Effect of Light Impurities on the Divertor Performance in ITER

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Numerical studies of the expected performance of the ITER divertor have been carried out intensively during the last few years. Different operational regimes with divertor plasma ranging from partially attached to fully detached have been modelled [1, 2]. The results showed a possibility to maintain divertor conditions which provide simultaneously acceptable power loading on, and erosion of, the divertor components and adequate helium exhaust from the burning plasma. However, the necessary level of radiation was ensured in those calculations only by neon seeding of the edge plasma, without allowance for the intrinsic impurities, such as sputtered carbon. Thus rather high neon concentrations, 0.5% or higher were required and high values of Z_{eff} resulted at the edge of the core plasma.

The present paper shows the effect of the intrinsic light impurities on the divertor radiation. The model (B2-Eirene code package) has been elaborated to include both physical and chemical sputtering of the wall material together with a full multi-fluid description of the transport of sputtered impurities in a self-consistent way.

Effect of light impurities

At present, we use a simplified model for the chemical sputtering, assuming that the carbon atoms are sputtered by hydrogen atoms and ions with a constant yield, typically, 1%. The cross-field transport coefficients have been selected as in Ref.[1,2], $D_\perp$=0.3 m^2/s and $\kappa_\perp$= 1 m^2/s. An ITER-relevant level of helium concentration, 10% at the core boundary, has been maintained in all the calculations, and neon seeding has been added to control the power balance. In order to study the sensitivity of the result to the impurity production and radiation characteristics, two further cases have been run. The first assumes reduced yield, 0.5%, for chemical sputtering. Carbon is replaced by beryllium in the second case, artificially keeping the sputtering yield at the same 1% level.

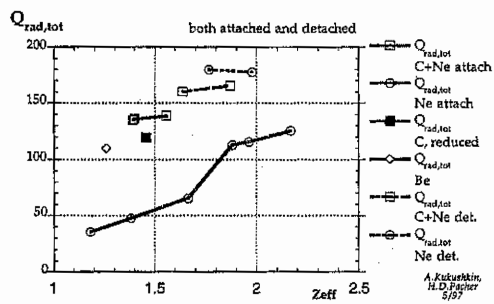


Fig. 1. Total radiated power vs. Z_{eff} at the core-edge boundary for different operational regimes (the case at Z_{eff}= 1.6, 140 MW, is the reference case)

First results show that, for similar divertor conditions and similar radiation from neutrals, higher power is radiated by impurities at lower Z_{eff} when both carbon and neon are used (see Fig. 1, curves marked C+Ne, C, and Be vs. Ne). The total power coming to the targets is reduced accordingly. With an increase of neon concentration, the plasma starts to detach from the inner target. The distribution of radiation sources along the poloidal co-ordinate is also worth noting. The radiation from the plasma edge inside the separatrix increases with Z_{eff} at the core boundary, Fig. 2, being somewhat lower in presence of carbon. The poloidal distribution of the radiation can also be represented as the poloidal integral of the power radiated between a reference point and the current position,

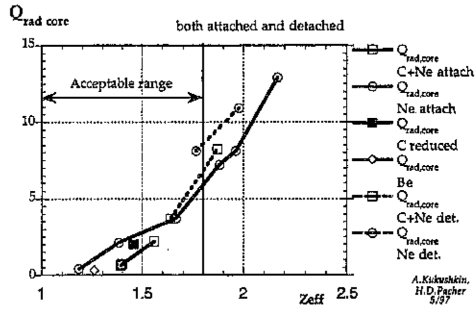
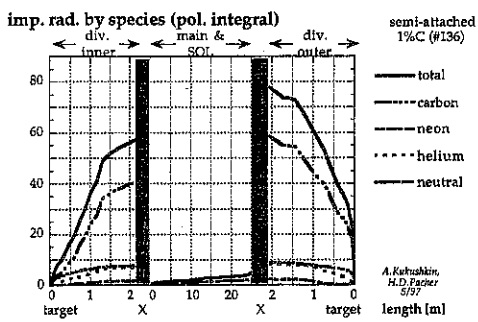


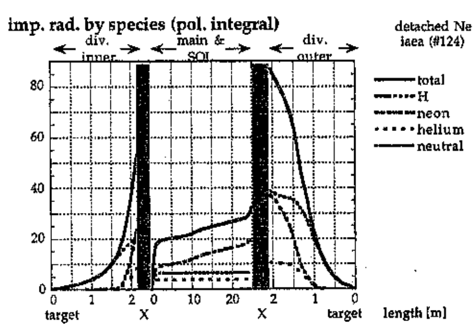
Fig. 2. Power radiated from the core edge vs. Z_{eff} for different operational regimes

$$f_{pol}(x) = \int_0^x dz \int_{r_{min}}^{r_{max}} q_{rad}(z,r)dr$$

These integrals are shown in Fig. 3 for two different cases in three separate regions: the two divertors and SOL together with plasma edge. The integrals are accumulated from targets in the divertors and clockwise from X-point in the main chamber. Fig. 3a shows f_{pol} for the semi-attached operation with sputtered carbon, whereas the profiles for the "deeply detached" case of Ref. [2] are given in Fig. 3b. For the semi-attached operation, Fig. 3a, essentially all the radiation comes from the divertors. The radiation source is somewhat peaked near the outer target, otherwise well spread out. No peak is seen near the X-point and little is radiated above the X-point. Therefore,



(a)



(b)

Fig. 3. Poloidal distribution of the radiated power for semi-attached (a) and deeply detached (b) operation modes

there is no trend to form a MARFE. This picture remains similar with variation of the neon seeding level up to detachment from the inner target. Only in a strongly detached case, Fig. 3b, which is not proposed for operation, is there a considerable radiation (30 MW) from above the X-point. Replacement of carbon by beryllium results in profiles similar to those with C, provided that enough Be is produced.

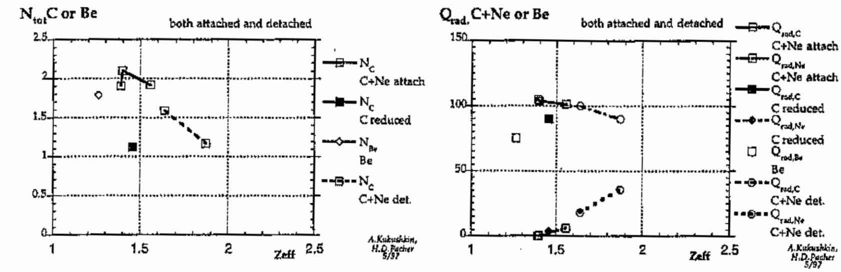


Fig. 4. Variation of C (or Be) inventory (a) of, and impurity radiation (b) from, the whole edge plasma with Z_{eff} at the core-edge boundary

The relation of the carbon source to the flux of hydrogen isotopes coming to the surfaces gives rise to a self-regulation which could have a stabilising effect on the plasma detachment. When radiation from the divertor plasma increases, the particle flux to the surface decreases due to reduction of the power spent for ionisation. As a result, the carbon influx becomes lower, tending to reduce the radiation. This effect is illustrated in Fig. 4, where the carbon content and total impurity radiation are plotted versus Z_{eff} at the core.

ITER implications

The presence of the sputtered carbon in ITER has a favourable effect on the trade-off between the target loading and Z_{eff} at the core. Therefore, highly-radiating, semi-attached plasmas with peak power loads onto the targets below 5 MW/m^2 become possible even with $Z_{eff} < 1.6$ at the core boundary. This peak load appears to be rather insensitive to the specified value of the chemical sputtering yield. The radiated power, although somewhat peaked towards the outer target, is well spread out and produces loads below 1 MW/m^2, concentrated mainly in the divertor region. The total power radiated from the plasma edge and divertors can be as high as 140 MW of 200 MW entering the edge plasma for semi-

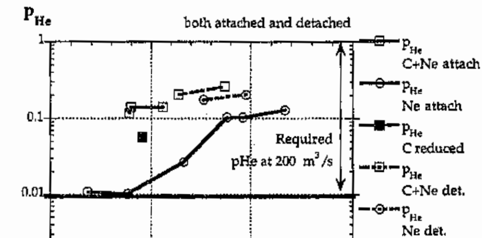


Fig. 5. Helium partial pressure at the pumping duct vs. Z_{eff} at the plasma core for different regimes

attached operation.

The conditions for helium exhaust are also acceptable for this regime, Fig. 5. There is a margin of one order of magnitude over the required minimum helium neutral pressure near the pumping duct. Moreover, a stand-alone calculation of neutral particle transport done with the Eirene code indicates favourable effect of elastic collisions between helium atoms and plasma ions (disregarded until now in coupled calculations) on the helium pumping efficiency. These collisions heat up the helium atoms thus facilitating their penetration through the divertor plasma.

Conclusions

Light (intrinsic) impurities – in a certain amount – are beneficial for the ITER divertor. They ensure higher radiation from the divertor at lower Z_{eff} at the plasma edge compared with the neon-dominated cases [1, 2]. The radiation in the divertors is weighted more towards the targets, inhibiting therefore formation of an X-point MARFE. Moreover, the impurity production by sputtering can have a self-regulating effect on the operational regime, reducing release of carbon when detachment becomes imminent.

Semi-attached operation with a realistic impurity mix can be taken as the primary option for ITER. It allows, in presence of carbon, to attain the ITER design criteria of low Z_{eff} (≤ 1.8) and low peak power load on the target (≤ 5 MW/m^2) simultaneously. The design value of 200 m^3/s for the pumping speed appears also to be adequate.

Further studies are necessary to explore the parameter space of ITER operation and to make the predictions of the divertor performance more reliable. Essential here are the model validation against experimental data from existing divertor experiments (ongoing effort) and model development which would provide a more accurate description of the divertor plasma on the long time scale of the ITER pulse.

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References

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