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R. Zagórski, I. Ivanova-Stanik, A. Czarnecka, G. Telesca,
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R. Zagórski[1], I. Ivanova-Stanik[1], A. Czarnecka[1], G. Telesca[2], S. Brezinsek[3] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Institute of Plasma Physics and Laser Microfusion, EHery Str. 23, Warsaw, Poland
[2]Department of Applied Physics, Ghent University, Plateaustr. 22, B-9000 Gent, Belgium
[3]IEK-4, FZ Jlich GmbH, Association EURATOM-FZJ, TEC, Jlich, Germany
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ABSTRACT

This paper describes integrated numerical modelling applied to JET ITER-like wall H - mode discharges using the COREDIV code, which self-consistently solves 1D radial transport of plasma and impurities in the core region and 2D multi- fluid transport in the SOL. In this paper we focus on sensitivity studies to give insight on the influence of different code input parameters on the simulations results. Simulations show, that for a given power and density value, there is always a limit on the seeding level, above which the self-consistent solution does not exists. This limit seems to be related to the edge density limit and might impose severe consequences on the accessible JET operational domain. Therefore, numerical investigations have been done to check how this limit can be released. It has been found that changes in the edge density, and in particular in the SOL transport can somehow mitigate this effect.

1. INTRODUCTION AND PHYSICAL MODEL

In order to contribute to characterize and understand the operational space of JET plasmas with the ITER-like wall, series of numerical scans have been performed with the self-consistent transport code COREDIV [1], which has been successfully benchmarked with a number of JET discharges, including the nitrogen seeded type I and type III ELMy H-mode discharges [2, 3] and recently, JET ILW configuration [4]. COREDIV has also been applied to ASDEX discharges in the full W environment [5]. 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 [1–7]. 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 energy and particle transport are defined by the local transport model proposed in [8] 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. It should be pointed out that only stationary solutions are considered and all the time dependent phenomena, like production as well as flushing out of W ions due to ELMs is not accounted for in the model. In this sense, the sputtered W fluxes should be treated as averaged in time (over 1–2-sec) and comparison with experiment is valid only for steady state discharges. The model, provides, from a number of inputs like the heating power, the average density and the confinement enhancement factor H_{98} , the core temperature and density profiles, the effective ion charge Z_{eff}, the power radiated, the W flux and concentration and the plasma parameters in the divertor. We have already simulated nitrogen seeded JET ILW discharges, where we found some discrepancies between the experimental results and simulations [9] and related them to the input assumptions. Therefore in the present paper, we focus on sensitivity studies to give insight on the influence of different input parameters on the simulations results. Extended series of simulations have been done to show the influence of input power level and plasma density on JET plasma parameters for different levels of nitrogen seeding and comparison to experimental data has been done.

2. RESULTS OF CALCULATIONS AND DISCUSSION

The main aim of these COREDIV numerical studies of JET-ILW experiments was to check whether we can achieve highly radiating plasmas with strong mitigation of the heat loads and tungsten production. The most important tool to achieve this goal should be impurity seeding, which is expected to lead to strong edge radiation and tungsten production mitigation but unfortunately it is not always the case, at least with the tungsten divertor. In the Figure 1, we show results of extended numerical studies for nitrogen seeding for different input powers and plasma densities with the basic input parameters as for the JET shot Pulse No: 83175 ($B_t = 2.7T$, plasma current $I_p = 2.47MA$, $H_{98} = 0.75$). We have run the code assuming the same ratio between the edge and average density $n_{es} / \langle n_e \rangle = 0.57$ and the transport in the SOL was fixed with radial diffusion $D_\perp = 0.25m^2/s$. In COREDIV, we have found that for every power and density value, there is always a maximum impurity seeding level above which no steady state solution exists. In the Figure 1, the maximum allowed nitrogen influx versus heating power, and for different plasma densities is plotted. This maximum value determines somehow the accessible JET operational domain. The allowed seeding level increases with the input power and decreases with plasma density. The Γ_{puff} limit is due to the edge density/radiation limit [10] or/and radiative collapse. It should be stressed that for low input powers the JET operation is only possible with relatively low density.

POWER AND DENSITY SCANS

In the following, we present the results of the power and density scans in more details. Different plasma parameters versus nitrogen influx for different plasma densities $\langle n_e \rangle = 7 \div 10 \times 10^{19} m^{-3}$ (Figure 2) and for different values of the heating power $P_{aux} = 13 \div 30MW$ (Figure 3) are shown. It can be seen that the radiation fraction ($f_{rad} = P_{rad}^{tot} / P_{aux}$) (Figures 2a and 3a) weakly depends on the input power, plasma density and even seeding levels, at least for $\Gamma_N > 10^{21} part/s$. The core radiation ($P_{core}$) (Figures 2b and 3b), being in principle tungsten radiation is almost independent on the seeding level, after initial increase for $\Gamma_N < 10^{21} part/s$. However, it depends strongly on the plasma density and heating power since they mostly determine the W production rate. In particular, tungsten production can be strongly mitigated by the plasma density (Figure 2b). Regarding the ratio between SOL and core radiations (Figures 2c and 3c), it is large only for low power and high density discharges and weakly depends on the seeding level. Z_{eff} is almost linear function of the seeding level and independent on the plasma density and power levels (from 1.1 to 2.3), whereas the power to the plate (P_{plate}) is independent on the plasma density and as expected reduced with the increased seeding (not shown here). The maximum radiation fraction found in the simulations is up to 80% and this level is consistent with the recent JET ILW experimental results (in the M3-17 campaign)[11]. It should be noted also that in the current JET-ILW configuration carbon plays no role, as the fraction of C in the ILW plasma is negligible and the baseline level of Z_{eff} is of the order 1.2.

SENSITIVITY ANALYSIS

It has been mentioned already that there is a maximum seeding level which can be applied. We have performed some studies in order to analyze how this limit can be released and to check how much the results are sensitive to some model assumptions like edge density, radial transport in the SOL or impurity type. It appears that seeding limit can be influenced by plasma density, as seen from Figure 2 as well by the heating power Figure 3. It can be regulated also by changes in the edge density, and in particular the SOL transport can an effect on it. This limit is also influenced by the type of the seeded gas. In Figure 4, the influence of both, the edge density (n_{es}) and radial transport in the SOL ($D_{\perp}$) on the plasma radiations is shown. Observed changes are related mostly to the improvement of the screening efficiency of impurity ions with higher density or increased transport. The increase of n_{es} leads to the reduction of tungsten concentration and corresponding P_{core} is also reduced. The SOL radiation increases but not strong enough to compensate reduction of P_{core} and consequently P_{rad}^{tot} is reduced as well. Similarly, higher $D_{\perp}$ improves confinement of impurities in the SOL and as consequence, we observe reduction of the core radiation being the effect of the reduced W concentration, which leads to the reduction P_{rad}^{tot}. It is important to note, that much more energy can be radiated in the SOL with the increased transport or increased edge density, which indicates that strong deuterium puffing might be beneficial for seeded discharges, since it increases the edge density and plasma colisionalty.

It appears that in the JET ILW configuration, the impurity seeding regulates the tungsten production. It can be seen in Figure 5 that with the increase of the seeding, the W flux increases first and next it is reduced with agreement with experimental observations [13]. The roll over begins when the W production starts to be reduced due to cooling effect of seeded impurity. Initially, seeding increases the W influx, because of the additional source due to the heavy ions (in comparison with D) impinging on the W target. It should be stressed however, that the the picture is only qualitative, as the W source is plotted against the electron temperature at the strike point, which does not determine the W source directly. There is a temperature profile along the plate and the maximum of the W flux is shifted away from the strike point (at least for high seeding levels). In fact, temperature at the strike point is usually the lowest for the high density plasmas in divertor.

Plasma radiation depends also on the impurity type, however the influence is not strong. In Figure 6, plasma radiations obtained from COREDIV simulations are shown for different seeding gases. It should be pointed out, that only with nitrogen the core radiation starts to be reduced at some seeding level. Since Ar and Ne radiate also in the core, there is always increase of the core radiation with those gasses which can have negative effect on the L-H transition and H-mode operation. According to our simulation results, argon seems to be the strongest radiator for the JET plasmas, whereas there is almost no difference in the radiation levels of nitrogen and neon. This code prediction is not yet fully confirmed by experimental results however, as only with nitrogen radiation fractions up to 75% are achieved [11]. Other gasses can not reach that level yet, which might be related to the degradation of confinement due to the increase of the core radiation for Ne and Ar.

JET SEEDING EXPERIMENTS

Here, few simulation results related to JET experiments aiming on achieving maximum radiation fraction with seeding will be presented. More information on the comparison of the COREDIV results with the JET ILW seeded discharges can be found in the Ref. [14]. In Figure 7, experimental radiations versus Z_{eff} level are shown together with the simulations results for N_2 seeding. It can be seen, that the experimental P_{core} weakly depends on the seeding level in agreement with the simulation results, whereas P_{rad}^{tot} increases with the seeding as a results of the increase of the SOL radiation. For nitrogen seeding, the experimental total radiation values are sometimes slightly larger than in the modelling. This larger radiation might be, as discussed above, recovered in simulations by increase of the edge densities and/or radial transport in the SOL. The use of higher edge density and radial transport might be justified by the strong deuterium puffing which was applied in the experiment. With neon seeding however, we do not observe such discrepancies. It can be seen in Figure 8 that for the neon seeded discharge Pulse No: 85441 plasma profiles are nicely reproduced together with the global parameters: P_{rad}^{tot} = 11.9MW, P_{core} = 7.49MW, tungsten concentration: $c_W = 7.4 \times 10^{-5}$, Z_{eff} = 2.28 in simulations and in experiment we have: P_{rad}^{tot} = 12.6MW, P_{core} = 7.3MW, $c_W = 6 \times 10^{-5}$, Z_{eff} = 2.14, respectively.

It is also true for a number of neon discharges with dPulse No's: 85438, 85439, 85441). It can be seen that the experimental points fit quite well into simulation curves.

CONCLUSIONS

The COREDIV code has been used to simulate JET discharges in the new ITER-like wall configuration. The focus has been put on sensitivity studies to give insight on the influence of different code input parameters on the simulations results.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 appears that the COREDIV code is well suited to analyze JET ILW nitrogen seeded discharges, showing reasonable agreement with the trends observed in the experiment as well as with global plasma parameters like radiations levels, Z_{eff} and tungsten concentrations and the plasma profiles, including density, temperature and radiation. We have analyzed influence of different parameters on the JET plasmas and the main findings can be summarize as follows. Z_{eff} level is defined mostly by the low Z impurity content (Be and seeding gas N_2, Ne, Ar). Limited range of accessible seeded gas puff levels has been found which might impose restrictions on JET operational domain. It appears that for low powers, only operation with low plasma density is possible. The seeding gas puff limit is due to the edge density limit or/and radiative collapse and only for low densities and high powers, large amount of seeding gas can be injected to the plasma, and in such cases the radiation fraction might be as large as 80%. It appears, that for high powers, mitigation of the heat load to the target plates is mostly due to W radiation, which can not be efficiently replaced by radiation due to seeding gas.

Well, is it not more a maximum radiation level in the divertor which is determined by a maximum level of seeding gas? To overcome this one needs a second radiator in the main chamber?

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REFERENCES
[1]. R.Zagórski et al., Contrib. to Plasma Physics **48**, No. 1–3 (2008) 179
[2]. J.Rapp,et al., Journal of Nuclear Materials **337–339** (2005) 826
[3]. R.Zagórski et al., Journal of Nuclear Materials **390–391** (2009) 404
[4]. G. Telesca et al, Journal of Nuclear Materials **438**, Supplement, July 2013, S567
[5]. R.Zagórski et al., Contrib. to Plasma Physics **52**, (2012) 379
[6]. G. Telesca, et al., Plasma Physics and Controlled Fusion **53**, 115002 (2011).
[7]. R.Zagórski et al., Nuclear Fusion **53** (2013) 073030
[8]. J. Mandrekas and W.M. Stacey, Nuclear Fusion **35** (1995) 843
[9]. I. Ivanova-Stanik et al. "Integrated modeling of Nitrogen seeded JET ILW discharges for H-mode and hybrid scenarios", 14th PET Workshop, September 2013, Cracow, Poland, in press in CPP
[10]. K.Borras, Nuclear Fusion **31** (1991) 1035
[11]. M. Wischmeier et al., High density divertor operation for reactor relevant power exhaust, this conference (R3)
[12]. S.Brezinsek et al., Journal of Nuclear Materials **438**, Supplement, July 2013, S303
[13]. G.J. van Rooij et al., Journal of Nuclear Materials **438**, Supplement, July 2013, S42
[14]. G. Telesca, et al., this conference.

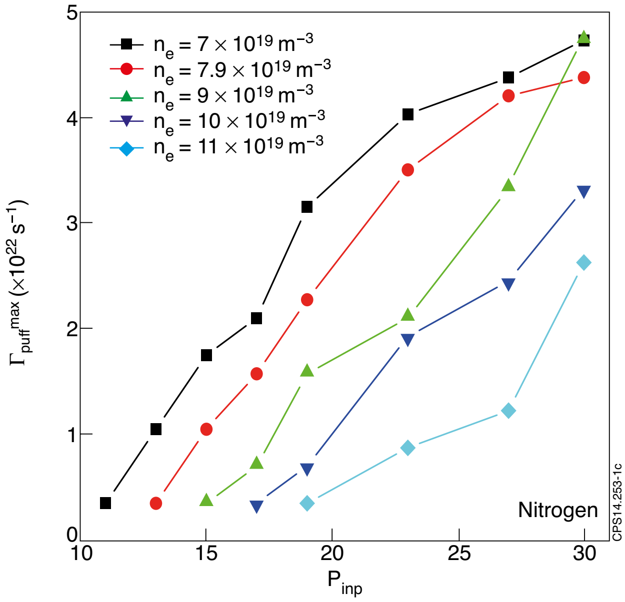

Figure 1: Maximum allowed nitrogen puff level for JET ILW discharges.

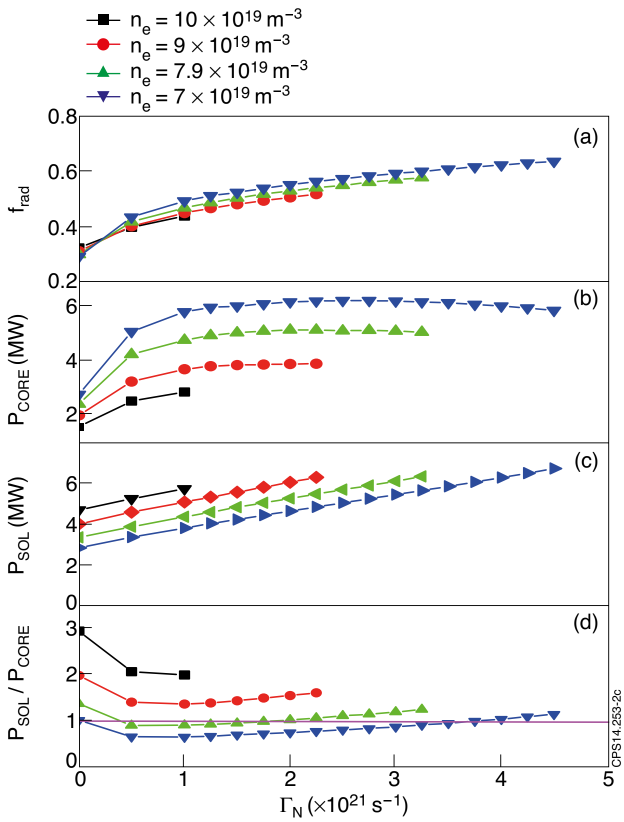

Figure 2: Plasma parameters versus nitrogen puff level for auxiliary heating power P_{aux} = 19MW and different plasma densities $<n_e>$ = 7 ÷ 10 × $10^{19}m^{-3}$: a) radiation fraction, b) core radiation, c) SOL radiation and d) ratio between SOL and core radiations.

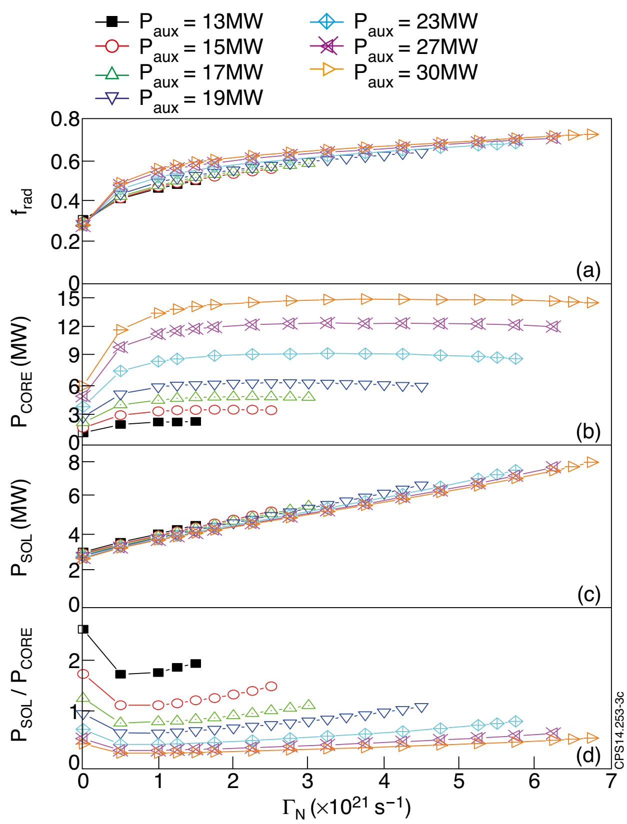

Figure 3: Plasma parameters versus nitrogen puff level for plasma density $<n_e>$ = 7 × $10^{19}m^{-3}$ and auxiliary heating powers P_{aux} = 13 ÷ 30MW : a) radiation fraction, b) core radiation, c) SOL radiation and d) ratio between SOL and core radiations.

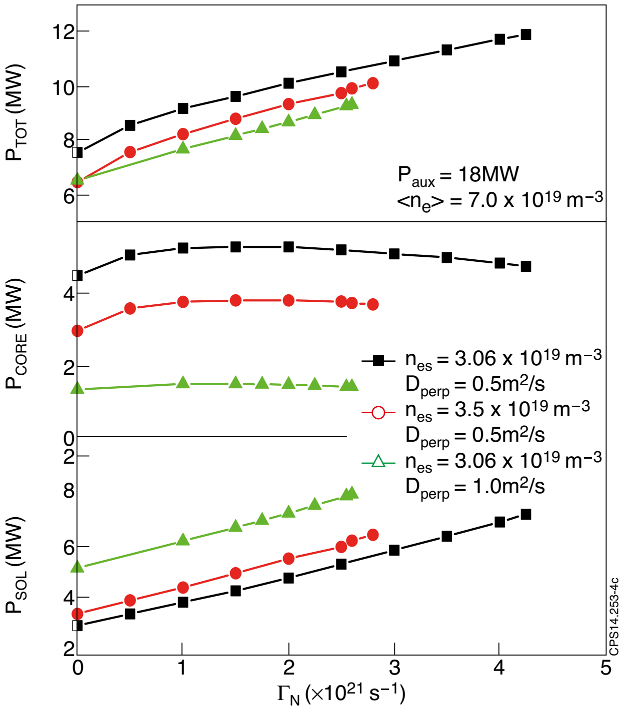

Figure 4: Plasma parameters versus nitrogen puff level for different edge densities, n_{es} = 3.06 × 10^{19} m^{-3}, n_{es} = 3.5 × 10^{19} m^{-3} and different radial diffusion coefficients in the SOL, $D_\perp$ = 0.5 m/s, $D_\perp$ = 1 m/s: a) total radiation losses, b) core radiation, c) SOL radiation.

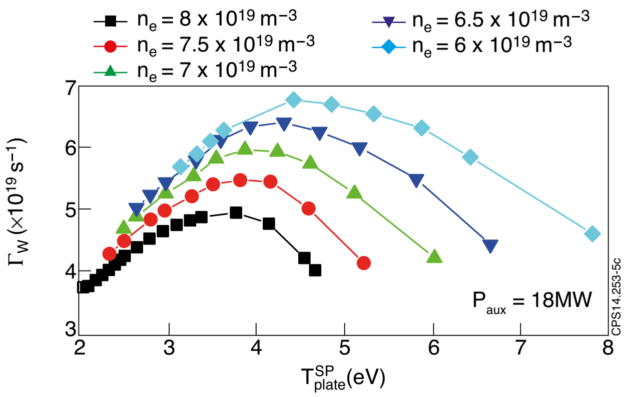

Figure 5: Tungsten flux versus electron temperature at the strike point for auxiliary heating power P_{aux} = 18MW and different plasma densities <n_e> = 6 ÷ 8 × $10^{19}$$m^{-3}$.

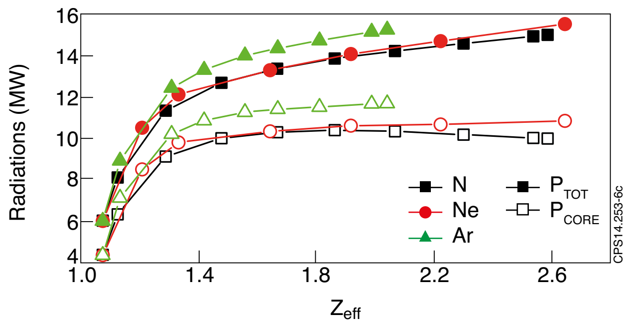

Figure 6. Total radiation losses (P_{TOT}) (full symbols) and core radiation (P_{CORE}) (open symbols) for different seeding gasses: N_2, Ne, and Ar.

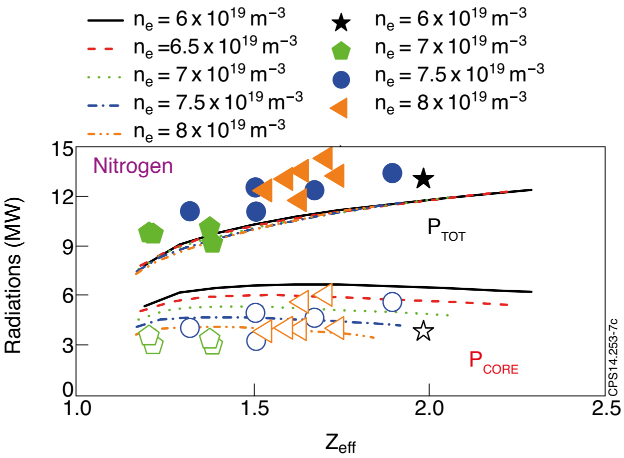

Figure 7. Experimental (points) and simulated (lines) values of total radiation losses (P_{TOT}) (full symbols) and core radiation (P_{CORE}) (open symbols) versus Z_{eff} value for different plasma densities and nitrogen seeding levels (Z_{eff} is almost linear function of the nitrogen influx).

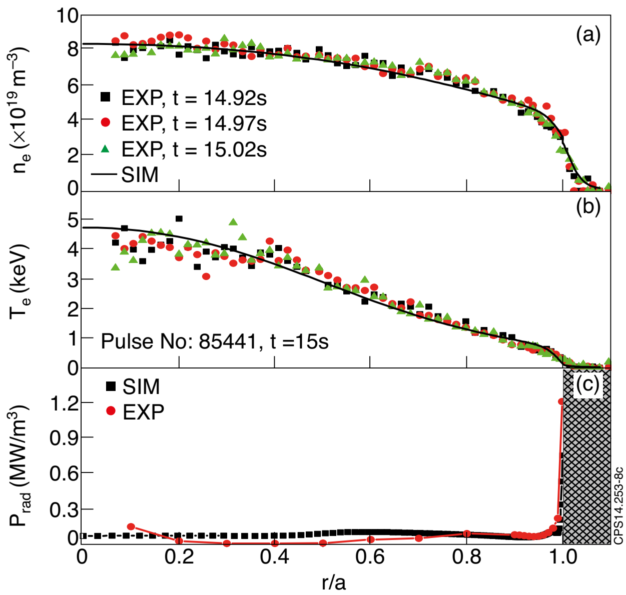

Figure 8. Experimental electron density (a) and electron temperature (b) profiles from HRTS diagnostic at different times and from COREDIV simulations, as function of the normalized minor radius for the JET shot 85441. For the same shot radiation profiles in the core from experiment and from simulations (c).

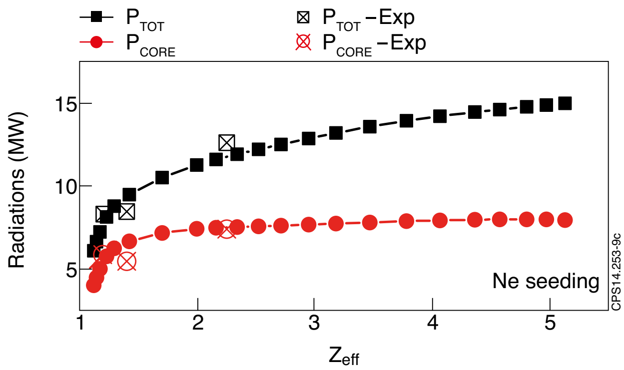

Figure 9. Calculated total radiation losses (P_{TOT}) (squares) and core radiation (P_{CORE}) (circles) versus Z_{eff} value for neon seeding together with experimental points for JET shots: 85438, 85439, 85441.