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J. Likonen[1], M.I. Airila[1], J.P. Coad[1], A. Hakola[1], S. Koivuranta[1], E. Ahonen[1], E. Alves[2], N. Barradas[2], A. Widdowson[3], M. Rubel[4], S. Brezinsek[5], M. Groth[6] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Association EURATOM-TEKES, VTT, PO Box 1000, 02044 VTT, Espoo, Finland
[2]Instituto Tecnológico e Nuclear, Sacavém, 2686-953, Portugal
[3]EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[4]Alfvén Laboratory, Royal Institute of Technology, Association EURATOM-VR, 100 44 Stockholm, Sweden
[5]Institute of Energy and Climate Research – Plasma Physics, Forschungszentrum Jülich GmbH, Association EURATOM-FZJ, Partner in the Trilateral Euregio Cluster, D-52425 Jülich, Germany
[6]Association EURATOM-Tekes, Aalto University, 02015 Espoo, Finland
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ABSTRACT

Migration and deposition of ^{13}C have been investigated at JET by injecting ^{13}C-labelled methane at the outer divertor base at the end of the 2009 campaign. The ^{13}C deposition profile was measured with Enhanced Proton Scattering (EPS) and Secondary Ion Mass Spectrometry (SIMS) techniques. A strong toroidal deposition band for ^{13}C was observed experimentally on each of the analysed four outer divertor floor tiles. In addition, ^{13}C was also found on the vertical edge of Load Bearing Tile (LBT) and at the bottom of the LBT tile facing the puffing hole. Local ^{13}C migration in the vicinity of the injection location was modelled by the ERO code. The ERO simulations also produced the strong toroidal ^{13}C deposition band but there is strong deposition also on the vertical edge of the LBT tile and elsewhere on the horizontal part of the outer divertor floor tile.

1. INTRODUCTION

Erosion of Plasma-Facing Components (PFCs), migration of impurities and their subsequent deposition on PFCs can lead to enhanced tritium retention and have an impact on the lifetime of first wall components in present and future fusion devices. An extensive postmortem analysis programme for studying erosion/deposition phenomena and fuel retention has been carried out at JET and after each major shutdown tiles have been removed for subsequent surface analyses. Campaign integrated results are, however, difficult to interpret quantitatively because post-mortem surface analyses are only available after PFCs have been removed after a campaign during which they have been exposed to a range of different plasma types, geometries and divertor plasma parameters. The deposition at the inner divertor vertical tiles and at divertor floor tiles, as analysed when tiles were removed from the vessel, is the result of typically two years of JET operations with about 3000–4000 discharges covering many types of plasma operation [1, 2]. It is thus difficult to conclude which aspects of operation are important in controlling the deposition. In contrast, tracer injection experiments in tokamaks executed at the end of a campaign provide information on material migration and deposition under a single plasma type. Thus, the tracer injection experiments are ideal for developing better understanding of the underlying physics via edge simulations.

In JET, tracer injections have been carried out in 2001 [3,4], 2004 [5], 2007 [6] and 2009 [7] by puffing isotopically labelled methane ($^{13}CH_4$) repeatedly into the torus during the last operational day before a shutdown. This paper concentrates on the 2009 experiment in JET with a carbon wall, in which $^{13}CH_4$ was puffed toroidally symmetrically through 24 injection locations into the outer Scrape-Off Layer (SOL) of H-mode plasma in deuterium with the Outer Strike Point (OSP) on the LBT tile made of Carbon Fibre Composite (CFC). For the tile layout and its labelling, see Fig.1. Although toroidally symmetric, the injection was inhomogeneous but periodic: it was through every fourth outer base tiles 6, which comprise one of the 24 divertor modules. The injection was thus toroidally periodic. In Ref. [7] global 13C migration was investigated with post-mortem analyses and computer simulations using EDGE2D and DIVIMP codes. This paper, instead, focuses on the local ^{13}C deposition on divertor floor tiles 6 and reports the results of post-mortem surface analyses obtained using Secondary Ion Mass Spectrometry (SIMS) and Enhanced Proton Scattering (EPS), and ERO [8] based modelling of the ^{13}C transport.

2. EXPERIMENTAL

On the final experimental day of the JET campaign prior to installation of the ITER-Like Wall (ILW) in 2009, 30 identical H-mode discharges in D (Pulse No's:79816–79853) were run with 13CH4 injection from the outer divertor base tile 6. The discharge parameters were: $B_t = 2.5T$, $I_p = 2.5MA$, line-averaged density $14.8 \times 10^{19} m^{-2}$ and heating power 15MW of NBI. The Edge Localized Modes (ELMs) were of type I having an average core energy loss of about 400kJ.

The Inner Strike Point (ISP) was on the lower inner vertical target plate (tile 3) and the outer strike point on the LBT (tile 5). The total injected amount was 3.3×10^{23} particles (7.12g) the average puffing rate being 2.5×10^{21} particles/s so the plasma was fuelled by the hydrogen in the ^{13}C labelled methane. Figure 1 shows the geometry of the divertor tiles made of CFC and the magnetic configuration in 2009. The geometry of the divertor near the puffing hole is shown in Fig.2. The puffing hole is completely underneath tile 5 and the gap between the tiles is about 3mm. A toroidal ^{13}C deposition band was visually observed, while it is partly covered by tile 5 and a further ~10mm of tile 6 is also shadowed from the plasma. During the shutdown in 2009, a set of four divertor tiles 6 was removed for post-mortem surface analyses.

The tiles were analysed by the EPS and SIMS techniques. A full toroidal set of samples were cut from the deposition band on each tile 6. In the EPS measurements at ITN in Portugal, the amount of ^{13}C deposited on tiles 6 was determined at a scattering angle of 145^o near the resonance energies for ^{13}C in the energy range of 1.5−1.8MeV. The EPS spectra were simulated using the WiNDF [9] program. SIMS analyses of the samples were made with a double focusing magnetic sector instrument (VG Ionex IX-70S) at VTT using a 5keV O+2 primary ion beam with a current of 500 nA [5]. Calibration samples were measured separately by time-of-flight elastic recoil detection analysis (TOF-ERDA) at the University of Helsinki.

3. EXPERIMENTAL RESULTS

^{13}C puffing experiments have been made in 2001, 2004, 2007 and 2009 at JET. In 2001 and 2007 the puffing was made from the main chamber whereas in 2004 and 2009 methane was puffed at the divertor. In 2001, most of the ^{13}C was found at the inner divertor whereas the deposition pattern is more balanced in 2004, 2007 and 2009 (see Table 1). This is most likely due to longer migration path in the SOL for the 2004, 2007 and 2009 experiments so less ^{13}C was migrating towards the inner divertor and more towards the outer divertor. The ^{13}C amount at the floor is the highest for the 2009 experiment. Gas analysis from the Activated Gas Handling System (AGHS) [7] indicated that about 33% of the puffed ^{13}C was pumped away and cannot be found in the post-mortem surface analyses. This could be one reason why the total ^{13}C inventory found in the post-mortem analyses was the lowest for the 2009 experiment. In the other experiments the puffing location was much further away from the pumping ducts.

A strong toroidal ^{13}C deposition band near each of the 24 puffing holes was observed visually on tiles 6. Figure 3 shows a 2D map of the ^{13}C distribution. The largest ^{13}C amounts were found at the same toroidal location as the puffing hole but slightly outwards. The deposit is probably caused by neutral radicals created by partial dissociation at the shadow boundary. These neutral radicals may return to the shadow and stick to that surface. They are unlikely to be pure methane molecules since they have low sticking coefficient.

Additional EPS measurements were made from the vertical edge of tile 5 and from the bottom of tile 5 near the puffing hole. Analyses from the bottom of tile 5 were performed from the side which is at ~ 45^{o} angle with respect to the horizontal level (see Fig.2). Unfortunately it was not possible to make analyses from the side facing the puffing hole. The ^{13}C amount first decreases and then increases along the vertical edge of tile 5 reaching the highest value at the bottom of the vertical edge. At the bottom of tile 5 the ^{13}C amount is lower than on the vertical edge of tile 5 (see Fig.4). These results were also included in the ^{13}C inventory in Table 1.

4. ERO SIMULATIONS

Local migration, erosion and deposition were simulated with the 3D Monte Carlo impurity transport code ERO [9]. The geometry used and the position of the simulation volume in the divertor is shown in Fig.1. The simulation was set up by defining a rectangular simulation volume tilted by 45^{o} to obtain maximal coverage of tiles 5 and 6 next to the injection location. The simulation domain is about 23cm along the divertor, 11cm high and 73cm long toroidally, corresponding to one toroidal period of the injection configuration. Periodic boundary conditions were applied in the toroidal direction to account for the effect of neighbouring injectors. ERO modelling focuses on a reference case where reflection of ions was calculated according to TRIM data whereas for hydrocarbons an effective sticking coefficient S = 0.1 was used. It was assumed that the erosion of deposited (soft hydrocarbon) layers is enhanced by a factor of 5 compared to the substrate (graphite). In Ref.[7] a uniform plasma background was used with $n_e = 5\times10^{18}\ m^{-3}$, $T_e = T_i = 5eV$ and the flow velocity calculated assuming M = 1. In the present work more realistic plasma background was used based on Langmuir probe measurements. These measurements included electron density and temperature measured in 8-10 points near the OSP. The Langmuir probe radial profiles for Te and ne were fitted with an exponential function. A plasma-shadowed region (very low temperature and density) was defined in front of the injection point as implied by the magnetic geometry. ELMs were not taken into account in the calculations. Several parameters including local plasma density, temperature, enhanced re-erosion, velocity distribution of injected molecules, perpendicular diffusion coefficient, Mach number assumption and shadow model were varied. In addition, simulations were made taking into account neutral particles with a density in the range of $1\times10^{19}\ m^{-3}\times10^{20}\ m^{-3}$. In Ref. [7] the neutrals were neglected. The deposition pattern and locally deposited fraction were rather robust with respect to these variations.

At the beginning of the puffing, injected ^{13}C starts building up layers originally on a clean carbon surface mainly downstream of the injection location. In the simulations, originally about 60% of the injected ^{13}C is deposited and the remainder of the puffed ^{13}C escapes into the Private Flux Region (PRF) and Scrape-Off Layer (SOL). As the layer builds up, re-erosion starts releasing some of the deposited ^{13}C and the loss rate increases. After about 3s of simulation time an equilibrium surface concentration is reached and the net deposition rate levels off at about 38% of the injection rate. Therefore the simulations were continued only until 7.5s and the results were normalized accordingly for comparison with the experiment.

Figure 5 shows the deposition pattern obtained with ERO: the bright rectangle shows the position of the puffing hole. About 37% of the injected ^{13}C is deposited within the simulation volume, whereas 59% is lost (mostly as neutrals) towards the outer divertor and 4% towards the X-point. In the experiment, about 16% of the injected ^{13}C was deposited inside the ERO simulation volume. A majority of the deposition occurs close to the injection location on the outer end face of tile 5 and on the horizontal part of tile 6, the deposition tail extending toroidally about 50cm. This indicates that the local deposition is dominated by ions. Interestingly, the deposition band has shifted poloidally outwards from the puffing location (see Fig.5b). This was also observed in the SIMS and EPS measurements (see Fig.3) and these measurements show that there is significant deposition also on the sloping part of tile 6 (see Fig.6). This was not explained in Ref. [7] not even by the parameter variations with significantly lower density or temperature that allow longer cross-field transport paths of the source particles before ionization.

The more realistic plasma background has some effect on the deposition pattern but the poloidal distribution is still too peaked and does not agree very well with the experimental results on the sloping part of tile 5 and on the sloping part of tile 6 (see Fig. 6). The gap at - 40mm in the distribution for the realistic plasma background curve is most probably Monte Carlo noise in the simulations. Figure 6 also shows the effect of the neutral density on the ^{13}C deposition. It can be observed that neutral density has only a small effect on the ^{13}C deposition and there is no real improvement in the agreement with the experimental results. The plasma temperature and density were also scanned in the ERO simulations and lowering the temperature to 1/3 did not improve the agreement between experimental and simulation data. On the contrary, lowering the density by a factor of 5 (to 1×10^{18} m^{-3}) resulted in much better quantitative agreement (see Fig.6). This low density could even be rather realistic noting that the Langmuir probe data had to be extrapolated over a long distance to the injection location. ERO underestimates ^{13}C deposition on the sloping part of tile 6 (XERO > 50mm) in Fig.6, though. Figure 7 shows the experimental and ERO results in the toroidal direction for s-coordinate s ~ 1326mm which is about 10mm outwards poloidally from the puffing hole. The experimental and simulation results agree well with each other and both results indicate that the ^{13}C amount decreases exponentially as a function of the toroidal coordinate. At poloidal coordinates >450mm ERO results seem to decay somewhat faster than the experimental results, though.

CONCLUSIONS

We have investigated local deposition of ^{13}C at JET by injecting $^{13}CH_4$ into the torus from the outer divertor base through 24 holes in tiles 6 at the end of the 2009 experimental campaign. The surface density of ^{13}C was determined from a set of four divertor tiles 6 using SIMS and EPS techniques. A strong toroidal deposition band for ^{13}C was observed experimentally on each of the analysed four tiles 6. In addition, ^{13}C was also found on the vertical edge of tile 5 and at the bottom of tile 5 facing the puffing hole. Local ^{13}C migration near the injection location was modelled with the ERO code. A more realistic plasma background than in Ref.[7] was used based on Langmuir probe measurements. The ERO simulations were able to predict the heavy toroidal ^{13}C deposition band but strong deposition is also expected on the vertical edge of tile 5 and elsewhere on the horizontal part of tile 6. The use of a realistic plasma background instead of a uniform one had only a small effect on the deposition pattern as did the neutral density and the plasma temperature. On the contrary, the plasma density had a marked effect and better agreement with the experimental results was obtained when the uniform plasma density was decreased by a factor of 5 to account for possible uncertainty in extrapolating the Langmuir probe data.

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	2001	2004		2007	2009
Inner div.	45	3.2	2.9	7.7	1.6
Floor	0.9	6.3	7.5	5.6	11.4
Outer div.	0.4	17	16.4	5.5	4
Main wall	n/a	n/a	2.7	4.1	0.4
Pumped amount	n/a	n/a	n/a	n/a	33
Total deposited	46.3	26.5	29.5	22.9	17.4

Table 1. Deposition of ^{13}C in different areas (in %) of the vessel during the puffing experiments.

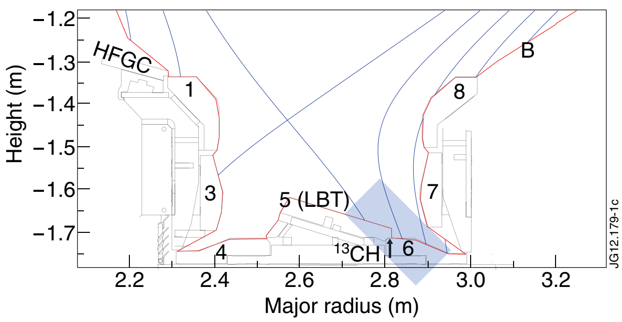

Figure 1: The geometry for JET divertor tiles (MkII-HD) in 2009. Magnetic configuration used in the ^{13}C puffing experiment is also shown. The arrow indicates the puffing location. Blue box shows the simulation volume used in the ERO calculations.

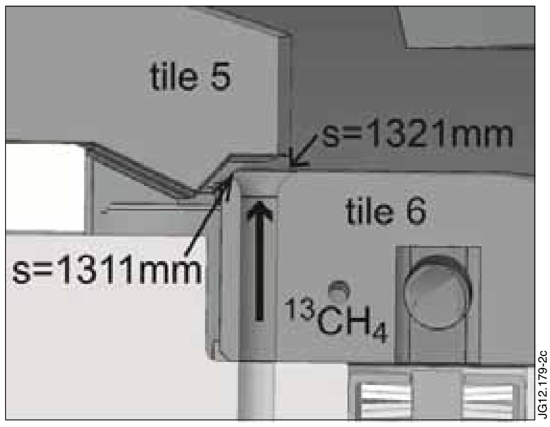

Figure 2: Geometry of the puffing hole on tile 6. The s-coordinates on tile 6 are also indicated.

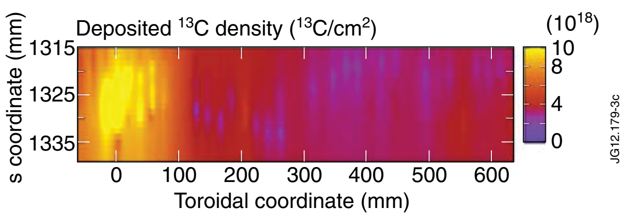

Figure 3: Experimental deposition pattern for ^{13}C. The ^{13}C amount is in at/cm^2. Puffing hole is located at toroidal coordinate 0mm and poloidal coordinate 1316mm.

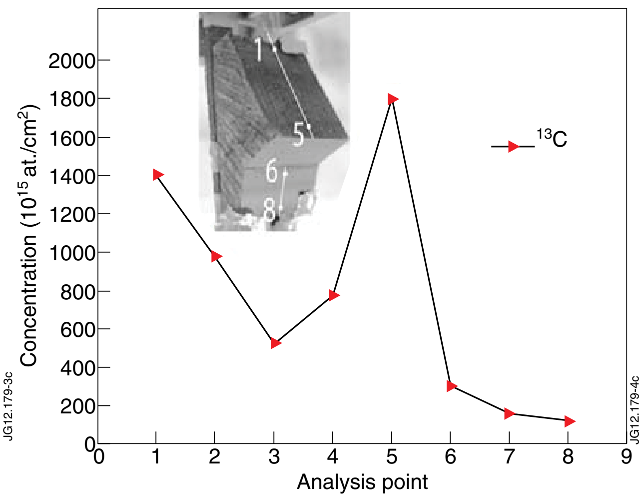

Figure 4: 13C results from the edge of tile 5 measured with EPS. Points 1-5 were measured from the vertical edge and points 6-8 from a surface which is ~45^o with respect to the horizontal level (see Fig.2).

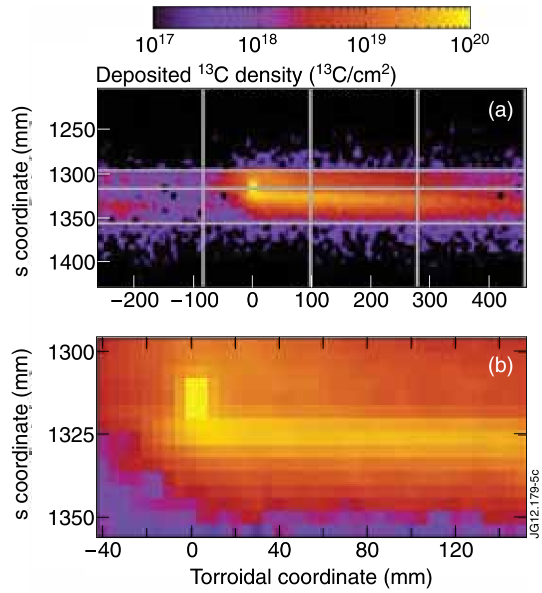

Figure 5: Deposition pattern of ^{13}C as simulated with ERO (a). Tile boundaries and edges are indicated with grey lines. The top row corresponds to the sloping part of tiles 5, the second row to the vertical part of tiles 5, the third row to the horizontal part of tiles 6, and the bottom row to the sloping part of tiles 6. In (b) the magnified deposition pattern near the puffing hole is shown (position indicated by the bright yellow rectangle).

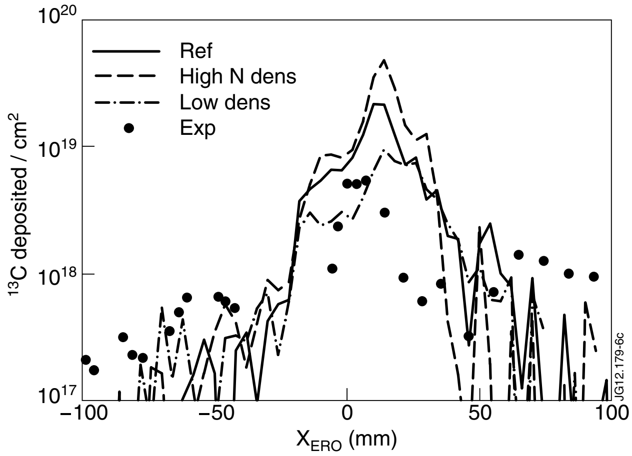

Figure 6: Experimental and simulated poloidal ^{13}C distribution at 2cm downstream from the puffing location. "Ref" is for the realistic plasma background, "High N dens" corresponds to a neutral density of $n = 3\times10^{20}\ m^{-3}$ and in "Low dens" curve the plasma density was decreased by a factor of 5.

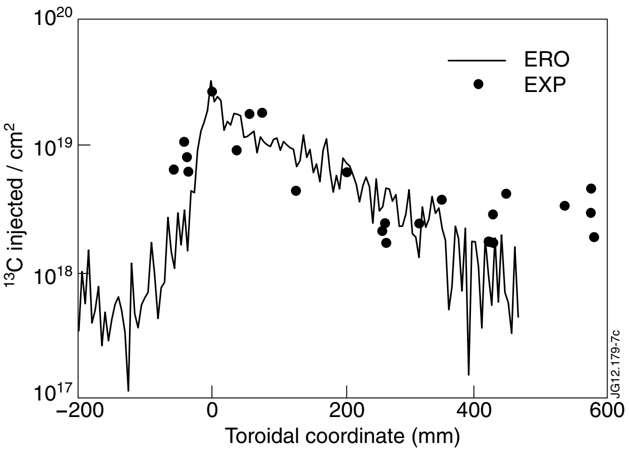

Figure 7: Experimental and simulated toroidal ^{13}C deposition profile at ~1cm outwards from the puffing hole (s = 1326mm).