Deuterium retention and depth profiling of co-deposits on bulk beryllium and tungsten tiles from JET-ILW

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1. Introduction

Fuel retention and material migration studies belong to top missions of the JET tokamak with the ITER-like wall (JET-ILW) consisting of Beryllium (Be) limiters in the main chamber and tungsten (W coatings and bulk metal) in the divertor [1]. Until now three ILW experimental campaigns were completed in 2011-2016. After each campaign a number of plasma-facing components (PFC) and wall probes was retrieved for the ex-situ analyses [2-7].

This work is focused on the detailed determination of: (i) hydrogen isotopes (H, D) and co-deposited species (Be, C, O, Ni, W) on plasma-facing surfaces (PFS) of the limiters and the bulk W lamellae (Tile 5 in the divertor), and on surfaces in the gaps of Be castellation and, between the lamellae; (ii) retention of seeded gases, such as ^{3}He, ^{4}He, N and Ar. The study was motivated by the need to obtain the best-possible predictions before the planned full D-T campaign in JET [8].

2. Experimental

The study was carried out with samples from bulk metal tiles exposed to plasma in individual (ILW-1, ILW-2, ILW-3) and in all three (ILW1-3) campaigns. The content of H, D and impurity species, and their depth distributions in PFC were determined with accelerator-based ion beam analysis (IBA): ^{3}He-based nuclear reaction analysis (NRA) using a micro-beam, and time-of-flight heavy ion elastic recoil detection analysis (ToF HIERDA) using bromine (^{80}Br^{7+} 32 MeV) and iodine (^{127}I^{n+} n=8 or 10, 36 or 44 MeV) beams. Samples were cut from the tiles at the Institute of Atomic Physics (Romania) under strict temperature control, <60 ºC, to avoid the release of fuel species. Photos in Fig. 1(a-c) show a segmented Be tile of the castellated inner wall guard limiter (IWGL) tile, a part cut off from that tile and, a side of single a castellation block with a co-deposit on the surface located in the gap. A scheme of the divertor module of Tile 5 in Fig. 1(d) shows a complex lamellae structure. Heat loading to the surface is not uniform: lamellae 1-3 are shadowed by the adjacent module, while 22-24 are the most exposed ones.

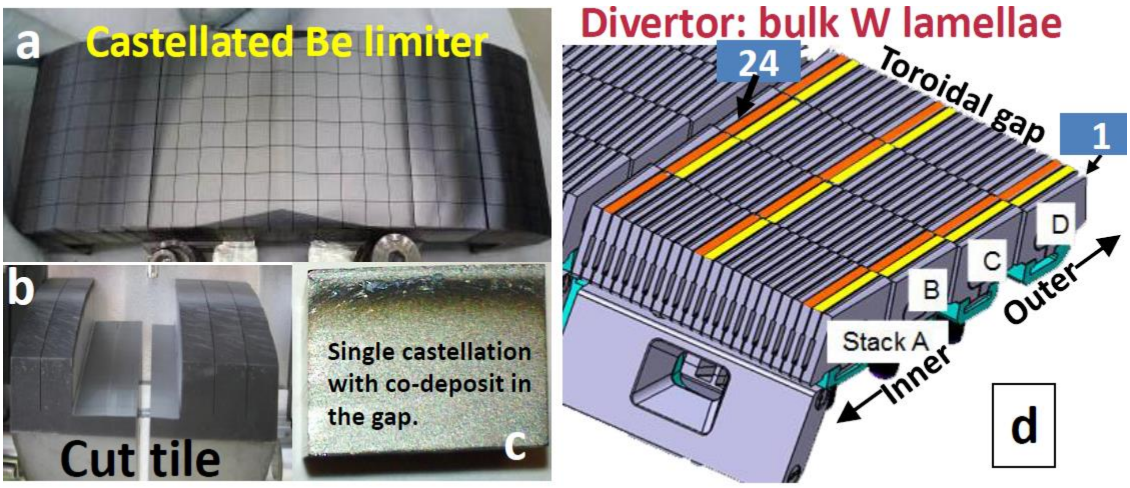

Figure 1. (a) Castellated Be limiter; (b) a segment cut from the limiter; (c) single castellation; (d) bulk W lamellae structure of the divertor module.

3. Results and discussion

3.1. Beryllium limiters

ToF HIERDA depth profiles shown in Fig. 2(a) and (b) were recorded on the IWGL exposed during ILW-1 and ILW-2, respectively. Both campaigns comprised nearly the same plasma operation time of ~19 h, while one of the major differences was the fuelling. The first one was performed using D_2, while the last 300 shots in ILW-2 were fuelled with H_2.

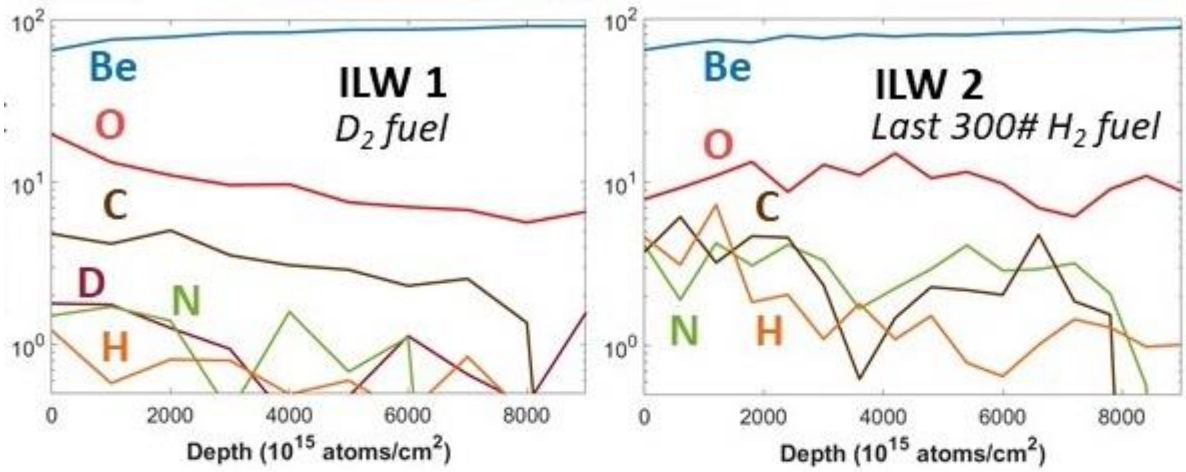

Figure 2. Quantitative depth profiles of hydrogen isotopes and other species in the surface layer of IWG limiters exposed to ILW-1 and ILW-2. Ni not included for clarity.

Details of the surface composition are given in Table 1. The main impurities are oxygen (O), carbon (C), nitrogen (N) and Inconel components (Ni). On the sample retrieved after ILW-2 no D is detected thus indicating the efficient exchange of D by H in the surface layer during the 300 pulses at the end of campaign. The depth profiles and Be:O concentration ratio around 8 proves that oxygen is predominantly in the very surface layer and no bulk oxidation occurred. The increase of N content in co-deposits a by factor of 3 perfectly reflects the fact of using 3 time more N_2 for edge cooling in ILW-2 than in ILW-1.

Table 1: Surface composition on IWGL samples exposed to ILW-1 and ILW-2. The results are the depositions on the right far end of the tile: right hand wing (RH wing).

			Atomic concentrations ($\times10^{15}$ atoms/cm^2)						
Tile	Position	Campaign	Be	O	D	H	C	N	Ni
IWGL	RH wing	ILW 1	7476	910	90	61	298	84	172
IWGL	RH wing	ILW 2	7104	933	0	185	249	261	157

Molten Be surfaces of the upper dump plate (UPD) were investigated. The aim was to verify a hypothesis whether the D retention is increased in the melt zones. Such suggestion was arising from the studies of the MkI-Be divertor (JET, 1995) [9]. Recent results clearly show that the molten Be surfaces are very pure (on average ~99 atomic %). They contain only ~0.9 % O and 0.1 % H isotopes. The molten Be surfaces are even cleaner than the unexposed reference samples with about 9 % (on average) of surface impurities.

Deposition on surfaces located in the grooves of castellations was studied on one UDP sample exposed to ILW 1-3 and two outer poloidal limiter (OPL) samples exposed to ILW-3. The main aim was to determine the C content. Therefore, ToF HIERDA was used because of its unique ability to quantify carbon on Be surfaces. The C content into the gap is constant: 0.5×10^{17} cm^{-2} on UDP and 1×10^{17} cm^{-2} on OPL. No D was found on OPL close to the PFS.

3.2 Solid tungsten lamellae: Tile 5

The shaping of Tile 5 (see Section 2) implies that the deposition is on lamellae 1-3 shadowed by the adjacent module, while the other lamellae are prone to erosion, especially those receiving the greatest heat load (12-24) if the strike point is on Tile 5. HI-ERDA depth profiles for lamellae C3 and C2 (elements of Stack C) exposed respectively to ILW-2 and ILW1-3 are compared in Figure 3. C and O contents in both cases are similar (around 10%), but the Be amount is greater after ILW-2. It can be attributed to a greater erosion of UDP at the end of that campaign when dedicated experiments on run-away electron generation were carried out [10]. A remarkable difference is the content of H isotopes. The surface exposed to ILW-2 contains 25×10^{15} D cm^{-2} and 42×10^{15} H cm^{-2}, whereas the one exposed to ILW 1-3 contains 39×10^{15} D cm^{-2} and 13×10^{15} H cm^{-2}. Again, as in the case of Be limiters (Table 1), the difference is related to the ILW-2 finish in H_2, while D_2 was used in the final stages of ILW-3.

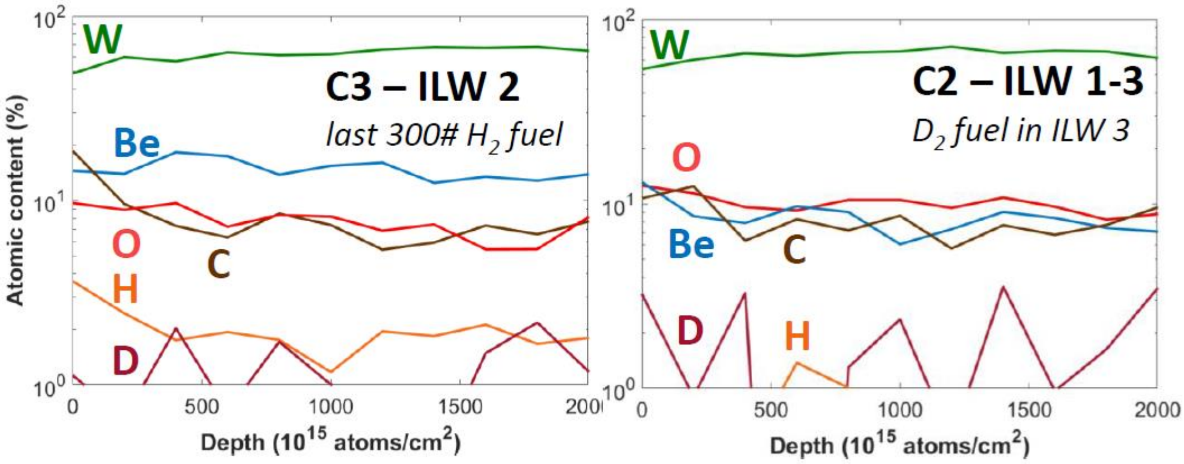

Figure 3: Depth profiles on sample in deposition zone of stack C, retrieved after ILW-2 and ILW 1-3. Some impurity species are not included for clarity: ILW 2: N, ILW 1-3: N, Al, Ni.

For the first-time ever side surfaces of the lamellae were analysed in very detail using the micro-beam NRA to determine D, Be and C distribution and content. Results in Fig. 4 are for surfaces on lamella C13 exposed to ILW-2: (i) the side located in the 1.5 mm wide toroidal gap between Stacks C and D; (ii) the side facing lamella 12 in the 0.4 mm wide gap between the lamellae. The X-axis is the distance from PFS, i.e. 0 denotes the PFS position. The deposition of impurities (Be and C) increases with the gap width, and it is consistent with earlier data for the castellated limiters [5].

For the given surfaces the deposition profiles and amounts of Be and C are very similar. The amount of all co-deposited species (including D) is very small; in neither case the sum of Be+C exceeds 2×10^{19} cm^{-2}, thus corresponding to the maximum total layer thickness of 2 µm. The maximal D content is similar in both cases: 4×10^{17} cm^{-2} for the toroidal and 6×10^{17} cm^{-2} for the poloidal gap. The lightly higher D amount in the poloidal narrow gap than in the toroidal one is most probably related to the fact that the side of C13 was shadowed by the shaped PFS edge of C12.

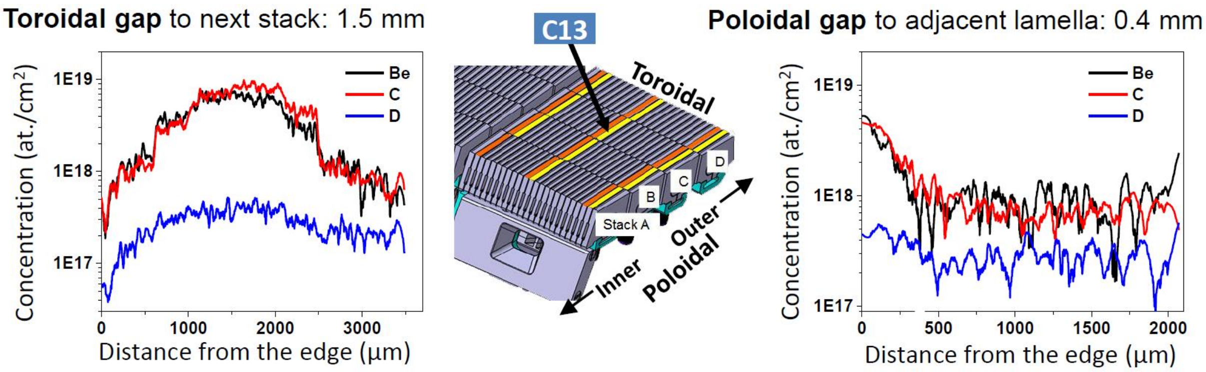

Figure 4. Deuterium, beryllium and carbon contents and distribution on side surfaces of the bulk W Tile 5: between the stacks and between the adjacent lamella.

4. Concluding remarks

The results obtained have shown low D contents both on PFS and in the gaps of Be castellation and between the W tiles. The H – D exchange in the surface resulting from the change of fuelling has been clearly demonstrated. The presence of co-deposited nitrogen has been detected on all studied components. The N content in co-deposits increases with the increased amount of gas puffed for edge cooling. Also the traces of ^{3}He, ^{4}He (both used for auxiliary heating) and Ar (used for edge cooling) on the Be limiters and W lamellae has been measured.

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