div}$ and Φ_{puff} is observed (Fig. 4b – C/D). Hence an appropriate hypothesis to describe this phenomenon is the movement of the ionization front from corner tile 6, causing an increase of available volume for the neutrals in the LFS divertor corner. This causes a temporary saturation of the pressure measured in the sub-divertor, until it equilibrates with the increased volume in the LFS corner.

The roll-over current is 35% higher in hydrogen plasmas than in deuterium plasmas and the density at which the roll-over occurs is 10% higher in hydrogenic plasmas (Fig. 5d). In addition density limit is 25% higher in hydrogen than deuterium in both magnetic configurations. In the deuterium experiments, the increased proximity of the strike point to the pumping plenum seems to not affect the peak ion saturation currents, while for hydrogen a 15% difference between the peak ion saturation currents was observed between the two horizontal target locations (Fig. 5d). While the strike point location has little influence on the peak plate-integrated ion current in deuterium plasmas, a 30% increase in $I_{div,LFS}$ was seen in hydrogen plasmas when the strike point was moved from the horizontal tiles D to C. The fueling isotope and strike point location have no significant effect on the total radiated power (Fig. 5 a-b)

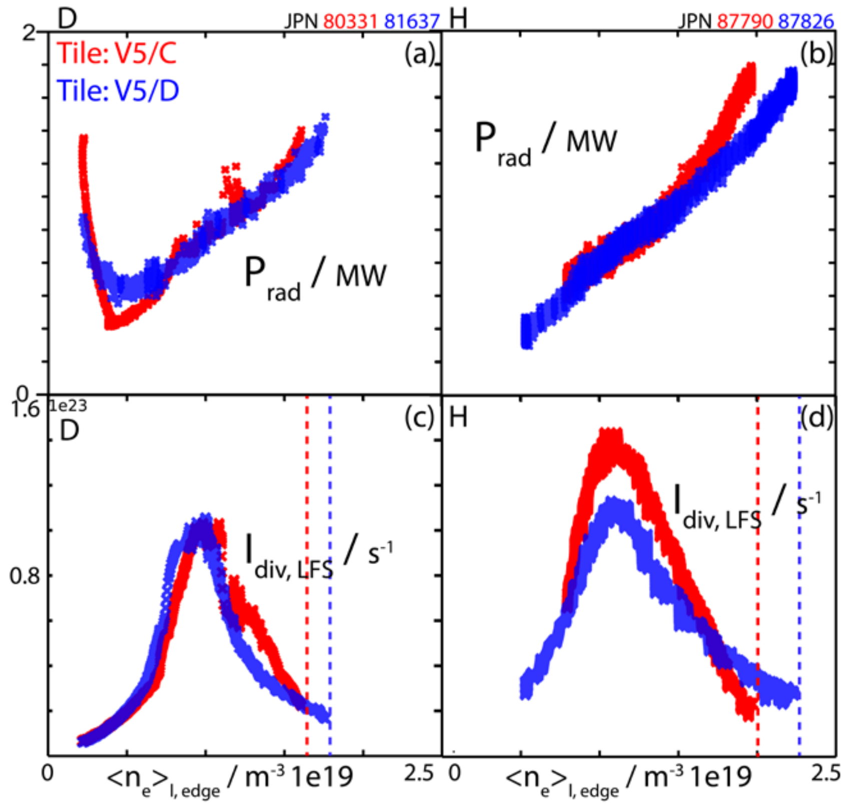

Figure 5: Comparison of experimental radiated power and the LFS plate-integrated ion current at different strike point locations in deuterium (a,c) and hydrogen (b,d) plasmas.

3. EDGE2D – EIRENE SIMULATION RESULTS

EDGE2D-EIRENE simulations predict that the power deposition and ion saturation currents at the LFS divertor plate are approximately the same in both the hydrogen and deuterium simulations (Fig. 6a to 6d). The peak electron densities at the LFS target are *25%* higher in deuterium than in hydrogen (Fig. 6.e,f). This is likely due to the higher mobility of hydrogen allowing it to reach the target plates in greater densities.

In both cases the plate-integrated ion current and the peak electron density at the LFS plate is *15%* and *30%* higher at horizontal tile D than it is at the horizontal tile C, respectively. This indicates that the magnetic configuration has an effect on the divertor conditions. This effect is not observed in the experimental data (Fig. 5). In addition, the difference in the density limits between the two horizontal target locations is approximately 10*%*. This is in agreement with the experimental data [4]. However the 25% higher experimental density limit seen in hydrogen when compared to deuterium, is not observed in the simulation.

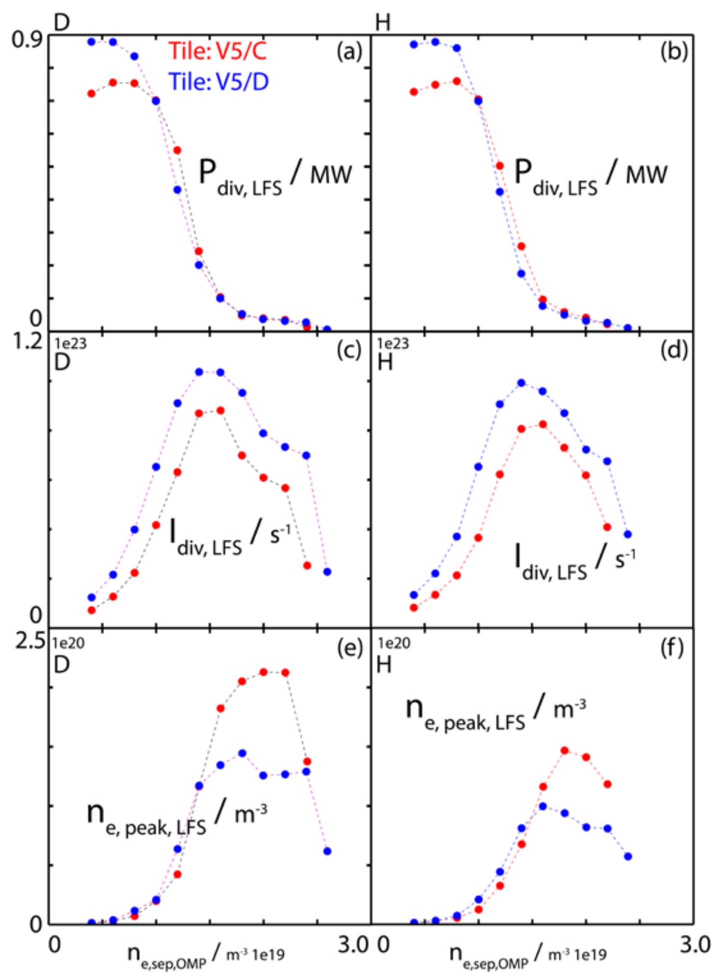

Figure 6: Comparison of simulated target and divertor conditions at different strike point locations in deuterium (a,c,e) and hydrogen (b,d,f) plasmas.

The absolute pressure values are a factor-of-two lower in the simulations than in experiment, the reasons for this are explored in previous studies of neutral particle simulation [3][10]. As in experiments, higher pressures at the baratron were obtained in deuterium than in hydrogen plasma, for the same upstream densities and similar puff rates (Fig. 7a, b) [10][6]. The consequence of increased proximity to the pumping plenum is not as pronounced in the simulated results as it is in the experiment, but it is still observed (Fig. 7c,d). In deuterium simulations a maximum increase of *50%* in the baratron pressures is observed in comparison to hydrogen, while the experimental data shows a 3-fold increase, when the target location is moved closer to the pumping plenum. Similarly, for hydrogen, the simulations predict an increase of about *50%* while the experimental increase is two-fold as we move closer to the pumping plenum. Interestingly, the strike point location shows a greater effect on neutral pressures in hydrogen than in deuterium simulations, particularly in the low-recycling regime.

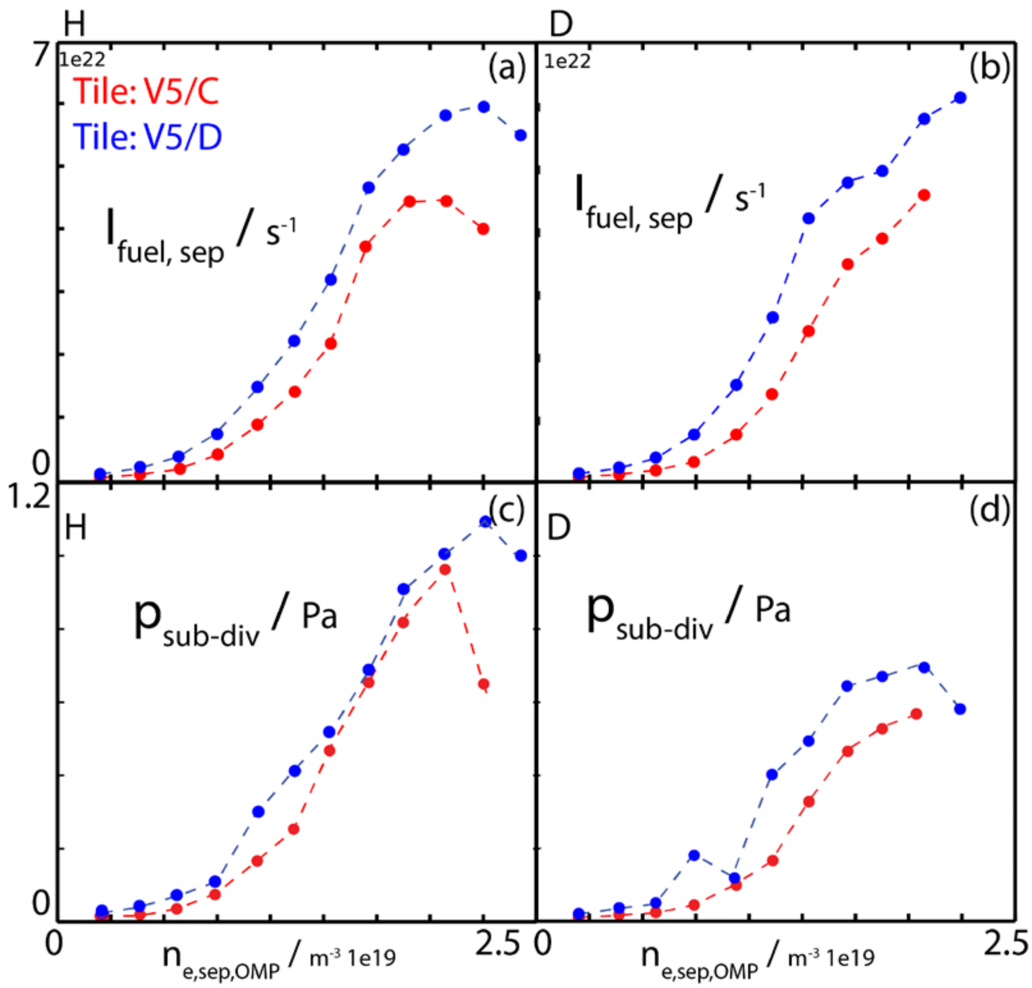

Figure 7: Comparison of simulated fuelling and pumping at different strike point locations in deuterium (a,c) and hydrogen (b,d) plasmas.

4. Conclusion

Experiments in JET Ohmic plasmas using hydrogen and deuterium, and EDGE2D-EIRENE simulations thereof, showed a modest isotope effect on divertor plasma conditions. This study shows about 25% increase in the density limit, 10% increase in the roll-over density and 35% increase in the roll-over current, when hydrogen is compared to deuterium.

The neutral dynamics, however, is significantly affected by the isotope mass. This is demonstrated by an to an up to three-fold decrease of neutral pressures in the hydrogen case when compared to the deuterium case, at the same upstream densities. Based on the observed trend of increased sub-divertor pressures and decreased LFS target roll-over densities in deuterium compared to hydrogen. A continuation of this study into tritium is expected to yield a further decrease in the sub-divertor pressures and increase of LFS target roll-over densities when compared to deuterium and hydrogen plasmas.

The strike point location affected the divertor conditions in hydrogen plasmas in similar fashion as in deuterium plasmas, with the notable exception of 30% increase in plate-integrated ion current seen in hydrogen plasmas when the strike point was moved from the horizontal tiles D to C. Sub-divertor pressures in deuterium plasmas were more susceptible to change in LFS strike point position, leading up to a three-fold increase in sub-divertor pressure with strike-point relocation from tile C to tile D. This suggests that a compound effect of isotope and LFS strike point position exists. The higher susceptibility of the sub-divertor pressures to the proximity of the LFS strike-point to the pumping plenum for deuterium is contrary to previous understanding of the isotope effect on divertor conditions [4].

A decrease in neutral throughput in the corner configuration was observed to occur during the onset of the ionization front withdrawal out of the LFS corner. This was confirmed via CII spectroscopic emission. Precluding that the increased volume occupied by the neutrals in the corner, expands the neutral pressure and hence the pressures within the sub-divertor. Thus the pressure in the sub-divertor does not increase until particle recycling at the plate or recombination become important.

EDGE2D-EIRENE simulations with the inclusion of the divertor sub-structure showed that the isotope choice affects the sub-divertor pressures, in much the same way as in experiment. On the other hand, the divertor plasma conditions did not show a significant dependence on isotope, as was observed experimentally. A two-fold decrease in absolute sub-divertor pressures was observed in simulated results when compared to experiment. This shortfall remains to be further explored by simulating these plasmas with both, neutral-neutral collisions and altered pumping albedo [3]. A step-by-step procedure of iteratively changing the vessel file while avoiding loss of corner geometric effects will be used to simulate the corner configuration in the future.

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