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Beryllium accumulation at the inner divertor of JET

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Abstract

MkIIGB divertor tiles exposed in JET for the 1998–2001 and 1999–2001 campaigns have been used to assess the amount of beryllium and carbon deposited at the inner divertor wall. Total amount of Be at the inner divertor tiles was determined and integrated toroidally. Results were compared with data obtained with optical spectroscopy and good agreement was obtained. The amount of deposited C was computed from the amount of deposited Be assuming that the Be/C ratio arriving in the divertor is the same as the Be/C ratio in the main chamber. On the basis of this analysis we would expect there to be ~0.4 kg of C deposited. This gives an average C deposition rate lower than during the MkIIA phase.

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1. Introduction

Previous analyses of plasma-facing tiles removed from JET have shown that material is eroded from outer divertor and vessel walls [1–5]. The material is mostly carbon from the tiles, plus beryllium (evaporated over the tiles and other in-vessel surfaces periodically from sources within the vessel), and metals from the nickel-based vessel walls. Eroded material flows around the scrape-off layer (SOL) from outboard to inboard and deposits in the inner divertor together with hydrogen isotopes from the plasma. Carbon is subsequently chemically sputtered from the inner divertor deposits, leaving behind films rich in beryllium and other metals that cannot be chemically sputtered, and is transported to regions shadowed from the plasma, such as the inner louvres. From the fact that the layers deposited in remote areas contained vast amounts of hydrogen isotopes and carbon, but no beryllium, one concluded that their presence was associated with chemical erosion of carbon and long-range transport of hydrocarbons [1]. No re-erosion of Be and metals occurs due to the low electron temperature in the inner divertor. For the JET Mk IIA

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campaign the total amount of deposition in the divertor (~1 kg) was determined from the long term tritium retention (resulting from the DTE1 campaign) and the tritium content of the flakes recovered from the inner pump duct [1]. However, for the Mk IIGB divertor it is difficult to get a reasonable estimate of the re-deposited carbon directly and therefore an attempt has been made to estimate the overall deposition from the amount of beryllium left on the inner divertor wall tiles [6].

2. Experimental

The gas box divertor (Mk IIGB) was first installed in 1998 in exchange for the Mk IIA divertor tiles. During the period with the MkII GB configuration there was an intervention in 1999 when a poloidal set of divertor tiles was removed and replaced with a special set of marker tiles. The special marker tiles were retrieved for analysis during the 2001 shutdown (period II). Another full set of divertor tiles which was exposed from 1998 to 2001 (period I) also became available for surface analyses. JET is operated with plasma facing components (PFC) made of carbon fibre composite (Concept I manufactured by Dunlop Ltd.). The special marker tiles consisted of two layers (prepared by Plansee AG); firstly, a thin layer (0.5 μm) of rhenium (Re), and secondly, a layer of a 90% carbon/10% boron mixture 2.5 μm thick. At the beginning of 2001 the vessel temperature was decreased from 320 °C to 200 °C and there were four weeks of operation in He prior to the 2001 opening.

Carbon and beryllium sources were determined using KS3 survey spectrometer which has lines-of-sight at the mid-plane and from the top of the vessel to the inner and the outer divertor. Sources were integrated over the diverted phases of all discharges in period I. We estimate that errors of order a factor 2 are possible in the campaign integrated quantities [6].

JET is fitted with a system of 4 retractable beryllium heads to evaporate beryllium on to the vessel walls. Evaporation is done typically once per operation week. Total amount of Be evaporated during period II is estimated to be 130 g.

Poloidal positions of the analysed samples are shown in Fig. 1. RBS measurements were carried out using the 3 MeV Van de Graaff accelerator of the University of Sussex. Secondary ion mass spectrometry (SIMS) analysis of the samples was made with a double focussing magnetic sector instrument (VG Ionex IX-70S) at VTT. Layer thicknesses were calculated using sputter rates determined with a profilometer from redeposited layers on tile 1 and 3 separately for the C- and Be-rich layers. Some selected SIMS samples were measured with TOF-ERDA using the 5 MV tandem accelerator EGP-10-II of the University of Helsinki. Inductively coupled plasma mass spectrometry (ICP-MS) was used for chemical analysis of beryllium in the inner divertor tiles 1 and 3.

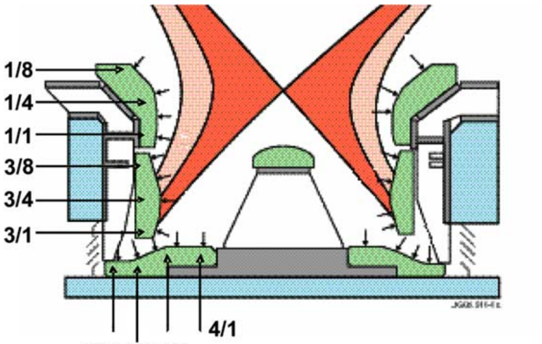

Fig. 1. The JET MkIIGB divertor tile set. The samples for SIMS and IBA measurements are indicated with numbers.

3. Results

SIMS depth profiling has been made from a number of samples on inner divertor tiles 1, 3 and 4. Fig. 2 shows typical depth profiles from marker tiles which were exposed during period II at JET. For each of the profiles, the rhenium containing marker layers are clearly visible at the interface between a deposited film and the CFC substrate. The deposit forms two layers on tiles 1 and 3. The outer layers (approx. 2–6 m thick on tile 1 and 10–16 μm on tile 3) contain mostly C together with D and smaller amount of Be. The surface composition is close to that found in deposits at the sides of limiters in the main chamber, and presumably to that arriving at the inner divertor along the SOL. The films underneath the surface layer are very rich in Be. On tile 1 the layer thickness of the inner Be-rich film varies between 2–14 μm, and on tile 3 between 12–21 μm. It thus appears that during the last part of the campaign, less C was being chemically sputtered from the films.

The film in the shadowed region on tile 4 (sample 4/10, Fig. 2(c)) is relatively pure C, with a very high D content, and with a well-marked interface to the CFC substrate. Be content in the deposit is very low. The film is ~85 μm thick, with a similar composition to that previously found for the flaking deposits at the inner louvres [7]. Deposits on the part of tile 4 shadowed by the septum are somewhat thinner (~15 μm). The D/C ratio varies from 0.3 (in the private flux region) to 0.8 (in the region shadowed by tile 3) [1]. The divertor inner wall tiles 1 and 3 exposed in period I contain similar deposits with a double layer structure. The layer thicknesses of the outer C-rich and inner Be-rich layer are, however, greater than on the marker tiles exposed in 1999–2001.

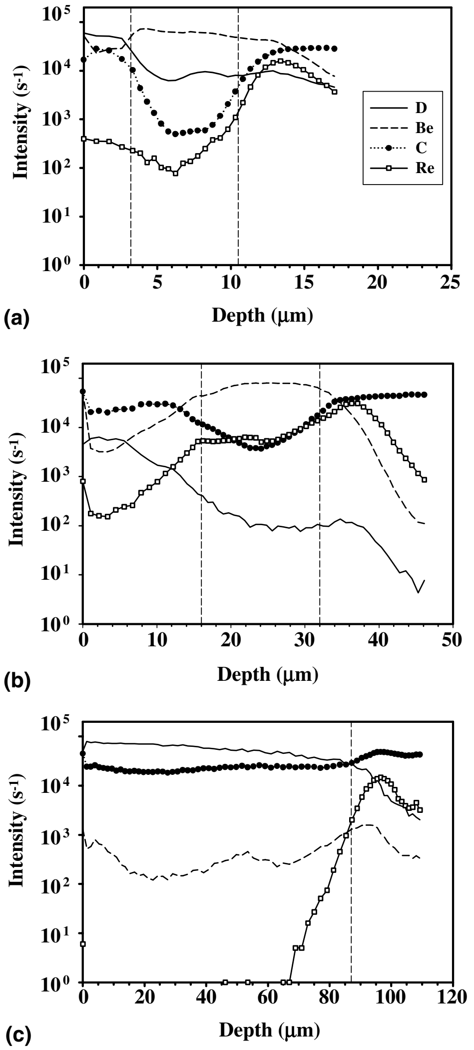

Fig. 2. SIMS depth profiles of D, Be, C and Re from (a) sample 1/1, (b) sample 3/4 and (c) from sample 4/10. Samples were exposed in 1999–2001. Vertical dashed lines show the approximate positions of the interfaces.

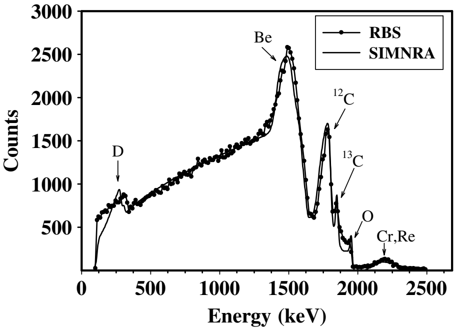

Fig. 3. RBS spectrum and SIMNRA simulation from the bottom of tile 1 which was exposed in 1999–2001.

Table 1
Composition of the deposit at the bottom of tile 1 exposed in 1999–2001 measured with RBS

Layer	D, at.%	Be, at.%	^{12}C, at.%	^{13}C, at.%	O, at.%	Cr, at.%
1	11	5	27	30	27	0
2	30	5	53	0	10	2
3	5	31	33	0	28	3

Fig. 3 shows a RBS spectrum measured from the bottom of tile 1 (sample 1/1). The spectrum was simulated using SIMNRA program [8]. The best agreement with the experimental spectrum was obtained by using three different layers in the simulations. Composition of the deposit is given in Table 1.

Ion fluxes measured with divertor Langmuir probes seem to be higher for tile 1 during 1999–2001 campaign than for 1998–1999 campaign (see Table 2). Langmuir probe measurements indicate that the 1998–1999 contributes only 14% of the total flux to tile 1 for period I, but for tile 3 the contributions of the 1998–1999 campaign and period II are almost equal. This may imply that the thickness of the deposit on tile 1 formed during period I and II should be comparable, whilst tile 3 should have twice the thickness of Be-rich film seen on the equivalent period II tile if films are additive. SIMS, RBS and ICP-MS analyses show that the films are thicker on the tiles exposed during period I, but SIMS measurements show that both the carbon rich outer layer and the carbon and beryllium oxide rich inner layers are similarly increased. In Table 2 ratios of total Be amounts on tiles mounted in 1998 to those of 1999 are given from RBS and ICP-MS measurements, plus the ratio of thickness of the Be-rich layers from SIMS. The deposited films are thicker on sample 1/8 and on tile 3 than the RBS analysis depth. All the results indicate that the deposits are thicker on tiles from period I and the results do not quite correlate with Langmuir probe results, especially in the case of samples 1/4 and 1/8. This suggests that the impurity profile within the SOL differs from the ion flux profile.

In an attempt to calibrate Be/C signal ratios for SIMS, RBS spectra for the tile 1 exposed in each of the periods I and II were simulated with SIMNRA, and the compositions of the deposits were calculated. SIMS Be/C signal ratios both for the inner and outer layers were plotted as a function of Be amount measured with RBS and a linear fit was made (see Fig. 4). Be amounts on analysed samples from tiles 1 and 3 exposed in period II were calculated using layer thicknesses determined with SIMS and compositions of layers from RBS, TOF-ERDA and SIMS analyses, and then integrated over the tile surface areas. A value of 1.6 g/cm^3

Table 2
Ratio of Be rich layer thickness in 1998 samples to that in 1999 samples measured with SIMS and ratio of Be amount in 1998 samples to that in 1999 samples measured with RBS and ICP-MS

Sample	SIMS (1998/1999)	RBS (1998/1999)	ICP-MS (1998/1999)	Ion flux (10^{26} mm^{-2}) 1998–1999	Ion flux (10^{26} m^{-2}) 1999–2001
1/1	1.1	1.7	1.3	0.09	0.65
1/4	2.6	2.5	2.0	0.086	0.84
1/8	1.6		1.1		
3/1	1.7		1.3	4.6	5.8
3/4	1.5		1.5	5.0	3.7
3/8	1.3		2.4	0.96	3.0

Cumulative ion fluxes measured with Langmuir probes closest to each sample for periods 1998–1999 and 1999–2001.

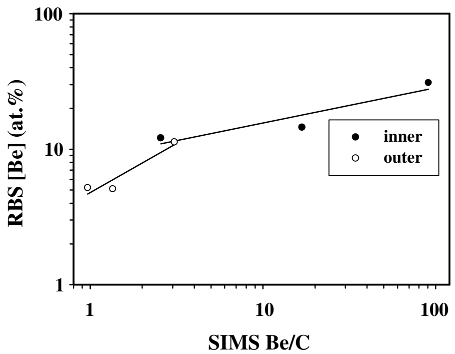

Fig. 4. Calibrations curves for SIMS. Be amount measured with RBS is plotted as a function SIMS Be/C signal ratios for inner wall tile 1 exposed in 1999–2001. Be/C ratios calculated separately for outer C-rich and inner Be-rich layer.

was used as the density of the deposits. The total amount of Be at the inner divertor can then be obtained by assuming uniform concentrations toroidally. The estimate for the total amount of Be at the inner divertor deposited during period II is 22 g. The uncertainty of the Be amount on tiles 1 and 3 is estimated to be 40%. This does not include possible toroidal asymmetry. Total amount of Be at the divertor inner wall tiles 1 and 3 obtained from surface analyses is clearly smaller than the total amount estimated to have been evaporated during period II.

4. Discussion

According to the analyses, the films on inner divertor wall tiles 1 and 3 are thicker on the tiles exposed in period I than on tiles exposed in period II, but both the carbon and deuterium rich outer layer and the carbon and beryllium oxide-rich inner layers are similarly increased. It could be that the outer region represents a modification of a film which was previously entirely Be-rich. During some operation phase at the end of the campaign (e.g. the change in vessel temperature, or operation in helium) chemical erosion was reduced at the inner divertor. If the ratios of discharge times of the low vessel temperature and He phase to the total discharge time for period I are compared with the ratios of outer C-rich layer to total thickness of the deposits, it can be observed that the discharge time ratio for the He phase is too small. Discharge time ratio for the low temperature phase, however, agrees quite well with the ratio of layer thicknesses. This does not, however, exclude the possibility that it was the He phase which changed the composition of the deposits.

It seems reasonable that at deposition dominated areas in the inner divertor, the films on tiles exposed in period I should be a composite of the film found on the tiles exposed in period II on top of the film deposited during the 1998–1999 campaign. However, another possible scenario is that there is a certain amount of erosion and re-deposition of elements at the inner divertor walls before they are finally buried within the surface films. Each erosion/re-deposition step involves toroidal transport of the order of centimetres, so the clean tiles installed in 1999 may end up with a typical tile analysis for that poloidal location, not an analysis characteristic only of its period in the vessel. On the other hand, the floor tile 4 gives rather different analyses in the cases of periods I and II, which cannot be explained by exposure time. Another possibility is therefore a toroidal variation in tile film thickness.

The picture we have of material migration in JET is erosion of C and Be from the main chamber, ionisation in the SOL and transport mainly to the inner divertor driven by parallel flows. The primary source of Be in JET is thought to be the periodic evaporation. C is subsequently eroded due to chemical sputtering. Spectroscopic measurements show that C is eroded and redeposited about 10 times before being finally deposited at remote areas in the divertor [6]. Be does not, however, appear to migrate significantly within the divertor. The amount of C deposited at the inner divertor in Mk IIA from 1996–1998 was estimated as ~1 kg, from the amount of tritium co-deposited with the C [1]. Since there was no tritium used during the MkIIGB phase in period I, the amount of deposition has been estimated from the Be build-up found on tiles 1 and 3 which are the only sinks for Be. This result is combined with the assumption, that the Be/C ratio arriving in the divertor is the same as the Be/C ratio in the main chamber. For the first pulse immediately after a Be evaporation there is a large Be plasma impurity fraction, but this rapidly drops to just a few per cent of the C, and the average Be level is ~7% of the C [6]. If we then take into account the Be impurity level of ~7% of the C in the plasma, we obtain ~400 g of deposited C. Estimations on deposited C amounts can be obtained from SIMS, RBS and quartz micro-balance (QMB) [9] measurements in a manner similar to that used for Be. The amount of deposited C at the inner divertor including tiles 1, 3 and 4 is estimated to be 310 g. At the louvres the amount of deposited C varies between 20 g and 60 g based on measurements using QMB and deposition monitor sample [9]. The amount of deposited C on the septum is relatively low and it is estimated to be 10 g. Thus, the total amount of deposited carbon is 340–380 g, which is in good agreement with the amount that was calculated from the deposited Be amount.

Be amounts from post-mortem tile analysis have earlier been correlated with calculations of Be flux from spectroscopic measurements for Mk IIGB [6]. According to spectroscopy data the wall carbon source was estimated to be 390–480 g and the Be wall source 20 g. Previous tile analyses predicted that the net C and Be deposition in the JET divertor is 2 to 4 times greater than the spectroscopy data for the main chamber sources. However, the earlier estimates were made before proper calibration of SIMS Be/C ratios was available. After calibration of SIMS, the results are now much more in line with the spectroscopy data. Both surface analyses and spectroscopy data now indicate that the average deposition rate during the MkIIGB phase (1999–2001) is somewhat lower than during MkIIA phase (1996–1998).

5. Conclusions

A double layer structure, with a C-rich outer layer and a C- and Be-rich inner layer, has been observed on JET inner divertor tiles 1 and 3 removed in 2001 by post-mortem surface analyses. The amount of Be deposited on the inner divertor wall tiles has been calculated, and by assuming that the ratio of C to Be arriving in the divertor is the same as the ratio in the main chamber, the amount of C deposited has been computed. On the basis of this analysis, the amount of C deposited is ~0.4 kg.

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