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“Overview of JET Post-Mortem Results Following the 2007-9 Operational Period, and Comparisons with Previous Campaigns”

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ABSTRACT

During 2010 all the plasma-facing components were removed from JET so that the carbon-based surfaces could be replaced with beryllium or tungsten as part of the ITER-Like Wall project (ILW). This gives unprecedented opportunities for post-mortem analyses of these plasma-facing surfaces; this paper reviews data obtained so far and relates the information to studies of tiles removed during previous JET shutdowns. The general pattern of erosion/deposition at the JET divertor has been maintained, with deposition of impurities in the Scrape-Off Layer (SOL) at the inner divertor, and preferential removal of carbon and transport into the corner. However, the remaining films in the SOL contain very high Be:C ratios at the surface. The first measurements of erosion using a tile profiler have been completed, with up to 200 microns erosion being recorded at points on the inner wall guard limiters.

1. INTRODUCTION

2010 is a watershed for JET and for the post-mortem analysis programmes. Since the installation of the divertor in 1992-4, JET has been an “all-carbon” machine in that all surfaces with direct interaction with the confined plasma have been made of carbon (for the most part from Carbon Fibre-reinforced Carbon composite, CFC). Most of the inner wall was covered with these CFC tiles, i.e. with Inner Wall Guard Limiter (IWGL) and Inner Wall Cladding (IWC) tiles, and there was a band of CFC dump plate tiles at the top of the vessel. However, apart from the antennae for additional heating and 12 narrow poloidal limiters (which prevent ions reaching the outer wall), the outer vessel wall itself was uncovered. Thus just over one-half of the vessel wall was actually covered with tiles, whilst in the remaining areas the inconel vacuum vessel was exposed to some erosion by Charge-eXchange Neutrals (CXN). In common with other “all-carbon” devices it is necessary to add an oxide-former to the internal surfaces to aid, *inter alia*, the control of plasma density, and in JET this is achieved by evaporating a few grams of beryllium (Be) approximately once a week. However, in 2010 JET is being converted to an “all-metal” device in that all surfaces interacting with the bound plasma will be either Be or tungsten (W). The new configuration is known as the ITER-Like Wall (ILW), since it is designed to demonstrate the differences in transport and H-isotope retention between the two scenarios, and to help predict the behaviour of ITER in these respects [1, 2]. This change requires the removal of all the CFC tiles previously mounted in JET to be replaced by Be or Be-coated inconel tiles in the main chamber, and W-coated CFC tiles in the divertor (with one row of solid W tiles), and allows unprecedented access to material to complete a final survey of erosion/deposition/fuel retention in the “all-carbon” JET. The general pattern of deposition and fuel retention in JET is unlikely to have changed significantly in the 2007-9 operational period of JET from that of previous campaigns [3-5], however a number of marker tiles have been installed in 2005 and 2007 with the intention of determining the main ***erosion*** sites responsible for the observed deposition using a tile profiler, developed following early measurements on divertor tiles in the 1999-2001 campaign [4].

In 2007-9 there has been a greater concentration on so-called “high-delta” discharges with the Outer Strike Point (OSP) on the Load-Bearing Tile (LBT), and the inner strike point (ISP) high on tile 3 (as shown in Figure 1) or on tile 1: the number of plasma seconds with the OSP on tile 5 rose from 13800 in 2005-7 to 21140 in 2007-9. Furthermore, a number of slightly revised plasma scenarios have been developed suitable for use with the ILW, which recognise the reduced power handling capability of the Be surfaces. It is important, therefore to provide an up-to-date and more complete assessment of the retention etc for comparison with the data to be obtained with the ILW.

A selection from the ~4000 tiles removed in 2010 have already been analysed by Ion Beam Analysis (IBA), and some also by Secondary Ion Mass Spectrometry (SIMS), whilst tile profiling has just started. Some of the first interesting results are presented in this paper.

2. ANALYSIS OF DIVERTOR TILES REMOVED IN 2010

2.1. INNER DIVERTOR TILES

A cross-section of the JET divertor configuration known as JET MkII-HD used throughout the period 2005-2009 is shown in Figure 1. The s co-ordinates, examples of which are given on the Figure, are the distances around the divertor tile surfaces, from inboard to outboard. For the majority of discharges in 2005-7 and 2007-9, a balanced plasma configuration was employed, with the ISP low on tile 3 or on tile 4 and the OSP similarly low on tile 7 or on tile 6. However for High Delta (HD) discharges, as indicated by field lines for the pulses employed on the last day of the 2007-9 operational period and shown in Figure 1, the ISP was high on tile 3 and the OSP on the LBT (details later). The principle impurities in the plasma (relative to the average electron density) are ~1-10%C, ~0.2-0.3%Be and <0.01%Ni and other metals [3], the remainder of the plasma being deuterium (the fuelling gas). The impurities migrate to and from the surrounding scrape-off layer (SOL) and can be transported together with deuterium along the SOL to deposit at tiles 1 and 3. The deuterium preferentially sputters the C chemically, leaving a film enriched in Be and the metals, and the C migrates to the shadowed corner between tiles 3 and 4 [3-6].

Figure 2 shows the ratio of Be/C in the surface layer and the D content on tiles 1 and 3 derived from Nuclear Reaction Analysis (NRA) data recorded with a ^{3}He ion beam at 2.5 MeV and using the reactions $^{9}\mathrm{Be}(^{3}\mathrm{He},^{1}\mathrm{H})^{11}\mathrm{B}$, $^{12}\mathrm{C}(^{3}\mathrm{He},^{1}\mathrm{H})^{14}\mathrm{N}$ and $^{2}\mathrm{D}(^{3}\mathrm{He},^{1}\mathrm{H})^{4}\mathrm{He}$. Since the analysis depth for Be is greater than for C in NRA the Be signal has been reduced by the factor 0.5 to compensate, so that the Be/C values plotted are the atomic ratios in the outermost micron of the surface film. This correction is only accurate if the ratio of Be to C remains constant through at least the outer 2-3 microns; variation in the composition of the outer layers can be seen by RBS and detailed evaluation of that data may indicate whether some correction to the NRA ratios is necessary in the future. The amount of D is an approximate integration over the first ~8μm into the surface, based on the D peak shape (which reflects the variation in composition with depth) and taking into account the variation in cross-section with incident energy. However, a rigorous quantitative solution is difficult due to limits in the inherent resolution, and the resulting values for thick films may be in error by about

±30%. The top edge of tile 3 is shadowed from the plasma by the bottom of tile 1 which explains the lower first two Be/C values on tile 3. Thus, the band of very high Be/C ratios straddling the change of tiles coincides with the maximum plasma flux levels at the ISP for HD discharges (and just within the inner SOL). There is another maximum in Be/C at the top of the front face of tile 1 (s ~250mm), which may be connected to the change in tile geometry. The high Be/C ratios on tiles removed in 2010 (with a maximum on tile 1 of 4.4 and averages for tiles 1 and 3 of 1.5 and 1.12) compare with average values for tiles 1 and 3 removed in 2007 of 0.94 and 1.24, and for tiles removed in 2005 of 0.83 and 0.81, respectively. The increase in the Be/C ratio may be due to the increased number of HD discharges in 2007-9 (i.e. with ISP at the top of tile 3 or bottom of tile 1). The NRA Be/C data is in agreement with profiles calculated from Rutherford Back-scattering (RBS) spectra using the Data Furnace simulation programme Windf [7], and by SIMS measurements of the tiles. The increase in the Be/C ration cannot be attributed to an increase in the number of Be evaporations during the campaign, as only 58 evaporations were made in 2007-9 compared with 73 in 2005-7. In addition the integrated collection of Be from a nearby probe [8] was 1.3 10^{19} atoms cm^{-2} during 2007-9 compared with 4 10^{19} atoms cm^{-2} in 2005-7. The D concentrations on tile 1 (i.e. in the SOL) correlate with the Be/C ratio, whereas on tile 3 levels are low in the vicinity of the strike point on the last day of operations. The explanation for this pattern is not immediately clear, and in some aspects conflicts with RBS data: further investigation is on-going.

2.2. OUTER DIVERTOR TILES

The outer divertor tiles 7 and 8 are normally a region of slight net erosion [4, 5, 8], and the tiles appear very clean. However, there is a pattern of ^{13}C deposition on the tiles removed in 2010, with the largest concentration (~10^{17} atoms cm^{-2}) occurring at the bottom of tile 7, decreasing by two orders of magnitude at the tile7/tile 8 junction, and rising again to ~10^{17} atoms cm^{-2} at the top of tile 8 [9]. This must result from the ^{13}C puffing (as CH_4) on the last day of operations, which was performed in the plasma configuration shown in Figure 1. On that day 30 pulses were run in the HD configuration and ^{13}C-labelled methane (i.e. $^{13}CH_4$) was puffed into the divertor via 24 puffing holes equally spaced around the torus at the location on tile 6 shown in the figure. The discharges were 2.5 T, 2.6 MA H-mode shots with 15 MW auxiliary heating and the ELMs were of type I with an average core energy loss of about 400 kJ. A total of 3.3 10^{23} $^{13}CH_4$ gas molecules were injected, however 30% of this injected gas was pumped directly by the divertor cryopump [10]. There are more details of the ^{13}C results in a companion paper [9]. The outer divertor leg is sensitive to small changes of plasma parameters, and can easily switch from net erosion to net deposition. During the Reverse Field campaign in 2003 films were shown to grow on previously clean outer divertor surfaces by IR camera observations [11], and on the last day of the 2001-2004 operations when $^{13}CH_4$ was puffed into the outer divertor between tiles 7 and 8 a deposit formed near the strike point on tile 7 as was observed with the IR camera [12]; this deposit was eroded away during the subsequent 2005-7 operations. Clearly on the last day of operation in 2009 the injection of impurities into the outer divertor has again temporarily changed the region into a net deposition zone. As yet there are no tile profiler results to show the extent of erosion on these tiles integrated over the operational periods.

2.3. BASE TILES

For about 20% of the discharges during the 2007-9 operations the OSP has been on the LBT. One of those tiles was replaced in 2007 with a tile coated with 10μm W, and a photograph of that tile after exposure 2007-9 is shown in Figure 3. The W coating is intact everywhere over the tile, and is still too thick to tell from RBS if there has been any thinning: cross-sections will be cut from the tile in future to determine this. The darkening of the right-hand (outboard) half of the tile corresponds to a (small) amount of deposited C, but the tile is generally quite clean; the maximum amount of carbon is equivalent to ~0.5 μm (using a density of 1 g.cm^{-3} for a re-deposited film) in the stripe at s ~1189 mm and at the outboard edge (s = 1289 mm). There is also a peak in ^{13}C seen by NRA at s ~1189 mm, and this stripe (which is clearly visible in Fig. 3) was seen to develop during the puffing experiment on the last day of operation with the IR camera [13]; the OSP was at s ~1170 mm during the inter-ELM periods [13].

Figure 4 shows the surface concentrations of D and Be by NRA across a tile 6 exposed 1998-2009: note that there are two peaks in the Be profile shown in the figure. This double peak in the Be concentration has been reported previously [8], and was shown to roughly correspond to the positions on tile 6 most favoured as the OSP for the 2005-2007 campaigns. However, during the 2007-9 campaigns the strike point when on tile 6 was concentrated at the outer of these two positions, at an s co-ordinate of ~1440 mm, and it is clear that the Be peak has moved outward beyond the strike point location and is in the region shadowed from the plasma by tile 7. Deposits on tile 6 can reach ~100 μm in the vicinity of the Be peak (and up to 800 μm at certain areas on the sloping part of the tile) [8], so as NRA is only measuring the Be at the surface, the analysis is of material deposited during the latter stages of the 2007-9 operations. Ion microprobe analysis of cross-sections through films on tile 6 from previous campaigns have shown distinct bands of higher Be concentration within the deposit [14, 15], and this tile will be analysed by the same technique in the future. It is also planned to look at the whole patterns of deposition in the outer corner of the JET divertor with the modelling codes ERO and 3D-GAPS.

There is a high D concentration on the outer part of tile 6 (>1490 mm), which is the region shadowed by tile 7 and is analogous to the region at the inner corner of the divertor shadowed by tile 3. This has been seen after previous campaigns [12, 8] (and the high D concentrations extend throughout these deposits) [14, 15], but there is also a peak near the inboard edge of these tiles (~1320-1330mm). This is associated with a toroidal belt of local re-deposition resulting from the $^{13}CH_4$ puffing on the last day of the campaign: in previous campaigns very little deposition has been seen in this area, which is shadowed from the plasma by the edge of the LBT. ^{13}C is seen in the NRA spectrum at these points, and can be seen more clearly in RBS and Enhanced Proton Scattering (EPS) spectra. The re-deposition extends all the way to the next puffing hole four tiles further round the torus toroidally. Note that although the puffed methane contains H, not D, there is still a lot of D present in the plasma and as neutrals in the region, and ^{12}C from recycling is also present in the deposits at about one-quarter the ^{13}C level: these re-deposits will be analysed and modelled in much more detail in the future.

Analysis of tile 4 shows heavy, but uneven, deposition on the sloping part of the tile (accessible by the plasma) and a thick smooth film on the flat inboard section of the tile that is shielded from the plasma by tile 3 – this is the pattern observed on tile 4 after every JET campaign. A Be peak is observed at the inboard end of the sloping part of the tile, but less than on the tile removed in 2007 [8] and with no second peak as seen previously. The averaged amounts of Be seen on tiles removed in 2010, 2007 and 2005 were 0.4, 1.5 and 0.6 10^{17} atoms cm^{-2}, respectively. The amount of Be on tile 4 deposited in 2005-7 may be the anomalous value of the three, because a number of experiments were carried out during that period to understand the factors controlling migration of impurities to the Quartz Microbalance (QMB) located at the inner corner of the JET divertor [16, 17]; these experiments involved sweeping the plasma from tile 3 to tile 4, which may have encouraged migration of Be.

3. ANALYSIS OF INNER WALL GUARD LIMITER (IWGL) TILES REMOVED IN 2010

The general pattern of erosion/deposition on the JET IWGL is for there to be erosion on the left tile of the pair and deposition on the right tile at the top of the limiter (tile numbers 1,2,3), gradually changing to deposition on the left and erosion on the right tile of the pair at the bottom of the limiter (tiles 19,18,17), as can be seen in Figure 5 and has been shown previously [18]. The concentrations of D and Be across each of the tile pairs at top, middle and bottom of the limiter (positions 2, 11 and 17) measured by NRA are shown in Figure 6. Distances are measured from the (toroidal) centre of the limiter, where the two tiles meet. Fig. 5 clearly shows the deposition moving from the right-hand side of the tile pair to the left as one progresses down the limiter. However the figure does not show the amount of erosion of the tiles. Results from a tile from position 12 (so also from the central part of a limiter) showed that a W coating was completely removed from the region nearest the plasma, whereas the coating on a tile near the bottom was unscathed [19]. It was pointed out that much of this erosion may occur during ramp-up or ramp-down phases when tiles near the centre of either the IWGL or the Outer Poloidal Limiters (OPL) act as limiters. In 2007-9 the ratio of time in the limiter phases to time in the X-point phase was 1:2.36 (and for 2005-7 it was 1:3.46), and whilst in the limiter phases, 52% of the time the plasma was in contact with the central part of the IWGL (60% in 2005-7). However, there are striking visual patterns of erosion and deposition all along the JET IWGL as shown in Figure 5. It has long been known that the main chamber has to be a major source of the deposition found in the JET divertor [18, 20, 21], and it is also known that there is erosion of the Inner Wall Cladding tiles (protecting the wall between the IWGL) [22].

The top part of Figure 7 is the cross-section of a left-hand side IWGL tile, and the lower part is the result of tile profiler measurements on a marker tile from the middle of the limiter (position 11 left) which was in the torus 2005-9. The tile surface profile measured over a grid of 28x12 points with 5mm spacing before mounting in JET has been subtracted from measurements at the same grid points after exposure and removal in 2010. The difference (which is averaged across the 12 poloidal points) represents the erosion/deposition across the tile; it shows a maximum in deposition of ~50μm (which will be checked by sectioning) and a maximum erosion of ~200 μm. It is possible that there can be a distortion of the bulk shape of the tile during exposure due to stress and thermal cycling. Comparison of belt limiter tiles exposed before and after operations in 1988-1992 showed a change in dimension of up to 5 microns. There is also evidence of a slight distortion to the tile shown here: although the grids are matched to give no erosion or deposition across the tile where a clean marker stripe is visible at -120mm (on Figure 7), the data in the region of reverse slope from -5 to -15mm show a variation from ~0 to -50 μm deposition from top to bottom of the tile. This is a largely systematic variation since visual inspection of the tile shows there is only slightly less deposition at the top than at the bottom of the tile, indicating the tile has twisted during operations. Compensating for this twist could remove the systematic contribution from the error bars shown in the measurement of maximum erosion. Several other IWGL marker tiles have yet to be measured and it will be interesting to see when tile profiling of these is completed to what extent the IWGL are net erosion sources during the X-point phase as well as when acting as limiters.

CONCLUSIONS

Many of the tiles removed during the 2010 shutdown have already been analysed by IBA. The basic picture of transport within JET is unaltered: impurities such as C, Be and metals such as Ni eroded from the main chamber are deposited on tiles 1 and 3, then C is preferentially sputtered and transported towards the divertor corner. This leaves a Be-rich (and Ni-rich) layer on the tiles: the greatest values of the Be/C atomic ratios at the surface of the deposits were near the bottom of tile 1 and top of tile 3 (4.4 and 3.7, respectively): the average Be/C ratio over tile 1 has almost doubled on tiles removed in 2010 (1.5) compared with tiles removed in 2004 (0.83). This is the region of the ISP during the high-delta discharges that formed a significant part of the 2007-9 operations, and (perhaps significantly) also for the last day of operations. There will be a maximum in deuterium flux in that region, so a maximum in the amount of carbon chemical sputtering may be expected. At the divertor base, the patterns of deposition were as previously reported, that is heavy deposition on the sloping parts and shadowed areas of each tile 4 and 6: peaks in the amount of Be detected occur near the top and at the bottom of the sloping part of tile 6, as was observed previously, and the amounts of Be at the surface (1.3 and 1.6 10^{18} cm^{-2}) were higher than previously observed [8]. However, the latter of the two points appears to be in the region shadowed from the plasma by tile 7, thus beyond the strike-point: deposition in this region requires modelling with the ERO and 3D-GAPS programmes. The amount of Be observed on tile 4 in 2010 was less than measured in 2007 but similar to that observed in 2004 (0.4, 1.5 and 0.6 10^{17} atoms cm^{-2} following the three phases, respectively), suggesting that the particular pulses used to investigate deposition at the inner

QMB in 2005-7 [16, 17] may have resulted in the increased movement of Be onto tile 4 at that time. On the last day of operations in 2009 $^{13}CH_4$ gas was puffed through one tile 6 in each module into H-mode plasmas with type I ELMs with the OSP on the LBT. A band of heavy deposition is seen running toroidally across tiles 6 all the way between puffing holes.

An LBT that was coated with ~10 μm W as a test for the ILW has been analysed. This showed that the W coating remained intact at all places, despite the large number of discharges run with the OSP on the LBT during 2007-9 operations. The tile was generally clean in the PFR, with some ^{12}C and ^{13}C deposition close to the strike point seen to accumulate visibly and by IR camera during the last day of operations, and near the outer edge of the tile (in each case ~0.5 μm thick).

Tiles 7 and 8 were clean, indicating that they were generally in a net erosion zone; however low concentrations of ^{13}C ($10^{15} – 10^{17}$ atoms cm^{-2}) resulting from the puffing experiment on the last day of operations were observed, indicating that the impurity puffing may have changed conditions in the SOL temporarily into a deposition zone.

IWGL tiles including marker tiles installed in 2005 have been analysed by IBA, and the erosion/deposition patterns are as normal in JET [18]. Tile profiling measurements show the maximum erosion on a tile from near the middle of a limiter to be ~200 μm. This is in contrast with the relatively pristine W-coated LBT, despite the time the OSP was on tile 5 in 2007-9 being approximately the same as the time the plasma was in contact with the IWGL. This demonstrates that more sputtering occurs at limiter surfaces and/or sputtered atoms in a divertor plasma have a very high probability for prompt return to the surface, whereas at a limiter any sputtered atom enters the confined plasma and its eventual return to somewhere in the SOL is governed by cross-field diffusion.

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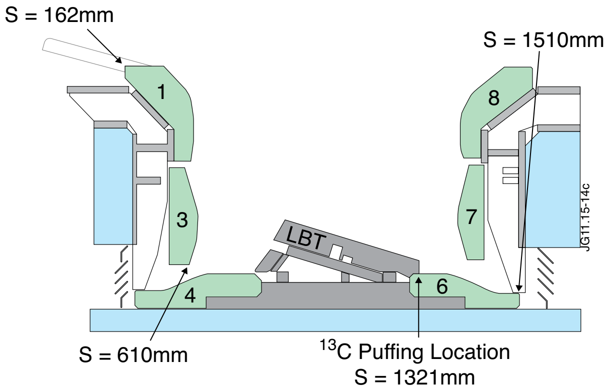

Figure 1: Cross-section of the JET MkII-HD divertor showing the tile numbering, some relevant s co-ordinates (see text), and the plasma configuration used during the ^{13}C (as methane) puffing experiments on the last day of the 2007-9 operational period.

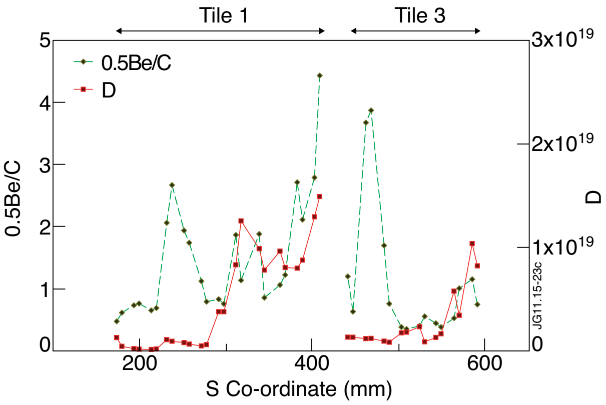

Figure 2: The ratio of Be to C and of D in the surface layer on tiles 1 and 3 from NRA data. The factor 0.5 for the Be data compensates for the greater analysis depth for Be than for C in NRA.

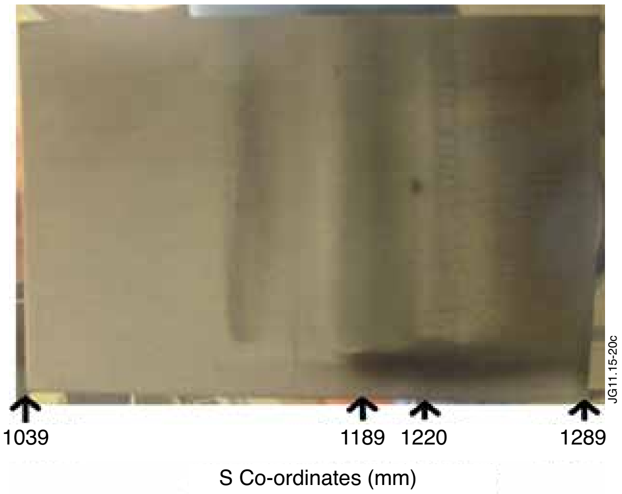

Figure 3: A photograph of the W-coated load-bearing tile after exposure 2007-9. The s co-ordinates indicate the inboard and outboard edges of the tile (1039 and 1289mm), and the area of maximum ^{12}C and ^{13}C (1189mm) for the puffing experiments on the last day of operations in 2009: the strike point was at ~1170mm during the inter-ELM periods.

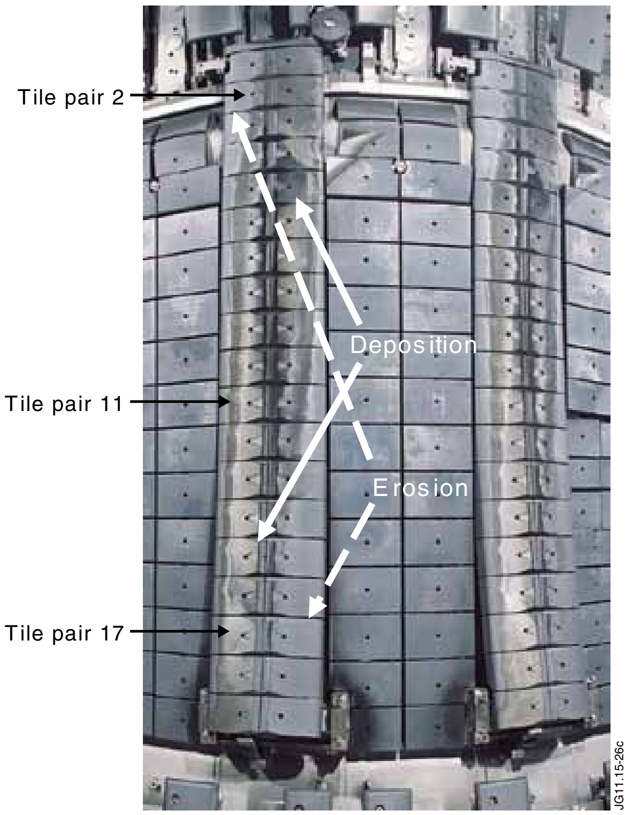

Figure 5: Photograph of a JET Inner Wall Guard Limiter (IWGL) showing the tile numbering and the progressive changes to areas of erosion and deposition.

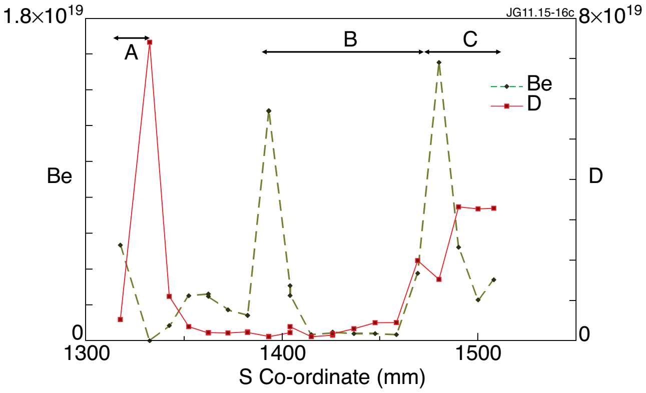

Figure 4: NRA concentrations of D and Be across tile 6 (exposed 1998-2009). Region A is shadowed by the LBT, region B is the sloping part of the tile, and C is the region shadowed by tile 7.

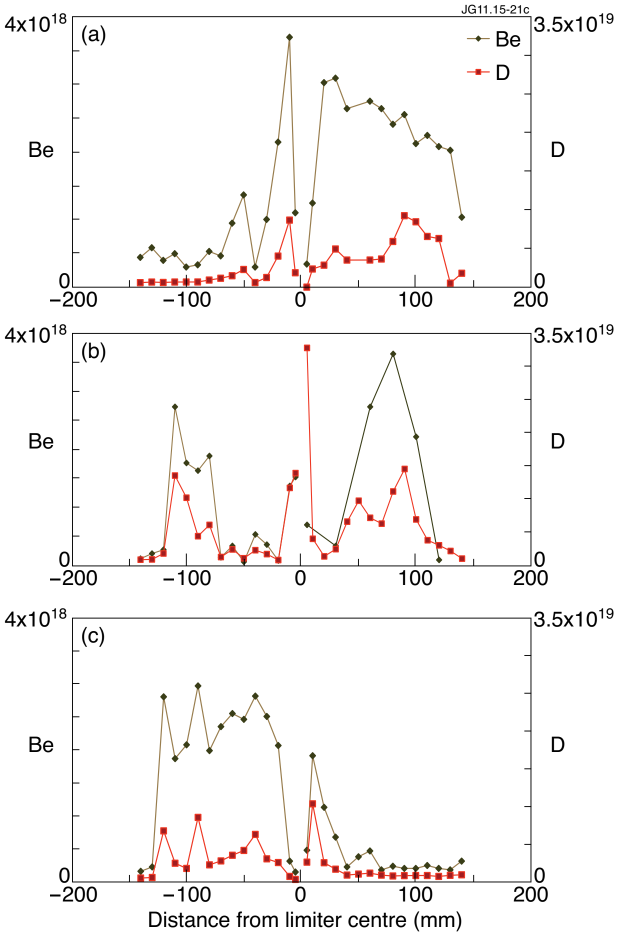

Figure 6: Concentrations of Be and D from NRA data plotted across the IWGL tile pairs (a) from position 2 (top), (b) position 11 (middle) and (c) position 17 (bottom) of a limiter. Distances are measured from the (toroidal) centre of the limiter, where the two tiles meet.

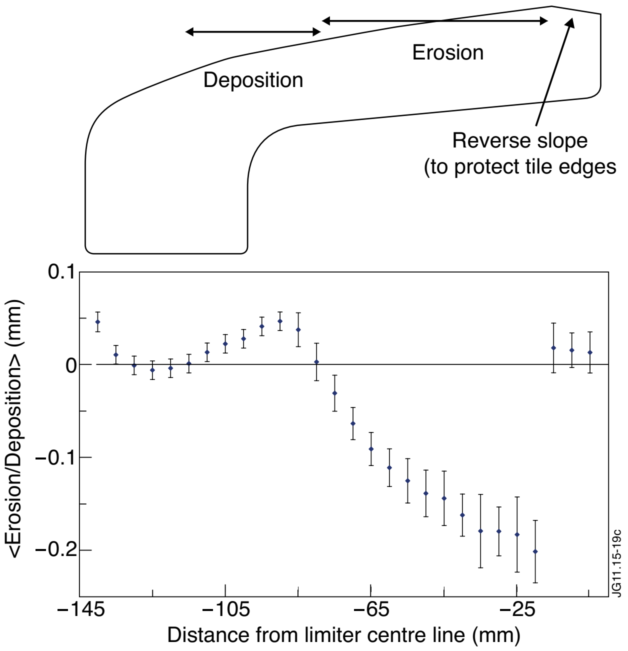

Figure 7: Lower part shows the amount of erosion or deposition on a tile exposed 2005-9 from position 11 left (at the middle) of an IWGL from the difference in tile profiles before and after exposure; the mean value of the poloidal grid is plotted against the distance from the limiter centre line. The upper part shows the cross-section of the tile.