NUMERICAL SIMULATION OF HIGH NEUTRON RATE JET-ILW DD PULSES IN VIEW OF EXTENTION TO DT EXPERIMENTS

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Abstract

Two high performance JET pulses, pertaining to the 2016 experimental campaign, have been numerically simulated with the self-consistent code COREDIV with the aim of predicting the power load to the target when extrapolated to DT plasmas. The input power as well as the total radiated power and the average density are similar in the two pulses, but for one of them the density is provided by combined low gas puff and pellet injection, characterized by low SOL density, for the other by gas fuelling only, at higher SOL density. Considering the magnetic configuration of these pulses and the presence of a significant amount of Ni (that we have chosen not to be included in the actual version of the code), a number of assumptions are made in order to reproduce numerically the main core and SOL experimental data. The extrapolation to DT plasmas at the original input power of 33 MW, and taking into account only the thermal component of the alpha-power, doesn’t show any

1 See the author list of X. Litaudon et al 2017 Nucl. Fusion 57 102001
significant difference regarding the power to the target with respect to the DD case. In contrast, the simulations at input power=40 MW show that the power to the target for both pulses is possibly too high to be sustained for about 5 s by strike-point sweeping alone without any control by Ne seeding. Even though the target power load may decrease to about 13-15 MW with substantial Ne seeding for both pulses, as from numerical predictions, there are indications suggesting that the control of the power load may be more critical for the pulse with pellet injection.

1. INTRODUCTION

In the frame of the JET contribution to establishing a consistent scenario for deuterium-tritium ITER operation, DT experiments are planned at JET for the near future. The DT JET experiments will have to be based on well developed high power-high performance DD pulses, both for ELMy H-mode baseline and for hybrid scenarios. Quite a number of successful high power experiments have been recently performed at JET in both scenarios with plasma density provided either with gas fuelling only (hereafter: gas puff) or with combined low gas puff and pellet injection (hereafter: pellet) showing a neutron rate up to 2.8x10^{16} sec^{-1} [1,2]. The idea is to reproduce these DD pulses in DT plasmas, first keeping the auxiliary power at the original level of 33 MW, then increasing the power at the maximum JET availability (40 MW). Apart from a variety of problems related to the technical feasibility of such a challenge a non-marginal issue refers to the aim of keeping the maximum performances for 5 s, with the related long lasting power load to the divertor plates. In the above mentioned experiments the goal of sustainable plate power was reached by strike point sweeping, but the question arises if this technique might be sufficient for the DT plasmas, considering the additional contribution of the alpha- power and the planned longer flat top phase as well as the higher level of auxiliary power. Although power as well as Ne seeding scans (nitrogen seeding is not an option for the JET tritium handling facility) have already been simulated in view of the DT phase of JET on the basis of general discharge parameters [3] our study intends to contribute to understanding the operational constrains starting from selected high performance experimental JET pulses.

This paper is focused on the simulation of the power load on the divertor target of high performance JET ELMy H-mode DD pulses pertaining to the baseline scenario and to their numerical extension to the corresponding DT pulses. We have selected two pulses (I_p=3 MA, B_t=2.8 T) at medium density (n_e=6.5-7x10^{19} m^{-3}) which show very high neutron rates and are characterized by T_e/T_i >1 [1], with T_e(0) about 7 KeV. The auxiliary power, P_{aux}, is in excess of 30 MW provided mostly by NBI, with ICRF heating level around 5 MW. For one of them (record neutron flux, H_{98}=1.1) the density was provided by combined low level gas puff and pellet injection (hereafter: pellet) while for the other one (without pellets, H_{98}=1) the gas fuelling rate was at medium level, 1.8 x 10^{22}e/s (hereafter: gas puff). As a consequence, the SOL density in the pulse with gas puffing is higher than that in the pulse with pellets. A peculiar aspect of these pulses is their magnetic configuration with the outer strike point close to the pump out valve, the so-called corner configuration (see Fig. 1). This has some implications both for the experimental determination of the edge parameters of the pulses and for the modeling of the W penetration into the plasma. These pulses are slightly Ne seeded (c_{Ne} about 0.1-0.15 % in the core, from CXRS) and although the radiated power fraction, f_{rad}, is quite similar in the two pulses (about 0.40), the ratio of the radiated power in the SOL to the total one (P_{rad,SOL}/P_{rad,TOT}) is = 0.15 for the pulse with pellets and it is = 0.21 for that with gas puffing, related to the different SOL densities.

The W atoms which enter the divertor plasma are only a small fraction of the sputtered ones (< 10%) due to prompt re-deposition processes. The geometry of the system for the corner configuration (Fig.1) with the outer strike point close to the pump out valve, is such that a fraction of the sputtered W atoms at the outer target is deposited directly onto non-accessible areas, thus not contributing to the W flux. Considering the slab geometry of the divertor in COREDIV (see Sect. 2), this is technically accounted for by reducing the W sputtering yield level, by about one third, with respect to the COREDIV setting used for other magnetic configurations. A second issue refers to the fact that for both
these experimental pulses a significant amount of Ni is released by the interaction of the radiofrequency fields with the wall ($c_{Ni} = 4 \times 10^{-4}$ and $5.5 \times 10^{-4}$ for the pulses with puffing and with pellets, respectively, see Fig. 2.

Considering that, after numerical reconstruction of the experimental DD JET pulses, these pulses will be extrapolated to the DT plasmas with consequent production of He, we will be faced to five impurities: the intrinsic Be and W, and Ne, Ni and He. Although the number of impurity species which can be used in COREDIV is, in principle, not limited, we have considered in the present simulations only four impurities in order to limit CPU time required to achieving the steady state solution. Therefore, we had to choose either Ne or Ni for the simulation of the experimental DD pulses, since once the experimental pulses are numerically reconstructed, the simulation of the corresponding DT plasmas is performed by keeping everything unchanged, but only DT instead of DD. In fact, this study is limited to the evaluation of the thermal DT fusion reactions neglecting all possible other components of the fusion power as, for example, the beam-target component as well as the influence of supra-thermal ions generated in the specific ICRH scenario chosen. However, note that the contribution of the above mentioned neglected components of the alpha-power is marginal to the evaluation of the total power to the plate, which is the aim of the present study. Although most of the simulations have been performed with Ne, some tests in which Ne is replaced by Ni show substantial agreement. Indeed, both with Ne or with Ni all the experimental main parameters of the two pulses (as the core $T_e$, $T_i$ and $n_e$ profiles as well as the total stored energy and radiated power in the core and in the divertor and the core $Z_{eff}$) are satisfactorily reproduced in the simulations.

As a further step, in the simulations of the two DT plasmas we have increased $P_{aux}$ to 40 MW (assumed to be the maximum power level achievable in JET) while keeping $I_p$, $B_t$, the $H_{98}$ factor and $n_e$ as unchanged. For both pulses the power load to the target plate increases at a non-sustainable level, with related need for additional neon seeding.

In sect. 2 the COREDIV model for the core and the SOL is shortly described. Sect. 3 is devoted to the experimental data and to the simulation of the two experimental DD pulses. The simulation of the corresponding DT pulses together with the extension to the DT pulses at $P_{aux} = 40$ MW and the numerical neon seeding scan of the extended DT pulses at 40 MW is discussed in Sect. 4. Conclusions are drawn in Sect. 5.

2. COREDIV MODEL

We have used the COREDIV code [4], self-consistent with respect to the core-SOL as well as to impurities-main plasma. In spite of some simplifications, especially in the SOL model (slab geometry and model of the neutrals), the exchange of information between the core (1D) and the SOL (2D) module renders this code quite useful when, as in the case of the JET ILW, the interaction SOL-core is crucial.

In the core, given as code input the volume average electron density $\langle n_e \rangle$, the 1D radial transport equations for bulk ions, for each ionization state of impurity ions and for the electron and ion temperature are solved. The electron and ion energy fluxes are defined by the local transport model proposed in ref. [5] which reproduces a prescribed energy confinement law. In particular, the anomalous heat conductivity is given by the expression $\chi_{e,i} = C_{e,i} \cdot a^{2/\gamma} \tau_e \cdot F(r)$ where $r$ is the radial coordinate, $a$ is the plasma radius, $\tau_e$ is the energy confinement time defined by the ELMy H-mode scaling law and the coefficient ($C_e = C_i$) is adjusted to have agreement between calculated and experimental confinement times. The parabolic-like profile function $F(r)$, which may slightly

FIG. 2. Tomographic reconstruction of the radiated power density of JPN 92436 $t = 10.4$ s. The highest radiation density at the mid-plane in the LFS is due to Ni.
change from run to run in order to match with the actual profiles of the experimental pulse to be modelled, can be modified at the plasma edge to provide for a transport barrier of chosen level. The main plasma ion density is given by the solution of the radial diffusion equation with diffusion coefficients $D_i = D_e = 0.2 \chi_e$, as in ref.[5]. Note, however, that the solution of the diffusion equation is largely independent of the exact value of $D_e/\chi_e$.

Indeed, a change in $D_e/\chi_e$ causes a consistent change in the source term, since the average electron density is a COREDIV input. For the auxiliary heating, parabolic-like deposition profile is assumed $P_{aux}(r) = P_0 \left(1-r^2/a^2\right)^y$ where $y$ is in the range 1.5-3, depending on the quality of the auxiliary heating, NBI or/and ICRF. In conclusion: once the power deposition profile, the confinement time $\tau_E$ and the profile function $F(r)$ are assigned the electron temperature and density profiles are unambiguously determined. For the pulses considered in this study $y=2$. Impurity diffusion coefficient is set to be equal to that of the main ions and the anomalous impurity pinch, which is a code input, is set to zero for these two pulses (see Sect.3).

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. An analytical description of the neutrals is used, based on a simple diffusive model. COREDIV takes into account the plasma (D, Be 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 and neon sputtering and tungsten self-sputtering the yields given in refs. [6,7] are used). The recycling coefficient is an external parameter which in COREDIV depends on the level of the electron density at the separatrix, $n_{e,sep}$, given as an input, and increases with increasing $n_{e,sep}$.

A simple slab geometry (poloidal and radial directions) with classical parallel transport and anomalous radial transport ($D_{SOL} = \chi_i = 0.5 \chi_e$, where $\chi_i$ ranges typically 0.4-1 m$^2$/s), is used and the impurity fluxes and radiation losses by impurity ions are calculated fully self-consistently. Although the values of the transport coefficients in the SOL are generally quite comparable to those at the separatrix, in the present simulations the value of $D_{SOL}$ is set arbitrarily (in the range 0.2-0.3 m$^2$/s) in order to match with the core-SOL distribution of the radiated power (see Sect.3). All the equations are solved only from the midplane to the divertor plate, assuming inner-outer symmetry of the problem. This implies that the experimental in–out asymmetries, observed especially at high density-high radiation level, are not reproduced in COREDIV results. However, for all the different situations examined so far (with carbon plates and with the ILW, and with different seeding levels [8]) the COREDIV numerical reconstructed total radiation in the SOL matches well with the total experimentally measured SOL radiation, indicating that for JET conditions the edge-core COREDIV model can describe the global trend of this important quantity. 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. EXPERIMENTS AND SIMULATION OF DD PLASMAS

Due to the corner magnetic configuration of the considered discharges, probe measurements are missing (no probe on, or near, the outer strike point) as well as many spectral line intensity measurements. The only available SOL data are the intensity of Be I line at 441 nm taken along a horizontal chord at the mid-plane and bolometric data.

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. An analytical description of the neutrals is used, based on a simple diffusive model. COREDIV takes into account the plasma (D, Be 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 and neon sputtering and tungsten self-sputtering the yields given in refs. [6,7] are used). The recycling coefficient is an external parameter which in COREDIV depends on the level of the electron density at the separatrix, $n_{e,sep}$, given as an input, and increases with increasing $n_{e,sep}$.
In the simulations, \( c_{\text{Ne}}, P_{\text{rad,SOL}}/P_{\text{rad,TOT}} \) and \( c_{W} \) are significantly higher than in experiment. This is a consequence of the higher Ne seeding level used in the simulations to compensate for neglecting the Ni contribution to \( P_{\text{rad}} \) and \( Z_{\text{eff}} \). With respect to the Be flux, considering that the level of the measured Be I line is about a factor of three higher in the pulse with gas puff and that the ionization per photon (S/XB) for the Be I line is rather insensitive to changes in electron temperature from about 3-4 eV to 100 eV (S/XB about 100, see ref. [10]), the level of Be puff in COREDIV has been set as \( 3.4 \times 10^{21} \text{ s}^{-1} \) and \( 1.18 \times 10^{21} \text{ s}^{-1} \) for the two pulses, respectively. To give an example, in Fig. 3 the experimental and reconstructed density and temperature core profiles for the pulse with pellets are compared.

<table>
<thead>
<tr>
<th>TABLE 1. SUMMARY OF EXPERIMENTAL AND SIMULATED QUANTITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>PARAMETERS # 92432, ( t = 9.5 \text{s} ) # 92436, ( t = 10.4 \text{s} )</td>
</tr>
<tr>
<td>( W_{\text{th}} ) [MJ]</td>
</tr>
<tr>
<td>8.1</td>
</tr>
<tr>
<td>( P_{\text{rad,TOTAL}} ) [MW]</td>
</tr>
<tr>
<td>( P_{\text{rad,SOL}}/P_{\text{rad,TOTAL}} )</td>
</tr>
<tr>
<td>( Z_{\text{EFF}} )</td>
</tr>
<tr>
<td>( P_{\text{PLATE}} ) [MW]</td>
</tr>
<tr>
<td>( C_{W} ) ( \times 10^{-5} )</td>
</tr>
</tbody>
</table>

*power to the plate in experiment \( (P_{\text{PLATE}}) \) : not considered charge exchange losses

**FIG. 3**. Experimental and simulated electron density and electron (and ion) temperature profiles for JPN #92436 \( t = 10.4 \text{s} \).

4. SIMULATION OF DT PLASMAS

Replacing DT for DD while keeping unchanged the auxiliary power and the confinement enhancement factor \( H_{98} \) as well as the Ne seeding rate doesn’t lead in our simulations to major differences both for the pulse with pellets and for that with gas puff, what the target power load is concerned. (Please, recall that our simulations are limited to the estimation of the thermal component of the \( \alpha \)-power). A slight increase in \( \tau_{E} \) (mass dependence) together with the little contribution of \( P_{\alpha} \) (0.5 MW and 0.7 MW for the two pulses, respectively) lead in COREDIV only to a little increase in the power to the plate. At \( P_{\text{aux}} = 40 \text{ MW} \) the situation changes in relation to the power to the plate. Indeed, the little increase in \( c_{W} \) and in the core radiation is not sufficient to compensate for the increase in the power to the SOL, resulting in a significant increase in the power to the plate, see Table 2.

The target power load can be mitigated by increasing the level of Ne seeding which leads to different scaling depending on which parameter is kept as constant in the simulations: the \( H_{98} \) factor (total energy) or the energy (and particle) transport coefficients. Indeed, depending on the specific JET-ILW experimental situation, in some cases the \( H_{98} \) factor decreases [11] with increasing the Ne seeding level, in others it remains nearly constant [12] and in some others it may even increase [13]. We have chosen to perform a Ne seeding scan for the two considered pulses keeping constant the \( H_{98} \) factor. Note that, without excluding possible SOL modifications, in the case the total plasma energy remains constant with increasing the Ne seeding rate the net energy confinement time, \( W/(P_{\text{th}}-P_{\text{rad,CORE}}) \), and the effective \( \tau_{p} \) (effective particle residence time) increase since the power lost into radiation in the
plasma core generally increases too, leading to a further enhancement in the core radiation. On the other hand, this enhancement in the total radiation tends to limit the tungsten sputtering.

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>Gas puff</th>
<th>Pellet injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_\alpha$ therm. [MW]</td>
<td>0.593</td>
<td>0.846</td>
</tr>
<tr>
<td>$W_\alpha$ [MJ]</td>
<td>8.88</td>
<td>9.96</td>
</tr>
<tr>
<td>$P_{rad}^{TOTAL}$ [MW]</td>
<td>16</td>
<td>15.36</td>
</tr>
<tr>
<td>$P_{rad}^{SOL}/P_{rad}^{TOTAL}$</td>
<td>0.25</td>
<td>0.22</td>
</tr>
<tr>
<td>$Z_{EFF}$</td>
<td>1.58</td>
<td>1.76</td>
</tr>
<tr>
<td>$P_{PLATE}$ [MW]</td>
<td>21.3</td>
<td>21.3</td>
</tr>
<tr>
<td>$C_W \times 10^{-5}$</td>
<td>12.5</td>
<td>14.9</td>
</tr>
<tr>
<td>$C_{Ne} \times 10^{-2}$</td>
<td>0.18</td>
<td>0.46</td>
</tr>
<tr>
<td>$T_{e,PLATE}$ [eV]</td>
<td>17.9</td>
<td>20.6</td>
</tr>
</tbody>
</table>

In Table 2, predictive simulations for DT plasmas at 40 MW are shown. In both Ne scans the power to the plate can be reduced to less than 13 MW with some differences, however, for the two pulses. For the pulse with pellets, although the power to the SOL is lower than that for the gas puff one, $T_{e,plate}$ is higher and saturates at about 18 eV, due to the lower $n_e$ sep. This is correlated with the low $P_{rad}^{SOL}$ and the high $C_W$. With respect to the alpha-power, COREDIV simulations predict an increase in the thermal $P_\alpha$ level at higher Ne seeding rate as a consequence of the increase in the main ion temperature, dependent on the main ion dilution. Decreasing the power to the plate with Ne seeding from 22 MW to 15 MW, $P_\alpha$ increases from 0.59 to 0.66 MW for the pulse with gas puff and from 0.85 to 0.96 MW for that with pellets. If, on the other hand, one assumes the constancy of the fusion reactivity (at the level of the lowest Ne seeding rate), the $\alpha$-power decreases with increasing the neon seeding rate, from 0.59 to 0.45 MW and from 0.85 to 0.68 MW, respectively, see Fig. 5.
FIG. 5. Thermal alpha-power for the two pulses as a function of $C_{\text{Ne}}$. The two curves for each pulse refer to the COREDIV self-consistent reactivity (full symbols) and to the reactivity kept constant at the level of the lowest Ne seeding rate.

5. SUMMARY AND CONCLUSION

Both the experimental high performance pulses, with gas puff and with pellets, have been numerically simulated resulting in the target load of 16-17 MW. While the two pulses are similar in input power (about 33 MW) as well as in radiated power (13-14 MW), their main difference, in experiment and simulation, refers to the edge density, which in the pulse with pellets is lower than that with gas puff, resulting in slightly higher plate temperature: 19 eV and 17.5 eV, respectively. For the two experimental pulses a significant amount of Ni is detected (especially for that with pellets) the W sputtering yield had to be reduced and a large amount of Ne (more than in experiment) had to be seeded in order the total radiated power and $Z_{\text{eff}}$ could be numerically reproduced. Indeed, in the COREDIV simulations here presented the number of impurities is limited to four. Extrapolation to DT plasmas, keeping unchanged input power, leads to little difference with respect to the reconstructed DD pulses, with thermal alpha-power (the only component of $P_\alpha$ we are concerned with) of about 0.5 MW and 0.7 MW for the pulse with gas puff and with pellets, respectively. The most relevant result of the extrapolation of the two DD pulses to DT plasmas at $P_{\text{aux}}=40$ MW is the power to the target, which becomes in excess of 21 MW, for both pulses. Indeed, the increase in the radiated power is not sufficient to compensate for the increase of the input power. In order to investigate for a possible mitigation of the power to the plate a numerical Ne scan has been performed, showing the possibility of achieving $P_{\text{plate}}$ below 15 MW at $Z_{\text{eff}}=2.4$ and 2.9 for the pulse with gas puff and with pellets, respectively. At $P_{\text{plate}}=15$ MW, $P_\alpha$ may increase by about 10 percent or decrease by 20-25 percent with respect to the unseeded case, depending on the assumption made.

Recalling that the numerical results for the DT plasmas here presented refer only to the thermal alpha-power (the actual total $P_\alpha$ is expected to be higher, as well as $P_{\text{plate}}$) and considering the number of assumptions made both for the reconstruction of the experimental pulses and for the Ne scan of the DT plasmas at $P_{\text{aux}}=40$ MW, only qualitative conclusions can be drawn from this study. However, even though the pulse with combined low gas puff and pellet injection shows higher performance in the DD experiments as well as in the DT simulations, it has to be taken into account the high tungsten concentration (or, in general, the high $P_{\text{rad CORE}}$) needed to bring down $P_{\text{plate}}$ to a sustainable level, at such low SOL density. Without excluding possible positive effects by the increase of the strike-point sweep amplitude and by increase of the density as well as the change in the ELM behavior, considering also the numerical impossibility of reducing $T_e$ below 18 eV as a consequence of the low SOL density, it seems that control of the power to the plate might be more critical for the pulse with pellets than that for the pulse with gas puff.

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