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ABSTRACT
In this paper numerical simulations with COREDIV code of JET discharges with ITER-like wall are presented. We concentrate on the JET H-mode and hybrid scenarios with nitrogen seeding and all simulations have been performed with the same transport model and only the discharge input parameters like auxiliary heating P_{aux}, line average plasma density n_e^{lin}, confinement factor H98, nitrogen input flux Γ_N^{puff} were changed in the calculations. The separatrix density n_e^{sep} is an input parameter in our model and has been kept equal to $0.4 \div 0.5 n_e^{lin}$ in the simulations, with the recycling coefficient adjusted accordingly. It has been shown that COREDIV is able to reproduce basic parameters of nitrogen seeded discharges for both H-mode and hybrid scenarios. We have achieved reasonable agreement with global plasma parameters like radiations levels, Z_{eff} and tungsten concentrations and the plasma profiles, including density, temperature and radiation are in very good agreement with experimental data. The agreement of the code results with the experimental data might be even better, if the simulations are further tuned taking into account uncertainties to the sputtering model, separatrix density or SOL transport. Simulations show that the observed Z_{eff} level is defined mostly by the low Z impurity content, Be and N_2 in the considered shots. It has been found that the tungsten radiation plays always very important role and can not be mitigated even by strong influx of nitrogen.

1. INTRODUCTION AND PHYSICAL MODEL
Impurities released from interactions between plasma and material surfaces can lead to major effects on plasma behaviour in tokamaks. This is in particular true for JET experiments with the new ITER-like wall (ILW) configuration (ILW: Beryllium wall + W divertor), which show that the plasma performance is strongly affected by tungsten impurity [1]. In view of possible realistic prediction for ITER plasma scenarios, it is necessary to developed validated numerical tools. For this aim, COREDIV code [2] has been constructed, which self-consistently couples the plasma core with the plasma edge and the main plasma with impurities. The code was in the past succesfully benchmarked against a number of JET discharges with carbon plates and impurity seeding [2–4] 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}. The model has also been applied for ASDEX-U discharges in the full tungsten machine environment [4] and more recently, first results for L-mode pulses of JET ILW configuration has been presented is Ref.[6].

In this paper numerical simulations with COREDIV code of JET discharges with ITER-like wall for H-mode and hybrid scenarios with nitrogen seeding are presented. Since the energy balance in tokamaks with metallic walls depends strongly on the coupling between bulk and the SOL plasma, joint treatment of both regions is necessary. Therefore the physical model used in the COREDIV is based on a self-consistent coupling of the radial transport in the core to the 2D multifluid description of the scrape-off layer (SOL) and has been already presented elswhere [2, 4–6, 8]. 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 paraboliclike deposition profile is assumed and the energy losses are determined by Bremsstrahlung, ionization and line radiation. The energy and particle transport are defined by the local transport model proposed in Ref. [7] which reproduces a prescribed energy confinement law. In the SOL, the 2D fluid equations are solved in the simplified slab geometry but taking into account plasma recycling in the divertor and sputtering processes due to all ions (D, Be, N_2, W) at the target plate.

2. MODELLING RESULTS FOR H-MODE AND HYBRID SCENARIO

In this paper, we concentrate on the JET H-mode and hybrid scenarios with nitrogen seeding. We note that all simulations have been performed with the same transport model and only the discharge input parameters like auxiliary heating P_{aux}, line average plasma density n_e^{lin}, confinement factor H_{98}, nitrogen input flux Γ_N^{puff} were changed in the calculations. The separatrix density n_e^{sep} is an input parameter in our model and has been kept equal to $0.4 \div 0.5 n_e^{lin}$ in the simulations, with the recycling coefficient adjusted accordingly. The input power has been split between electrons and ions, as 3/1.

The code was run in a steady-state mode neglecting fast phenomena like e.g. ELM's. This corresponds to the experimental results averaged over energy confinement time and seems to not impose strong limitations on the code-experiment comparison.

Results of simulations of two series of JET H-mode discharges with different level of auxiliary power are considered first and the comparison of global parameters with experimental data is shown in the Table 1 for Pulse No's: 82031 and 82033 (I_p = 1.98MA, B_T = 2.18T) with P_{aux} = 10.8MW whereas in the Table 2 we present Pulse No's: 83178–80 (I_p = 2.47MA, B_T = 2.7T) with P_{aux} = ~17MW. Here P_{rad}^{core} is the core radiation (mostly by tungsten), P_{rad}^{tot} is the total radiation, n_e^{lin} is line average plasma density (experimentally measurement by HRTS diagnostic) and c_W is the volume averaged tungsten concentration.

The beryllium flux from the wall has been assumed to be equal to $\Gamma_{Be} = 2\times10^{20}\ s^{-1}$ for the low power shots and to be proportional to the particle flux crossing the separatrix with the proportionality coefficient equal to 0.8 for all other shots in order to reproduce the low Z impurity level.

For the low power shots (Table 1) the comparison with the experimental data is very good whereas for high power H-mode discharges (Table 2) there is some discrepancy when comparing all radiations and the Z_{eff} values. We note also that the experimental values of the nitrogen influx (Γ_N^{puff}) are usually larger than in simulations since in latter case all the gas goes to the plasma which is not necessarily true for experimental situation (a significant part of the gas might be lost to the wall not reaching the plasma). The simulated Z_{eff} is lower than the experimental value for two Pulse No's: 83179-83180, but simultaneously the total radiation is correct in contrast to the Pulse No: 83178, when Z_{eff} is correct but the total radiation is higher in the experiment, however the radiation in the core is similar to the experimental one.

The situation is different for JET hybrid scenarios with high additional power and strong nitrogen seeding (Pulse No's: 83568, 83570; I_p = 1.68MA, B_T = 1.975T). In this case, measured values of

Z_{eff} and total radiated power are very well reproduced by simulations, but there is some difference between simulations and experiment regarding power radiated in the core as it can be seen from Table 3. We note, that W concentration for hybrid scenarios is much higher than for H-mode shots mostly due to the lower plasma density and stronger heating.

That means that in spite of very strong seeding, the tungsten radiation remains important energy loss channel. In Figs.1-3, the experimental and simulated electron density and temperature profiles are shown for Pulse No's: 82031, 83179 (H-mode) and 83570 (hybrid scenario), respectively. It can be seen that radial profiles are nicely reproduced by the code. We note also, that in the considered shots tungsten accumulation is not observed which is consistent with our assumption, that the impurity transport is dominated by anomalous contribution.

This assumption is also consistent with the radiation distribution as it can be seen from Figs.4-6 where experimental and simulated radiation profiles in the plasma core are shown for H-mode shots (Pulse No's: 82031, 83179) and hybrid scenario (Pulse No: 83570), respectively. The calculated radiation profiles agree relatively well with the experimental data showing strong contribution of tungsten to the radiation losses. Radiation losses due to nitrogen are important only very close to the separatrix.

It is important to note that in all considered shots tungsten radiation in the core is the dominant energy loss mechanism, which is good correlation with JET experimental results showing that the JET plasma performance is strongly affected by tungsten impurity [1]. This is even true for strongly seeded hybrid Pulse No: 83570 (Γ_N^{puff} 3 510^{22} el=s for which 37% of the radiated power is still due toW. For this particular case, COREDIV simulations indicate semi-detached conditions in the divertor, with the plate temperature $T_e^{plate} \approx 2$eV but still with significant tungsten production by N ($\Gamma_W = 6.64 \times 10^{19}$ s^{-1}).

3. SENSITIVITY ANALYSIS

As already mentioned, in some cases it is difficult to fit by COREDIV simulations all the experimental global parameters like radiations and Zeff simultanously. It can be attributed to the assumptions made in the model as well as to the unknowns related to the experimental data. It is important to know for example what is the role of sputtering model used in the code and in particular the effect of prompt redeposition on the results. Certainly plasma parameters in the SOL, like separatrix density, deuterium puff or radial transport have influence on tungsten retention and in consequence on core parameters. In order to understand the reason for the differences between experimental and computation results, we have performed numerical studies to see which parameters have strong influence on the plasma parameters, in particular on the radiation level and its distribution.

3.1 INFLUENCE OF THE SPUTTERING COEFFICIENT

It is believed that in case of tungsten, the prompt redeposition might strongly reduce effective sputtering yield. Therefore, simulations have been performed to check sensitivity of the results on the total sputtering yield. For this aim, the sputtering yield due to all ions was reduced by factor:

0.3, 0.24, 0.18 and 0.06 in comparison to the standard model (first row in the table) and the results are presented in Table 4. It can be seen, that the reduction of the sputtering coefficient leads as expected to the smaller tungsten production and in consequence to the reduction of the core and total radiation. However, the effect is rather moderate, since the change of the sputtering yield by factor ~17, reduces W concentration 4 times, core radiation by factor 3 and total radiation only by 1.5. The reason is such that the reduction of the sputtering yield is compensated by the increase of the plate temperature due to self-regulating mechanism coupling efficiently W production in the SOL with tungsten radiation in the core. In addition, sputtering yield has almost no influence on the effective charge and SOL radiation.

3.2 INFLUENCE OF THE RADIAL TRANSPORT

We have also checked the influence of the radial transport in the SOL on the overall plasma performance. In the Fig.7, we present main plasma parameters versus radial diffusion coefficient.

It can be seen that larger diffusion leads to the better screening of W impurity by SOL plasma leading to the reduction of the core W concentration radiation as well as Z_{eff} . However, the effect is relatively small, 3 times higher D_{perp} leads only to 25% reduction of the core radiation.

3.3 INFLUENCE OF THE NITROGEN PUFF LEVEL AND THE SEPARATRIX DENSITY

In the figure 8 we present scan with nitrogen gas puff for hybrid scenario with input parameters fixed for the Pulse No: 83570 and with three different density values at the separatrix. The initial increase of the N_2 influx ($\Gamma_N^{puff} < 1\times10^{21}$ 1/s) leads to strong increase of the tungsten concentration and consequently core radiation as a result of increased tungsten production. However, for higher fluxes ($\Gamma_N^{puff} > 1\times10^{21}$ 1/s) the changes to the core parameters are rather weak. This is the result of a self-regulating mechanism being a specificfeature of tungsten (metallic) targets. This mechanism regulates the tungsten production due to sputtering processes at the target plates by radiative cooling of tungsten ions in plasma centre. Since the radiation efficiency of tungsten is very high and simultaneously the dependence of the sputtering yield on the temperature (incident ion energy) is very steep the equilibrium between production and radiation appears at temperature values very close to the sputtering threshold (in this case for nitrogen). The SOL radiation increase linearly with gas puffing reducing effectively power to the targets. For the highest seeding levels, semi-detached conditions are achieved in divertor with (T_e^{plate} <3eV). The separatrix density being the code input parameter appears to be a very important quantity controlling the SOL plasma properties. In the self-consitent simulations its effect is however limited mostly to the changes in the screening efficiency of the SOL, which leads to the better confinement of W ions in the edge and consequently to lower radiation losses in the core.

CONCLUSIONS AND DISCUSSION

The COREDIV code has been used to simulate JET discharges in the new ITER-like wall configuration. The focus has been put on auxiliary heated H-mode and hybrid scenarios with nitrogen seeding. The work was motivated by the need to develop validated numerical tool which can be used for fast analysis of the experimental data and for prediction of future experiments, in particular with extensive level of auxiliary power and seeding. It has been shown that COREDIV is able to reproduce basic parameters of nitrogen seeded discharges for both H-mode and hybrid scenarios. We have achieved reasonable agreement with global plasma parameters like radiations levels, Z_{eff} and tungsten concentrations and the plasma profiles, including density, temperature and radiation are in very good agreement with experimental data. The agreement of the code results with the experimental data might be even better, if the simulations are further tuned taking into account uncertainties to the sputtering model, separatrix density or SOL transport. Simulations show that the observed Z_{eff} level is defined mostly by the low Z impurity content, Be and N_2 in the considered shots. It has been found that the tungsten radiation plays always very important role and can not be mitigated even by strong influx of nitrogen. The first simulations for seeded plasmas indicate the existence of the limited range of accessible N gas puff levels which might impose restrictions on the JET operational domain. This problem is however outside the scope of this paper and will be subject of future publications.

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JET Pulse No:	P_{aux} [MW]	τ_E [sec]	Z_{eff}	P_{rad}^{core} [MW]	P_{rad}^{tot} [MW]	Γ_N^{puff} [$\times 10^{22}$ el/s]	n_e^{lin} [$\times 10^{19} m^{-3}$]	c_W $\times 10^{-5}$
82031	10.8	0.31	1.36	3.10	5.4	1.1	6.34	1-2
COREDIV	11	0.30	1.26	2.3	5.51	1.05	6.8	1.36
82033	10.8	0.34	1.26	2.1	5.0	1.6	7.1	1-2
COREDIV	11	0.30	1.26	2.46	5.88	1.05	7.34	1.19

Table 1: The experimental and simulated global plasma parameters for Pulse No's: 82031 and 82033.

JET Pulse No:	P_{aux} [MW]	τ_E [sec]	Z_{eff}	P_{rad}^{core} [MW]	P_{rad}^{tot} [MW]	Γ_N^{puff} [$\times 10^{22}$ el/s]	n_e^{lin} [$\times 10^{19} m^{-3}$]	c_W $\times 10^{-5}$
83178	16.7	0.32	1.46	3.54	6.31	3.03	7.23	~3.5
COREDIV	17	0.29	1.41	3.78	8.7	1.05	8.17	1.52
83179	16.7	0.34	1.36	4.13	7.8	1.54	7.9	-
COREDIV	17	0.29	1.18	4.66	7.88	0.35	8.26	2.2
83180	17	0.32	1.33	4.38	6.8	0.78	7.8	~2.1
COREDIV	17	0.32	1.12	3.14	6.71	0.35	8.26	1.38

Table 2: The experimental and simulated global plasma parameters for Pulse No's: 83178-80.

JET Pulse No:	P_{aux} [MW]	τ_E [sec]	Z_{eff}	P_{rad}^{core} [MW]	P_{rad}^{tot} [MW]	Γ_N^{puff} [$\times 10^{22}$ el/s]	n_e^{lin} [$\times 10^{19} m^{-3}$]	c_W $\times 10^{-5}$
83568	25.7	0.16	2.51	~5	17	6.2	6.77	
COREDIV	24	0.17	2.5	11	17.25	2.8	6.79	9.01
83570	20.5	0.17	3.07	5.1	15.7	4.9	6.46	
COREDIV	20.5	0.15	2.94	7.6	14.7	3.3	6.86	6.65

Table 3: The experimental and simulated global plasma parameters for hybrid regime.

Sput. coeff.	c_W [10^{-5}]	Z_{eff}	T_e^{plate} [eV]	P_{rad}^{tot} [MW]	P_{rad}^{core} [MW]
1	1.96	1.14	5.62	5.63	2.92
0.3	1.72	1.13	5.95	5.3	2.62
0.24	1.49	1.11	6.13	5	2.33
0.18	1.22	1.11	6.27	4.64	1.98
0.06	0.5	1.11	7.25	3.66	1.05

Table 4: The caption inside a table environment.

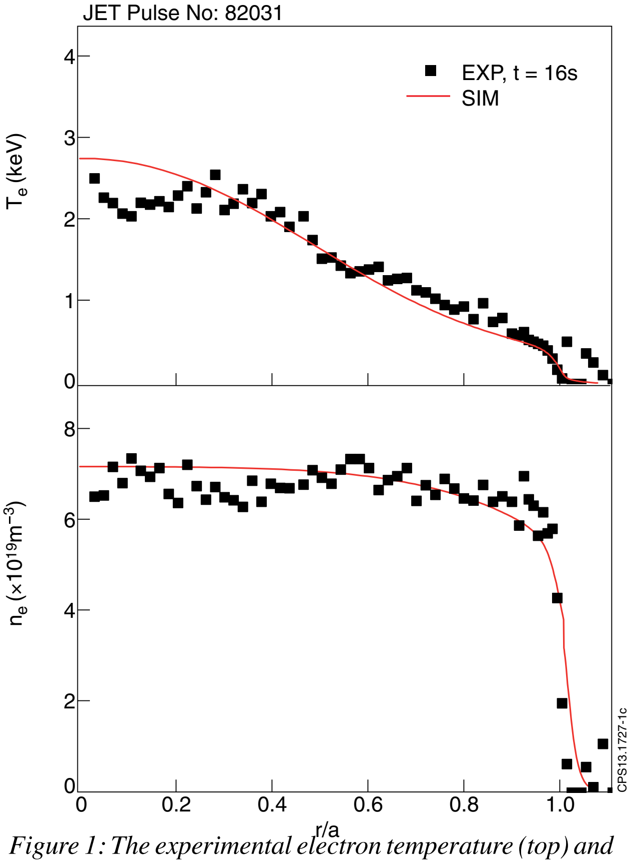

Figure 1: The experimental electron temperature (top) and density (bottom) profiles from HRTS diagnostic at different time and from COREDIV simulations, as function of the normalized minor radius for Pulse No: 82031.

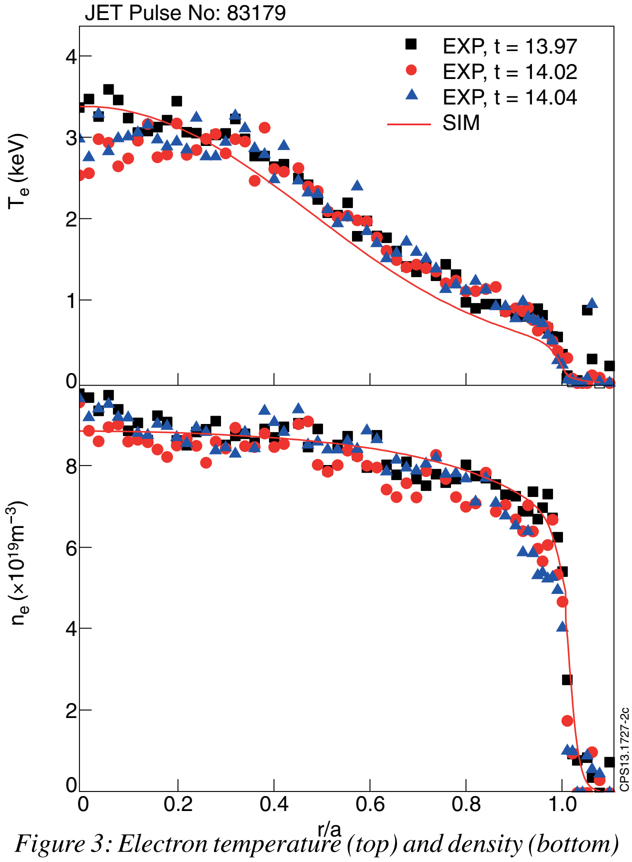

Figure 3: Electron temperature (top) and density (bottom) profiles from HRTS diagnostic at different time and from COREDIV simulations, as function of the normalized minor radius for Pulse No: 83179.

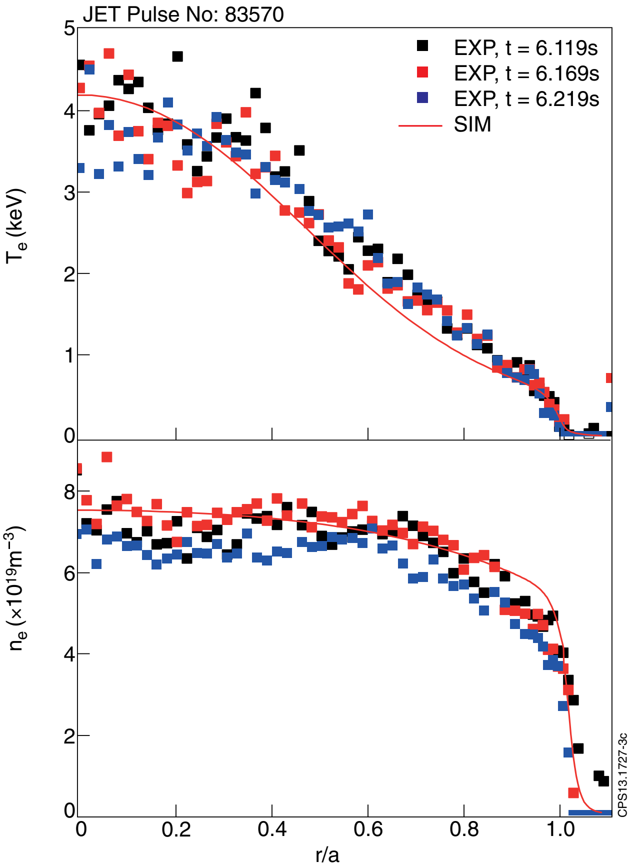

Figure 3: Electron temperature (top) and density (bottom) profiles from HRTS diagnostic at different time and from COREDIV simulations, as function of the normalized minor radius for Pulse No: 83570.

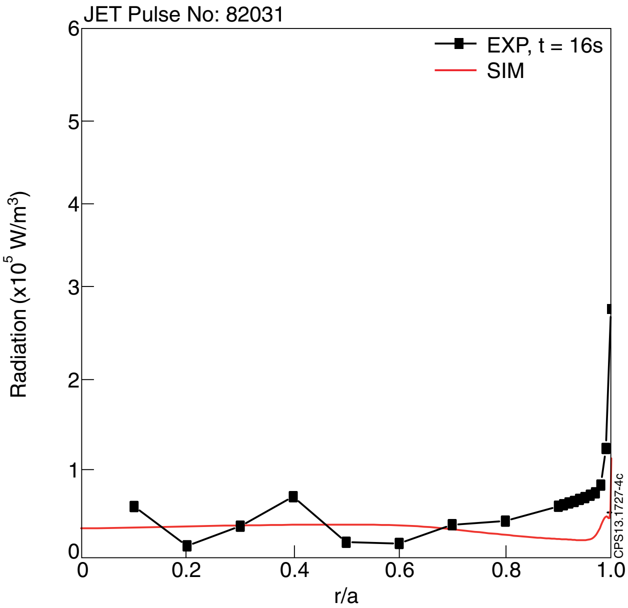

Figure 4: The experimental electron temperature (top) and density (bProfile of the radiation at t =16s for Pulse No: 82031.

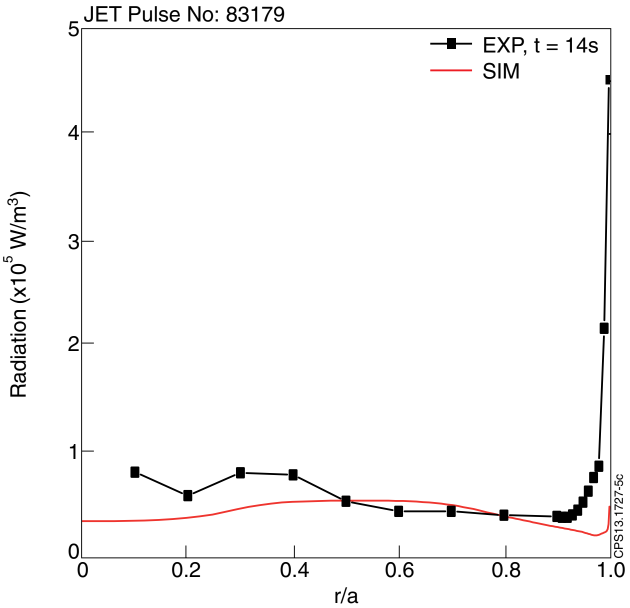

Figure 5: Profile of the radiation at t = 15s for Pulse No: 83179.

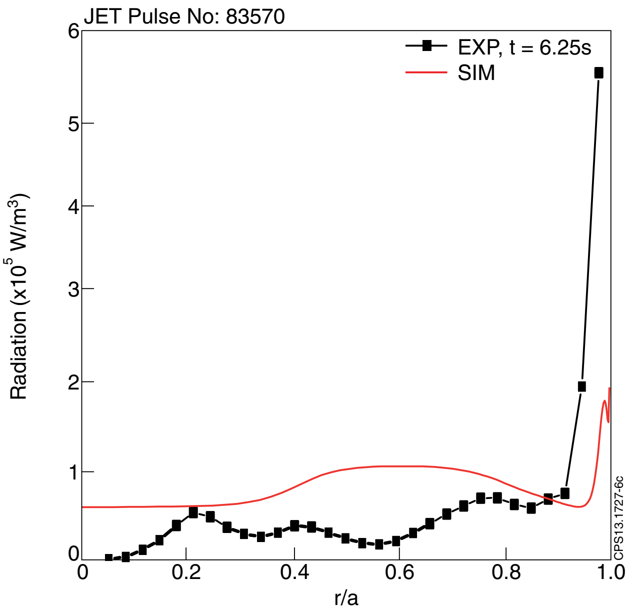

Figure 6: Profile of the radiation at t = 6:25s for Pulse No: 83570.

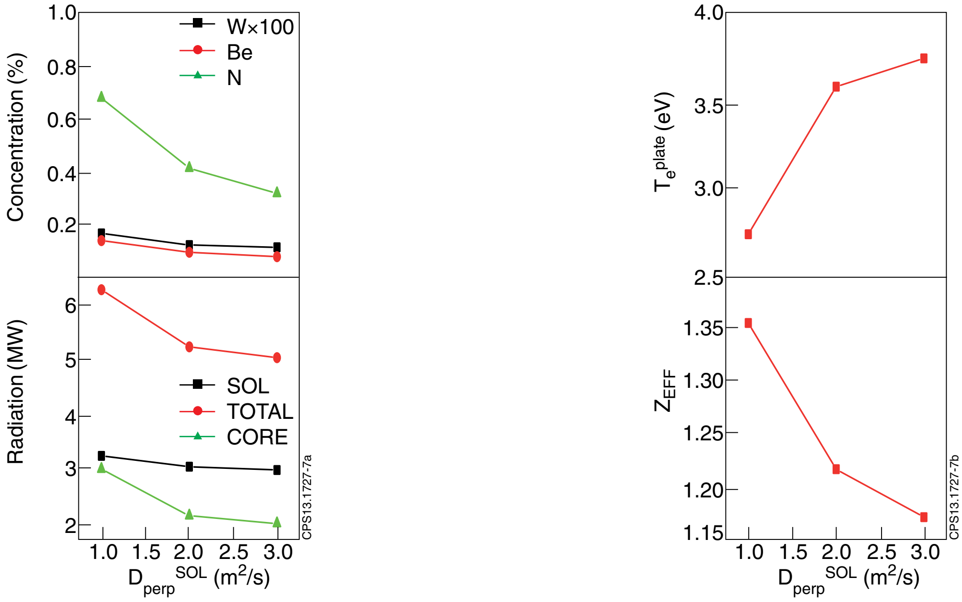

Figure 7: Plasma parameters for different radial diffusion coefficient in SOL (D_{perp})

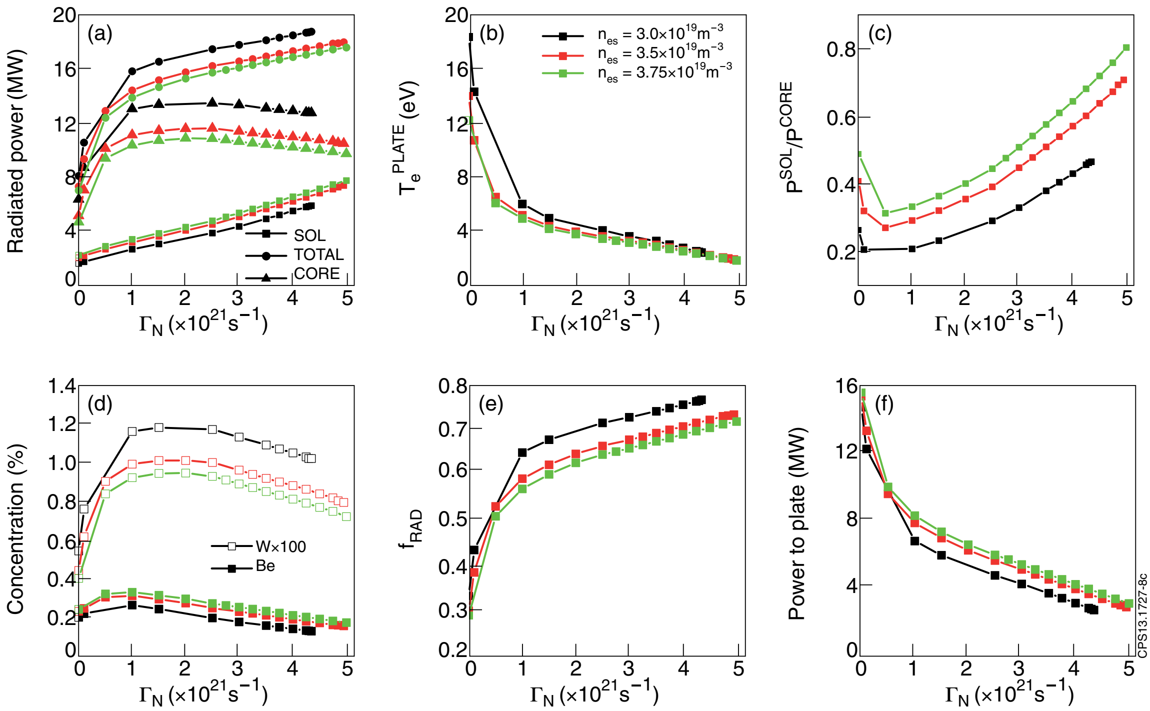

Figure 8: Hybrid regime: plasma parameters versus nitrogen gas puff for three different electron density on the separatrix electron density is $n_{sep} = 3.0\times10^{19}\ m^{-3}$ (black line), $n_{sep} = 3.5\times10^{19}\ m^{-3}$ (red line)$n_{sep} = 3.75\times10^{19}\ m^{-3}$ (green line): total (circle simbols), core (square simbol) and SOL (triangle) radiation (a), electron temperature at the plate (b), radiation SOL/CORE (c), W and Be concentration (d), radial fraction (e), power to plate (f).