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Divertor Power Spreading in DEMO Reactor by Impurity Seeding

Roman Zagórski[a], Krzysztof Gałązka[a], Irena Ivanova-Stanik[a]

[a]*Institute of Plasma Physics and Laser Microfusion, Hery 23, 01-497 Warsaw, Poland*

Numerical simulation with COREDIV code of DEMO H-mode discharges (tungsten divertor and wall) are performed considering the influence of seeding impurities with different atomic numbers: Ne, Ar and Kr on the DEMO scenarios. The approach is based on integrated numerical modelling using the COREDIV code, which self-consistently solves radial transport equations in the core region and 2D multi-fluid transport in the SOL. In this paper we focus on investigations how the operational domain of DEMO can be influenced by seeding gasses.

Simulations with the updated prompt re-deposition model implemented in the code show that only for Ar and Kr, for high enough radial diffusion in the SOL, it is possible to achieve H-mode plasma operation (power to the SOL> L-H transition threshold power) with acceptable level of the power to the target plates. For neon seeding such regime of operation seems not to be possible.

Keywords:

1. Introduction

The operating point of a future DEMO fusion reactor will be optimized to fulfill the following criteria: 1) maximize the fusion power output, 2) allow for an H-mode operation through keeping the power flux to scrape-off layer (SOL) considerably higher than H-L transition threshold and 3) minimize the heat load to divertor plates [1]. One of the ways to manage the plasma performance and power exhaust to realize these requirements is by controlling the impurity content in the plasma.

From our earlier simulations [2], it comes out that the level of the power going to the SOL depends strongly on the tungsten radiation in the core, the latter being quite significant. It is expected that by increasing the seeding level, the radiation in SOL is increased leading to the decrease of power to plate and tungsten production. But the smaller tungsten concentration in the core results in the reduction of the tungsten radiation and increase of the power to SOL, which in turn, increases the tungsten production. In order to account properly on this strongly nonlinear behavior, only integrated approach can to be used taking into account the coupling between the core and edge regions.

In this paper, numerical simulation with COREDIV code [3] of DEMO discharges with tungsten as armor material (divertor and wall) for H-mode scenarios are presented. Calculations are performed for inductive DEMO 2012 steady-state configuration [4] and focus on two especially important issues related to DEMO operation: finding an appropriate kind and amount of seeded impurity to mitigate the heat load to the divertor to an acceptable level (5 – 10 MW m^{-2}) [5], [6] and replacing the intrinsic W impurity in the core which by high line radiation might lead to radiative collapse [7]. In existing devices (JET, ASDEX-Upgrade) a beneficial influence of nitrogen puffing on lowering the L-H threshold, improvement in the pedestal stability and reduction of the divertor heat load was observed [8]. This results were reproduced by numerical modeling by COREDIV code [9], which brought some insight in the JET operational domain [10]. COREDIV was applied also to DEMO scenarios to study various impurities (Ne, Ar, Ni) and the main conclusion was that for DEMO an element with atomic number Z ≥ 18 would be suitable [2], [3]. Referring to a recent publication on an optimal impurity mix for DEMO [1] we would like to present here a systematic study on Kr seeding and compare it to Ar and Ne impurities analyzed before. Additionally, the calculations included a simple model for prompt re-deposition processes for W on the divertor plate, as described below.

2. Model

The simulations were performed by using COREDIV code which solves 1D radial transport equations of plasma and impurities in the core region and 2D multifluid transport in 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 [3].

The prompt re-deposition process in case of W plate was recently modeled with PIC and Monte Carlo methods [11], [12], but here we use a relatively simple description taking into account only single ionization processes. The fraction of the re-deposited W to all sputtered W atoms f_{prompt} is given by

$$f_{prompt} = 1 + \frac{{}_{ion}}{{}_{W^{+}}}{}^{2}{}^{1} , \qquad (1)$$

where λ_{ion} is the ionization length calculated from ionization frequency and average thermal velocity and ${}_{W^{+}}$ is the gyro-radius of singly ionized W in magnetic

author's email: Roman.Zagorski@ipplm.pl

field [13], [14]. The resulting f_{prompt} is incorporated into W sputtering yield Y as follows: $Y' = Y\left(1 \quad f_{prompt}\right)$.

The simulations are prepared for the European DEMO1 configuration with the following main parameters [4]: toroidal radius R_T = 9m, minor plasma radius a =2.49 m, plasma current I_p = 16.79MA, toroidal magnetic field B_T = 6.5T, elongation ε = 1.56, volume averaged electron density $<n_e>_{VOL}$ = 0.933x10^{20}m^{-3}, separatrix density n_e^{sep} = 40%$<n_e>_{VOL}$, H-factor (IPB98(y,2)) H_{98} = 1.1 and auxiliary heating power P_{aux} equal to 50 MW.

3. Results and discussion

In the recent JET ILW experiments with nitrogen and neon seeding [15, 16], high radiation in the SOL (> 50% of total radiation) is observed. In order to reproduce by COREDIV this experimental situation it was necessary to increase the value of radial anomalous transport in the SOL, from our standard value of D_{SOL}=0.25m/s^2 to D_{SOL}=0.5m/s^2. It has been also shown in the Kukushkin's study for ITER [17] that the increase of the radial transport in the SOL results in the extension of the ITER operational space.

3.1 Influence of the radial (anomalous) transport in the SOL

In this part, the influence of the radial transport in the SOL on the DEMO working space is investigated. We have done simulations for two different values of the radial diffusion in SOL D_{SOL} =0.25m/s^2 and 0.5m/s^2 which leads to the λ_q values of about 5 mm and 6 mm, respectively. Some global plasma parameters for two different seeding impurities: argon and krypton are presented in the Fig.1. The main effect of the increased transport is related to the improvement of the screening efficiency of the SOL, which has important consequences for the discharge parameters.

First we note that better confinement of tungsten in the SOL, reduces W concentration in the core and correspondingly the W radiation. Alpha power (Q-factor) is weakly affected by the SOL transport, and is only slightly reduced due to dilution effect by seeding impurity. Therefore the power crossing separatrix (P_{SOL}) increases significantly for both impurities (Ar and Kr), but only for argon it stays always above the power threshold for the L-H transition (P_{L-H}=151 MW [Martin]) whereas for Kr seeding P_{SOL} only marginally exceeds the threshold close to the highest allowed seeding level. Important consequence of the higher P_{SOL} is the possibility of working with higher puffing levels and the power to divertor plates (P_{plate}) can be reduced to technologically acceptable value (< 50 MW, assuming 5 m^2 of wetted area (10% larger than in ITER) with large enough seeding. In case of Ar seeding and for larger radial transport in the SOL (D_{SOL} =0.5m/s^2) very favorable conditions might develop with strong seeding. It appears that for sufficiently large Γ_{puff} (>11 × 10^{22}el/s) P_{SOL} increases well above P_{L-H} threshold whereas P_{PLATE} is reduced allowing for the development of the semi-detached plasma in the divertor region with T_{PLATE} e < 3 eV and total radiation above 78%. In case with Kr seeding, similar conditions can be achieved only for very large seeding Γ_{puff}> 13x10^{22}el/s.

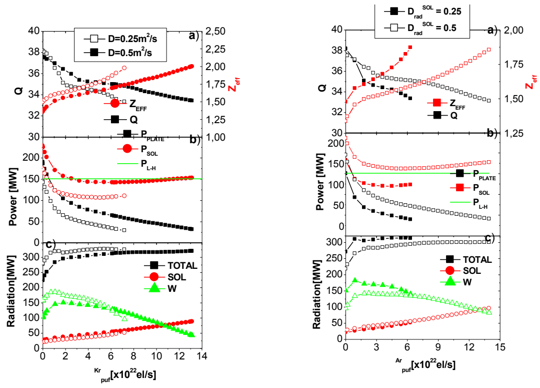

Fig. 1. Plasma parameters as functions of Kr (left) and Ar (right) injection rates and different SOL diffusion coefficient: (a) Q-factor and Zeff , (b) power to plate (PLATE), to SOL (SOL) and L–H power threshold (P^{L-H}) and (c) radiation in SOL, W radiation in the core, and total radiation

3.2 Effect of the seeding impurity type: Ne, Ar, and Kr

In the present day experiments, different gasses have been successfully used to mitigate the heat loads to the target plates: N, Ne, Ar, Kr [18]. In DEMO reactor, one would need good radiators in the SOL region like N or Ne but simultaneously it might be necessary to replace the W radiation in the core which can be done only by higher Z impurities (Ar, Kr, Xe). In order to give some insight on the proper impurity choice for fusion reactor, we have done simulations for three different gasses with different atomic number: Ne (Z=10), Ar (Z=18) and Kr (Z=36) assuming favorable situation with higher SOL diffusion (D_{SOL} =0.5m/s^2). Some plasma parameters are shown in the Figs. 2 and 3.

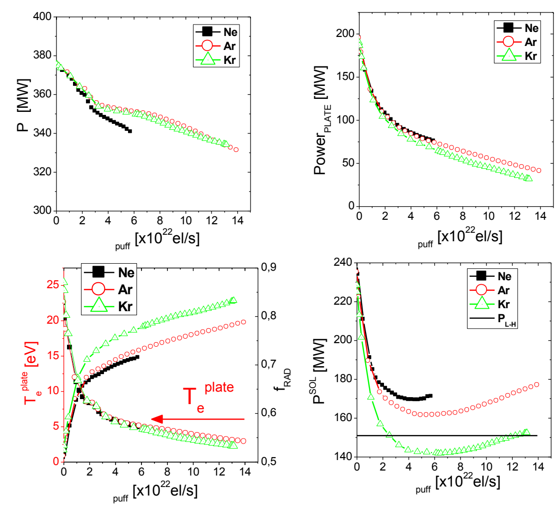

Fig. 2. Plasma parameters versus seeding level for Ne, Ar and Kr:(a) alpha power P_α(b) power to plate (P_{PLATE}), c) radiation fraction and plate temperature, and d) power to SOL (P_{SOL}).

author's email: Roman.Zagorski@ipplm.pl

First, it should be noted that the overall fusion performance (alpha power, Q- factor) is weakly affected by the impurity type. Neon leads to the lowest core radiation (highest power to the SOL) but seems to be not acceptable as the seeding gas in the fusion reactor due to strongly reduced radiation efficiency leading to an excessive heat loads to the target plates.

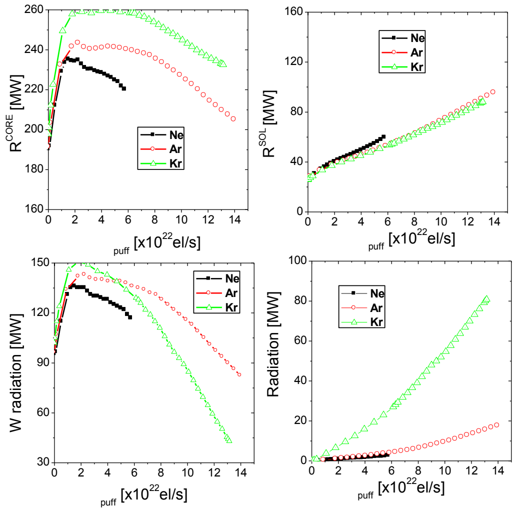

Fig. 3. Plasma parameters versus seeding level for Ne, Ar and Kr with radial diffusion D=0.5m^2/s: (a) core radiation (R^{CORE})(b) SOL radiation (R^{SOL}), c) W line radiation in the core and d) Ne, Ar and Kr radiation in the core.

In case of both, Ar and Kr impurities, the power to the plate can be reduced to an acceptable values with seeding. However, since Kr radiates effectively in the SOL and core regions, it mitigates the heat load more efficiently than Ar. Moreover, Kr is able also to mitigate significantly the W production (radiation) approaching 82% of the total radiation losses. But this significant core radiation in the case of Kr, leads to strong reduction of the power crossing the separatrix, which remains below the P_{L-H} threshold for most of the seeding levels. Therefore, control of the H-mode operation might be more difficult/critical in the case of Kr as compared to argon.

3.3 Influence of the prompt re-deposition

All the results discussed so far, have been obtained without considering the possible reduction of the W sputtering yield duo to prompt re-deposition process. In order to take this phenomena into account, a simply model for prompt re-deposition has been implemented in the COREDIV code (see sec.2).

In the Fig.4, simulation results are shown for the cases with and without prompt re-deposition model and for all three impurities: Ne, Ar and Kr. It can be seen that the effect of the reduced sputtering yield duo the prompt-re-deposition process is only important for relatively small levels of seeding, usually outside the DEMO operational window. It improves the fusion performance (larger Q-factor) due to reduced dilution effect with reduced W production.

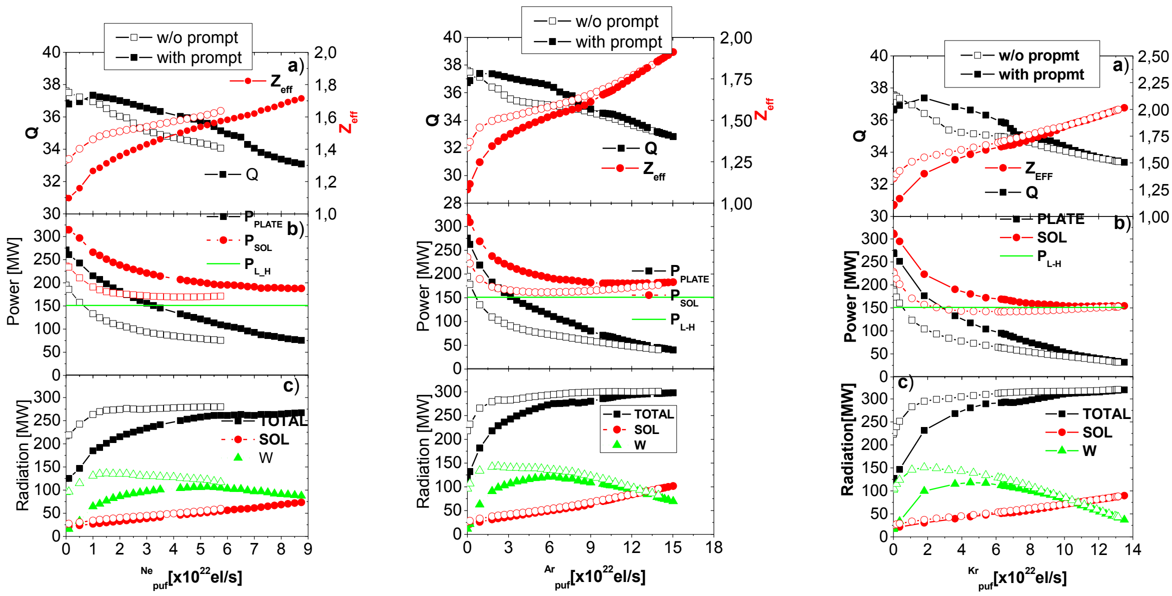

Fig. 4. Plasma parameters as functions of impurity injection rates and without and with prompt re-deposition for Neon (left), Argon (middle) and Krypton (right): (a) Q-factor and Z_{eff} , (b) power to plate (P^{PLATE}), to SOL (P_{SOL}) and L–H power threshold (P_{L-H}) and (c) radiation in SOL, W line radiation in the core, and total radiation

Simultaneously, the W radiation is smaller and the power crossing separatrix rises to be above P_{L-H} threshold for all considered impurities. However, the influence of the prompt re-deposition model on the DEMO working point is relatively week, since the reduction of the power to the target plates requires strong seeding, which leads to plasma condition in the divertor, close to target plates, with low plasma temperature (2-3 eV). Consequently the

author's email: Roman.Zagorski@ipplm.pl

sputtering reduction factor due to prompt re-deposition process is close to one and the sputtered tungsten flux is hardly reduced (see Fig.5).

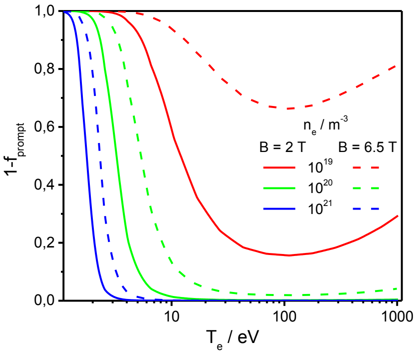

Fig. 5. The fraction of not promptly redeposited W ions escaping from divertor plate as a function of temperature in 2 and 6.5 T magnetic field (DEMO scenario) for different electron densities.

In the case with Ne seeding, prompt re-deposition model allows for significantly larger seeding levels, but still the DEMO working point could not be achieved (P_{PLATE}<50MW). For Ar seeding the prompt re-deposition model has almost not influence on the working space. However for Kr seeding, the prompt re-deposition leads to significantly larger operational window due to increase of the power crossing separatrix, which stays above the P_{L-H} threshold.

3. Conclusions

The COREDIV code has been used to simulate DEMO inductive discharges with impurity seeding. The work was motivated by the need to develop DEMO scenarios which satisfy simultaneously the requirement for high radiation fractions and good H-mode confinement. It appears that the COREDIV code is well suited to analyze DEMO seeded discharges due to its ability to perform self-consistent simulations of the core and edge regions of the reactor, and taking into account the influence of different impurities (seeded and sputtered) on the discharge parameters. Simulations with the updated sputtering model taking into account prompt re-deposition process, show that only for Ar and Kr, for high enough radial diffusion in the SOL, it is possible to achieve H-mode plasma operation (power to the SOL > L-H transition threshold power) with acceptable level of the power to the target plates. For neon seeding such regime of operation seems not to be possible.

4. Acknowledgments

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author's email: Roman.Zagorski@ipplm.pl