Investigation of carbon transport by ^{13}CH$_4$ injection through graphite and tungsten test limiters in TEXTOR

A. Kreter, D. Borodin, S. Brezinsek, S. Droste, T. Hirai[1], A. Kirschner, A. Litnovsky,
M. Mayer[2], V. Philipps, A. Pospieszczyk, Y. Sakawa[3], U. Samm, O. Schmitz, G. Sergienko,
T. Tanabe[3], Y. Ueda[4], P. Wienhold and TEXTOR team

Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, EURATOM Association,
Trilateral Euregio Cluster, 52425 Jülich, Germany
[1] *Institut für Werkstoffe und Verfahren der Energietechnik, Forschungszentrum Jülich GmbH,*
EURATOM Association,52425 Jülich, Germany
[2] *Max-Planck-Institut für Plasmaphysik, EURATOM Association, 85748 Garching, Germany*
[3] *Dep. of Energy Engineering and Science, Nagoya University, Nagoya 464-8603, Japan*
[4] *Graduate School of Engineering, Osaka University, Osaka 565-0871, Japan*

1. Introduction

The material choice for the plasma facing components (PFCs) in the next-step fusion device ITER is one of the crucial questions for a sustainable and safe operation. Tungsten (W) and carbon fiber composite (CFC) are foreseen for the divertor region of ITER. Carbon based materials have good mechanical as well as outstanding thermal properties, such as high heat conductivity and lack of melting, and therefore are widely used in the present generation of fusion devices. However, carbon is subject of a high physical sputtering by the background plasma particles and chemical erosion, leading possibly to a reduced lifetime of carbon PFCs. Even more crucial for a fusion reactor can be the problem of unacceptable tritium retention in re-deposited a-C:H layers. Therefore, in ITER carbon PFCs are foreseen for the strike point areas only. However, eroded carbon will be transported and re-deposited in divertor regions covered by W. This will cause mixed material effects and can influence the performance of the tungsten PFCs. The aim of the presented experiments in TEXTOR is to investigate the local C transport and possible mixing effects for the materials of the ITER divertor PFC choice. The experimental results are used to benchmark the ERO code[1], a Monte Carlo modelling tool describing erosion/deposition processes and the material transport.

2. Experimental results and ERO code modelling

Graphite and tungsten test limiters of spherical shape (size of 120 mm in toroidal direction, 80 mm in poloidal direction with a curvature of 70 mm) were inserted in the TEXTOR vacuum vessel (major radius $R_0 = 1.75$ m, minor radius $a = 0.46$ m) using the limiter lock system[2] and exposed in the scrape-off layer (SOL) for eight reproducible NBI heated plasma discharges with a density of $\bar{n}_{e0} = 3.5 \cdot 10^{19}$ m^{-3}. Electron density and temperatures at the last closed flux surface (LCFS) were in the range of $n_e^{LCFS} = (1.4\text{-}1.6) \cdot 10^{19}$ m^{-3} and $T_e^{LCFS} = 35\text{-}40$ eV, respectively. In the scrape-off layer (SOL) at the position of the limiter tip they decayed to $n_e^{LIM} = (1.5\text{-}2.0) \cdot 10^{18}$ m^{-3} and $T_e^{LIM} = 20\text{-}25$ eV, respectively. The limiters were pre-heated to 400-450°C.

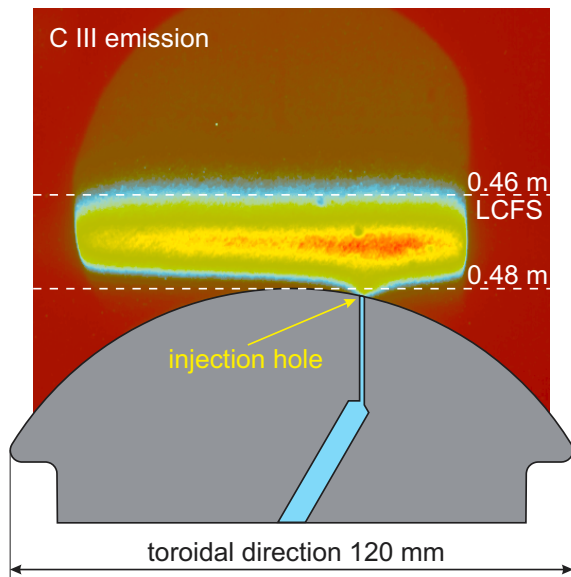*Fig. 1. Scheme of the spherical test limiter with injection hole. CIII light emission during the $^{13}CH_4$ injection through the graphite limiter is shown.*

The limiters were positioned at $r = 0.48$ m, 20 mm outside LCFS (Fig. 1). The injection hole was situated 15 mm toroidally away from the tip of the limiter, so that the radial position of the opening was 1.7 mm behind the limiter tip. The total amount of injected $^{13}CH_4$ ($5.5 \cdot 10^{20}$ molecules for the graphite and $5.7 \cdot 10^{20}$ for the tungsten limiter) was nearly the same. ^{13}C was used to distinguish puffed and intrinsic carbon in the layer deposited on the limiter surface. Several spectroscopic systems were used to observe the limiters horizontally and vertically.

A pronounced difference in the ^{13}C deposition pattern on the limiter surfaces was observed (Fig. 2). The a-C:H film deposited at W shows steep edges surrounded by a shiny net-erosion zone, whereas the deposit at graphite has a smooth profile. There is no clear border between the deposit caused by the injection and by the background carbon flux, as for W. Post-mortem surface investigations by interference fringe analysis, nuclear reaction analysis (NRA) and secondary ion mass spectrometry (SIMS) showed, that the ^{13}C deposition efficiencies (ratio of ^{13}C in the deposit near the hole to the injected ^{13}C amount) are 4 % for graphite and only 0.3 % for tungsten. The maximum of the deposition for both limiters is situated near the injection hole. The distributions of ^{13}C and D are strongly peaked at the hole, whereas ^{12}C is distributed more uniformly (Fig. 3). The maximum thickness is only about a factor of 2 larger for the graphite (2.1 μm) than for the tungsten (1.1 μm) limiter. Therefore, the large difference in the deposition efficiency is
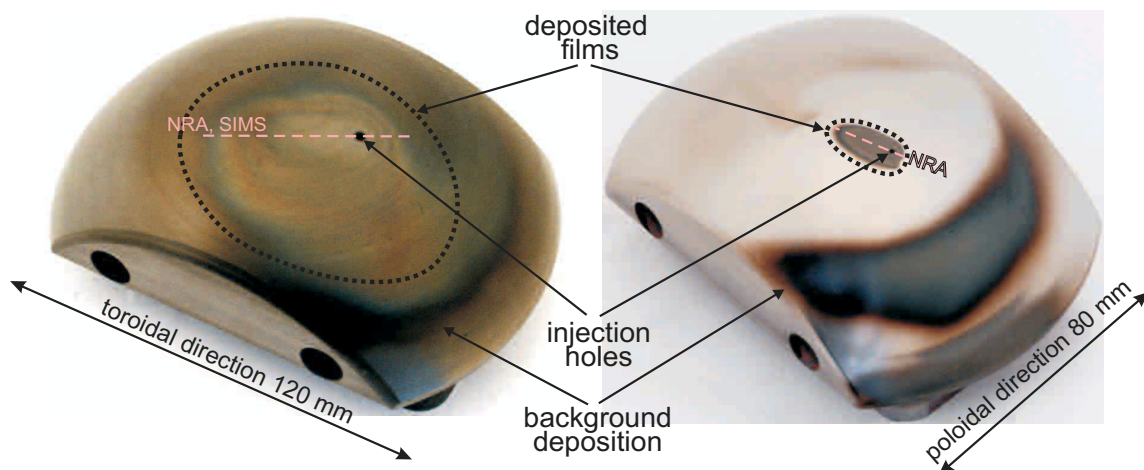

Fig. 2. Photographs of the graphite (left) and the tungsten (right) limiters after the exposure. Dotted contours indicate the areas where the deposition efficiency was defined.
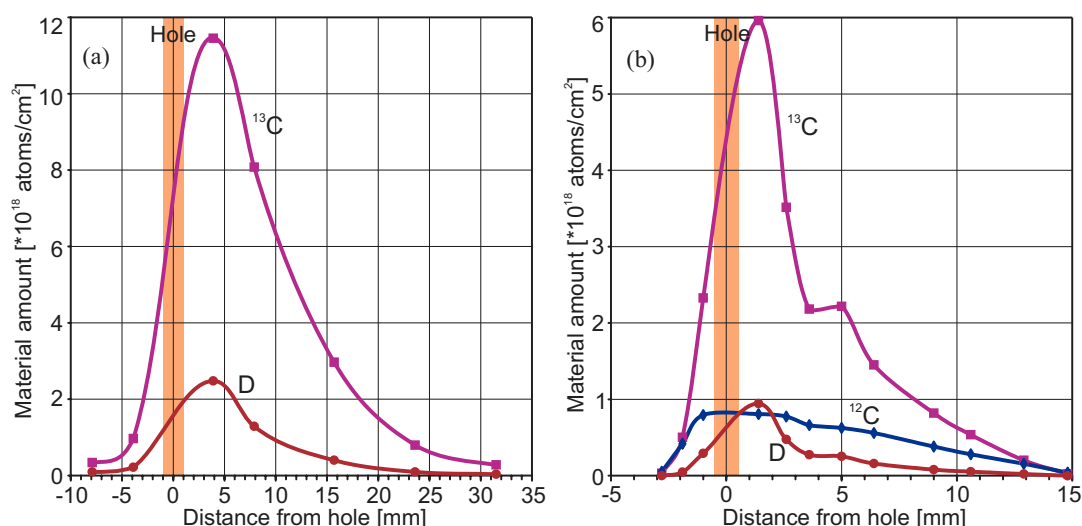
Fig. 3. Deposited material profiles obtained by NRA for the graphite (a) and tungsten (b) limiters along the lines shown in Fig. 2. NRA measurement points are indicated and connected by a spline.

mainly due to the difference in the area of the deposition on both limiters. The ratio of ^{13}C to total C obtained by NRA and SIMS varies from 90 % in the vicinity of the puffing hole to 30-40 % at the deposit edge for both experiments. The D to C ratios are in the range of 10-20 % for graphite and 5-15 % for tungsten.

Modelling by the ERO code was performed for the graphite limiter experiments. The modelling for W is not presented here, as the surface interlayer model currently implemented in the ERO code is not suitable to simulate the dynamic processes in mixed carbon-tungsten layers. At present there is an effort to implement a more sophisticated TriDyn based surface model in the ERO code to simulate mixed materials effects.

For the simulations the measured plasma parameters of the graphite limiter experiment were used. The best match with the measured ^{13}C deposition efficiency was found for the assumptions of an effective sticking of zero for hydrocarbons and an enhanced re-erosion of freshly deposited a-C:H layers (15 % vs. 1.5 % for graphite) resulting in a ^{13}C deposition efficiency of 10 %. Similar assumptions were also necessary to reproduce the results of previous ^{13}CH$_4$ puff experiments at TEXTOR[3]. A good agreement in the carbon deposition pattern (Fig. 4) supports the assumptions of low effective sticking of hydrocarbons. A fair agreement between experiment and modelling was also found for light emission distributions of both C III and the sum of CH and CD lines (not shown here).

3. Summary and discussion

In the ^{13}CH$_4$ injection experiments a large difference in the ^{13}C deposition efficiency was found for the graphite (4 %) and tungsten (0.3 %) limiters. Several effects can be considered as reasons for this. One of them is the effect of kinetic reflections of the incident C from the limiter surface (cf. the EDDY code modelling for the W-C twin limiter experiment in
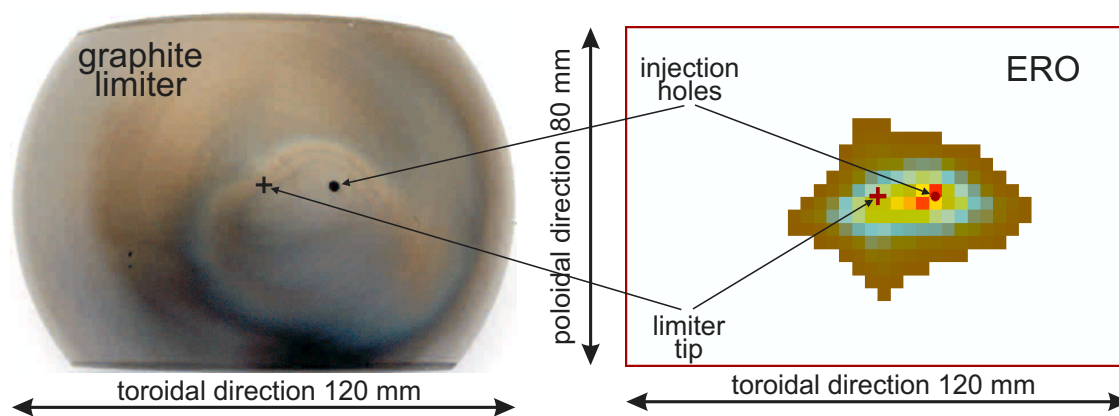
Fig. 4. Deposition pattern on the graphite limiter: (left) after exposure in TEXTOR; (right) of ^{13}C calculated by the ERO code.

TEXTOR[4]). The C reflection coefficients for carbon materials is low (<0.01), whereas it is ≈0.4 for tungsten. It leads to a change in the balance between C erosion and deposition causing a shift of the net-erosion and net-deposition zones in the direction of less C deposition on W substrate. In the region of high C flux near the injection hole the balance switches to net-deposition. After reaching a certain thickness the a-C:H layer protects the W substrate, so that incident C does not perceive the high-Z substrate under the a-C:H layer. It leads to even higher growth rates of the deposit (so-called nucleation effect). Sharp edges of the C deposit on W support this hypothesis.

Another possible reason is the enhancement of the physical sputtering of C deposited on W by the background plasma. To sputter a deposited atom, the incident plasma particle first has to change its momentum direction by a reflection from an underlying atom. Being reflected from heavy W, the plasma particle retains more energy and therefore has a higher probability to sputter C.

Mixed material effects (e. g. carbide formation) for W can also be considered as a possible reason for the different deposition efficiencies. These mixing processes would lead to less chemical erosion and a lower reflection coefficient[4], enhancing the nucleation effect.

The ERO code calculations reproduce reasonably the experimental results for the graphite limiter. The assumption of a low effective sticking for hydrocarbons can be explained by a self re-erosion of transiently deposited hydrocarbons under the influence of energetic background hydrogen[1].

References
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