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Modification of the Carbon and Beryllium Walls in JET by Erosion, Redeposition and Deuterium Trapping after the 1991 Discharge Period

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ABSTRACT

After plasma operation in 1991 samples were cut from C and Be tiles of the JET vessel walls, limiters, and X-point tiles along a poloidal cross-section in octant 4W, and the surface layers were analysed by the MeV-ion beam methods NRA, PIXE and RBS to determine the D and metal impurity distributions. The amount of trapped deuterium ranges from $5 \cdot 10^{15}$ to $5 \cdot 10^{17}$ D/cm^2, metal impurities such as Ni, Cr, and Fe are in the range of 10^{15} to $3 \cdot 10^{16}$/cm^2, Cl in the range of 10^{16} to 10^{18}/cm^2, K and Ca in the range of 10^{15} to 10^{16}/cm^2 and Ti about 10^{15}/cm^2. Except for Cl, all measured concentrations are a factor of up to about ten lower than those observed on JET walls tiles before Be evaporation and Be wall components were used. This observation is in agreement with the reduced impurity concentrations measured in the JET plasma. The D and impurity distributions along the X-point tiles were analysed in some detail. Generally, the deuterium trapping and impurity deposition show minima at areas where erosion dominates and amounts a factor of about ten larger in between.

INTRODUCTION

Controlled thermonuclear fusion research aims to confine the hot plasma within closed nested magnetic surfaces. However, drift and diffusion across the magnetic surfaces, limit this confinement, and the plasma comes in contact with the vessel walls. These are generally designated such that the major plasma load is taken by special components, such as limiters and divertor plates [1, 2]. During plasma operation erosion and redeposition are observed on the different wall areas. This causes material transport and modification of the composition of the vessel walls [3 - 7]. These processes have been studied in JET since the beginning of its operation [8 - 10].

In a future fusion device, such as ITER [11], these processes will be increasingly important. First estimates show that this material transport may make up several kg per year [11]. Furthermore, the relatively large amount of hydrogen which is collected in the vessel walls presents a major tritium inventory problem.

JET has been operational since 1983 for a total of about 28,000 discharges, corresponding to about 100 hours of operation, and its vessel walls have undergone considerable modifications. In 1990 several major wall components were renewed, namely parts of the limiters and the X-point tiles. Close to the end of the 1991 discharge period, thermonuclear fusion reactions in a plasma containing about 10% T and 90% D were demonstrated for the first time [12].

In this work samples were cut from the last installed Be and C wall tiles and were analysed with MeV ion beam techniques, giving a fairly complete D and impurity concentration distribution along a poloidal cross-section of JET.

EXPERIMENTAL

In the 1990/91 discharge period of JET with approximately 2000 discharges for times between 15 and 60 sec., including three discharges in D with the addition of T, the total discharge time was about 18 hours. During this period the vessel walls were regularly conditioned by Be evaporation. After opening of the vessel, targets of about $2\times1\times0.5$ mm^3 were cut from several tiles from the X-points, limiters and some other wall areas of the vessel wall along a poloidal cross-section in Octant 4W as shown in Fig. 1. The samples chosen were representative of the poloidal cross-section.

The upper and lower halves of the poloidal cross-cross are geometrically almost symmetric with respect to the midplane. However, different materials were installed in the top and bottom parts. The discharges were run partly with the limiter configuration, partly with the divertor configuration either with the lower Beryllium X-point plates, or the upper Carbon X-point plates, or both (double null X-point). The high power discharges in preparation for the preliminary tritium experiments (PTE) [12] used an upper X-point configuration (i.e. Carbon X-point plates).

Apart from the Be belt limiter in the upper torus, and the Be X-point tiles in the lower torus, most other wall components subjected to high plasma load consist of graphite, which protects most of the inconel vessel wall.

The surface layer composition of the C and Be samples was analysed by ion beam techniques, using the Garching 2.6 MeV Van de Graff accelerator. D was measured with NRA (Nuclear Reaction Analysis) within a layer of about 500 nm, and the impurities were measured by PIXE (Particle Induced X-ray Emission) within a layer of a few thousand nm and by RBS (Rutherford Backscattering Spectroscopy) within a layer of about 500 nm.

RESULTS

The concentrations measured along the poloidal cross section are summarised in Figs 2 to 4. There is no major difference between the concentrations measured on the Be and the C samples. The concentration of light elements such as Be, C, O, N, has not yet been evaluated in detail, however, they are expected in greater concentrations than the metals which mostly originate from the vessel walls [13].

Deuterium distribution

The measured distribution of D along the poloidal length in the lower and upper torus is shown in Fig. 2. The D coverage is poloidally fairly uniform along the walls within one order of magnitude (with values of about 10^{17} D/cm^2). This amount is very similar to that observed on the 1990 Be belt limiter [13]. In the areas of the largest plasma load, i.e. at limiters and X-point plates, the D concentration shows the largest variation up to one order of magnitude. An attempt to analyse deposited tritium with a sensitivity of 10^{13} T/cm^2 gave no tritium evidence.

Distributions of metal impurities (Ni, Cr, Fe, Ti, Cu)

The distribution of Ni along the poloidal length in the Torus is shown in Fig. 2. Ni concentrations up to 5×10^{16} Ni/cm^2 are observed all along the torus poloidal length, apart from the X-point tiles and the belt limiters, where the expected and observed erosion-dominated processes allow for Ni coverages $<2 \times 10^{16}$ Ni/cm^2, down to about 5×10^{14} Ni/cm^2.

The same distribution pattern as for Ni is observed for Cr (Fig.2), the concentrations for Cr (between 10^{15} and 10^{16} Cr/cm^2) being smaller than for Ni approximately in keeping with the composition of the different elements in the wall material Inconel, containing Ni, Cr, Fe, in decreasing percentage (80%, 14%, 6%).

Fig. 3 shows the Fe concentrations, ranging from 10^{15} to over 10^{16} Fe/cm^2. The distribution is similar to the Ni and Cr concentration distributions shown above. However, the Fe concentrations measured on the Be samples are higher than in Inconel. This is probably due to Fe being a bulk impurity ~ 570 ppm in Be. This is an additional source of Fe, which is redistributed by erosion and deposition during the JET discharges.

Similar considerations as for Fe hold also for the Ti concentration (around 10^{15} Ti/cm^2) distribution shown in Fig. 3, Ti being also a bulk impurity of 55 ppm in Be.

The measured Cu distribution ranges from 10^{16} Cu/cm^2 to 10^{17} Cu/cm^2 at the Be X-point tiles (Fig. 3). Cu is not contained in Inconel but it is an impurity in Be. A possible source of Cu in JET is also the neutral beam injection system. Further, the Faraday shield of the sample in the analysing chamber, is made of Cu, resulting in a uniform background of Cu in the PIXE spectra. This means that a constant background has to be substracted for the Cu signal.

Distribution of non-metallic impurities

The non-metallic impurities Ca, K, Cl (Fig. 4) have a distribution similar to that of the metals, with concentrations for Ca and K as already observed from previous JET wall analysis ($5 \cdot 10^{14} - 5 \cdot 10^{15}$ Ca/cm^2, $5 \cdot 10^{15} - 5 \cdot 10^{16}$ K/cm^2).

The Cl concentrations on the wall components range between 10^{17} and 10^{18} Cl/cm^2, somewhat higher than in previous JET wall analysis. On the Be targets the Cl concentrations are lower than on the C-targets, i.e. below 10^{17} Cl/cm^2.

DISCUSSION

The nearly uniform poloidal distribution of the measured D deposition of about 10^{17} D/cm^2 allows one to estimate the total D-inventory in the surface layer of the vessel walls if one further assumes toroidal uniformity. For a vessel wall area of 200 m^2 this gives a D inventory of about $2 \cdot 10^{23}$ D-atoms. In one JET discharge the total amount of D is about $8 \cdot 10^{21}$ D-atoms [15]. This means that after the integrated JET plasma operation of 18h the vessel walls contain the same amount of D as in the plasma of about 25 discharges. If all discharges were performed in a mixture of 50% D and 50% T, this would correspond to an inventory in the surface layers of the vessel of about $1 \cdot 10^{23}$T atoms.

The D inventory was also evaluated at the end of previous discharge periods of JET with carbon-dominated vessel walls and limiter/divertor plates [16]. The results are summarised in Table I. The lower (1/2 and 1/4) D inventory observed after this last discharge period is certainly due to the different composition of the plasma-facing material, i.e. the repeated Be evaporation and the presence of the upper Be limiter and lower Be X-point tiles. It should be pointed out, furthermore, that in all the measurements D was analysed only in a surface layer of about 500nm. A more detailed measurement at a C-limiter tile of JET, using a different technique, showed that the total amount of trapped D may be a factor of up to ten larger [17, 18]. The numbers given here represent lower limits.

Table I. D, retained in the surface layers of the JET vessel after the four discharge periods [16].

Discharge period	Number of discharges	Total D content ($x10^{23}$)
1985	1800	6
1986	2800	3.5
1987	250	4.7–7.2
1990/91	2000	2

It is further possible to estimate the total amounts of the redeposited metals and other elements on the vessel walls by assuming toroidal symmetry. The results are summarised in Table II.

Table II. Amounts of the different elements in the surface layers of the JET vessel after the 1990/91 discharge period.

Element	D	Ni	Cr	Fe	Ti	K	Ca	Cl
Quantity ($x10^{23}$ atoms)	2	0.6	0.2	0.3	0.03	0.06	0.01	10
Weight (gr)	0.66	5.8	1.7	2.7	0.32	0.4	0.16	44

The largest deposition measured is Cl, which is even larger than the measured amount of trapped D. The origin of these large quantities of 44gr of Cl is not clear, but Cl was also found spectroscopically to be a major impurity in the plasma, causing energy loss (20% to 75% of the total radiated power) by radiation [19].

The sum of all metals gives an amount of 10.5gr eroded and redeposited at the vessel walls in the last discharge period. The Ni, Cr and part of the Fe atoms originate from the Inconel vessel walls and are probably eroded by sputtering due to bombardment with energetic charge exchange (CX) hydrogen atoms from the plasma. Fe and Ti are impurities in the Be and are redistributed by erosion and deposition.

The measured poloidal distribution shows deposition minima at the limiters and X-point tiles, i.e. in the areas subjected to the largest power loads from the plasma. In these areas erosion dominates, but even at these erosion dominated areas metal deposition is found. Erosion and deposition are also observed in most areas of the vessel wall, where deposition dominates.

The similarities in the distributions of D and the other elements suggest that the major D-trapping mechanism is codeposition with all the other deposited elements.

Finally, large deposits of Be, C and O were found, but have not yet been evaluated in detail. Including these deposits, the weight transported by erosion and deposition is in the range of 10 to 20 gr in 18 h. This corresponds to a net weight transported of several kg per year for continuous operation, in agreement with the ITER prediction.

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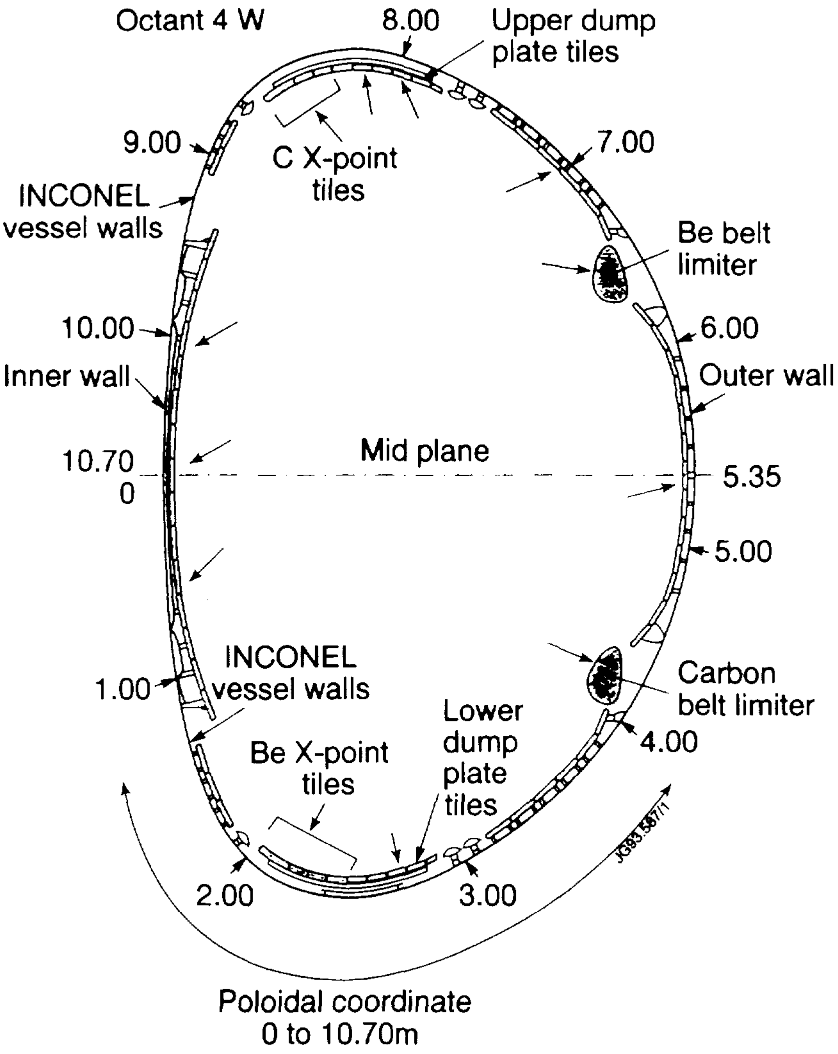

Fig.1 Poloidal cross-section of the JET torus. In the lower half-torus along the poloidal coordinate counter clockwise from 0 to 5.35 m one observes the C inner wall tiles, the Inconel vessel walls, the Be X-point tiles, the C outer wall tiles with the C belt limiter. In the upper half-torus along the poloidal coordinate further counter clockwise from 5.35 m (midplane) to 10.70 m one observes the C outer wall tiles with the Be belt limiter, the C X-point tiles, the Inconel vessel walls, and the C inner wall tiles. The areas from which the samples were cut are indicated by arrows.

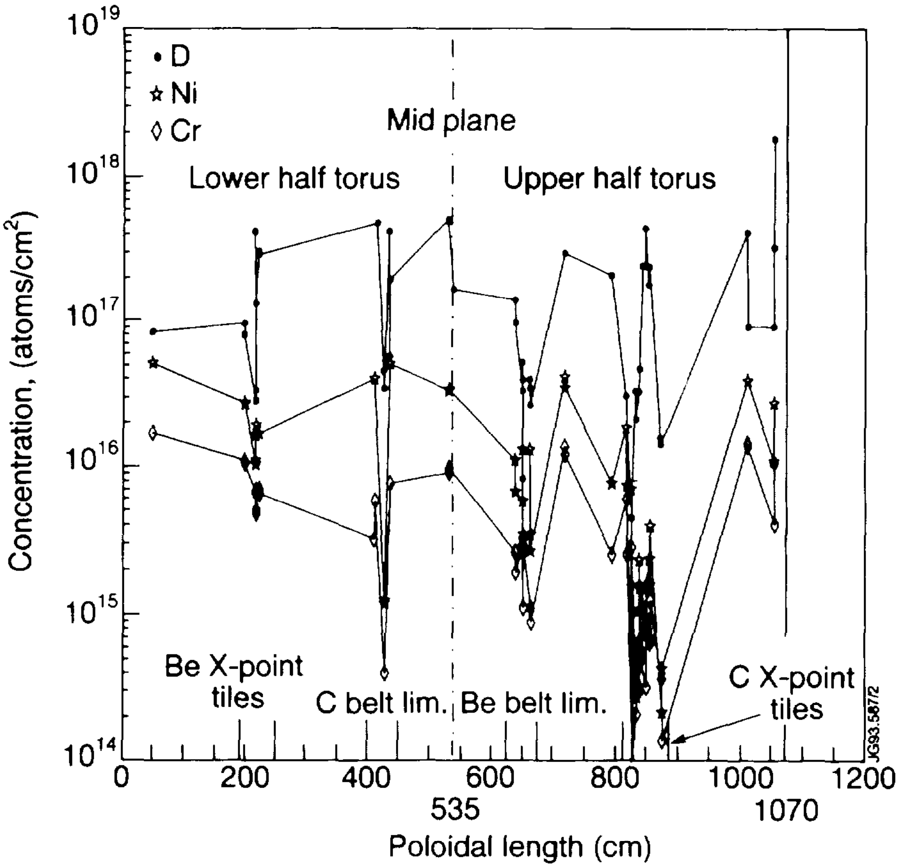

Fig. 2 D, Ni, Cr poloidal distribution in the JET poloidal cross section.

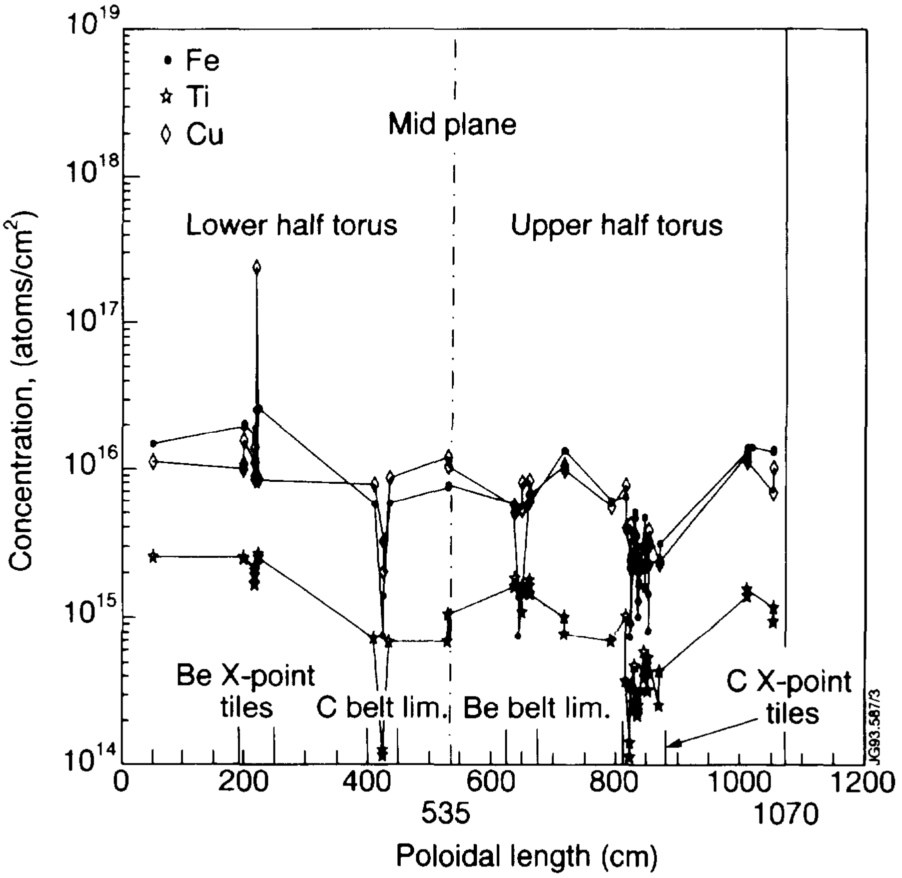

Fig. 3 Fe, Ti, Cu poloidal distribution in the JET poloidal cross-section.

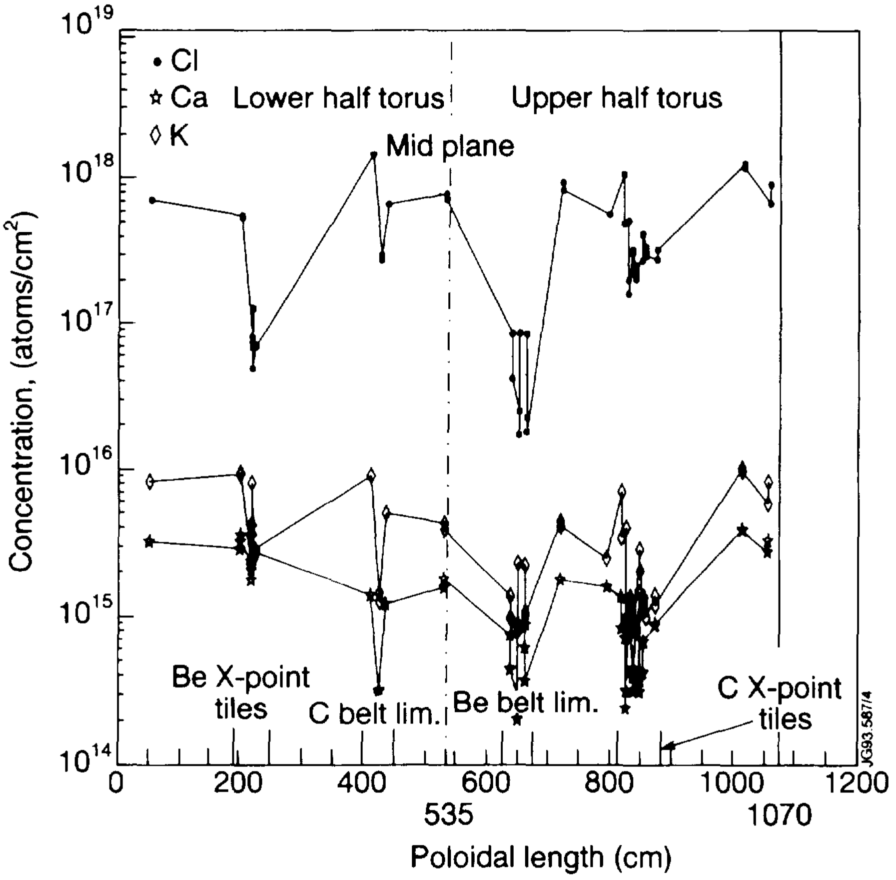

Fig 4 K, Ca, Cl poloidal distribution in the JET poloidal cross-section.