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Fuel retention in JET ITER-Like Wall from post-mortem analysis

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ABSTRACT

Selected Ion Beam Analysis techniques applicable for detecting deuterium and heavier impurities have been used in the post-mortem analyses of tiles removed after the first JET ITER-Like Wall (JET-ILW) campaign. Over half of the retained fuel was measured in the divertor region. The highest figures for fuel retention were obtained from regions with the thickest deposited layers, i.e. in the inner divertor on top of tile 1 and on the High Field Gap Closure tile, which resides deep in the plasma scrape-off layer. Least retention was found in the main chamber high erosion regions, i.e. in the mid-plane of Inner Wall Guard Limiter. The fuel retention values found typically varied with deposition layer thicknesses. The reported retention values support the observed decrease in fuel retention obtained with gas balance experiments of JET-ILW.

1. Introduction

Fuel retention in the plasma-facing first wall material has an essential role in economical operation of a fusion device. Moreover, the accumulation of the hazardous hydrogen isotope tritium (T) into the wall dictates the radiologically safe operation limit. Presently the maximum allowed T retention in the wall materials in ITER is 0.7 kg. The JET ITER-Like Wall (JET-ILW) project [1] allows to investigate the plasma-surface interactions which can take place in the course of ITER operation. In JET-ILW the vessel main chamber is made out of bulk beryllium (Be) and the divertor region comprises of bulk tungsten (W) tiles and W-coated carbon-fibre composite (CFC) tiles. The resulted net plasma-surface interactions, such as Be erosion and deposition and plasma fuel (deuterium, D) retention to wall tiles via implantation or codeposition, can be analyzed with post-mortem analyses performed on tiles removed from the vessel. The removal and replacement of vessel wall tiles can be done only during dedicated shutdowns between JET experimental campaigns.

During the JET-ILW experimental campaign 2010–2012 the fuel retention was studied with a dedicated gas balance experiment [2]. In this experiment, identical plasma pulses for different plasma modes (ohmic, L-mode, type III ELMy H-mode, type I ELMy H-mode) were repeated to achieve statistically sufficient number of injected fuel particles for avoiding any history effects caused by the JET operation. The outgassing of the retained D was monitored short term (in between the pulses) as well as longer term (up to 2 days). Based on these gas balance measurements the JET-ILW shows fuel retention which is 10–20 times smaller than what was measured with the JET all-Carbon (JET-C) wall. The present work continues the retention studies by analyzing JET first wall tiles removed from the vessel after the 2010–2012 experimental campaign. The fuel detected in these analyses shows the net retention of D beyond the long-term outgassing, and the results map the retention distribution in the vessel.

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[1] See the Appendix of F. Romanelli et al., Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, USA

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0022-3115/

2. Experimental methods

The deuterium concentrations were determined from selected JET-ILW first wall armour tiles removed from the vessel during the 2012 shutdown. The tiles were a representative selection from the main wall [3]: the upper region, mid-plane and lower region of Inner Wall Guard Limiters (IWGL) and Outer Poloidal Limiters (OPL), as well as tiles from the divertor (inner and outer divertor). No samples were taken from the central part of the divertor (Tile 5) at this stage. The selected tiles have a special interlayer coating near the tile surface for measuring the tile erosion/deposition accurately. The main wall marker tiles have a Be (bulk)/Ni (4 μm)/Be (7 μm) structure. The marker coated divertor tiles have a structure of CFC (bulk)/Mo (3 μm)/W (12 μm)/Mo (4 μm)/W (4 μm), except Tile 3 which has the Mo layer as the plasma-facing coating.

Post-mortem analyses were carried out with ion beam analysis (IBA) methods. Nuclear Reaction Analysis (NRA) was used for determining the deuterium concentrations via the $D(^3He,p)^4He$ nuclear reaction. Elastic Backscattering (EBS) and Particle Induced X-ray Emission (PIXE) were used for detecting Be and heavier elements. The NRA, EBS and PIXE experimental setups are described more in detail in Refs. [4,3]. In addition to NRA also the Secondary Ion Mass Spectrometry (SIMS) was used in the D analysis. Details for the SIMS setup and the preparation of cored samples from the divertor using a hollow drill are presented in Ref. [5].

The inner divertor tiles were analyzed with NRA, EBS and PIXE and fitted with WiNDF data furnace software package [6]. The outer divertor tiles were studied with NRA [7] and Elastic Recoil Detection Analysis (ERDA) [8]. SIMS analysis was performed for both the inner and the outer divertor samples. A set of D reference samples was prepared by implanting 60 keV/D_2 into polycrystalline W (see details in Ref. [9]). The retained D in the implantation-induced defects determined with Elastic Recoil Detection Analysis (ERDA) was 3.47×10^{16} at./cm^2. These D implanted reference samples were used for calibrating the SIMS results.

Presently the analytical fitting results are not available for all of the Be main chamber tiles, but the WiNDF simulations for the full main chamber are under way. The Be tile fuel retention results were obtained with NRA and calibrated using the aforementioned D reference sample. The statistical uncertainty for the NRA measured D retention is assessed to be $\lesssim$6%. Details are described in Section 3.1.2.

In addition to the IBA methods also Thermal Desorption Spectrometry (TDS) was applied to a selected number of cored divertor tile samples. This paper presents the first results for JET-ILW samples analysed with TDS. The analysis was done in a ultra-high vacuum (UHV) system with a starting pressure of $\lesssim 1 \times 10^{-9}$ mbar. Samples were annealed with linear ramp rates (10 K/min or 5 K/min) from room temperature (RT) up to 1000 °C. The released gases were measured with a line-of-sight quadrupole mass spectrometer as a function of time and annealing temperature. The TDS data was collected for mass-to-charge ratios corresponding to various molecules, e.g. H_2, HD, D_2, DT, T_2 and Be. The D signal was calibrated with the D reference sample described previously.

The IBA for main wall tiles was performed using each individual Be tile as a sample. The divertor tiles were cored into small-sized samples (diameter 17 mm), which were then analysed with SIMS and NRA. An additional set of divertor samples were cored to be used with TDS. The topmost part of these cored samples were further sliced horizontally into two pieces. The resulted TDS depth profile represents depths of 0–1 mm (surface coating sample) and 1.5–2.5 mm (bulk CFC sample).

Finally, although the analysis methods used in this work provide accurate results locally, the biggest uncertainty arises from the assumption of toroidal symmetries used in the extrapolations of the results to cover the full JET first wall surface area.

3. Results and discussion

3.1. Main chamber

3.1.1. Upper Dump Plates

In earlier work it was shown that the plasma-facing surfaces of the Upper Dump Plate (DP) tiles were modified due to melting and arcing, which e.g. induced droplets of molten Be being ejected to the outer divertor [10,3]. These strong interactions with plasma and DP region were mostly taking place before the active use of JET's Disruption Mitigation Valve protection system.

The DP surface profiling indicated surface modifications, but no evident large scale erosion could be determined. A DP tile (identification 2B2C) surface was analysed with NRA and EBS providing information on the thickness of the residual Ni–Be coating and on fuel retention. 21 measurement points were used to cover the DP tile surface analysis. The orientation of the selected points was chosen to represent a toroidal distribution across the middle of the tile. Each individual measurement point was then analysed with WiNDF and the impurity quantities and concentration profiles were determined respectively. Due to the large-scale surface roughness on the DP tile the resulted D areal concentrations varied significantly. The mean D concentration value and its deviation obtained was $(3.4 \pm 1.2) \times 10^{17}$ at./cm^2. Integrating over the whole upper DP region yields a retention value of 2.1×10^{22} D atoms.

3.1.2. Outer Poloidal Limiters

Outer Poloidal Limiter (OPL) tiles used for post-mortem analysis were removed from the upper region, mid-plane and from the lower outer wall region (identification 4D23, 4D14 and 4D3, respectively). Each of these tiles were measured with NRA, EBS and PIXE using 52 measurement points across the tile in the toroidal direction. The tiles showed thinning of the Be layer in the centre part of the tile [11]. The centre region was neighboured by some deposited Be in the far ends of the OPL tiles. In Fig. 1 is presented the total D concentration in the toroidal direction as measured along the mid-plane OPL tile (4D14) and analysed with WiNDF. Integrating over the whole tile surface yields 2.81×10^{20} D atoms. A simple D concentration assessment using the D reference sample for NRA calibration and a constant value for nuclear reaction cross-section provides a value of 1.14×10^{20} D atoms. The factor of ~2.46 difference to WiNDF fit arises from the use of a non-varying value for the $D(^3He,p)^4He$ reaction cross-section. This correction factor $f = 2.46$ will be used later in Section 3.1.3 where the NRA results of the IWGL tiles are calibrated using only the D reference sample and the single value for reaction cross-section.

The lower region OPL tile (4D3) analysis results to an integrated D total retention value of 2.26×10^{20} D atoms. This value was obtained by using the combined method of NRA calibration sample and the aforementioned correction factor *f*. Using the same method, the result for the upper region tile (4D23) was 1.15×10^{20} D atoms. Assuming parabolic symmetry for the D retention along the OPL beam in the poloidal direction and interpolating the retention values, an integrated value for the total D retention in one OPL beam can be obtained 5.48×10^{21} D atoms. In the JET machine there are smaller limiters near the antennas which are likewise made out of bulk Be. Taking into account the difference in areal surfaces of an OPL and an antenna limiter, a D retention value for one antenna limiter can be assessed as 2.63×10^{20} D atoms. Multiplying the OPL and antenna limiter D

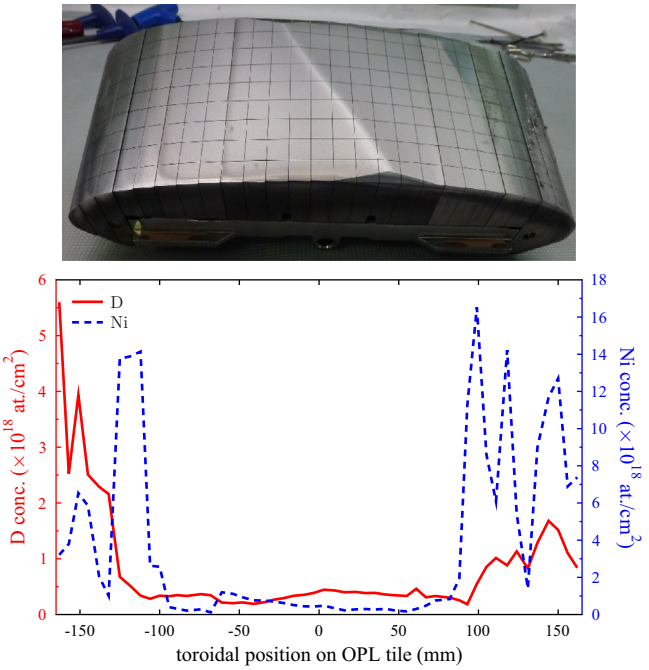

Fig. 1. Toroidal distribution of D on the mid-plane OPL tile as obtained with NRA measurements and analyzed with WiNDF. Also shown the Ni marker interlayer results from EBS and PIXE measurement: low Ni concentration values correlate with thinning or erosion of the OPL tile surface. The centre part region (−60 mm . . . + 60 mm) of the OPL is the eroded zone and has low D concentration values of $\sim 3.3 \times 10^{17}$ at./cm^2.

values by their corresponding number of limiters to cover the whole machine, yields to a global retention of 5.72×10^{22} D atoms on the outer wall.

3.1.3. Inner Wall Guard Limiters

IWGL tiles used in the present study were removed from the upper region, mid-plane and lower region of the inner wall (identification 2XR19, 2XR10 and 2XR3, respectively). As was with the OPL tiles, the IBA analysis for IWGL tiles was done in the toroidal direction of the tiles. The IWGL results are only calibrated by using the D reference sample (see Section 2) and corrected with the factor f presented in Section 3.1.2.

The D retention values obtained for upper, mid-plane and lower IWGL tiles were 1.87×10^{20}, 1.13×10^{20} and 1.71×10^{20} D atoms, respectively. The lowest D retention is measured at the mid-plane with the highest erosion rate as was previously shown with tile surface profilometry [10]. Assuming a parabolic retention symmetry in the poloidal direction and interpolating the retention values along the IWGL beam, a total D retention value of 2.75×10^{21} D atoms per one IWGL beam is obtained. Multiplying this by the number of IWGLs in the machine gives a global inner wall D retention value of 2.75×10^{22} D atoms.

3.2. Divertor

The divertor Tiles 1, 3, 4 and Tile 0 (HFGC) were analysed with IBA and SIMS for D and deposition composition. In addition to SIMS also NRA (Ref. [7]) and ERDA (Ref. [8]) was used for Tiles 6, 7 and 8. The measurement points form a poloidal distribution along the divertor. For locating the analysis points an S coordinate system is used and presented in Fig. 2.

The measured total concentration values of retained D in JET-ILW divertor is presented in Fig. 3. The overall D retention trend implies clearly that most of the retained D is on the inner

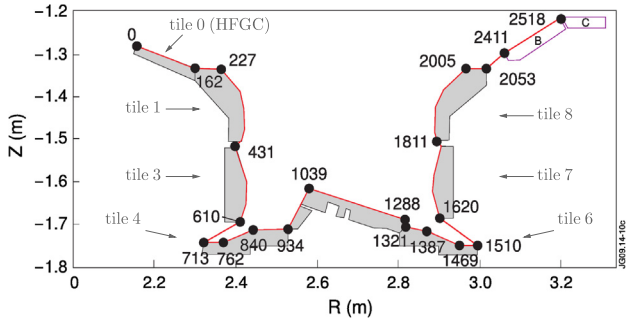

Fig. 2. The divertor S coordinates showing poloidal trajectory following the tile surfaces. The tile 1 apron is between S coordinates 162 mm and 227 mm.

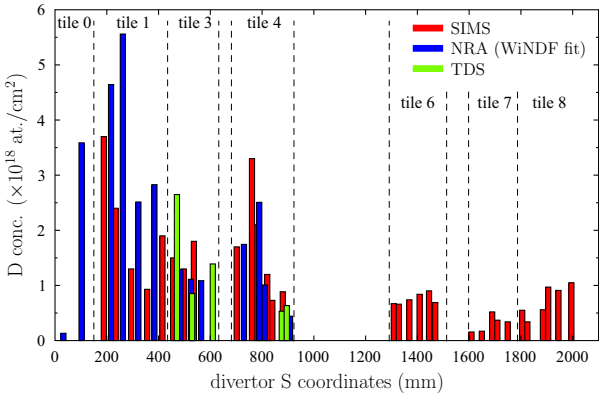

Fig. 3. The poloidal distribution of retained D in the JET-ILW divertor tiles as measured with SIMS, NRA and TDS. D concentration is presented as a function of S coordinates. The divertor tile positions at corresponding S coordinates are separated with dashed lines.

divertor. Some variation is observed in the values obtained with different analysis methods. These may be due to toroidal variation of D concentration, surface roughness effects or even microscopically local nonuniform D surface distribution [12]. Averaging the D retention values presented in Fig. 3 and integrating over all the divertor tiles in toroidal direction gives total D concentration values of 2.0×10^{23} and 5.0×10^{22} D atoms for the inner and outer

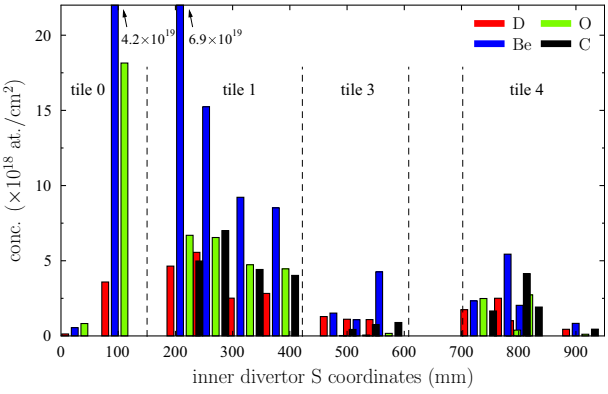

Fig. 4. The D, Be, C and O poloidal distribution in the JET-ILW inner divertor tiles as a function of S coordinate. The concentrations shown were obtained with NRA and EBS and fitted with WiNDF. Most of the deposition takes place on the plasma wetted region on tile 0 (S coordinates 60 . . . 160 mm) and on the apron of tile 1 (162 . . . 230 mm), where also most of the D co-deposition takes place $\sim 5 \times 10^{18}$ at./cm^2. The plasma shadowed region on tile 0 (<60 mm) show concentrations for D: 1.3×10^{17} at./cm^2, Be: 6×10^{17} at./cm^2 and O: 0.8×10^{17} at./cm^2, which are similar as obtained for tile 4 shadowed region (>900 mm).

divertor, respectively. Nearly 66% of the inner divertor D retention takes place on Tile 0 (HFGC) and Tile 1. This correlates with the fact that most of the deposition was measured from that region. Fig. 4 presents the qualitative and quantitative information of the inner divertor deposited layers. A more detailed analysis of the multilayered deposition structure is in Ref. [11]. Most of the Be, O and C is on Tile 0 and Tile 1. The presence of impurities such as O and C in Be deposits can have a major effect on D retention. Further IBA studies with higher ion beam energies are underway for additional quantification of the impurity contents in the deposits [7]. From the divertor results it is not unambiguous whether the D retention is composition dependent of the deposited layer. Some correlation of D retention is with the thickness of the deposited layer on the inner divertor. The outer divertor deposited layers do not vary as much as the layers on the inner divertor (see Figs. 4 and 5).

The divertor remote areas had installed passive diagnostic Louvre Clips (LC) for monitoring deposition on the cold regions in the inner and outer divertor (remote areas between Tiles 3 and 4 and Tiles 6 and 7, Fig. 2). The amount of retained D on the inner and outer LC was $(3.0 \pm 1.7) \times 10^{18}$ at./cm^2 and $(1.9 \pm 0.8) \times 10^{18}$ at./cm^2, respectively. The relative concentration of D/(Be + O + C) was (0.49 ± 0.22) on the inner LC and (0.36 ± 0.07) on the outer LC. For comparison, Tile 1 concentration ratio is (0.14 ± 0.06), Tile 3 (0.48 ± 0.24) with miniscular amounts of O and Tile 4 (0.20 ± 0.07) with nearly 1:1 Be:C ratio.

The TDS spectra were calibrated with an identical D implanted polycrystalline W sample that was used for calibrating the main chamber NRA and divertor SIMS results. TDS was performed in the present work only for selected samples representing Tile 3 and Tile 4. The integrated D concentration values from TDS are presented in Fig. 3. The Tile 4 D concentration results are somewhat lower than obtained with other analyses methods. This is probably due to the fact that the Tile 4 TDS samples were cored from the vicinity of the plasma-shadowed region on that tile. In addition to the 1 mm thick sample of the W-coated surface, a bulk CFC sample was prepared from Tile 4. The sample depth of this sample corresponds to 1.5 mm from the tile surface at which the TDS showed a D concentration of 1.0×10^{14} at./cm^2 when annealed to 1000 °C.

The D_2 desorption spectra for Tile 3 and Tile 4 samples are fairly broad with the desorption starting at ~80 °C in UHV. Interestingly, the Tile 4 samples showed two clear desorption maxima (first peak at 300–320 °C and second at 460–480 °C) whereas Tile 3 samples had only one desorption maximum (between 400 and 430 °C). This difference can be due to the tile coatings: Tile 4 has a W coating, whereas the presently analysed Tile 3 surface coating was Mo.

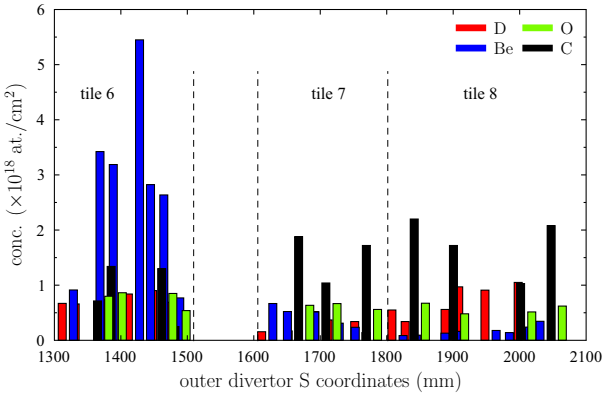

Fig. 5. The D, Be, C and O poloidal distribution in the JET-ILW outer divertor tiles as a function of S coordinate. D concentrations were obtained with SIMS and Be with NRA [7], C and O impurities with ERDA [8]. D retention values do not exceed 1×10^{18} at./cm^2. Highest Be values were measured on the sloping part of Tile 6.

Some random T_2 peaks were recorded at low temperatures, but a clear T_2 outgassing took place at high temperatures starting at ~800 °C. The quantification of T_2 will be part of a future work. Additionally, at high temperatures $\gtrsim 900$°C the desorption of Be was initiated. Since bulk Be is having a melting point at ~1200 °C, it is concluded that the observed signal is due to the evaporation of the Be deposits from the sample surface. As the Be desorption takes place at the high end of the annealing profile, total quantities were not concluded within this work.

4. Summary and conclusions

Table 1 summarises the present results on global D retention of JET-ILW as measured from the first wall components. Presented quantities are based on measurements done on selected first wall tiles, which represent a poloidal cross-section of the main chamber and divertor. The biggest uncertainty in the global values arises from the assumption of toroidal symmetry of the locally obtained results, which leads to the extrapolation to cover toroidally the full first wall surface area.

Highest retention values were measured from regions with highest deposition. Lowest retention was obtained in areas with thin impurity layers or where implantation might be the main retention mechanism. During the 2010–2012 experimental campaign approximately 1.67×10^{26} D atoms were puffed into JET [13]. The post-mortem analyses of the present work map the distribution of the 3.92×10^{23} retained D atoms, which corresponds to ~ 0.24% or 1.31 g of retained D. This results to a global retention rate of 5.7×10^{18} D/s when normalised to 6.8×10^4 s operational time of the 2010–2012 JET-ILW campaign.

Using the JET-ILW limiter (6 h) and divertor (13 h) plasma configuration times results in retention rates 4.9×10^{18} D/s and 6.1×10^{18} D/s for the main chamber and divertor, respectively. For comparison, the JET-C 2007–2009 campaign main chamber (12 h) [14,15] and divertor (33 h) [16,15] retention rates are 1.9×10^{19} D/s and 1.3×10^{20} D/s. The JET-C 2007–2009 results have been re-assessed [15] and e.g. include retention in the remote areas. The resulted JET-C global retention in 2007–2009 is 1.0×10^{20} D/s, which is by a factor ~18 higher than the corresponding JET-ILW 2010–2012 result.

It is important to note, that the obtained JET-ILW D retention values can be considered as upper limit of retention since no glow discharge cleaning pulses were performed during the 2010–2012 period. It is expected the retention values to be significantly lower after 2013–2014 JET-ILW campaign, since that period is planned to end with a H-cleaning pulse campaign.

The JET-ILW main chamber erosion zones do not show high retention values for D. Trapped D is mostly in main chamber

Table 1
Summary of the retained D total amounts from JET-ILW 2010 – 2012 campaign.

JET vessel component	Number of D atoms
Upper Dump Plates	2.1×10^{22}
Outer Poloidal Limiters	5.72×10^{22}
Inner Wall Guard Limiters	2.75×10^{22}
Divertor, total	2.4×10^{23}
– Inner divertor (incl. Tile 0)	2.0×10^{23}
– Tile 0 and Tile 1	1.3×10^{23}
– Outer divertor	5.0×10^{22}
– Tile 5	Not measured
Remote areas, total	4.2×10^{22}
– Inner louvre	2.0×10^{22}
– Outer louvre	2.2×10^{22}

regions with less plasma-surface interactions. These areas have small and varying amounts of Be deposits but it remains to be determined more accurately the concentrations of C or O [11]. 73% of the retained D is on the divertor (incl. remote areas) and the rest is trapped in the main chamber. Most of the eroded material from the main chamber ends up in the upper region of the inner divertor, where the highest D retention values are also measured. However, elevated D retention values were also obtained from remote region of Tile 4 with comparably low values for deposited impurities.

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