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ABSTRACT.

Post mortem analyses of tiles removed from the JET MkII HD divertor in 2007 are presented. The results indicate an increase in deposition at the outer plasma shadowed region of the divertor, not seen prior to 2004 and indicating a shift away from the asymmetric picture of net deposition at the inner divertor compared with no overall deposition or erosion at the outer divertor. Surface analysis of the inner and outer vertical divertor tiles are largely the same as observed previously, however a notable increase in Be composition on the inner and outer floor tiles is observed. Analysis of campaign averaged plasma configurations can provide some explanation for the changes in deposition/erosion characteristics observed however further input can be provided by diagnostics and 13C puffing experiments from which time resolved data to be obtained. In particular, data from rotating collector diagnostics are presented.

1. INTRODUCTION

Post mortem analyses of tiles removed periodically from the JET vessel have established the current picture of asymmetric deposition/erosion characteristics between the inner and outer divertor legs. Such empirical data have provided information for modelling of plasma surface interaction and material migration. Since 1995 sets of tiles forming a poloidal cross section have been taken from each of the divertor geometries; 1994-1995 MarkI (MkI), 1996-1998 MkIIA, 1999-2001 MkII Gas Box (MkII GB), 2002-2004 MkII Septum Replacement Plate (MkII SRP) and 2005-present MkII HD divertor, with the latest results reported here coming from tiles removed from the MkII HD divertor during the intervention of the JET vessel in 2007. Since the installation of the MkII GB divertor the vertical tiles (tiles 1, 3, 7 and 8) and floor tiles (tiles 4 and 6) have remained the same, with the central section at the bottom of the divertor being the principal difference between geometries. Figure 5 shows these geometries along with terminology used throughout this paper. Details of the earlier geometries (MkI and MkIIA) can be found elsewhere [1].

The most obvious evidence for net deposition at the inner divertor compared with no overall deposition or erosion at the outer divertor came from the analysis of tiles from the MkIIA divertor. In particular a tritium rich spalling deposit was found on the inner floor tiles and the inner louvers whereas the outer floor tiles and louvers were essentially clean with only small amounts of tritium being found. This asymmetric behaviour has continued in subsequent campaigns. For example the direct measurement of tiles using a micrometer showed net deposition on the inner divertor tiles compared with that of the outer divertor tiles [2], except for deposition on the sloping surface of the outer floor tile 6, which is accessible by the plasma. The deposition at this location on tile 6 was similar in nature to that observed in the equivalent location on the inner floor tile 4 and was dusty and easily compressed compared with other co-deposited material. By contrast material removal has continued at the outer divertor with tungsten marker coatings on the vertical outer divertor tiles (tiles 7 and 8) of the MkII SRP being eroded [3].

Following the installation of the MkII SRP divertor some changes in the erosion and deposition characteristics at the inner and outer plasma shadowed regions of the divertor have been noted. Prior to the MkII SRP deposition on the shadowed region of the outer floor tile 6 was minimal with a deposit of only 4.2mm being measured on the tile removed from the MkII GB divertor, compared with 87mm at the inner shadowed region of floor tile 4. This has increased for the MkII SRP to 32μm at the outer divertor and 110μm at the inner divertor. Thus the ratio of deposit on the plasma shadowed region of the inner and outer floor tiles reduced from 20:1 to 3:1. Post mortem analysis of MkII HD floor tiles shows a similar trend.

In addition to this change other notable results that have been observed for the tiles removed from the MkII HD divertor are reported here, in particular for the apron of the inner divertor tile 1 and the plasma accessible sloping surface of the inner and outer floor tiles. Some correlation of these results with campaign averaged plasma configurations has been possible however it is clear that time resolved data provided by diagnostics in conjunction with the globally averaged information is required. Results of the diagnostics installed in the JET vessel in 2004 are also discussed.

2. EXPERIMENTAL DETAILS

The MkII HD divertor was installed in 2004 and will remain in JET until the end of 2009. In 2007 there was a vessel intervention during which a poloidal set of divertor tiles was removed. Compositional analysis of the tile surfaces and their deposits has been performed using ion beam analysis (IBA) techniques including nuclear reaction analysis (NRA) as well as Secondary Ion Mass Spectrometry (SIMS). The thickness of deposits was measured using cross sectional optical microscopy and SIMS.

Diagnostics were installed into the JET vessel in 2004 to provide time resolved information on deposition and erosion. The diagnostics consist of quartz microbalances (QMB), rotating collector (RC), mirror test units (MTU) and silicon deposition monitor details of which can be found elsewhere [4,[5,[7]. The QMBs and RCs were installed at the outer corners of the divertor and under the Load Bearing Septum Replacement Plate (LBSRP). The QMBs enable pulse-by-pulse monitoring of deposition and erosion in these locations during the JET experimental campaign whilst the RC can provide deposition information of a resolution of 30-60 pulses but only from post mortem analysis. The first RCs were removed from the JET vessel in 2007 and initial detailed results from the RC located under the LBSRP are presented elsewhere [9]. In addition, two RCs and two MTUs were installed at the outer mid-plane of the JET main chamber in locations such that they were exposed to the beryllium (Be) flux from the Be evaporator head in octant 3 of the vessel. The Be evaporator heads are extended periodically into the vessel during non-operational days (usually weekends) and run for approximately 50-60 minutes to condition the vessel wall. Post mortem analysis of these components have provided information on the Be evaporation during the 2005-2007 experimental campaigns.

3. RESULTS AND DISCUSSION

3.1. DEPOSITION AT THE INNER DIVERTOR

During the JET intervention in 2007 all tiles were inspected using a camera controlled via remote handling. During this inspection a rough appearance was noted on the apron (i.e., the top horizontal surface) for all tiles 1 around the vessel. This rough appearance was due to a spalling deposit which extended over two thirds of the apron surface, with the remaining third being deposit which was in the region shadowed by the adjacent tile. Spalling was observed on tiles that had been in vessel since 1998 as well as tiles that had been newly installed in 2004, although the extent of the spalling was noticeably less on those installed later into the vessel. From optical microscopy the thickness of the deposit on the apron of tile 1, was 119mm for a tile installed 1998-2007 and 115mm for a tile installed 2005-2007. As spalling was evident on both tiles and the overall thickness had not increased this indicates that the critical thickness for the deposit has been reached. The first signs of spalling were seen on a tile removed from this location in 2004 when the thickness of the deposit on the apron was 98mm.

From NRA of a tile 1 removed from the MkII HD divertor, the Be concentration of the deposit on the apron of tile 1 relative to carbon (C) is found to be lower than on the front surface of the tile. This corresponds with typical results for the MII SRP divertor with the Be/C ratio =0.5 on the tile 1 apron with values of Be/C=1 or higher on the front vertical surface. This implies that the chemical sputtering which in known to occur on the front vertical surface of tile 1 does not extend to the horizontal surface of the apron. The fact that C is not preferentially eroded from the apron by chemical sputtering means that most of the deposition from the SOL remains on this surface. In addition the flux is higher on the apron than just around the edge to the front face, since the poloidal component on the angle of incidence is much greater. This increases the rate of build-up of material on the apron resulting in a thick deposit of 115mm, compared with 49mm near the top of the front vertical surface of tile 1 and 14mm at the bottom of the tile, for the tile installed from 2005-2007.

The installation of the MkII HD divertor has allowed high-delta plasma configurations with the inner strike point high on tile 3 and on tile 1. Thus the top and bottom of tile 3 were frequently exposed to different regions of the plasma. In the high-delta configuration the top of tile 3 is at the strike-point, resulting in higher temperatures, incident C and Be flux and plenty of deuterium (D) for chemical sputtering, whereas the bottom of the tile is in the private flux region with lower temperatures, no incident Be and lower D fluxes. However the strike point distribution looks similar between the MkII SRP and MkII HD divertor configurations thus indicating that there were also many pulses with the strike-point at the bottom of tile 3 (or even on tile 4), when conditions across tile 3 are more uniform. Consequently the Be/C ratios for tile 1 and tile 3 surfaces for the MkII HD divertor were similar to those obtained from tiles removed from the MkII SRP divertor in 2004.

3.2. DEPOSITION ON THE DIVERTOR FLOOR TILES

Deposits from the plasma accessible sloping surface and plasma inaccessible shadowed region of tiles 4 and 6 from different divertor campaigns have been measured directly by cross sectional optical microscopy. Direct measurements of tiles for the MkII GB and MkII SRP campaigns for tiles installed 1998-2001 and 2002-2004 respectively are available, however the thickness of deposit for the MkII HD divertor geometry from 2005-2007 has been obtained indirectly by subtracting the previous campaign values from the results for a tile which was in the vessel from 1998-2007. Based on these optical microscopy results and assuming that the deposit was a result of divertor plasmas, the rates of deposition were determined. In the case of the outer floor tile 6 the rate of deposition was found to increase from 0.023 mm/s in the period 1999-2001 to 0.0038mm/s for the period 2005-2007. The increase in rate of deposition in the shadowed region of the outer leg was markedly higher, rising from 0.6x10-4 mm/s to 3.4x10-4 mm/s. The results for the inner divertor leg are less clear; there was a overall decrease in the thickness of deposit on the sloping surface of tile 4 deduced from the 1998-2007 tile samples. There could be a discrepancy arising from the exact location of the samples taken from the tile 4 positions over the different periods however until further analysis of tiles that will be removed from the JET vessel in the planned intervention in 2009-2010 it is uncertain if this is an anomalous result or whether a true net-erosion has occurred in this region. In the shadowed region of the inner divertor floor tiles an overall increase in the rate of deposition has been observed, from 0.013 mm/s in 1999-2001 to 0.0024mm/s, this was still higher than the outer divertor but the ratio has decreased. The increase in deposit at the outer shadowed regions of the floor tiles is supported by the observation of deposits on the inner and outer divertor carrier on to which the inner and outer vertical divertor tiles are mounted and are far into the shadowed regions of the divertor. In 2007 when a selection of divertor carriers was removed from the vessel, flaking deposits were observed on the ribs of the outer divertor carrier as well as on the inner carrier. However the deposit at the outer divertor was flaking even though it was much thinner than the deposit at the inner divertor, indicating that it was more stressed.

In addition to the increase in deposit at the outer divertor the other deposits on the floor tiles display different characteristics from previous campaigns, for example the deposit on the outer sloping surface of tile 6 has reached 800mm in 1998-2007 and is still well adhered to the surface. The deposit on the sloping surface of both the inner and outer floor tiles is markedly different for the MkII HD divertor geometry; they appear more stable and are denser than those seen in previous campaigns, in particular compared with the MkII GB divertor where films were reported as being soft when micrometer measurements were made [2]. This could be due to the difference in composition or alternatively different plasma conditions on these tiles.

In addition to the change in amount of deposition at the inner and outer floor tiles the composition of the deposits is markedly different. Figure 7 shows a comparison of the Be/C ratio for tiles removed from the JET vessel after the last three JET operating periods (MkII Gas Box, MkII SRP and MkII HD divertors.) Be/C ratios are plotted to reduce error associated with variation in mounting tiles over such large time intervals. In this figure the data are plotted from inboard to outboard using the s-coordinate system which follows the contour of the surface of the tiles with the origin being at the inboard corner of the High Field Gap Closure tile inboard of tile 1. This scale has been adopted for the MkII HD divertor, however for ease of comparison data for previous campaigns have been plotted on equivalent s-coordinate positions where the coordinates of tile 4 are 713mm-934mm from the inboard corner to the outboard corner and for tile 6 are 1321mm-1512mm from the inboard to outboard corners. The Be/C ratio has increased on the sloping surface of the 2005-2007 tiles. The increase in the amount of Be is particularly noticeable for tile 6. The ratio has increased from <0.1 for a tile removed in 2001 up to 0.8 for a tile removed in 2007 at some locations. However these are still lower than for the surface of tiles 1 and 3 above, which undergo chemical sputtering from D flux and are thus Be enriched. Similar increases are seen on tile 4 where the Be/C ratio has increased from <0.1 up to ~0.4 in some regions for tiles removed in 2001 an 2007 respectively. For the inner divertor the Be/C ratio was similar for the MkII GB and MkII SRP divertors with the increase in the Be being observed only for the most recent MkII HD divertor tiles, however for the outer divertor tile there is an increase in Be concentration observed at the top of the sloping surface in MkII SRP, with a marked increase on the 2007 tile. The structure of the Be concentration shows some correlation with the distribution of the strike point positions for the MkII SRP and MkII HD divertor geometries as shown in Figure 8. There is some discrepancy between the two sets of data, this could be due in part to the allocation of the s-coordinate for the NRA measurement point for the Be/C ratio which could be ±3-4mm. An additional source of discrepancy is the use of the magnetic configuration to determine the strike point distribution. The magnetic strike point does not indicate the energy or flux distribution on the tiles, which might offer a better correlation with the Be/C ratio. In fact discrepancies between the strike point allocation determined from magnetic configuration and from the infrared camera images of the tiles in the divertor have been observed. Whilst the structure seen in the amount of Be may correlate with the strike point position the increasing in Be concentration is not understood. Campaign averaged spectroscopy data [10] indicates that the C and Be levels in the main chamber are similar for the MkII GB, MKII SRP and MkII HD divertors, which suggests that the amount of Be has not increased as an impurity source over the periods being compared. In addition the number of beryllium evaporations has decreased over the period since 1998 as the condition of the vessel has improved. Early in this period Be evaporations were carried out twice weekly to condition the vessel, this has now reduced to intervals grated than a week in the MkII HD operating period.

During Type 1 ELMs BeII and CIII spectral emissions have been observed in the outer divertor, this is evidence of sputtering of deposit from the (inner) divertor and transport of Be and C across the private flux region [12], which may act as an additional source of Be in the divertor.

3.3. DEPOSITION AT THE OUTER DIVERTOR

The vertical outer divertor tiles (tiles 7 and 8) removed in 2007 were generally very clean as has been observed with previous tiles in this location. This is expected as tiles 7 and 8 were frequently deep in the outer SOL during the 2005-2007 campaign due to the high-delta plasma configuration.

3.4. ^{13}C PUFFING EXPERIMENTS

On the last day of the 2001 JET operational period, carbon-13 (^{13}C) was puffed into the plasma boundary during a series of identical discharges in the form of methane ($^{13}CH_4$). A poloidal selection of tiles was then removed for the regular post-mortem analysis, but additionally analysing for ^{13}C at the surface of each tile. The objective of the puffing and the additional analysis is to discover where the ^{13}C is deposited, and how much, so that the transport can be mapped from this particular source and under those specific plasma conditions. This data can then be used as the basis of a plasma boundary modelling exercise. This experiment has been repeated at the end of subsequent operational periods, in 2004 and 2007. In the first experiment, the methane was puffed at one location at the top of the vessel into ohmic plasmas, whilst in 2004 the methane was puffed into the outer divertor (at 24 locations round the vessel between tiles 7 and 8) into H-mode discharges; results have been reported in [3,[13]. In 2007 the methane was again puffed at the top of the vessel, though at a different single location, and this time into H-mode discharges with strike points on tiles 3 and 7. However, there were difficulties with the gas supply valves, so an order of magnitude less gas in total than planned was puffed into JET. So far only a small amount of ^{13}C has been found in comparable quantities near the centre of the inner and outer tiles where the strike points were located. The total amount of 13C found in the divertor is probably only a fraction of the total methane puffed into the vessel, however the tiles from the main chamber are still to be analysed. Associated modelling is also continuing.

3.5. TIME-RESOLVED DIAGNOSTICS

Details of measurements with the QMBs during the 2005-2007 operational period have been reported elsewhere [15,[16,[18]. In general terms, the amount of deposition on the QMB sited at the inner corner near the inner louvres of the divertor was greatest when the strike-point was moved to be on tile 4, and increased non-linearly with ELM energy [15]. The QMB sited at the outer corner near the outer louvres of the divertor received small amounts of deposit in some pulses, and the deposit on its sensing crystal experiences a small amount of erosion during other pulses; the net deposition was close to zero, and attempts to correlate the behaviour with plasma parameters are proving difficult but are continuing [15]. The QMB in the LBSRP unit which faces the inner divertor tiles showed two clear periods of “integral deposition”, separated by a period of “integral erosion”, with another period of erosion in progress when the QMB exceeded its operating limit [16]. The periods of “integral deposition” and “integral erosion” correlate with operational periods when the strike points were normally of tiles 3 and 4, respectively [16]. A correlation has been made of the deposition/erosion data from the QMB in the LBSRP with deposition on a Rotating Collector (RC) at a similar location [9]. The results showed that the QMB only collects ~25% of the deposition at the RC, and suggests the difference may be due to the heating of the QMB crystal during the plasma pulse.

As mentioned in the Experimental Details, RCs were mounted at two positions at the outer mid-plane; in each case the RC shared a bracket with a MTU [6]. One of the RC units was close to a Be evaporator head, and the slit (2mm wide) was aligned with the evaporator so that the full Be flux would impinge on the collector. Since the evaporated Be normally deposits on carbon surfaces within JET, in order to provide a calibration for the flux from the evaporator this collector was made of carbon, whereas all other RC collectors are made of polycrystalline silicon. A photograph of the collector after removal in 2007 is shown in Figure 10.

It can be seen in Figure 10 that the collector only rotated though about 100^o. The reason why the rotation stopped is unknown, however stripes from four separate evaporations and a double stripe at the start are clearly visible; there is also a thick band where the rotation stopped. The first pulses after each of these six evaporations are 63758, 63788, 64540, 64640 64861 and 64940. There were a total of 84 Be evaporations from this head during the 2005-2007 operational period, so there is a much thicker deposit in the area exposed after the rotation stopped (which was exposed to 78 evaporations). The amount deposited in each of the six identifiable stripes varies considerably – the average of the first two is 2.2×10^{18} Be atoms cm^{-2}, the average of the next four is 0.25×10^{18} Be atoms cm-2 (but varies within this sub-set by a factor of four), and the amount at the end point is 14.4×10^{18} Be atoms cm-2 (that is, an average of ~0.2×10^{18} Be atoms cm^{-2} for each of the 78 contributing evaporations).

When the Be heads are inspected during a shutdown they are invariably covered with an oxide film, and it is standard procedure to clean the heads during shutdown, as was done in the 2006-2007 shutdown. It would appear from this analysis that the efficiency of the head dropped off by almost an order of magnitude after the first two evaporations and thereafter remained reasonably constant. This is consistent with the scenario in which after the initial evaporations the head becomes covered with an oxide film, and the efficiency of evaporation is then limited by the diffusion of Be atoms to the surface through the oxide film. The side of the MTU adjacent to the RC facing towards the Be evaporator was also covered with Be, and may be expected to have experienced a similar total flux of Be. The mean of two analysis points on the MTU was 21.1×10^{18} Be atoms cm^{-2}, which compares well with the total deposition on the RC collector of 20.8×10^{18} Be atoms cm^{-2}. However, it should also be noted that the exposed end point of the collector and the side of the MTU would have been exposed to bombardment by charge exchange neutral atoms throughout all (or nearly all, in the case of the collector) the operational period, so some of the Be film may have been eroded and agreement with the mean of the four deposits that were largely protected from this erosion may be fortuitous.

CONCLUSIONS

Post mortem analyses of tiles removed from the different divertor geometries have provided empirical data showing the asymmetry of deposition/erosion at the inner and outer divertor legs. However the most recent results from tiles removed in 2007 indicate that more deposition is occurring at the shadowed region of outer divertor. In addition the Be concentration of deposits on the plasma accessible surfaces of the inner and outer divertor floor tiles has increased. Whilst the distribution of the Be can be correlate with average strike point position the transport of Be to these tiles and the increase deposit at the outer divertor leg has not so far been explained by campaign averaged plasma configuration data. This shows that the time resolved data provided by diagnostics located in the vessel and the ^{13}C puffing experiments play an important role in conjunction with post mortem analysis in understanding material migration. For example the QMB and RC diagnostics have shown that the balance between deposition and erosion is strongly dependent on plasma configurations, particularly under the LBSRP and at the outer divertor.

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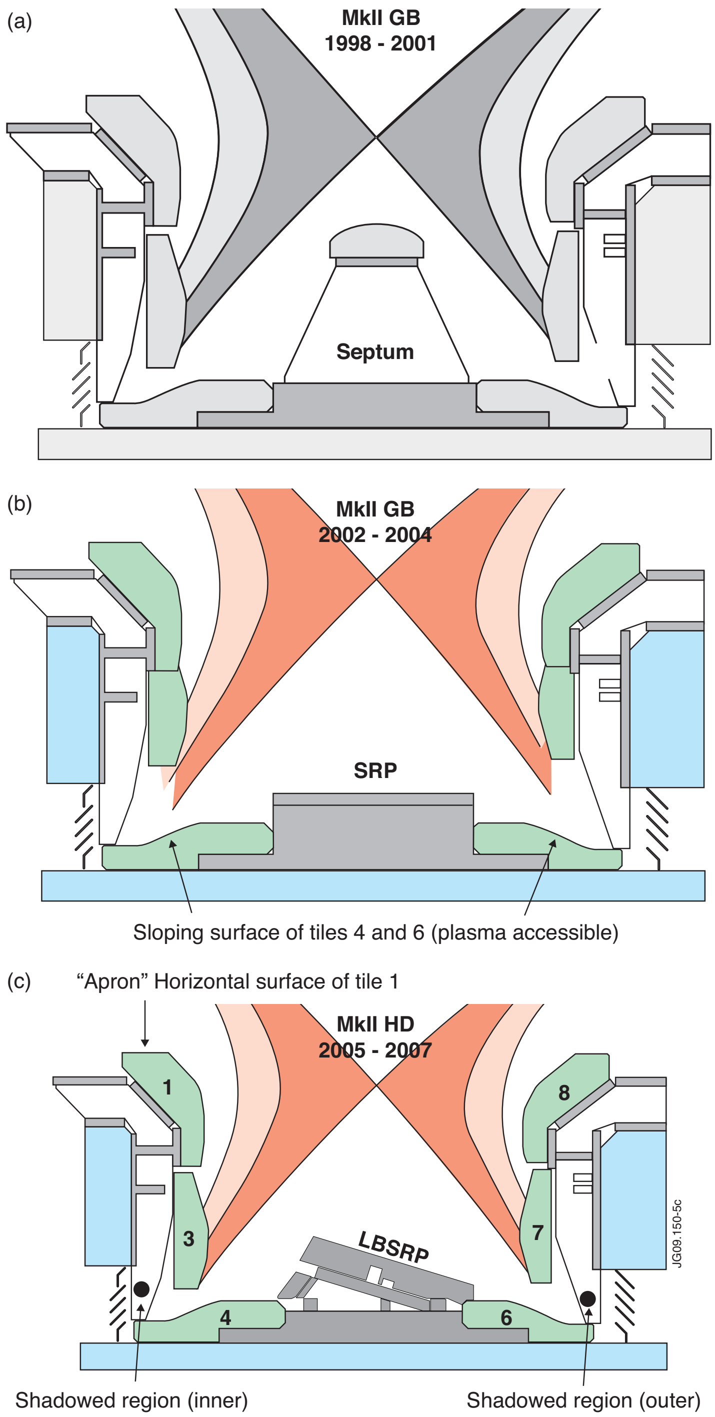

Figure 1: Divertor geometries in JET
(a) 1999-2001 Mk II Gas Box (MkII GB) divertor,
(b) 2002-2004 MkII Septum Replacement Plate (MkII SRP),
(c) 2005-2007 the MkII High Delta (MkII HD) divertor.

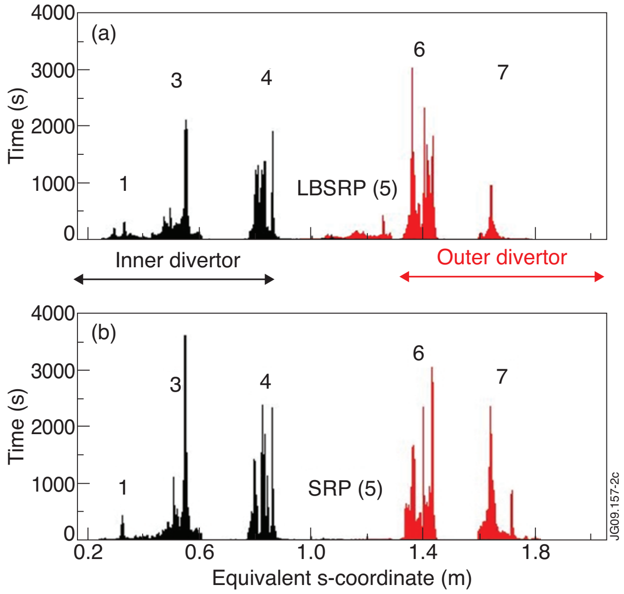

Figure 2: Be/C ratio for inner and outer divertor floor tiles (tile 4 and tile 6 respectively) for tiles from the MkII GB, MkII SRP and MkII HD operating periods. The s-coordinate system has been adopted for the MkII HD divertor geometry. For ease of comparison, equivalent s-coordinates for the MkII GB and MkII SRP have been plotted for tile 6.

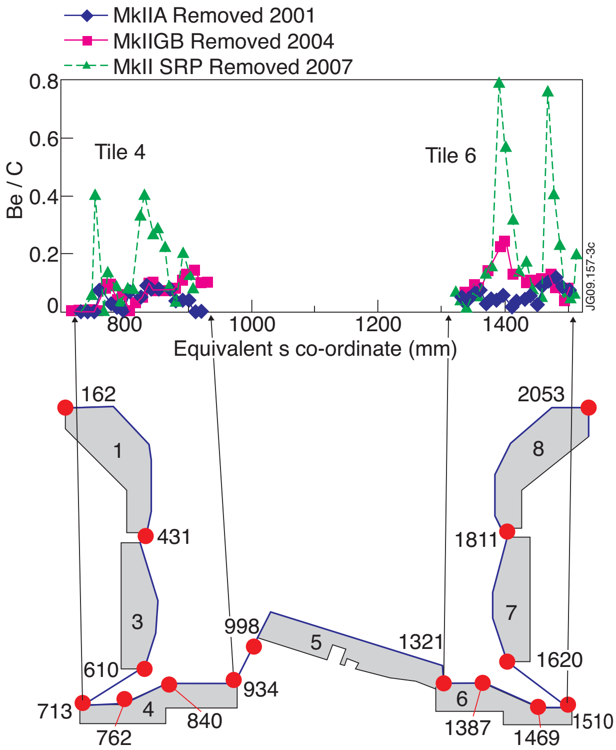

Figure 3: Correlation between strike point position and Be/C ratio on inner and outer divertor floor tiles.

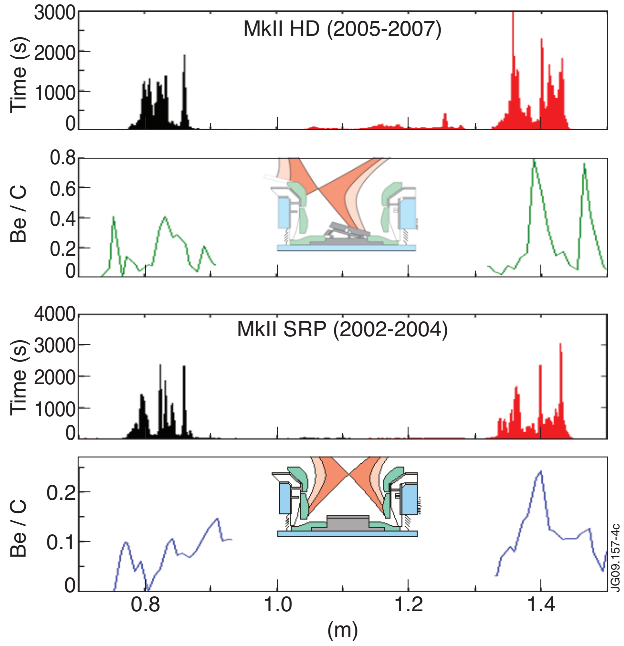

Figure 4: Carbon disc removed from rotating collector located at the outer mid-plane of the JET main chamber. Bright stripes are correlated with deposition from the beryllium head in octant 3E at the outer mid-plane.

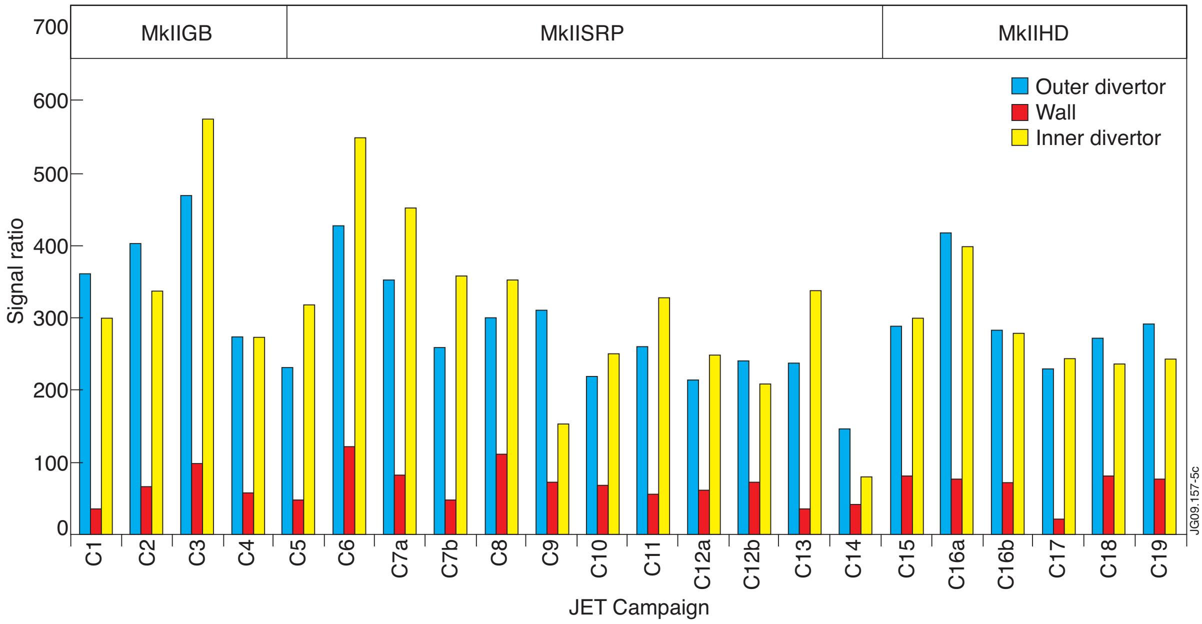

Figure 5: Divertor geometries in JET (a) 1999-2001 Mk II Gas Box (MkII GB) divertor, (b) 2002-2004 MkII Septum Replacement Plate (MkII SRP), (c) 2005-2007 the MkII High Delta (MkII HD) divertor.

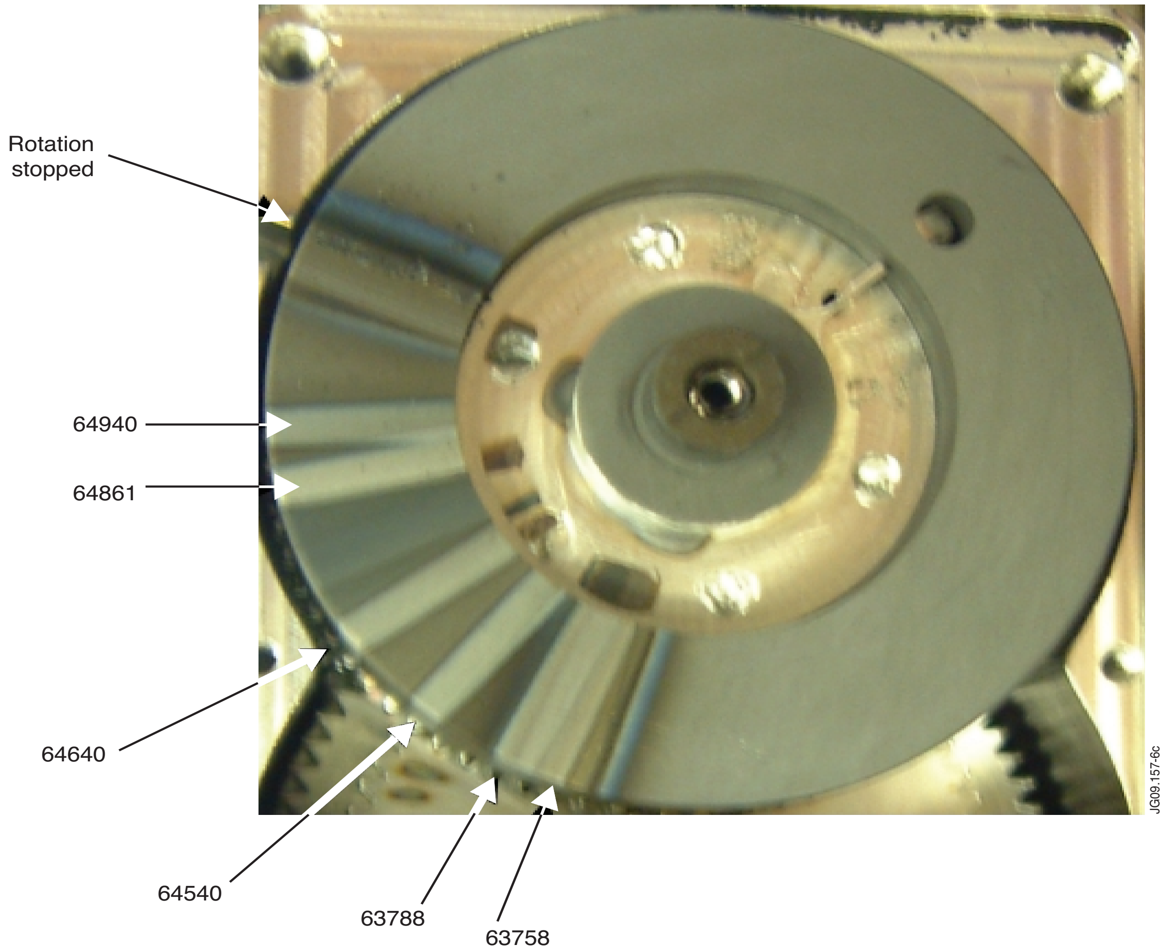

Figure 6: Carbon disc removed from rotating collector located at the outer mid-plane of the JET main chamber. Bright stripes are correlated with deposition from the beryllium head in octant 3E at the outer mid-plane.