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Post-mortem measurements of fuel retention at JET with MKII-SRP divertor

J. Likonen [a,*], J.P. Coad [b], D.E. Hole [c], S. Koivuranta [a], T. Renvall [e], M. Rubel [d], E. Vainonen-Ahlgren [a,1], A. Widdowson [b], JET-EFDA Contributors

[a] Association EURATOM-Tekes, VTT, P.O. Box 1000, FI-02044 VTT, Finland
[b] JET EFDA Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[c] Department of Engineering and Design, School of Science and Technology, University of Sussex, Brighton, BN1 9QH East Sussex, UK
[d] Alfvén Laboratory, Royal Institute of Technology, Association EURATOM-VR, 100 44 Stockholm, Sweden
[e] Radiation and Nuclear Safety Authority, P.O. Box 14, 00881 Helsinki, Finland

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ABSTRACT

The deuterium inventory at JET after 2001–2004 operational campaign has been determined using nuclear reaction analysis (NRA) and secondary ion mass spectrometry (SIMS). A full poloidal set of divertor tiles and a set of outer poloidal limiter (OPL) tiles were analysed providing an estimation for the total deuterium retention of about 66 g. Deuterium is trapped mainly at the inner divertor on horizontal target tile and at the inner divertor louvre area where ~60% of the trapped D is found. The long-term D retention is ~4% of the total D input.

1. Introduction

Material lifetime and fuel retention are critical issues for next step fusion devices. In present, machines carbon is used as the plasma facing material due to its excellent thermal properties and carbon impurities in the plasma centre lead to only small increases in radiated power. The major disadvantage of carbon based materials is its chemical erosion under hydrogen bombardment and associated to this the ability to trap large amounts of tritium. In ITER, retention of the injected tritium would lead to the in-vessel tritium safety limit of 700 g set by the nuclear licensing authorities in some hundreds of full performance ITER discharges without any cleaning effort [1]. Thus, determination of deuterium retention in plasma facing components in present machines is of high priority in order to understand the mechanisms of fuel retention and to allow extrapolations to ITER.

In the period 2001–2004 JET operated with the MkII-SRP divertor [2]. A set of W-coated divertor tiles for erosion and deposition studies was installed prior to the 2001–2004 experimental campaigns. The W layer acts as a marker layer for surface analyses. In this paper, results on deuterium retention determined by NRA, SIMS and optical microscopy in plasma facing components exposed in JET at the 2001–2004 campaign are presented. NRA analyses give quantitative D/C ratio near the surface region (up to depth of ~2.5 μm), whereas SIMS provides information from greater depths (~100 μm). Thickness of the co-deposited layers was determined both with SIMS and optical microscopy.

2. Experimental

JET is operated with plasma facing components (PFC) made of carbon fibre composite (Concept I manufactured by Dunlop Ltd.). During the shutdown in 2001 a poloidal set of tiles that were coated with a W marker layer of 3 μm thickness (prepared by DIARC Technology Inc.) were installed in the vessel and removed in 2004 for analysis [3].

Depth profiles of these tiles were taken at several poloidal positions of the analysed samples shown in Fig. 1. NRA measurements were carried out using the 3 MeV Van de Graaff accelerator of the University of Sussex. Carbon (C), beryllium (Be) and deuterium (D) were analysed using the NRA reactions $^{12}C(^3He,p_0)^{14}N$, $^9Be(^3He,p)^{11}B$ and $^2D(^3He,p)^4He$ simultaneously and a 2.5 MeV beam of ^3He. Different information depths for D and C were taken into account in calculation of the D/C ratio. NRA analyses give quantitative D/C ratio near the surface region (up to depth of ~2.5 μm). SIMS analysis of the samples was made with a double focusing magnetic sector instrument (VG Ionex IX-70S) at VTT. A 5 keV O_2^+ primary ion beam with a current of 500 nA was used and the ion beam was raster-scanned over an area of $300 \times 430\ \mu m^2$. SIMS provides information from much greater depths (~100 μm) than NRA. Details of the analyses have been published earlier [4]. From optical microscopy of cross sections, the thicknesses of co-deposits were assessed. The cross-sectional

* Corresponding author.
E-mail address: jari.likonen@vtt.fi (J. Likonen).
[1] Present address: Fortum Nuclear Services Ltd., P.O. Box 100, 00048 Fortum, Finland.

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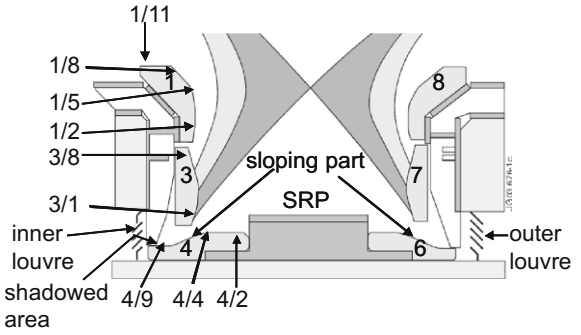

Fig. 1. The JET MkII-SRP divertor tile set. The samples for SIMS and IBA measurements are indicated with numbers. First number in the sample code refers to the tile and the second one to the poloidal location.

samples were prepared by cutting the core sample poloidally and placing it into cold mounting epoxy (Epofix, Struers). Polishing was made using Tegrasystem (Struers) with pre-programmed preparation method.

3. Results

SIMS depth profiling has been made from a number of samples on the inner divertor Tiles 1, 3 and 4 (see Fig. 1). Fig. 2 shows typical SIMS depth profiles from Tile 3 for the top part (sample 3/8) and bottom part (sample 3/1).The deposited film on Tiles 1 and 3 consists mainly of C with some D, Be and O as measured with Rutherford backscattering (RBS) [5]. The SIMS depth profile shows the same high Be/C ratio as the inner part of the 2001 films (see Fig. 2) [5]. The original source of Be is the Be evaporation performed periodically in the main chamber. Other metallic elements such as Ni, Cr and Fe (from inconel components in the main chamber) behave in the same way as Be. Films on Tile 3 are thicker than on Tile 1 (~30 μm at the bottom of Tile 3 and ~40 μm at the top of Tile 3). For profiles from vertical Tile 3, the tungsten containing marker layers are clearly visible at the interface between a deposited film and the CFC substrate. The Be/C ratio is at a similarly high level to Tile 1 [5].

The film on the horizontal part of the divertor floor Tile 4 has a high C concentration, with some D and O. The Be content in the deposit is very low [5]. The deposit on the sloping part (see Fig. 1) of floor Tile 4 is very thick (~200 μm), but there is a much smaller D content than on the private flux region area [6]. The film in the shadowed area of floor Tile 4 is also very thick (~150 μm) with a similar composition to that previously found for the flaking deposits at the inner louvres [6].

The D/C ratio determined from NRA results is shown in Fig. 3. The D/C ratio on Tile 1 increases from the top of the tile towards the bottom reaching ~1. There is a peak in the D/C distribution at the apron which has heavy deposition. The D/C distribution does not correlate with the thickness of the co-deposited layer on Tile 1 [7]. The D/C ratio increases constantly from the top to the bottom of the tile, whereas the thickness of the co-deposit has a minimum at the centre of the tile. The D/C distribution on Tile 3 has a complicated structure. At the top of the tile the ratio is the smallest, whereas the co-deposit is the thickest. The strike point during the 2001–2004 operations was mostly at the centre of Tile 3. Although there is some variation in D/C ratio across Tile 3 this is not correlated with the strike point position.

The highest amount of retained D on Tile 4 is on the shadowed area. The D amount on the sloping part and in the private flux region is lower and the D/C ratio varies from 0.2 in the private flux region to 1 in the region shadowed by Tile 3. During the 2001–2004 operations there were some discharges with the strike point on floor Tiles 4 and/or 6. The strike point position on Tile 4 was most frequently at ~685 mm which corresponds to the dip in the D/C distribution.

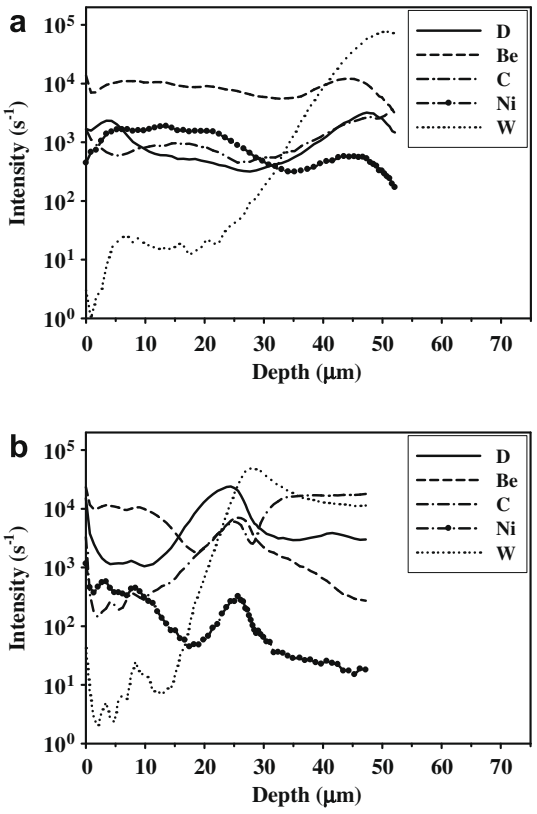

Fig. 2. SIMS depth profiles of D, Be, C, Ni and W: (a) from top of Tile 3 (sample 3/8) and (b) from bottom of Tile 3 (sample 3/1) (exposed in 2001–2004).

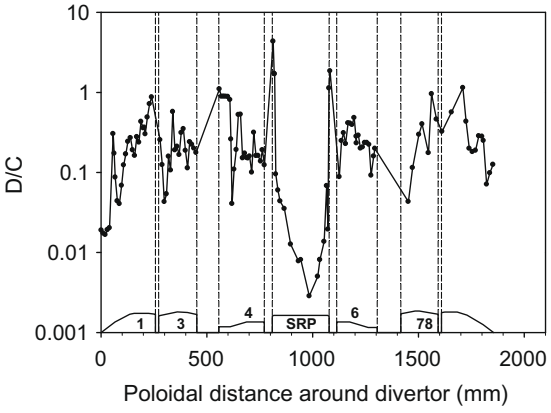

Fig. 3. D/C ratio as a function of poloidal distance around divertor measured with NRA.

The D/C ratio on SRP tile is generally low except at the inner and outer bevelled edges of the tile where the D/C ratio is similar to that typically on the shadowed region of Tile 4. The D/C ratio on Tile 6 is generally lower than on Tile 4 even though there are very thick deposits on the sloping part of the tile. Moreover, the D/C ratio is relatively low at the shadowed region of Tile 6. D inventory at the outer divertor is highest on Tile 6 at the sloping part, and is at a

similar concentration to that at the analogous position on Tile 4 at the inner divertor.

During the 2001 shutdown deposition monitor samples were installed at the shadowed area of both the inner and the outer divertor. These cavity samples allow the layer deposition mechanisms to be identified. Ion beam analyses indicate that the layers deposited inside both cavities have high amounts of trapped D with D/C ~ 1 [8]. The covers of the deposition monitors were analysed with SIMS and optical microscopy. The deposited film on the cover installed at the inner divertor has a thickness of ~115 μm. The co-deposited layer on the cavity sample at the outer louvre area had a high D/C ratio, similar to that on the inner cavity sample. Inspection of the deposition monitor cover indicates that the film has spalled at some stage and SIMS analyses show that the thickness of the remaining film is about 25 μm.

There is some D deposited on the outer divertor Tiles 7 and 8 and the D/C ratio is relatively high at some areas. The minimum in the D/C ratio at ~1450 mm coincides with the most frequent strike point position on Tile 7 and the D/C ratio increases from the bottom towards the top of the tile. There is some net deposition on Tile 7 but the deposited films are very thin. Tile 8 has, however, been eroded. The total amounts of retained D on Tiles 7 and 8 are very small and do not contribute significantly to the overall D inventory.

At the top of the outer limiters in the main chamber the plasma boundary is normally some distance away from the limiter. The flux of the impurities decreases with the distance from the last closed flux surface (LCFS) and thus the central part of the limiter is likely to collect most impurities. Fig. 4 shows the amounts of D, C and Be along OPL tile 8D 09 which is near the centre of the limiter and the outer mid-plane of the vessel. This region interacts most strongly with the plasma and is likely to experience high power loads during ion cyclotron resonance (ICRH) heating experiments when the plasma comes closest to the outer limiters. This indicates that the central part of the tile could be a region of net erosion. On the other hand, there is likely to be associated net deposition deeper in the scrape-off layer (SOL) towards the ends of the tile. This is observed in the Be build-up towards both ends of the tile, whereas there is little deposition in the central part of the tile. D is deposited at high levels but only at one end of the tile. The plasma boundary is normally further away from the lower part of the limiter than from the centre and top of the limiter and there is less interaction between the limiter and the plasma. SIMS depth profiles from OPL tiles near the bottom of the limiter indicate that the deposited films are thin with a thickness of few microns.

The total retained D amounts are obtained by assuming toroidal symmetry in deposition. The volume of the deposited layer on each tile segment was calculated by multiplying the area of the tile segment with the thickness of the layer. The thicknesses of the layers were obtained from SIMS and optical microscope measurements. For each tile segment an average D/C ratio obtained from NRA analyses was calculated. The density of the deposited layers is assumed to be 1 g/cm^3. The D amounts are summarised in Table 1.

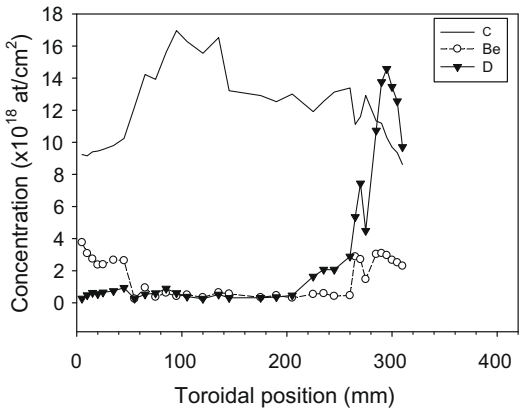

Fig. 4. Concentrations of C, Be and D along OPL tile 8D09 measured with NRA.

4. Discussion

During the MkII-SRP phase in 2001–2004 the total D input was 1800 g. As can be seen from Table 1 the measured amount of retained D is about 66 g which corresponds to a retention of 4% of the D input. The error due to inaccuracies of the analysis and due to the extrapolation from a specific toroidal location to the whole machine is estimated to be below 50%. The majority of the retention (~40%) is found on the inner floor Tile 4. Highest retention on Tile 4 is in the shadowed region with D/C ratio of 0.8–0.9, whereas in the sloping part the deposited film is much thicker but the D/C ratio smaller (0.1–0.3) resulting in smaller D retention. The reason for the smaller D/C ratio on the sloping part is not clear. There is also significant D inventory in the inner louvre area. This is the region where C and D are accumulated as a final step in the transport when strike point is on the sloping part of Tile 4 (so-called "corner shots") [9]. The septum replacement plate (SRP) tile has a very high D/C ratio especially along the inner and outer edges, whereas at the centre of the tile the ratio is very small. EDGE2D simulations suggest that the erosion at the centre of SRP tile is caused by deuterium neutrals originating from the strike points [10]. A hollow profile was also observed for ^{13}C distribution after the $^{13}CH_4$ puffing experiment at JET in 2004 [10]. The overall D inventory on the SRP tiles is relatively small. Very thick deposits were found on the sloping part of outer floor Tile 6 with D/C ~ 0.1 similar to that on Tile 4. The D inventory in this area is also very significant (~20% of the total in-vessel inventory). The calculated D inventory at the outer louvre area is a lower limit because a major part of the film has spalled at some stage during the operations.

Most of the outer divertor is an erosion dominated area, except the outer divertor floor. During the 2001–2004 operations thin deposits were found on Tile 7. The deposition occurred during the ^{13}C puffing experiment at the end of the campaign and part of the deposition occurred during the reversed field campaign. The overall D amount on Tiles 7 and 8 is small. There is some deposition on the OPL tiles near the top and centre of the limiters. The D/C ratios on the OPL tiles are, however, rather small (~0.1) resulting in low amounts of retained D. The total D inventory on the OPL limiters is only ~0.3 g.

For long-term retention integrated over an experimental campaign, post-mortem analysis is a proven method to assess the D retention. The D inventory (~4%) obtained in this work is comparable to other results obtained with post-mortem analysis. In JET, analysis of the divertor tiles after the MkII-GB divertor campaign found a C deposition of about 400 g mainly at the inner divertor [11]. During these plasmas a total amount of 766 g of D was in-

Table 1
Amounts of D trapped in different areas of JET.

Location	Amount of D (g)
Inner divertor Tiles 1 and 3	5.4
Floor Tile 4	26.1
Inner louvre	13.0
SRP tile	1.5
Floor Tile 6	12.9
Outer divertor Tiles 7 and 8	2.2
Outer louvre	4.6
Outer poloidal limiters	0.3
Total	66

jected. In the deposits on the inner divertor the D/C ratio was about 0.2 and the overall D retention estimated from these data is about 4% (34 g) of the total amount injected [12]. In AUG the long-term D retention for different campaigns obtained with surface analysis is about 3–4% of the D input [13]. The long-term D retention fraction evaluated from integrated gas balance (~10–20%) for various devices is larger than the D retention deduced from the post-mortem analysis of tiles [12]. Both gas balance and post-mortem measurements are, however, subject to large error bars. With gas balance it is difficult to determine the contributions over a full experimental campaign, e.g. D recovery from wall conditioning, disruptions or out-gassing over long periods (compared with plasma operation). Gas balance is performed typically for an experimental day or week and the accuracy depends thus on the integrated difference between the injection and the exhaust. Post-mortem analyses are based on restricted sets of samples from various plasma facing surfaces and not all D-containing components can be analysed. The results are then extrapolated to the whole device assuming toroidal symmetry: for example in JET the tile gaps have not been analysed at all. It can be thus concluded that post-mortem analyses tend to underestimate the D retention whilst gas balance overestimates it.

5. Conclusion

A full poloidal set of MkII-SRP divertor and OPL tiles exposed in 2001–2004 at JET have been characterised using NRA and SIMS techniques allowing determination of deuterium inventory. The D/C ratio was determined with NRA and the thicknesses of the co-deposited layers were obtained with SIMS and optical microscopy. The total retained D amounts were obtained by assuming toroidal symmetry in deposition. The total deuterium retention during 2001–2004 operations is estimated to be ~66 g. Most of the deuterium is trapped at the inner divertor on floor Tile 4 and at the inner louvre area where ~60% of the trapped D is found. The long-term D retention is ~4% of the total D input. This is comparable to the long-term D retention during the MkII-GB divertor campaign.

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