Scrape-Off Layer opacity to D and T gas puff fuelling in JET baseline scenario

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Introduction Determining the particle sources within the separatrix is crucial for understanding the fuelling efficiency of fusion devices. Particle sources from Neutral Beam Injection (NBI) and pellets can be confidently assessed through modelling and experimental measurements, whereas those from gas puff injections remain challenging to determine in present experiments, and often are not measured (e.g. at JET). Experimental observations of the baseline pulses performed at JET indicate different behaviours for deuterium (D) and tritium (T), influenced by the opacity of the Scrape-Off Layer (SOL) and the diffusion of these elements into the separatrix due to their distinct neutral dynamics. This study investigates the SOL opacity for different D and T fuelling levels in JET (DTE2) baseline plasmas through Core-SOL integrated modelling, using the JINTRAC [1] suite of codes equipped with the semi-empirical Bohm/gyro-Bohm transport model [2]. The experimental overview of the pulses analysed in this work can be find in [3]. The simulation settings are briefly presented in section 2, while the modelling results of a core-SOL coupled simulation for the Deuterium pulse (JPN 96482) and the Tritium one (JPN 99282) are presented in section 3. The nominal gas rate is then varied to evaluate the SOL opacity and the gas puff fuelling efficiency to different gas puff levels, at first in steps (Sec. 3) and then in linear ramps with different ramp velocities (Sec. 4).

2. Simulation settings Core simulations, performed using JETTO [4], start from the fully predictive results presented in [5], where the turbulent transport is modelled with the first-principle transport model QuaLiKiz [6,7] and the profiles are evolved self-consistently with the equilibrium computed by ESCO. The transport in the pedestal region is empirically modelled according to the following methodology (presented and validated in [8, 9]). The heat transport in the edge transport barrier (ETB) is adjusted in order to match the experimental height of the temperature pedestal. The width of the pedestal is imposed to match the experimental value. Once the heat transport in the ETB has been fixed, we assume a $\chi/D = 4$ in the pedestal and tune the gas puff particle source in FRANTIC [10], by means of a feedback loop, to match the density at the top of the ETB. The thermal diffusivity χ and the particle diffusivity D are assumed to be the same for electrons and ions in the ETB. The NBI and ICRH heating deposition and current drive profiles are computed with PENCIL and PION, respectively, while the impurity transport is computed with SANCO. In order to study the SOL opacity, the domain of JETTO simulations is extended in the SOL using COCONUT [11], where the neutrals dynamic is modelled using a 3-D Monte-Carlo code, EIRENE [12].

3. Coupled Core-SOL simulations for D and T pulses We started from the core modelling of the Deuterium pulse (JPN 96482) using JETTO, and then extended the modelling in the SOL with COCONUT. Using EDGE2D as the ions transport model in the SOL and EIRENE to simulate neutrals dynamics, we can evaluate the ionization sources (S_I) in the core imposing the nominal gas puff used in the experiment (S_{nom}). In COCONUT the separatrix boundary conditions that we imposed in JETTO are now relaxed, and the separatrix quantities are evolved consistently with the modelled source. In Fig.1 we show the comparison between the experimental data of JPN 96482 and the predicted electron density, electron temperature and ion temperature with JETTO and COCONUT. We can see how both modelling are capturing the transport of the discharge, well reproducing the plasma kinetic profiles within the experimental error bars. Looking at the upper boxes of Fig. 2 we can see the agreement between the predicted separatrix and pedestal densities and temperatures with respect to the experimental values. The latter are obtained from HRTS experimental profiles by fitting "composite" profiles selected in the pre-ELM phase during a stationary time interval, as reported in [13]. COCONUT quantities are found to be within the uncertainty error bars of the experimental values, and, as is clearly visible from the profiles of Fig. 1, the separatrix values are higher than what we are imposing in JETTO. The higher separatrix density is followed only by a mild increase in the pedestal value, therefore decreasing the electron density gradient in the ETB and leading to a lower outgoing flux, giving that the transport in the ETB has been fixed. The pedestal increase is not matching the increase in the separatrix due to the of the lower ionization source found in COCONUT, as visible in the bottom-left box of Fig. 2.

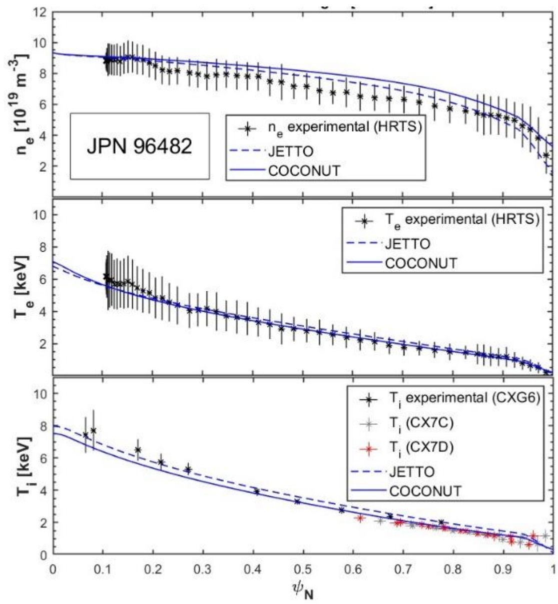

***Figure 1**: Comparison between experimental and modelled profiles, with electron density and temperature measured by the high-resolution Thompson scattering and ion temperature measured by charge exchange spectroscopy.*

The same methodology used in reproducing the D pulse (JPN 96482) was then applied to the Tritium pulse (JPN 99282). The two shots share similar plasma parameters, however the T pulse shows an increased line average density and pedestal top density, which has been modelled scaling the T gas puff source obtained from the DT modelling presented in [5]. In Fig. 3 we are plotting the JETTO and COCONUT predicted kinetic profiles against the experimental ones. The former are computed in two-time intervals [red: 8.22 – 8.27 s, black: 8.02-9.52 s]. JETTO simulation shows that we are able to follow the electron density increase in the core, matching the

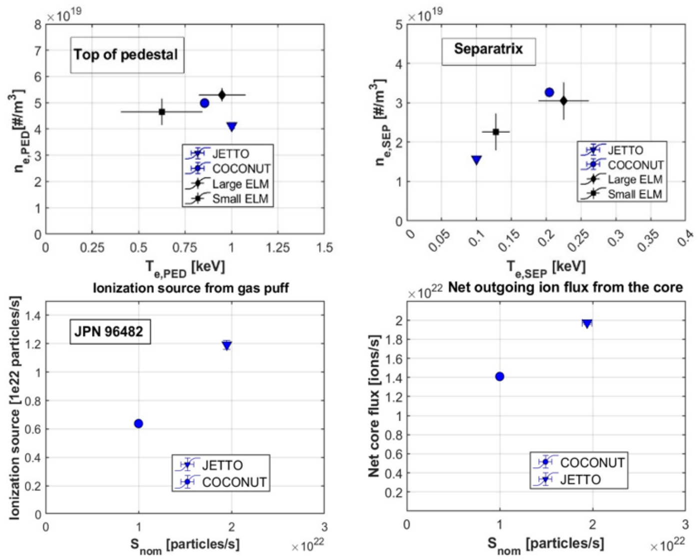

***Figure 2**: Upper boxes show the modelled separatrix (right) and pedestal (left) electron densities plotted against the electron temperatures, together with the experimental data. The bottom-boxes compare the gas puff ionization sources (left) and the net outgoing ion fluxes (right)of the JETTO and COCONUT simulations.*

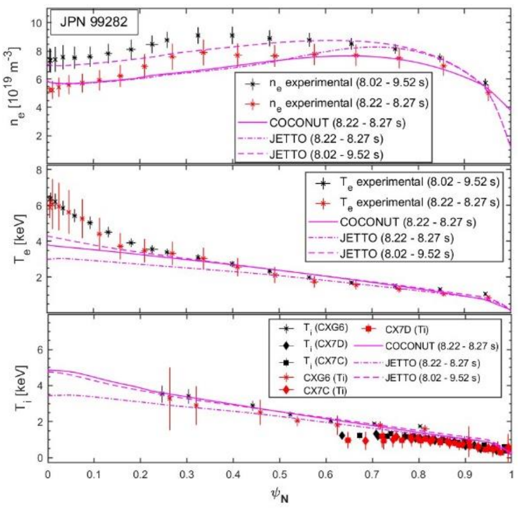

Figure 3: Comparison between experimental and modelled profiles, with electron density and temperature measured by the LIDAR, and ion temperature measured by charge exchange spectroscopy.

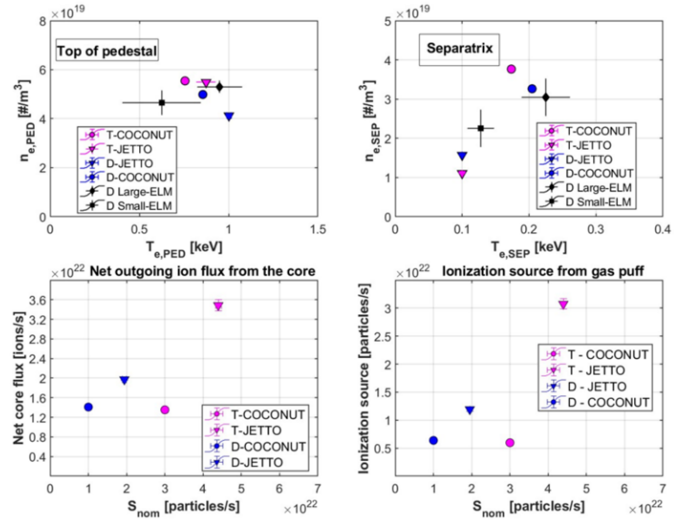

Figure 4: Comparison between D and T simulations against JPN 96482 (D) experimental data. There are no HRTS fit for JPN 99282 (T) to obtain the separatrix and pedestal quantities.

experimental profiles in both time intervals, especially in the core, while keeping the pedestal within the experimental error bars, thus providing a good core simulation to start the core-SOL coupling. As seen in the Deuterium case, COCONUT separatrix density tends to be higher than what we impose in JETTO, which is followed by a somewhat similar pedestal density, given the lower ionisation source (bottom-left box of Fig. 4). Comparing the D and T core-SOL simulations in Fig. 4, we see similar ionization sources and separatrix ion fluxes, obtained with a nominal gas puff which is three times higher in the T case with respect to the D one. We therefore introduce the global fuelling efficiency from gas puff (η_{puff}), defined as:

$$\eta_{puff} = \frac{S_I}{S_{nom}} = \frac{S_I}{S_n}\frac{S_n}{S_{nom}} = f_{sep} t_{SOL}.$$

Where S_n is the rate at which neutrals arrive at the separatrix, considering both direct fuelling and recycling, S_I is the core ionization source and S_{nom} is the nominal gas puff rate, which is imposed in the modelling equal as the experimental one. The quantity f_{sep} can be defined as the fraction of neutrals that ionize in the core after reaching the separatrix, while t_{SOL} represents the transmissivity of the SOL to a given S_{nom}. For the D case, the $\eta_{puff} \approx 66\%$, while for the T case $\eta_{puff} \approx 20\%$. This different value can be attributed both to isotopic effects, and to the different magnitude of the nominal gas puff.

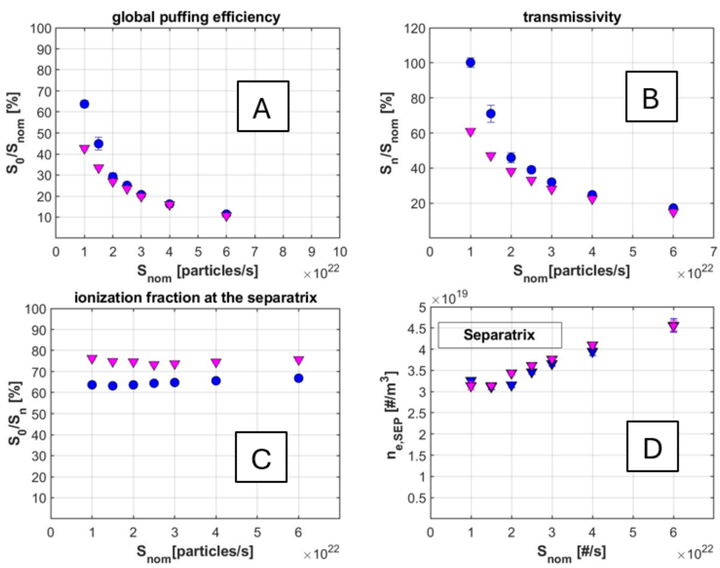

Figure 3: Comparison between D (blue) and T (magenta) simulated puffing efficiency(A), transmissivity(B), ionization fraction(C) and electron density(D) at the separatrix, for different nominal gas puff levels.

In order to better investigate this difference, we scanned the nominal gas puff in both pulses (S_{nom}). As a general result, both for T and D, we can see a decreasing global puffing efficiency (η_{puff}) with increasing gas rate (S_{nom}) (Fig. 5A). Since we see a very weak dependence of the ionisation fraction (f_{sep}) from S_{nom} (Fig. 5C), the decreasing η_{puff} is mainly due to the decreasing SOL transmissivity (t_{SOL}) when increasing the nominal gas puffing (Fig. 5B). This opacity is probably generated by the increase of the separatrix density (Fig. 5D), which is linked to a higher ion density profile in the SOL. Even though the η_{puff} for D and T are very similar at high S_{nom}, the same thing does not hold true for $S_{nom} < 2 \times 10^{22} s^{-1}$, with the D one being higher than the T one. This is due to the effect of a higher t_{SOL}, which is dominating over the effect of a lower ionised fraction f_{sep}. A possible explanation can be the different mass of the two isotopes, leading to a denser and more opaque plasma edge. Another possible explanation can be attributed to a different recycling, especially in the low gas puff region, where the higher deuterium mobility leads to higher recirculating fluxes. Further investigations are needed to discriminate between the two effects.

4. Gas puff ramp: the non-linear relationship between ETB density profile and source The particle balance inside the pedestal is subject to non-linearities. In fact, the increase of the separatrix density ($n_{e,sep}$) is associated with a decrease of the net outgoing flux, for a fixed (or mildly increasing) pedestal density ($n_{e,ped}$). However, the increase of $n_{e,sep}$ leads to a reduction of the SOL transmissivity (t_{SOL}) and of the global puffing efficiency (η_{puff}), until the SOL and the plasma edge reach a convergent solution. For D, in the gas puff region $1 \times 10^{22} s^{-1} < S_{nom} < 2 \times 10^{22} s^{-1}$, we find an oscillating $n_{e,sep}$ (Fig. 6). Varying the nominal source with four linear ramps of different velocity, we can see the progressive damping of the oscillation with increasing ramp velocity. We find that all simulations converge once $S_{nom} = 3 \times 10^{22} s^{-1}$, when the ratio of separatrix and top of pedestal density reach about 0.7, which coincides with the stable point found for the gas puff step from $1 \text{ to } 3 \times 10^{22} s^{-1}$. The nature of the oscillations can therefore be traced back to the balance between sources and sinks in the SOL and in the pedestal.

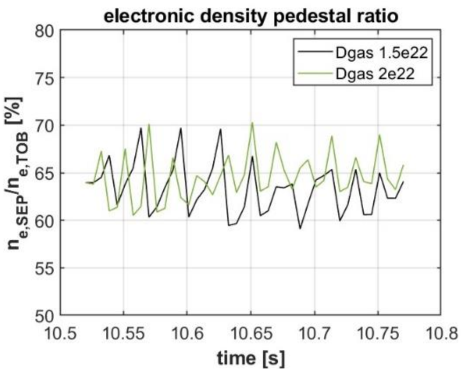

***Figure 6**: the oscillating behaviour of the separatrix density height is generated by alternation of the sign of the local particle balance, which is indeed dependent on the separatrix height.*

If the separatrix density does not converge on a constant value, the oscillation of the separatrix quantities causes the oscillation both of the outgoing fluxes and of the rate of neutrals reaching it.

In conclusion, we obtained an estimate of the effective ionization source from D and T gas puff, which is consistent both with the nominal gas puff, and with experimental measurements at the separatrix and at the top of the pedestal. Furthermore, we have shown the dependency of the fuelling efficiency both on the mass of the isotope and on the magnitude of the nominal source, for two similar JET D and T baseline plasmas, showing the progressive increasing of the SOL opaqueness. Future studies will investigate more deeply the non-linear connection between separatrix and particle balance, and similar analysis could be extended to JET ITER baseline plasmas in D-T [14].

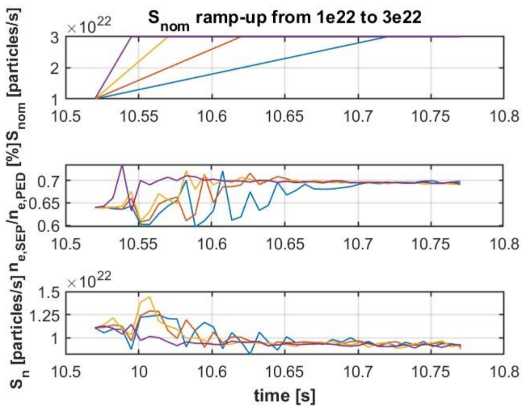

***Figure 7:** four different ramps of the nominal gas puff source, leading to the same converging particle balance in the pedestal: purple (8e23 #/s²), yellow (4e23 #/s²), orange (2e23 #/s²) and cyan (1e23 #/s²).*

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