

## Investigation of local transport and deposition efficiency of reactive gases puffed into the scrape-off layer of TEXTOR

P.Wienhold<sup>1</sup>, H.G.Esser<sup>1</sup>, D.Hildebrandt<sup>2</sup>, A.Kirschner<sup>1</sup>, V.Philipps<sup>1</sup>, M.Rubel<sup>3</sup>

<sup>1</sup>Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, EURATOM Association, D-52425 Jülich, Germany

<sup>2</sup>Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-10117 Berlin, Germany

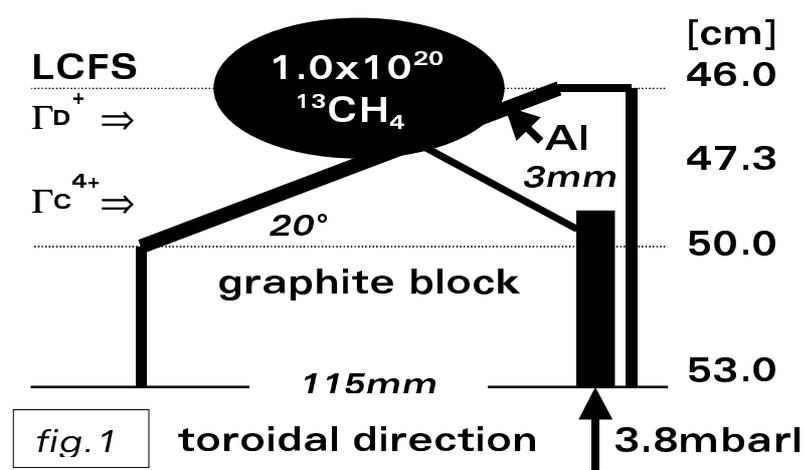
<sup>3</sup>Alfvén Laboratory, Royal Institute of Technology, S-10044 Stockholm, Sweden

### 1. Introduction

The erosion of carbon and its subsequent transport and deposition at other locations remain key issues in fusion devices with wall components made from carbon fiber composites or graphite [1]. Considerable amounts of tritium will be stored in the carbonaceous layers by co-deposition. The layers can become several 100µm thick or form flakes on areas not accessible by cleaning procedures. They are found far distant from the divertor [2] or deep in the scrape-off layer (SOL) as well as at the plasma edge on the belt limiter of TEXTOR [3]. It is rather unclear, however, which mechanisms can cause carbon accumulation under such different conditions, but it seems to be obvious, that deposition and erosion due to the background plasma are not the only responsible processes. At least the local transport of impurities over shorter distances can also affect the accumulation processes. In order to distinguish local from background phenomena an experiment was set up in TEXTOR where <sup>13</sup>C containing methane (<sup>13</sup>CH<sub>4</sub>) has been puffed through a hole of a limiter kept at the plasma edge. Post-mortem analysis discriminated the <sup>13</sup>C from <sup>12</sup>C deposition. The findings could be simulated by means of the ERO-TEXTOR code [4]. The calculations suggest a high re-erosion of the deposited <sup>13</sup>CH<sub>x</sub> species. Other assumptions led to contradictions with the experimental observations.

### 2. Puffing experiment with <sup>13</sup>CH<sub>4</sub>

For the experiment, a graphite block (115x75x70mm<sup>3</sup>) was positioned with its outer end at the last closed flux surface (LCFS, r=46cm) and kept there for 20 ohmic discharges in deuterium (total exposure time 107.7s). The surface with its aluminum target plate (108x70x3mm<sup>3</sup>) was declined by 20° in toroidal direction and covered by this the radial range until 50cm (see fig.1). The first two discharges were carried out without puffing. In the following 18 discharges puffing began at 1s with the calibrated amount of 1.3 mbarl of <sup>13</sup>CH<sub>4</sub>-gas (corresponding to 1.0x10<sup>20</sup> molecules) through a hole (1.7mm diameter). It intersected the block under 60° in radial direction and ended at r=47.3cm. The CH and CII light emission between the declined surface and the plasma edge region was observed two-dimensionally in poloidal direction ('side view'). Both reached maximum intensity at 1.26s, but levelled off beyond 2s. According to the stepwise degradation of the CH<sub>x</sub> fractions, the light emission of CH was found to be centered near the blowing hole and closer to the surface (r≈46cm) while to the CII

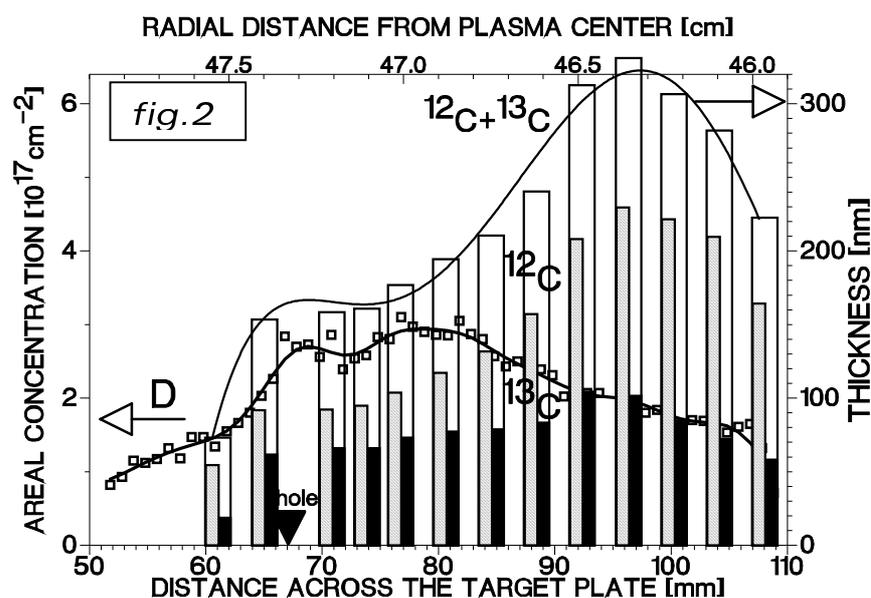


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emission was toroidally extended at  $r \approx 45$  cm. Part of the  $^{13}\text{C}$  contributed to the plasma impurities and raised the CV signal (by about 33%), but part became also re-deposited on the target plate together with the  $^{12}\text{C}$  carried by the SOL plasma. After each of the puffs the incremental growth of the coating has been determined colorimetrically by means of the shift of the interference fringes. Nuclear reaction analysis (NRA) and secondary ion mass spectroscopy (SIMS) were applied after the experiment to determine space and depth distributions of especially the carbon isotopes and the co-deposited deuterium.

### 3. $^{13}\text{C}$ deposition and efficiency

As observed already earlier [5] the deposition efficiency was found to be very low. The value of  $<0.5\%$  has been confirmed, however, in a second puffing experiment using silane ( $\text{SiH}_4$ )



instead of methane (not described here). Lack of space does not allow to describe the colorimetric evaluations yielding the efficiency, but an estimate will be presented. Fig.2 summarises the results of SIMS sputter depth profiling carried out at 13 spots along a line connecting the puffing hole and the maximum of deposition. The distances across the target plate are given as abscissa in

the figure and correspond to different radial distances (upper axis) to the plasma center. The total thicknesses ( $^{12}\text{C} + ^{13}\text{C}$ , light columns) are determined by means of the sputter time elapsed until the Al substrate is reached taking into account the yield of 1 nm/s. The smoothing curve increases between hole ( $r = 47.3$  cm) and target end (LCFS), but shows a maximum value of about 320 nm (right scale) at  $r \approx 46.3$  cm still in the SOL. This may indicate the begin of the erosion zone. The results fully agree with the colorimetric determined thickness profile and yield a first estimate of the efficiency if a deposition area of  $8.7 \text{ cm}^2$  is considered which has been observed after each puff. Taking into account the average deposited thickness of  $\approx 240$  nm, a carbon density of  $6.5 \times 10^{22} \text{ cm}^{-3}$  as for a-C:D and a  $^{13}\text{C}$  content of 40%, the resulting value represents 0.2-0.3% only of the total amount of the  $18 \times 10^{20}$  molecules puffed during the experiment. In addition, this value is confirmed within a scatter of about 50% by the colorimetric evaluation of the incremental growths after each of the 18 shots.

Since SIMS analysis discriminates  $^{13}\text{C}$  and  $^{12}\text{C}$ , the concentration  $^{13}\text{C}/(^{12}\text{C} + ^{13}\text{C})$  could be determined. It was found increasing within the deposit (and hence within the exposure time of 107.7 s) from  $\approx 0.3$  at the Al substrate to  $\approx 0.5$  at the upper surface. The increase is likely due to the initial  $^{12}\text{C}$  coverage of roughly 40 nm grown during the first two plasma exposures before puffing. The  $^{13}\text{C}$  concentrations decrease, however, with distance from the blowing hole because of the increasing fraction of  $^{12}\text{C}$  deposition out of the background. There averages are given as thickness values in the figure (black and hatched columns) and demonstrate the local

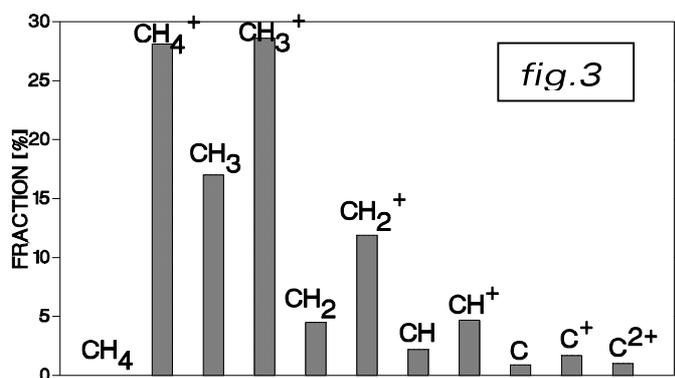
transport of  $^{13}\text{C}$  across the target plate over several cm. The maximum deposited amount of  $^{13}\text{C}$  is found at a location 25mm distant from the hole and 8mm near to the LCFS. In addition, the figure shows the co-deposited amount of deuterium (squares) measured by NRA along the midline of the target. The increase of the areal concentration (left scale) coincides with the increase of the thickness and corresponds to a ratio  $\text{D}/\text{C}\approx 0.3$ . But, the ratio decreases against the plasma near end to  $\approx 0.1$  likely due to temperature excursions which deteriorated also the transparency of the deposited a-C:D(H) film. The H content of the film was not measured yet.

More than 99% of the introduced  $^{13}\text{C}$  is deposited elsewhere in the machine, most likely on the toroidal belt limiter ( $3.5\text{m}^2$ ). Provided the interaction zone is 40nm extended into the graphite bulk ( $^{12}\text{C}$ ), the  $^{13}\text{C}$  concentration should reach about 25% and feed the impurity flux in the SOL with an according isotopic ratio. Indeed, a value  $^{13}\text{C}/(^{12}\text{C}+^{13}\text{C})\approx 0.23$  was measured by NRA on a target mounted perpendicularly to the toroidal direction. The question remains, however, whether the higher concentrations (0.4) found on the declined target despite the low efficiency can be explained.

#### 4. Calculations with the ERO-TEXTOR Monte-Carlo code

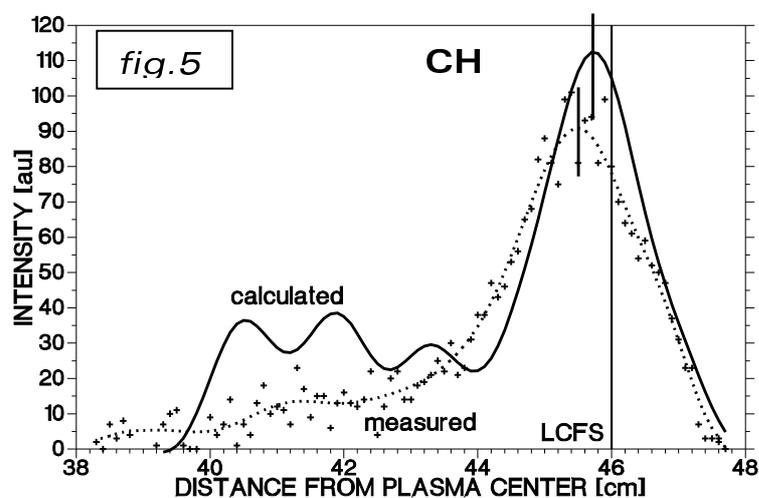
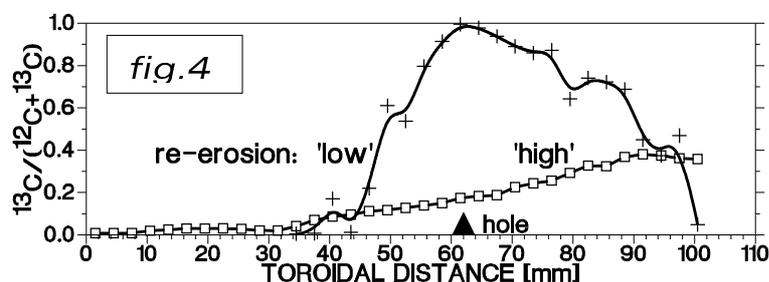
This code models three-dimensionally the local transport and re-deposition of eroded impurities under the influence of a background plasma taking into account magnetic and electric field forces, friction and cross field diffusion and thermal forces. Major input parameters were density  $n_e(\text{LCFS})=1.9\times 10^{12}\text{cm}^{-3}$  ( $\lambda_n=22\text{mm}$ ) and temperatures  $T_e=54\text{eV}$ ,  $T_i=81\text{eV}$  ( $\lambda_T=40\text{mm}$ ) for electrons and ions as measured by the He- and Li-beam diagnostics. The values result into an ion flux of  $\Gamma_D^+=1.33\times 10^{19}\text{cm}^{-2}\text{s}^{-1}$  at  $r=46\text{cm}$  with  $\lambda_D=17\text{mm}$  liberating  $\text{CD}_4$  by chemical erosion with a yield  $Y_{\text{chem}}=0.015$ . 3.6% of  $\Gamma_D^+$  was assumed as  $^{12}\text{C}$  impurity flux  $\Gamma_C^{4+}$  at the LCFS [3]. The physical sputtering of carbon is treated by TRIM while the sputter yield  $Y_{\text{phys}}(T_e)$  of hydrocarbons depends on energy [6]. The intermittent  $^{13}\text{CH}_4$  puffing was replaced by a constant rate of  $1.5\times 10^{19}/\text{s}$  of thermal molecules. By collisions in the SOL plasma all hydrocarbon molecules become disintegrated stepwise and ionised, return to the target surface partly or are carried away. It is assumed that only ions can stick and change concentrations within a 40nm deep interaction zone. Neutral hydrocarbons do not contribute to the deposition. Outputs of the code are e.g. the time evolutions of the  $^{13}\text{C}$  and  $^{12}\text{C}$  deposition/erosion pattern on the target plate and the distributions of the CH, CD and CII light emissions which can be compared with the experimental findings. For further details and references we refer to [4].

As example fig.3 shows that the calculated  $^{13}\text{CH}_x$  fractions after puffing reach the surface mostly as  $\text{CH}_4^+$  or  $\text{CH}_3^+$  ions. They do not travel far in the SOL, but gain energy in the sheath



potential ( $\approx 100\text{eV}$ ) and are deposited. Key parameter seems to be the probability for a process which leads to the direct re-erosion of the charged hydrocarbon radicals. Usually, only 50% are assumed to be reflected (in the form of  $^{13}\text{CH}_4$ ), the rest sticks. This leads, however, to drastic disagreements with the observations: the efficiency for  $^{13}\text{C}$  deposition reaches 40% which causes thicknesses of 80-160 $\mu\text{m}$  peaking at the hole while experimentally 0.3 $\mu\text{m}$  were found

several cm away. The behaviour becomes fully dominated by the  $^{13}\text{C}$  deposition as shown in fig.4 ('low' re-erosion case, crosses). Its near surface concentration approaches 100% while  $^{12}\text{C}$  deposition plays a negligible role.



'erosion' case was realised in the calculations by setting the reflection coefficient for ions to the extreme ( $R_{\text{ion}}=1$ ). This reduces the efficiency to the much lower value of 2.5% because the remaining deposition is due to carbon only. It brings the  $^{13}\text{C}$  concentrations into the observed range of 10-40% (fig.4, squares) and shifts the deposition maximum by about 3cm towards the end of the target plate. The calculated  $^{13}\text{C}$  pattern agrees well with the observed deposition area, outside of which net erosion of  $^{12}\text{C}$  could be identified (not shown). In addition, the calculated distributions for CH and CII light emission agree well with the measured ones within the statistical limits. An example for radial CH scans intersecting the maximum is given in fig.5. According to the deposition efficiency of 2.5% the maximum thickness of 1.4-2.3 $\mu\text{m}$  is still 4-7 times too high. This may be due to remaining uncertainties of the input parameters or to the not considered additional erosion by oxygen impurity ions or hydrogen released from hydrocarbon after disintegration.

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