Simulations of tungsten screening in STEP

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Introduction

Accurately characterizing impurity transport and radiative effects in fusion plasmas is essential for advancing reactor efficiency and reliability. In tokamaks, heavy metallic first walls are attractive compared to carbon and beryllium due to their good thermomechanical properties and low tritium retention levels, but the release of high-Z impurities can lead to strong core radiation and confinement degradation. Fast ions are a particular concern for reactor-grade devices where fusion-born alphas are abundant, as they can impact first wall elements in regions outside the divertor, where mitigation methods are difficult. Recent design studies carried out for the STEP tokamak (planned for completion by 2040) have used a sequential approach with multiple simulation codes to model the radiative impact of tungsten (W) eroded by fast ions. In this contribution, the results of W transport and core radiation modelling are discussed.

Modelling approach

STEP scenarios have been previously modelled using the JETTO transport code as the primary modelling tool [1], and we use the results of that work as a basis for our study. The guiding-centre following ASCOT code has been applied to calculate the flux of fusion-born alpha particles on the first wall [2], and the corresponding erosion yields of W are calculated using the SDTrimSP code. Finally, the integral erosion rate over the entire first wall is used as a separatrix boundary source in the JETTO simulations to estimate the radiative impact of W. The work focuses on two different design candidates for STEP, differing mainly by the size of the machine, which impacts the kinetic plasma profiles. The larger candidate has a major radius of R_{geo}=4.2 m, motivated by better component lifetime compared to the predecessor with R_{geo}=3.6 m.

The JETTO simulations are coupled to the SANCO impurity transport code and include the fusion product He and the seeded impurities Xe and Ar, which in the absence of W result in more than 300 MW of impurity radiation. Detailed specifications of the impurity boundary sources are presented in Table 1. The neutral outflux across the separatrix, $\Gamma_{\mathrm{edge}} = \Gamma_{\mathrm{in}} + \Gamma_{\mathrm{S}}$, where Γ_{in} is the specified neutral influx and Γ_{S} is the specified or calculated core impurity source term. For He and Xe, Γ_{in} is a comparatively small separatrix source term specified for numerical reasons, and Γ_S is either the source term from fusion reactions (He) or the pellet injection source (Xe). For Ar and W, Γ_S is set to zero as there are no sources in the core, and Γ_in is either the specified puffed flux (Ar) or the specified erosion source (W). The entire W source is assumed to reach the separatrix, representing a worst-case scenario.

Table 1. Separatrix boundary values in the JETTO simulations. The numbers in bold show the inputs obtained from the sequence of JETTO, ASCOT and SDTrimSP simulations, whereas the numbers in dark red italics are the W-specific assumptions used in the JETTO simulations carried out in this work.

R_geo	Impurity	n_edge	Γ_edge	v_edge
3.6 m	Xe	6e13 m^{-3}	1.8e18 s^{-1}	55 m/s
	He	2.4e18 m^{-3}	6e20 s^{-1}	0.46 m/s
	Ar	4e17 m^{-3}	3e21 s^{-1}	14 m/s
	W		**1e18 s^{-1}** (*1e18 s^{-1}*)	*0.1…100 m/s*
4.2 m	Xe	6e13 m^{-3}	1.4e19 s^{-1}	310 m/s
	He	1e17 m^{-3}	6.2e20 s^{-1}	8.2 m/s
	Ar	9e17 m^{-3}	3e21 s^{-1}	4.3 m/s
	W		**6e17 s^{-1}** (*1e18 s^{-1}*)	*0.1….100 m/s*

The simulations require for the impurities either a fixed separatrix density, n_edge, or a fixed escape velocity, v_edge. For the main impurities (Xe, He, Ar), n_edge has been derived from more detailed SOL simulations, and the resulting values are shown in Table 1 (also for v_edge, which is calculated by JETTO when n_edge is fixed). For W, detailed boundary simulations have not been attempted in this work and, instead, a set of simulations is performed scanning over reasonable values of v_edge (switching to fixed v_edge for the other impurities as well). The charge states of W are bundled into 6 groups, with neutrals, singly ionized and fully ionized species each forming their own groups.

Results

Figure 1 shows the simulated impurity radiation levels assuming, for ease of comparison, the same W erosion source for both configurations. The simulations show that in both designs, W radiation stays below 8 MW if the escape velocity of W is assumed to be above 0.5 m/s. At values of v_edge smaller than 0.5 m/s, W radiation increases rapidly with decreasing v_edge and is approximately twice as high in the smaller configuration as in the larger one. As shown in Table 1, v_edge values below 0.5 m/s are significantly lower than those obtained for Ar and Xe; however, He falls within this range, with v_edge = 0.46 m/s in the smaller configuration.

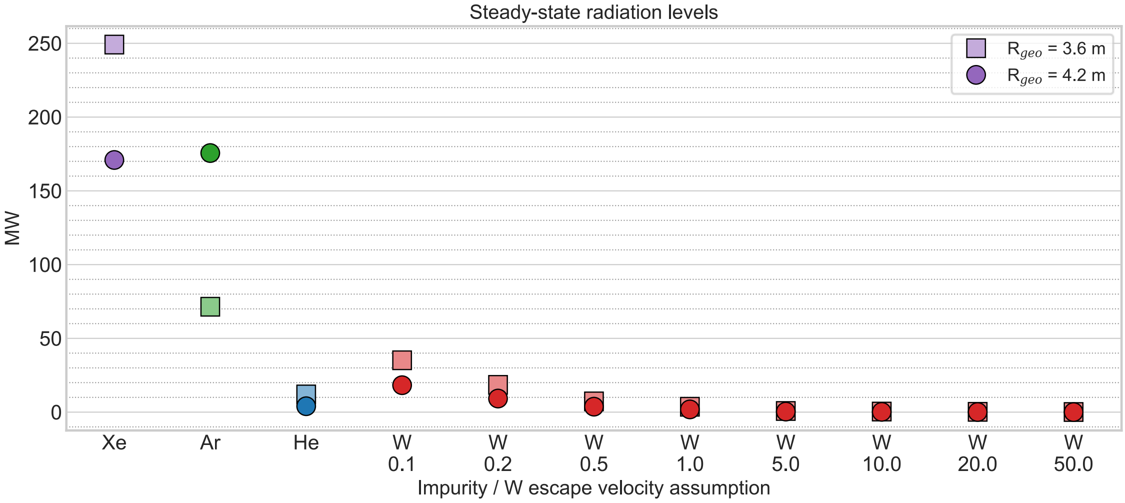

Figure 1. Radiated power of He, Ar, Xe and W for the various assumptions of v_{edge} in the two STEP configurations

Figure 2 shows several simulated profiles as a function of the normalized minor radius a, assuming v_{edge} = 0.5 m/s in both configurations. We observe that at $a < 0.7$ the total density (summing over all charge states) of W decreases towards the plasma centre in the larger configuration but increases in the smaller one. The W core density in the larger configuration is only 10% of the level obtained in the smaller configuration and the total number of W impurities is 50% smaller in the larger configuration, in line with a shorter confinement time of W impurities (0.2s) compared to the smaller configuration (1s). Consequently, the radiation densities of W at $a < 0.7$ are more than 10 times smaller in the larger compared to the smaller configuration, explaining the factor of 2 difference in total radiation of W. W is more effectively screened in the larger configuration than in the smaller configuration, and the observations hold qualitatively for all the boundary conditions explored in the work.

We observe several differences that can contribute to the better screening of W [3, 4, 5] in the larger compared to the smaller configuration. 1) The core density of both electrons and ions is significantly smaller, and the density profile is flatter at $a < 0.9$ in the larger configuration. Consequently, inward convection driven by ion density gradient is weaker in this region compared to the smaller configuration. 2) Diffusion levels of W are observed to be on average twice as high in the larger compared to the smaller configuration, reducing further the effect of the inward pinch in the larger configuration. 3) Both configurations have strong outward convection near the boundary ($a > 0.9$), but the convection is stronger in the larger configuration, likely due to the stronger temperature gradient in this region.

The difference in core density between the two configurations can be attributed to the 25% lower Greenwald density (n_{GW}) in the larger configuration, resulting in a lower line-average density, which is set to be feedback controlled at n_{GW} by the pellet fuelling. Both W and Xe radiate less in the larger configuration, increasing the role of Ar radiation, recall Figure 1.

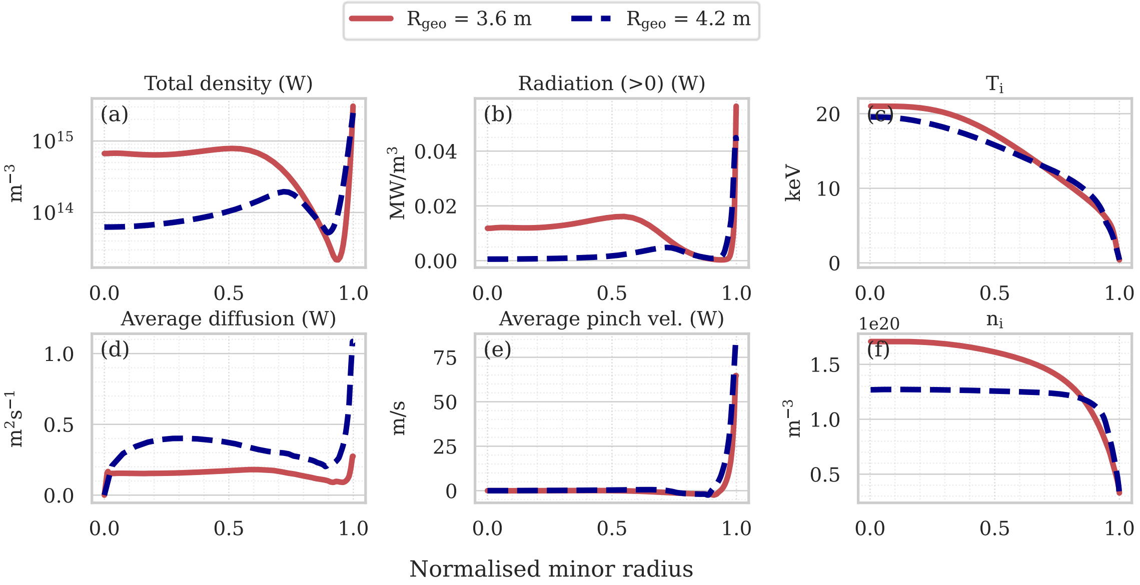

Figure 2. Simulated W impurity profiles (a)-(b), kinetic profiles (c), (f) and transport levels (d)-(e) as a function of the normalized minor radius in the two STEP configurations

Summary and outlook

Our simulations indicate a favorable effect of a recent configuration update on W screening in STEP: the erosion of W by fast ions is reduced, transport of W into the core plasma is reduced, confinement time of W is reduced and the total radiation of W is reduced when increasing the device size and lowering the plasma density. Considering that not all of the eroded W is expected to reach separatrix, W eroded by fast ions does not appear to have a large effect on the radiation levels in STEP, unless the escape velocity at the plasma boundary is significantly smaller for W than for Ar and Xe.

Acknowledgements

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