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Surface Analysis of Tiles and Samples Exposed to the First JET Campaigns with the ITER-Like Wall

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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT

This paper reports on the first post-mortem analyses of tiles removed from JET after the first campaigns with the ITER-like Wall (ILW) [1]. Tiles from the divertor have been analysed by the Ion Beam Analysis (IBA) techniques Rutherford Back-scattering (RBS) and Nuclear Reaction Analysis (NRA) and by SIMS to determine the amount of beryllium deposition and deuterium retention in the tiles exposed to the scrape-off layer. Films 10-20 microns thick were present at the top of Tile 1, but only very thin films (<1 micron) were found in the shadowed areas and on other divertor tiles.

1. INTRODUCTION

This paper reports on the first post-mortem analyses of tiles removed from JET after the first ILW operations June-July 2012. Previous JET post-mortem analyses have shown that during plasma operations material is eroded from the main chamber and deposited at the inner divertor, so tiles from the inner divertor have been analysed by the Ion Beam Analysis (IBA) and SIMS to determine the amount and mix of beryllium/carbon deposition and deuterium retention in the tiles exposed to the scrape-off layer. Previously, most of the carbon was re-sputtered and transported towards the (shadowed) inner divertor corner where it trapped large amounts of fuelling gas [2-4]. If similar migration occurs with a metal wall, this would pose a problem for ITER, so particular attention has been paid to deposition found in this area.

These are the first analyses of the JET tiles following the ILW campaign out of a comprehensive analysis strategy planned by the JET-EFDA Task Force Fusion Technology (TFFT).

2. EXPERIMENTAL AND RESULTS

A cross-section of the JET divertor showing the tile numbers and showing the plasma configuration that was used predominantly during ILW operations is shown in Figure 1. The outer strike point was located on the outer part of the Load Bearing Tile (LBT) and the inner strike point was near the top of Tile 3, so that the inner Scrape-off Layer (SOL) along which most impurities in JET migrate intersects Tile 1 and the High Field Gap Closure (HFGC) tile - the so-called High Delta or HD-configuration. This differs from previous campaigns with the carbon wall when there were also many more pulses with the inner strike point low on tile 3 or on tile 4 [4].

Divertor tiles 1, 3 and 6 have been analysed by Ion beam Analysis (IBA) techniques such as Rutherford Back-Scattering (RBS), Particle Induced X-ray Emission (PIXE) and Nuclear Reaction Analysis (NRA) with ion beam energies of 2.3MeV. In NRA the reactions $^{9}Be(^{3}He,p)^{11}B$, $^{12}C(^{3}He,p)^{14}N$ and $^{2}H(^{3}He,p)^{4}He$ are used for analysis of Be, C and ^{2}H (or D, deuterium) respectively. No carbon was detected by IBA on any of the tiles, but unfortunately at 2.3 MeV the NRA cross-section for carbon is very low, and the detection limit by RBS in the presence of a W background is also low, so more sensitive measurements will be made elsewhere. These techniques analyse to a depth of a few microns at the surface; to assess the profile of the elements within the surface and to monitor the composition to greater depths, SIMS has been used to study tiles 1, 3 and 4.

Following the ILW operations 2010-2 all the divertor tiles appear very similar to the freshly W-coated divertor tiles prior to operation in all regions that were, or could be, exposed to plasma. Parts of tiles 4 and 6 that are permanently shadowed from direct plasma exposure by tile 3 or tile 7 and other surfaces within shadowed regions were covered with dark, coloured, films.

NRA shows that there is Be present everywhere at the surface of tiles 4 and 6. There is more Be present on the sloping parts of each tile, peaking at the region that is the limit of plasma access into the corner. However, the levels are low reaching on tile 4 ~3×10^{18} Be atoms cm^{-2} at maximum, and being about 6×10^{17} Be atoms cm^{-2} in the area shadowed by tile 3 (equivalent to ~50nm), with only slightly higher levels at corresponding points on tile 6. Some D was detected in the shadowed areas, but not on the sloping parts of the tiles. Figure 2 shows SIMS spectra from the shadowed area and the sloping part of tile 4. In the shadowed region there is clearly a discrete Be film on top of the W coating containing D, whereas on the plasma-exposed sloping surface there is a mix of Be and W for some distance into the tile, with the ratio of W to Be gradually increasing, and negligible D. This is confirmed by the 3He RBS spectra in Fig. 2.

NRA detected large amounts of Be on the horizontal part on top of tile 1 (the so-called "apron") and on the adjacent upper section of the front face of the tile. RBS and SIMS spectra from similar points on the top and the lower sections of the front face of tile 1 are shown in Figure 3. The 1H RBS spectrum from the upper section shows a small surface peak of W, then a gradual build-up in concentration deeper into the surface. SIMS also shows a steady build-up in W signal into the surface, with a slight accompanying reduction in Be signal, which continues for many microns. RBS and SIMS from the tile apron show similar behaviour, though over about half the depth. Tile 1 is, like tile 4, a standard marker tile with ~4 microns W and ~3 microns Mo layers on top of the thick W coating. There is a very sharp rise in the SIMS Mo signal after ~8000 seconds sputtering time (~4 microns) (not shown), just as expected for the marker layer. However, the trends in W and Be signals do not show any discontinuities. It is difficult to assess the total amount of Be from the spectra, but tile profiling indicates an increase in tile dimension of 10-20 microns [5].

RBS shows that there are no significant deposits of Be on the lower front face of tile 1. A typical spectrum from this region is included in Figure 3 and is similar to the reference spectrum taken before exposure in JET, showing the outer W layer is ~4 microns thick. SIMS also shows a clean surface, but the spectra show the Mo interlayer appearing after progressively less sputtering time the lower the analysis is made on the front face of tile 1. The SIMS spectrum in Fig. 3 (bottom panel) taken at the same point as the RBS shows the Mo appearing after ~4000s, and in a measurement made about 40mm from the bottom of the tile the Mo appeared after ~2000s suggesting just a quarter of the top W layer remains. This suggests a thinning of the outer W layer the closer one is to the bottom of the tile (and to the ISP). This result is in direct contrast to the RBS data. It would be somewhat surprising if 3 microns of W had been eroded at the inner divertor leg since measurements at the outer strike points (where ion energies are greater) in previous campaigns have shown only about 1 micron was eroded from a W layer during a longer campaign [3]. The beam conditions for each of the SIMS profiles were identical, but surface conditions and composition may affect the sputtering rate: the crater depths will be measured to check on the data.

The tile 3 examined by SIMS was a "special" marker tile with just a 3 micron Mo coating on the standard W coating (i.e. no top layer of additional W). This was designed to investigate whether there was transfer of W from tile to tile at the inner divertor. The SIMS analyses of tile 3 revealed a Mo layer right from the surface, showing that there is no discrete film on the surface. There was indeed some W at the surface and there was quite a high Be concentration, which decreased steadily into the surface along with the W signal, until the W substrate started to appear.

Among the items from the shadowed areas in the corners of the divertor that have been analysed by IBA were the inner and outer louvre clips. There are a set of baffle plates that protect magnetic field coils from radiation from the plasma. Heavy deposition has been observed visually on the louvres in the past [6], and the clips are installed to allow the amount of deposition to be assessed periodically. ^{1}H RBS spectra from the outer louvre are shown in Figure 4. The clips are covered with a dark coloured layer like other surfaces in the shadowed regions. The RBS spectra show sharp peaks from Be and O on the stainless steel substrate, indicating a thin but complete film over the surfaces. The film on the outer louvre is mostly Be, but on the inner louvre there is more C than Be, and the film is a little thicker than on the outer one.

DISCUSSION

In previous JET campaigns with the carbon wall, the main plasma impurity was carbon, with ~10% Be originating from the regular Be evaporations in the main chamber, and ~1% made up of Ni, Fe, Cr and other metals from the inconel vessel walls and tile fixings. This was the basic composition of deposited films in the main chamber, and of the material travelling along the SOL towards the inner divertor to deposit principally on tiles 1 and 3. At tiles 1 and 3 some of the deposits were re-eroded, particularly the carbon by chemical sputtering by deuterium, with migration to tile 4 (predominantly carbon) and thence to the shadowed regions at the inner divertor corner where co-deposition with deuterium occurred. Tiles 1 and 3 were left with films rich in Be and the other metals (Be/C typically ~1). At the outer divertor there was also deposition on tile 6 and in the shadowed regions, though with a greater Be content than on tile 4: there was normally no residual deposition on tiles 7 and 8. One of the objectives of the ILW is to see whether the migration of impurities to the shadowed areas, and the trapping of fuelling gas (which is a particular concern for ITER), is greatly reduced having removed (as far as it is possible) carbon from the plasma-facing surfaces. Encouraging signs during the 2012 operations with the ILW were that the Z_{eff} for the plasma was low and there was negligible carbon in the plasma [7] Furthermore gas retention was an order of magnitude lower for the ILW campaign than for similar pulses with the carbon wall [7].

The overall amounts of Be in the divertor are more than an order of magnitude less than the amounts of carbon found after operational periods with the carbon wall; deposition other than at the top of tile 1 is negligible in comparison [2-4]. The difference between operations with the ILW and with the carbon wall is probably due mostly to chemistry in two ways. Firstly greatly reduced chemical sputtering in the main chamber reduces the amount of Be entering the plasma, then entering the SOL and being transported to the top of the inner divertor. Then secondly, the lack of chemical sputtering means there is negligible re-erosion of the (reduced) deposits at the inner wall, transport to the bottom of the divertor and into the shadowed regions.

It is important to note that in plasma-accessible regions there are no discrete surface Be films, but IBA and SIMS both show a mixture of Be and W, which extends into the surface with a steadily decreasing ratio of Be to W. The analysis areas for SIMS and RBS are 0.4×0.4mm and 1mm diameter, respectively. Since the W-coated CFC surfaces are very rough, there may be localised deposits of Be interspersed with areas of clean W surface. Thin W films on carbon tiles were exposed in 2005-7 and 2007-9, and the W tended to be sputtered from prominent areas by the plasma and re-deposited in their lee. In the area on tile 4 shadowed from the plasma a discrete film was able to cover the rough surface as shown in Fig.2. Alternatively there may a reaction between Be and W, with inter-diffusion and possibly alloying taking place. This will be the subject of further analysis by TFFT, using techniques such as SEM, Nuclear Microprobe, XPS and XRD.

CONCLUSIONS

The total amount of Be deposition in the divertor following the first JET campaign with the ILW in 2012 was more than an order of magnitude less than C deposited in campaigns using the carbon wall. The Be deposition in the divertor was largely restricted to the top of tile 1, the region that is exposed to the inner SOL, with negligible migration to the corners of the divertor.

Deuterium was only observed in shadowed areas of the divertor, in the thin (<1 micron) deposited layers. Carbon was also present there in small quantities, but it should be noted that these areas are close to the carbon support structure for the divertor tiles.

Be and W are both present in SIMS and RBS profiles into the surface in plasma-wetted areas. It is important for further analysis to show if this is due to the rough surface or if there is any interaction between the Be and W substrate.

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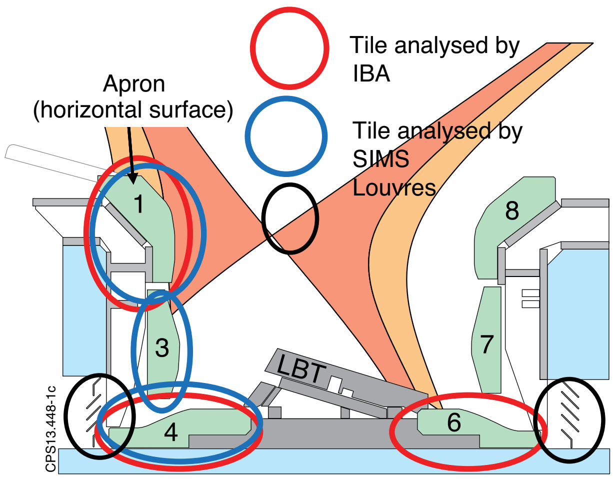

Figure 1: Areas of the JET divertor analysed

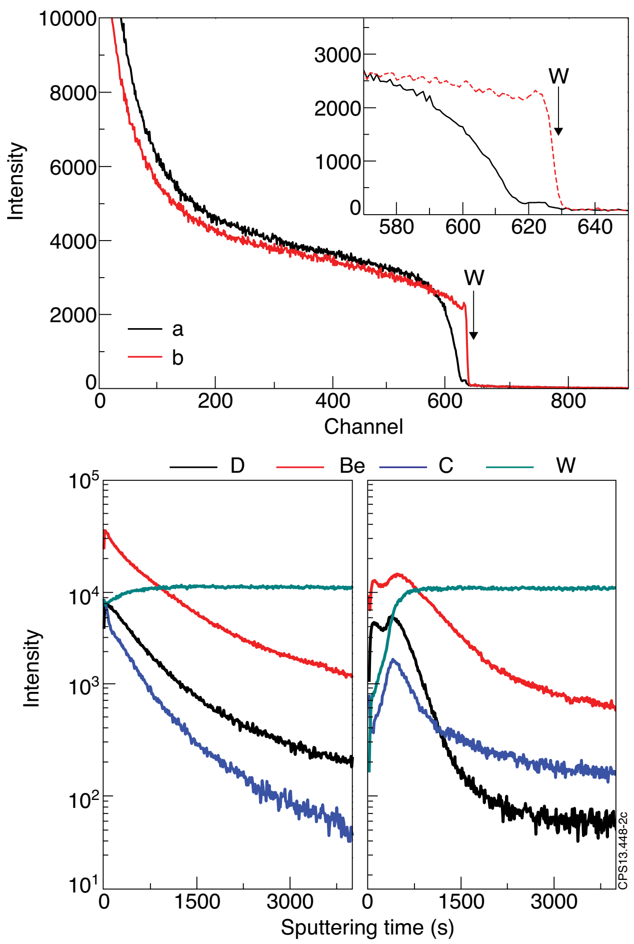

Figure 2: Top panel: ^{3}He RBS spectra from the plasma-exposed slope (red) and shadowed part (black) of tile 4. Lower part: SIMS from the plasma-exposed slope (left) and shadowed part (right) of the tile

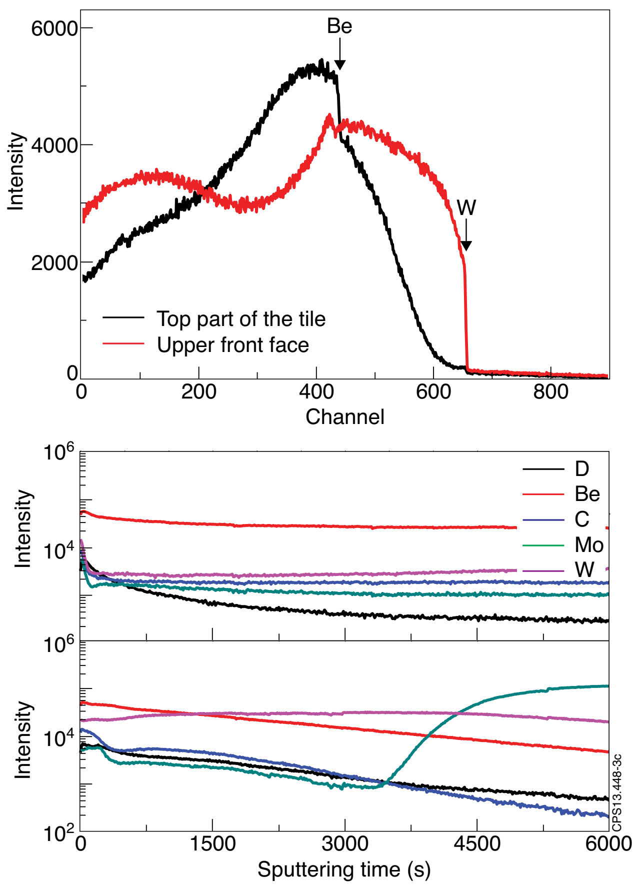

Figure 3: Top panel: 1H RBS spectra from the top part (black) and from the lower part (red) of the front face of tile 1.Below: SIMS from the top part (middle panel) and from the lower part (bottom panel) of the front face of the tile.

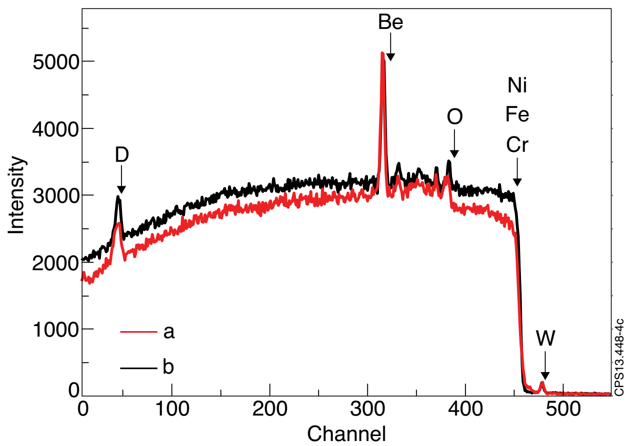

Figure 4: 1H RBS spectra from the outer louver clip (two analysis points).