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ABSTRACT.
Carbon and beryllium migration within JET has been measured by post-mortem analysis of divertor and main chamber tiles removed after 2-3 year periods of plasma operation in JET [1,2,3]. Impurity sources and screening have also been studied in individual pulses using puffs of CD_4 to provide a calibration for the spectroscopic sources [4]. In this paper, we discuss the consistency of the deposition measured in the divertor with the spectroscopically determined sources integrated over the relevant periods of operation.

1. CALCULATION OF CAMPAIGN INTEGRATED SOURCES FROM SPECTROSCOPY

The relationship between the carbon influxes and the spectroscopic signals (CIII - 4647Å) available experimentally was derived from an ensemble of EDGE2D/NIMBUS simulations [4] of L-mode and inter-ELM H-mode plasmas spanning a wide range of parameters. The code results were then post-processed by a diagnostic simulation code which takes account of diagnostic viewing geometry and ADAS atomic data. This provides a purely simulated relationship between total main chamber and divertor impurity sources and spectroscopic signals for actual JET diagnostic lines of sight (fig.1).

To validate this method, experimental spectroscopic data were used to derive total wall and divertor carbon sources for specific shots using the scale factors derived from the simulations. These carbon influxes were then combined with empirical screening factors from CD_4 injection experiments in order to predict intrinsic Z_{eff} for these shots. This method reproduced both the absolute value and scaling of intrinsic Z_{eff} in L and H-mode plasmas with density, power and confinement time thus showing that derived carbon sources and screening are consistent with plasma impurity content.

Beryllium sources were also quantified in a similar manner using visible spectroscopy (BeII at 5272Å). The absence of empirical screening data for beryllium means that the EDGE2D/NIMBUS results for a beryllium wall cannot be independently validated. However, the work with carbon has validated the approach and all we need from the modelling is the relationship between total wall influx and the spectroscopic signal.

1.1 INTEGRATION OVER CAMPAIGNS

Wall and divertor sources were integrated over the diverted phases of all discharges in the periods for which the tile samples were exposed. Other relevant diagnostic data were collected in a similar way. We estimate that errors of order a factor 2 are possible in the campaign integrated quantities.

2. ESTIMATES OF CARBON AND BERYLLIUM DEPOSITION FROM SURFACE ANALYSIS

In the MkIIGB phase (1999-2001), figure 1, the amount of carbon deposited on the plasma facing sides of the divertor tiles is measured by direct thickness measurement [1] and SIMS depth profiling calibrated to surface concentration by TOF-ERDA[2]. However, the majority of the carbon is

transported to remote areas such as the divertor septum and inner pump duct by chemical erosion and these areas have not been fully investigated. However, the available data from remote areas suggests a lower limit of 500g of C deposition.

2.1. MEASUREMENTS OF DEPOSITED BERYLLIUM

The primary source of beryllium in JET thought to be the periodic evaporation. In contrast to carbon, beryllium is only found in significant quantities on divertor tile surfaces which are in contact with the plasma. Almost all of the beryllium found in the divertor is located on the inner vertical target and is highly enriched (Be:C>10:1) throughout most of the deposit due to preferential chemical erosion of the carbon [1,3]. Combining this data we can estimate that 91g of beryllium was deposited in the divertor during the MkIIGB phase (1999-2001). It should be noted that although the sample tiles were only installed from 1999-2001, migration from neighbouring tiles might make the data more representative of the whole MkIIGB campaign in which case the deposition rate could be overestimated by up to a factor 2.

2.2. ESTIMATING CARBON DEPOSITION FROM BERYLLIUM

Comparing EDGE2D/NIMBUS simulations with pure beryllium and carbon walls we have computed the relative photon efficiencies for BeII (5272Å) with CIII (4647Å) for our main chamber lines of sight. Averaged over the MkIIGB phase (1999-2001) we estimate that the main chamber beryllium influx is 7% that of carbon. Since we know the mass of beryllium deposited on the divertor, we can compute the amount of carbon assuming that the ratio of carbon to beryllium arriving in the divertor is the same as the observed source ratio in the main chamber. On the basis of this analysis we would expect there to be 1.7Kg of carbon deposited. This gives an average carbon deposition rate similar to the estimate made from the JET tritium experiment DTE1 (table 2) for which the MkIIA divertor was installed (fig.1). In MkIIA, carbon deposition (1Kg) was estimated from the long term tritium retention and the tritium content of flakes recovered from the inner pump duct [5].

3. RESULTS

3.1. CAMPAIGN INTEGRATED PARAMETERS COMPARED TO ONE ITER PULSE

In terms plasma duration both JET campaigns are equivalent to ~200 ITER pulses (table 1). Scaled by input energy the JET campaigns were equivalent to ~4 ITER pulses and related to the divertor ion fluence the campaigns equalled one third of an ITER pulse.

Basic Parameters (table 1)	MkIIGB (1999-2001)	MkIIa (1996-1998)	ITER
Integral time in diverted phase	16hrs	19hrs	0.1hrs
Number of pulses	5748	8130	1
Energy input to JET	220GJ	260GJ	60GJ
Average power	4.5MW	4MW	150MW
Divertor ion fluence	1.8×10^{27}	2.5×10^{27}	6×10^{27}

3.2. WALL SOURCES AND DIVERTOR DEPOSITION

The picture we have of material migration in JET is of erosion of carbon and beryllium from the main chamber, ionisation in the SOL and transport mainly to the inner divertor driven by parallel flows. Since the only possible sources of Be are in the main chamber and Be does not appear to migrate significantly within the divertor, we would expect that our estimate of the Be wall source should equal or exceed the amount found in the divertor (to allow for some diffusion of ions back to the main chamber wall). In fact, our measured Be and C wall sources (table 2) account for around one quarter of what is found in the divertor. Note that MkIIGB screening factors were used when computing the MkIIa wall source from the intrinsic Z_{eff}.

Sources and deposition yields (table 4)	MkIIGB (1999-2001)	MkIIa (1996-1998)
Wall carbon source from horizontal CIII	390g (8×10^{-3}gs^{-1})	390g (6×10^{-3}gs^{-1})
Wall carbon source from Z_{eff} + screening	480g (8×10^{-3}gs^{-1})	790g (11×10^{-3}gs^{-1})
Divertor C deposition	1700g (35×10^{-3}gs^{-1})	1000g (15×10^{-3}gs^{-1})
Wall Be source from Bell	20g (0.4×10^{-3}gs^{-1})	32g (0.5×10^{-3}gs^{-1})
Divertor Be deposition	91g (2×10^{-3}gs^{-1})	Under analysis

Carbon could also be generated within the divertor from the tile material but measurements of a poloidal set of MkIIGB tiles indicates little erosion and so the main chamber carbon source should equal or exceed the divertor redeposition.

Despite the different divertor geometries in the MkIIA and MkIIGB phases, average main chamber sources and divertor deposition rates are similar (table 2).

3.3. SPUTTERING YIELDS AND BE WALL COVERAGE

Our analysis of the divertor carbon fluxes, also based on the calibrated CIII spectroscopy [4], shows that that the total carbon flux from the divertor surfaces is about ten times the carbon flux entering the main plasma from the wall (table 3).

Wall to target influx ratios (table 3)	MkIIGB (1999-2001)	MkIIa (1996-1998)
Divertor C influx / Wall C influx	9	14
Divertor Be influx / Wall Be influx	1.7	2.6

This is consistent with the picture of C atoms arriving in the divertor from the main chamber and being eroded and redeposited about ten times before being lost to remote areas. In contrast, the divertor Be flux is only about twice the main chamber influx which is consistent with the much slower rate of migration seen for the Be by surface analysis.

Effective sputtering yields (table 4)	MkIIGB (1999-2001)	MkIIa (1996-1998)
C sputtering yield - divertor	3.2%	4.7%
C sputtering yield – main wall	4.5%	4.2%
Be sputtering yield – main wall	0.3%	0.4%

Campaign integrated divertor ion fluences deduced from D_α (S/XB = 20) were similar to ion saturation currents from divertor Langmuir probes (within 20% in the outer divertor and to within a factor 2 in the inner divertor). The average sputtering yields in the inner divertor, outer divertor and main chamber (table 4) derived from combining the particle fluxes deduced from D • with the carbon fluxes derived from CIII spectroscopy are all close to 4%. Beryllium on the other hand, has a much lower effective yield in the main chamber due to the partial surface coverage by beryllium in this area. For experimental yields to be consistent with our modelling with a pure beryllium wall the campaign averaged surface concentration of beryllium would need to be ≈20%.

4. EXTRAPOLATION TO ITER WITH A PURE BERYLLIUM WALL

In scaling first wall Be erosion from JET to ITER we first increase the erosion/deposition rates in JET by a factor 5 to allow for the partial coverage of the wall by Be. If we then extrapolate to ITER on the basis of input energy alone (table 1), which is equivalent to assuming the same flux distribution and energy per particle in the two machines, the beryllium deposited in an ITER pulse is similar to that seen in the whole of the MkIIGB campaign i.e. 40-110g (the range indicating the spectroscopic or surface analysis data).

Alternatively we can extrapolate on the basis of the divertor ion fluence (table 1) and assume that the ratio of divertor flux to wall flux is ten times higher in ITER than JET. This approach gives an erosion rate of 45-135g per ITER pulse which is very similar that obtained on the basis of the energy.

These simple extrapolations have considerable uncertainty and future work will be aimed at scaling the results with EDGE2D/NIMBUS and other edge codes. Extrapolation of main chamber carbon sources is not relevant because ITER will not have a carbon main chamber wall. The critical question is whether the beryllium deposition will be sufficient to suppress the carbon erosion in ITER and thus reduce the tritium retention. Without experiments in an ITER relevant tokamak with an all beryllium (and carbon free) main chamber wall this question cannot be reliably answered.

CONCLUSIONS

We conclude that the net carbon and beryllium deposition in the JET divertor are 2 to 4 times greater, than our estimate for the main chamber sources. This suggests that there may some other mechanisms such as material transport due to ELMs or erosion of the Be ICRH antenna screens which we are not correctly accounted for spectroscopically. However, the discrepancy may simply reflect systematic errors in our measurements both of the wall sources and surface analysis techniques which are difficult to quantify. Although there is some question over the level of quantitative agreement, both the spectroscopic sources and surface data are consistent with the picture of substantial material migration from the main chamber to the divertor where beryllium layers are enriched and carbon migrates to remote areas.

ACKNOWLEDGEMENTS

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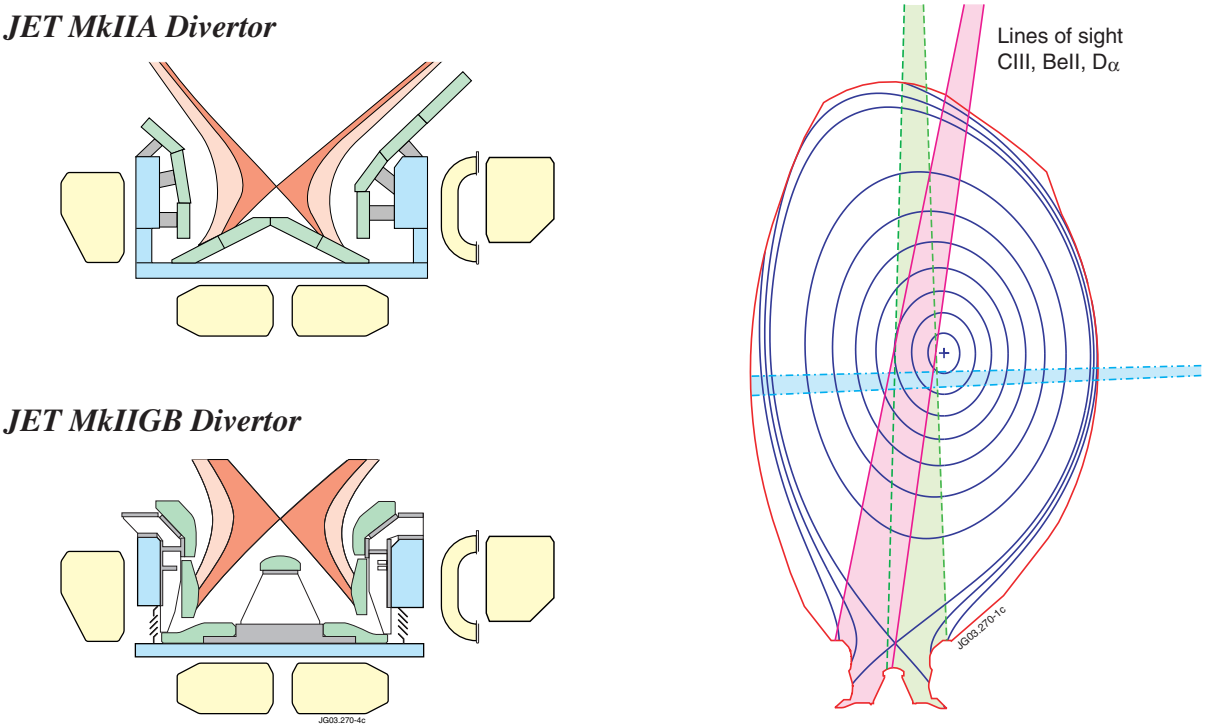

Figure 1: Divertor geometry during the MkIIA and MkIIGB campaigns and the lines of sight used in determing the carbon and beryllium influxes.