

MODELING OF PARTICLE FLUXES FROM THE JET DIVERTOR

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Introduction

Carbon is the best favoured material for the ITER divertor plates [1]. It is therefore important to understand the erosion mechanisms of the target plates to assess both the target life-time and the impurity contamination of plasma.

Ion beam experiments demonstrate that production of deuterated methane molecules (CD_4) through chemical processes enhances the carbon sputtering [2].

The addition of chemical to physical sputtering becomes even more important in high recycling or detached plasma regimes as, with the decrease of the ion temperature, the physical sputtering yield decreases. The chemical sputtering yield however does not appear to have a ion temperature threshold and remains high [2].

Many attempts have been done in recent years to fit the ion beam experiment data to the different experimental conditions of a tokamak plasma. However there has been no conclusive experimental evidence of the importance of chemical sputtering at the divertor target plates of a tokamak. Moreover there has been no quantification of the percentage of CD_4 that promptly redeposits after desorption without breaking up in C atoms and participating to the contamination of the discharge.

In order to clarify the issue JET has conducted experiments designed to specifically address the issue of CD_4 redeposition. Either D_2 or CD_4 was injected in two separate discharges with the same magnetic configuration and plasma parameters. Injection was arranged so that the amount of D atoms was the same in both pulses and that the C atoms injected in the CD_4 pulse significantly perturbed the ‘natural’ carbon content of the discharge.

In the analysed discharges the gas was injected either in the SOL, with the strike point on the horizontal target, or in the PFR with the strike points on the vertical target plates.

The wide range of JET diagnostics ranging from spectroscopy for the measurement of D_α , CII, CIII, CIV, CV and CD photon fluxes to charge exchange spectroscopy and bolometry for the measurement of total C^{6+} content and Z_{eff} respectively allowed to follow up the CD_4 molecules ionisation and break-up and the increase of the discharge impurities content. Additionally two spectroscopic CCD cameras allowed spatially resolved measurement of D_α and CII photon flux across the divertor target with $\delta R \sim 1$ cm, $\delta t \sim 5$ ms and $\delta \lambda \sim 1$ nm to be obtained. The latter measurements combined with the J_{sat} and T_e measured at the target by the Langmuir probes allowed the extrapolation of the ionisation/photon coefficients from the ADAS database [3] and the evaluation of the D and C particle fluxes in the JET divertor.

Results

Figure 1 compares the CD band photon fluxes (431.0 nm) between the D_2 and the CD_4 injection discharges for the SOL injection. Data are shown for both the inner and the outer strike points. The PFR injection shows similar behaviour to the SOL one. No difference in the CD photon flux is detectable at the inner strike point, while, at the outer strike point, the photon flux more than doubles for the SOL injection. Remembering that in the SOL injection experiments the gas was puffed on the outer horizontal part of the target plate, one can already draw the conclusion that the CD_4 molecules promptly ionise and redeposit locally as CD_x^+ molecular ions without being able to diffuse in all the divertor area. Moreover the PFR injection result suggests that the ionisation and redeposition of the deuterated methane molecules is particularly efficient even at the low values of T_e and n_e . If the deuterated methane molecules would break-up to form C^+ ions, this would be detectable as an increase of the measured CII, CIII, CIV and CV fluxes and ultimately in an increase of the core carbon content and of the Z_{eff} .

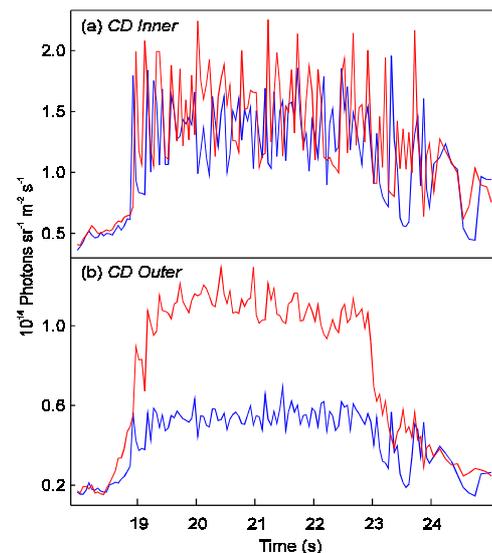


Figure 1: Comparison of measurements of CD photon fluxes (431.0 nm) averaged over the inner (a) and outer (b) divertor target for the two SOL injection pulses: #38757 with D_2 (blue curves) and #38748 with CD_4 (red curves)

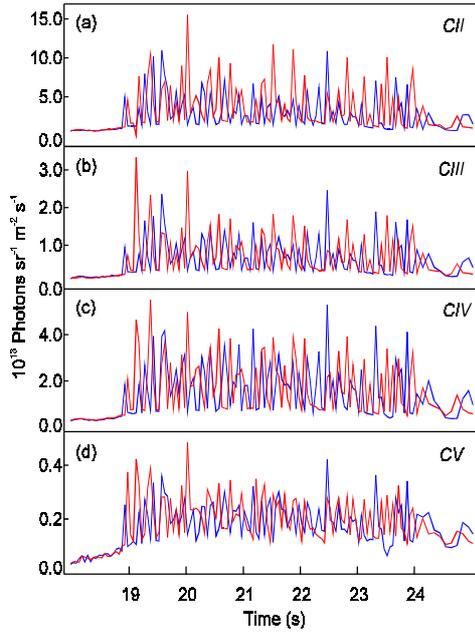


Figure 2: Comparison of the standard spectroscopy measurements of (a) CII (589.0 nm), (b) CIII (570.0 nm), (c) CIV (502.0 nm) and (d) CV (494.0 nm) photon fluxes averaged over the outer divertor target for the two SOL injection pulses: #38757 with D_2 (blue curves) and #38748 with CD_4 (red curves)

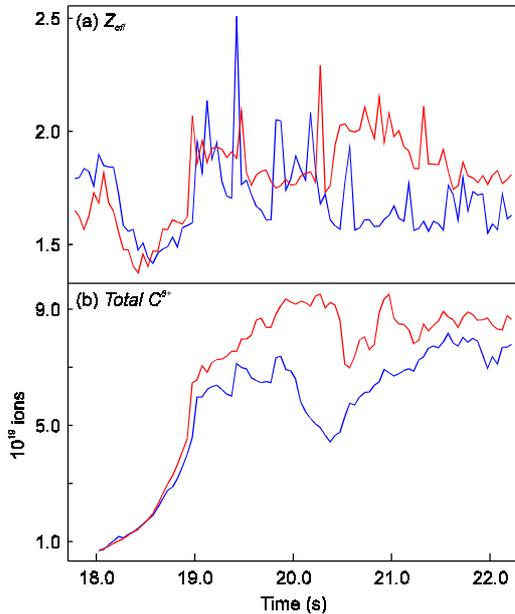


Figure 3: Comparison of the Z_{eff} averaged along the vertical line of sight (a) and the total core C^{6+} content (b) for the two SOL injection pulses: #38757 with D_2 (blue curves) and #38748 with CD_4 (red curves)

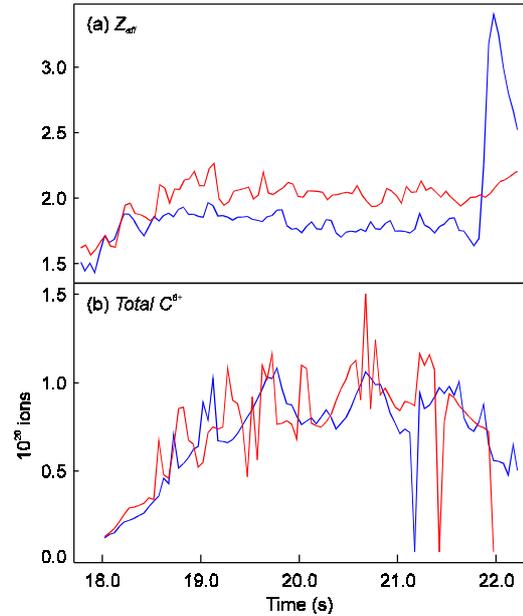


Figure 4: Comparison of the Z_{eff} averaged along the vertical line of sight (a) and the total core C^{6+} content (b) for the two PFR injection pulses: #40001 with D_2 (blue curves) and #39996 with CD_4 (red curves)

Figure 2 compares the impurity photon fluxes (for different charge states) between D_2 and CD_4 injection for the SOL case (again the PFR case shows similar behaviour). The CII photon fluxes show little or no increase between the deuterium and the methane injection and virtually no difference is observed in the higher charge states. This of course strengthens the former hypothesis that little or no methane molecules disintegrate into carbon ions and virtually none penetrate the main plasma.

The total C^{6+} content (from CX spectroscopy) and the plasma Z_{eff} (see figures 3 and 4) show however an increase in the discharges when CD_4 was injected. For the SOL injection pulses the increase of Z_{eff} is on average $\sim 18 - 20 \%$, while the total C^{6+} content increases by $\sim 14 \%$. The increase of Z_{eff} in the PFR pulse is on average $\sim 11 \%$ while the total C^{6+} is higher by $\sim 5 - 7 \%$. This increase is much smaller than what would be expected by a methane injection that causes a doubling of the CD band and in contradiction with the lack of increase of the carbon photon fluxes. Possibly, part of the methane, injected in the SOL with a cosine distribution, does not enter the plasma but diffuses in the empty space between the plasma and the vessel, entering the discharge somewhere in the mid-plane SOL. This appears to be confirmed by the lower increase of C^{6+} and Z_{eff} in the PFR injection discharges. The methane molecules injected in the PFR are directly in contact with the plasma whatever direction they

are diffusing and promptly ionise. In fact the C^{6+} increase is below the experimental error bars and the increase of Z_{eff} is very small. This small increase can be due to a small amount of CD_4 diffusing in the space below the divertor and finding a path to the mid-plane through the by-pass leaks in the vessel structure.

Additionally to the presented 1D spectroscopic data, it is possible to evaluate the deuterium and carbon flux using the radially resolved measurement of D_α and CII from the 2D spectroscopic CCD cameras. Figures 5a and 5b compare the deuterium particle flux with the perpendicular ion flux for the SOL injection discharges. While the deuterium and the perpendicular ion fluxes show an almost perfect agreement in the CD_4 pulse, in the D_2 pulse the ion flux is around 40 % smaller than the deuterium flux. The deuterium flux being higher than the ion one can be explained by remembering that the D_2 injection occurs directly in the SOL plasma. In steady state conditions, part of the deuterium molecules will break-up into excited atoms which will contribute to the increase D_α radiation and therefore to the calculated deuterium flux. Only some of these atoms will then ionise and contribute to the absolute increase of the perpendicular ion flux, set by the recycling plasma in the divertor.

The remaining part undergoes charge exchange collisions with the energetic plasma ions, resulting in an energetic neutral atom and a slow ion. Part of these neutrals exits the SOL plasma and increases the atoms outflow towards the wall. In exiting the plasma those atoms undergo excitation by electron collisions and further increase the D_α photon flux without affecting the perpendicular ion flux to the target plates.

The lack of any appreciable difference between the deuterium and the perpendicular ion flux in the discharge where methane rather than deuterium is injected, suggests that a quite big percentage of the CD_4 molecules redeposit immediately after being injected without breaking up into C and D atoms and participating in the increase of the neutral deuterium particle flux. From the difference in the deuterium flux between the D_2 and the CD_4 injection discharges, it is possible to estimate which injection rate corresponds to the difference between the fluxes by using: $\text{Rate} = \text{Area} \cdot \Delta\Gamma_D = 1/2 \cdot 2\pi \cdot \bar{R} \cdot \delta R \cdot \Delta\Gamma_D$, where \bar{R} is the average value of the major radius inside the deuterium flux peak and δR is the peak width, the factor 1/2 is introduced as the peak is approximated to a triangle. Using $\bar{R} \sim 2.80$ m, $\delta R \sim 0.034$ m and $\Delta\Gamma_D \sim 4.32 \cdot 10^{22}$ D/m²s, one obtains a deuterium rate of $\sim 1.3 \cdot 10^{22}$ atoms/s, which can be compared with the injection rate in pulse #38757 of $\sim 1.33 \cdot 10^{22}$ atoms/s showing an almost surprising agreement.

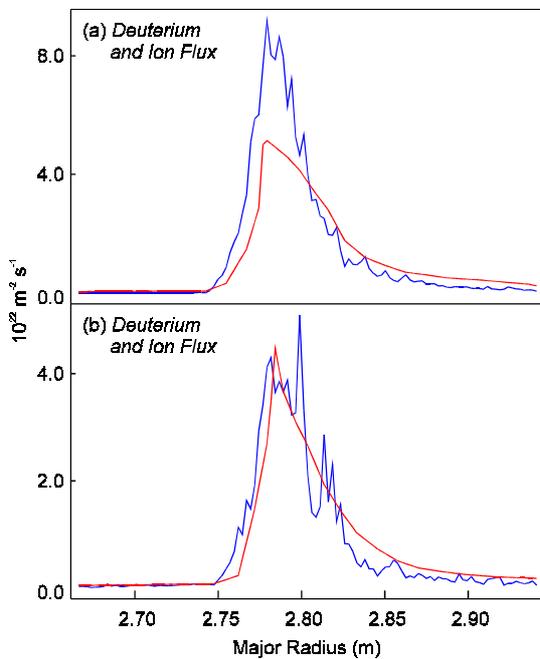


Figure 5: Comparison of the radially resolved outer divertor profiles of neutral deuterium flux (blue curves) and perpendicular ion flux (red curves) at time 20.60 s for the two SOL injection pulses: #38757 with D_2 (a) and #38748 with CD_4 (b)

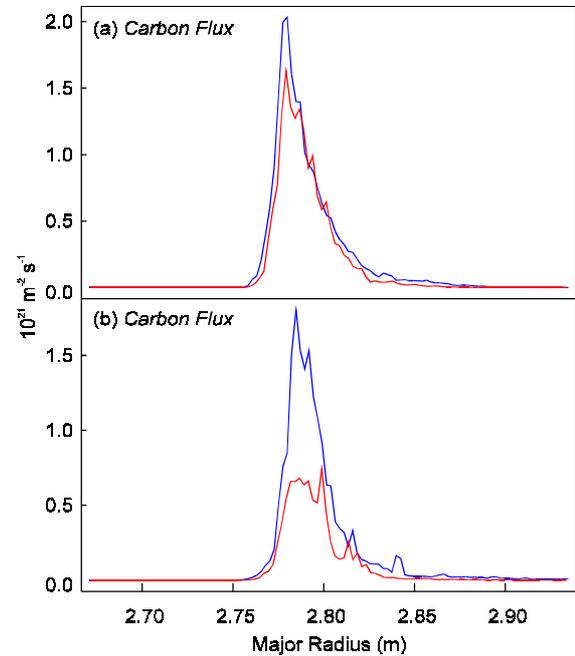


Figure 6: Comparison of the radially resolved outer divertor profiles of carbon flux evaluated from CII (blue curves) and the calculated from deuterium flux (red curves) at time 20.60 s for the two SOL injection pulses: #38757 with D_2 (a) and #38748 with CD_4 (b).

Confirmation of the CD₄ redeposition should come from the analysis of the carbon fluxes for the two discharges. The carbon flux is evaluated both from the CII photon fluxes, using the ionisation per photon coefficients, and from the deuterium flux assuming physical sputtering and impurity self-sputtering as erosion mechanisms. In the latter case the sputtering yield is calculated assuming that the impacting ions have a shifted Maxwellian energy distribution and an isotropic angular distribution [4] [5]. In figure 6a and 6b the carbon particle flux calculated from the deuterium flux is compared to the carbon flux evaluated from the CII photon flux for the deuterium and methane injection experiments respectively. In the D₂ injection (figure 6a), the two C fluxes agree quite well while in the case of the CD₄ discharge (figure 6b) the C flux evaluated from the CII is a factor > 2 higher than the one calculated from the deuterium flux. Thus some methane molecules break up and contribute to the total carbon content of the divertor plasma. To assess what rate of CD₄ would have produced the unaccounted amount of C flux the same method used for the D flux is used. From figure 6b, it is possible to establish that $\bar{R} \sim 2.80$ m, $\delta R \sim 0.02$ m and $\Delta\Gamma_C \sim 1.11 \cdot 10^{21}$ C/m²s, which, if it is assumed that all the puffed methane breaks up into carbon atoms, would correspond to an injection of $1.95 \cdot 10^{20}$ CD₄/s while the injected methane rate was $3.21 \cdot 10^{21}$ CD₄/s. The relation between the injected CD₄ rate and the increase in the carbon fluxes allows to establish an upper limit for the percentage of molecules that disintegrate into carbon atoms and enter the discharge. Only up to 6 % of the total number of CD₄ molecules contaminates the divertor plasma while the remaining 94 % redeposits immediately on the target in the form of CD_x⁺ molecular ion.

Conclusions

The analysis of the spectroscopic data from the methane injection experiments and the modelling of both the deuterium reference and the methane discharges has led to the following conclusions:

- The highly localised increase of the CD band signals shows that the methane is present in the discharge only very close to the injection point.
- The slight or negligible increase of the carbon photon fluxes from ionisation states +1 and higher indicates that only a small fraction of methane molecules disintegrate in carbon atoms and contribute to the increase of the discharge carbon content.
- The modelling of the deuterium flux shows that the deuterium associated with the injected CD₄ molecules is not observed in the discharge. This suggests that it becomes trapped on the surface after redeposition.
- The modelling of the carbon flux shows that at least 94 % of the CD₄ molecules should redeposit as molecular ions immediately after production and therefore that only a small percentage of them should break-up into carbon atoms or ions.
- The net impurity production and divertor target erosion due to chemical sputtering is very small.

This is of course a good result for the choice of carbon as a target material of future reactor size machine as ITER. There is no need to take the high erosion yields of chemical reactions into account as most of the desorbed molecules will redeposit immediately after formation without interfering too much with the purity of the plasma and with the divertor target plate lifetime.

Acknowledgements

The financial support from EPSRC, Imperial College and JET Joint Undertaking is gratefully acknowledged

References

- [1] H. D. Pacher et al., *Journal of Nuclear Materials*, **241-243** (1997) p. 255
- [2] J. Roth and C. Garcia-Rosales, *Nuclear Fusion*, **36**, 12 (1996)
- [3] H. P. Summers, *Atomic Data and Analysis Structure User Manual*, JET-IR(94) 06
- [4] W. Eckstein and V. Philipps, *Physical Processes of the Interaction of Fusion Plasmas with Solids*, edited by W. O. Hofer and J. Roth, Academic Press, 1995
- [5] W. Eckstein, *Private Communications*, December 1997