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I Ivanova-Stanik et al.

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Analysis on the Optimum Impurity Mix for the DEMO scenario

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In this paper numerical simulations with COREDIV code, which self-consistently solves radial transport equations in the core region and 2D multi-fluid transport in the SOL of DEMO discharges in full tungsten environment (W divertor and wall) for H-mode scenario has been performed with different impurity seeding. The optimal impurity mix for reactor would require the use of high Z impurity (low dilution, higher P_α) in core and low/medium Z impurity radiating in the SOL region. In this paper we focus on investigations how the operational domain of DEMO can be influenced by different seeding (Ar, Xe) and mix gasses.

In case of Xenon seeding, H-mode operation can NOT be achieved for standard radial diffusion (D_{SOL}=0.5m^2/s) in the SOL. In the simulation, we have considered combined seeding of Ar (good radiator in SOL) and Xe (good radiator in core). In order to find the optimal impurity mix, simulations have been performed in such a way that for a few fixed levels of Xe puff, Ar puff has been increased from zero to the maximum value allowed by the code stability. For combined seeding: xenon + argon working point for DEMO can be found.

Keywords: numerical modeling, edge plasma, impurity seeding, fusion reactor

1. Introduction

The concept of the fusion reactor has to be based on an optimized set of key parameters. The radiative exhaust of energy in fusion reactor (DEMO) by sputtered and by externally seeded impurities is considered as possible way of spreading energy over wall area. The operating point of a future DEMO fusion reactor with impurity seeding needs to be optimized to fulfill the following criteria: first - the power reaching the divertor needs to be smaller than technology limit (the heat load to the divertor should be bellow the acceptable level of 5 – 10 MW/m^2[1]); second - good confinement at the working point in H-mode, which requires that the power to the scrape-off layer SOL (power crossing the separatrix) is higher than the threshold power for L–H transition ($P^{SOL} > P_{L\text{-}H}$) and third – maximum of the fusion power. 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.

It has been concluded in Ref. [2], that the level of the power going to the SOL depends strongly on the tungsten radiation in the core, which is quite significant (about 50% of the core radiation). We analyzed for inductive DEMO 2012 steady-state configuration [3], influence of different impurities: neon, argon, nickel, [4] and main conclusion is that only impurity with atomic number Z ≥ 18 would be suitable. For EU DEMO1 2013 configuration systematic study of Kr seeding in comparison to Ar and Ne impurities has been performed in Ref. [5]. Krypton radiates effectively in the SOL and core regions and it mitigates the heat load more efficiently than Ar. The significant core radiation in the case of Kr, leads to the strong reduction of the power crossing the separatrix, which remains below the $P_{L\text{-}H}$ threshold for most of the seeding levels.

In this paper, we continue numerical simulations with COREDIV code [2] of DEMO discharges with tungsten as armor material (divertor and wall) for H-mode scenarios with Xe and combined Xe+Ar 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. Calculations are performed for EU DEMO1 2015 steady-state configuration [6] and focus on analyzing of the optimum impurity mix: Argon and Xenon.

2. Model

The simulations were performed using COREDIV code which is based on an integrated approach. It couples 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. [2,4] 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 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

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formation in the edge region 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, T, He, Xe, Ar and W at the target plate. The model provides main plasma parameters, from a number of inputs like the heating power, the average density and the confinement enhancement factor H_{98}. In the Ref.[7] the most important system code parameters of flat-top phase are listed including values for the designs EU DEMO1 2015 are present.

The following main parameters are: toroidal radius R_T = 9.1m, minor plasma radius a =2.926 m, plasma current I_p = 19.6MA, toroidal magnetic field B_T = 5.667T, elongation ε = 1.59, volume averaged electron density $<n_e>_{VOL}$ = 0.793x10^{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 [8, 9], 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^2/s to D_{SOL}=0.5m^2/s. It has been also shown in the Kukushkin's study for ITER [10] 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 and prompt re-deposition phenomena

In this part, the influence of the radial transport in the SOL on the DEMO working space is investigated for the case with Xe seeding. We have done simulations for three different values of the radial diffusion in SOL D_{SOL} =0.25; 0.5 and 1.0m^2/s which leads to the λ_q values in the midplane of about 5÷ 6mm, respectively. Some global plasma parameters as functions of Xe concentration for different radial SOL diffusion coefficient: (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 radiation in the core, and total radiation are presented in the Fig.1.The vertical dashed line indentifies, the starting working space for DEMO reactor in H-mode with acceptable level of the power to the plate for case D_{SOL} = 1m^2/s. 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.

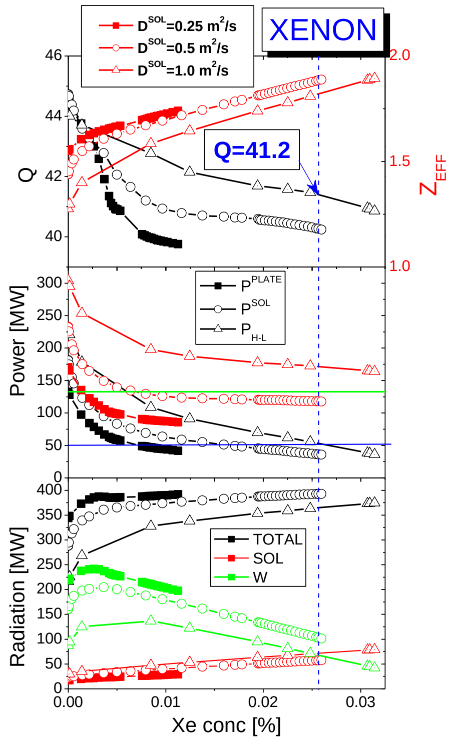

Fig. 1. Plasma parameters as functions of Xe concentration for different radial SOL diffusion coefficient D_{SOL}=0.25; 0.5; 1.0m^2/s: (a) Q-factor and Z_{EFF}, (b) powers to plate, to SOL and L–H power threshold and (c) radiation in SOL, W radiation in the core, and total radiation

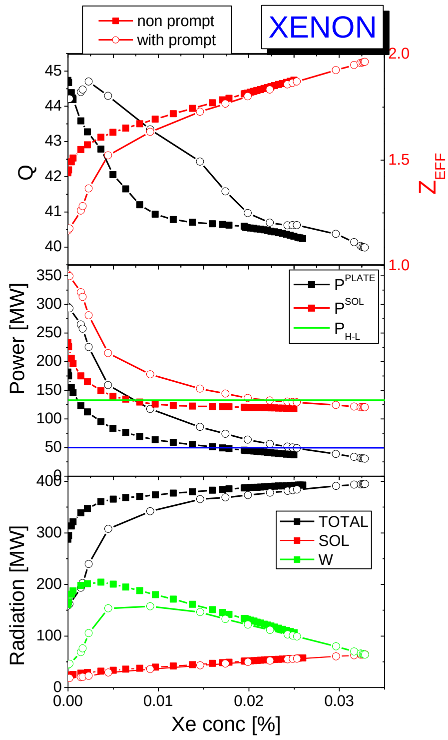

Fig. 2. Plasma parameters as functions of Xe concentration with (open symbol) and without (full symbol) prompt re-deposition: (a) Q-factor and Z_{EFF} , (b) power to plate, to SOL and L–H power threshold and (c) radiation in SOL, W radiation in the core, and total radiation

First we note that for higher radial diffusion in the SOL, W concentration in the core is reduced and correspondingly the W radiation from 210MW to 130MW (Fig.1 (c)) for the same Xe concentration of

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0.011%. Alpha power (*Q*- factor) (Fig1.a) is weakly affected by the SOL transport, and is only slightly reduced from 45 to 41 due to dilution effect by seeded impurity for D=0.5m^2/s. The power crossing separatrix (P^{SOL}) increases significantly, but only for the case with largest radial diffusion in the SOL D_{SOL} = 1.0m^2/s and it stays always above the power threshold (based on Martin's law [11]) for the L-H transition (P_{L-H}=132 MW). Important consequence of the higher P^{SOL} is the possibility of working with higher puffing levels (higher Xe concentration) and the power to divertor plates (P^{PLATE}) can be reduced to technologically acceptable value (< 50 MW, assuming 5 m^2 of wetted area (20% larger than in ITER) with large enough seeding. We observe, that with the increase of the radial diffusion in the SOL, the level of the Xe concentration, for which P^{PLATE} < 50MW increases from 0.006% to 0.026%. It appears that only for the case with highest D_{SOL} for Xe concentration larger than 0.026% P_{SOL} is higher than 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} < 3 eV and total radiation of about 80%.

3.2 Influence of the prompt re-deposition

The prompt re-deposition for DEMO discharges with Ne, Ar and Kr seeding are analysed in Ref. [5]. For Ar seeding the prompt re-deposition model has almost no influence on the operational point, 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.

In this apart, we analyse the influence of the prompt re-deposition for the case with Xe seeding. In the Fig.2, simulation results are shown for the cases with and without prompt re-deposition model for the situation with radial diffusion in the SOL D_{SOL} = 0.5m^2/s. It can be seen that the effect of the reduced sputtering yield due the prompt-re-deposition process is only important for relatively small gas puff with Xe concentration < 0.02%, usually outside the DEMO operational window (P^{PLATE} >50MW). 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 semi-detachment plasma condition in the divertor when the prompt-redeposition is not very effective.

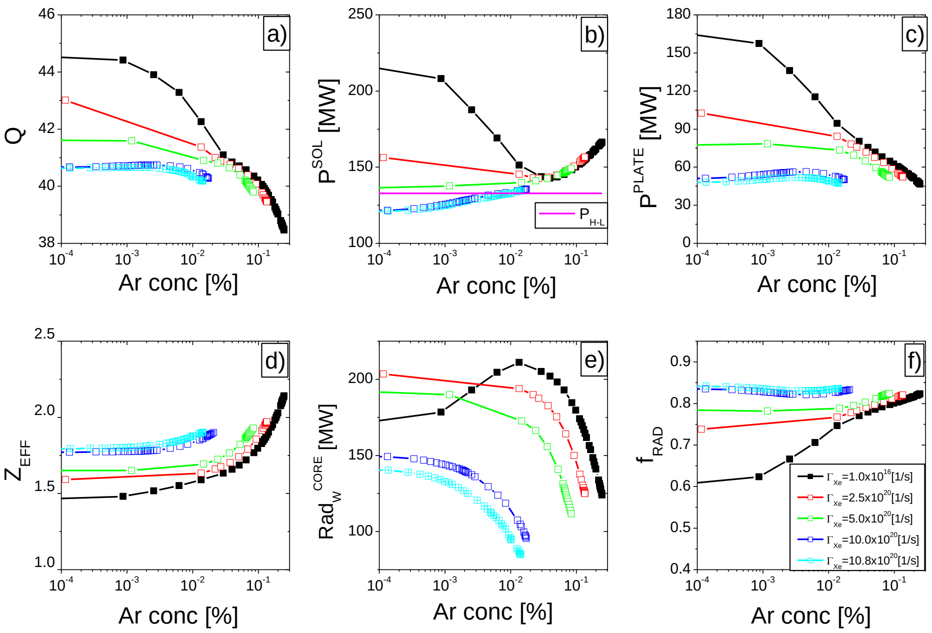

Fig. 3. Plasma parameters versus Ar concentration with radial diffusion D_{SOL}=0.5m^2/s for different level on Xe gas puff: (a) Q-factor , b) P^{SOL} ,c) P^{PLATE}, d) Z_{EFF} , e) W line radiation in the core R_W^{CORE}), f) radiation fraction (f_{RAD})

3.3 Effect of the combined seeding impurity: Ar, and Xe

First, for the low atomic number (*Z*) impurities (Ne, Ar) the radiation occurs mostly in the scrape-of- layer, whereas for high Z impurities (Kr, Xe, W) it appears mostly in the central region (core). For divertor power studies low core radiation level is helpful to maximize the power crossing the separatrix and to keep a stable H-mode operation. But, on the other hand, high Z-impurities generally leads to lower dilution of the main plasma, which is important for fusion reactor. To this aim, experiments have been carried out on ASDEX Upgrade with combined N and Kr seeding for divertor control to further reduce the power flux to the scrape of layer [12]. Krypton seeding is increased in the

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discharged step by step with 3 different puffing levels substituting simultaneously the (feedback -controlled) N seeding level [12, 13]. Optimum impurity mix is analysed in Ref. [14] with code ASTRA, for the W concentration $C_W = 10^{-5}$ and $C_{He} = 0.05$. Contrary to the mentioned analyses, the W concentration in our simulation is self-consistently regulated by sputtering and depends on impurity flux to divertor.

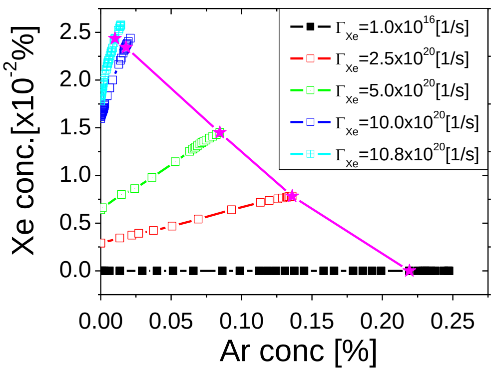

Fig. 4. Working point (power to SOL higher than the power threshold and power to plate <50MW) for DEMO1 (magenta line) for different Xe puff levels versus Ar and Xe concentration. Start point marks the identified optimum impurity mix.

The main simulated plasma parameters: Q-factor, power to SOL and plate, effective charge (Z_{EFF}), tungsten radiation and radiation fraction (f_{RAD}) versus Ar seeding level at different levels of Xe puffing (Γ_{Xe}= 0.0001; 2.5, 5.0, 10.0; 10.8 x 10^{20}1/s) are shown in Fig. 3. The increase of the Ar puff for Xe puff levels Γ_{Xe}= 10.0; 10.8 x 10^{20}1/s leads to the increase of the power crossing separatrix above the L-H power threshold for Xe puff levels and helps to achieve H-mode working point. This is the effect of the replacement of the W radiation in the core by Ar radiation in the SOL region. The simulation results indicate, that with increase of the Xe puff level, strong reduction of the power to the plate is observed. However, the best fusion performance is achieved for xenon influx larger than $\Gamma_{Xe}>5x10^{20}$ 1/s.

The use of the Xe and Ar puff enables to increase Q factor from 38.2 (only Ar puff) to 40.2 for combined Ar+Xe seeding. For $\Gamma_{Xe} > 10.8x10^{20}$ 1/s with increase on the Ar seeding, no effectively increase power cross separatrix to higher on power threshold and the possibility to work in H-mode is not observed in numerical simulation.

In the Fig 4, we show changes to the Xe concentration for different constant Xe puff with increase of the Ar puffing rate. Star points mark the threshold values for the Ar concentration from which it is possible to work in DEMO reactor in H-mode with acceptable level of power load to target plates. It should be noted also, that the increase of the Xe concentration for constant Xe impurity puff with increase of the Ar puff is related to the effect of the thermal forces – reduction of the edge temperature induced stronger temperature gradients and hence thermal force.

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3. Conclusions

The COREDIV code has been used to simulate DEMO inductive discharges with Xe and mixed Ar+Xe seeding. 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 prompt re-deposition process included show that in the case with Xe impurity puff prompt redeposition has no influence on the DEMO working point. For Xe seeding only, 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 only for the case with highest radial diffusion in the SOL (D_{SOL}=1m^2/s). For the case with impurity mix (Ar+Xe) the working point can be achieved for lower value of D_{SOL}=0.5m^2/s but there is upper limit on Xe concentration of 2.5x10^{-4}.

4. Acknowledgments

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