Impurity Radiation in DEMO

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On the path towards a commercial fusion power station, future demonstration power plant reactors will operate at significantly higher heating powers (alpha and auxiliary) than currently existing machines. To stay within the heat load limits of the divertor ($\lesssim$ 10MW m^{-2}), the power passing into the scrape-off layer (SoL) and then to the divertor must be reduced, without compromising the plasma confinement. Introducing a large amount of impurity radiation from the plasma edge and within the divertor is one way of achieving this goal. However, these operating modes are very different from those in much of the current experimental database and their effects on plasma confinement, plasma dilution and general power plant design still need to be evaluated.

Modelling future power plants like DEMO as part of conceptual design activities is the task of system codes like `PROCESS` [1]. It is necessary for such a code to accurately capture the general physics of impurity radiation and its influences on overall plant design. Additionally, it should be able to evaluate the implications of current model uncertainties on its predictions.

Radiation Model To best capture the form of plasma profiles with an H-mode transport barrier, the temperature $T(\rho)$ and density $n(\rho)$ profiles are described by a pedestalised profile [2]. As a first approximation, the impurities are modelled assuming a constant fraction $f_{imp}(Z)$ with respect to the electron density n_e. Currently models for Be, C, N, O, Ne, Si, Ar, Fe, Ni, Kr, Xe and W are avalaible. Each concentration can be set individually allowing to model both seeded impurities and contamination from plasma facing components (PFC) at the same time.

Based on a given plasma temperature and density profile as well as impurity radiation loss functions from the ADAS database[1], total power lost through (multiple) impurity radiation within the separatrix is calculated. A model for radiation from within the divertor as well as the scrape off layer (SoL) is currently under development. Synchrotron radiation is calculated with a separate model following the description in [2].

While synchrotron radiation is assumed to come from the core region of the plasma, the impurity radiation is split into core and edge radiation based on a cut off radius r_{core}. Only the radiation from the core is subtracted from the loss power used in the confinement scaling.

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Benchmarking Comparing our results of equivalent runs of a DEMO like machine with Argon seeding ($f_{imp}(18) = 0.005$) by the `Sycomore` systems code [3], we find that the line radiation power in `PROCESS` is about 1/3 lower than in `Sycomore`, while the Bremsstrahlung results are the same within numerical errors. This disagreement can be fully explained by the different loss function data used, suggesting that accurate loss function data is essential for these kind of physically motivated impurity radiation models. As a result, we aim to always use the most recent ADAS data within `PROCESS` and keep up to date with relevant developments in the field.

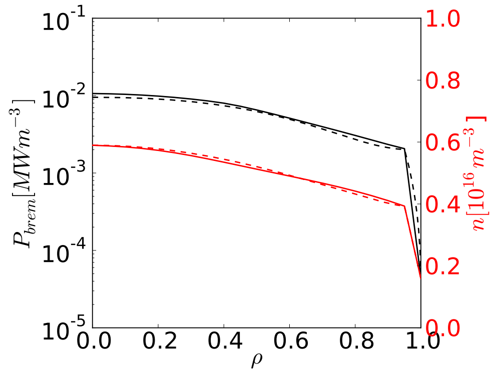

Figure 1: *Comparison of the Bremsstrahlung radiation (black) and corresponding impurity density profile vs normalised radius $\rho = r/a$ (red) for W from `METIS` simulations (solid lines) and the impurity profile model in `PROCESS` (dashed lines).*

In Figure 1, we show the results of a comparison with simulations by the `METIS` transport code [4] for a pulsed DEMO power plant with high impurity radiation [5]. While only the bremsstrahlung radiation is shown, both the differences in the line radiation as well as the bremsstrahlung radiation are below 10%. Unlike `PROCESS` `METIS` takes relativistic corrections for the Bremsstrahlung into account. However, these do not seem to have a signifcant effect for DEMO like machines independent of the impurity species in question.

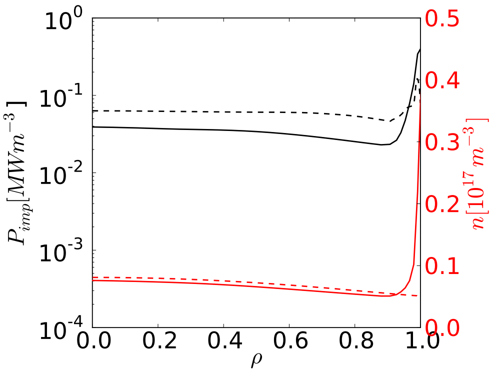

Figure 2: *Comparison of the total impurity radiation (black) and corresponding impurity density profile (red) for W from `JETTO` simulations (solid lines) and the impurity profile module in `PROCESS` (dashed lines).*

Figure 2 shows a comparison of the `PROCESS` impurity profile model and simulations with the `JETTO` transport code [6] for a pulsed DEMO machine [5]. The `JETTO` simulations use the NCLASS neoclassical transport model [7] for both fuel and impurity species as well as an analytical anomalous transport model that has been scaled to match the expected plasma performance. The main difference between the results of both codes is the lack of peaking in impurity densities at the edge, where the impurity line radiation is strongest. These type of profiles cannot be described by our simple model and just matching the average impurity fraction in the simulation can lead to errors of $\sim 20\%$ for Ar and more than $\sim 50\%$ for W. However, as the predicted impurity profile depends on the assumptions of the impurity transport model a more detailed model that at the same time evaluates the uncertainties in impurity transport will be challenging for a systems code.

DEMO Experimental results in the literature are contradictory with respect to the effect of impurity radiation on confinement scaling [8, 9]. In Figure 3, we show the effect of varying the core radius r_{core} which changes the amount of impurity radiation subtracted from the loss power in the confinement scaling. We find that while the H-factor has a weaker dependence, the confinement time scaling is affected signifcantly. This emphasises the need for clarification from experiments to be able to make reliable predictions for DEMO type machines. Please note, that the H-factor is given by $H_{98,y,2} = \tau_E/\tau_E(98,y,2)$, where both the confinement time τ_E and the confinement scaling $\tau_E(98,y,2)$ are dependent on the loss power $P_L = P_{aux} + P_\alpha - P_{rad,core}$, where P_{aux} is the auxilliary heating, P_α is the α-heating power and $P_{rad,core}$ the radiative power within r_{core}.

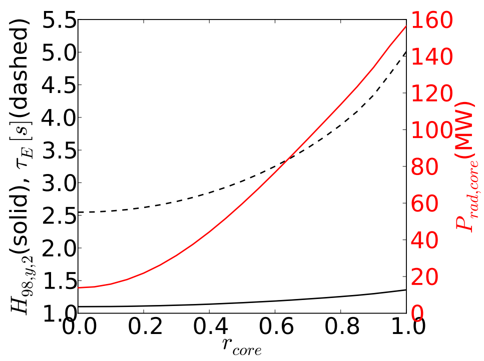

Figure 3: *Changing the fraction of the impurity radiation that affects the confinement ($P_{rad,core}$, red solid line) based on a cut off radius (r_{core}), while keeping the total impurity radiation fixed.*

In Figure 4, we evaluate the effect of plasma dilution due to Argon seeding while ignoring possible contamination from PFC. When varying the Argon fraction in a fixed plasma scenario of a steady state DEMO like machine, the fusion power decreases due to fuel dilution. However, the decrease in heat load on the divertor (P_{div}/R) due to the increase in total radiative power is much more significant. Hence, for DEMO type systems protecting the divertor ($P_{div}/R < 20$ MW/m) with impurity radiation is unlikely to cause any significant fuel dilution. As a range of impurities are available for seeding, it is possible to adjust the desired radiation properties to the relevant plasma conditions, but Argon seems a

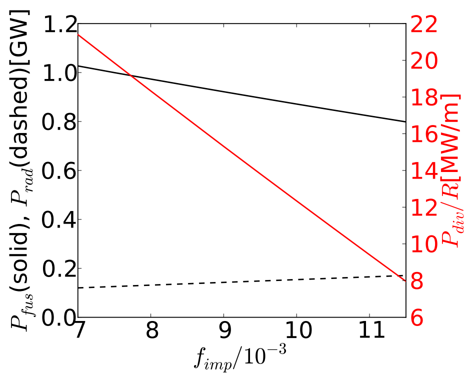

Figure 4: *Varying the impurity fraction in a DEMO like machine with fixed plasma scenario. While the fusion power P_{fus} (solid black line) decreases due to fuel dilution, the total radiated power increases and reduces the heat load on the divertor P_{div}/R.*

good candidate for main chamber radiation on DEMO [9].

Summary Correctly modelling impurity radiation - in particular its effect on divertor protection, confinement and plasma dilution - is a crucial part of conceptual DEMO design activities. In this work, we presented a newly implemented impurity radiation model in the `PROCESS` systems code that uses detailed atomic loss function data and pedestalised temperature and density profiles. Currently, the two main error sources in our model are uncertainties in the atomic data and the inflexibility to mimick more realistic impurity profiles due to the assumption of constant impurity fractions in the plasma. A better model for the impurity distributions is currently being investigated. In DEMO like machines with divertor protection, the confinement time scaling is significantly affected by the amount of impurity radiation subtracted from the loss power. Hence, a clarification from experiments is necessary for reliable DEMO predictions. Inceasing the impurity fraction in the plasma, to reduce the heat load on the divertor in a DEMO type machine is unlikely to have a significant effect on fuel dillution, as comparatively little amounts of impurities are necessary to protect the divertor.

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