Gas scan to probe fuelling through the H-mode pedestal in JET

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Three-point gas scan experiment in JET H-mode plasmas (Bt=2.7 T, I=2.15 MA, P_{NBI}=14 MW, low triangularity, strike points in the divertor corners) has been performed to study plasma fuelling while applying gas puff modulations. In this regime ELMs are of mixed type with large variations in their size and frequency. The average ELM frequency is above 100 Hz and the plasma responds well to gas fuelling with pedestal density going up from 3.6 to $4.8 \times 10^{19} m^{-3}$ when the average fuelling is doubled from 2 to 4×10^{22} electrons/s. The modulated gas fuelling, @3Hz, is injected from the main chamber (see Fig. 1) while the steady state fuelling is spread out between divertor and main chamber valves and is varied to alter the pedestal and SOL densities.

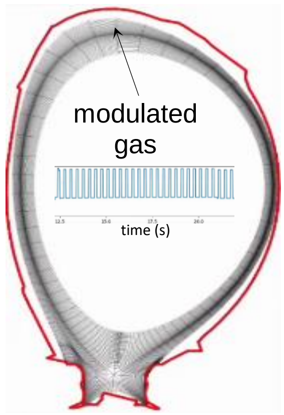

Figure 1 EDGE2D/EIRENE grid illustrating the modelled domain and plasma configuration

Figure 2 shows the electron density response to the gas modulation and to the gas fuelling scan measured with reflectometer at outer midplane. Due to limited time available we were unable to

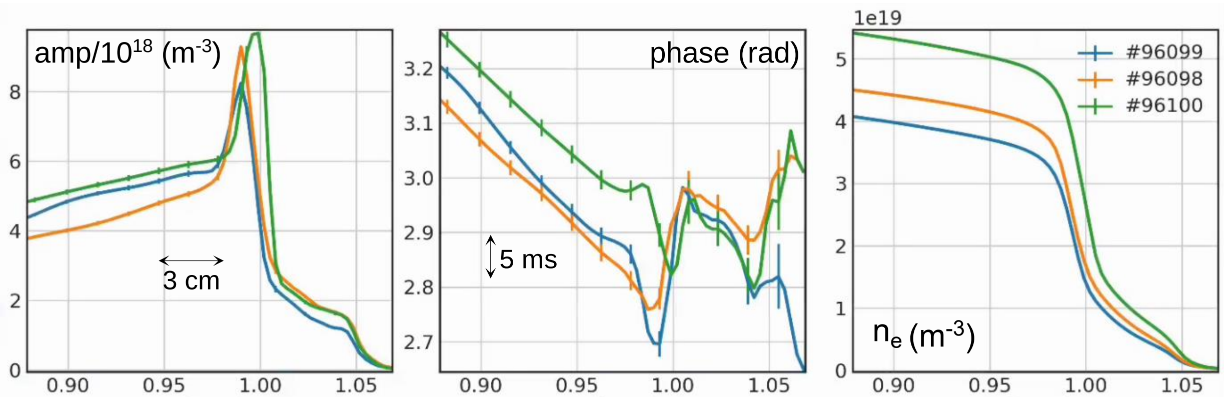

Figure 2 (left) Electron density modulation (3 Hz) amplitude, (middle) phase and (right) time averaged profile for the three-point gas scan. The arrows in the figure illustrate the spatial and temporal scales.

extend the scan to lower and higher fuelled cases. Therefore, all discharges have outer target attached and their response to the modulation is quite similar. Qualitative differences at

* See the author list of "Overview of JET results for optimising ITER operational" by J. Mailloux et al. to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)

detachment were expected based on earlier DIII-D results [1]. The narrow peak in the modulation amplitude just inside separatrix coincides with the local minimum in phase which together are a good indication of the maximum ionisation (fuelling) location. There is a small shift outwards both in amplitude & phase profiles and in steady state electron density as fuelling is increased. Note that profiles are neither smoothed nor fitted despite their appearance. Error bars shown in measurements are just amplitude and phase fitting errors and they do not include, e.g. errors in equilibrium.

To gain more insight on the fuelling for this limited range scan we perform EDGE2D/EIRENE simulations. The scan is simulated by the following scheme: grid is generated for #96099 and divertor geometry is adjusted by as little as possible to allow 4cm SOL width at outer midplane (see magenta v grey contour in Fig. 5). Pumping surfaces are added in corners (marked with cyan colour in Fig. 5). Upstream electron temperature and density profiles (from Thomson scattering) are matched by tuning the perpendicular transport (diffusion only) profiles together with pumping albedos (0.93) while using experimental feed forward gas fuelling. We assume $T_i = T_e$ and neglect drifts due to numerical difficulties. Then, keeping transport and albedos fixed, gas fuelling is varied as in the experiment.

Fig. 3 shows the comparison between the simulated and experimental profiles at outer midplane. One can see that the simulations go in the right direction when increasing the fuelling but fail to match the high pedestal density at highest fuelling (and consequently overestimate the temperature). While it is not possible to conclude that some other combination of albedos / fuelling locations / transport profiles would not improve the match for the whole scan one can point out obvious other limitations in the simulations that could explain the differences: fluid approximation of the SOL, divertor geometry modifications, limitations in the fuelling locations, assuming identical transport across the scan, CX neutral source from ELM filaments, etc. With these known limitations, the following shows some more details of the simulations.

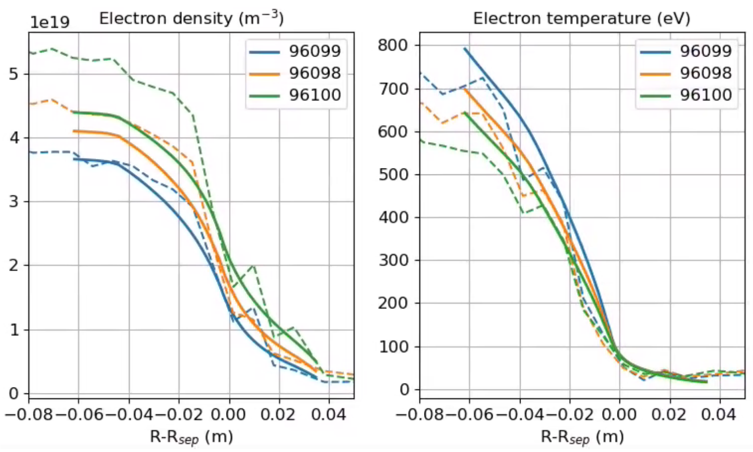

Figure 3 Time averaged experimental profiles (Thomson) v simulated profiles (EDGE2D/EIRENE) for the scan.

Fig. 4 shows the radial and poloidal variation of the calculated ionisation source inside the separatrix. The volume integrated source rates in the legend can be compared against the total gas fuelling rates ($2-4\times10^{22}\,\frac{1}{s}$). In the low fuelling case ~50% of injected gas ends up inside the separatrix while in the high fuelling case the efficiency is reduced to ~29%. Experimental match (with above assumptions) would have required ~33% efficiency. One can see that the flux surface averaged radial profiles are fairly similar (top) while clear qualitative differences are visible in the poloidally resolved ionisation rates (bottom). With increased gas rate the fuelling rate increases mostly around the midplane (OMP) and near the fuelling source at the top of the plasma (TOP) while it reduces near the X-point.

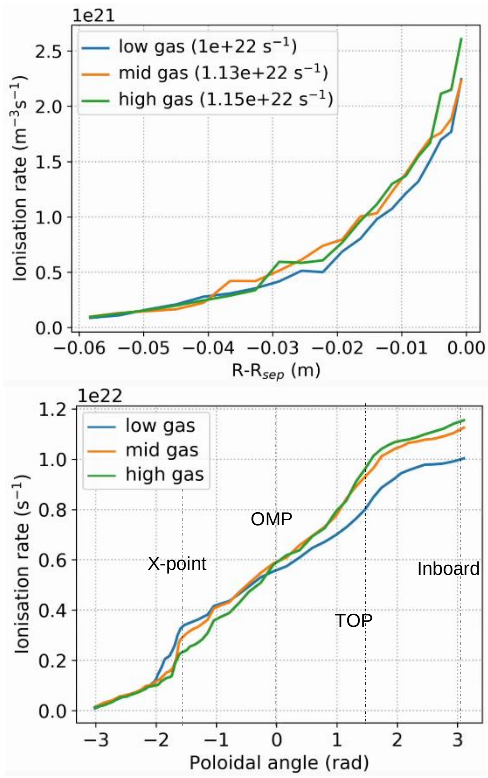

Figure 4 Volume integrated (top) and poloidal variation (bottom) of ionisation inside the separatrix.

Fig. 5 shows in detail the divertor region

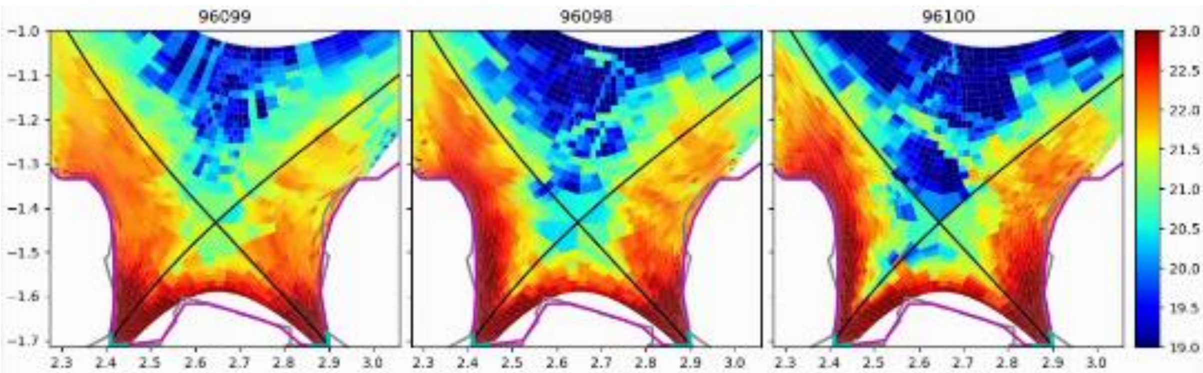

Figure 5 Ionisation rate ($m^{-3}s^{-1}$) around X-point region.

ionisation rate confirming the trend of reduced X-point ionisation inside separatrix with increased fuelling. This is explained by the increased electron density originating from the inner strike point and gradually extending towards inner midplane thus effectively shielding neutral fluxes across the separatrix. Since the simulations underestimate the core fuelling and it is possible that X-point region is a large part of it one might speculate that one key ingredient missing from the simulations could be energetic neutral sputtering from the inner (and outer) divertor aprons caused by hot filaments and ELMs.

Finally, Fig. 6 shows a comparison between (#96098) and another NBI heated discharge (#96095) with similar magnetic geometry and modulated gas puff. The latter discharge has lower B_t and more heating pushing it to well above L/H threshold and thus into pure type-I ELM regime. Despite various other difference in their parameters both have roughly the same pedestal density and comparable pedestal temperature (=similar neutral penetration). One can see that with the mixed ELM type plasma (left) additional gas induces less ELMs geared more towards type-I. ELM frequency is reduced which improves pedestal confinement thus effectively amplifying the gas fuelling effect. The opposite happens with type-I ELM case (right); ELM frequency increases with gas, more particles are expelled due to ELMs which counteracts the fuelling making pedestal density quite unresponsive to the gas fuelling. In the latter case gas puff also cools the pedestal more effectively as seen by comparing the max/min ratios in the subplots.

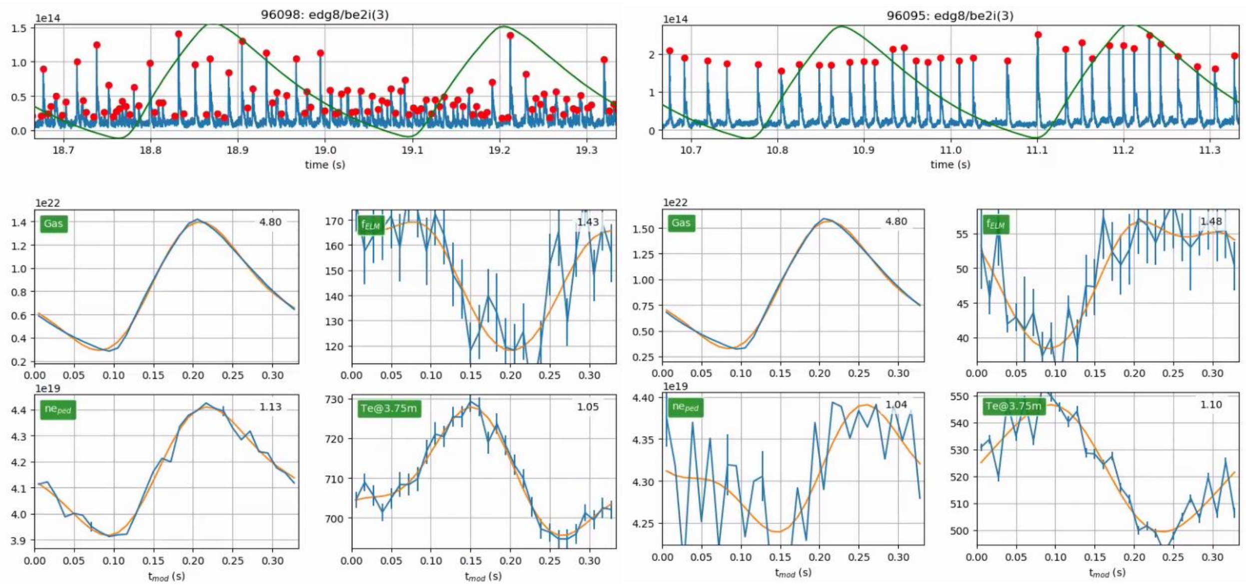

Figure 6 Comparison between ELM types. Top traces show Be II line radiation at inboard divertor apron (ELM signal). 2x2 frames show one coherently averaged modulation cycle for gas rate, line averaged electron density through pedestal, ELM frequency and electron temperature near pedestal top. Numbers in top right corners show the ratio between max/min for each trace.

The observations shown here are well in line with the expectation that ELMs and pedestal stability can effectively either oppose or amplify the gas fueling efficiency depending on the regime. Also, while it is not trivial to model the fuelling of an H-mode plasma taking into account the intermittent nature of the SOL [2] and the effects of ELMs this might be needed for improving the quantitative agreement.

Refs [1] S. Mordijck et al, Nucl. Fusion 60 082006 2020 [2] A.S. Thrysøe et al, Physics of Plasmas **25**, 032307 2018

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.