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# Chemical erosion yields and photon efficiency measurements in the JET gas box divertor

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**Abstract**

Hydrocarbon injection into the JET gas box divertor in ohmic and L-mode discharges has been used to investigate the intrinsic hydrocarbon erosion yields and to determine the variation of the photon efficiency with the edge ion flux. Constant methane erosion yields were measured (5% for $CD_4$, 3% for $CH_4$) with no sign of any flux dependence. The erosion yield of ethane/ethene was lower but increased with plasma density (increasing edge ion flux, decreasing edge electron temperature) such that it dominated the molecular carbon source at high density. The measured photon efficiencies (the number of molecular dissociations per emitted photon) were not constant, but were found to increase with increasing density (increasing edge ion flux, decreasing edge electron temperature). 

*Keywords:* Carbon; Chemical erosion; Flux dependence

## 1. Introduction

The low $Z$ and good thermal and mechanical properties of graphite make it a candidate material for the walls and divertor of a fusion reactor. Its major drawbacks are the high erosion rate from chemical sputtering and the tritium inventory in redeposited carbon films [1]. Recent in situ erosion measurements [2–4] have indicated a promising trend of reduced erosion yields at high incident particle fluxes, though these studies assumed a constant photon efficiency (D/XB, the number of molecular dissociations per emitted photon) for their determination of the methane flux from spectroscopic observation of the CD molecular band at 431 nm.

We have investigated the behaviour of the hydrocarbon erosion yield in the JET gas box divertor with a series of dedicated experiments in which methane ($CD_4$ and $CH_4$) and ethene/ethane ($C_2H_4$, $C_2H_6$) hydrocarbons were puffed from the divertor gas introduction modules (GIMs) into either deuterium or hydrogen plasmas. Ohmic and L-mode (2MW NBI) 2.4MA, 2.5T vertical target $X$-point plasmas were mainly used for this study. The typical magnetic configuration is shown in Fig. 1, which also shows the locations of the divertor Langmuir probes and some spectroscopic lines-of-sight (LOS). Light collected from the global inner and outer divertor views was routinely monitored by the KS3 survey spectrometer, which clearly showed CD (from break-up of $CD_4$) and $C_2$ (from break-up of $C_xD_y, x > 1$) molecular band features.

The hydrocarbon gases were mostly injected through GIM 9 (slots in a toroidal ring in the floor of the outer divertor) rather than GIM 10 (in the sidewall of the outer divertor) because the spectroscopy has an un-vignetted view of GIM 9, see Fig. 1. The observed increases in molecular band intensities ($\Delta I_{puff}$), compared with the intrinsic intensities ($I_{intrinsic}$) in deuterium/hydrogen puffed reference pulses, were used

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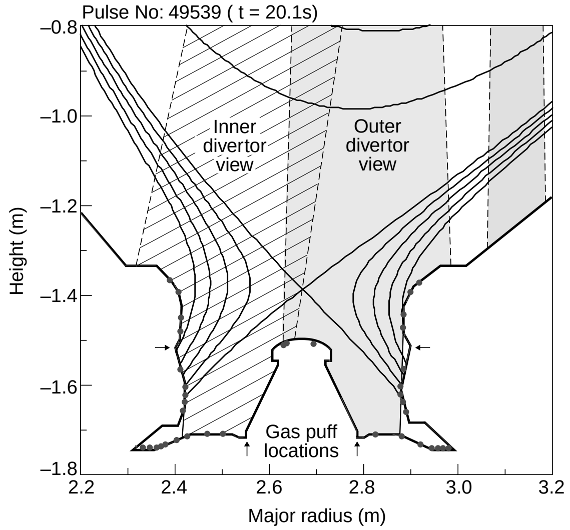


Fig. 1. The magnetic configuration of the discharges used, showing the fixed Langmuir probe positions and the LOS of the visible spectroscopy. The inner and outer divertor LOS are the integral over the shaded and coloured areas indicated.

to deduce the intrinsic hydrocarbon influxes, $\Gamma_{\text{intrinsic}}$ ($\Gamma_{\text{intrinsic}} = \Gamma_{\text{gas}} * I_{\text{intrinsic}}/\Delta I_{\text{puff}}$) and erosion yields, $Y$ ($Y = \Gamma_{\text{intrinsic}}/\ \Gamma_{\text{D,H}}$), as well as the D/XB ($\text{D/XB} = \Gamma_{\text{gas}}/\Delta I_{\text{puff}}$), where $\Gamma_{\text{gas}}$ is the flux of puffed hydrocarbon gas, and $\Gamma_{\text{D,H}}$ is the intrinsic deuterium influx calculated from either Langmuir probe measurements or the intrinsic deuterium intensity, $I_{\text{D,H}}$ ($\Gamma_{\text{D,H}} = I_{\text{D,H}} * \text{S/XB}$, where S/XB is the deuterium photon efficiency).

The assumption is made that the different source distributions (intrinsic vs. puffed) do not have a significant effect on the measurements. This assumption is supported by earlier measurements of D/XB in Elmy H-mode plasmas that found the same value whether the methane was injected into the private flux region (as here), or into the scrape-off-layer [5]. We also assume that the divertor cryopump does not pump a significant portion of the injected hydrocarbon gas, because the gas is directed vertically upwards towards the plasma edge and not towards the pumping slots at the junction between the horizontal and vertical divertor tiles.

## 2. Results

Experimental signals from 2.4MA, 2.5T L-mode plasmas are shown in Figs. 2(a) and (b). Fig. 2(a) shows data for $CD_4$ puffs into a deuterium plasma, whereas Fig. 2(b) shows data for $CH_4$ puffs into a hydrogen plasma. For these plasmas the outer divertor peak edge electron temperature ($T_{\text{ed}}$) was typically 20 eV at low density, and 8 eV at high density. The peak edge density was more variable, but typically varied from $2 \times 10^{19}$ to $1.5 \times 10^{20}\ \text{m}^{-3}$. The ratio of D-alpha intensity to the ion saturation current was typically about 20, increasing slightly with density, indicating that the plasma in the outer divertor was always attached, as would be expected for these $T_{\text{ed}}$. In contrast, the inner divertor was only completely attached at the lowest plasma densities.

The GIM 9 (outer divertor) hydrocarbon puffs in these discharges led to increases in the CD(CH) molecular signals (Figs. 2(a) and (b)), and some increase in the

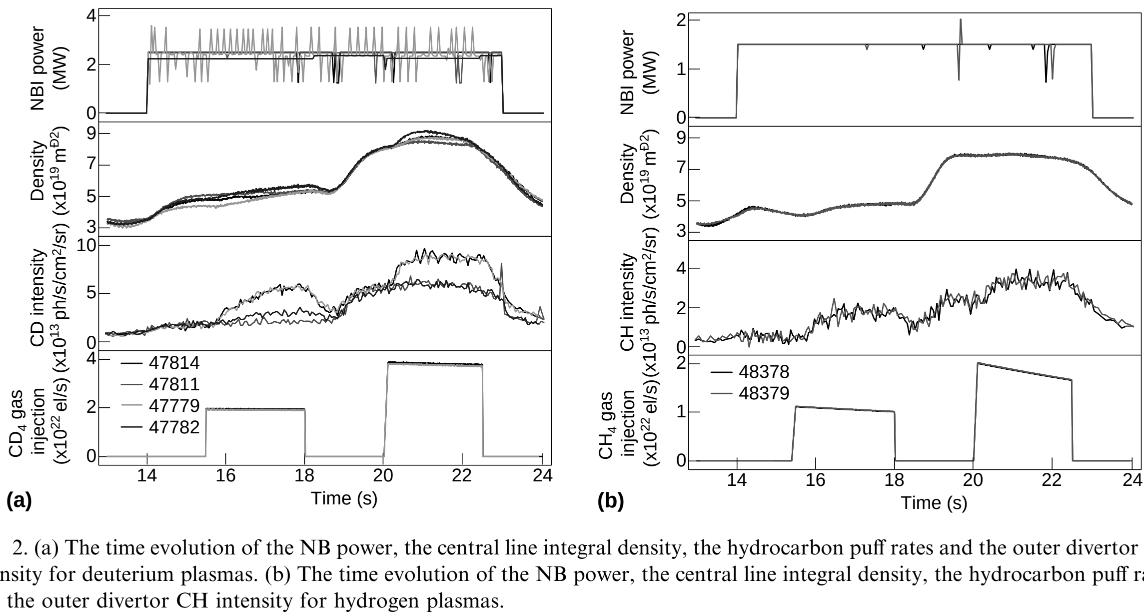


Fig. 2. (a) The time evolution of the NB power, the central line integral density, the hydrocarbon puff rates and the outer divertor CD intensity for deuterium plasmas. (b) The time evolution of the NB power, the central line integral density, the hydrocarbon puff rates and the outer divertor CH intensity for hydrogen plasmas.

low charge states of carbon. However, the line-averaged $Z_{eff}$ showed almost no change ($\Delta Z_{eff} < 0.1$). Note that at high density twice as much methane injection was needed to achieve the same increase in CD(CH) signal as at low density. This implies that the photon efficiency is higher at higher edge densities (lower edge temperatures). The figures also illustrate that: (a) the intrinsic CD(CH) intensities are strongly density dependent, so reference discharges with a well-matched density are desirable, and (b) the intrinsic CD intensity in deuterium discharges is about twice as large as the intrinsic CH intensity in hydrogen discharges. This would suggest that the intrinsic erosion yield of $CD_4$ is twice that of $CH_4$, assuming that D/XB is isotope independent. Reference discharges were not available for the hydrogen plasmas in Fig. 2(b), but by plotting the CH signal vs. density (Fig. 3) the intrinsic CH intensity can be estimated.

Ethane and ethene were also puffed from GIM 9 into 2.4MA, 2.5T ohmic hydrogen discharges. Again it was seen that twice as much gas was needed to be puffed at high density in order to achieve the same increase in molecular $C_2$ intensity as at low density. It was also striking that the $C_2$ intensity was identical in the $C_2H_4$ and $C_2H_6$ puffed discharges, implying identical D/XB. Additionally, it was observed that the CH intensity was possibly showing a small increase when $C_2H_4$ and $C_2H_6$ were puffed, although no increase in inner divertor CH was seen for a strong inner divertor $C_2H_4$ puff. Thus we conclude that for our divertor plasma conditions the break-up of $C_2H_y$ produces few CH molecules, though this is an area worth more detailed study.

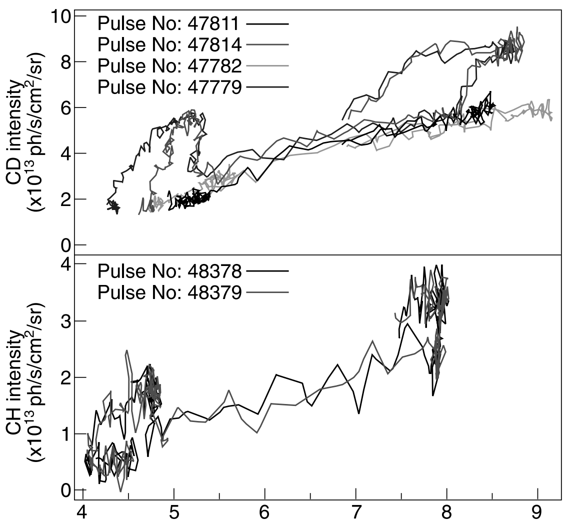


Fig. 3. The evolution of CD(CH) intensities as a function of line integral density for deuterium (hydrogen) discharges with $CD_4(CH_4)$ puffing.

The isotopic dependence of the methane D/XB was also explicitly investigated. $CD_4$ was first puffed from GIM 9 into a 2.4MA, 2.5T ohmic deuterium plasma with a density ramp. The filling gas to GIM 9 was then changed to $CH_4$, and the discharge repeated. The different methane isotopes were therefore puffed from the same location into the same edge plasma. The increases in the CD and CH intensities were found to be the same, within errors, and hence the methane D/XB was shown to be isotope independent.

Figs. 4 and 5 show the full datasets for the hydrocarbon erosion yields and photon efficiencies. The erosion yields are all measurements from the outer divertor, except for a single point from the inner divertor, which will be discussed later. Each outer divertor erosion yield measurement (Fig. 4) is represented by two data points; one where the yield is calculated from an incident flux derived from the D-alpha measurement and a constant $S/XB = 20$, the other where the yield is calculated from a total incident flux derived from the Langmuir probe signals. The probe measurements ought to be the more robust, but depend critically on the relative location of the strike point relative to the probe positions. In the worst case, if the strike point was just missing a probe so that this nearest probe was in the private flux region, the total integrated ion flux would be significantly underestimated. This was probably the case for the $C_2H_4$ puff into a high density hydrogen plasma, where $Y_{C_2H_4} = 5.5\%$ from Langmuir probe data and $Y_{C_2H_4} = 3.3\%$ from D-alpha data (see Fig. 4 data points at an integrated ion flux of $8.2 \times 10^{22}$ s$^{-1}$).

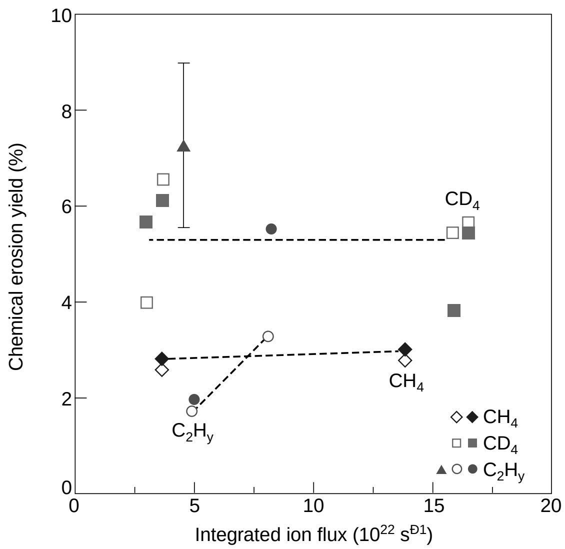


Fig. 4. Hydrocarbon erosion yields as a function of the integrated ion flux to the outer divertor. The incident flux is calculated from Langmuir probe data for the solid data points, and from D-alpha ($S/XB = 20$) for the open points. The ▲ is a $C_2H_y$ yield measurement from the inner divertor.

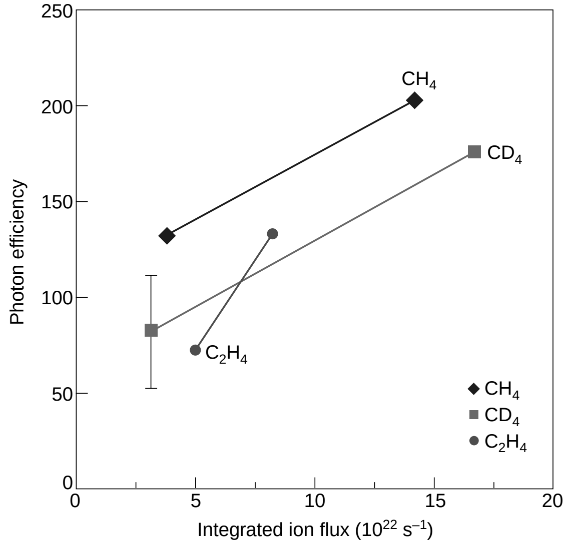


Fig. 5. Hydrocarbon photon efficiencies as a function of the integrated ion flux to the outer divertor.

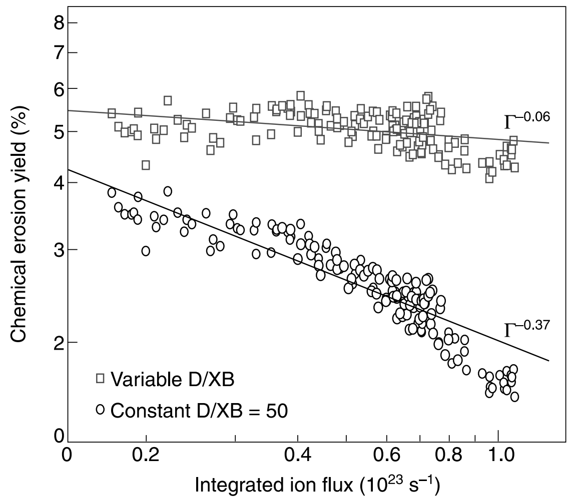


Fig. 6. Revised plot of the chemical erosion yield data from [4] as a function of the integrated ion flux to the outer divertor, both for a constant D/XB (= 50), and the measured variable D/XB.

Fig. 4 shows that the methane erosion yields are constant; about 5% for deuterium plasmas and 3% for hydrogen plasmas, and do not show any flux dependence. In contrast, the erosion yield for $C_2H_y$ (in hydrogen plasmas) does show an increase with the ion flux, rising from 1.8% to 3%. This means that at high density (i.e., high ion flux, or low electron temperature) in hydrogen plasmas the total carbon chemical erosion yield is three times the methane erosion yield! If the same were true in deuterium plasmas, then the total carbon chemical erosion yield would be 15% in the outer divertor.

Fig. 4 also includes a data point for $C_2H_4$ injection into the inner divertor of a deuterium plasma. Assuming that the ethene D/XB is isotope independent, as found for methane, then the intrinsic erosion yield at the inner divertor is determined to be about 7%. Thus the total carbon chemical erosion yield at the inner divertor could be as high as 19%, assuming the same 5% $CD_4$ yield at the inner divertor that was measured in the outer divertor.

The photon efficiencies plotted in Fig. 5 show a strong increase with increasing ion flux. From our data it is not possible to determine whether the changes in photon efficiency are due to the changing ion flux, electron density, or electron temperature. In any case, these results are not consistent with the modelling of Naujoks [6], which showed that the D/XB for methane had little density dependence, and increased with increasing electron temperature.

Earlier JET hydrocarbon yield data [4] had been analysed with the assumption of constant photon efficiency, and showed a decrease of the hydrocarbon yield with increasing flux density. If this earlier JET data is reanalysed using the $CD_4$ photon efficiencies from Fig. 5, and assuming a linear variation of D/XB with integrated ion flux, then the hydrocarbon yield becomes constant with increasing ion flux, Fig. 6. Other measurements that assumed a constant D/XB [2,3], and which also showed decreasing erosion yield with increasing ion flux, would most likely show a similar effect.

## 3. Summary

New measurements of the methane erosion yield in the JET gas box divertor found that it was a constant 5% for $CD_4$ in deuterium plasmas, and 3% for $CH_4$ in hydrogen plasmas. The recently reported flux dependence of the methane yield [2–4] was not observed, and seems to be a consequence of assuming a constant D/XB. Our measurements of D/XB (methane and ethane/ethene) show that D/XB increases strongly with increasing ion flux or decreasing electron temperature.

The erosion yields of higher hydrocarbons were also measured and showed an unfavourable increase with ion flux, from 1.8% to 3% in hydrogen plasmas. Consequently, in hydrogen plasmas the total carbon chemical erosion yield was always at least double the methane yield. In a deuterium plasma, the ethene erosion yield was determined to be about 7% at the inner divertor. This is higher than the 3% maximum $C_2H_y$ yield found at the outer divertor, and supports the hypothesis of readily eroded soft films that has been invoked to explain the thick carbon layers found on the inner louvers at JET [7].

It should be noted that these erosion yields are only the gross local yields. Net erosion yields will be much lower because these hydrocarbons are readily dissociated and ionised by the plasma and returned promptly to the divertor target plates. However, erosion yields of this magnitude, and the concomitant trapping of tritium in redeposited films, would present a tritium inventory problem for ITER [1], which might be alleviated by operating with the graphite at elevated temperatures (>600 K [8]).

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