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Erosion and deposition behaviour of a-C:H layers in the private flux region of the JET MKII-HD divertor

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ABSTRACT

Material deposition was measured in the private flux region of JET by means of a quartz microbalance (QMB) for ∼11 900 s of successive plasma discharges with moderate additional heating (2–3 MW). The QMB was located under the load bearing septum replacement plate with a view towards the inner divertor. In total a ∼270 nm thick hydrogenated amorphous carbon layer was measured assuming a density of 1 g/cm^3 correlated with a fluence of 2.36×10^{23} D$^+$ ions into a toroidal section of 1 cm length of the inner divertor. The area of the QMB in the private flux region was deposition dominated when the inner strike point position was on the vertical tiles, line-of-sight with the quartz crystal, and turned into erosion solely by moving the strike point from vertical tile 3 to horizontal tile 4. The most likely reason is a change of the C/D flux ratio of the particles impinging on QMB turning this area from a deposition to an erosion dominated region.

1. Introduction and motivation

The applicability of carbon fibre composite (CFC) as the target plates of ITER depends strongly on the erosion and redeposition behaviour of graphite and co-deposition of tritium in subsequently formed amorphous hydrogen rich carbon (a-C:H) layers on plasma wetted and remote areas. Progress in understanding of the underlying physics of these processes has been recently achieved by quartz microbalance diagnostics (QMBs) installed at different locations in the divertor of JET [1]. It allows for in situ and shot resolved measurements of material (carbon) deposition in remote areas of the divertor. An overview of QMB investigations during JET campaign 2005–2007 can be found in [2]. This contribution reports in particular on measurements from a QMB which was placed in the private flux region (PFR) of the MKII-HD divertor. The QMB is located below the supporting wedge of the load bearing septum replacement plate (LBSRP) with a direct view towards the lower vertical tile of the inner divertor. The position is analogue to the lower dome region facing the inner divertor of ITER.

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[1] See the Appendix of M.L. Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA, (2006).

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2. Experimental

The QMB was positioned beneath the load bearing septum removal plate, LBSRP, behind a diagnostic protection tile 5a, as shown in Fig. 1. A gap like aperture in the protection tile provides an open view towards the inner divertor plasma. It is line-of-sight with the vertical tiles 1 and 3 and partly with the horizontal tile 4. The QMB is recessed in a gap by 4.5 cm from the front surface of the protection tile. Thus only neutral atoms – or macroscopic C-clusters containing deuterium atoms D can contribute to the erosion/deposition processes on the QMB. The crystal surface of this QMB is continuously exposed during JET operations. It measures the integral deposition during a plasma discharge including start up and ramp down phase. A frequency resolution of ±3 Hz is achieved under the JET conditions, corresponding to a thickness of approximately one monolayer for typical redeposited carbon layers with densities of about 1 g/cm^3 [3]. The sensitivity is 4.4×10^{14} C$_{at}$/Hz cm^2 and the sensitive area 0.95 cm^2 with a toroidal extension of ≈1 cm. The measuring method and use of QMBs is explained in [1,4,5]. Since the frequency depends not only on mass but also on temperature, a second quartz crystal is placed inside the QMB housing and protected from plasma impact to separate mass from thermal effects. Thermal equilibrium of both crystals is a necessary condition for reliable measurements.

3. Results and discussion

The presented database derives from 607 successive discharges from the JET restart in 2005 (JET Pulse Numbers, (JPN)

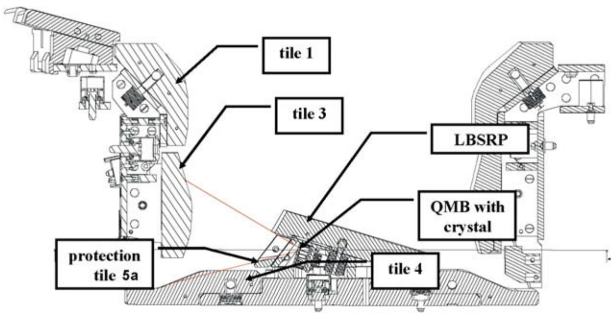

Fig. 1. Location of QMB in private flux region of the MKII-HD divertor of JET.

64 861–65 697) with a total divertor plasma time of about 11 900 s. Throughout this period in most of the discharges the QMB crystals did not reach thermal equilibrium on a shot by shot basis due to the high plasma pulse repetition rate. Thus, only data measured in the morning before start of plasma operation were evaluated to ensure optimal thermal equilibrium over night. Therefore, the data deliver absolute values for layer erosion/deposition averaged over a group of successive plasma pulses, mostly on a daily basis. Seventeen pulse groups were evaluated and labelled with the number of the first pulse of the group. The frequency of the crystal, ν, which is directly proportional to the mass of both the crystal and a deposited layer on top of the quartz, is plotted for each group of pulses in Fig. 2 versus the JPNs.

Increasing frequencies – as shown in the shot sequences marked II and IV – represent layer deposition whereas the frequency decrease in sequence III represents erosion. Neither deposition nor erosion was observed in sequence I since no deposited layer was left from previous operation to be eroded in sequence I. The erosion/deposition measured on the quartz is caused by complex physical and chemical processes on the target plates [6]. D ions and impurities (C, Be) from the main chamber plasma hit the carbon fibre CFC divertor tiles at the strike point releasing neutral deuterium and eroded carbon species. The eroded carbon is distributed onto adjacent tile surfaces and into remote areas and forms with deuterium hydrogenated amorphous carbon co-deposits. The source of the neutral D, responsible for erosion during layer formation, is as well localized at the strike point. Net layer formation is always a superposition of deposition proportional to incoming carbon fluxes and erosion due to deuterium fluxes. Since deposition and erosion are competing processes, the flux ratio C/D determines largely the net erosion or net deposition of the layer. It is these net processes which are measured by the QMB crystal located in the PFR.

Fig. 3 shows the absolute number of C-atoms deposited on the QMB as a function of the D^+ fluence impacting onto a toroidal section of 1 cm length of the inner divertor, the same toroidal extension as the QMB. The final value of 1.3×10^{18} C_{at} corresponds to a layer thickness of 270 nm, a density of 1 g/cm^3 assumed. The plot reflects again the deposition/erosion sequences as appeared in Fig. 2. The D^+ ion fluence is measured by the D_α – light in the inner divertor [7] using geometrical factors and an D/XB of 20 which includes a correction of deuterium molecules [8]. The plot shows the turn over from deposition into erosion and back into deposition together with different erosion/deposition yields $Y_{C/D+}$ of removed or deposited C-atoms per incident ion on the inner targets. This yield $Y_{C/D+}$ averaged over pulse groups is shown as a bar graph in Fig. 4. A broad scatter in the yield is observed to a maximum value of $+2.5 \times 10^{-5}$ C/D^+ for deposition in pulse group 64977 to a maximum value of erosion of $\sim -2.5 \times 10^{-5}$ C/D^+ in pulse group 65 370. A yield of $+2.5 \times 10^{-5}$ C/D^+ means that about 40 000 D^+ ions are required to enter a toroidal section of 1 cm length of the inner divertor to deposit 1 C-atom on the QMB. The negative yields are related to the sequence III in Fig. 3 and quantify the averaged erosion per D^+ ion hitting the target of the inner divertor. The probability for a C-atom released at the strike point to contribute to the net layer formation on the QMB was estimated as follows. The incoming D^+ flux produces C-atoms with a yield of 2% at the strike point. Fifteen percent of the C-atoms are assumed to escape the local redeposition. These are typical numbers obtained from ERO modelling of standard inner divertor plasma conditions in JET [9]. Further, carbon particles are assumed to be released normal to the surface towards the QMB. A geometry factor of 5, the ratios of the area of C released on the target to the deposition area on the QMB is considered. Based on those assumptions for pulse group 64977, 6.2×10^{18} C-atoms escaped a 1 cm^2 area of the target and hit the QMB whereas 2.7×10^{17} C-atoms were deposited. Thus the yield C released to C deposited is 4.3×10^{-2} i.e. 23 atoms have

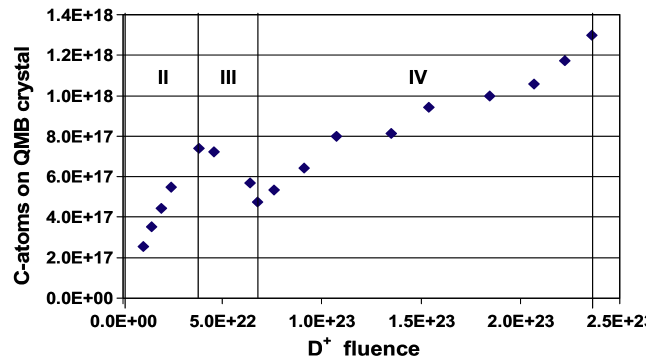

Fig. 3. Deposition of C-atoms on QMB crystal depending on D^+ fluence into toroidal section of 1 cm length of inner divertor.

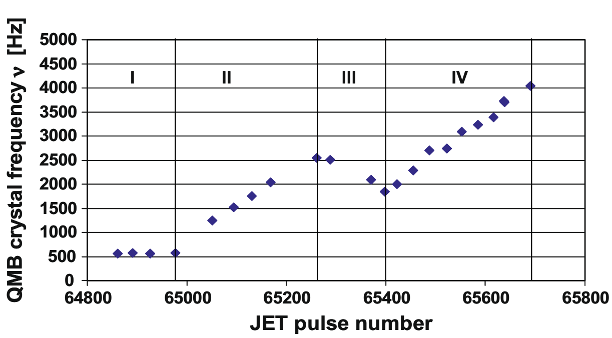

Fig. 2. Carbon layer formation on QMB in the PFR of JET; change over from deposition (II) to erosion (III) and back to deposition (IV).

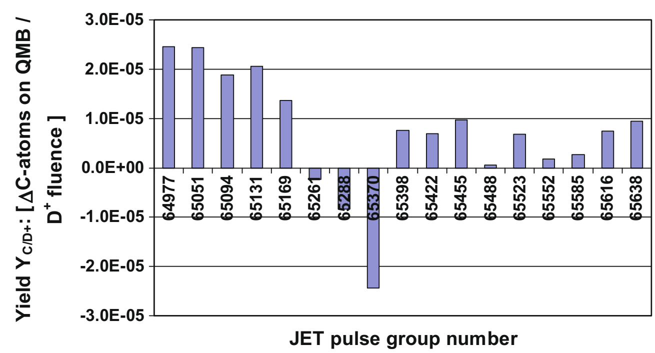

Fig. 4. Yield YC/D^+ of carbon atom deposited/eroded on the quartz depending on D^+ fluence into a toroidal section of 1 cm length of the inner divertor.

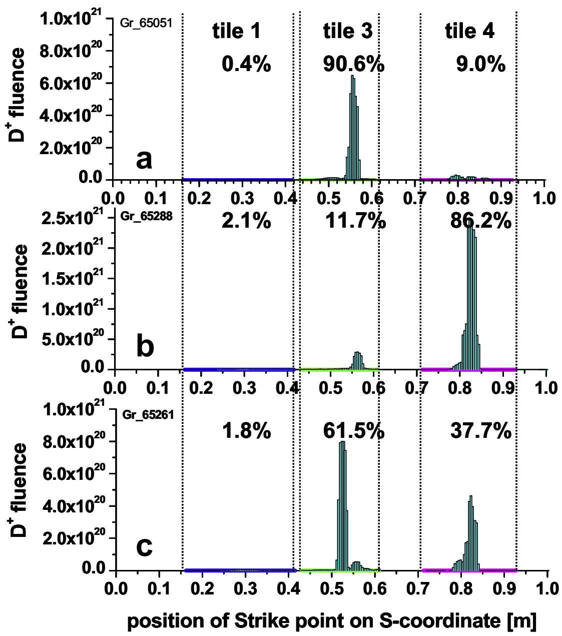

Fig. 5. Typical D+ fluence distribution for to the tiles 1, 3 and 4 in the inner divertor for: (a) deposition, (b) erosion, and (c) reduced erosion.

to be released from the target before 1 atom sticks and contribute net to the layer deposition. The effect of the change over from deposition to erosion and back to deposition as shown in Figs. 2 and 3 correlates with a change in the predominant strike point position from vertical tile 3 in sequences II to horizontal tile 4 in sequence III and back to vertical tile 3 in sequence IV.

Nevertheless, the strike point was no more than 90% of the time exclusively on one of the tiles integrated over a pulse group. Various strike point positions were overlaid including sweeping. Therefore the net erosion or net deposition of the layer is always a result of superposition of erosion and deposition processes throughout a pulse and in particular a pulse group. To understand the large scatter in the yields of Fig. 4, a detailed analysis of the distribution of the D^+ ion flux from the main chamber plasma to the tiles of the inner divertor was carried out for all 17 pulse groups. Fig. 5 shows 3 typical distributions for the D^+ ion fluence as a function of the S-coordinate, defined as a contour line along the surface of the divertor tiles. Fig. 5(a) shows the distribution of pulse group 65 051 representing deposition dominated behaviour with 90.6% of the D^+ flux on tile 3, 9.0% on tile 4 and 0.4% on tile 1. In contrast, Fig. 5(b) shows the erosion dominated case for pulse group 65 288 with a majority of 86.2% of the D^+ ion fluence on tile 4, 11.7% on tile 3 and 2.1% on tile 1. A more balanced situation is shown in Fig. 5(c), pulse group 65 261. 61.5% of the D^+ fluence impinges on tile 3, 36.7% on tile 4 and 1.8% on tile 1. The latter shows that the dominant process at the QMB is already erosion with less than 61.5% D^+ fluence on tile 3. The total D^+ ion fluence and its fraction to the horizontal tile 4 and vertical tiles 1 and 3 for all 17 groups and the resulting deposition/erosion is listed in Table 1. A comparison with the erosion/deposition yields in Fig. 4 shows a clear correlation and the effect of superposition of different configurations explains the scatter of the yield $Y_{C/D+}$ in Fig. 4.

4. Extrapolation of deposition rates in the PFR to ITER

The JET plasma configuration in the pulse groups with the highest percentage of the D^+ fluence on tile 3 in sequence II are most similar to the ITER reference inner strike point position. Thus data of pulse group 65 051 were used for a rough extrapolation of the amount of deposition that might be expected on the dome of ITER. The D^+ ion fluence into the inner divertor of ITER is expected to be 2.5×10^{24} D^+/s, corresponding to a D^+ fluence of 1×10^{27} D^+ for a 400 s pulse. This would lead to a release of 2×10^{25} C-atoms/pulse from the vertical target toward the dome in the private flux region. All of them will hit the dome due to narrow geometry of the deep inner divertor of ITER. Thus, with the measured deposition yield of 0.043, 8×10^{23} C-atoms/pulse would contribute to net layer formation. Assuming a typical ratio of $(D + T)/C = 0.4$, 1.6×10^{23} T–atoms/pulse would be co-deposited in the layer corresponding to 0.8 g Tritium per ITER shot. Considering the inaccuracy of the D^+ fluence measurement in JET, an error of ±0.5 g T can be assumed.

Table 1
Total D^+ fluence into toroidal section of 1 cm of the inner divertor per pulse group and corresponding erosion/deposition effect on the QMB layer.

no pulse group	total D^+ fluence	% D^+ tile 1	% D^+ tile 3	% D^+ tile 4	ΔC-atoms on QMB
64 977	1.00E+22	0	0.92	0.08	2.7E+17
65 051	4.10E+21	0	0.91	0.09	1.0E+17
65 094	4.80E+21	0	0.91	0.09	9.6E+16
65 131	5.10E+21	0	0.91	0.09	1.1E+17
65 169	1.40E+22	0	0.79	0.21	2.0E+17
65 261	7.60E+21	0.02	0.62	0.37	−1.8E+16
65 288	1.80E+22	0.02	0.12	0.86	−1.6E+17
65 370	3.90E+21	0.01	0.09	0.91	−1.0E+17
65 398	8.00E+21	0.02	0.68	0.3	6.4E+16
65 422	1.50E+22	0.1	0.82	0.08	1.1E+17
65 455	1.60E+22	0.05	0.83	0.12	1.6E+17
65 488	2.80E+22	0.06	0.78	0.16	1.7E+16
65 523	1.90E+22	0.07	0.8	0.13	1.4E+17
65 552	3.10E+22	0.07	0.79	0.15	5.7E+16
65 585	2.20E+22	0.02	0.81	0.17	6.3E+16
65 616	1.60E+22	0.01	0.84	0.15	1.2E+17
65 638	1.30E+22	0	0.62	0.38	1.3E+17

5. Summary and conclusion

In situ measurements of erosion/deposition were done in the PFR region of JET using a quartz microbalance (QMB) system. The most striking result is that the PFR in JET changes from deposition into erosion dominated area solely by moving the strike point position from vertical tile 3 to horizontal tile 4. Largest deposition was measured with the strike point position on tile 3. Under those conditions a maximum effective deposition yield (ratio of C deposited on QMB to D^+ impinging at the target) of 2.5×10^{-5} was measured. The minimum value of -2.5×10^{-5}, representing strongest erosion, was measured with the strike point on tile 4. The change from a net deposition to a net erosion area is explained by a change of the flux ratio D/C toward the PFR. When shifting the strike point from the vertical to the horizontal tile, the carbon flux impinging onto QMB decreases stronger in comparison with the atomic deuterium flux, responsible for erosion. The data confirm that the local geometry plays a key role for the formation of hydrogen (tritium) containing carbon layers [10]. Based on the presented measurement the PFR of ITER is expected to be a deposition dominated area since the ITER plasma reference scenario is similar to the measurements at JET with the strike point on tile 3 showing deposition. A rough calculation predicts about 0.8 ± 0.5 g Tritium to be co-deposited on the dome area per ITER pulse.

References

[1] H.G. Esser et al., Fus. Eng. Des. 66–68 (2003) 855.
[2] A. Kreter, these proceedings.
[3] H.G. Esser, V. Philipps, et al., J. Nucl. Mater. 363–365 (2007) 146.
[4] V. Rohde et al., J. Nucl. Mater. 290–293 (2001) 317.

[5] C.H. Skinner et al., J. Nucl. Mater. 363–365 (2007) 247.
[6] W. Eckstein, V. Philips, in: W. Hofer, J. Roth (Eds.), Physical Processes of the Interaction of Fusion Plasmas with Solids, Academic, San Diego, 1996.
[7] M.F. Stamp, S.K. Erents, W. Fundamanski, et al., Phys. Scr. T91 (2001) 13.
[8] Atomic Data and Analysis Structure. <http://adas.phys.starth.ac.uk>.
[9] A. Kirschner et al., J. Nucl. Mater. 337–339 (2005) 17.
[10] S. Brezinsek, M. Stamp, A. Kreter, et al., in: Proceedings of the 34th EPS Conference on Plasma Physics, Warsaw ECA, vol. 31F, 2007, p. 1.050.