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Migration of ^{13}C and deposition at ASDEX Upgrade

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Abstract

To investigate material transport in scrape-off layer plasma and long term deposition in divertor, $^{13}CH_4$ was puffed at the end of 2004 and 2005 experimental campaigns into ASDEX Upgrade from the outer mid-plane. Ex situ analyses of the tiles were performed by secondary ion mass spectrometry. The peaks of ^{13}C were detected below the bottom inner strike point and at the horizontal tile at the outer lower divertor. It was detected ~21% of the total puffed ^{13}C amount. The deposition rate for carbon by plasma was also calculated in long term experiment. It was obtained to be 22×10^{-3} and 8.7×10^{-3} g/s for the upper (campaign 2004) and lower (campaign 2003) divertors, respectively.

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1. Introduction

Understanding the balance of erosion and redeposition in a divertor with an ITER-like plasma facing component arrangement (metallic first wall and carbon divertor) is very important in order to predict material migration from the main wall to the divertor, and vice versa. Moreover, because carbon is known to trap hydrogen isotopes and form co-deposited hydrocarbon layers [1,2], study of material transport in the scrape-off layer (SOL) plasma helps to estimate the expected size and localisation of the retained tritium in ITER.

Some experiments using ^{13}C as a tracing element for carbon redeposition were performed at JET [3] and DIII-D [4]. Different puffing locations and plasma operation regimes were utilized. To complete our earlier study performed on ASDEX Upgrade [5], we present in this paper results on ^{13}C transport in SOL and deposition on upper and low divertors obtained by measuring the deposition pattern of carbon on plasma facing components under controlled source conditions.

2. Experimental Setup

For post mortem erosion/deposition analyses a full poloidal set of marker tiles (stripes of 3 μm thick

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carbon layer on a 100 nm Re interlayer and 0.5 μm thick *W* layer, prepared by arc discharge method) was installed in the upper divertor (see Fig. 1) during the shutdown in 2003.

At the end of 2004 experimental campaign $^{13}CH_4$ was puffed into the torus from the outer mid-plane during 5 identical top single null H-mode (ELM type I) discharges in hydrogen. The puff was localized only in the sense that one gas valve was used. However, the valve is quite remote in the port. Therefore effectively the whole port acts as a source, which means it has the size of about 0.5 m^2. The molecules will penetrate the SOL to quite different depths which, combined with the large shear in the SOL, will lead to a very rapid distribution of the particles and therefore to a quite symmetric toroidal distribution [6]. The main plasma parameters were $I_p = 0.8$ MA, $B_t = -2.0$ T, $n_e = 9.0 \times 10^{19}$ m^{-2} and $P_{aux} = 5.1$ MW.

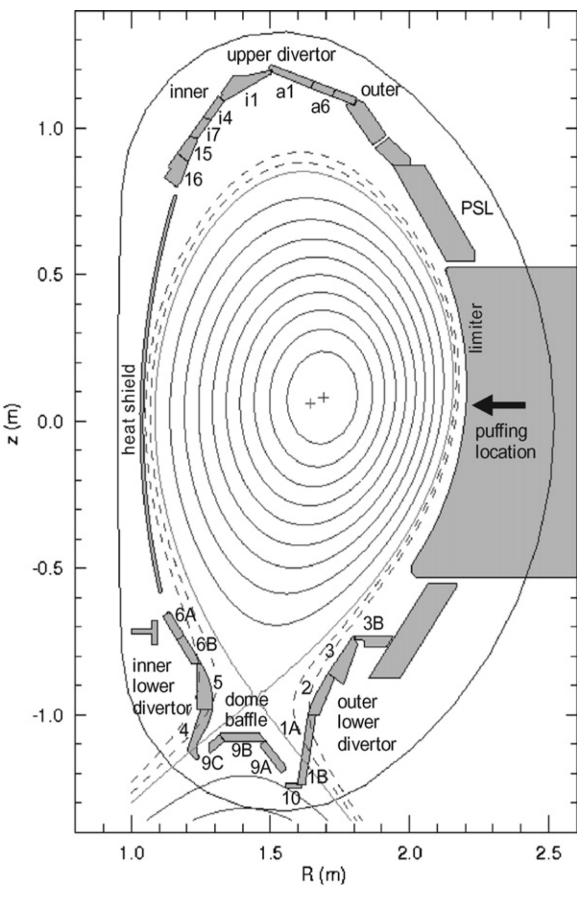

Fig. 1. Cross-section of the ASDEX Upgrade vacuum vessel together with the magnetic surfaces. Numbers correspond to the divertor tile numbers.

The total amount of ^{13}C injected during the experiment was 1.48×10^{22} atoms. ^{13}C serves as a marker because it can be distinguished from the ^{12}C isotope with surface analytical methods. A set of samples of 10 mm in diameter was cut from the divertor tiles on IPP site.

$^{13}CH_4$ was also puffed at the end of the 2005 experimental campaign into the torus from the outer mid-plane at one toroidal location during 13 identical bottom single null L-mode discharges (#20646–20659) in hydrogen. The main plasma parameters were $I_p = 0.8$ MA, $B_t = -2.5$ T, $n_e = 6 \times 10^{19}$ m^{-3} and $P_{aux} = 2.9$ MW. The total amount of ^{13}C injected during the experiment was 1.72×10^{22} atoms.

For ^{13}C profiling secondary ion mass spectrometry (SIMS) was utilised. A set of samples of 17 mm in diameter was cut from the tiles exposed in 2005 using a coring technique [3,7]. The number of the samples (1–3 samples from each tile depending on the tile size) was chosen to provide as many measurement points as possible along the marker stripes. SIMS analysis was made with a double focusing magnetic sector instrument (VG Ionex IX-70S) at VTT. The current of the 5 keV O_2^+ primary ions was typically 500 nA during depth profiling and the ion beam was raster-scanned over an area of 300×430 μm^2. Crater wall effects were avoided by using a 10% electronic gate and 1 mm optical gate. ^{13}C was profiled using a high mass resolution of 2000 ($m/\Delta m$ at m/z 28) to separate the element peak from the interfering isobar $^{12}CH^+$. The pressure inside the analysis chamber was 5×10^{-8} Pa during the analysis. The depth of the craters was measured by a profilometer (Dektak 3030ST) after SIMS analysis. The uncertainty of the crater depth was estimated to be 5%.

3. Results and discussion

3.1. $^{13}CH_4$ puffing experiment

Fig. 2 shows ^{13}C depth profiles for lower outer divertor tiles exposed in 2005 1B and 2 corresponding to *v*-coordinate of 0.27 and 0.62 m, respectively. *v*-coordinate represents the distance from the private flux region along the tiles surface and describes poloidal positions ($v = 0$ corresponds to the top edge of the dome baffle tile 9 A). ^{13}C signal was normalised with ^{12}C level and natural ^{13}C background was subtracted. Data indicate presence of ^{13}C at the surface region with following decrease

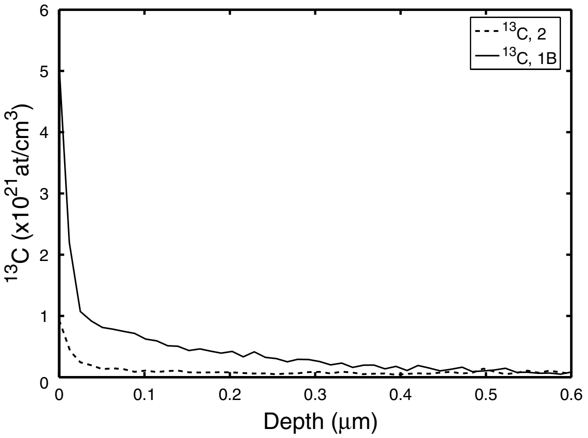

Fig. 2. SIMS depth profiles of ^{13}C normalised to ^{12}C signal and natural ^{13}C background subtracted. Presented are profiles for tiles 1B ($v = 0.27$ m) and 2 ($v = 0.62$ m).

within the bulk. Larger content of ^{13}C accumulated in the strike point tile 1B compared to tile 2 can be observed.

Distribution of ^{13}C on the lower divertor together with strike point position from magnetic reconstruction during last 13 shots of the 2005 campaign as a function of v-coordinate is presented in Fig. 3. During the ^{13}C puffing experiments the strike points were at the inner divertor tile 4 and the outer divertor tile 1B. ^{13}C peaks are observed on tiles 1B ($v = 0.27$, 0.31 and 0.35 m), 6B ($v = 5.55$ m) and 5 ($v = 5.73$ m). The peaks on the tile 1B are shifted toward the roof baffle with respect to the outer strike point. Unfortunately samples from the inner strike point tile 4 were not available. Huge peak of ^{13}C was observed on the outer divertor tile 3B ($v = 0.83$ m) located horizontally at the chamber. Similar high deposition on the horizontal section of the outer divertor was observed at JET [8], where $^{13}CH_4$ puffing was done from the lower outer divertor in H-mode configuration. Despite of H- and L-mode configurations were used in JET and ASDEX Upgrade experiments, respectively, high deposition on the horizontal section of the outer divertor baffle remains to be observed, so ELMs cannot cause the effect. A material transport loop for ^{13}C may be established in the SOL from the outer divertor close to the separatrix, migrating into the main chamber and returning to the far SOL. However, the reason for such a high deposition is not completely understood.

Amount of ^{13}C deposited onto the lower inner and outer divertor was found to be 4.17×10^{20} and 1.11×10^{21} atoms, respectively, what makes together 8.9% of the total puffed amount.

It was found 6.86×10^{20} and 9.82×10^{20} atoms of ^{13}C to be deposited onto the upper divertor and heat shield tiles, respectively. These numbers represent 4.0% and 5.7% of the total puffed amount, respectively. Detailed distribution of ^{13}C as a function of v-coordinate over the whole torus is shown in Fig. 4. A peak was observed at the top outer divertor at $v = 3.42$ m. At the heat shield ^{13}C deposition increases from the top towards the middle part and then decreases towards the bottom of the chamber.

To investigate prompt deposition of ^{13}C samples from the limiter tiles located nearby the puffing valve were measured. Because the samples only from the limiter tile close to the valve and from the top tile were available, assumption of linear

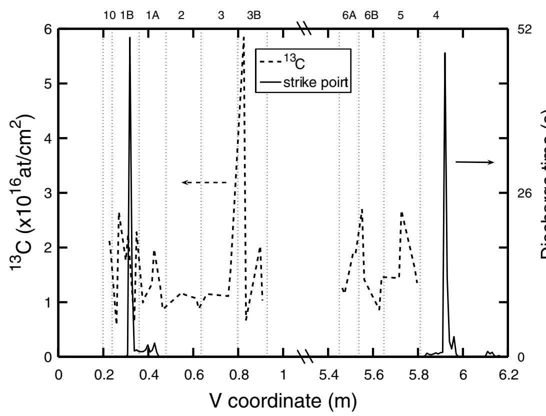

Fig. 3. ^{13}C distribution at the lower divertor (dashed line) together with strike point position from magnetic reconstruction during last 13 shots (solid line).

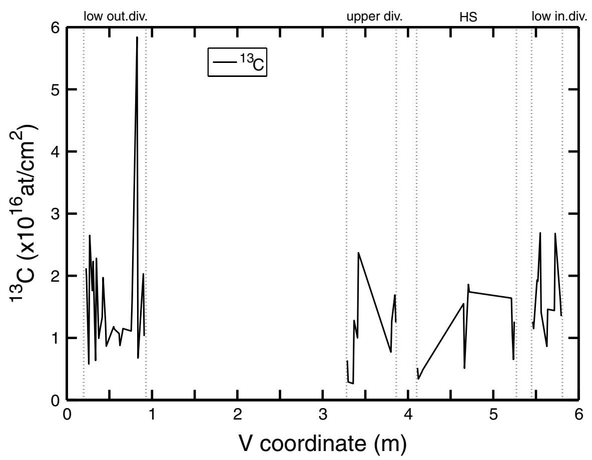

Fig. 4. ^{13}C distribution over the whole chamber.

decrease of the ^{13}C deposition along the limiter surface from the middle to the top and to the bottom was made. Integrating over the limiter surface, it was obtained 4.2×10^{20} atoms, i.e., 2.4% of the puffed amount of ^{13}C was deposited onto the limiter tiles in the vicinity of the puffing location. Combining this number with data for lower and upper divertor, and heat shield tiles provides 21.0% of the total puffed amount of ^{13}C that was detected. Summarized data are presented in Table 1. It can be seen that the main areas of ^{13}C deposition are the lower outer divertor and the heat shield. Apparently part of the puffed ^{13}C is transported by the plasma along the field lines from the outer midplane first towards the top divertor with following passing the heat shield and ends up at the lower inner divertor. Some field lines intersect the heat shield what causes carbon deposition in this region. The other part of the puffed ^{13}C moves from the valve straight to the lower outer divertor and deposits there.

At the end of 2004 experimental campaign $^{13}CH_4$ was puffed during top single null H-mode discharges. Distribution of the ^{13}C on the top divertor together with the strike point position from the magnetic reconstruction during the experiment as a function of *v*-coordinate is presented in Fig. 5. Then 1.84×10^{21} atoms, i.e., 12% of the puffed ^{13}C was found to be deposited at the upper divertor. The main reason for distinction between these data and the ones obtained for the upper divertor in 2005 campaign is different strike point position during the experiment.

An experiment with puffing of $^{13}CH_4$ in bottom single null regime using H-mode plasma was performed earlier in the end of 2003 campaign [5].

Table 1
Amount of deposited ^{13}C (percent of the puffed amount) found in different experiments

Vessel part	L-mode, bottom null (%)	H-mode, bottom null (%)	H-mode, top null (%)
Lower inner divertor	2.4	1.2	–
Lower outer divertor	6.5	5.9	–
Upper divertor	4.0	–	12
Heat shield	5.7	11	–
Limiter	2.4	–	–
Total	∼21	18.1	12

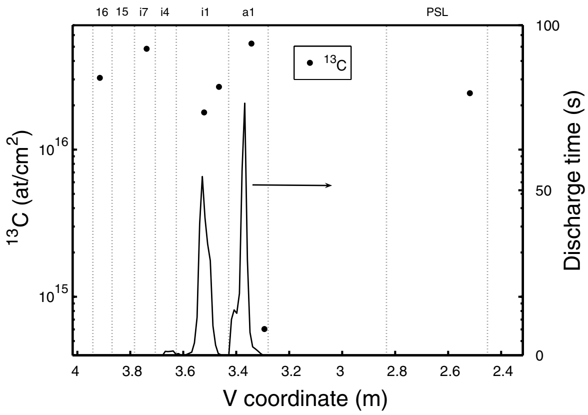

Fig. 5. ^{13}C distribution at the upper divertor (H-mode top single null, campaign 2004). Numbers corresponds to the divertor tile numbers.

^{13}C amount deposited on the heat shield tiles was found to be of 11% of the total amount puffed. At the same time it was obtained 7.1% of ^{13}C deposited at the lower inner and outer divertor, i.e., 18.1% all together (see Table 1). Amount of ^{13}C deposited at the lower divertor and heat shield together obtained for L-mode regime in this study is 14.6%. The numbers are quite close to each other, the margin can be resulted by different modes used.

To summarize all experiments consistent results from the point of view of strike point position and considered area of the deposition can be compared. Although different plasma types were investigated, nevertheless numbers for ^{13}C accumulated at the divertor agree with each other quite well (7.1%, 12% and 8.9% for the low divertor H-mode, upper divertor H-mode and low divertor L-mode, respectively). They are also close to the expected penetration of 10% [9].

Migration of ^{13}C was also studied on JET and DIII-D [3,4]. In both cases puffing of $^{13}CH_4$ was done from the top of the torus and L-mode plasmas were used. The part of ^{13}C deposited on the bottom divertor was found to be ∼35% and 46% of the injected amount, respectively. Numbers are quite close to each other, however, far away from our results. The discrepancy can be explained by the different location of the puffing valves and geometry of the tokamaks. Puffing of $^{13}CH_4$ from the bottom of the torus in H-mode configuration was performed in JET [11]. About 26% of the puffed amount of ^{13}C was found to be deposited on the lower divertor. Most of the deposition was found on the outer divertor, i.e., in the vicinity of the puffing valve.

However, deposition pattern cannot be explained only by this fact. Definitely part of ^{13}C was transported with plasma flow.

4. Long term erosion/deposition

Long term erosion/deposition data were also measured on the upper divertor tiles with W and C marker stripes after 2004 campaign. Depth profiles obtained on the limiter tile PSL ($v = 2.5$ m) on C and W marker stripes are presented in Fig. 6(a) and (b), respectively. In the case of C stripe (Fig. 6(a)), layer deposited by plasma during the campaign can be observed near the surface. Then the original C film with following Re interlayer can be seen. For the W stripe (Fig. 6(b)), layer deposited by plasma and original W film can be seen. In both cases films deposited by plasma are enriched with hydrogen, deuterium and boron. Presence of B caused by boronization. Furthermore, presence of carbon was observed in the layer deposited by plasma on the W stripe. The deposition rate of carbon by plasma was obtained to be 22×10^{-3} g/s. Density of the deposition layer was assumed to be 1.8 g/cm^3. Total time of plasma in the top divertor configuration during the campaign was 231 s.

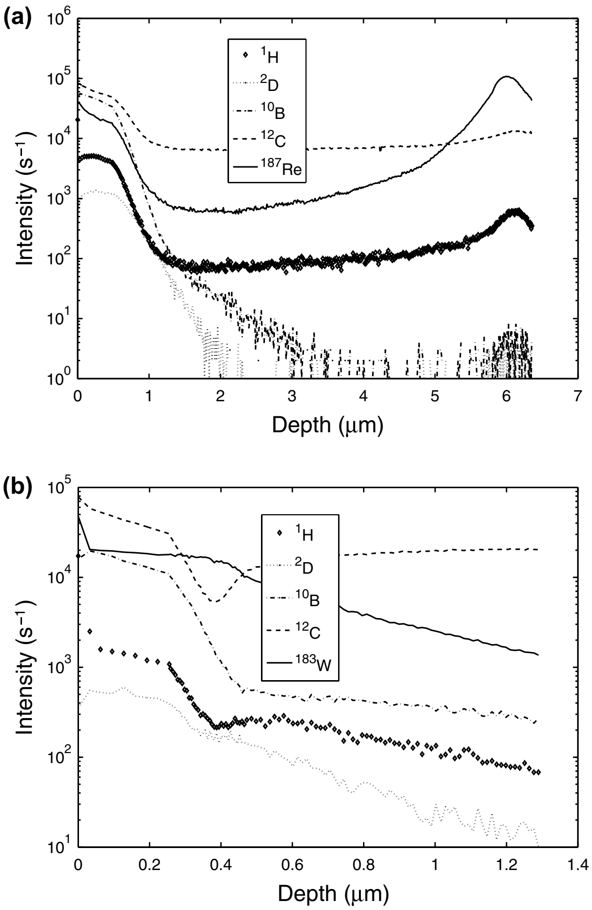

Fig. 6. Long term depth profiles on C (a) and W (b) marker stripes measured on the upper divertor tiles after 2004 campaign. Presented spectra measured on the limiter tile PSL $v = 2.5$ m.

Similar study on the long term carbon erosion/deposition was performed earlier with marker stripes on the lower divertor tiles after 2003 campaign [5]. The deposition rate of carbon by plasma was obtained to be 8.7×10^{-3} g/s. Density of the deposition layer was assumed to be 1.8 g/cm^3. Total time of plasma in the bottom divertor configuration during the campaign was 4944 s. It can be suggested that the deposition rate is affected by the divertor configuration. In support of this conclusion, results obtained in earlier experiments at JET can be referred [10,11]. The deposition rate was found to be 15×10^{-3} and 8×10^{-3} g/s for MkIIA and MkIIGB divertor configurations, respectively. Both AUG lower and JET MkIIGB divertors have quite 'closed' geometry because of the dome baffle and the septum, respectively. Results for the deposition rate for these divertors agree with each other very well. In the other hand, both AUG upper and JET MkIIA divertors are quite open. Result 22×10^{-3} g/s found for the AUG upper divertor after 2004 campaign is closer to the one determined for JET MkIIA divertor. It seems that obtained carbon deposition rates depend rather on the divertor configuration than the machine size, however, the reason for this is not clear. Similar results were reported earlier by Phillips et al. [12].

5. Conclusions

Experimental investigation of material transport in the SOL plasma and the study of long term divertor deposition was performed by measuring the deposition pattern of carbon on plasma facing components under controlled source conditions. For this purpose $^{13}CH_4$ was puffed at the end of the 2004 and 2005 experimental campaigns into the torus from the outer mid-plane. Peaks of ^{13}C were detected below strike points towards the roof baffle at the lower inner divertor, and at horizontal section of the lower outer divertor. This contribution of the main chamber processes to the deposition can be associated with transport by the SOL plasma.

The deposition rate of carbon by plasma was obtained to be 22×10^{-3} and 8.7×10^{-3} g/s for the upper and lower divertors, respectively, in long term experiments.

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