

Simulation of DEMO Core Operation Consistent with Divertor Constraints

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Introduction

DEMO operation has been modelled with self-consistent parameters for the core and edge using the Integrated Core Pedestal SOL Model (ICPS Model [1, 2]) in the 1.5D Astra code, coupled to B2-EIRENE simulations of the SOL and divertor [3]. For typical DEMO parameters ($R = 8.1$ m, $a = 2.8$ m, $I = 21$ MA, $B = 5.7$ T), the radiated power from the plasma core is augmented by seeding with medium-Z impurities, in order to reduce the power conducted into the scrape-off layer.

SOL-Divertor Simulations

Extensive SOL-Divertor simulations with B2-EIRENE had resulted in scalings for the principal edge plasma parameters for ITER [3]; these are now confirmed for DEMO [4]. The size scaling enters as powers of $R_{\#}$, the ratio of the outer strike point radii for DEMO and ITER, and the results are now expressed in terms of $P_{\#}$, the power normalised by $R_{\#}^3$, and $S_{\#}$, the pumping speed normalised by $R_{\#}^2$, with additional size factors in terms of $R_{\#}$. Other factors for type of fuelling, wall, neutral model, and connection length are given in [3, 4]. Following [3], the key parameter for characterising the edge plasma operational point is μ , the neutral pressure normalized to 1 at detachment of the inner divertor [4] is now written for DEMO [6]: $\mu \equiv p_{DT\#} P_{\#}^{-0.87} f_f^{-0.8} f_w^{-1} q_{95\#}^{-0.27} f_{nn}^{-1} R_{\#}^{-1.21}$.

Here $p_{DT\#}$ is the average divertor neutral pressure at the entrance to the private flux region. The edge-based density limit occurs at detachment of the inner divertor ($\mu = 1$). Simulations with the linear neutral model and intrinsic carbon impurity (carbon-covered walls) show [4] that at the same SOL power per unit volume of the device, and the same specific pumping speed for ITER and DEMO, the separatrix helium density remains constant ($\sim R_{\#}^{0.15}$), the helium neutral influx decreases ($\sim R_{\#}^{-1.46}$), and the peak power loading of the divertor plates remains constant ($\sim R_{\#}^{-0.02}$) in the transition from ITER to DEMO – all positive results. These scalings [4] are then used for the coupled DEMO simulations. (Initial results with the more complete full neutral model [4] show further improvement in helium but this is not yet implemented in the full modelling.)

Core transport

The core energy transport is given by the MMM95 transport model [5, 6], stabilised by a combination of ExB velocity shear and magnetic shear as described in [1, 2], and will not be further described here.

Particle transport is determined according to:

$$D = D_{neo} + D_{an}; \quad v = v_{neo} + v_{an} \quad \text{with} \quad D_{an} = C_n (\chi_e + \chi_i) \quad \text{and} \quad v_{an} = C_v D_n (2r/a^2)$$

C_n and C_v are equal for all species. As shown previously [2, section 2], the choice of $C_n = 0.1$, $C_v = 0$ reproduces well the density profiles in present experiments. However, the JET profile can also be produced with $C_n = 0.5$ and $C_v = 0.5$.

Two types of impurities are considered in addition to the helium produced by the fusion reactions, an intrinsic low-Z impurity (carbon) and an additional seeded medium- to high-Z

impurity. For helium, the diffusion coefficient and convective velocity are taken equal to those used for the hydrogen isotopes. In the present B2-Eirene modelling, the intrinsic low-Z impurity is carbon (and the walls are assumed to be carbon-covered), which is unlikely to be the case for DEMO. Nevertheless, carbon is retained for now in core modelling to represent some effect due to low-Z contamination of the plasma but with an edge density half of that resulting from SOL modelling. The additional seeded medium-Z impurity is not yet included in SOL simulations; therefore, the edge density is an input parameter and impurity transport determines the profiles.

For impurities other than helium, the reference case uses theoretical neoclassical transport coefficients determined according to the routine NCLASS [7]. This results in flat profiles for all species (Fig. 1). Two variants are also investigated. For variant A, the parameters $C_n = 0.5$ and $C_v = 0.5$ for all species result in moderately peaked DT and impurity profiles. For variant B, with $C_n = 0.1$, $C_v = 0$ for all species, but with neoclassical transport for impurities determined according to the analytic formulation of [8], flat DT profiles are associated with strongly peaked impurity profiles (the expression for transport is given in [1, 2]). For DEMO as for ITER, direct fuelling inside the pedestal is required to sustain the operating density because the SOL is almost opaque to neutrals injected into the vacuum vessel and therefore the neutral DT flux across the separatrix is insufficient to fuel the plasma. Core fuelling is provided by a particle source profile peaked just inside the separatrix with a full-width at half-maximum (FWHM) of 29 cm.

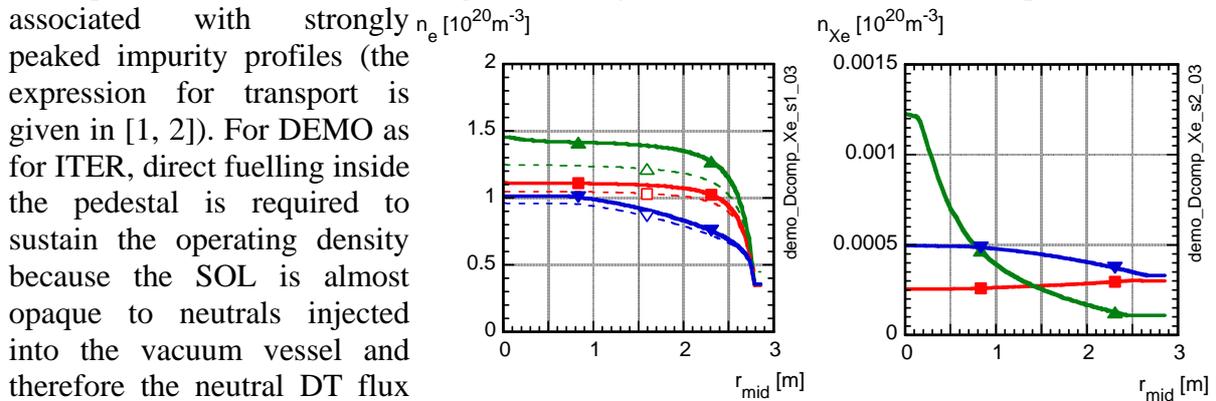


Fig. 1 - Electron and xenon density profiles for reference case (red), variant A (blue) and variant B (green) at $q_{pk} \sim 5 \text{ MW/m}^2$. Dashed lines: without impurity seeding ($q_{pk} \sim 10 \text{ MW/m}^2$)

just inside the separatrix with a full-width at half-maximum (FWHM) of 29 cm.

Description of the simulations

The core-pedestal (1.5D code ASTRA), and the SOL-divertor (2D code B2-Eirene) regions are linked via scaling relations at the separatrix [4]. Inputs to ASTRA include separatrix DT, He, and C densities, separatrix ion and electron temperatures, and separatrix inward neutral DT and He fluxes. Outputs from ASTRA (inputs to the scaling relation) are the power transported across the separatrix by electrons, that transported by ions, the fusion power, and the DT and He ion fluxes into the SOL. The control parameters for the core simulation are the core fuelling flux Γ_{core} , the gas puff flux into the vessel Γ_{puff} , and the additional heating power P_{aux} . An additional control parameter is the edge density of the seed impurity $n_{Z,edge}$.

For each variant of the transport model, and for each of three typical seed impurities (Ar, Fe, and Xe), a quasi-time-dependent simulation is carried out, with a step-wise increase of the edge impurity density $n_{Z,edge}$. The plasma is allowed to relax at each step. The core fuelling flux Γ_{core} is controlled to obtain the desired fusion power of $\sim 3 \text{ GW}$. It was found beneficial to apply some additional heating power to control the transient behaviour during the impurity increase. P_{aux} is accordingly fixed at 20 MW, giving $Q = 150$, i.e. the plasma is essentially ignited. Finally, the gas puff rate Γ_{puff} is adjusted for a given operating point, i.e. a given fraction μ of the edge-based density limit. The maximum divertor heat load q_{pk} from the scaling relation is an output of the simulation.

Results

The parameter variation as the edge impurity density is raised is illustrated in Fig. 2 for three different fractions of the edge-based density limit μ [3, 4]. As impurity content increases, the conducted power, and therefore also the particle transport, decrease, and thus

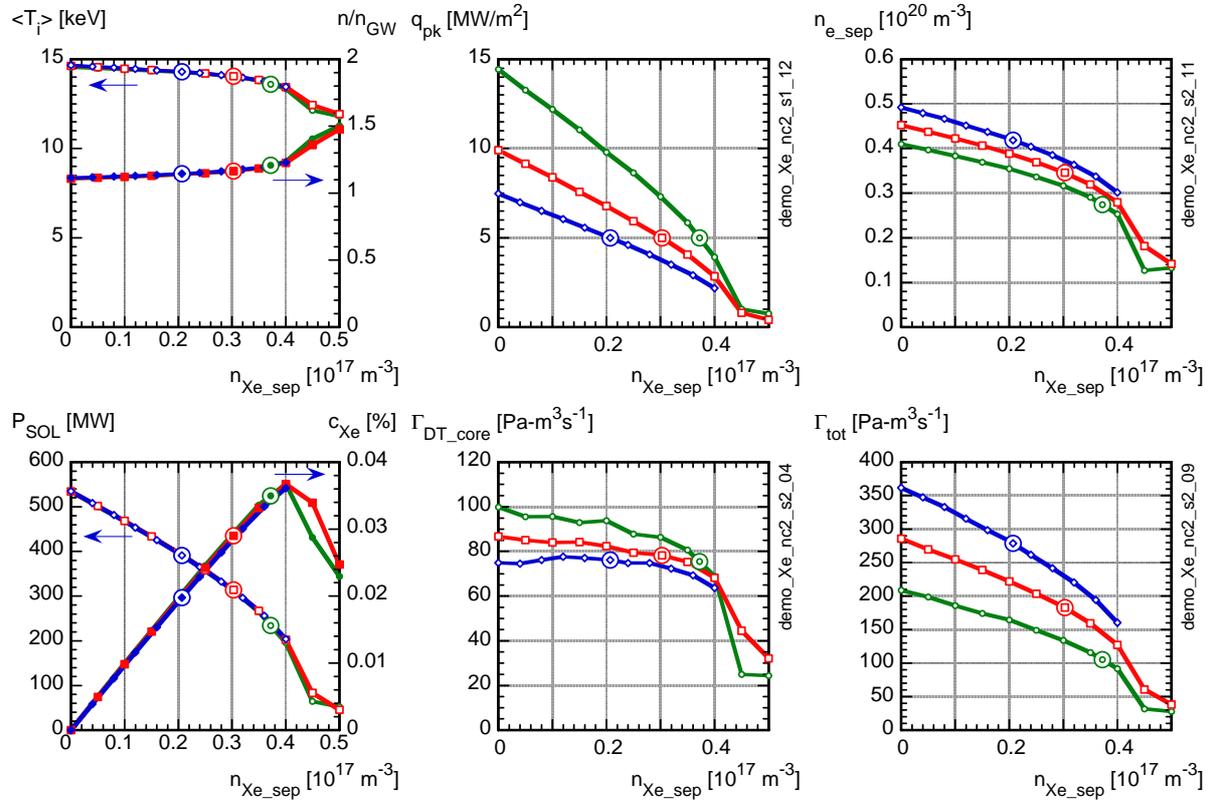


Fig. 2 - Parameter variation as Xe edge density is raised for the reference model at different fractions of edge-density limit (green - 0.5, red - 0.7, blue - 0.9). Circles at $q_{pk} \sim 5 MW/m^2$ the density rises even though core fuelling decreases. For increasing μ , i.e. increasing throughput Γ_{tot} , the power load decreases and the edge density increases, so that lower core fuelling maintains the density for 3 GW operation. However, the core is largely decoupled from the divertor in DEMO (left Fig.2 - similar curves for different μ). This is explained by

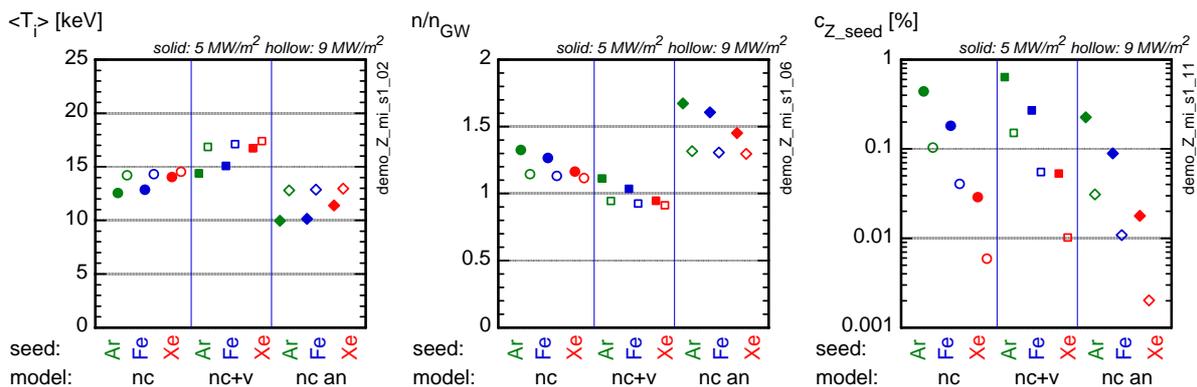


Fig. 3 - Parameters at $q_{pk} = 9$ and $5 MW/m^2$ (hollow and filled symbols resp.) for three different seed impurities (Ar - green, Fe - blue, and Xe - red) and different particle transport models (reference - "nc" - left, variant A - "nc+v" - center, variant B - "nc an" - right of each figure). All results at 70% of edge-based density limit ($\mu = 0.7$)

the opacity of the SOL to neutrals. Additional coupling will result when the seed impurity is included in the SOL modelling. Fig. 3 summarizes the results at given power load of 9 and

5 MW/m². The required seed impurity concentrations (Ar: 0.1 to 0.8 %) drop as the impurity Z increases. Similarly (Fig. 4), the average effective Z obtained with the reference mode lies between 1.5 and 2.5 for Argon, and is lower than 1.8 for Xenon seeding. Z_{eff} is appreciably higher for variant A with peaked profiles and lower for variant B with peaked impurity profiles only. The required average density is lowest for variant A ($\sim n_{Greenwald}$), somewhat higher but still near that value for the reference model, and appreciably higher for variant B (up to 1.5 $n_{Greenwald}$) (Fig. 3). Note, however, that all results are at 70% the edge-based density limit ($\mu = 1$).

Conclusion

Integrated core and edge/divertor modelling of a plasma prototypical of DEMO ELM's H-mode (pellet-triggered ELM's if necessary) has been performed in which medium- to high-Z impurity seeding was employed to reduce the power into the scrape-off layer and thereby the divertor power load at a constant fusion power of 3 GW. The core plasma simulation is linked to the SOL and divertor plasma simulation via scaling relationships determined from extensive series of B2-Eirene SOL simulations.

The reference transport model used is that calibrated to JET and Asdex-UG experimental results and previously applied to ITER. Very flat profiles result for electrons and seed impurities. As a sensitivity study, two variants were also investigated, one in which anomalous diffusion and pinch terms were added to all particle transport parameters resulting in moderately peaked profiles for all species, the other in which only impurity profiles were strongly peaked. Three different seed impurities were investigated, representing typical medium-low, medium, and high Z seed impurities. Depending on the seed impurity and the transport model, the required density is between 0.9 and 1.5 of the Greenwald value, but at the same fraction (70%) of the edge-based density limit.

For all impurities and all transport models investigated, close to ignited operation ($Q = 150$) is found feasible at a fusion power of 3 GW down to 50% of the edge density limit based on divertor detachment. In every case, the normalised β is near 2.7. The peak divertor power load can be brought well below 10 MW/m², with SOL power well above the LH threshold. Impurity seeded operation of DEMO at 3 GW fusion power is therefore consistent with the requirements of a helium-cooled divertor (peak power < 10 MW/m²) over a reasonable operating window.

Many caveats exist in the model and must be resolved in future. These include notably the validation of impurity transport, extension to scalings using the full neutral model, and the inclusion of the seed impurity in SOL modelling. This last point is especially important because it introduces a new strong coupling effect between core plasma and divertor operation, which is presently absent in the coupled simulation.

References

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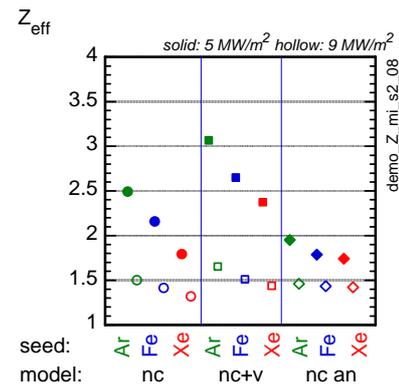


Fig. 4 - Z_{eff} for cases of Fig. 3.