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Modelling of the JET DT Experiments in Carbon and ITER-like Wall Configurations*

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In this paper numerical simulations with the self-consistent COREDIV code of the planned JET DT experiments have been performed. First, record shot from the 1997 experiments was simulated and good agreement with experimental data has been found. Direct extrapolation of the carbon wall results to the new ILW configuration (discharge parameters as for the shot #42746) shows very good core plasma performance with even higher fusion power but with too large power to the divertor. However, with the neon seeding the heat load and plate temperatures can be efficiently reduced keeping good the plasma performance. Investigations have been done also for the planned DT operation scenario based on a conventional ELMy H-mode at high plasma current and magnetic field. Simulations for the reference ELMy H-mode shot #87412 show good agreement with the experimental data but the direct extrapolation of the DD results to deuterium-tritium operation shows relatively poor performance in terms of the achieved fusion power. The situation improves, if the highest heating power is assumed (41 MW) and fusion powers in the excess of 12 MW can be achieved. All the high performance shots require the heat load control by neon seeding which shows rather beneficial effect on the plasma performance allowing for relatively wide operational window in terms of the amount of the allowed neon influx.

1 Introduction

A series of high power discharges(P_{aux} $\sim$ 21-26 MW) using DT mixtures in ELM-free H mode was performed in 1997 during the JET DTE1 experimental campaign with carbon walls and divertor. A fusion power of 16.1 MW was achieved at 4.0 MA/3.6 T corresponding to the record fusion yield of $Q = 0.64$ [1]. These high performance fusion shots were characterized by good confinement with very high central ion temperature up to 28 keV (hot ion mode [2]), relatively low plasma density ($\sim$ 3-4 $\times$ 10^{19} m^{-3}) and by moderate values of Z_{eff} ($\sim$ 2-3). It is planned to perform DT experiments at JET in 2017/2018 in the ITER -like wall (ILW) configuration, with beryllium walls and tungsten divertor. Direct extrapolation of the results from the old DTE1 experimental campaign to the new situation seems however difficult, since degradation of the plasma performance in the ILW configuration is usually observed and the compatibility of high power operation with divertor performance is questionable. Therefore at present, the high performance plasmas to be tested with tritium are based on either a conventional ELMy H-mode at high plasma current and magnetic field (operation at up to 4 MA and 4 T is being prepared) or the so-called improved H-mode or hybrid regime of operation in which high normalized plasma pressure at somewhat reduced plasma current results in enhanced energy confinement [3].

In order to assess the plasma parameters in the planned DT experiments COREDIV code [4] has been used to perform self-consistent core-edge simulations of JET DT plasmas. The code has been already successfully benchmarked with a number of JET discharges for both carbon and ILW discharges proving its capability of

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*** See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference, 2014, Saint Petersburg, Russian Federation reproducing the main features of JET seeded plasmas [5–8]. As a first step (section 3) we have simulated the record shot #42976 to fix the code free parameters. To adjust to the experimental results, the assumption of strong reduction of the ion transport has been made to obtain the hot ion mode features. Next the results have been extrapolated to the new wall configuration by changing the wall material from carbon to ILW composition. The effect of neon seeding on the plasma performance has been investigated as well. In section 4, the analysis of the JET DT performance based on the H-mode baseline scenario [3] are performed. First, the JET ILW H-mode reference shot #87412 is simulated and next predictive modeling is done for the corresponding high current DT scenario (4.1 MA/3.9T/41MW). Final remarks and conclusion are given in section 5.

2 Physical model

Simulations were performed by using COREDIV code which is based on an integrated approach coupling the radial transport in the core and the 2D multifluid description of the SOL. The interaction between seeded and intrinsic impurities as well as the effect of the impurities on the fusion power significantly affects the particles and energy flows in the plasma, therefore the self-consistent approach is essential for a correct evaluation of the average power to the divertor plate. As this work is a follow-up of our previous calculations the detailed description and parameters used can be found in Refs. [4,6–8] and only the main points of the model are reported here. In the core, the 1D radial transport equations for bulk ions, for each ionization state of impurity ions and for the electron and ion temperatures are solved. For auxiliary heating parabolic-like deposition profile is assumed and heating due to alpha power is calculated self-consistently taking into account the dilution effect due to helium and impurity transport. The energy losses are determined by Bremstrahlung and synchrotron radiation together with ionization and line radiation losses. The energy and particle transport are defined by the local transport model with prescribed profile of transport coefficients taking into account the barrier formation in the edge region and which reproduces a prescribed energy confinement law [9]. 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, (T, He), Be, Ne, and C (or W) at the target plate. 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 radiated and fusion power, the W flux and concentration and the plasma parameters in the divertor/SOL region.

3 Simulations of the JET DT experiment - hot ion mode operation

In order to perform predictive simulations of the new JET DT experiments with the COREDIV code, we have started first with the analysis of the record shot #42976 from the old (1997) DT experimental campaign to fix some code free parameters. Calculations have been done for the average plasma density ($<n_e> = 4\times\ 10^{19}$ m^{-3}) and auxiliary heating power of $P_{aux} = 25.7$ MW. To reproduce the high ion temperature (hot ion mode) observed in the experiment, it was necessary to introduce the reduction of the ion conductivity by factor 10 in respect to the electron conductivity in the plasma core ($\chi_i = 0.1\chi_e$) and using our standard assumption regarding the splitting of the heating power ($P_e/P_i = 0.65/0.35$) between electrons and ions. The code is able to reproduce the density and the temperature profiles in the core as well as the global plasma parameters, which can be seen from the Fig. 1 and Tabele 1, where comparison between COREDIV results, experimental measurements and interpretive TRANSP simulations [1] of this particular shot is shown. The temperature and density profiles are nicely reproduced by the code as well as the global parameters. Some discrepancies in the predicted fusion power values are due to the fact that the contribution of the fast ions to the fusion power is not considered in the COREDIV simulations since we have assumed that the fusion power comes only from thermal processes neglecting completely contributions from beam-plasma and beam-beam reactions. It should be stated however, that P_α is a small fraction of the total power and inclusion of P_α from beam-plasma and beam-beam reactions would not alter the conclusions about the heat loads and plate temperatures. Therefore, our predictions regarding the fusion performance should be treated as indicative only and the corresponding numbers have only qualitative meaning. It should be noted, that similar results (4th row in the table) can be obtained with the code replacing the assumption about the ion heat conductivity reduction by requirement that most of the input power goes to ions: $\chi_i = \chi_e$, $P_e/P_i = 0.1/0.9$).

In the last row of the Tab.1, we show also the extrapolation results for the ILW configuration (discharge parameters as for the shot #42976) with the same transport assumptions. The core plasma performance is very good with even higher fusion power than in carbon case (dilution effect reduced with tungsten) but the plasma parameters in the divertor might be not acceptable. The plate temperature is high (> 40 eV) with significant heat load (> 15 MW) to the target plates, which results in very high tungsten production ($Z_{eff} > 2$ due to W ions). Therefore, if such low density scenario is to be considered in the planned DT experiments, impurity seeding would be obligatory.

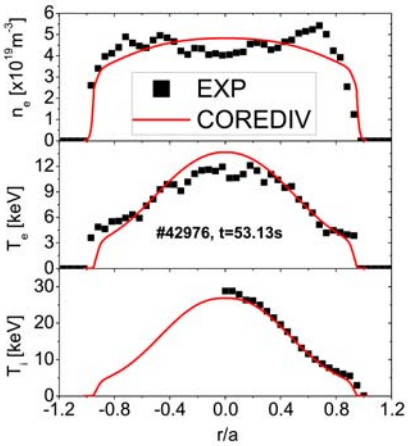

Fig. 1 Calculated and experimental plasma profiles for the JET shot #42976 at $t = 53.13$ sec.

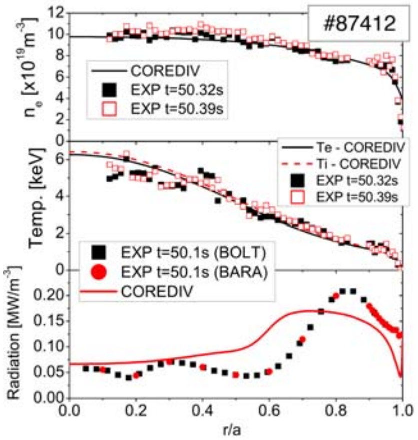

Fig. 2 Calculated and experimental plasma profiles for the JET ILW shot #87412 at $t = 50.3$ sec.

Table 1 The experimental and simulated global plasma parameters for shot #42976 at t=53.13 sec

JET Shot	P_{DT} [MW]	Z_{eff}	$n_T + n_D(0)$ [$\times 10^{19}$m^{-3}]	$T_i(0)$ [keV]	$T_e(0)$ [keV]	P_α [MW]	W_{dia} [MJ]	P_{rad} [MW]	P_{plate} [MW]	T_e^{plate} [eV]
42976	15.8	2.9		28.84	11.5	3.16	16.9			
TRANSP	14.2	1.9±0.2	3.3±0.3	28±2	14	2.83	15.5			
COREDIV	9.9	2.73	3.28	26.9	13.67	1.98	13.2	3.22	23.7	95.4
COREDIV ($P_i/P_e = 9$)	11.6	2.31	3.2	28.9	13.2	2.32	13.83	3.37	22.8	60
COREDIV (W)	15.5	2.03	4.34	24.5	12.4	3.12	13.5	12.35	15.07	44

In order to check the effect of seeding on the plasma performance, numerical scan has been performed assuming different levels of the Neon puff, keeping all other code parameters unchanged.

The influence of neon seeding on the plasma performance of this low density, hot-ion mode discharge is quite positive. Already small amount of neon puff ($\Gamma_{Ne} \geq 10^{20}$ s^{-1}) leads to significant plasma radiation (Fig. 3a) and reduction of the power to the divertor (Fig. 3b). The plasma radiation, which even for the highest seeding levels is due to tungsten ions radiation, saturates at the level of 80% and the seeding has relatively week effect on the plasma parameters, except the initial phase for $\Gamma_{Ne} < 10^{20}$ s^{-1}. The reduction of the power to the plate is accompanied by the strong reduction of the ion temperature (down to 3 eV), whereas T_e stays at the 20 eV level in spite of the high radiation fraction. That ion cooling is related to our assumption about hot-ion mode and corresponding reduction of the core ion conductivity, which results in the reduction of the power to the SOL in the ion channel. The increase of T_i at the highest seeding levels can be explained by significant plasma dilution as can be seen from the Fig. 3c where Z_{eff} is shown, Z_{eff} increases almost linearly with the neon puff level (please note that in our model the same temperature is assumed for all ions). Surprisingly, the fusion performance improves at the low level of neon seeding, P_α achieves maximum at $\Gamma_{Ne} \sim 10^{20}$ s^{-1} and next gradually goes down as the seeding increases. However, this effect is not drastic, as the reduction of the fusion power due to dilution is compensated partially by the increase of the ion temperature (Fig. 3f), which exceeds 40 keV at the highest seeding level. It should be noted that at the maximum of the fusion performance the reduction of the heat load is already quite significant (< 10 MW), which might be tolerable from the operational point of view.

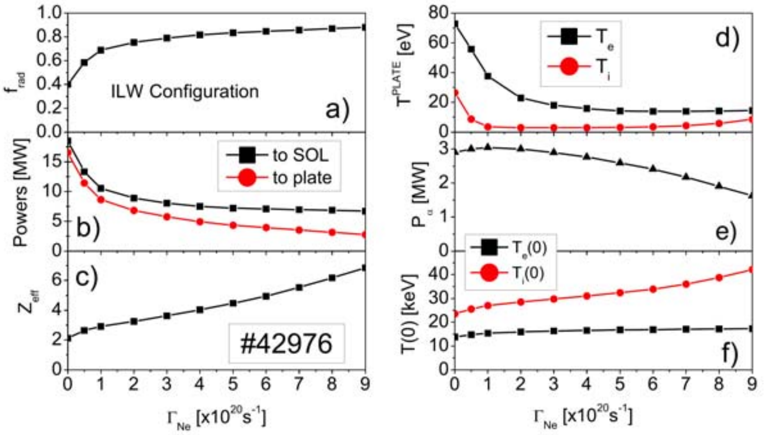

Fig. 3 Plasma parameters versus neon puff level: a) radiation fraction (f_{rad}), b) Power to SOL and to the target plates, c) Z_{eff}, d) plasma temperatures at the divertor plate, e) alpha power (P_α), f) central plasma temperatures.

Working at the medium seeding levels (10^{20} s^{-1} $\leq \Gamma_{Ne} < 3\times10^{20}$ s^{-1} allows to control the heat flow to the target with simultaneous good plasma performance and would form an optimal operational window for this low density, hot-ion mode discharge. The only worry is related to the relatively high electron temperature and corresponding significant W erosion ($\Gamma_W < 2 \times 10^{20}$ s^{-1}), and in addition, to the possibility of achieving this type of operation (high ion mode) in the ILW configuration (this question is however outside the scope of this paper). We have checked also, how the hot-ion mode scenario extrapolates to higher plasma densities, which seems favorable for the high power operation in the planned JET DT experiments. The results are summarized in the Tabele 2.

Table 2 Simulated global plasma parameters for different plasma densities (shot #42976)

$< n_e >$ [$\times 10^{19}$ m^{-3}]	P_{DT} [MW]	Z_{eff}	$T_i(0)$ [keV]	$T_e(0)$ [keV]	P_α [MW]	W_{dia} [MJ]	P_{rad} [MW]	P_{plate} [MW]	T_e^{plate} [eV]
4	15.5	2.03	24.5	12.4	3.12	13.5	12.35	15.07	44
5	14.25	1.45	18.7	11.2	2.85	13.7	10.0	17.1	36
6	12.35	1.19	14.9	9.9	2.47	13.8	7.83	19.1	26
7	10.55	1.09	12.4	9.0	2.11	14.0	6.72	20.0	20

It can be seen, that with the increase of $<n_e>$, the fusion power is strongly reduced (and corresponding P_α) being the effect of the reduced ion plasma temperature, which can not be compensated by the increase of the density. Simultaneously radiated power is decreased, leading to the increase of the power to the plate but the plate temperature goes down as well as Z_{eff} (density effect). Independent of density, impurity seeding is necessary to control the power load to divertor.

4 Simulations of the JET DT experiment - H-mode operation

The results from the section above indicate that repeating of the old DT experiments based on the ELMy free discharges with low density and in hot-ion mode might be an interesting option for the ILW configuration but this kind of scenario is not fully compatible with the new situation. First with the power level expected to be available in the DT experiment (up to 41 MW) the conditions in the divertor might be difficult to control. Secondly, we are interested in the steady state high performance ITER like scenarios which require type I ELM operation. Therefore, the high performance plasma scenarios to be proposed recently for the DT operation are based on a conventional ELMy H-mode at high plasma current and magnetic field and on the so-called improved H-mode or hybrid regime of operation with enhanced energy confinement [3]. Both of these regimes are being re-developed in conjunction with JET's ITER-like Wall (ILW) of beryllium and tungsten. In our study we focus on the type I ELMy discharges which as a starting point take the reference shot #87412 (3.5 MA/3.2T) with 31 MW of additional heating power. This shot has been simulated with COREDIV code assuming average plasma density $<n_e> = 7.2 \times 10^{19}$ m^{-3} and the experimental confinement factor $H_{98} = 0.8$. In the Fig. 2, experimental plasma profiles are compared to the code results. It can be seen that in addition to the density and temperature profiles, also the plasma radiation is well reproduced by COREDIV code. The agreement is satisfactory also for the global parameters like Z_{eff} = 1.14/1.12, energy content W_{DIA} = 8.35/8.7 MJ or tungsten concentration c_W = 7/5$\times$10^{-5} (the first number comes from simulations and the second one is from experiment).

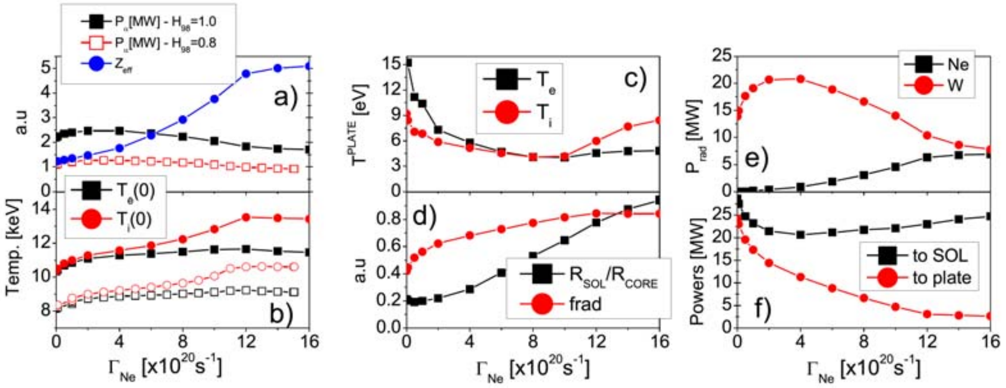

Fig. 4 Plasma parameters versus neon puff level for H_{98}=1 (close symbols) : a) alpha power (for two H-factors) and Z_{eff}, b) central plasma temperatures (for two H-factors), c) plasma temperatures at the divertor plate, d) radiation fraction (f_{rad}) and the ratio between SOL and core radiation, e) Total tungsten and neon radiations, f) Power to SOL and to the target plates. Note that open symbols refer to the case $H_{98} = 0.8$.

Direct extrapolation of the considered DD shot (#87412) to the DT operations, gives the alpha power equal to 0.44 MW, considering only thermal contribution. The radiation fraction in this reference shot appears to be relatively low (41%) and the corresponding heat load to divertor target plates (18 MW) might not be sustained in the steady state operation. Therefore, seeding is required to control the power to the divertor. Similarly as for the hot-ion mode simulations, there is an optimum neon puff level, which corresponds to the maximum of the achieved fusion power ($P_\alpha = 0.53$ MW at $\Gamma_{Ne} = 3 \times 10^{20}$ s^{-1}) and simultaneously the power to the target plates is reduced to an acceptable level (8.3 MW). The fusion performance of the considered baseline scenario H-mode shot is relatively weak in terms of the achieved fusion power, therefore extrapolations are foreseen of this shot to the maximum available heating powers (41 MW), magnetic field (3.9 T) and plasma current (4.1 MA) with the same Greenwald density fraction ($n_e = 9.6 \times 10^{19}$ m^{-3}). In order to check the plasma performance at these extreme conditions, COREDIV predictive simulations have been done. Since the seeding is obligatory with strong plasma heating, calculations have been performed for different levels of neon puff and are presented in the Fig. 4. Two series of simulations have been done: in the first numerical scan we have assumed weak confinement degradation ($H_{98} = 0.8$) in line with the experimental observations for ILW plasma, whereas in the second case more optimistic plasma performance has bee assumed ($H_{98} = 1.0$). It has been found, that mostly plasma temperature in the center, and thus the fusion performance, is affected by the changes to the H-factor with other global parameters almost unchanged. Therefore in the Fig. 4 we present basically the results for the ($H_{98} = 1.0$) case, except plots 4a and 4b, where also results for the reduced confinement are shown ($H_{98} = 0.8$ - open symbols in Fig. 4).

It can be seen, that even at the highest performance the fusion power approaches 12.5 MW (6.5 MW for $H_{98} = 0.8$), which remains below the old record value of (16.1 MW). However, the overall plasma performance seems to be quite stable and controllable by neon seeding with relatively wide operational window in terms of the amount of the allowed neon influx. The profile of the alpha power is relatively flat versus neon puff level, with a maximum at $\Gamma_{Ne} \sim$ 3-4 $\times$ 10^{20} s^{-1}. At this seeding level, the power to the target plates falls down already below 10 MW, which seems to be acceptable for the divertor operation. It should be noted that at this low levels of the seeding level, the the W radiation is still quite high and consequently the viability of the discharge will also depend on the distribution of the W in the discharge. Further increase of the seeding, does not reduce the fusion performance significantly but has beneficial influence on the power exhaust problem. The radiation fraction exceeds 80% level with strong contribution of the radiation coming from the SOL region related to the neon ions radiation. The plasma temperatures in the divertor are low, indicating the semi-detached divertor plasma operation with strongly reduced power to the target plates. It should be noted, that the increase of the ion temperature in the divertor (Fig. 4c) at the highest seeding levels is related to the plasma dilution effect. In spite of the strong plasma radiation, the power crossing separatrix is well above the L-H transition threshold level allowing for a good H-mode operation.

5 Conclusions

In order to assess the plasma parameters in the planned JET DT experiments, COREDIV code has been used to perform self-consistent core-edge simulations of DT plasmas. First, record shot from the 1997 experiments was simulated and good agreement with experimental data has been found under the assumption of the ion transport reduction to obtain the hot-ion mode features. The code is able to reproduce the density and the temperature profiles as well as the global plasma parameters. Direct extrapolation of the carbon wall results to the new ILW configuration (discharge parameters as for the shot #42746) shows very good core plasma performance with even higher fusion power (dilution effect reduced with W) but the plasma parameters in the divertor might be not tolerable, due to high plasma temperature in the divertor (> 40 eV) and significant heat load (> 15 MW). However, with the neon seeding the heat load and plate temperatures can be efficiently reduced keeping good the plasma performance (without degradation of the fusion power). Extrapolation of the hot-ion mode discharges to higher plasma densities shows some degradation of fusion performance (by 30%) and would require neon seeding to control heat load to divertor.

We have analyzed also the high performance plasma scenario, which was proposed recently for the DT operation based on a conventional ELMy H-mode at high plasma current and magnetic field. Simulations for the reference shot #87412 show good agreement with the experimental data but the direct extrapolation of the DD results to deuterium-tritium operation shows relatively poor performance in terms of the achieved fusion power. The situation improves, if the highest heating power is assumed (41 MW) and JET configuration with high magnetic field (3.9 T) and plasma current (4.1 MA) is considered. Assuming good energy confinement ($H_{98} = 1$), fusion powers in the excess of 12 MW can be achieved. All the high performance shots require the heat load control by neon seeding which shows rather beneficial effect on the plasma performance allowing for relatively wide operational window in terms of the amount of the allowed neon influx.

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