EUROFUSION WPJET2-CP(16) 15435

K Heinola et al.

Long-term fuel retention and release in JET ITER-Like Wall at ITER-relevant baking temperatures

Preprint of Paper to be submitted for publication in
Proceedings of 26th IAEA Fusion Energy Conference

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Long-term fuel retention and release in JET ITER-Like Wall at ITER-relevant baking temperatures

K. Heinola[1], J. Likonen[2], T. Ahlgren[1], S. Brezinsek[3], I. Jepu[4], G. F. Matthews[5], R. A. Pitts[6], G. De Temmerman[6], A. Widdowson[5] and JET Contributors*

[1]Department of Physics, University of Helsinki, P.O. Box 64, 00560
[2]VTT Technical Research Centre of Finland, P.O. Box 1000, 02044 VTT, Finland
[3]Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung Plasmaphysik, Partner of the Trilateral Euregio Cluster (TEC), 52425 Jülich, Germany
[4]National Institute for Laser, Plasma and Radiation Physics, Bucharest-Magurele 077125, Romania
[5]Culham Centre for Fusion Energy, Abingdon, OX14 3DB, United Kingdom
[6]ITER Organisation, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance Cedex, France

Corresponding Author: kalle.heinola@helsinki.fi

Abstract:
The fuel outgassing efficiency in JET-ILW has been studied at ITER-relevant baking temperatures. Samples retrieved from the W divertor and Be main chamber were annealed at 350 and 240°C, respectively. Annealing was performed with TDS for 0, 5 and 15 hrs to study the deuterium removal effectiveness at the nominal baking temperatures. Remained fraction was determined by emptying the samples fully of deuterium. Results showed the deposits in the divertor having an increasing effect to the remaining retention at temperatures above baking. Highest remaining fractions 54 and 87% were observed with deposit thicknesses of 10 and 40 μm, respectively. Substantially high fractions were obtained in the main chamber samples from the limiter erosion zones. A 15 hrs anneal of deposit-free bulk Be from the limiter midplane resulted in >90% remained deuterium. TDS results from the divertor were simulated with TMAP7 calculations. The spectra were modelled with three deuterium activation energies resulting in good agreement with the experiments.

*See the Appendix of F. Romanelli *et al.*, Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

1 Introduction

The JET ITER-Like Wall (ILW) experiment provides a unique environment to study critical plasma-material interactions (PMI) for ITER such as material erosion and migration and in-vessel fuel retention and removal [1]. The ILW comprises of bulk beryllium (Be) main chamber limiters and upper dump plates, and the divertor region is a mix of bulk tungsten (W) tiles and W-coated carbon fibre composite (CFC) tiles [2]. Removal and replacement of the plasma-facing components (PFC) allows for post-campaign (*post-mortem*) analyses to scrutinize the net effects of the PMIs.

ITER is a nuclear licensed facility and the in-vessel tritium (T) retention will be limited to 1 kg to minimize the risks of release of the mobilized T during accidents [3]. The ITER strategy to recover the trapped T in the vacuum vessel is to perform baking of the PFCs, at 240°C for the Be first wall and at 350°C for the W divertor [4]. In the present work, the effectiveness of annealing on the fuel removal at ITER-relevant baking temperatures is studied with samples removed from JET-ILW PFCs. Recent post-mortem analyses of JET-ILW PFCs have shown the majority of the deuterium (D) retained in the divertor region within deposited Be layers [5]: erosion of the Be main chamber PFCs leads to material migration to the inner divertor [6], where the fuel particles are co-deposited. Such co-deposited layers in the divertor will be the driving mechanism behind the T inventory in the ITER PFCs [7]. The release of the fuel particles from the co-deposited layers is challenging due to the fuel release dynamics being slowed down by the deposited layer thickness [8] and its morphology. Moreover, the presence of additional impurities, such as oxygen (O) and carbon (C), or layers with elements being mixed with W, may affect the resulting release rate [9]. The samples used in this study have been taken from the W-coated divertor tiles and from the main chamber bulk Be limiters (Sect. 2.1). The condition of the sample surfaces were as-received after the JET-ILW operational periods and had varying amounts of surface deposition. Annealing, fuel release and remaining fuel fractions were assessed using Thermal Desoprtion Spectrometry (TDS) (Sect. 2.1) and the results were analyzed with TMAP7 simulations (Sect. 2.2).

2 Methodologies

2.1 Experimental

Cross-section of the JET-ILW divertor is shown in Fig. 1. The highest retention is found on top of the inner divertor with the thickest deposition layers on Tile 0 and on the top region (*apron*) of Tile 1 [5]. Fig. 2 represents an ion beam analysis (IBA) result of the impurity depth profile concentrations found on Tile 1 apron. Also shown is an optical microscopy image presenting the morphology of the coating[1]. The W-coated CFC tiles used in the present study are Tile 0, 1 and 6. Sample selection was based on having a varying thickness of deposit on the samples and to study the effect of thickness on fuel release. All samples were from the ILW 2011-2012 period, whereas Tile 0 was

[1]The analyzed Tile 1 has a special marker coating with a W/Mo/W structure on CFC.

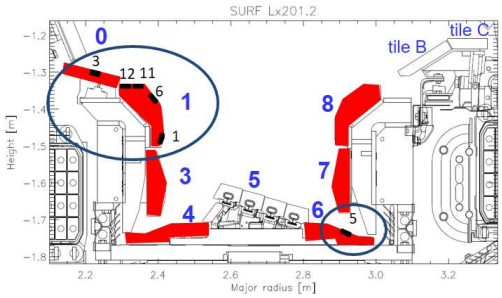

FIG. 1: Divertor W-coated CFC tiles highlighted in red and the tile numbering from Tile 0 to Tile 8 is from the high field to the low field side, correspondingly. TDS sample locations are circled and highlighted with black ID numbering.

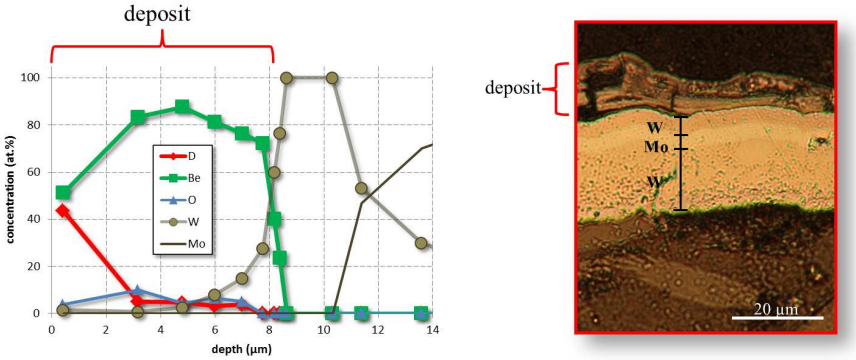

FIG. 2: Left: IBA result of the deposit impurity depth profiles found on top of Tile 1. The main impurity component is Be forming up to ∼10 μm thick layers, other impurities C and O visible. Right: Optical microscopy image of the deposit found on top of Tile 1.

exposed for two periods 2011-2012 and 2013-2014 and hence providing the thickest deposit information. The nominal deposit thicknesses found on tiles, the tile in-vessel ILW periods and the sample IDs are listed in Table I. Divertor sample preparation for TDS has been described in detail in Ref. [12].

In addition to divertor samples, a set of bulk Be samples from the main chamber limiters was prepared and analyzed with TDS. Locations chosen were from the midplane of the inner and outer limiters (tile IDs 2XR10 and 4D14, respectively). All the main chamber samples are from 2011-2012 period. The limiter midplane has been shown to be the major Be source in JET-ILW [13]. However, part of the eroded material gets toroidally redeposited locally to the edges of the limiters [14]. These regions are radially ∼3 cm further away from the plasma contact point of the limiters. Deposited layers on the edges do not show uniform patterns, but a rough surface with local deviations from 0 to several μm. Samples for the fuel retention studies were prepared both from the central main erosion zone and from the deposited edges of the limiters. The cutting and preparation method of bulk Be samples to meet the TDS requirements has been presented

TABLE I: SUMMARY OF DIVERTOR SAMPLE PROPERTIES USED IN THE TDS ANALYSES. SAMPLE IDS AS SHOWN IN FIG. 1.

Sample location	**sample ID**	**ILW period**	**deposition (μm)**
Tile 0	Tile 0-3	2011-2012, 2013-2014	40 †
Tile 1 apron	Tile 1-12, Tile 1-11	2011-2012	10 ‡
Tile 1 upper vertical	Tile 1-6	2011-2012	3 ‡
Tile 1 lower vertical	Tile 1-1	2011-2012	0 ‡
Tile 6 slope	Tile 6-5	2011-2012	5 ‡

† Reference [10]. ‡ Reference [11].

recently in Ref. [15].

The TDS measurement setup is described in Ref. [12]. The system is operated at 10^{-9} mbar and comprises of a heating stage on to which the samples are clamped. Heat is transferred via a molybdenum (Mo) annealing plate and the heating and the resulted Mo temperatures are recorded with thermocouples. A quadrupole mass spectrometer (QMS) is positioned perpendicularly with a line-of-sight view to the sample surface to maximize the collection of desorbed molecules (Fig. 3).

The TDS annealing profile can be preprogrammed freely. For the present work, the temperature was increased with an annealing rate (β) of 10 or 1 K/min until the required ITER-relevant bake temperature of 350°C for W and 240°C for Be was reached. A schematic temperature profile is shown in Fig. 3. Once the set temperature is reached, the ramp was kept constant for 0, 5 or 15 hrs to study the fuel release efficiency. After the residence/dwell time the samples were emptied of D by increasing the temperature to its maximum. For W-coated CFC samples 1000°C was used, whereas the bulk Be sample maximum temperature was set to 775°C. This is due to an increased Be evaporation from the sample at high temperatures and to prevent the TDS chamber being internally coated with Be.

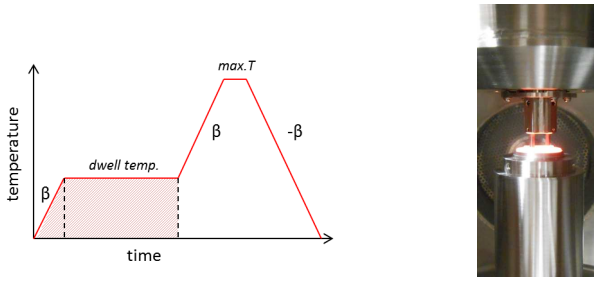

FIG. 3: Left: Schematic annealing profile used for JET-ILW samples. Shaded area corresponds to the ITER baking time. Right: ILW sample positioning in the TDS chamber.

2.2 Computational

The D desorption spectra for the full annealing profile of the W-coated samples were simulated with TMAP7 calculations. Details of the calculations can be found in Ref. [17]. TMAP7 is a 1-D diffusion-trapping code, which is used for calculating time-dependent evolution of concentrations of atomistic elements in material structures and fluxes of these elements across the structural boundaries. In the present work, the deposited Be layer with its experimental thickness was included in each simulation. W substrate was included in the system, but a no-flow condition at the boundary was assumed. As an initial input to the calculations, the D diffusion and recombination coefficients in Be co-deposits were taken from Ref. [16] and the fitting was done to trap populations and their activation energies until an agreement with the experimental TDS spectra was found.

3 Results and Conclusions

3.1 Divertor: W-coated CFC samples

Examples of D outgassing spectra with 0 and 15 hrs annealing at 350°C are presented in Fig. 4. The D release takes place already at low temperature (∼40°C) and the full spectrum has three release maxima (∼328, 418 and 552°C). Each maxima corresponds to a D trapping site. Also shown the T_2 release and Be evaporation. Keeping the temperature constant for 15 hrs at 350°C, the first trap was found to be outgassed, but 61% of the total D was found to be retained in the second and third trap. Identical D release characteristics was found in all of the divertor samples: the first trap is emptied fully and the second trap partially as temperature is increased from RT to 350°C followed by constant anneal at 350°C for extended periods. The remaining fraction of D was found to correlate with the thickness of the deposited layer. The highest fraction of 87% was measured on Tile 0 with a 40 μm deposit thickness. Results are summarized in Fig. 7. In general, the TDS results indicate the annealing of samples with deposits at 350°C will require heating times longer than several tens of hours in order to meet the ITER fuel removal criterium [17].

The TMAP7 simulations were found to be in good agreement with the TDS spectra (example in Fig. 5). As expected from TDS, a three-trap model was required to fit the data. The resulted D trap energies obtained were 0.75-0.8, 1.1 and 1.4 eV, respectively. The two lowest trapping energies agree well with the model presented in Ref. [16]. The lowest trapping energy may be related to the weakly bound D atoms found close to the deposit surface (Fig. 2) and which can get released at low temperature. It is worth to mention, that JET-ILW 2011-2012 did not finish with hydrogen cleaning pulses, hence a high near-surface D concentration is formed. Also, all the divertor samples studied were from the plasma scrape-off layer (SOL) regions which do not have the highest temperatures and particle fluxes and impact energies. The retention in these regions is a mixture of co-deposition and low-energy implantation. The second trapping site may be related to the deposit morphology and/or to the observed C and O impurities within the deposited layer. It is worth noting, that deposits in Ref. [16] had very little amounts of C, O making the second trap due to impurities less plausible. The third and highest trapping

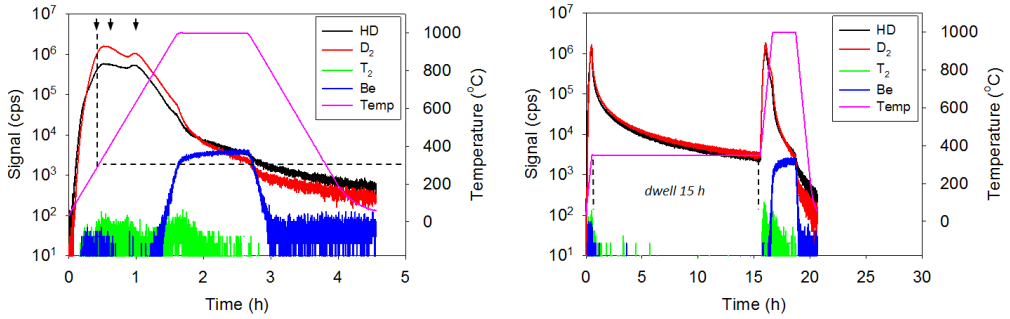

FIG. 4: Annealing at 350°C of samples from Tile 1 apron (ID: Tile 1-12). Left: Standard anneal with β =10 K/min showing three D desorption maxima. Right: Effect of 15 h baking to the D release. Significant amount of D is outgassed above 350°C.

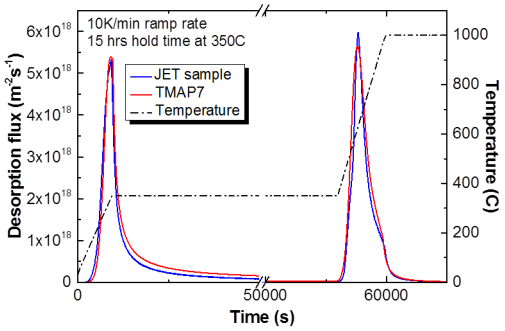

FIG. 5: TMAP7 simulation result for the anneal of Tile 1 apron (ID: Tile 1-12).

energy may correlate with the impurities and/or large-sized defects within the deposit i.e. the deposit may contain void-like defects or other open volume structures, which can efficiently trap D. Detailed computational work is ongoing for confirming the origin of these trapping sites.

3.2 Main chamber: bulk Be limiter samples

The main chamber limiter samples represent the main erosion region with the highest PMI and the limiter edge, which resides deeper in the SOL. An exemplary TDS result of the outer limiter midplane (Fig. 6) reveals up to four D desorption maxima. Computational analysis of these results is ongoing, which will provide more detailed conclusions on the experimental observations. Only the first trap can be seen to be emptied as the temperature is increased to 240°C, and the remaining D is released at higher temperatures. In general, results indicate even after 15 hrs bake at 240°C over 90% of D is remained in the midplane of inner and outer limiters (Fig. 7). These samples are free from deposits due to erosion from the high heat and particle loads during JET plasma limiter

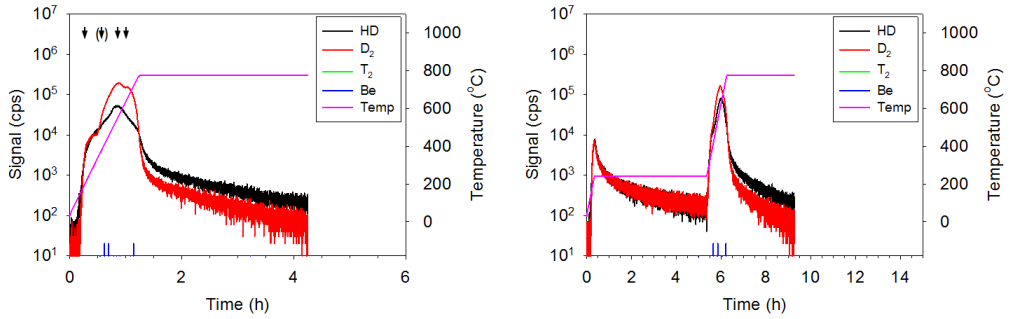

FIG. 6: Annealing at 240°C of bulk Be from the outer limiter midplane. Left: Standard anneal with β =10 K/min. The D release spectrum consists of three to four maxima (pointed by arrows). Right: Effect of 5 h annealing to the D release. The first trap is emptied at 240°C, remaining traps are outgassed during the second ramp.

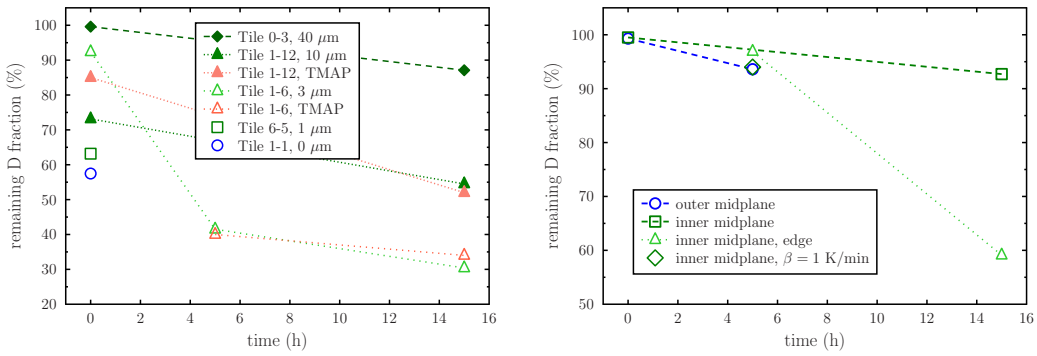

FIG. 7: Summaries of the remaining fractions for the W-coated divertor (left) and bulk Be limiter (right).

phase. Hence the remained D can be considered to be trapped in intrinsic defects and impurities (e.g. C, O), but also in implantation-induced traps, or in some other lattice imperfections. On the other hand, a bulk Be sample removed from the toroidal edge of the inner limiter showed a high decrease in the D retention after a 15 hrs anneal. The decrease may be due to the in-vessel position of the sample: the edges of the limiters are recessed and do not have direct contact with the plasma. Fuel retention to these regions may be low-energy implantation and co-deposition making the majority of D retention in traps with low activation energies. Investigations are under way to study the parameters effecting the fuel retention in different regions of the main chamber limiters. Finally, even though the earlier JET-ILW post-mortem results in Ref. [5] showed an order of magnitude less *global* retention in the main chamber compared to the divertor, the relatively larger main chamber Be surface area in ITER and its low baking temperature 240°C with low fuel release may play an important role in assessing the accumulated T. However, this is expected to be compensated by the saturation of hydrogen in Be, according to which

at local hydrogen concentrations of 30 at.% further hydrogen will be re-emitted from Be (Ref. [18] and references therein).

References

[1] Matthews, G. F., et al., Phys. Scripta T128, 137 (2007).

[2] Widdowson, A., et al., Phys. Scripta T159, 014010 (2014).

[3] Taylor, C. A. and Cortes, P., Fusion Sci. Technol. 64, 111 (2013).

[4] Pitts, P., et al., J. Nucl. Mat. 415, S957 (2011).

[5] Heinola. K., et al., Phys. Scripta T167, 014075 (2016).

[6] Brezinsek, S., et al., Nucl. Fusion 55, 063021 (2015).

[7] Schmid, K., Nucl. Fusion 48, 105004 (2008).

[8] Baldwin, M. J., et al., Nucl. Fusion 54, 083032 (2014).

[9] Sugiyama, K., et al., J. Nucl. Mat. 438, S1113 (2013).

[10] Lahtinen, A., et al., Nuclear Materials and Energy, submitted (2016)

[11] Coad, P., et al., Phys. Scripta T159, 014012 (2014)

[12] Likonen, J., et al., Phys. Scr. T167, 014074 (2016).

[13] Heinola, K., et al. Phys. Scripta T159, 014013 (2014)

[14] Baron-Wiechec, A., et al., J. Nucl. Mat. 463, 157 (2015)

[15] Widdowson, A., et al., Phys. Scripta T167, 014057 (2016)

[16] Baldwin, M., et al., Nucl . Fusion 54, 073005 (2014).

[17] De Temmerman, G., et al., Nuclear Materials and Energy, submitted (2016)

[18] Roth, J., et al., J. Nucl. Mat. 390, 1 (2009)

This work has been carried out in the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission and of the ITER Organization.