Direct measurement of carbon erosion rates in the divertor of ASDEX Upgrade

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1. INTRODUCTION

Carbon is considered as a favourable first wall material for fusion reactors, in particular for plasma facing components subject to exceptionally high thermal heat loads. Apart from the lifetime of a material under such conditions, a critical issue in the case of carbon is the possible formation of significant tritium inventories by codeposition with redeposited carbon atoms. Both issues are mainly determined by the carbon erosion rate resulting from physical sputtering and chemical erosion.

Measurements of the chemical carbon erosion yield by spectroscopic observation of the CD molecular band emission in the divertor of ASDEX Upgrade [1] show a pronounced decrease of the yield with increasing flux of the impacting hydrogen ions. The semiempirical model of carbon erosion by Roth et al. [2], relies, for low surface temperatures and high fluxes, mainly on these spectroscopic measurements. To confirm the spectroscopically determined yields, which depend strongly on the accuracy of atomic and molecular rate coefficients, carbon erosion rates were alternatively determined by exposing material samples for single discharges at the outer strike point area of the ASDEX Upgrade divertor II using a probe manipulator system as shown in figure 1.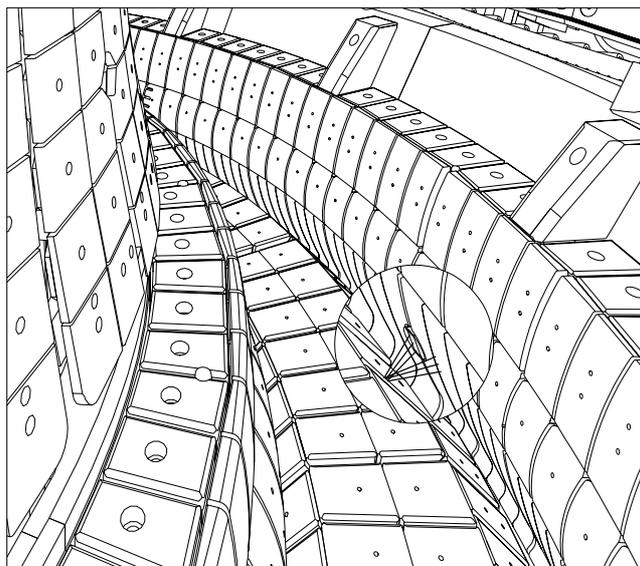 In addition, an array of optical fibres viewing directly at the probe surface (Fig. 1) provides simultaneous spectroscopic flux measurements to allow direct comparison of both methods.

Figure 1: *Schematic view into the ASDEX Upgrade vessel. The magnified inset denotes the position of the divertor probe.*

2. EXPERIMENTAL

To match the surface conditions of the target plates as close as possible, the material samples were made of the standard EK98 graphite. Additionally, they were covered with a 50-100nm ^{13}C isotope layer deposited from an isotope clean HF methane discharge [3]. This allows separating the ^{13}C isotope from the ^{12}C bulk

isotope by means of Rutherford backscattering spectroscopy (RBS) while retaining identical chemical properties compared to the normal carbon target surface. To increase the RBS depth resolution the samples were, however, polished before the deposition of the ^{13}C-layer in contrast to the normal target tiles with grinded surfaces and a correspondingly higher surface roughness.

The probes were exposed to discharges with long stationary phases in which the particle flux and the plasma temperature at the probe position were kept at a constant level. Ideally, by analysing these stationary phases, erosion yields can be obtained. In discharges with diverted plasma configuration during the non-stationary ramp up and ramp down phases, the accuracy will, however, be limited by the corresponding additional erosion / re-deposition processes.
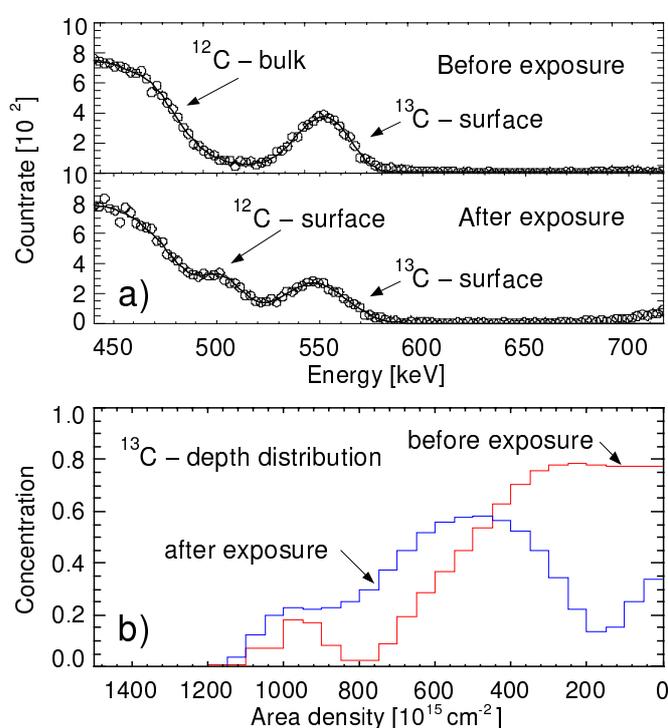
Figure 2a shows the 2 MeV-^{4}He RBS spectra of a ^{13}C sample before and after exposure to a 1 MA L-mode discharge with 2.6 MW neutral beam heating at moderate density ($\bar{n}_e = 6 \times 10^{19}\,\mathrm{m}^{-3}$). The ^{13}C atoms of the virgin sample produce a clear distinct peak indicating a homogeneous layer. In contrast, the spectrum of the same sample after exposure shows a second peak, which corresponds to ^{12}C atoms deposited on top of the ^{13}C layer. In this case it is not possible to derive the total ^{13}C area density by simply integrating over the corresponding RBS peak. Instead the depth distributions of the carbon isotope fractions had to be derived by

Figure 2: *a) RBS energy spectra of a ^{13}C sample before and after exposure to a plasma discharge. b) Depth profiles of the ^{13}C concentration before and after exposure derived from the spectra in (a) by means of Maximum-Entropy deconvolution.*

means of Maximum Entropy deconvolution [4]. The ^{13}C area density and in addition the amount of redeposited ^{12}C on top of the ^{13}C layer were obtained by integration over the respective depth profiles. The gross erosion of the ^{13}C layer is then given by the difference of the ^{13}C area density before and after exposure to the plasma discharge.

Figure 2b shows the depth profiles of the ^{13}C concentration derived from the RBS spectra in Fig. 2a. Before exposure the depth profile reflects the homogeneous ^{13}C-layer with a remaining fraction of approximately 20% ^{12}C. In similar ^{13}C layers deposited on Si single crystals in the same HF discharge the ^{12}C-fraction is below the detection limit ($\approx$5%), which

indicates that the ^{12}C-fraction originates from the bulk material of the carbon sample itself and not from the deposition method. After exposure, the overall concentration of ^{13}C has decreased. As indicated already by the RBS spectrum, one finds a layer of mainly ^{12}C isotope deposited on top of the ^{13}C-layer. The total area density of ^{13}C obtained by integrating over the concentration depth profiles in Fig. 2 is 4.53×10^{17}cm^{-2} before and 3.58×10^{17}cm^{-2} after exposure, resulting in a discharge integral of $\int \Gamma_C \, dt = 0.95\times10^{17}$cm^{-2} eroded ^{13}C atoms. At the same time, $\approx 1.59\times10^{17}$cm^{-2} [12]C atoms were, however, redeposited at the probe surface from other locations and therefore the observed erosion of ^{13}C represents only the lower limit of carbon gross erosion. To obtain the erosion yield $Y(E, \Gamma_D) = \int \Gamma_C \, dt \, / \int \Gamma_D \, dt$, the fluency of plasma ions $\int \Gamma_D \, dt$ impacting at the probe position was determined from the ion saturation current of a flush mounted Langmuir probe at the same poloidal position as the material sample. The mean ion impact energy, E, was determined either from the electron temperature, T_e, measured by the Langmuir probe or, approximately, from the ratio of power flux, P_{target}, and particle flux with corrections for radiation power, P_{line}^{bolo}, and recombination contributions according to the expression [1]

$$E \cong (P_{target} - P_{line}^{bolo} / 2 - \Gamma_D \times E_{rec}) / \Gamma_D \times \gamma_i / \gamma$$

with γ_i / γ denoting the ion temperature fraction of the sheath transmission factor.
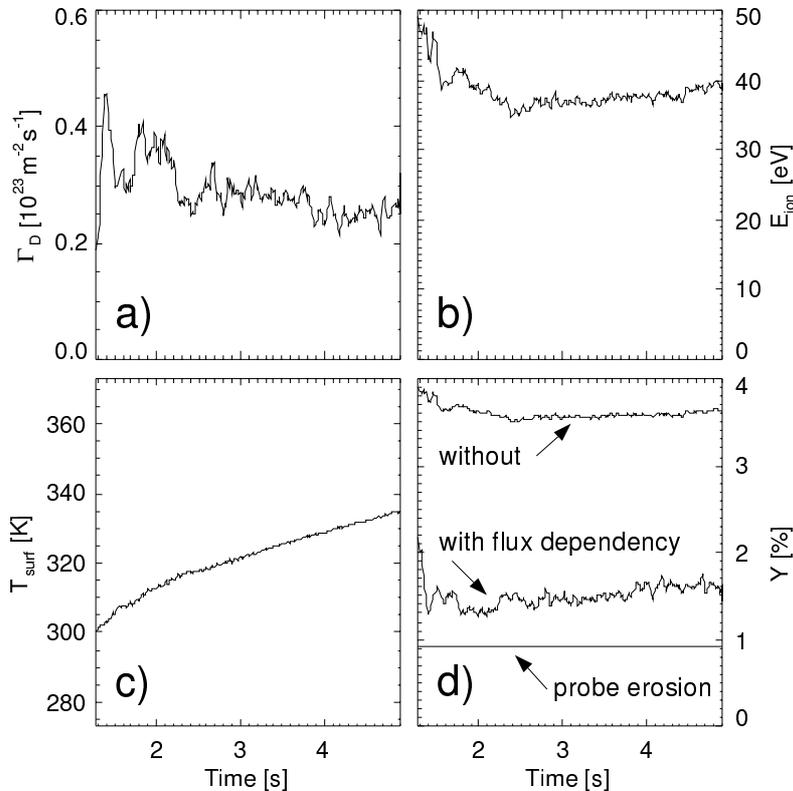

Figure 3: *Time traces of particle flux (a), mean ion energy (b), surface temperature (c) and the erosion yield calculated using the Roth formula with and without flux dependency (d).*

Figure 3 shows the time evolution of the L-mode discharge discussed above during the diverted plasma phase. Ion flux (Fig. 3a) and mean impact energy (Fig. 3b) were in good approximation constant in the divertor phase. The surface temperature at the probe position increased slightly (Fig. 3c). Using the semiempirical model by Roth et al. [2], one can now calculate the carbon erosion yield for these parameters, as shown in Fig. 3d. Comparing both values to the measured result of $\approx 0.9\%$ obtained

from the probe erosion, the best agreement is clearly found for the model with the flux dependency included.

A similar analysis was done for probes exposed in a number of discharges with varying particle fluxes at the probe position. Figure 4 shows the directly measured erosion yields together with the spectroscopically determined yields, low-flux ion beam data, and the semiempirical model described in [1]. Probe results and spectroscopic results agree well for
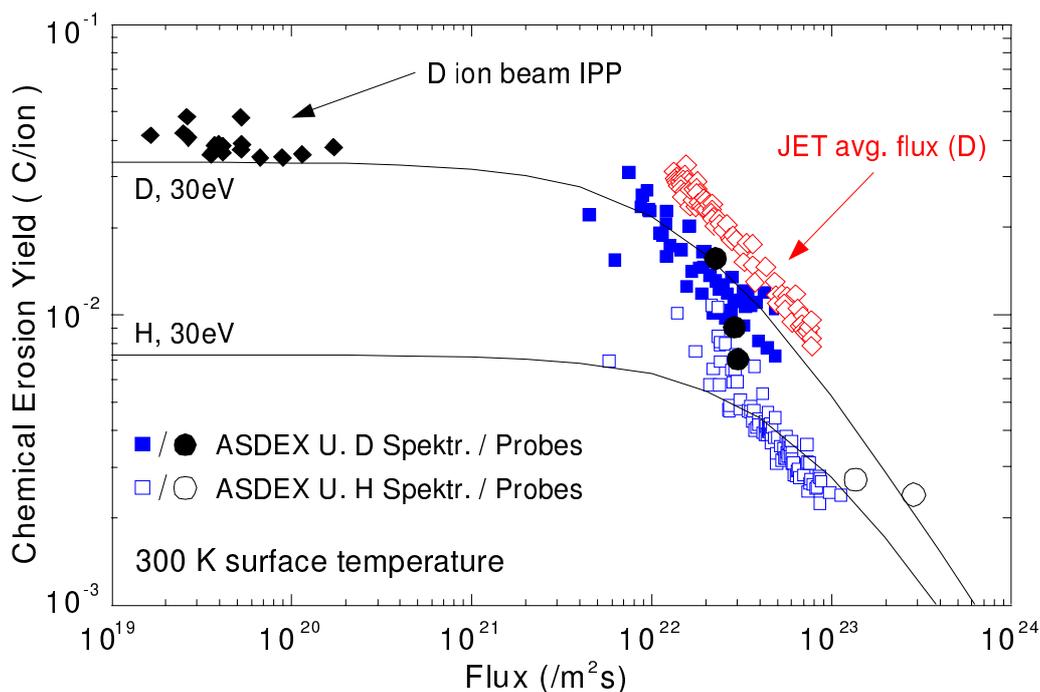

Figure 4: *Comparison of chemical erosion yields of carbon obtained by different experimental methods.*

hydrogen as well as for deuterium. At very high fluxes the probe erosion data indicate, however, a less pronounced decrease of the erosion yield as predicted by the model.

3. SUMMARY

Carbon erosion rates have been measured directly by exposing material probes covered by a ^{13}C isotope layer and analysing the change in thickness by means of Rutherford backscattering. The results confirm erosion yields obtained by spectroscopic observation of CD molecular band emission. It can be concluded that the model of carbohydrate formation and dissociation including the respective atomic data provides a robust description of the chemical erosion of carbon surfaces by hydrogen impact.

[1] A. Kallenbach et al., J. of Nucl. Mat. **266-269** (1999) 343.

[2] J. Roth, J. of Nucl. Mat. **266-269** (1999) 51.

[3] A. Annen, M. Saß et al., Thin Solid Films **312** (1998) 147.

[4] U. v. Toussaint, R. Fischer et al., New J. Phys. **1** (1999) 11.