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ABSTRACT

A complete global balance for carbon in JET requires knowledge of the net erosion in the main chamber, net deposition in the divertor and the amount of dust and flakes collecting in the divertor region. This paper describes a number of measurements on aspects of this global picture. Profiler measurements and cross section microscopy on tiles that were removed in the 2009 JET intervention are used to evaluate the net erosion in the main chamber and net deposition in the divertor. In addition the mass of dust and flakes collected from the JET divertor during the same intervention is also reported and included as part of the balance. Spectroscopic measurements of carbon erosion from the main chamber are presented and compared with the erosion measurements for the main chamber.

1. INTRODUCTION

2010 marked the end of an era for the JET vessel and subsequent post mortem analysis of tiles. Since the installation of the divertor in 1994, JET has operated as an "all carbon machine" in that all surfaces with direct interaction with the confined plasma were made from carbon, either as graphite or latterly Carbon Fibre Composite (CFC). Just over half of the vessel was covered in carbon tiles and the remaining uncovered area was the inconel vacuum vessel. In 2010 JET was converted to an "all metal" device such that all surfaces interacting with the plasma are now beryllium and tungsten. This new configuration is known as the ITER-Like Wall (ILW) since it is designed to demonstrate the differences in transport and hydrogen isotope retention between the two scenarios and to help predict the behaviours of ITER in these respects. In order to complete the transition from "all carbon" to "all metal" all CFC tiles were removed and replaced with Be, Be-coated inconel or W coated CFC tiles in the main chamber and W coated CFC with one row of solid W tiles in the divertor. As with other JET interventions a set of tiles removed from the vessel have been made available for analysis. The complete refurbishment also provided a unique opportunity to collect dust and flakes found in the divertor as the divertor carriers were removed from the vessel.

In this paper the mass of carbon eroded in the main chamber is compared with the mass of carbon found in the form of deposits and dust/flakes in the divertor. In addition an estimate of the carbon source is determined from spectroscopy of the CIII line in the main chamber throughout the last operating period (2007−2009). The results give an insight into the scale of carbon migrating around the vessel during a JET operating period typically lasting > 100,000 seconds.

2. EXPERIMENTAL

The erosion and deposition of the Inner Wall Guard Limiters (IWGL), Outer Poloidal Limiters (OPL) and dump plate tiles from the main chamber and tiles constituting a divertor cross section has been measured by profiling of a set of tiles before and after exposure in the vessel. Figure 1 shows the poloidal location of the tiles analysed for this paper. The evaluation of erosion in previous campaigns could only be determined via the thinning of a marker coating, typically 10μm thick deposited on the surface of a tile, however if the marker coating is completely eroded then it is not possible to calculate gross erosion. In this paper tile profiling is used to evaluate erosion on a scale $>10\mu$m.

The profiler consists of a X-Y table and a Z probe. The tile to be profiled is mounted onto the X-Y table which is moved using two stepper motors to a series of specified (X,Y) co-ordinates forming a grid. At each grid point the Z probe is extended to touch the surface of the tile thus recording a relative value for the height.

The comparison of the grid measurements on a tile before and after installation in the JET vessel gives the change in the surface profile, i.e. the erosion and deposition on the tile surface. The profiler itself provides repeatable measurements to within a few microns, however errors can arise if the tile is not repositioned on the X-Y table accurately. On horizontal surfaces this error is minimal, however where the tile surface slopes the errors increase. From simple trigonometry the errors in the height is 0.18μm per micron misalignment on a surface at 10° to the horizontal. Using the profiler results the volume of the deposited and eroded material is determined. To convert volume to mass a density of 1g/cm^3 has been used for the co-deposit [1] [2] and a density of 1.65g/cm^3 has been used for erosion from the CFC tiles - this is an average value for batches of Dunlop CFC material. The mass of eroded/deposited carbon is scaled with the number of similar tiles found in the vessel to give values for the whole vessel.

Information on deposition has also been obtained from the optical microscopy of cross sections of cores taken from tiles. This has enabled the deposition results from the tiles profiled to be bench-marked against the core samples thus providing a calibration and giving confidence in the erosion assessment provided from the profiler results. The comparison of cross section optical microscopy with profiler results is on going and has so far only been completed for a sub-set of profiler results presented in this paper.

Ion beam analysis of tiles with marker coatings can also provide information on erosion where the erosion is less than the thickness of the marker coating, typically 10μm. This technique has been used for the Inner Wall Cladding (IWC) tiles discussed elsewhere [3].

Loose dust and flakes were collected using a vacuum cleaner and cyclone adapted for use by remote handling. A cyclone pot was installed at the bottom of the cyclone to capture the dust/flake sample during vacuuming. Six different vacuum samples from different poloidal regions of interest in the divertor were collected into cyclone pots. The regions are indicated in Figure 2 in different colours. In order of collection the regions are; the outer vertical divertor tiles and above (tiles B, C, 7, 8), the inner divertor tiles (High Field Gap Closure tile, tile 1, 3), the inner and outer divertor carrier ribs, the outer floor tiles (Tile 6), inner floor tiles (Tile 4), the inner and outer louvre regions. The cyclone pots were weighed before and after collection to determine the mass of dust/flakes collected. It was necessary to compensate for masses obtained in the cyclone pots in several ways, for example: (i) some dust may be lodged in the hose or cyclone or may have bypassed the cyclone (due to the mass of the particle) and be captured in the dust bag; (ii) 11/12ths of the divertor area was vacuumed in 5 out of 6 samples, only the inner and outer louvre region was vacuumed in its entirety; (iii) some surfaces have been vacuumed in previous interventions, i.e. there is a range of histories for different surfaces.

In order to compensate for (i) the tritium off-gas rates for each of the six dust samples collected

into the cyclone pots was measured. From this the specific off-gas rate (Bq/day/g) for each of the six dust/flakes sample was determined. Using the specific off-gas rate for each dust/flake sample it was possible to determine the mass of material trapped in the hose, cyclone and dust bag from off-gas measurements, thus providing an additional contribution to the overall samples. A typical compensation due to trapped dust/flakes in the vacuum hose and cyclone was <1% of the total mass collected in that sample. However the mass of dust/flakes in the vacuum bag was considerably higher, ranging from <10% to >30% of the dust collected in the corresponding sample.

During the vacuuming of the tile surfaces twenty two of the twenty four JET divertor modules (i.e. 330° of the divertor) were vacuumed because the remaining two modules (one from octant 1 and the one from octant 5) were reserved for post mortem analysis and thus the tile surfaces were preserved. The surface area was scaled accordingly to take account of this. The sample from the divertor louvres was taken from 360°.

Vacuuming of the divertor tile surfaces (excluding those identified for post mortem analysis as discussed above) takes place during each JET intervention as part of the safety case for the shut-down procedures. The extent of the vacuuming is dependent on the level of refurbishment of the divertor. In brief the majority of the divertor tile surfaces were vacuumed in the 2004 and 2007 interventions, however the louvre area was only vacuumed in the 2004 intervention. To compensate for the differences in vacuuming history the dust samples were scaled with the total plasma seconds during different operating periods to give a scaled mass for the most recent 2007 - 2009 operation.

Evaluation of the main chamber carbon source was also determined from spectroscopy using the CIII line at 465 nm with a horizontal line of sight onto the inner wall, in a region next to an inner wall guard limiter, sampling the inner wall. The total photon signal from the CIII line for the 2007−2009 operating period was evaluated. The spectroscopy results have also been scaled with the time for limiter and for the X-point (divertor) phases to take account of the different erosion/deposition regimes during a plasma pulse. To provide the number of C atoms eroded from the main chamber the photon signal is scaled with the interaction area of the plasma, this has been estimated for the limiter phase as the wetted area of the plasma on the IWGLs and during the X-point phase the total plasma surface area. Finally an effective photon efficiency S/XB = 3.08 is applied. The effective photon efficiency is determined from calculation of main chamber fluxes given in [4].

3. RESULTS
Erosion and deposition of IWGL tiles from the horizontal mid-plane and from the lower end of the limiter have been evaluated by profiling and cross section microscopy. The results indicate that a total of 1.75g of carbon has been eroded from the mid-plane limiter tile pair and 0.40g has been deposited at the edge of the tile pair in the region beyond the last closed flux surface as shown in [5], resulting in net erosion of 1.35g. For a tile pair lower down the inner limiter a net deposition of 0.30g is observed; on the left tile (i.e. with plasma current) this is net deposition of 0.25g with no erosion and on the right tile there is net deposition of 0.05g made up of 0.20g of deposit and 0.15g of erosion. Deposit is also observed at the bottom of the inner limiter, by ion beam analysis,

with a similar split between the left and right tiles, whereas at the top of the limiter the opposite is observed with deposition on the right tiles probably exceeding the erosion on the left tiles [5]. Taking these results, an estimate for the total erosion, total deposition and net erosion at the IWGL in the main chamber are estimated 140g and summarised in Table 1. This assumes that the bottom three rows and the top three rows of the nineteen row of IWGL tiles are subject to net deposition and the remaining sixteen rows are subject to net erosion.

For an OPL tile pair also situated at the mid-plane of the main chamber there is a total deposition of 0.05g and total erosion of 0.19g giving a net erosion of 0.14g. The net carbon source due to erosion from the outer limiter, assuming the result for this one tile and taking into account forty five OPL limiter pairs on each of twelve limiter beams is 72g, Table 1. However the profiler results for this tile are subject to some errors due to the shape of the tile. The long thin tiles (34 mm $\times$ 26mm) bound together in pairs are difficult to mount; there is tilt from the vertical and the sloping surface of the tiles increases errors in the profiling results. In order to assess this tile fully cross section microscopy of the deposits on the ends of the tiles is required. Based on secondary ion mass spectrometry of tiles removed in 2007 it is known that a 1μm W/10μm C coating was completely removed in the centre of the tile and deposition of the order 2 Dm was observed at the ends. This results in a total deposition of <0.01g and total erosion of 0.24 g giving a net erosion of 0.23g of carbon from the equivalent OPL pair which equates to erosion for the whole vessel from the OPLs of 124g, a factor of two higher than determined by profiling.

Three dump plate tiles in the vessel from 2005−2009 were profiled. From the profiler results no strong erosion or deposition was observed from these tiles. On one of these tiles installed in 2005 there was a 1μm W/10μm C marker coating stripe which has been almost completely eroded. It is still possible to see where the marker stripe was located but the metallic layer is not visible to the naked eye. This confirms that the level of erosion is of the order of 10μm in the dump plate region. Assuming this level of erosion and scaling for the exposure period 2007−2009 using plasma time, and the dump plate area ~14m^2, the upper limit for erosion from the dump plate region is 130g.

Erosion for the IWC tiles has also been calculated from the analysis of marker coatings by proton backscattering. The markers were exposed from 2005−2009 and the total C source is estimated at 230g [3]. The fraction of this attributable to the 2007−2009 operating period is 129g for the inner wall.

Based on the tile profiler measurements, cross section microscopy of cores taken from tiles and ion beam analysis, an upper estimate for the main chamber carbon source (erosion) for the 2007−2009 operating period is 436 g, Table 1.

Results for the total erosion, total deposition and net erosion/net deposition taking into account the number of tiles of each type found within the divertor are also shown in Table 1. Profiler results for Tiles 4, 6, 7 and the Load Bearing Tile (LBT) have been evaluated. Data for Tile 7 was for a tile installed in the vessel from 2005 - 2009 and has been scaled according to plasma time for the 2007 - 2009 operating period as for other tiles. Tiles 1, 3 and 8 have yet to be evaluated, however this will not significantly change the result as the deposition on the sloping surface of tiles 4 and 6 dominate the total amount of deposit of carbon in the divertor. This is also supported by results

4

presented in [9]. For this analysis the extent of deposition on Tile 6 can be seen in Figure 3(a) whilst net erosion is observed on Tile 7, Figure 3(b), but not on the scale of the deposition found on tiles 6 and 4. Based on the results available the net deposition onto tiles in the divertor is 533g. Although Tile 1 has not been analysed a thick deposit was observed on the top horizontal surface of Tile 1 at the inner divertor on a tile removed in 2007, this deposit had reached a critical thickness of ~120μm and was spalling readily [6] therefore any carbon reaching this surface during the 2007−2009 operating period is more likely to contribute to the dust/flake sample taken.

The masses of dust and flakes collected from the divertor region also contribute to the amount of carbon found in the divertor. The masses collected are shown in Figure 2. The highest amounts of dust collected were in the regions where significant deposition has taken place; notably at the inner divertor (115g) where heavy deposition has been observed on the top horizontal surface of Tile 1s, Tile 4s and Tile 6s (22g and 51g respectively) where thick deposits form on the sloping regions as shown in Figure 3(a) and also the inner and outer louvres (91g) remote from the plasma. In total the mass of dust/flakes collected after scaling for the areas surveyed and the vacuuming history of the tiles was 300g.

This carbon source is compared with the CIII line spectroscopy from the mid-plane of the main chamber. The total carbon signal for the operating period (2007−2009) was 7.91×10^{18} photons / cm^2 sr for 178449s (49.6 hours). This is split into 44964s (12.5 hours) of limiter phase and 133485s (37.1 hours) of x-point phase. The signal is from a horizontal line of sight in the main chamber onto the inner wall near to an inner wall limiter and may therefore be lower than the signal expected from the inner limiter. The main issue in interpreting the main chamber source is establishing the appropriate area for scaling the raw data. During the limiter phase there is a strong interaction between the limiters and the plasma giving rise to a carbon source which is re-deposited in the main chamber. If the integrated spectroscopy signal during the limiter phase is scaled with the wetted area of the IWGLs, 3.6m^2 determined from erosion zones visible on the tile and scaled to include all the IWGL tiles, then the mass of carbon eroded is calculated as 57g. This value is higher than the 35g total deposition (i.e., locally re-deposited carbon in the limiter phase) determined from the profiler measurements on the IWGL tiles. The evaluation of the wetted area for limiter-plasma interaction is difficult to define and therefore presents some error in the spectroscopy calculation, possibly as much as 50%. Recycling of carbon can also lead to a higher carbon source being determined from spectroscopy signals.

The 28g of locally re-deposited carbon observed on the OPL tiles from profiling results indicates that the interaction area of the plasma with the outer limiters during the limiter phases is less than that of the IWGLs.
It should be noted that although a strong interaction between the limiters and the plasma during the limiter phase is expected the total amount of erosion account for 20−30% of the gross erosion from these areas.

In order to determine the main chamber carbon source during the X-point phase from the spectroscopy signal the whole plasma area of 139m^2 is used, giving ~2000g of eroded carbon. During

the X-point phase this mass of carbon will migrate from the main chamber into the divertor. This mass of carbon is a factor of 2−3 times higher than the net deposition observed in the divertor and the mass of dust/flakes collected, 533g and 300g respectively.

4. DISCUSSION

The carbon balance of JET in the period 2007−2009 can be considered as the balance of net erosion in the main chamber = net deposition in the divertor + dust/flake collected in the divertor + remote carbon. The net erosion of the main chamber tiles has been evaluated from profiling and optical microscopy of tiles giving a value of 436 g, whereas spectroscopy results gives ~2000g during the X-point phase. Deposition and dust/flakes in the divertor give a net deposition value of 833g. Clearly there are some discrepancies arising in this balance. The carbon source calculated from the spectroscopy is likely to overestimated due to recycling of carbon in the main chamber. However the spectroscopic carbon source calculated for this operating period is somewhat higher than calculated for previous operating periods. Analysis from the horizontal line of sight for CIII for the 2005−2007 operating period was calculated as 770g [7]. The total plasma time during 2007−2009 operations was 20% longer than for 2005−2007. Based on this the scaled up value for carbon in the main chamber would be 924g, less than half the value presented here. This would be comparable with the net deposit and dust/flakes in the divertor but still a factor of two higher than the profiler results for the erosion from the main chamber. A factor of two error has previously been quoted in this method of determining main chamber carbon source [8] due to scaling assumptions that the sampling volume is representative of the whole plasma surface area. Further work to check these calculations are on going. If the carbon source estimated from spectroscopy in the main chamber is accurate then the remote carbon (100g−1100g) may be have been directly pumped from the machine as CD4, be in remote areas as flakes under the divertor or possibly held as long chain hydrocarbon on cryo-panels. The evaluation of these potential sources of lost carbon has not been evaluated here. The contribution of remote carbon is unlikely to exceed the other errors contributing to the balance.

As far as the net deposit in the divertor is concerned the value obtained from profiling and the amount of dust collected are lower than for earlier campaigns showing a total of 1700g for 1999−2001, [8] albeit it still a factor of 2 higher than the net erosion measured in the main chamber. It is also slightly lower than that observed in [9] where significant levels of deuterium observed in these same tiles 4 and 6 scale to give a mass of 1370g of carbon deposit for an average D/C ratio of 0.5. The deposition rates in the divertor are also lower, 6×10^{-3} g/s compared with 35×10^{-3} g/s for 1999−2001 [8]. The errors associated with this calculation of net erosion and deposition arise from the scaling up from representative tiles to the whole chamber, the density of the deposits and the CFC bulk used in calculation of the mass of material and the sensitivity of the tile profiler.

The tiles analysed from the main chamber represent < 1% of the total surface area and the tiles analysed in the divertor represent ~1% of the surface area in the divertor. Toroidal symmetry is accepted therefore the individual divertor tiles scale to the whole divertor. It is poloidal variations in the main chamber that could make a significant difference when scaling, particularly in the case of

the limiter tiles. If all nineteen tile pairs making up an inner limiter were assumed to show the same level of erosion as the mid-plane tile pair then the total erosion would increase by 20%. Conversely if the belt of erosion around the mid-plane of the vessel was assumed to be narrower by an additional three rows of limiter tiles then the erosion would decrease by 10%. This does not account fully for the discrepancies between net erosion in the main vessel and net deposition in the divertor.

An additional source of error is the choice of density for the deposited carbon layers. The density of deposited carbon may be lower ($0.8g/cm^3$ [2]) than used in these calculations, $1g/cm^3$ [1]. This would increase the net erosion from the main chamber to 485g (an increase of 10%) and decrease the net deposition in the divertor to 412g (a decrease of >20%), bringing the balance closer. In fact it is likely that the density of re-deposited carbon varies depending on where it is found in the machine and the operating conditions. Clearly the variation in density of the deposited material has an effect on the overall picture of the carbon balance.

These results indicate that the erosion source from main chamber may be underestimated. In order to account for the discrepancy (200–300g) an additional erosion depth of >30μm would need to be eroded across the main chamber (assuming $10m^2$ interaction area) which is within the resolution of the profiler measurements. However an additional 100g of erosion cold arise from erosion of the order of 10μm.

Another factor of interest from this analysis is the conversion factor from deposit to dust/flakes. Based on the results for total deposition in the divertor the conversion rates are up to 36%. The conversion factor is likely to vary depending on the thickness and stability of the deposits formed. For example from the inner vertical divertor tiles, including the heavily deposited horizontal surface on Tile 1, 115g of dust/flakes were collected. The deposit on this surface reaches its critical thickness of 120μm in a typical operating period and does not increase when tiles are left in for more than one operating period [6]. Therefore for the majority of tiles in the tile 1 location a conversion factor of 100% with a calculated mass of 54g of carbon expected to spall from this horizontal surface during the 2007–2009 operating period. Evidence that the growth and spallation of carbon have reached an equilibrium is also found on the inner and outer divertor corner tiles 4 and 6 that have been in JET from 2005–2009, i.e., two operational periods. When the total amount of deposit on these two tiles determined from profiling is scaled by total plasma seconds for the 2007–2009 operating period the amount of deposit attributed to the this period is 20% lower than that determined for tiles that were new in the vessel in 2007. This indicates that the deposits have reached there critical thickness and layers are readily spalling.

In contrast the mass of dust/flakes collected from the vertical outer tiles (Tile 7 and 8) is < 1g, indicative of this region of the divertor being an erosion zone. The dust/flakes collected from Tiles 4 and 6 in the vessel from 2007–2009 indicate a conversion factor of 7% and 19% respectively. The overall conversion rate of 36% is therefore reasonable, as the areas covered by Tile 4 and 6 is larger than for the top of Tile 1. However the mass of dust/flakes collected may also be revised down following analysis by as much as 20%, particularly if foreign objects introduced from shutdown activities are found in the samples. This would decrease the conversion factor.

CONCLUSION

The main chamber net erosion (485 ± 100 g) and divertor net deposition plus dust/flakes (up to 833 g) determined experimentally agree within a factor of two. After considering the errors in scaling discussed in section 4 an agreement within a factor of two is acceptable. Further evaluation of the profiling data by comparison with cross sectional microscopy data is on going and may bring the balance closer together. The main chamber carbon source from spectroscopy is estimated to be as high as 2000 g. This is somewhat larger than in previous calculations and scaling issues need to be reassessed.. In addition evaluation of lost carbon in the form of CD4 pumped from the vessel, dust/flakes in remote areas and long chain hydrocarbons on the cryo-panels need to be considered to complete the global picture. Whilst the carbon balance is not exact the results continue to support the picture of carbon eroded in the main chamber and being transported via the scrape off layer into the divertor. These results provide a benchmark for comparison of erosion and deposition between the "all carbon" and "all metal" scenarios in JET. Beryllium and tungsten main chamber tiles and tungsten divertor tiles from the "all metal" ILW wall will be removed during the 2012 JET intervention and analysis will start in 2013.

ACKNOWLEDGEMENTS

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	Total Deposition (g)	Total Erosion (g)	Net erosion (−) / Net Deposition (+) (g)
Inner Wall Guard Limiter	35	−175	35
Outer Poloidal Limiter	14	−50	14
Dump Plate	−	−130	−
Inner Wall Cladding*	−	−	−
Tile 4	312	0	312
Load Bearing Tile	21	−38	21
Tile 6	272	<−1	272
Tile 7	1	−36	1

*Table 1 Summary of total erosion, total deposition and net erosion/deposition estimated for the whole vessel from profiling of main chamber and divertor tiles. * Data from ion beam analysis [3].*
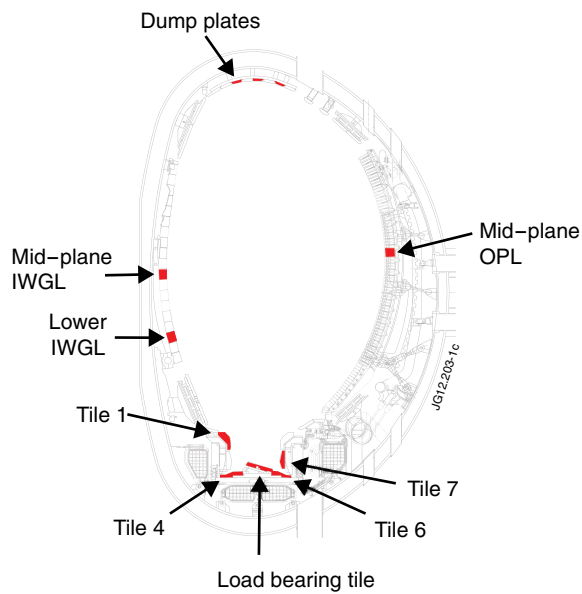

Figure 1: Poloidal cross section of the JET vessel with the MkII-HD divertor. The tiles with results presented in this paper are indicated.
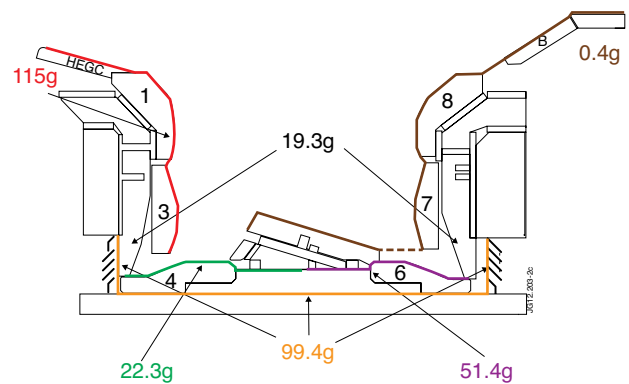

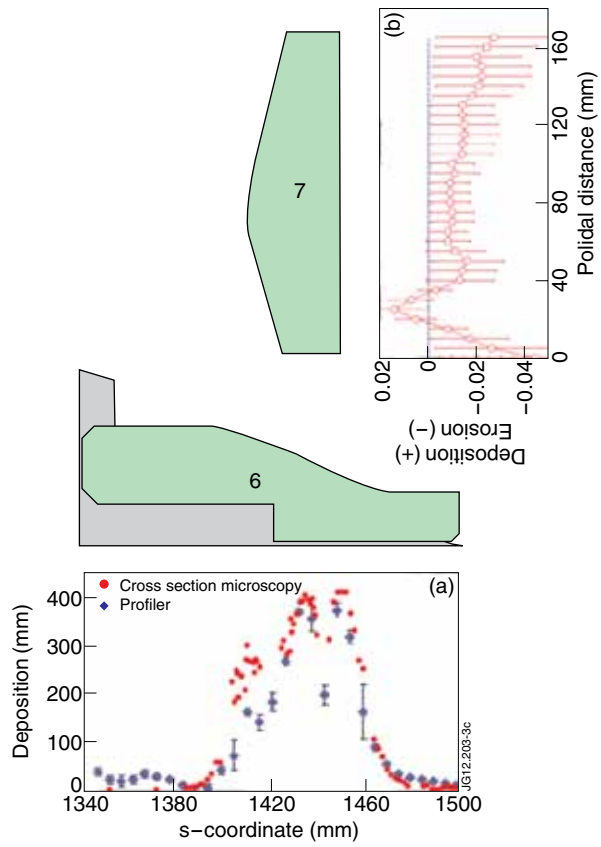*Figure 2: Cross section of Mk-HD divertor section showing the mass of dust/flakes vacuumed from different regions.*

Figure 3: Profiler results for (a) Tile 6 (b) Tile 7.