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Investigation of local carbon transport in the ASDEX Upgrade divertor using $^{13}CH_4$ puffing

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ABSTRACT

To investigate the combined effect of re-deposition, re-erosion and local transport, known quantities of $^{13}CH_4$ were puffed at the end of the 2007 experimental campaign in the ASDEX Upgrade outboard divertor. Exposed tiles were carefully removed for analysis. The amount of ^{13}C locally deposited was measured by nuclear reaction analysis (NRA) and colorimetry. About 100% of injected carbon is deposited within $a \pm 15$ cm extension in the toroidal direction. In contrast to H-mode results where re-deposition was exclusively downstream, in L-mode, more than one third of the injected hydrocarbon is found upstream. Colorimetric analysis of images taken with different lighting angles to the surface reveals a strong asymmetry in the carbon deposition pattern with respect to the injection facing/averting side of the surface roughness, with 4× thicker layers on the side facing the puffing location. The deposition pattern deviates clearly from the magnetic trajectories showing the effect of downward and radial drifts. ERO modelling of a similar experiment carried out in 2003 in H-mode background plasma can nicely reproduce the toroidal deposition pattern but drifts are not yet satisfactory described.

1. Introduction

Carbon composite is still a candidate material for the ITER divertor but critical questions remain concerning its compatibility with tritium operation. The major obstacle is the chemical erosion of carbon via hydrocarbon formation, which may lead to co-deposition of hydrogen isotopes in hydrogen-rich carbon layers on plasma facing or even remote surfaces. If this process cannot be suppressed in ITER, the use of carbon during the D-T phase would require active tritium removal techniques due to the small tritium inventory allowed for safety reasons [1]. Investigating the local carbon transport/deposition is not only important in connection with tritium retention, but also makes it possible to get a 'snapshot' of the primary forces acting at the outer target on neutrals and ions. Correct modelling of the measurements is an essential ingredient on the way to understanding divertor physics and of the proper inclusion of such physics in the modelling codes, therefore giving better prediction capability for ITER. Carbon deposition, erosion and local transport at the outboard divertor in ASDEX Upgrade have been investigated puffing known quantities of $^{13}CH_4$ at the end of the experimental campaigns in 2002/2003 [2] and in 2007, during H-mode and L-mode discharges, respectively. The amount of ^{13}C locally (re-)deposited near the puffing location has been analysed by means of nuclear reaction analysis (NRA) and colorimetry techniques. Surface analysis of the 2007 injection experiment and modelling results of the 2003 experiment are discussed.

2. Experimental

$^{13}CH_4$ has been injected in the outer target scrape-off-layer plasma (Fig. 1) during an ohmic deuterium shot repeated 12-times at the end of the 2007 campaign (22 573–22 585). The main parameters of the discharge were: Plasma current 800 kA, electron line-averaged density 3.2×10^{19} m^{-3} and $^{13}CH_4$ injection rates 6×10^{18} and 3×10^{18} C-atoms/s for the lower valve (LV) and upper valve (UV), respectively. The puffing rates are controlled using piezo valves. A baratron for each valve measures the differential pressure loss during the injection. The distance from the outer strike point to the puffing location is 73 mm and 144 mm for the LV and UV, respectively. The puffing holes have a diameter of 6 mm. The plasma parameters at the injection location were

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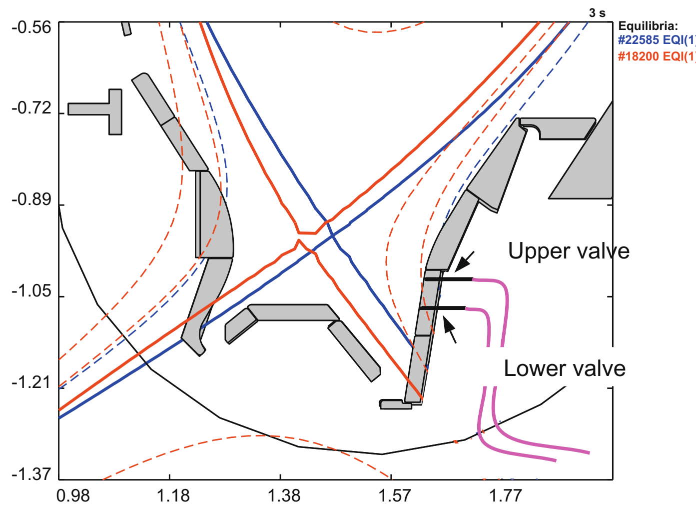

Fig. 1. Experimental arrangement in the divertor of ASDEX Upgrade. The puffing location for the upper valve (UV) and the lower valve (LV) and the separatrix position for the 2007 (blue) and 2003 experiment (red) are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$T_e \simeq 15$ eV and ne $\simeq 1 \times 10^{18}$ m^{-3} for both valves. After the shot sequence the machine was vented, the tiles near the puffing location (Fig. 2(a)) were dismounted and the 2D deposition of ^{13}C was measured using NRA and colorimetry. At the beginning of the 2007 campaign the fine grain graphite outer divertor tiles had been VPS coated (auf PVD layer) with a 200 µm thick tungsten layer, roughness typically $R_z \sim 30$—50 µm [3]. The tungsten substrate made it possible to use colorimetry in addition to NRA to obtain the amount of deposited carbon.

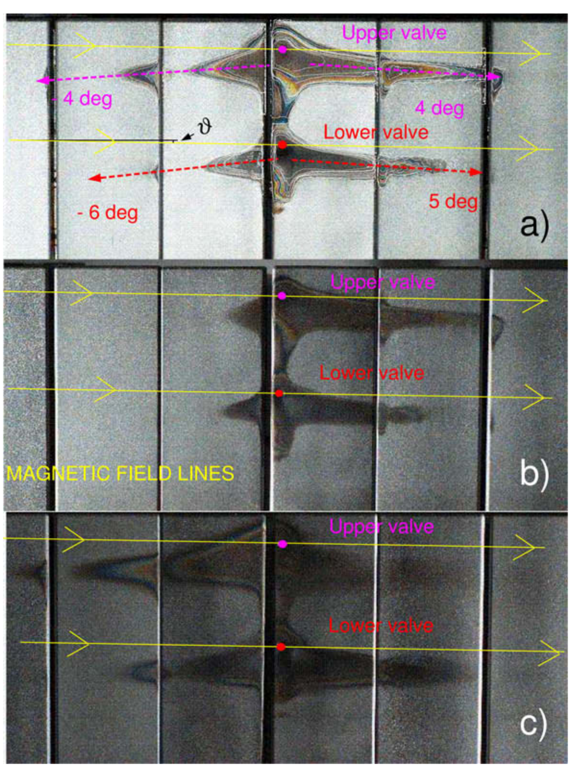

Fig. 2. Tiles pictures after the vessel removal: the upstream (left of the center) and downstream (right of the center) deposition tails from the injection holes (red dots) and the interference colors are easy to observe. The magnetic pitch angle direction is shown. For the images (a), (b) and (c) the tiles have been lighted from the front, the left and the right, respectively. In (a) the iso-thickness contour lines from colorimetry are overplotted. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Ion beam analysis

The tile surface was bombarded with 2.4 MeV ^{3}He ion and the protons from the nuclear reaction ^{3}He(^{13}C,p)^{15}N were detected using a semiconductor surface barrier detector with a solid angle of 26 msr, corresponding to 1.5 mm spot size. The detector was shielded by a 12 µm Mylar foil to prevent backscattered ^{3}He ions from entering the detector, which would otherwise lead to distortions of the proton peak by pulse pile-up. Each spectrum was measured with a ^{3}He charge of 2 µC. The areal density of ^{13}C was determined by comparing the respective proton peak count integral to that of a calibration sample with known amount of ^{13}C. With this procedure, the experimental error is given by that of the beam charge integration (≈20%). In Fig. 3 the 2D ^{13}C surface density distribution obtained by NRA is shown.

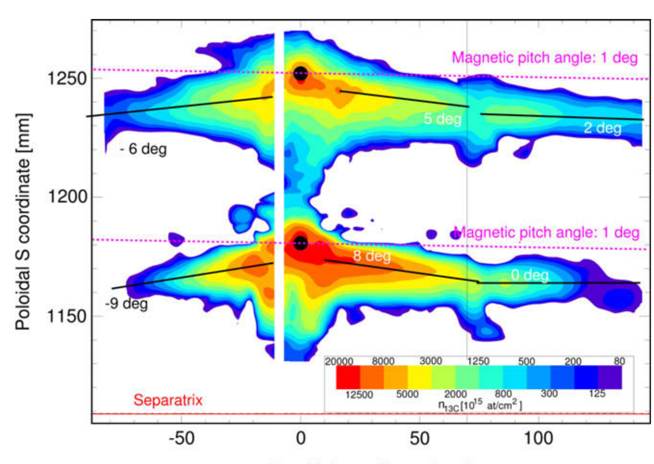

Fig. 3. 2D distribution of deposited ^{13}C obtained by NRA. The magnetic pitch angles (magenta) and the separatrix position (red) are shown. The puff location is shown as a black circle. The estimated redeposition pitch angles are plotted in black and the corresponding angles are labeled. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Colorimetry

Colorimetry is a technique already successfully used in fusion devices to measure erosion/deposition rates and thickness of layers of amorphous films (*a*-C:H) [4]. As long as the film remains transparent it shows colors which depend on the thickness, without significant infuence from surface roughness and geometry. The divertor tiles have been photographed using a 36-bit Nikon camera D2-X with objective Micro-Nikkor 60 mm 1:2.8, then the data converted in Tiff format and analysed using IDL. The RGB image was converted into HSV format and the hue image was analysed. To obtain the 2D gradient map and recognise the transition to the next interference color order (when hue angle jumps from 360° to 0°) a Canny Algorithm has been used. For the conversion from hue to deposit thickness a linear interpolation of the data in [4] obtained for *a*-C:H layer on Si has been used. To calculate the surface density a layer density of 1.5 g cm^{-3} has been assumed (soft layers: $\sim$1 g cm^{-3}, hard layers: $\sim$2 g cm^{-3}, graphite: 2.1–2.2 g cm^{-3}). The colorimetric technique is suitable only for layer thickness between about 100 nm and 600 nm. Outside those limits interference colors cannot be observed. The thicknesses obtained in the present analysis are occasionally near the upper limit and the colorimetric measurements should be considered as approximate, especially concerning the total integrated values. However, the agreement between colorimetry and NRA is very good, indicating that the carbon layers are just above the level of the interference color extinction.

5. Discussion

The ^{13}C 2D distribution obtained by NRA (Fig. 3) and colorimetry (Fig. 4) shows that the deposition pattern is approximately toroidal along the magnetic field direction, but with an additional downward drift. Magnetic field lines run from the mid-plane downstream to the target plate and impinge on the outer divertor surface, in the figures from the upper left to the lower right direction. Magnetic lines as projected onto the surface have a pitch angle θ of about 1° (Fig. 2). The incidence angle of the magnetic line onto the surface is about 0.5° at the UV and 1° at the LV. Magnetic field line tracing gives a toroidal travelling distance along the magnetic lines downstream of 110 mm (55 mm) for each radial mm in front of the UV (LV). This means that a particle ionized 0.1 mm in front of the valve (about one Larmor radius) would travel along the magnetic field 11 mm (5.5 mm for the LV) in toroidal direction before impinging into the tile surface. Particle following upstream along the magnetic field lines would never impact the outer target: explanation of the upstream deposition using a radial drift to the surface is necessary. A strong downward drift is observed in the proximity of the valve (±1 cm) where carbon ions result from ionisation close to the wall. This is likely caused by the ExB drift due to the pre-sheath and sheath potentials. The deposition pitch angle estimated from NRA and colorimetry measurements are shown in Figs. 3 and 4. Downstream is initially 5(8)° for the UV (LV) on the injection tile and becomes comparable to the magnetic pitch angle (1°) after about 80 mm. Upstream of the puffing location the deposition pitch angle is 6(8)° for the upper(lower) tile. The left edge of the injection tile (toroidal position −10–10 mm) is in the shadow of the adjacent upstream tile, and the puffing location is at the limit of the shadowed area. The higher ^{13}C density in the shadowed area indicates that part of the puffed gas can escape in the shadowed volume and diffuse more than the particles dragged away by the background plasma.

The amount of redeposited ^{13}C in the different regions is summarized in Table 1. The total ^{13}C injected is 3.2×10^{20} particles, to be compared with the 2.9×10^{20} from NRA and 2.8×10^{20} from the colorimetry. Within the experimental errors all the ^{13}C is deposited along a stripe starting from the puff location and extending no more than ±15 cm. The decay lengths (also in Table 1) are shorter for the lower valve with respect to the upper one, and shorter upstream with respect to downstream.

Pictures taken using different lighting angles are shown in Fig. 2, (a) with normal incidence lighting, (b) with lighting from the left side and (c) with lighting from the right side. It is evident that an asymmetric deposition occurs: uUpstream of the injection, the surface parts facing the puffing valve are preferentially coated (lighting from right), while on the ones facing the opposite direction less deposition is observed (lighting from left). Downstream from the puffing location the asymmetry is observed only for the UV. In Fig. 5 the layer thickness from colorimetric analysis for the UV upstream 'tail' is shown for the different lighting; about a factor 2 thickness increase is observed between the injection averting side and the perpendicular, and another factor 2 between perpendicular and injection facing directions. This indicates that the carbon deposition happens primarily as a single step process, with high sticking probability and little re-erosion. Otherwise the re-eroded carbon, which is preferentially transported downstream, would remove the asymmetry, eventually reversing it.

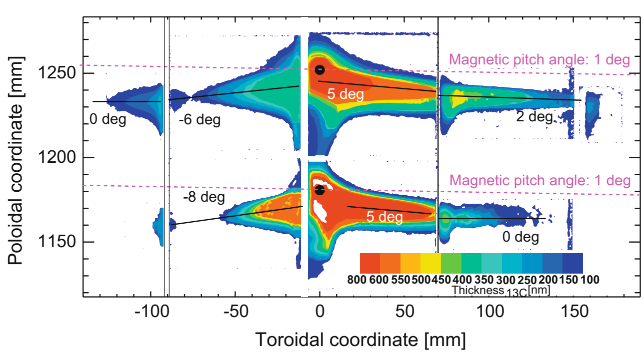

Fig. 4. 2D distribution of ^{13}C obtained by colorimetry. Note, a longer toroidal scale is used compared to Fig. 3.The magnetic pitch angles (magenta) are shown. The estimated redeposition pitch angles are plotted in black and the corresponding angles are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

Summary of the injected and deposited amount of ^{13}C at the lower valve (LV), the upper valve (UV) and the total (sum of the two). Upstream means away from the target (left in the figures), downstream following the plasma flow (right in the figures).

Valve Location	UV Upstream	UV Downstream	UV Total	LV Upstream	LV Downstream	LV Total	Both Upstream	Both Downstream	Both Total
Puffed (at)			1.2e20			2.0e20			3.2e20
NRA (at)	4.1e19	6.7e19	1.08e20	6.8e19.	1.1e20	1.8e20	1.1e20	1.8e20	2.9e20
Colorimetry (at)	3.7e19	1.1e20	1.5e20	2.7e19	1.0e20	1.3e20	6.3e19	2.2e20	2.8e20
Decaylength (mm)	17	37		10	30[a]/17[b]				

[a] First tile downstream.
[b] Second tile downstream.

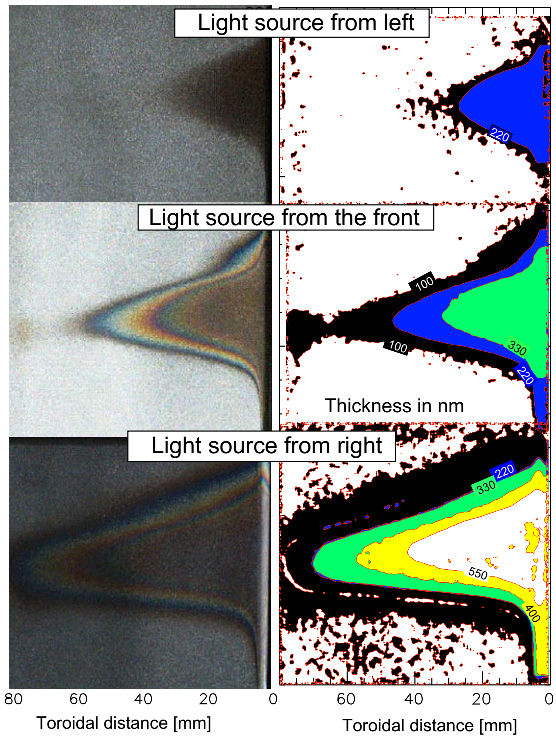

Fig. 5. Effect of roughness on ^{13}C layer thickness from colorimetric analysis for three different lighting angles for the upper valve upstream tile: the thickness on surfaces averting the injection location is half as much as the normal surfaces and one forth of surfaces facing the injection.

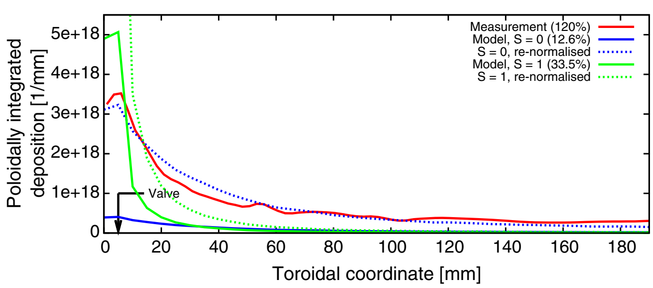

Fig. 6. Carbon toroidal deposition profiles (poloidally integrated) from NRA measurements and from the modelling in the assumption of sticking probability 0 and 1. The two modelling profiles are also plotted renormalized to the experimental profile.

6. Modelling

Modelling is necessary to understand the integrated effects of fragmentation, excitation, ionisation, local transport, re-deposition and re-erosion of the hydrocarbons. The $^{13}CH_4$ puff in H-mode discharges experiment [2] has been modelled with the ERO code [5] using a B2-EIRENE background plasma [6]. B2-EIRENE uses midplane electron and temperature profiles as input. The ERO modelling has been done in two extreme re-deposition assumptions: Sticking = 0 (the hydrocarbon molecules hitting the wall are released again as CH_4 with thermal velocity and cosine distribution), and sticking = 1 (the molecules always stick to the wall upon collision). The poloidally integrated profiles of redeposited carbon (from NRA) are shown in Fig. 6, together with the profiles from modelling. The assumption of sticking = 0 match better the toroidal decay but give a prompt redeposited fraction of 10%, a factor 10 lower than the experiment. In ERO modelling most carbon ions travel out of the simulation volume toroidally along the magnetic field lines. The magnetic field angle is such that only those ions, that are born through ionisation within 2 mm from the surface, would contribute to the measured deposition - unless there is a radial drift not accounted for by our modelling. In the modelling results the only noticeable drift is a small poloidal deviation (at most 1 mm) of the guiding centres from the field line during passing the sheath. Inclusion of other drifts would require appropriate models for the prevailing electric fields and other external forces.

7. Conclusion and outlook

The present injection experiment shows that the (re-)deposition in the divertor is strongly influenced by poloidally-downwards and radially outwards drifts. A conspicuous upstream transport is observed in the L-mode experiment, which is observed neither in the corresponding H-mode experiment nor in recent L-mode experiments using 4× lower puffing rates, suggesting a thermal-force driven upstream diffusion. Colorimetric analysis show that the injected particle diffusing upstream are deposited in a single-step process during the movement with no/little successive erosion. Also, the downstream UV deposition shows similar characteristics: The particles are deposited preferentially on the upstream side of the surface roughness. Those measurements give an optimal insight on the forces acting on neutral/ions in the proximity of the divertor target plate. Outwards and downwards drift are suggested to have a major role in the buildup of the deposition pattern. Drifts from electric fields are currently not included in the modelling but discussion on the their origin and on the inclusion in the modelling is already ongoing.

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