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ABSTRACT

ICRF heated L-mode pulses of JET with the new ITER like wall are simulated for the first time with the transport code COREDIV. The model, which couples self-consistently the core with the SOL as well as the main plasma with impuries, provides, from a limited number of inputs, output quantities as the core temperatures and densities profiles, Z_{eff}, the power radiated, the W fluxes and concentration, the plasma parameters on the divertor and so on. Due to the slab geometry of the SOL, the Be flux can not be calculated self-consistently, but it is given as an input, according to the experimental data. Comparison of simulations with experimental data both of the core and of the SOL is generally quite satisfactorily, with the exception of Z_{eff} for discharges at very low density, possibly due to radiofrequency-specific effects which are not accounted for in the model.

1. INTRODUCTION

One of the most challenging issues of fusion research is the development of an ITER scenario which satisfies simultaneously the requirement of sufficiently high power amplification with the needs for sustainable power exhaust. In view of possible realistic prediction for ITER-relevant scenarios, discharges of JET with carbon plates and impurity seeding have been successfully simulated in the past using the integrated transport model COREDIV [1], which self-consistently couples the plasma core with the plasma edge and the main plasma with impurities. In particular, the code has been benchmarked against nitrogen seeded Type I and Type III ELMy H-mode discharges [2,3] as well as neon seeded AT scenarios [4], proving its capability of reproducing the main features of JET seeded discharges as the elecrton density and temperature profiles, the total radiated power, and the effective ion charge, Z_{eff}. However, the applicability of the model to a device with Be wall and W divertor, as JET with the ITER Like Wall (ILW) has not been addressed, so far.

In this paper the first numerical simulations with COREDIV discharges of JET with the ILW are presented. Although some preliminary runs with nitrogen seeding have recently been performed, we limit the present study to the analysis of simulations of JET discharges without impurity seeding and without ELMs, i.e. to L-mode discharges.

We have selected three well diagnosed discharges [5] heated by ICRF at a power level of $P_{ICRH} = 3MW$ and with central line average density $ne/la = 1.65, 2.3$ and $2.8\times10^{19}\ m^{-3}$, respectively. Numerical simulation of these discharges with COREDIV is a real challenge due to:
i) The simplified geometry of the SOL in COREDIV ii) Strong coupling edge-core in the relevant temperature range iii) The significant level of the Ohmic power (about one third of the total input power) and iiii) last but not least, uncertainties in the value of some experimental data.

i) The SOL geometry in COREDIV is simplified (see Sect.2) and does not take into account details of the wall as the plasma limiters and ICRH-antennas' limiters. While for CFC surroundings the main carbon source is located at the divertor plates [3], for ILW the main source of Be is, indeed, located on the wall. A detailed description of the JET wall is therefore essential to derive quantitatively the Be fluxes, which, at the end, are responsible for W fluxes from the divertor plates in the relevant temperature range of these pulses (electron temperatute at the divertor plate, $T_{e\text{-plate}} < 50eV$). Indeed, W sputtering due to deuterium impact is negligible below 60÷70eV. First, we have taken the experimental divertor Be fluxes as a COREDIV input, and then we have slightly adjusted their values to match with the total radiated power.

ii) The electron density at the separatrix (n_{sep}) is taken in COREDIV as a free parameter to match, when available, with the experimental data. Due to the self-consistency of COREDIV, even a small change in $n_{\_sep}$ may lead to change in the density profile in the core as well as in the SOL, resulting also in changes in the electron density at the divertor plate, $n_{e\text{-plate}}$, and, consequently, in $T_{e\text{-plate}}$. This may lead, and does indeed lead for these pulses, to significant change in W sputtering and W concentration and radiation losses in the plasma core. Therefore the choice of n_{sep} should be made carefully, step by step, and, deedless to say, is very much time consuming. For these pulses, the egde Thomson scattering diagnostic was not operational, while from the Li-beam diagnostic the edge density profile could be measured only for two (out of three) discharges.

iii) Considering that for these pulses the Ohmic power (P_{OH} = 1.3-1.4MW) is about one third of the total input power (P_{tot} ~ 4.4MW) any change in the computed temperature and in Z_{eff} leads to not negligible changes in P_{tot}, which leads to further changes in Te profile, $T_{e\text{-plate}}$, W sputtering and so on. Again, due to the self-consistency of COREDIV, care should be used when fixing the code parameters to simulate low input-power pulses with the ILW.

iiii) Bolometric data is a matter of concern for these ICRF heated pulses since a localised radiation is seen in the plasma core in front of one of the radiofrequency antennas. This is possibly due to some interaction of the RF electric fields with the beryllium antenna's limiters which may cause significant release of beryllium. Therefore, in order to avoid overestimation of the radiated power, the horizontal channels of the bolometric system pointing at the RF antenna are not taken into account in the process of de-convolution. This, of course, leads to some increase in the level of uncertainty of the experimental data.

In Sect.2 a short description of the code COREDIV is given. Sect.3 is devoted to the comparison of the simulations with experimental data. In Sect.4, the discussion of the results is made and the conclusions are drawn.

2. THE CODE COREDIV

Since the energy balance depends strongly on the coupling between the bulk and the Scrape-Off Layer (SOL) plasma, modeling requires the transport problem to be addressed in both regions simultaneously.The physical model used in the COREDIV code is based on a self-consistent coupling of the radial transport in the core to the 2D multifluid description of the SOL. Since the model is relatively complex [1,4] we point out only the most important aspects, relevant to the present study. **In the core**, the 1D radial transport equations for bulk ions, for each ionization state of impurity ions and for the electron and ion temperature are solved. For auxiliary heating parabolic-like deposition profile is assumed and the energy losses are determined by bremsstrahlung, ionization and line radiation. The equation for the poloidal magnetic field has been neglected and thus the current distribution is assumed to be given in our approach. The electron and ion energy fluxes are defined by the local transport model proposed in ref.[6] which reproduces a prescribed energy confinement law. In particular, the anomalous heat conductivity is given by the expression $\chi_{e,i} = C_{e,i} \frac{a^2}{\tau_E} F(r)$ where r is the radial coordinate, a is the plasma radius, τ_E is the energy confinement time defined by the ELMy H-mode scaling law [7] and the coefficient ($C_e = C_i$) is adjusted to have agreement between calculated and experimental confinement times. The parabolic like profile function $F(r)$ can be modified to provide transport barrier. The main plasma ion density is given by the solution of the radial diffusion equation with diffusion coefficients $D_i = D_e = 0.1\chi_e$. The source term takes into account the attenuation of the neutral density due to ionization processes: $S_i = S_{i0}\, exp\left(\frac{a-r}{\lambda_{ion}}\right) r \leq a$, where λ_{ion} is the penetration length of the neutrals, calculated self-consistently. The source intensity S_{i0} is determined by the internal iteration procedure in such a way that the average electron density, obtained from neutrality condition, remains constant in time (input parameter). In consideration of the relatively low confinement ($H_{98(y,2)}$ is about 0.6) of the considered ICRF heated pulses with sawteeth, in the present simulations the radial impurity transport is described only by anomalous transport, without pinch.

In the SOL we use the 2D boundary layer code EPIT which is primarily based on Braginskii-like equations for the background plasma and on rate equations for each ionization state of each impurity species [8]. An analytical description of the neutrals is used, based on a simple diffusive model. COREDIV takes into account the plasma (deuterium and seeded impurities) recycling in the divertor as well as the sputtering processes at the target plates including deuterium sputtering, self-sputtering and sputtering due to seeded impurities. (For deuterium sputtering and tungsten self-sputtering the yields in ref. [9] are used). The recycling coefficient is an external parameter (in the present simulations it is determined by the level of the electron density at the separatrix, given as an input) and the energy losses due to interactions with hydrogenic atoms (line radiation, ionization and charge exchange) are accounted for in the model. A simple slab geometry (poloidal and radial directions) with classical parallel transport and anomalous radial transport ($D_i = \chi_i = 0.5\, \chi_e = 0.5 m^2/s$) is used and the impurity fluxes and radiation losses caused by intrinsic and seeded impurity ions are calculated fully self-consistently. The equations are solved only from the midplane to the divertor plate, assuming inner-outer symmetry of the problem. The standard sheath boundary conditions are imposed at the plate, whereas the boundary conditions are given by decay lengths (λ_n = 3cm, λ_T = 4cm) at the wall. The parallel velocities and the gradients of densities and temperatures are assumed to be zero at the midplane (stagnation point).

The coupling between the core and the SOL is made by imposing continuity of energy and particle fluxes as well as of particle densities and temperatures at the separatrix. The computed fluxes from the core are used as boundary condition for the SOL plasma. In turn, the values of temperatures and of densities calculated in the SOL are used as boundary conditions for the core module.

3. NUMERICAL RESULTS AND EXPERIMENTAL DATA.

In Fig.1 the experimental and simulated density and temperature profiles in the plasma core are shown for the three discharges considered. The density profiles have been numerically derived by setting the electron density at the separatrix $n_{e\text{-sep}}$ = 7.2, 4.5 and 2.9×10^{18} m^{-3} for the high, medium and low density discharges, respectively. These values are a little lower than the two values available from the Li-beam diagnostic (8.5 and 4×10^{18} m^{-3} for the high and low density discharge, respectively), but lead to more comparable simulated-experimental profiles in the core as well as to more consistent densities and temperature at the strike point, see below. The experimental-simulated density profiles match generally well**,** while some discrepancy is seen in the temperature profile. This is a consequence of the linear dependence (multiplicative factor, see Sect 2) in COREDIV between particle diffusivity and heat conductivity coefficients, implying recostructed steep edge temperature profiles when steep edge density profiles have to be numerically reconstructed. However, the influence of the numerical overestimation of the temperature profile has a moderate impact on the radiation patterns since Be radiates mostly in the SOL and W mostly for T_e around about 2keV. In Fig.2 *a)* the simulated and experimental D fluxes are shown for the three discharges considered and in Fig.2 *b)* the experimental and the COREDIV input (based on the experimental ones, please see Sect.1) Be fluxes. While the simulated-experimental D fluxes match well, the COREDIV input Be fluxes, although within the uncertentainties of measurements, are sistematically higher than the experimental ones. Setting lower Be fluxes in COREDIV input in order to match with the experimental ones, would lead to too low power radiated in the plasma core by W, see Figs.2 *c)* and 2 *d)* . On the other hand, Be fluxes higher in COREDIV input than in experiment (while the simulated power radiated matches well with the experimental one) are consistent with the presence in the real discharge of no negligible amount of other light impurities as C and O, which normally lead to further release of W from the divertor. In fact, in the present COREDIV simulations, only C is considered and the C flux is set to be at very low level: only about 10% the of Be flux.

The substantial agreement of simulated-experimental power radiated is correlated with the very good match between simulated and experimental W concentration in the core, see Fig.3 *a)*. (It is worth noticing that for these disharges the COREDIV calculated W self-sputtering is a significant fraction of the total W sputtering). Indeed, in the relevant range of temperature, only W ions are responsible for the power radiated in the plasma core. It has to be pointed out that the observed decrease of P_{rad} with increasing density is not a general trend of the ILW plasmas, but apply only to these ICRF heated discharges and it is possibly correlated to specific-radiofrequency effects, see below.

Measurements of the absolute W fluxes are not available so far, but the ratios of the intensities (in a.u.) of the WI line at λ = 400.9nm for the three pulses considered are quite compatible with the ratios of the COREDIV calculated W fluxes, which are in the range of a few 10^{19} particles/s. Some problems arise, however, by the comparison of the simulated with the experimental Z_{eff}, see Fig.3 *b)*. Although the experimental Z_{eff} has been derived from the horizontal chord of the bremsstrahlung diagnostic which generaly leads in JET to lower Z_{eff} values than that from the vertical one, the simulated Z_{eff} is significantly lower than the experimental one for the two pulses at lower density. In the present contest only higher input fluxes of Be and/or of other light impurities would cause the increase of Z_{eff} in COREDIV, but this would also lead to the increase in the W sputtering and, consequently, in the power radiated. At present, we do not have an explaination for this anomaly, which, however, on a speculative basis and partly in agreement with bolometric observations, would be consistent with radiofrequency-specific effects. Indeed, the coupling of radiofrequency-power with the plasma is generally rather weak at low electron density and this normally leads to interactions of the electric fields with the antennas' limiters, causing release of Be. This Be flux enters directly the plasma core affecting significantly Z_{eff}, but only marginally the power radiated. On the other hand it should be pointed out that Be transport might be different depending on the position where Be is released from (different screening, for example) while for these three pulses the same impurity transport is assumed in COREDIV.

The experimental electron temperature at the strike point, T_e_plate, measured with probes, is higher on the outer divertor than on the inner one, while the electron density, n_e_plate, is lower on the outer divertor. In Figs. 3 *c)* and 3 *d)* the experimental T_e_plate and n_e_plate measured at the outer divertor are shown together with COREDIV results. It is difficult to compare COREDIV results with experimental measurements on one of the two divertor legs, and this comparison has to be considered more from a qualitative point of view than quantitatively. However, the data in Figs. 3 *c)* and 3 *d)* show that we are dealing with similar values and trends, thus contributing to the overall consistency among edge parameters.

DISCUSSION AND CONCLUSION.

In contrast with previous COREDIV simulations with carbon divertor plates in which the action of the ELMs can be averaged in time without loss of generality, in the case of W plate the role of ELMs might be essential in determining the global W release. That is the reason we started the simulation of JET plasmas with the ILW by choosing pulses at low input power, ELMy free.

On the one hand the simulation of low power ICRF heated JET pulses allow the use of the standard COREDIV version without ELMs, but on the other hand ICRH pulses show a number of radiofrequency-specific effects (as the release of impurities from the antennas' limiters and/or from other surfaces) which can not be simulated with COREDIV due to the slab geometry of the SOL. However, with the relevant exception of Z_{eff}, the overall comparison simulation-experiment is rather satisfactorily, both in the core and in the SOL. To this point it has to be stressed that the Be fluxes on the divertor target are not calculated self-consistently with the plasma parameters, but are given as input in COREDIV, partly according to the experimental Be fluxes and partly to the level of the power radiated.

In conclusion, the results above reported show that, in spite of the limitations related to the slab geometry of the SOL of COREDIV and of those related to the self-consistent simulation of complex and strongly inter-dependent systems like JET plasmas with the ILW, the most relevant critical issues have been solved, leading to the accomplishment of the first step towards the integrated numerical modelling of JET plasmas with the ILW.

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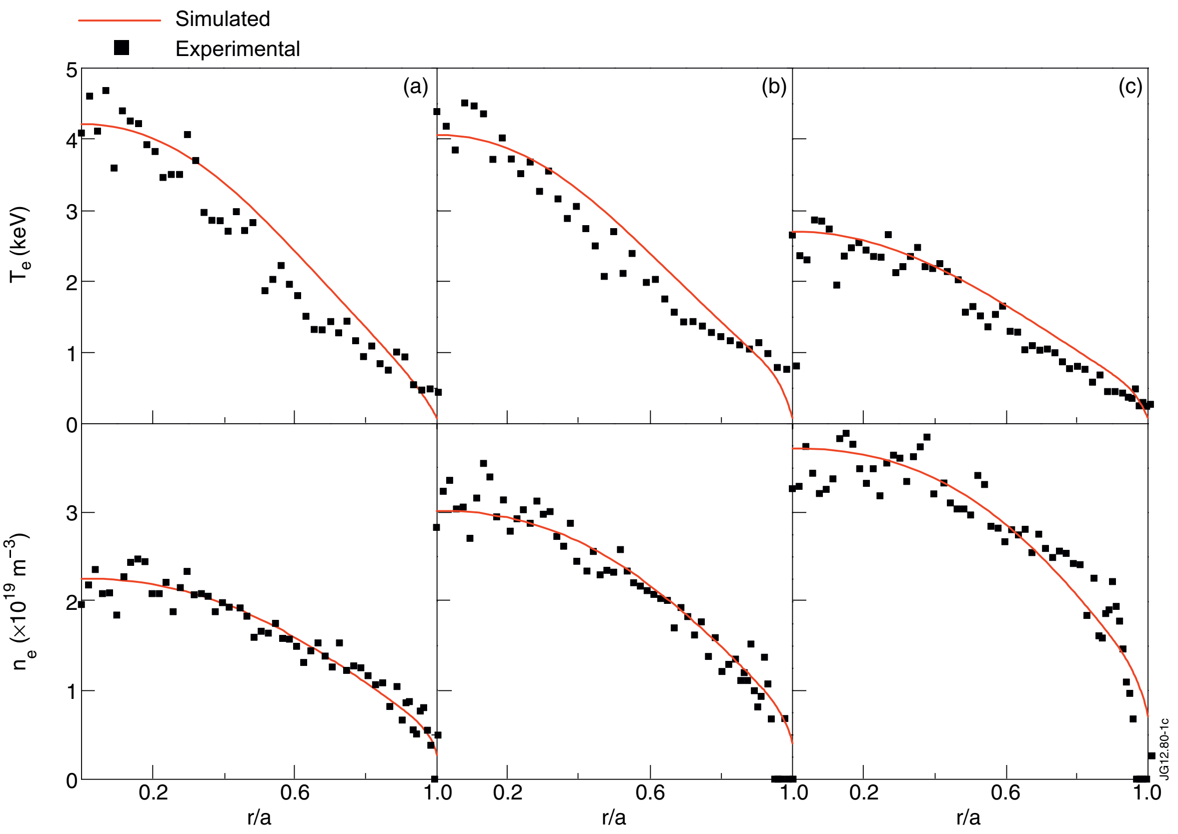

Figure 1: Electron temperatute (top) and density (bottom) profiles from HRTS diagnostic and from COREDIV simulations as function of the normalized minor radius. From left to right: JET Pulse No: 80896 @ t = 19.5s, JET Pulse No: 80889 @ t = 19.5s, JET Pulse No 80893 @ t = 19.5s.

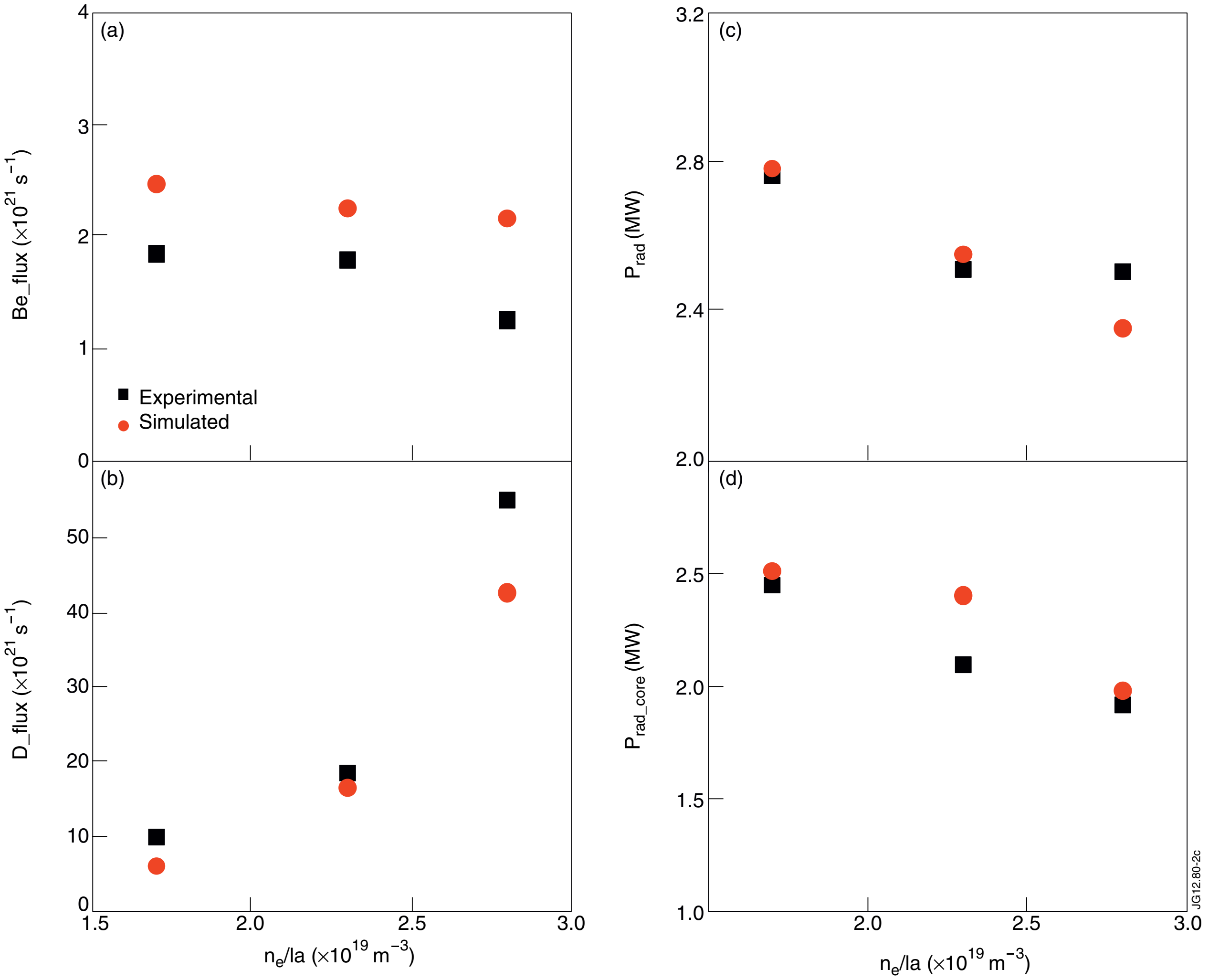

Figure 2: a) Experimental and simulted D fluxes, b) experimental and COREDIV input Be fluxes, c) experimental and simulated total radiated power, d) power radiated inside the separatrix for the three discharges considered, labelled according to their line average density, ne/la.

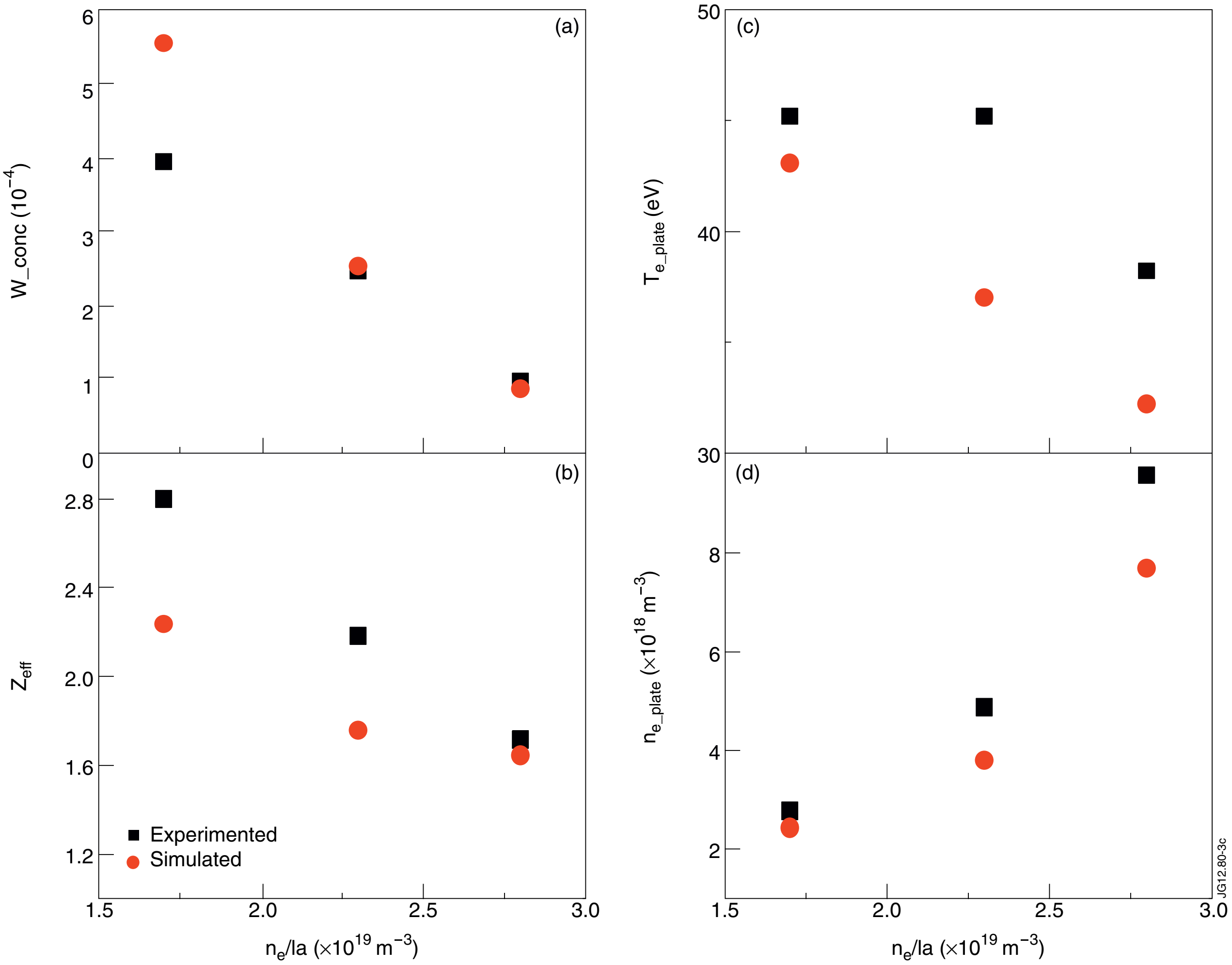

Figure 3: a) Experimental and simulated W concentration, b) experimental and simulated Z_{eff}, c) experimental electron temperature measured at the outer strike point and simulated with COREDIV, d) experimental electron density measured at the outer strike point and simulated with COREDIV for for the three discharges considered, labelled according to their line average density, n_e/la.