Analysis of the influence of the different impurity seeding on the burn-up fraction and plasma confinement in the EU DEMO reactor

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This work describes integrated numerical modelling applied to DEMO discharges with tungsten wall and divertor, using the COREDIV code, which self-consistently solves 1D radial transport equations of plasma and impurities in the core region and 2D multi-fluid transport in the SOL. The model is self-consistent with respect to both the effects of impurities on the α-power level and the interaction between seeded (Ar, Kr and Xe) and intrinsic impurities (tungsten, helium). This work is to analyse the influence of the impurity seeding on the burn-up fraction and plasma confinement in EU DEMO reactor. For the simulation with constant electron density at the separatrix, it is found that impurity seeding has a small influence on the burn-up fraction, which remains around 6 – 7%., but fuelling source is reduced from 2.7 to 2x10^{22} 1/sec when moving from lowest to highest seeding level. The degradation of confinement for high Z seeding impurity, which is correlated to radiation in the core (due to seeded Kr and Xe) is observed. Better confinement for Ar at middle and high seeding level is observed in comparison to the case without seeding, because Ar radiation is small in the core (about 40-55MW).

Keywords: numerical modeling, confinement, impurity seeding, fusion reactor, burn-up fraction

1. Introduction

Divertor heat load is a critical issue for the high-power operation of future reactor-relevant machines, as DEMO. The impurity seeding provides an effective mean of reducing the divertor target flux by: first enhancing core/pedestal radiation and second increasing the radiation in the divertor scrape-off layer (SOL) by cooling the plasma near the target plate. Both the core and divertor/SOL plasma impurity enrichment is strongly dependent on the impurity species [1, 2]. The impurity seeding has also influence on the plasma confinement. Experiments with impurity seeding have been carried out on machines worldwide, e.g. C-Mod, JET, EAST, DIII - D, JT60-U and AUG with different effects on plasma confinement. Recently, the energy confinement improvement with low or medium *Z* impurity seeding has been reported in metallic wall devices, such as JET [3, 4] and ASDEX Upgrade [5, 6]. Indeed, depending on the specific experimental situation, in some cases the H_{98} factor decreases and in some others it may increase. For example, in ASDEX Upgrade experiments, the nitrogen impurity seeding does not only protect the divertor tiles but also considerably improves the performance of H-mode discharges by up to 25%. The energy confinement increases up to H_{98}-factors approaching 1.3 [5]. At JT-60U better confinement with Ar seeding was achieved, accompanied by peaked core density profiles, as well [7]. Better confinement is sustained at high density by argon seeding accompanied by higher core and pedestal temperatures. The effects of low-Z and high-Z impurities on divertor detachment and plasma confinement in the DIII-D tokamak on type-I ELMy H-mode plasmas is analyzed in Ref. [8] and for Ne or Ar seeding, it tends to lead to confinement degradation, especially after the transition to detachment, with normalized confinement factor H_{98} smaller, than that in the non-seeded and N seeded plasmas. For nitrogen seeded plasmas, the confinement shows an inverse scaling with the power ratio for lower gas puffing rates, while at strong N gas puffing, a 20% confinement loss at the onset of detachment is observed, followed by a recover of the inverse scaling.

The demonstration of electricity production in a DEMO fusion plant with closed tritium fuel cycle around the middle of this century represents primary objective of the fusion development program in Europe [9]. One of the key challenges for a fusion power plant is the need to significantly increase the fuel burnup fraction at least above 5% in order to make fusion energy sufficiently attractive [10, 11]. A low burn-up fraction is not a problem in terms of tritium self-sufficiency. A sufficiently high tritium burn-up fraction is necessary for sustaining tritium self-sufficiency. Tritium burn-up fraction is negatively correlated with the required Tritium Breeding Ratio (TBR) for tritium self-sufficiency, which needs to be lower than the achievable TBR of the reactor blankets. The point is that, if the burn-up fraction is too low, the T inventory on site becomes huge, and this creates issues in terms of nuclear safety and licensing. Therefore, one of the most important missions for DEMO operation is mainly determined by tritium burn-up fraction (f_{br}) and the design of blanket and tritium reprocessing systems. It is difficult to estimate the quantities of tritium needed for start-up, as values are heavily dependent on the advances in technology allowing for improved performance parameters in tritium burn-up fraction, recycling time (of

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the tritium systems), fueling efficiency, and Tritium Breeding Ratio (TBR). With technical advancements to the point where DEMO concept reactor would operate at 2.4 GW, with a 5% burn-up fraction, a 1-h tritium processing time, and a net TBR of above unity, the tritium required for full power start-up is still expected to be around 8 kg [12], but more optimistic calculation 3.9 kg exists as well, for example in Ref. [13]. Conditions necessary to achieve deuterium-tritium fuel self-sufficiency in fusion reactors are derived through extensive modeling and calculations of the required and achievable tritium breeding ratios as functions of the many reactor parameters and candidate blanket design concepts. For example, the inventory can be reduced by attaining high tritium fractional burn-up. Fueling and burn-up fraction evaluation requires complex and integrated models due to strong coupling between fueling, helium transport and power exhaust.

For this reason, the aim of this work is to analyse the influence of the different impurity seedings on the plasma confinement and burn-up fraction. In this paper, numerical simulations with COREDIV code [14] of EU-DEMO discharges with tungsten as armor material (divertor and wall) for H-mode scenarios with Argon (Ar), Krypton (Kr) and Xenon (Xe) seeding are presented. The work was motivated by the need to develop EU DEMO scenarios which satisfy simultaneously the requirement for high radiation fractions, good H-mode performance and high burn -up fraction.

2. Model

The 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 effects of the impurities on fusion power significantly affect 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. [1, 14] and only the main points of the model are reported here. The heating due to alpha power is calculated self-consistently considering the dilution effect due to helium and impurities accumulation. The energy and particle transport are defined by the local transport model with prescribed profile of transport coefficients considering the barrier formation in the edge region and which reproduces a prescribed energy confinement law. Our model includes both the hot plasma and the scrape-off layer (SOL) plasma and applies empirical scaling relations for the transport coefficients. It should be noted that transport level in the core is determined by the chosen energy confinement scaling law. More precisely the ion and electron conductivities are defined by the formula: $\chi_{e,i}^{an} = C_E(a^2/\tau_e)\times F(r)$, where a is the minor radius, τ_e is energy confinement time calculated from the scaling law formula (IPB98$_{(y,2)}$) in absence of impurities and the function $F(r)$ describes the parabolic like profile of the conductivity coefficients with a drop near the separatrix due to H-mode barrier formation. In the model we have two options. In one scenario, the parameter C_E is adjusted to keep the calculated confinement time obtained from the solution equal to the value defined by the scaling law in absence of impurities. Second option is to fix C_E (and thus $\chi_{e,i}^{an}$) and therefore the confinement will be changed accordingly with changes to the seeding level. By increasing the radiation with impurity seeding, the net heating power decreases, thus when using the first option transport is reduced in order to keep the total plasma energy constant. In the case the total plasma energy is set to remain constant with increasing the impurity seeding rate the net energy confinement time ($W_{th}/(P^{TOT} - P^{CORE})$, where W_{th} is thermal energy, P^{TOT} is total input power and P^{CORE} is total radiation power in the core)) and the effective τ_p (effective particle residence time) increase during the impurity seeding scan since the power lost into radiation in the plasma core generally increases too.

With the second option instead, transport coefficients are fixed, then the total plasma energy might change. In the SOL, 2D multifluid equations are solved considering plasma recycling in the divertor and sputtering processes due to all ions: D, T, He, seeded impurities (Ar, Kr, Xe) and W at the target plate. In order to keep the prescribed plasma density at the separatrix (at stagnation point), the hydrogen recycling coefficient (R_H) was iterated accordingly. For helium, the recycling was assumed to be dependent on the hydrogen recycling coefficient according to the simple formula: $R_{He} = mR_H - (m - 1)$ in standard simulations and our old work [14 - 16], $m = 2$ was used. The He confinement time is defined by $\tau_{He} = N_{He}/(\Gamma_{He}\times S_{sep})$, where N_{He} is the number of helium particles in the plasma, Γ_{He} is the He flux across the separatrix and S_{sep} is the surface area of the separatrix. In Ref. [16], we shown that the helium recycling coefficient has strong influence on the He confinement time. The He confinement increases linearly from 7.25 s to 26.9 s for R_{He} values going from lowest to highest recycling coefficient.The burn-up fraction in our model is defined as: $f_{br} = 2\Gamma_\alpha/\Gamma_{ful}$, where Γ_α is α-particle source and Γ_{ful} is the fueling source.

3. Numerical results

The simulations are prepared for the EU DEMO1 2018 configuration with the following main parameters: toroidal radius R_T= 9.0 m, plasma radius a = 2.9 m, plasma current I_p = 17.75 MA, toroidal magnetic field B_T =5.85 T, elongation – 1.65, electron density $<n_e>_{VOL}$ = 7.26×10^{19}m^{-3}, separatrix density was kept at the 40% level of the volume average (n_e^{sep} = 0.4 $<n_e>_{VOL}$) and for standard case is n_e^{sep} = 2.9×10^{19}m^{-3}, the confinement factor H-factor (IPB98(y,2) [16]) was equal to H_{98} = 1.1 whereas the auxiliary heating power was set to P_{aux} =50 MW. In our simulation, we have assumed that 28.4% of alpha power (P$_\alpha$) is transfer to ions and remaining 71.6% to the electrons [18].

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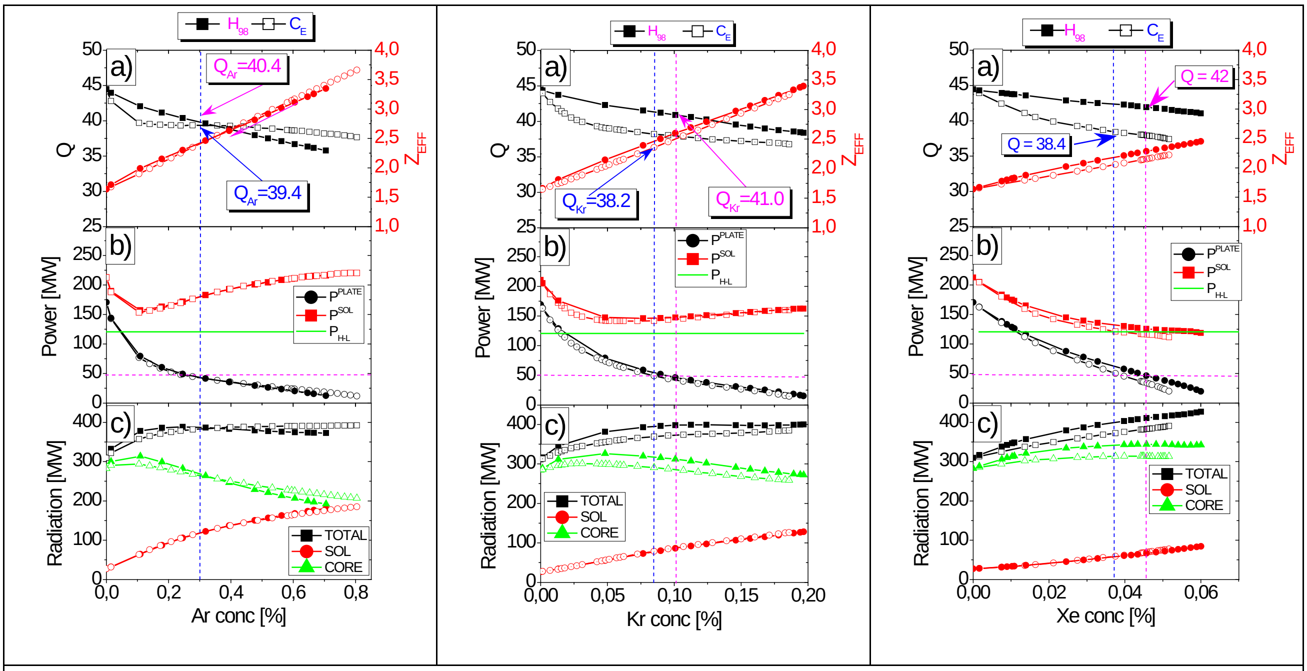

Fig. 1. Plasma parameters versus impurity seeding concentration (Ar (left), Kr (central) and Xe (right)) for two different transport schemes: $H_{98(y,2)}$ = 1.1 (full symbols) and CE = constant (open symbols): (a) Q-factor and Z_{EFF}, (b) power to plate (P^{PLATE}), to SOL (P^{SOL}) and H–L power threshold (P_{HL}) and (c) total, SOL and core radiation.

3.1 Influence of the transport model on the confinement

The He source profile depends on plasma fuel density and temperature. As previously discussed, simulations are prepared for two different transport schemes: constant H_{98} factor and constant transport coefficient (C_E). In Fig. 1., the main plasma parameters: Q – factor, the Z_{EFF} volume averaged in the core, P^{PLATE}; P^{SOL} (being integrals of power flux across target and separatrix, respectively) and integrals of radiated powers (in SOL, in the core, and total radiation) for both transport schemas are shown for different seeding gases: argon (Ar) (left), krypton (central) and xenon (right).

Vertical lines (blue line for case with H_{98} = const and magenta line for case C_E =const) in Fig. 1. indicates working point (when simultaneously $P^{SOL} > P_{HL}$ (power threshold for H-L transition) and $P^{PLATE} <$ 50MW). It comes out, that for Ar seeding, the influence of the transport model on the results is relatively small. First, the operation region starts at the same Ar concentration with almost the same Q – factor (about 1 difference). For Ar concentration higher than 0.4%, the Q factor for case C_E =const is higher in comparison to the situation with H_{98} = const. This is the effect of improvement in plasma confinement. For the maximum Ar concentration in both cases P^{PLATE} is lower than 30MW and W radiation in core is less than 20MW (Fig.2a). The important feature of Ar seeding case is that 50% of the radiation occurs in the SOL region and radiation fraction amounts up to 87%.

For the cases with Kr and Xe seeding, we observe that Q-factor for the case with constant transport is smaller in comparison to the case with constant H_{98} – factor for all impurity seeding levels. This difference goes up to 9% for maximum Xe seeding (see Fig 1(a) right). This is the reason, why in the case with constant H_{98} it is possible to put more Kr and Xe seeding gasses. The core radiation increases, and SOL radiation decreases with increasing the atomic number of the impurity.

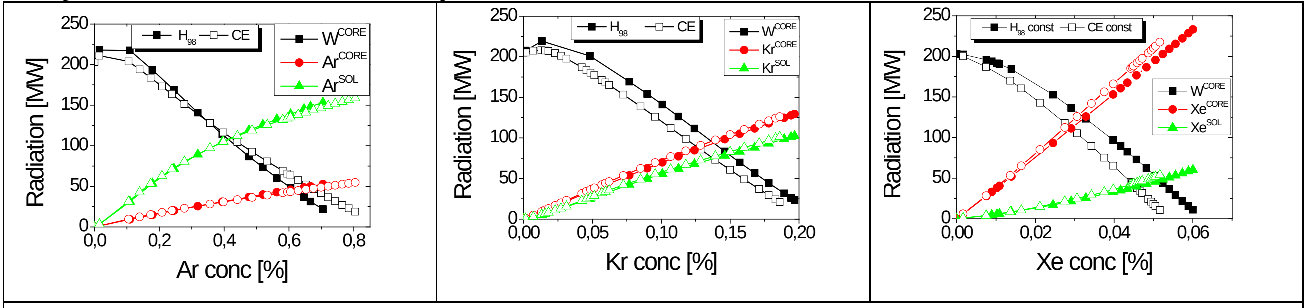

Fig. 2. Plasma radiation versus impurity concentration for Ar (left), Kr (central) and Xe (right) for two different transport schemes: $H_{98(y,2)}$ = 1.1 (full symbols) and CE = constant (open symbols).

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In the Fig. 2., radiation by W and seeding impurity in the core and SOL regions: argon (left), krypton (central) and xenon (right) are presented. We observe the increase of the SOL radiation with decrease of the atomic number. For all seeding gasses (Ar, Ke and Xe), W radiation is steadily replaced by impurity radiation and for maximum impurity seeding W^{CORE} is smaller than 20MW. For the case with Xe seeding and for $C_{Xe} > 0.05\%$ (see Fig.2. (right)). Xe radiation in the core is higher than W radiation without seeding. The radiation by seeding impurity in the core has strong influence on the plasma confinement.

In the Fig.3, the comparison of the H_{98} for both transport schemas is presented in the case with different seeding. It can be noticed, that the behavior of the H_{98} factor is similar to that of the power to the SOL (see Fig. 1b). For the case with argon and krypton seeding, after initial decrease of the H_{98} factor, H_{98} increases for highest seeding. This is the effect of the decrease of the radiation in the core (tungsten radiation in core decrease). For Ar, at the highest seeding level H_{98} is higher than for the case without impurity seeding and goes up to 1.18. In this case, in spite of the strong dilution of the plasma ions caused by Ar, the higher plasma confinement leads to higher core temperature, which influences the alpha production and Q-factor.

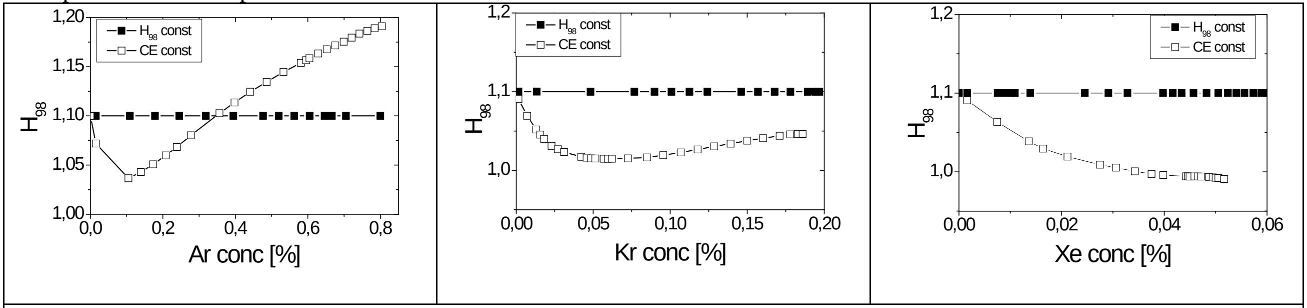

Fig. 3. The $H_{98(y,2)}$ versus impurity concentration for Ar (left), Kr (central) and Xe (right) for two different transport schemes: $H_{98(y,2)} = 1.1$ (full symbols) and CE = constant (open symbols).

3.2. Influence of different seeding gasses on the fuelling and burn-up fraction

The influence of different seeding impurity on the fueling and burn-up fraction is shown in the Fig. 4. The simulations with COREDIV code performed to steady state phase of the discharges with constant volume electron density $<n_e>_{VOL}$ (input parameters). In order to keep $<n_e>_{VOL}$ constant, the source of the fuelling intensity is determined by an internal iteration procedure in such a way that the average electron density obtained from the neutrality condition equal to prescribed value. That means, that the calculated fueling source recompensates D,T losses across the separatrix We point out that the exact description of the fuelling process is outside the scope of this paper as the fuelling of the DEMO reactor is still an open problem.

With the increase of the impurity seeding the fuelling source decreases and for the highest seeding level it goes to the same level for all three impurities. It appears that, the transport has small influence on the fuelling. Therefore, the difference of burn-up fraction is mainly due to the difference of alpha source, which is related to the main plasma profiles in the core.

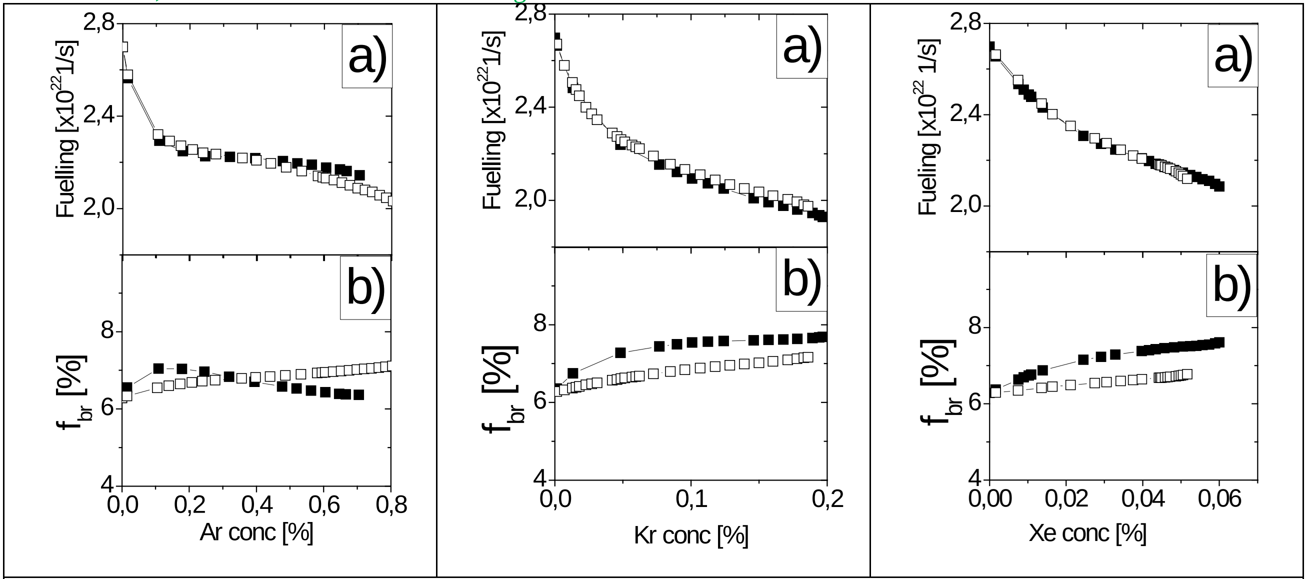

Fig. 4. The fueling source and burn-up fraction versus impurity concentration for Ar (left), Kr (central) and Xe (right) for two different transport schemes: $H_{98(y,2)} = 1.1$ (full symbols) and CE = constant (open symbols)

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The burn-up fraction is at the same level for all impurities and it is as high as 6%, which is rather high compared to previous results for DEMO [10, 11]. We observe that for cases with Kr and Xe f_{br} increases with impurity seeding for two different transport schemas.

The difference in burn-up fraction between both schemas increases with impurity seeding and goes to 0.8%. The fueling source is reduced from 2.7 to 2x10^{22} 1/sec when moving from lowest to highest seeding level. In most situations (except initial Ar seeding), the burn-up fraction is higher for the fixed H_{98} scenarios, which is related to the larger alpha particle sources (Q-factor)

4. Conclusions

The COREDIV code has been used to simulate DEMO1 2018 inductive discharges with different impurity seeding with the special focus on the influence of the impurity seeding on the burn-up fraction, fueling and plasma confinement. For the simulations with constant electron density at the separatrix, it is found that impurity seeding has a small influence on the burn-up fraction, which remains around 6 – 7%., but fueling source is reduced from 2.7 to 2x10^{22} 1/sec when moving from lowest to highest seeding level. The degradation of confinement for high Z seeding impurity, which is correlated to radiation in the core (due to seeded Kr and Xe) is observed. Better confinement for Ar at middle and high seeding levels is observed in comparison to the case without seeding.

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