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ABSTRACT.
Migration of ^{13}C has been investigated at JET by puffing $^{13}CH_4$ into the outer midplane at the end of the 2007 campaign. ^{13}C deposition profile was measured with Secondary Ion Mass Spectrometry (SIMS) and Rutherford backscattering (RBS) techniques. ^{13}C was mainly found on tile 1 and near the Outer Strike Point (OSP) on tile 7. The ^{13}C transport was modelled with the EDGE2D/NIMBUS code and a number of migration paths were transport was modelled with the EDGE2D/NIMBUS code and a number of migration paths were identified. These pathways are: (1) migration through the main chamber Scrape-Off Layer (SOL), (2) migration through the Private Flux Region (PFR) aided by E×B drifts and (3) neutral migration originating near the strike points. The underlying assumption is that erosion/re-deposition cycle occurs along the targets and leads to a multi-step migration of ^{13}C towards the separatrix called 'walking' which creates carbon neutrals at the OSP and results in ^{13}C deposition in the PFR.

1. INTRODUCTION

Erosion/deposition of plasma facing components has a great impact on the tritium retention and the lifetime of first wall components in present and future fusion devices. Campaign integrated results are, however, difficult to interpret quantitatively because post-mortem surface analyses are available only after components are removed after a campaign during which they have been exposed to a range of different plasma types (L-mode, H-mode and advanced scenarios), geometries (different inner and outer strike point locations) and divertor plasma parameters (e.g. temperatures, densities, heating power). In contrast, tracer injection experiments in tokamaks executed at the end of a campaign provide information on material migration and deposition under constant plasma conditions. Thus, the tracer injection experiments are ideal for modelling purposes.

In JET, tracer injections have been carried out in 2001 [1,2], 2004 [3], 2007 and 2009 by puffing isotopically labelled methane ($^{13}CH_4$) repeatedly into the torus during the last operational day before the shutdown. This paper focuses on the 2007 experiment, in which $^{13}CH_4$ was puffed from near the lower hybrid antenna, and reports the results of post-mortem surface analyses obtained using SIMS and RBS, and EDGE2D/NIMBUS based modelling of the ^{13}C transport. The results for the 2007 experiment will be compared with the results for the previous experiments.

2. EXPERIMENTAL

On the final experimental day of the JET campaign in 2007, 17 identical discharges were run with $^{13}CH_4$ injection from near the lower hybrid antenna (GIM 6). GIM6 consists of a pipe with 8 puffing holes. The total injected amount of ^{13}CH was 9.3×10^{22} particles. The main parameters of the discharges were 1.6 T, 1.6MA H-mode with line-averaged density of 2.7×10^{19} m^{-3}, 9MW NBI in hydrogen plasma and strike points on tiles 3 and 7. The geometry of the divertor tiles in 2007 is shown in Figure 1. During the shutdown in 2007, a set of divertor tiles was removed for post-mortem surface analyses. In 2001, $^{13}CH_4$ was injected through a gas introduction module at the top of the vessel (GIM 5) during 13 ohmic pulses [1]. In 2004, the puffing experiment was performed in ELMy H-mode discharges and $^{13}CH_4$ was puffed through 48 nozzles from the outer divertor wall between tiles 7 and 8 [3].

RBS measurements were carried out using a 2.5MeV H^+ beam of the Van de Graaff accelerator at the University of Sussex. SIMS depth profiles of the tiles were taken at several poloidal positions of the analysed samples. 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 500nA [3].

3. EDGE2D SIMULATIONS

Modelling of global migration of ^{13}C in JET injection experiments has been made using the 2D fluid code EDGE2D with injected atomic carbon and supplemented with especially developed postprocessors to extend the modelling to re-erosion [3]. EDGE2D [4] models the plasma and impurity ions as separate fluids and the neutrals with a Monte Carlo code NIMBUS. The fluid equations are applied for each cell in a grid where prominent sources of neutrals include gas puffing and recycling locations. The neutrals are followed along straight trajectories which start from a source or a recombination site and end at ionization or wall impact. After ionization, the fluid of each ionized species can move both parallel and perpendicular to the field lines. All ionization states of carbon are included. In the modelling, the carbon deposits are derived from carbon ion fluxes to the divertor targets and neutral carbon fluxes leaving the edge of the simulation grid. EDGE2D assumes that carbon is nonrecycling: it remains where it is deposited. For this reason, post-processors were developed to consider further erosion of the deposited ^{13}C. The re-erosion of deposits is treated like the sputtering of carbon substrates of fractional ^{13}C content.

4. EXPERIMENTAL RESULTS

In Figures 2-4, the normalised surface density of ^{13}C (deposited $^{13}C/cm^2$/injected ^{13}C) as a function of the x coordinate is shown for the 2001, 2004 and 2007 puffing experiments. In addition, EDGE2D data for the 2007 experiment is included. In 2007, the injected ^{13}C was typically deposited on all the divertor tiles. The highest ^{13}C concentrations were found on the inner divertor wall tile 1 and the ^{13}C amount on the inner divertor tiles is higher than on the floor and outer divertor tiles (see Figures 2-4). On tile 1, the ^{13}C amount is higher in the 2001 and 2007 experiments than in 2004. This can be due to a longer migration path along the SOL in 2004 since puffing was carried out from the outer divertor. The peaks in the 2001 results were speculated to be due to those regions on the inner divertor tiles with ^{13}C peaks being magnetically connected to the puffing location [2]. The main difference between the 2001 and 2007 experiments is that 2001 was injection into an L-mode plasma and 2007 was into an H-mode plasma. Therefore 2007 had different SOL transport coefficients, an H-Mode pedestal, and ELMs.

The divertor floor located in the PFR in all the ^{13}C puffing experiments (see Fig. 1). In 2001, only a few samples from the divertor floor tiles were analysed so comparison with the other experiments is not possible. The deposition pattern on the floor tiles for the 2007 experiment is different from the

2004 deposition. For the 2004 case, the ^{13}C amount is relatively constant on the horizontal part of tile 4 and decreases towards the sloping part of tile 4. In contrast, the ^{13}C deposition pattern in 2007 has a maximum on the sloping part of tile 4 and the ^{13}Camount on the horizontal part is smaller. The ^{13}C distribution on tile 5 in 2004 has a hollow profile with maxima at both ends of the tile. In 2007, the profile is different: the deposit decreases all the way along tile 5 and has a maximum towards the larger major radius side of the tile. On tile 6, the ^{13}C distribution has a peak on the horizontal part of the tile both in 2004 and 2007. The 2007 distribution has, however, a broader peak. ^{13}C has also migrated to the sloping part and the shadowed area of tile 6, and the amount is higher in 2007 than in 2004.

The 2007 ^{13}C deposition pattern on the outer divertor has both similarities and differences with respect to the 2004 deposit (see Fig.4). In 2007, the ^{13}C amount is higher at the bottom of tile 7 but lower on tile 8. The OSP was located in a different position on tile 7 during the 2004 and 2007 experiments. The ^{13}C distribution has a dip near the OSP (x ~ 1320 mm in 2007 and x ~ 1400 mm in 2004) which probably results from the walking process along the outer divertor tile 7 and re-erosion [3]. The 2004 distribution has also a peak in the shadowed area near the top of the tile just below the puffing location which is caused by local deposition near the opening of the gas inlet system. On tile 8, more ^{13}C was observed in 2004 than in 2007 which is most likely due to the leakage out of the gas injection pre-chamber to the top of tile 8. This leakage allows methane to reach the main chamber outside of the divertor (on the top of the baffles).). This area is a region of preferential flow of the ^{13}C from the main chamber, however more deposit occurred in 2004, due to the leakage in this area.

5. EDGE2D RESULTS AND DISCUSSION

Basically, three factors account for the deposition on the inner divertor. Firstly, erosion rates are larger on the outer target (due to higher deuterium fluxes, temperatures, and more energetic particles) so that deposits have more difficulty accumulating there [5]. Secondly, thermal forces are larger near the outer (compared with the inner) divertor entrance causing the carbon to preferentially enter the inner divertor [2]. Thirdly, the experimental SOL flow is directed towards the inner target where it is measured at the machine top [5]. In the EDGE2D simulations of the 2001 experiment, a force was added to either/or both the deuterium and carbon in the main chamber SOL [6] and with a magnitude so that the calculated flow matched the experimental measurement. The experimental results for tiles 1 and 3 in Fig. 2 indicate that the ^{13}Camount decreases as a function of divertor coordinate x whereas the EDGE2D fit suggests that the ^{13}C amount increases slightly. The fit is not perfect and a better fit might be obtained by modifying the impurity diffusion coefficient in the SOL. In addition, ELMs were not included in the simulations and the model [2] used for the 2001 puffing experiment was applied. ELMs are believed to have an insignificant effect on long range migration, and a major effect on re-erosion of deposits.

To achieve the fit in the PFR, the emission of ^{13}C from each strike point was used as a free parameter, since it is too difficult to calculate the magnitude of the C neutral emission from the strike point. For these fits, we used 60% from the ISP and 30% from the OSP. This 60% means that 60% of the injected ^{13}C was eventually emitted from the ISP. This number is large since much of that emitted from the strike point goes back into the divertor SOL and thus recycles to the strike points. These numbers are higher than 2004 which were 18 % and 25%, respectively. The emission from the strike point was assumed isotropic. This is different from what is normally assumed (cosθ- or cos2(θ)-like distribution with respect to the surface angle) for the emission of sputtered material from a surface. The 2007 (as we also stated for the 2004) deposits cannot be explained by cosθ- or cos2(θ)-like ^{13}C emission from the strike points. The caveat is, however, that re-erosion inside the PFR might alter the cosθ-like deposits to somehow look like isotropic deposits. The ^{13}C measurements provide no direct evidence that this happens but since re-erosion in the PFR [7,8] has not yet been considered here, such possibilities cannot be excluded.

Migration of ^{13}C ions to the ISP might be explained by ***E x B*** drifts through the separatrix to the ISP from where it is subsequently eroded and finally ends as deposits in the PFR or by walking along the inner target from deposits further up tile 3. The agreement between the experimental data and EDGE2D fit is good on tile 4 (see Fig. 3). The ^{13}C deposit on tile 4 in 2007 is quite different from the 2004 deposit. The 2007 peak is away from the edge between 4 and 5. In other words, it appears to have come out of the shadow of tile 5 as illuminated by the OSP. For the 2004 experiment, we concluded that the deposit on tile 4 right next to tile 5 must have originated from the ISP [3]. In addition, the motion of ^{13}C ions through the PFR had occurred and subsequent re-erosion by ELMs had removed 13C from the ISP causing the deposit on tile 4.

In 2004, the centre of tile 5 has a minimum in the ^{13}C deposition profile with maxima at both ends of tile 5 (see Fig. 3) [3]. The 2007 deposit is different. The deposit decreases all the way along tile 5 and reaches its maximum close to the OSP. The tilt for tile 5 is large enough that the front face of this tile does not see the ISP. This is probably the reason that the deposit on tile 5 decreases monotonically unlike the 2004 results. In the simulations, that part of the 2004 model was applied to the deposit on tile 5, and agreement between the experimental distribution and the EDGE2D fit is obtained by assuming that about 5% of the originally deposited ^{13}C exits the OSP as neutrals. There are, however, some problems since the deposit on tile 6 is much larger which means that this mechanism does not explain both deposits simultaneously.

Tile 6 shows strong deposition both in 2004 and 2007 (see Fig. 3) which means that conversion to neutrals at the OSP and deposition in the PFR had about an equal probability in both 2004 and 2007. As the agreement for tile 5 is good, the model does not explain simultaneously the deposits on tiles 5 and 6. This may indicate that either the model is wrong, or tile 6 has an extra deposit or extra erosion has taken place on tile 5. The 2004 data exhibits a similar issue which was assumed to be caused by extra erosion on tile 5 due to emission of deuterium ions from the OSP. Such a possibility for the 2007 results has not yet been considered.

There is a deposit beyond the shadow of tile 3 (for the ISP) on tile 4 and beyond the shadow of tile 7 (for the OSP) on tile 6. At the moment we have no explanation for such deposits. It has previously been thought these deposits might be due to such processes as the scattering of carbon neutrals travelling from the strike point to tile 4 or 6, the observed decrease (on tile 5) with distance from the OSP required that the ^{13}C neutrals had a long mean free path. Kreter et al. [9] have observed that the deposition rates measured with a QMB located at the inner divertor leg depend strongly on the location of the ISP. The highest deposition rates were observed when the ISP was moved from tile 3 to the horizontal part of tile 4 but deposition was also observed when the ISP was on tile 3. This indicates that there is a long-range multistep process from the ISP towards the louvre region.

At the outer divertor, the erosion/re-deposition cycle along the outer target leads to a multistep migration of ^{13}C towards the separatrix called 'walking' [3]. This walking process creates carbon neutrals at the OSP and the released carbon is subsequently ionized within a cm from the release location. EDGE2D indicates that the friction force dominates the carbon flow and forces carbon back to the target. The ions must follow the field lines, and so are re-deposited a step closer to the OSP than from which they started. Finally, walking causes the eroded ^{13}C to sequentially be deposited and re-eroded nearer the separatrix until it cross into the PFR. The EDGE2D fit is not perfect at the outer divertor. The EDGE2D fit near the OSP (Fig. 4) seems to be displaced by about 10 mm from the experimental data. This displacement is common and is probably due to uncertainties in the EFIT reconstruction which provides the equilibrium used to generate the EDGE2D grid. Displacement of either strike point is unlikely to influence the modelling since erosion effects dominate this region.

CONCLUSIONS

We have investigated the migration and deposition of ^{13}C at JET by injecting $^{13}CH_4$ into the torus injection from near the lower hybrid antenna (GIM 6) at the end of the 2007 experimental campaign. The surface density of ^{13}C was determined from a full poloidal set of divertor tiles using SIMS and RBS techniques. The highest ^{13}C amounts were found on tile 1 and near the OSP on tile 7. The experimental ^{13}C distribution was compared with the data from previous ^{13}C puffing experiments made in 2001 and 2004. EDGE2D/NIMBUS was used for modelling the 2007 experiment. ^{13}C deposits along the inner divertor tiles on the SOL side of the ISP arrive at the inner divertor leg from the main chamber SOL. Carbon at the ISP arrives via the PFR as ions aided by the E×B drift. Deposits on the PFR side of the ISP are due to neutral C transport across the divertor originating near the OSP. Deposits in the PFR are due to neutrals originating at the OSP or ISP. These deposits also are subject to further erosion from deuterium neutrals that originate at the OSP and ISP. The deposits on the outer target are mainly residuals from re-erosion along the outer target. A multistep migration called walking seems to occur along the outer target allowing carbon to cross into the PFR.

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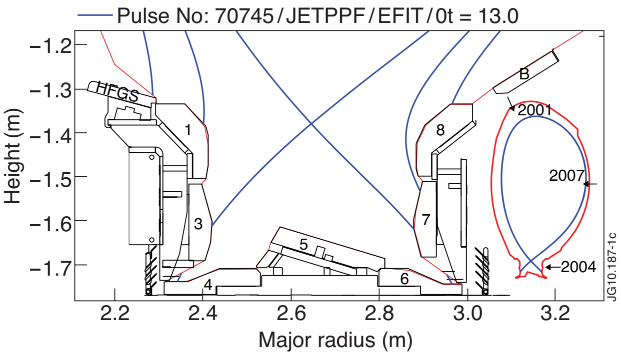

Figure 1: The geometry for JET divertor tiles (MkII-HD) in 2007. Magnetic configuration used in the 13C puffing experiment is also shown. The insert shows the puffing locations for the 2001, 2004 and 2007 experiments.

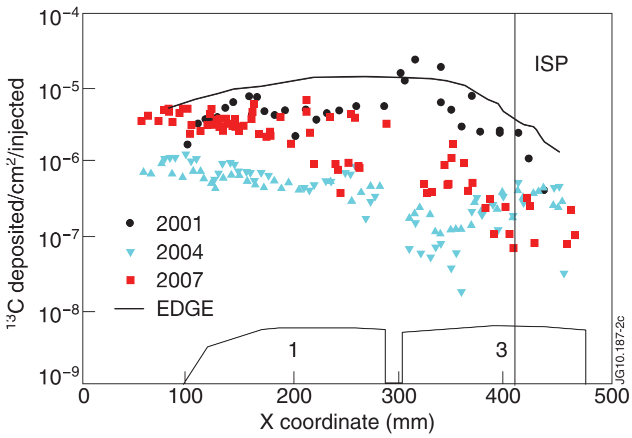

Figure 2: Experimental and normalised ^{13}C distribution on divertor tiles 1 and 3 for the 2001, 2004 and 2007 experiments. ISP shows the location of the inner strike point for the 2007 experiment. The origin of the X coordinate is on the left-hand side of HFGS tile and at the inner divertor it goes along the vertical axis, on the floor along the radius, and on the outer divertor along the vertical axis. EDGE stands for EDGE2D.

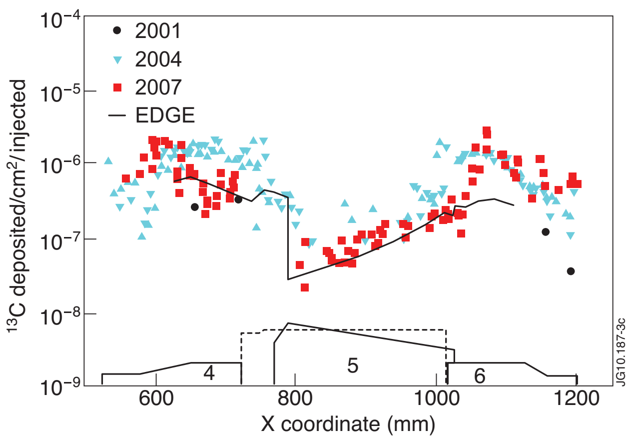

Figure 3: Experimental and normalised ^{13}C distribution on divertor tiles 4, 5 and 6 for the 2001, 2004 and 2007 experiments. Dashed line shows the profile for tile 5 in 2004.

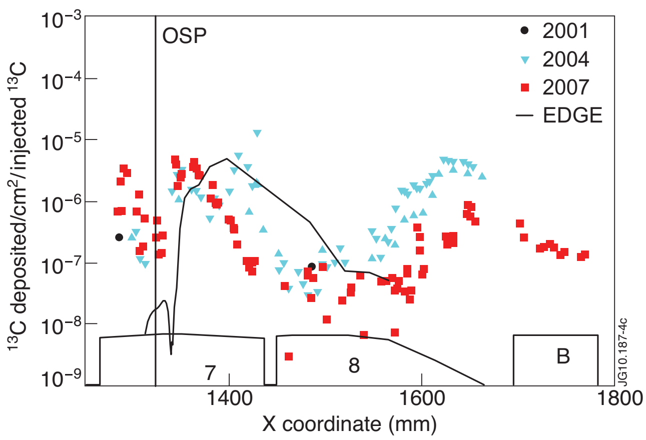

Figure 4: Experimental and normalised 13C distribution on divertor tiles 7 and 8 for the 2001, 2004 and 2007 experiments. OSP shows the location of the outer strike point for the 2007 experiment.