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## ABSTRACT.

The numerical modeling presented in this work shows the importance of taking into account an effect of the LH power on the SOL heating, and hence on the ionization, when modeling the SOL plasma. The modeled density growth due to SOL heating and gas puff is consistent with the modeled SOL ionization source profiles, which for puff and heating are strongly enhanced and extend into the far SOL, contrary to the case without heating and/or without the gas puff. This could explain the observed improvement of the LH wave coupling at the near grill gas puffing.

## 1. INTRODUCTION

Gas puffing with a gas pipe GIM6 situated near the JET Lower Hybrid (LH) antenna increases the Scrape-Off Layer (SOL) electron density, $n_{e,SOL}$, in the region magnetically connected to the gas pipe, which improves the LH wave coupling [1], [2]. This is especially important for ITER where a large distance between the separatrix and the LH grill mouth is foreseen. Numerical modeling with the fluid code EDGE-2D [3] suggested that enhanced edge radial plasma transport [4] can play a role in the $n_{e,SOL}$ increase, but the agreement with the measured profiles was reached by using ad hoc modifications of the transport. The modeling also did not take into account direct ionization by the LH wave, which is thought to contribute [1], either because of the SOL heating by collisional dissipation of the LH wave, or due to the fast electrons created by the LH wave parasitically in front of the grill mouth [5], or both. In the work presented here, EDGE-2D was used to include a simple representation of the SOL heating by LH waves and used to explore its effect on $n_{e,SOL}$. Since EDGE-2D is a two-dimensional code, it is assumed that the ionisation by the LH wave is produced due to the local SOL electron heating by the LH waves and possibly locally generated fast particles in a radially narrow belt near the separatrix, with a poloidal width corresponding to the LH grill height. We supposed therefore that the overall SOL heating (which is an input to the code) is about 20 times higher. This coefficient of 20 was obtained as the ratio of the toroidal tokamak circumference $2\pi R$ (R taken as 3m) to the grill toroidal width L (L taken as 1m). As we assume, this option might give a better estimate of the sources due to ionization. The ionization is computed in the code under the assumption that the electron velocity distribution is Maxwellian. Modifications to EDGE-2D were required to accommodate the large SOL widths in the discharges which are of interest for LH wave coupling in ITER, where the distance between the separatrix and the LH launcher $d_{PL} > 8$cm. The effects of varying the LH heating and the gas puffing rate on $n_{e,SOL}$ are shown, and compared to experiments. For example, the slope and magnitude of the measured $n_e$ profile for two shots with $d_{PL} = 8$ and 9cm, are reproduced by the modeling, with the SOL temperature locally increased by the LH power launched. Note that the maximum ionisation cross section for hydrogen is about 30eV, and decreases with increasing temperatures. Also, the ionization sources were calculated for various LH heating and puffing rates. The two values of the plasma density at the separatrix used in the modeling ($10^{18}$ and $10^{19}$ $m^{-3}$) correspond to typical values measured in JET for plasma scenarios under consideration in this paper.

## 2. COMPUTATIONAL RESULTS AND COMPARISON WITH EXPERIMENTS

We will illustrate the EDGE2D modeling results on a shot with a long distance between separatrix and between the LH grill mouth. It is a discharge (JET Pulse No: 58667) from experiments to study long distance coupling [2], exhibiting also hot spots on the divertor apron, caused by the fast particles locally accelerated in front of the grill mouth [5]. For this LH shot, there are available SOL density and temperature data from Reciprocating Probe (RCP) measurements. Even if the data have some spread due to ELM activity, they allow a comparison with the modeling. We also modeled the discharge (JET Pulse No: 59187) from an experiment in which effects of gas puffing on the LH wave coupling were studied [6]. Even if the modeled density curve also fits into the measured data limits, we do not show here the comparison, because the RCP data from this shot have a large spread due to ICRF effects on the RCP measurements.

The magnetic surfaces located in the radial layer in front of the grill mouth hit the inner wall. EDGE2D can only cope with intersections of magnetic flux surfaces in the divertor region, and consequently the intersections with the inner wall were approximated by introducing particle and energy sinks [7]. The resulting neutralisation of the plasma creates sharp ion and electron pressure gradients at the plasma-vessel interface, which drives a plasma flow to the vessel, where it is recycled as neutrals via recombination. As the exact radial profile and the rate of the LH wave dissipation in the boundary plasma is not known, two values of the width of the SOL layer with LH wave heating were considered in the computations: a narrower one of 2cm width between 2-4cm and alternatively between 6-8cm from the separatrix, and the wider one of 7cm width between 2-9cm from the separatrix. The narrow layer is more suitable for fast particle heating, as the fast particles are generated in a layer of this width in front of the grill mouth, while the wider layer corresponds better to the SOL heating by the collisonal LH wave dissipation.

The wall is 9.5cm from the separatrix in the midplane in the modeling. LH heating rates between 100kW and 1MW in the JET SOL plasma were considered in the computations. The case of 300kW heating in the SOL appears to give the best comparison with experiments. The $D_2$ gas puffing was varied between $10^{21}$ el/s and $10^{22}$ el/s. The distance from separatrix is denoted by r.

Figures 1 - 3 show SOL outer mid-plane density profile modeling results for two widths of the LH heating slab, and for various puff and heating rates. The plasma density at the separatrix is 5.e18 $m^{-3}$. Figure 1 demonstrates that the larger the puff, the larger is the far SOL plasma density, provided that there is a SOL LH heating of 300kW. Figure 2 demonstrates that the far SOL density grows strongly with growing heating, for the gas puff of $10^{22}$ el/s. As Figure 3 shows, a puff without heating leads even to a decrease of the far SOL plasma density, cf. the red and blue curves in Fig.3. This is connected with the decrease of the far SOL mid-plane electron temperature due to the cooling by the puff without heating. On the other hand, heating even without a puff leads to an increase of the far SOL plasma density (and temperature), cf. the green curve in Fig.3. The next Figure 4 then shows the modeled temperature for two widths of the SOL heating layer, and for various puff and heating rates.

The SOL temperature from the scanning probe measurements is in Fig.5, for the JET Pulse No: 58667 with a long distance between separatrix and the LH grill mouth, at LH wave launching.

As Fig.6 shows, the gas puff strongly enhances the ionization source near the separatrix (the red curves in Fig.6). The puff and heating together (the black curves in Fig.6) broaden the enhanced ionization source profile into the far SOL mid-plane, which allows the density there to stay rather high and above the cut-off density for the LH wave, cf. the black curves in Fig.3.

The density profiles measured by the reciprocating probe at gas puffing and LH heating are shown in figure 7, cf. [2], for a shot with a large distance between separatrix and the LH grill mouth. The probe was magnetically connected to the grill mouth at the time of measurement. The measured density decreases near to and behind the limiter for *r* larger than about 0.07m. However, this density decrease can not be modeled by the two-dimensional code EDGE2D. Let us note that we present more broadly the parameter variations (heating rate, gas puffing rate) for the plasma density 5.e18 $m^{-3}$ at the separatrix, even if a better fit to experimental data was obtained for the plasma density of $10^{19}$ $m^{-3}$ at the separatrix. The reason is that, for some values of puff and heating, the EDGE2D exhibits numerical problems for the higher value of the plasma density of $10^{19}$ $m^{-3}$ at the separatrix.

## CONCLUSION

The numerical modeling presented in this work shows the importance of taking into account an effect of the LH power on the SOL heating, and hence on the ionisation, when modeling the SOL plasma. In addition to the modeling of the plasma density and of the ionisation source, we also studied the results of variations of the gas puff and of the SOL heating rate on the temperature: The gas puff without or with a low LH heating cools the SOL, and therefore, can even result in a decrease of the plasma density. On the contrary, sufficient LH heating enhances the SOL plasma temperature and also the density. This increase in the SOL temperature is largest without gas puff. When the gas puff is accompanied by sufficient SOL heating, the SOL plasma density strongly rises, which can possibly explain the observed improvement of the LH wave coupling. However, the grill is usually retracted into the limiter shadow, and EDGE2D can not model the density decrease behind the limiter, which is important for the LH coupling predictions. Therefore, we plan to introduce into EDGE2D features, enabling estimates of the density profile also behind the limiter. The modeled density growth due to SOL heating and gas puff is consistent with the modeled SOL ionization source profiles, which for puff and heating are strongly enhanced and extend into the far SOL, contrary to the case without heating and/or without the gas puff.

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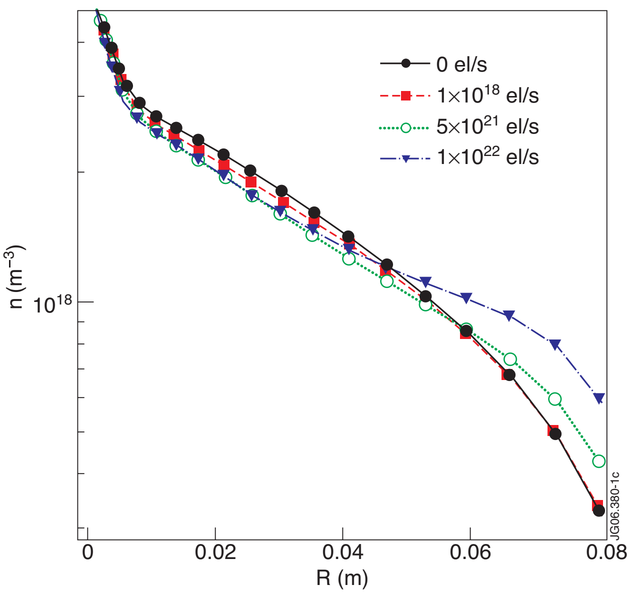

Figure 1: Comparison of outer mid-plane SOL density profiles for various puffing rates, LH heating 300kW between 2-9cm from the separatrix.

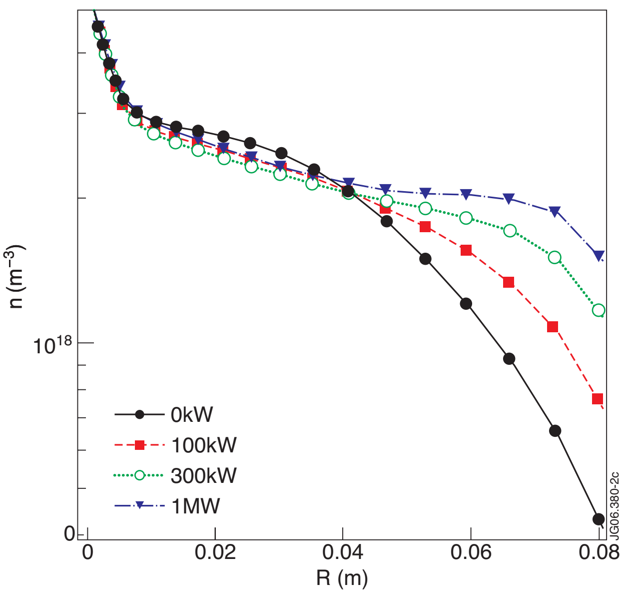

Figure 2: Comparison of outer mid-plane SOL density profiles for various heating rates, puff 1.e22 el/s, heating between 2-9cm from the separatrix.

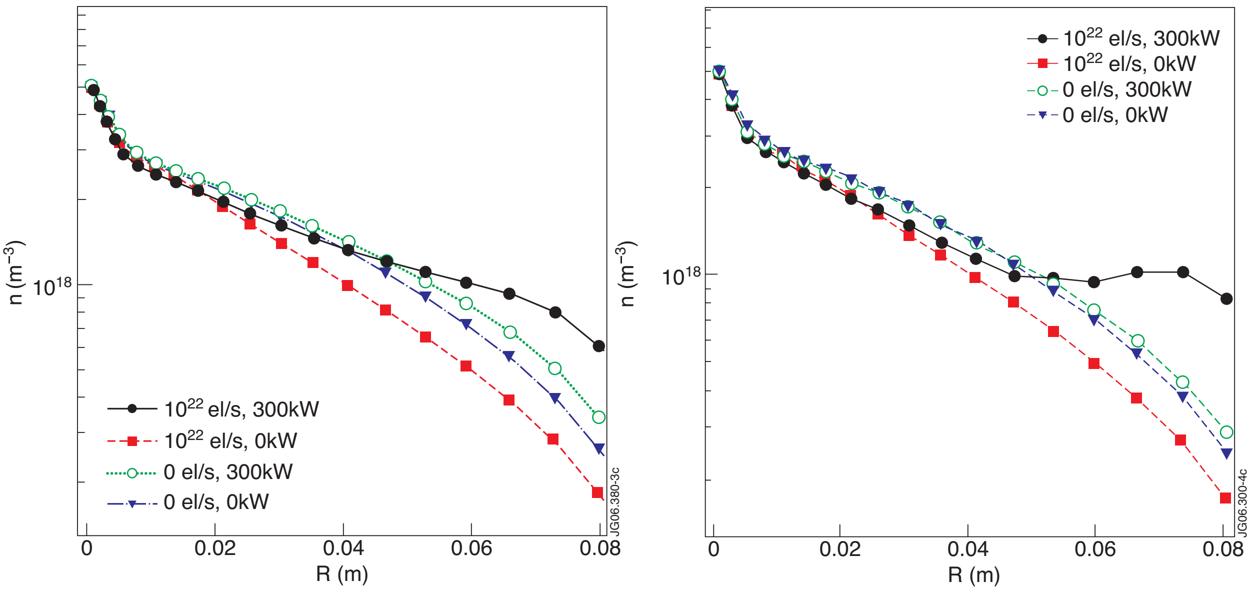

Figure 3: Comparison of outer mid-plane SOL density profiles for various puffing and heating rates, heating in a more narrow slab, left figure: between 2-4cm, right figure: between 6-8cm from the separatrix.

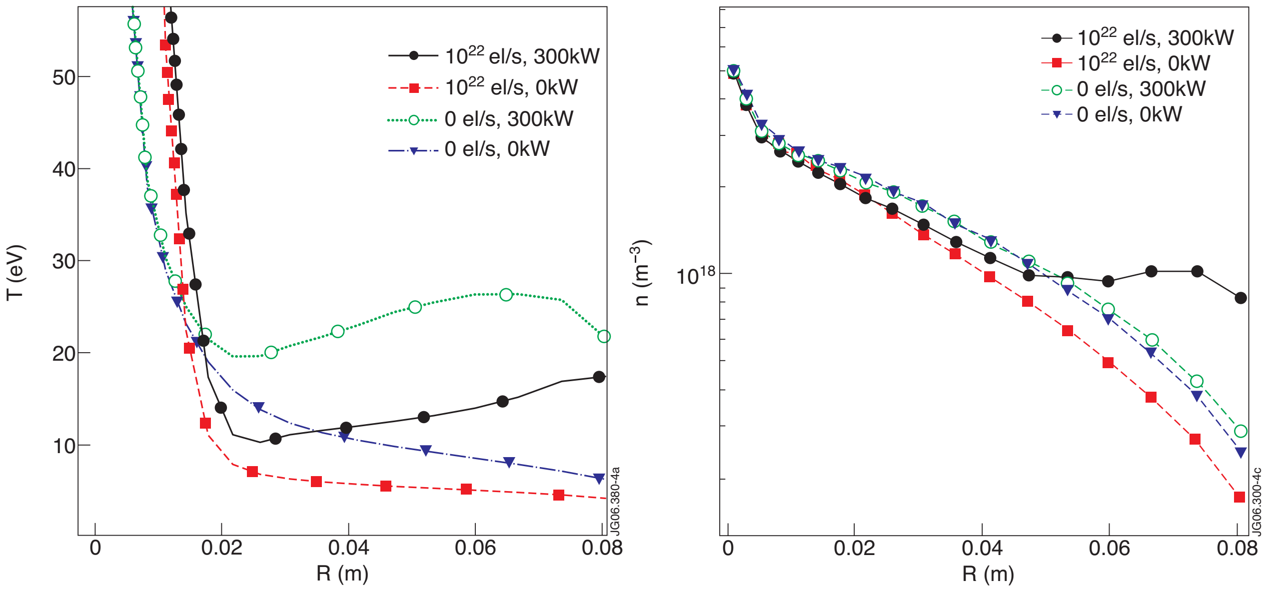

*Figure 4: Comparison of outer mid-plane SOL computed temperature profiles for various puffing and heating rates, heating in a more narrow slab, left figure: between 2-4cm, right figure: between 6-8 cm from the separatrix.*

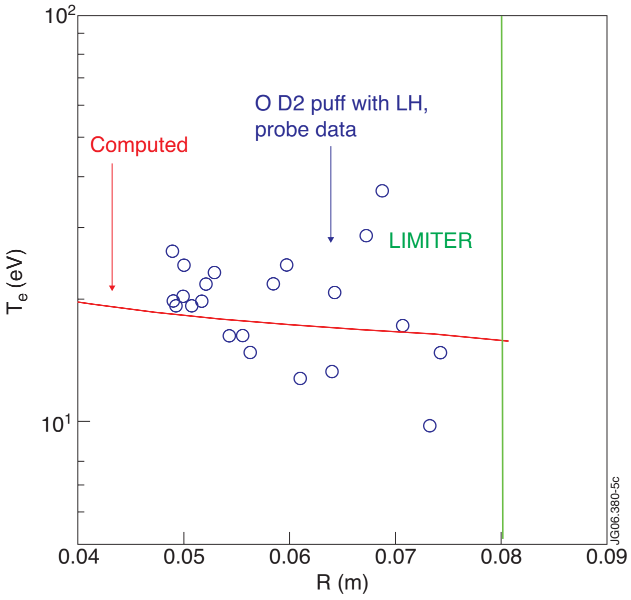

*Figure 5: Blue circles: SOL temperature measurements by the reciprocating probe, Pulse No: 58667 at 12.7s, LH heating 2.5MW, B=3T, Ip ramp from 1.5 to 2.7MA. The red curve is the computed curve, puff 1.e22 el/s, heating 300kW in the slab between 2-4 cm from the separatrix. Plasma density is 1.e19 $m^{-3}$ at the separatrix in the modeling.*

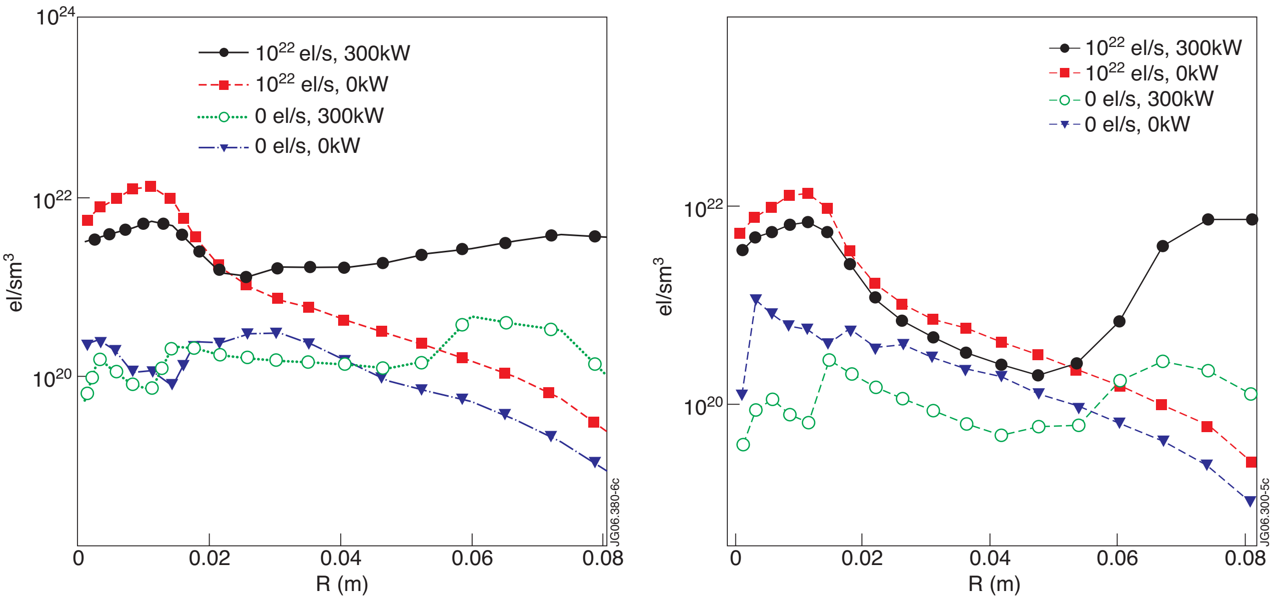

*Figure 6: Comparison of ionization source profiles for various puffing and heating rates, heating in a more narrow slab, left figure: between 2-4cm, right figure: between 6-8cm from the separatrix. The plasma density is 5.e18 m$^{-3}$ at the separatrix.*

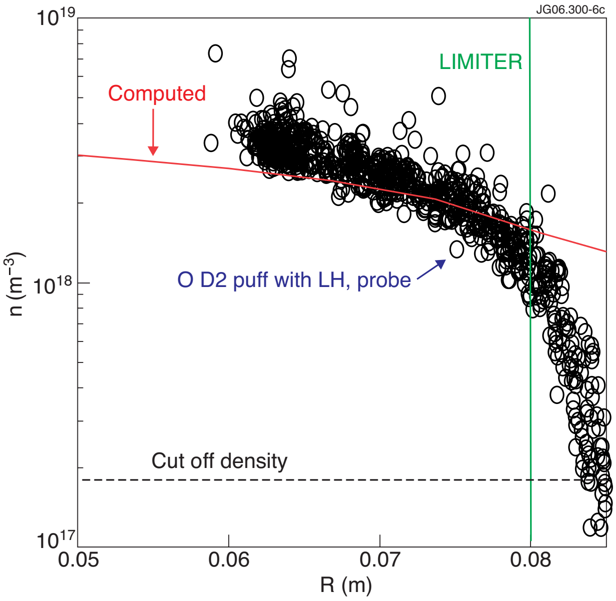

*Figure 7: Electron density profile (blue circles) measured by the reciprocating probe, Pulse No:58667 at 4.8 s, D2 puff 8.e21 el/ s. The red curve is the computed curve, puff 1.e22 el/s, heating 300kW in the slab between 2-4cm from the separatrix. Plasma density at the separatrix is 1.e19 m$^{-3}$ in the modeling.*