

FLUX DEPENDENCE AND ISOTOPE EFFECT OF THE CHEMICAL EROSION OF CARBON UNDER TOKAMAK CONDITIONS

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Abstract

Chemical erosion of carbon is investigated in the outer Divertor II of the ASDEX Upgrade tokamak for ion flux densities up to $10^{23} \text{ m}^{-2} \text{ s}^{-1}$ and up to reactor-relevant values of the power per major plasma radius, $P/R \leq 12 \text{ MW/m}$. Surface temperatures are relatively low and do not exceed $100 \text{ }^\circ\text{C}$ at the position of the measurements. The erosion yields calculated from CH molecular line emission exhibit a pronounced hydrogen flux dependence and an isotope effect, resulting in lower yields for higher fluxes and a factor of 2 higher yields for deuterium in comparison to hydrogen. Corresponding yields derived from carbon ion lines corroborate these results. The observed parameter dependences of the chemical erosion yields can be described with the analytical model of Roth and Garcia-Rosales, Nucl. Fusion **36** (1996), if an additional, empirical time constant for the hydrogenation process is introduced.

Introduction

Carbon is an attractive target plate material for a fusion reactor concerning its high heat conductivity, neutron compatibility and good mechanical properties. The major caveat originates from its high erosion rates, in particular owing to chemical erosion via hydrocarbon formation, which reduce the component lifetime and may lead to the codeposition of considerable tritium inventories within carbon layers in cold regions of the vessel. Chemical erosion depends on a number of experimental parameters, like surface temperature, impact energy and incident flux density (see, e.g. the review by Davis and Haasz [1]). Many of the observed dependences can be explained by the analytic model of Roth and Garcia-Rosales [2]: The chemical erosion yield Y_{chem} is described as the sum of a thermal and a surface process. The thermally activated process, represented by the yield Y_{therm} , peaks at surface temperatures T_{surf} around 1000 K, but has a negligible contribution to the chemical yield at room temperature. The surface process is attributed to the formation of sp^3 hydrocarbon complexes on the surface. The corresponding yield Y_{surf} dominates the total yield Y_{chem} in particular for low surface temperatures and low impact energies. Since the analytic model was originally based on ion beam data, high values of the ion flux density had not been considered. This paper describes spectroscopic measurements of chemical erosion in the divertor of the ASDEX Upgrade tokamak for conditions which are most attractive for power removal in a fusion reactor, namely high fluxes, moderate impact energies and low surface temperatures. Particular emphasis is placed on the dependence of Y_{chem} on the incident flux density, which has been recently observed under cold [3] as well as hot surface conditions [4] [5]. The experimental results are compared with an extended version of the analytical model proposed by Roth [6].

Measurement of chemical erosion yields

The experimental set-up to determine carbon erosion yields Y_{chem} at the outer divertor target (CFC material) is shown in Fig. 1. Line intensities of C^+ and C^{2+} ion lines, hydrogen Balmer series and CH molecular band emission are measured along the indicated line of sight using a low resolution spectrometer [3]. Electron temperature T_e and density n_e in front of the target as well as the ion flux density Γ_i are measured by Langmuir probes. Viewing lines identical to that shown in Fig. 1 are

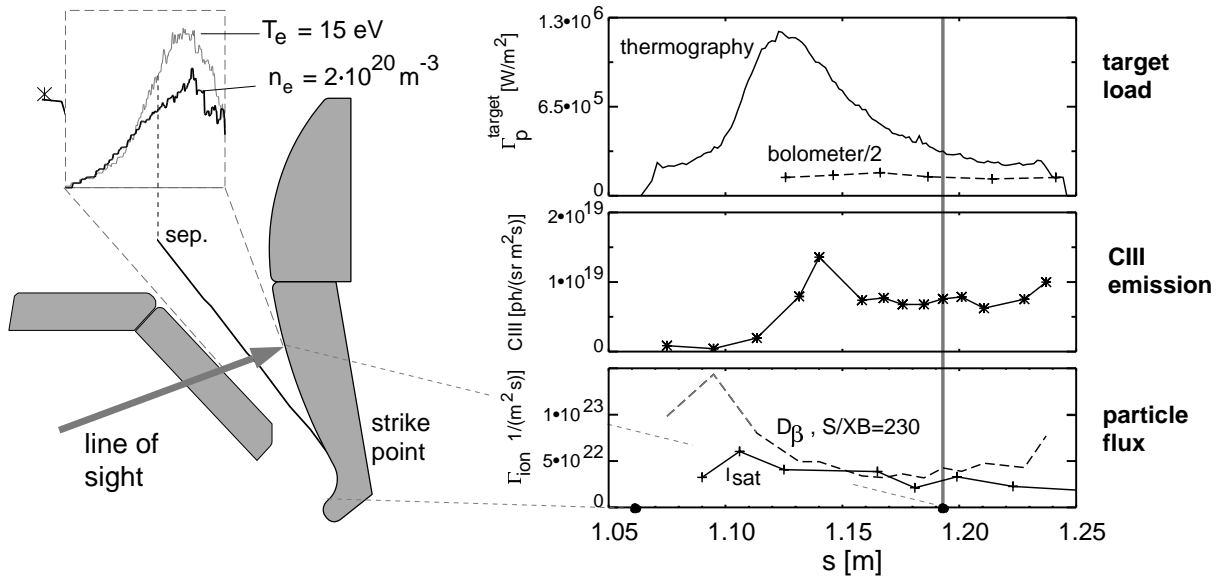


Figure 1: *Left: Experimental arrangement in the outer divertor (Div-II) of ASDEX Upgrade. The arrow indicates the line-of-sight (l.o.s) of the spectroscopic measurements. Typical profiles of n_e and T_e along the l.o.s. from B2-EIRENE modelling are also shown. Right: Target plate power load, contribution from radiation, CIII emission and deuterium fluxes from Langmuir probes and D_β spectroscopy along the target plate for an 8 MW neutral beam heated discharge.*

available for the infrared thermography diagnostic, used to measure the surface temperature T_{surf} and the power flux density Γ_p^{target} . A corresponding bolometer viewing line supplies the line integrated total plasma emission, Γ_{rad}^{bolo} . The latter is also used to correct the power flux density Γ_p^{target} for the contribution of radiation, which is about $\Gamma_{rad}^{bolo}/2$ for the quite homogeneous conditions at the position of the measurements. We restrict our analysis to attached plasma conditions ($T_e^{sheath} \geq 4$ eV), where the mean free path of the particles is short compared to the geometrical dimension and the hydrogen line emission is not affected by recombination. The term hydrogen is used for the element generically, while deuterium refers to the particular isotope.

Evaluation of hydrocarbon and hydrogen fluxes

To calculate the hydrocarbon flux from the spectral line intensity of the CH molecular band, the photon flux is multiplied with an atomic physics factor, D/XB . The chemical erosion yield is obtained according to $Y_{chem} = D/XB \cdot I(CH)/\Gamma_i$, where the ion flux Γ_i is taken from Langmuir probe measurements. Details on the evaluation procedure are described in Refs. [3], [7]. The D/XB values used are called effective because they contain a recalculation to the initial CH_4 flux. The recalculation takes into account the fast redeposition of molecular fragmentation products during the breakup chain leading to the directly observable CH molecules. Heavier hydrocarbons like C_2H_x and C_3H_y contribute to the measurement via the production of CH during their fragmentation. Alternatively to the Langmuir probes, the hydrogen flux is determined by H_β spectroscopy. With the approximation of a constant atomic physics factor, $S/XB=230$, the hydrogen flux evaluated via $\Gamma_H = S/XB \cdot I(H_\beta)$ is found to match the ion flux taken from Langmuir probes within a factor of 2 over a broad experimental parameter range.

Fig. 2 compares fluxes and erosion yields evaluated in different ways for a discharge where heating power and density were ramped up in parallel keeping the divertor temperature approximately constant.

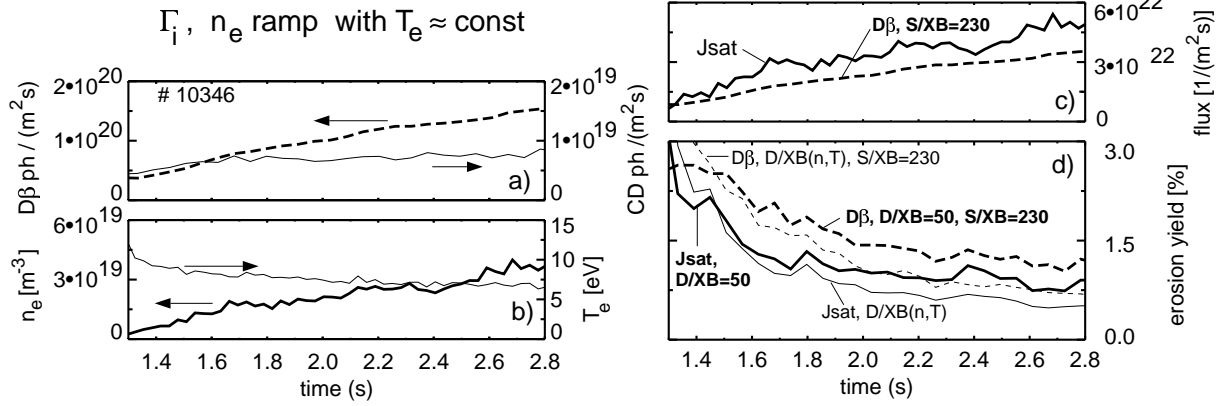


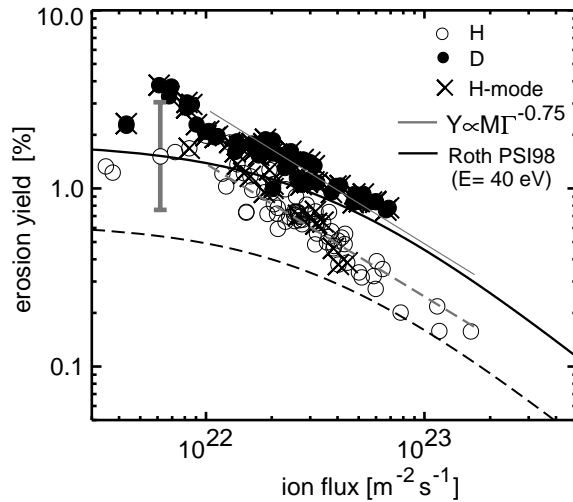
Figure 2: Time traces of a deuterium H-mode discharge with a combined density and power ramp. Shown are a) photon fluxes of $D\beta$ and the CD band, b) electron density and temperature at the target, c) deuterium fluxes and d) chemical erosion yields evaluated with different models.

The hydrogen fluxes obtained from the ion saturation current and $D\beta$ spectroscopy agree quite well. The hydrocarbon fluxes are evaluated with the simple ansatz $D/XB=50$ [3] as well as with $D/XB(n_e, T_e)$ according to Ref. [8]. All combinations of the fluxes exhibit a reduction of the erosion yield Y_{chem} with increasing hydrogen flux, the individual deviations can be taken as a measure of the uncertainties of this experimental technique. We also have analysed discharges with pronounced variations of T_e using the parameter dependent $D/XB(n_e, T_e)$. Unrealistically high and low erosion yields were obtained for high and low values of T_e , as well as unrealistically high values of the flux dependence of Y_{chem} . We conclude that approximations made in Ref. [8] (like constant T_e and n_e along the viewing line) lead to an overestimation of the variation of D/XB . Therefore, we use $D/XB=\text{const}=50$ in the following.

Erosion yield database

To establish a data base for chemical erosion under divertor conditions, a variety of L-mode and H-mode discharges with heating powers $P_{heat} = 1 \dots 20$ MW has been analysed with hydrogen or deuterium as working gas. Each data point represents a temporal average over at least 100 ms. For H-modes, the data are averaged over many ELMs. Fig. 3 shows chemical erosion yields, calculated via $Y_{chem} = 50 \cdot I(CH)/\Gamma_i$. The obtained erosion yields for fluxes $\Gamma_i > 10^{22} \text{ m}^{-2}\text{s}^{-1}$ are fitted by the expression $Y_{chem}[\%] = 1.38 \cdot M_H \cdot (\Gamma_i/10^{22} \text{ m}^{-2}\text{s}^{-1})^{-0.75}$ with the atomic mass $M_H=1$ for hydrogen and $M_H=2$ for deuterium discharges, respectively. No significant parameter dependences have been found on the surface temperature T_{surf} at the position of the measurement and on the mean hydrogen impact energy [9]. T_{surf} varies between 20 and 100 °C in the data base. The data are also quite well described by the extended analytical model proposed in Ref. [6], where the flux dependence is introduced via a finite time constant in the hydrogenation of carbon atoms (term c^{sp^3}). The analytic expression given in Fig. 3 has the asymptotic flux dependence $Y_{chem} \propto \Gamma^{-1}$. Spatially resolved measurements of CH emission in the inner divertor suggest a pronounced drop of hydrocarbon production for detached conditions, corresponding to a reduction of the yield for low impact energies. The quantification of this effect in terms of yields, however, is hampered by the long mean free path of the particles.

Emission lines of C^+ and C^{2+} show generally a behaviour very similar to the CH molecular band. Carbon ion erosion yields, derived with the approximation of a parameter-independent atomic physics factor S/XB exhibit flux dependences slightly stronger than $1/\Gamma_i$, supporting the assumption that chemical erosion is the predominant origin of the carbon content in the divertor plasma.



Cold surface approximation:

$$Y_{\text{surf}} = c^{\text{sp}3} \frac{Y_{\text{des}}(E)}{1 + \exp((E - 65\text{eV})/40\text{eV})}$$

$$c^{\text{sp}3} = \frac{1}{1 + 3 \times 10^{-23} \Gamma} \ll !$$

$$Y_{\text{des}}(E) = QS_n(E) \left[1 - \left(\frac{E_{\text{des}}}{E} \right)^{2/3} \right] \left(1 - \frac{E_{\text{des}}}{E} \right)^2$$

$$S_n(E) = \frac{0.5 \ln[1 + 1.2288 (E/E_{\text{TF}})]}{E/E_{\text{TF}} + 0.1728 \sqrt{E/E_{\text{TF}}} + 0.008(E/E_{\text{TF}})^{0.1504}}$$

Parameter:	Q	E_{des}	E_{TF}
hydrogen:	0.035	2 eV	415 eV
deuterium:	0.1	2 eV	447 eV

Figure 3: Chemical erosion yields Y_{chem} derived from CH band spectroscopy.

Conclusions

Chemical erosion via hydrocarbon formation and release has been found to be the dominant impurity production mechanism in a tokamak divertor at low surface temperature, low electron temperature and high electron density. The erosion process exhibits pronounced isotope and flux dependences, quite independent of the assumptions made during their evaluation. These parameter dependences can be explained with the analytical model [2], if an empirical time constant is introduced for the hydrogenation rate.

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