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Analysis of Highly Radiative Scenarios for the EU-DEMO Divertor Target Protection

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Abstract

We employ the SOLPS5.1 code to analyse different impurity choices and injection methods as possible drivers for highly radiative scenarios in the EU-DEMO. We aim at assessing the existence of a suitable parameter region to safely operate the divertor in H-mode discharges. It turns out that such operational region exists, and that puffing is strongly preferred to pellet as impurity injection method. It also appears that many different impurity mixtures can meet the divertor survival requirements, with a low level of W sputtering. This provides an additional degree of freedom, which will be exploited in the future to optimize the overall reactor performance

Keywords: DEMO, impurities, SOLPS, divertor, highly radiative scenarios

1 Introduction

The EU-DEMO tokamak fusion reactor is being designed to output 500 MW of net electrical power into the grid, demonstrating the economical attractiveness of nuclear fusion as a viable and clean energy source [3]. To achieve this goal, a number of difficulties has to be overcome, among which the need of exhausting a massive amount of power in a technologically affordable way, without compromising the plasma performance. Many options are under consideration; the baseline solution foresees that ≈ 90% of the power P_{SOL} should be radiated by impurity injection, resulting in thermal load spreading over a large fraction of the wall area [8]. The best impurity (or mixture) suitable for the task has yet not been chosen.

We compare various possible impurity mixtures and injection schemes, modelling the EU-DEMO SOL with the SOLPS5.1 code. We aim at determining if a window can be found, in which the divertor operates safely. It turns out that this exists, and the most sensitive parameter appears to be the injection method, puffing being strongly preferred over pellets. For the conditions examined, our modelling does not show a clear impurity combination winner, since acceptable divertor operations can be achieved with different mixtures. This provides an additional degrees of

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freedom which can be exploited by selecting the best impurity to optimize the fusion power output [8]

The paper is organized as follows. In section 2 we describe our modelling setup: we detail both the physical model selected and the most relevant features of the numerical solution implemented. Section 3 presents our main results: we explore the operational window of the EU-DEMO divertor and which parameters have most influence on it. Finally, in section 4 we draw our conclusions and discuss some perspectives for future work.

2 Modeling setup

We employ the SOLPS5.1 code for modelling the EU-DEMO SOL and edge plasma. In order to perform a relatively large number of simulations with a limited resource request, we selected the fluid model for neutrals. Although this is a restrictive choice, it fits our present purposes, which aims at a first selection of promising parameters, to be obtained by scanning a relatively large set of cases; a deeper analysis of the most relevant configurations found with more physically comprehensive models is postponed to future work. Another simplification is the neglect of drift effects. This speeds-up the simulations, at the cost of physical simplifications whose importance may be estimated following [4] . Furthermore, we adopt the bundled charge-state model [1], which reduces the number of charged states to three per impurity species. A discussion of the consequences of the simplifications adopted can be found in [6].

Our computational domain includes the near SOL and 10 cm of the edge plasma, approximately identified with the pedestal, see figure 1. At the core boundary a particle flux of $5 \times 10^{20}\ s^{-1}$ enters the domain, representing a possible diffusive contribution from the main plasma. The major contributions to the particle balance are a volumetric source in the pedestal at a rate of $2.3 \times 10^{22}\ s^{-1}$ (simulating a possible pellet fuelling), and a variable puff from the outer wall boundary, which is feed-back controlled to fix the outboard mid-plane electron separatrix density. We scanned $n_{e,OMP}$ in the range $3.5 \times 10^{19} - 4.5 \times 10^{19}\ m^{-3}$. The lower limit is suggested by the need to enter the high-recycling regime relatively easily, while the upper one was chosen accounting for observations on current experiments, suggesting that this value should be on the upper range of the acceptable densities before confinement starts to deteriorate [2]. At the targets, both fuel and injected impurities recycle completely. At the private flux (PFR) boundary, a neutral flux at a level of $10^{-3} \times n_{neut} c_s$ leaves the domain (for both, fuel and impurities), representing the contribution of a pumping system. We consider a number of possible impurity mixtures, namely Ar + Kr, Kr only, N + Kr, N + Xe, and Ar + Xe. Depending on the selected injection scheme, we fix the highest charge state density for each impurity at the core boundary (roughly representing a possible pellet injection) or puff neutral atom impurities from the wall boundary. In both cases, scans are performed to analyse parametrically the effect of different radiator levels in the plasma.

The main contributors to the energy balance are the power entering the domain from the pedestal P_{ped}, the volumetric losses generated by atomic processes, and the power deposited on the targets. The value of P_{ped} is

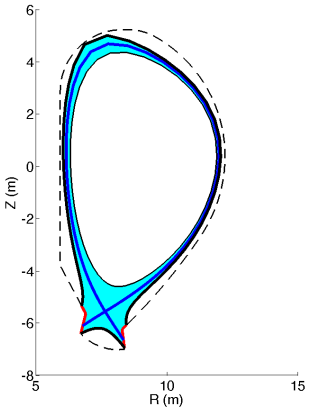

Figure 1: The computational domain used in our simulations. The red lines are the target plates, the dashed line is a simplified sketch of the first wall.

unknown, depending on the power balance in the inner core region. We considered tentatively two possible values: $P_{ped} = 250\ MW$ and $P_{ped} = 300\ MW$. Volumetric losses and power to targets are computed self-consistently during the simulations.

For our studies we selected a computational grid of 96 (poloidal) × 36 (radial) cells. A study presented in [6] shows that, while keeping the required computational time within reasonable bounds, this choice should provide an acceptable accuracy, at least for high-recycling and detached divertor plasmas. For low-recycling regimes the selected grid would probably poorly resolve the strong temperature gradient regions. However, such regimes are not of interest in the present study, because they do not correspond to an acceptable DEMO operating condition.

3 Results and discussion

We considered a number of candidate impurity mixtures to be injected in the DEMO plasma, and run, for each of them, a number of cases at both P_{ped} levels above. A first classification of the results obtained was then produced, based on two parameters: the peak T_e at the outer target and the power crossing the separatrix P_{sep}. The outer target was selected because, in many cases, it receives most of the power, and it is more difficult to detach than the inner one [5]. A limit of $T_{e,peak} < 5\ eV$ was set, to guarantee a sufficiently low level of W sputtering [8]. In addition, still following [8], it was estimated that, in order to maintain H-mode operation, also the condition $P_{sep} > 150\ MW$ should be satisfied.

Figure 2 shows the operational space explored by our simulations. Different colours and symbols are used to classify the cases according to the injection scheme adopted (left), the P_{ped} value (center), or the impurity mix considered (right). The acceptable cases, according to this first screening, are those lying within the bottom-right area. The picture shows that a non-negligible number of points correspond to acceptable cases. This suggests that, provided the amount of impurities injected is sufficiently large, it should be possible to achieve a level of radiation high enough to allow safe divertor operation. Inspection of the left plot, shows that, when impurities are injected via a pellet-like scheme, the $T_{e,peak}$ criterion can only marginally be met.

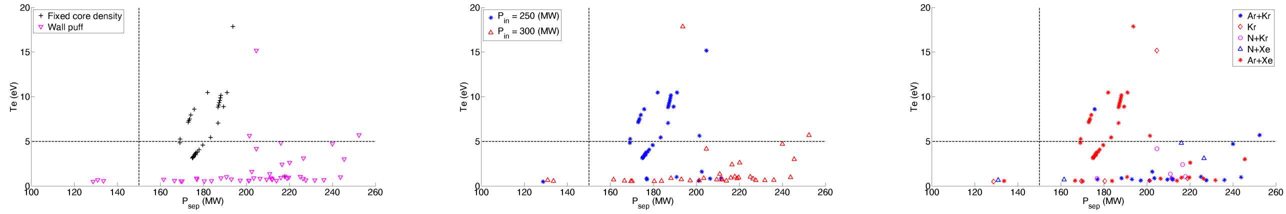

Figure 2: The operational space explored by our simulations. Cases are classified according to the impurity injection scheme (left), the pedestal power level (center) or the sampled impurity mix (right). In each case, further data spreading is due to varying n_e, OMP and impurity concentration. The threshold levels assumed to avoid W sputtering and H-L transition are shown by dashed lines.

Figure 3 shows a refinement of the previous analysis. It considers the same set of cases, but now we plot on the horizontal axis the peak energy flux density impinging on the outer target including conduction/advection, kinetic and potential energy $q_{targ,peak}$. Consistently, the dashed line marking the region of acceptable cases has been placed now to 10 MW/m^2, roughly the limit of the currently available cooling technology. This representation makes strikingly apparent the influence of the impurity injection scheme: when the radiator is fed into the plasma via a pellet-like system in our simulations it is impossible to push the target load down to acceptable values, although the electron temperature can reach levels affordable from the W sputtering point of view. It is obviously possible that in a real experiment sufficiently low values for the power density to the target could indeed be obtained, but our simulations give anyway a strong indication that this should be difficult to achieve. To give an idea of the impurity level needed, for $P_{ped} = 250(MW)$ a concentration in the SOL of 8.5×10^{-4} for Ar and 2.8×10^{-4} for Xe results in $T_{e,peak} = 0.81(eV)$, $P_{sep} = 206(MW)$, and $q_{targ,peak} = 3.9(MW)$. Both figures 2 and 3 suggest that acceptable divertor operations can be obtained with some flexibility on the actual power level entering the pedestal or impurity mix chosen. This is a positive for the reactor design, because it indicates some flexibility in the final mixture choice The reason for the strong effect of the impurity injection method lies in the diffusive transport mechanism, which

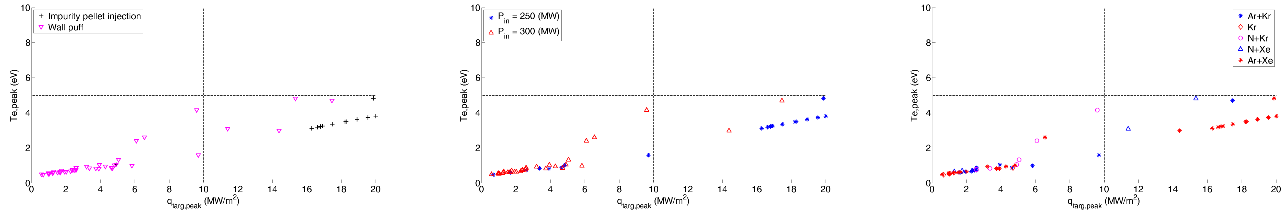

Figure 3: The set of points produced by our simulations, represented in the $T_{e,peak} - q_{targ,peak}$ space.

leads impurities to accumulate.

Figure 4 compares impurity ionized density profiles at the OMP for two shots as comparable as possible, implementing the pellet-like injection and the puffing methods, respectively. Both cases have $n_{e,OMP} = 4.5 \times 10^{19}\ m^{-3}$, include D+Ar+Xe and have $P_{ped} = 250MW$. P_{sep} is comparable but different: 187 MW for the pellet-like case and 218 MW for the puffing. As expected, ions accumulate much more in the core for pellet-like injection.

The consequences on the overall power balance are illustrated in figure 5, showing the maps of radiation power density near the X-point for the same two cases of figure 3. The larger pedestal radiation originating from core Xe accumulation in the pellet-like injection case is apparent. In the simulations, attempts to increase indefinitely the impurity level causes the run to crash, most likely due to the too strong core cooling. This could probably correspond, in experiments, to the formation of a marfe. In any case, we think we have here an indication that reaching robustly a properly detached divertor state requires the impurity puff strategy.

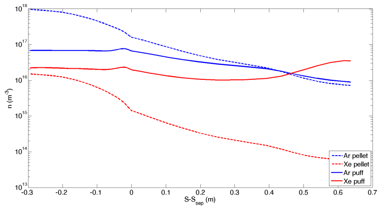

Figure 4: Density profiles at the outboard mid-plane for neutral (solid) and ionized (dashed) Ar and Xe. The horizontal coordinate is the radial distance from the separatrix.

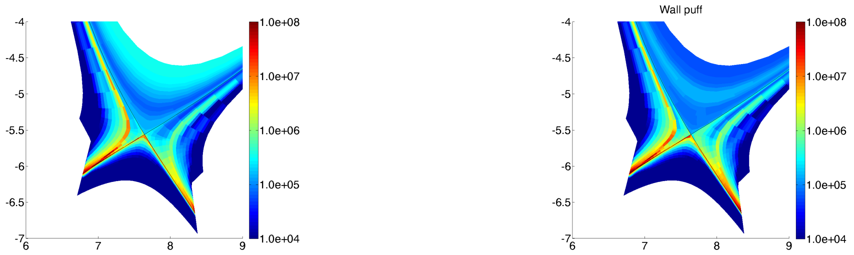

Figure 5: Radiation maps (MW/m^3) in the X-point region. Left: pellet-like injection. Right: neutral puff

4 Conclusions and perspective

We presented an analysis of the DEMO pedestal region and SOL plasma, aiming at establishing the possible existence of a region of operational parameters compatible with acceptable divertor conditions. In DEMO, this is expected to require the radiation of a large fraction of the power entering the SOL by means of purposely added impurities. We tried several possible mixtures, and explored a relatively large parameter range scanning over the impurity densities, the OMP electron density and the pedestal input power. Our simulations show that the condition $q_{targ,peak} < 10\ MW/m^2$, set by the current cooling technology, is stronger than the low-temperature requirement imposed to avoid W sputtering. This allows refining the acceptability criteria sometimes used in previous works [7], which account for the sputtering threshold only. Our major result is the strong preference for impurity puffing as opposed to pellet injection as the selected injection method. This is due to the tendency of impurities to accumulate near their source location. In the case of pellets, such accumulation ultimately entrains an overcooling of the pedestal plasma. The final consequence is that impurity puff guarantees a much wider set of plasma conditions compatible with safe divertor operation. Finally, we notice that, according to our modelling, the target constraints do not allow, by themselves, to select an optimal impurity mix. This is a welcome additional degree of freedom: it will allow in the future to assess the feedback of the radiator presence on the core plasma, in order to ultimately optimize the reactor performance.

Acknowledgments

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