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IMPROVED MODELLING OF NEUTRALS AND CONSEQUENCES FOR THE DIVERTOR PERFORMANCE IN ITER

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In B2-EIRENE modelling of ITER, the usual, linear Monte-Carlo modelling of neutral transport is inadequate, since the large dimensions and high neutral density make the neutrals in the PFR collisional, providing bulk particle scattering, an effect which is important when removal of the dome is examined. We have developed and implemented [1] a non-linear Monte-Carlo model, including neutral-neutral and molecule-ion collisions, which renders possible for the first time meaningful comparisons among divertor geometries, including those without dome. Relative to the model introduced in [1], we have now introduced collisions of carbon atoms with other neutrals. The plasma consists of D, He, and C ions, whose energy and particle transport are described by constant cross-field diffusivities $D_\perp = 0.3\ m^2s^{-1}$ and $\chi_\perp = 1\ m^2s^{-1}$. For neutrals (D, He, and C atoms and D_2 molecules) a constant albedo A at the divertor bottom represents pumping. All the surfaces are covered by carbon. The power input from the core P_{in} and the gas puffing are varied to explore the parameter space in P_{in} and neutral pressure in the private flux region (PFR), p_{DT}.

The dome affects the compression of neutrals in the PFR to facilitate helium exhaust, reduces the neutral influx to the core plasma near the X-point, and provides neutron shielding (not treated here). Using the full model, we have re-examined aspects of the dome design (transparency, [2]) and compared the plasma parameters with and without dome.

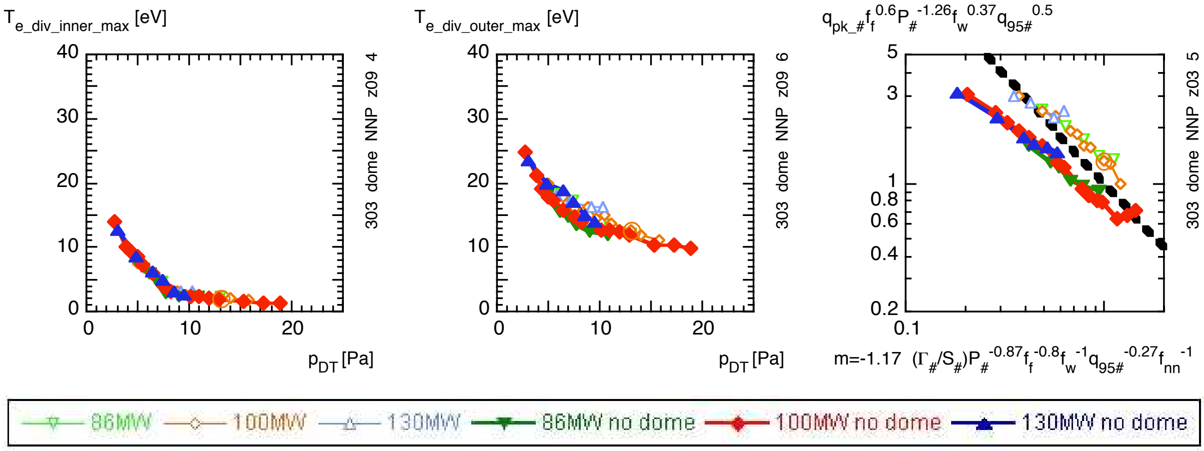

Fig. 1. Maximum electron temperatures at inner and outer targets vs. p_{DT}, and normalised peak power loading of the outer divertor vs. normalised p_{DT}. See [3] for the normalisation.

With respect to the reference (with dome), at the same normalised [3] p_{DT}, removal of the dome results in the same temperatures at both inner and outer divertors, and a peak power loading q_{pk} lower by 30% whose scaling with P_{in} is unchanged (Fig. 1). No negative effect is seen on the helium removal. Total impurity radiation increases by 10 to 20%, Fig. 4a, and net target erosion decreases by a factor 2, Fig. 2a. This can be attributed to an increased residence time of the sputtered carbon. Some of the carbon that was deposited on the lower dome surface and the inner sides of the liner (carbon deposition areas [4]) is now returned to the target. Note that without the dome, the absorption probability 1−A at the pump duct (the actual pumping speed) has to be increased ~ 3 times to compensate increased neutral absorption by the plasma.

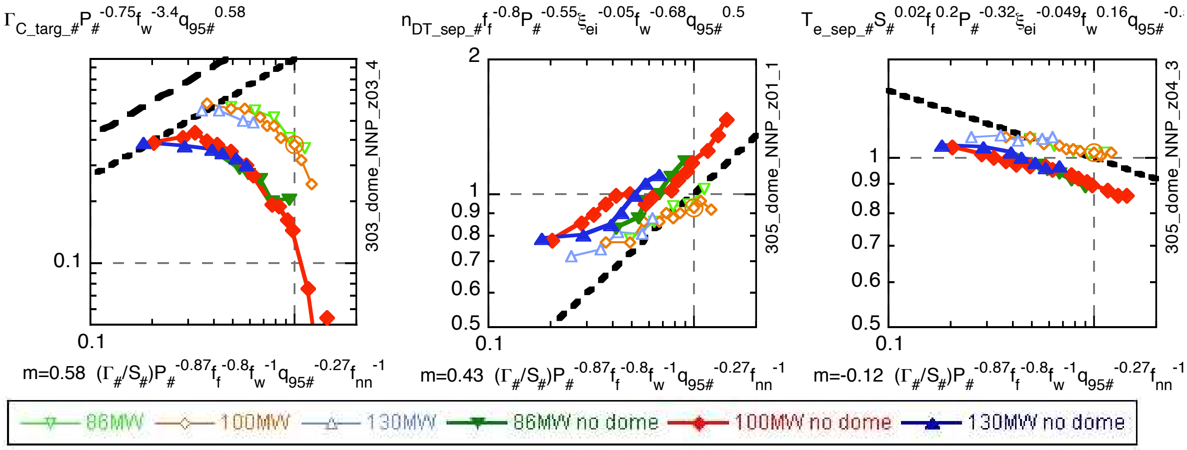

Fig. 2. a) Normalised net target erosion, b) separatrix DT density and c) separatrix electron temperature vs normalised p_{DT}*; for cases with dome and without (indicated as such).*

Removal of the dome leads to a 20 to 30% increase of the separatrix temperature upstream for the same divertor conditions, and a corresponding decrease of the plasma density. The neutral density just inside the separatrix remains insignificant, < $1.10^{15}m^{-3}$, i.e 20x lower than for an AUG simulation, because the neutral temperature in the PFR is low and the distance to the X-point is high in ITER, so that the screening by the PFR plasma is effective. The Z_{eff} at the separatrix does not increase – apparently, because of the increase of the D ion density there. Initial calculations done with the Astra code [5] using these results as the boundary conditions indicate that the core plasma performance (power multiplication factor Q) remains the same for the same operating point in p_{DT}.

There is no sign that dome removal leads to an X-point MARFE in ITER for this simulation with carbon impurity. The separatrix density peaks (Fig. 3a) but the poloidal variation of the separatrix temperature remains minor, the carbon remains almost fully stripped (Fig. 3b) and no radiation peak is seen near the X-point, Fig. 3c. Although radiation increases with removal of the dome, it stays rather low, around 0.05 MW/m^3. On the contrary, code runs with the same model for ASDEX-Upgrade-like parameters do show a local peak in carbon radiation there when the outer divertor is close to detachment.

The parameters of operation with the dome have also been re-evaluated,. In particular, the transparency to neutrals of the dome-supporting structures (liners) was varied. The previous simpler model led to the recommendation [2] that the transparency ζ be kept above 0.5 to avoid increases of the outer peak power load due to increased in-out asymmetry. Results with the present, more realistic, non-linear neutral model, indicate that this limit can be relaxed to 0.1 (Fig. 4b) because the gas conductance of the channel below the dome increases [1]. Accordingly, the dome supports can be rendered more robust.

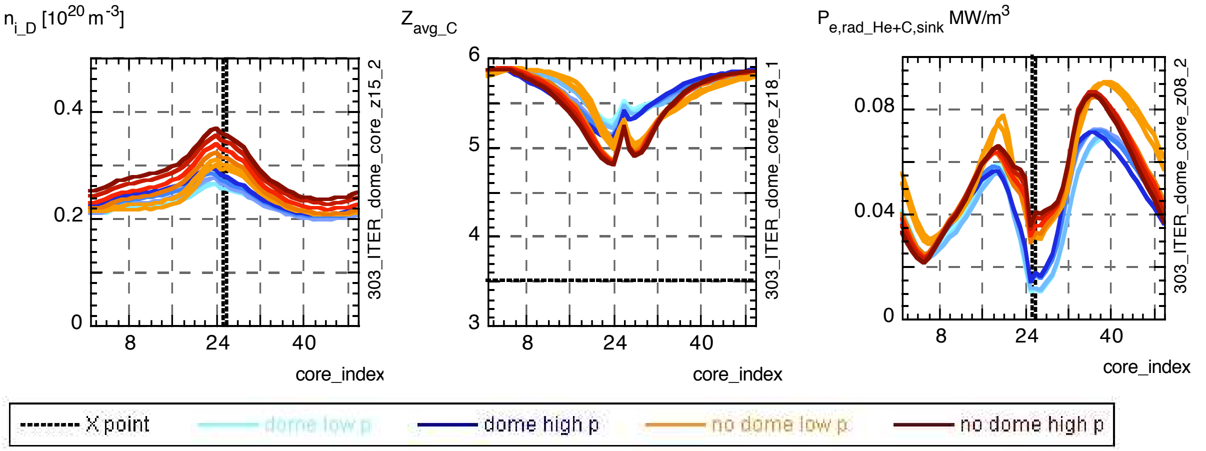

Fig. 3. Poloidal variation of a) deuterium density, b) average C ion charge state, c) line radiation per unit volume just inside the separatrix, Ordinate is poloidal coordinate counter-clockwise, starting from the top, X-point at 25.5; blue with dome, red without dome, darker shades are higher p_{DT}.

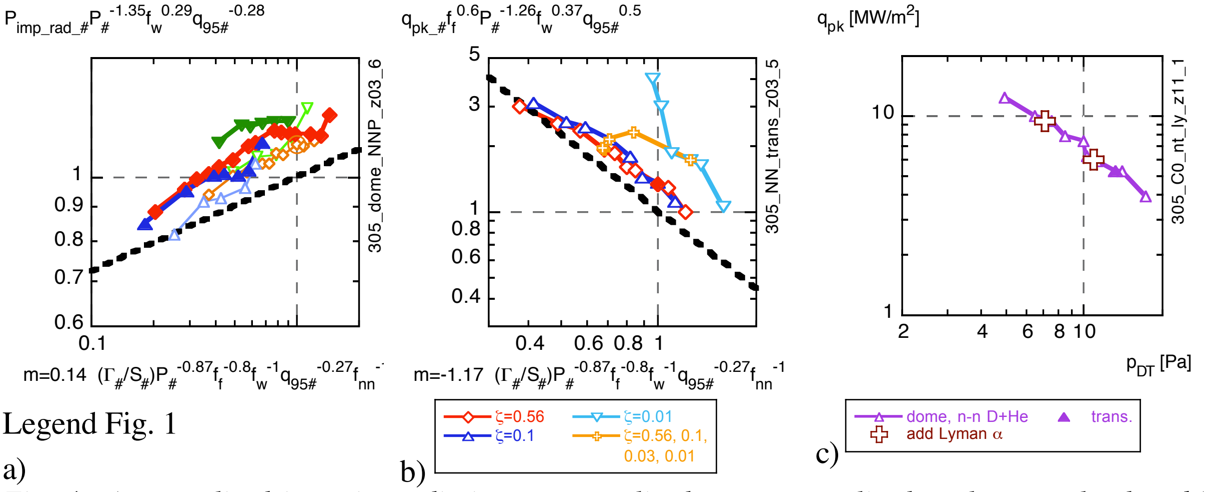

Fig. 4. a) normalised impurity radiation vs normalised p_{DT}, *; normalised peak power load vs b) norm.* p_{DT} *for variation of transparency and vs. c)* p_{DT} *for radiation transport effect (see text).*

Because of its large dimensions and high neutral density, the ITER divertor is opaque for Lyman-series radiation, whose absorption and re-emission changes the ionisation-recombination balance. Transport of this radiation is now modelled in the Eirene code in the same way as the neutrals (photons are treated as extra neutral species). The reaction rates are obtained from the collision-radiative model modified to allow for the extra excitation source. Both natural and Doppler broadening of the spectral lines are taken into account, and the five first lines in the Lyman series are included in the model. Initial results surprisingly show no strong change in global divertor performance, Fig. 4c. In fact, the radiation-induced ionisation rates increase by up to a factor 4 locally, principally in the cold region on the PFR side of the inner divertor, but the resultant increased plasma density there strongly enhances local three-body recombination, and therefore the enhancement remains local.

Conclusions

We have therefore performed a series of simulations for operation with and without the dome structure in the private flux region, with the full neutral and molecular model but with full carbon walls. A major effect is a factor 3 increase of the pumping speed necessary to replace the neutral compression by the dome. Removal of the dome leads to similar scaling as domed operation with power and divertor pressure (the temperature at the inner divertor follows the same curve). The separatrix densities are 20% higher and the separatrix temperatures 20% lower. The peak power load at the divertor plates is 30% lower at the same normalised pressure. These parameters used as boundary conditions for a 1.5D core simulation with ASTRA reveal similar performance (Q). The carbon radiation at the X-point is 3x larger upon removal of the dome, but not dangerously, since the level remains low, 0.05 MW/m^{-3}. There is therefore no indication of the occurrence of an X-point MARFE when the dome is removed. Indeed, ITER may be more robust than present-day devices against a carbon X-point MARFE because the carbon impurity is almost fully stripped ($Z_C > 5$); the situation may be different for medium or high Z impurities. The neutral density inside the separatrix remains unimportant for ITER even when the dome is removed, $< 1.10^{15} m^{-3}$, i.e. a factor 20 lower than present devices such as AUG because of the lower neutral penetration in ITER (lower temperature, larger distance).

In contrast to ITER, a simulation for AUG parameters with the same model reveals a peak in carbon radiation at the X-point, due to a peak in deuterium (and therefore electron) density there and a dip in average impurity Z to 4.2. The static pressure deviates from constant by 40% locally, indicating that local flows and momentum balance must be further investigated.

Initial investigation of Lyman alpha radiation transport has revealed strongly enhanced local ionisation, which is largely compensated by strongly enhanced local recombination, leading to similar global divertor parameters. Further studies show that he tliner transparency can be reduced to 0.1, rendering the dome design more robust, and that carbon neutral-neutral collisions do not modify the results strongly.

Although the lower peak heat load would favour removal of the dome and the absence of an X-point MARFE with carbon impurity and the insensitivity of the ITER core to neutrals are neutral factors, other concerns, such as flexibility, neutron shielding, impurity production and shielding, divertor diagnostic access, separation of the inner and outer divertor, pumping speed and the size of pumping slots in a protective target above the pump duct need to be examined. From the modelling side, the present full carbon solution must be replaced by realistic erosion-redeposition surfaces, the flow and momentum balance must be examined, a radial variation of transport investigated, and higher-Z impurities examined before a final conclusion can be drawn.

This report was prepared as an account of work undertaken within the framework of ITER Transitional Arrangements (ITA). These are conducted by the Participants: the European Atomic Energy Community, Japan, the People's Republic of China, the Republic of Korea, the Russian Federation, and the United States of America, under the auspices of the International Atomic Energy Agency. The views and opinions expressed herein do not necessarily reflect those of the Participants to the ITA, the IAEA or any agency thereof. Dissemination of the information in this paper is governed by the applicable terms of the former ITER EDA Agreement

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