EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(04)02-05

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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2002 (Proc. 19th IAEAFusion Energy Conference, Lyon (2002).*

Preprint of Paper to be submitted for publication in Proceedings of the
16th PSI Conference,
(Portland, Maine, USA 24-28 May 2004)

ABSTRACT

The deposition of carbon in the louver area of the inner divertor of JET was measured by means of a Quartz MicroBalance diagnostic (QMB) during 806 exposures in total for about 6479 seconds in various divertor conditions by means of a controllable shutter. The overall integrated frequency shift of the deposition crystal from the start of the measurements to the end was 23640Hz corresponding to an average carbon deposition flux of 5.5E-8g/cm^2 sec or 2.8x10^{15} C/cm^2 sec. Extrapolating this to the overall plasma divertor time of the MKII GB SR divertor (26.4 hours) yields a total amount of 35.4g of carbon layers deposited on the louver region.

It was found that the deposition increases significantly with decreasing distance of the strike point position to the louver entrance. Elmy-H-mode discharges with the strike point on the horizontal target dominate the carbon layer formation on the QMB.

1. INTRODUCTION

In the present design the divertor of ITER consists of about 100m^2 of tungsten armour and about 50m^2 of Carbon Fibre Composite (CFC). The CFC covers the areas of highest heat fluxes to avoid melting in transient heat loads leading to melt layer loss and surface irregularities [1]. However, the interaction of the plasma with the CFC-tiles leads to strong carbon erosion by physical and chemical erosion and subsequent re-deposition. The heaviest carbon deposition with up to 40µm thick flakes with a deuterium plus tritium ratio of about (D+T)/C = 0.7 were detected during the vessel inspections at the end of the MKIIA campaign on the water cooled louvers at the entrance of the inner divertor pump duct [2]. The observed carbon deposition and tritium retention rates are unacceptable when extrapolated to ITER. For a better understanding of the material transport in the divertor and to support erosion deposition modelling [3,4], time resolved data on the carbon deposition rates were highly required. Thus a quartz microbalance system was developed for JET and installed in 2001 in the remote area of the inner JET divertor in front of the louvers [5].

2. EXPERIMENTAL

The basic element of the quartz microbalance is a flat circular plate with a resonance frequency of 6MHz. excited by means of an external oscillator. The oscillating frequency is lowered by addition of material to the surface [6,7]. The crystal is exposed to the particle flux from the inner divertor by means of a controllable shutter. Since the resonance frequency depends also sensitively on the temperature, the JET-QMB was equipped with a second quartz, shielded against the particle flux to compensate the temperature effects when thermal equilibrium is reached [8]. First results based on QMB measurements carried out in the C5 campaign of JET are published in [9]. The QMB technique was applied first in the Tokamak de Varenne [10] and later in ASDEX [11] and TEXTOR [12]. The JET Quartz Microbalance was remotely placed in front of the inner louver in 2001, see Fig.1. The exposure time is controlled by a shutter with a time resolution of about 0.1 sec. Figure 1 shows a poloidal cross section of the inner divertor showing the QMB-system positioned in front of the louver perpendicularly oriented toward the radial direction and parallel to the toroidal field lines.

Above 573°C the piezoelectric quartz crystal (density ρ_{quartz} = 2.649g/cm^3, specific heat C = 710Jkgm^{-1}K^{-1}) changes its crystalline structure irreversibly from the piezoelectric “alpha quartz” to the non-piezoelectric “beta-quartz”. Also mechanical stress and large thermal stress can destroy the piezoelectric properties. The mass sensitivity was calibrated for carbon to be S = 1.5x10^{-8} [g /Hz cm^2]. The resolution is about 1 to 2Hz equivalent to about 1 monolayer of carbon. More details can be found in [13,14,15].

3. RESULTS

3.1 AVARAGE DEPOSITION RATES

The results presented in this paper are based on 806 QMB exposures in total with an exposure time of 6479 seconds during the EFDA campaigns C5-C12. The deposition on the QMB is below the detection limit when the plasma is not in the divertor phase. The exposure time was defined by the intersection of the shutter opening and divertor time. This time is used to calculate the total carbon deposition fluxes and to extrapolate to the whole operation time. The D+ ion fluxes into the inner divertor were deduced from integrated ion saturation fluxes on Langmuir probes or, alternatively, from the D-alpha light using an effective S/XB of 7.1. In January 2003 (# 57934) the reference temperature quartz failed leading the a decreased detection limit from 1 Hz to 2-3 Hz. In January 2004 the deposition quartz crystal failed due to overheating. The average depsition rates can be determined by measuring the frequencies at the beginning and at the end of any time interval which then can be related to the exposure times throughout this period. This method was used to estimate the total amount of carbon deposited on the QMB and thus the remote areas of the inner divertor in the time period 27.03.2001 to 27.01. 2004 (campaigns C5–C14). To get rid of the effect of temperature drifts on the deposition frequency (temperature crystal for compensation failed at Pulse No: 57934), the frequencies were measured during JET dry runs in the morning for which the QMB is in thermal equilibrium and at reproducible temperature. This is confirmed by the red curve in Fig. 2 showing the same frequency of the temperature crystal within more than a year of operation. In Fig. 2 the frequencies of the deposition- and temperature crystal are plotted versus the discharge number. During this period 806 QMB-exposures have been carried out with a total exposure time of 6479 sec. The corresponding frequency shift of the deposition crystal is 23640Hz resulting in an average rate of 3.65Hz/s corresponding to 5.5x10-8 g/cm^{2}s respectively to 2.8x10^{15} C/cm^{2}s. The flux at the entrance gap (5418cm^2) of the divertor pump slot, the narrowest pass for the particle fluxes, is assumed to be a factor of 1.5 higher due to geometry effects. This results in an estimated amount of 35.4g carbon in the louver area considering a divertor plasma time of 26.4 hours for the whole operation campaigns C5-C14. The corresponding total D^+ ion fluence into the inner divertor during that time was 2.9x10^{27} giving a carbon deposition yield of $Y_{C/D+}$ of 6.1x10^{-4}. The equivalent value at the end of the MkIIA divertor phase based on carbon collection during inspection was 3.2x10^{-2}, a factor of 52 more.

3.2. DEPENDENCE OF CARBON DEPOSITION ON STRIKE POINT POSITION

The following data are based on the evaluation of 307 L- and H-mode discharges in total and a subset of 159 discharges are considered for the calculation of the average values of deposition rates in dependence of different strike point positions. Figure 3 shows a summarx.of all these exposures, fixed and sweeped strike points included, plotted versus the discharge number. It is obvious that the contribution of individual exposures can differ very much. The averaged deposition rate for these shots is 3.2Hz/s in a total exposure time of 2631sec resulting in an total frequency shift of 8483Hz. This value is similar to the 3.65Hz/s deduced by the integral method shown in figure 2. The geometrical positioning of the strike point in the divertor with respect to the QMB location plays the most important role for the carbon deposition, as already mentioned in [9]. Therefore strike point regions were defined on the vertical target, around the positions of the diagnostic optimised plasma configurations, DOCU = -138±1.5 cm, DOC-L=-157±1.5 cm and DOC-LL =-161±1.5 cm as indicated in Fig.1.

Figure 4 shows the deposition rate of all the considered exposures with strike points on the vertical target in dependence on the Z-coordinate of the vessel. The same is shown in Fig.5 for the horizontal base plate, here as function of the major radius R. Figure 4 reveals a clear increase of the deposition rate in dependence on the distance to the lower edge of tile 3 respectively to the gap into the remote area. While the rates for DOC-U configurations are close to or below the sensitivity limit of the QMB ($\approx 1x10^{15}$C/cm^{2}s), highest values up to about $1.2x10^{16}$C/cm^{2}sec are measured in DOC LL and at the edge, with one value even reaching about $3.4x10^{16}$C/cm^{2}sec. The data with strike points at the edge are not considered here in the statistical evaluation since there is some uncertainty in the determination of the absolute strike point position thus they may belong as well to the group of discharges on the horizontal target. This group is plotted in Fig.5 and shows the highest values in average with a clear tendency to reach the highest values (about $6x10^{16}$C/cm^{2}s) at the crossing point of the base plate towards the corner plate at R = 244cm. This indicates that this area is a privileged zone for intermediate layer formation from which then the carbon is eroded preferentially in subsequent discharges. The averaged values of the deposition rates of all combinations of L- and H-mode discharges with strike point positions on the 4 defined areas are plotted as bar graphs in Fig. 6. It is obvious that exposures under H-mode discharge conditions with strike point positions on the base plate dominate the overall deposition towards the QMB and thus the louver remote area.

SUMMARY

The Quartz microbalance deposition monitor was exposed to about 800 discharges throughout the campaigns C5-C12 for about 6479 plasma seconds during the divertor phase. The average material deposition rate is $5.5x10^{-8}$ g/cm^{2}s respectively to $2.8x10^{15}$ C/cm^{2}sec assuming that the overwhelming majority of material arriving at this location is carbon, as found after the MKIIA campaign. From this a total amount of 35.4g of carbon accumulated in the remote area of the inner divertor throughout the JET campaigns C5–C14 can be estimated, based on extrapolation to the total divertor operation time. The average carbon deposition yield is about $6.1x10^{-4}$ related to the total flux of deuterium ions arriving in the inner divertor. And the deposition rate in the louver area is about $1.9x10^{19}$ C/sec.

The most important role for the carbon deposition is the position of the strike point with respect to the louver entrance. While the rates for DOC-U configurations are close to or below the sensitivity limit of the QMB of 2-3Hz, high values up to about $1.2x10^{16}C/cm^2sec$ are measured with the plasma at the lower vertical target (DOC LL and at the edge). The highest values are measured with the strike point on the base plate under H-mode operation conditions, with some tendency to reach the highest values (about $6x10^{16}C/cm^2sec$) at the crossing point of the base plate towards the corner plate at R = 244cm. The base plate configuration offers a direct line of sight to the QMB and the results are thus in line with the assumption that most of the released carbon species have a high sticking probability and deposition is thus largely line of sight. The results also indicate that not much carbon would arrive at the QMB location if the plasma would be always sitting on the vertical plates, but be deposited on the horizontal tile or escaping towards the PFR region. The large amount of carbon observed on the louvers after the MKIIA configuration is mainly a result of the plasma configuration with the strike point at the horizontal target during this campaign.

The QMB data show also that the material deposition is in general much higher if the plasma is moved for the first time on the horizontal target but then decreases fast in following discharges. This indicates a high erosion of freshly deposited carbon layers as also concluded from spectroscopic observations [16] and modelling of the carbon transport. More details about this will be published in a forthcoming paper.

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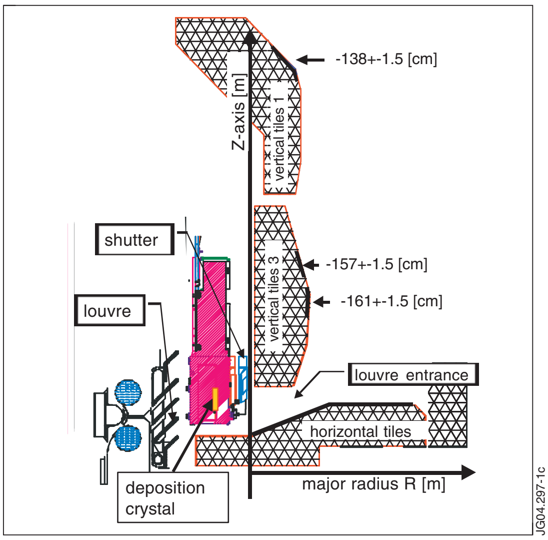

Figure 1: Cross section of inner divertor at the location of the QMB.

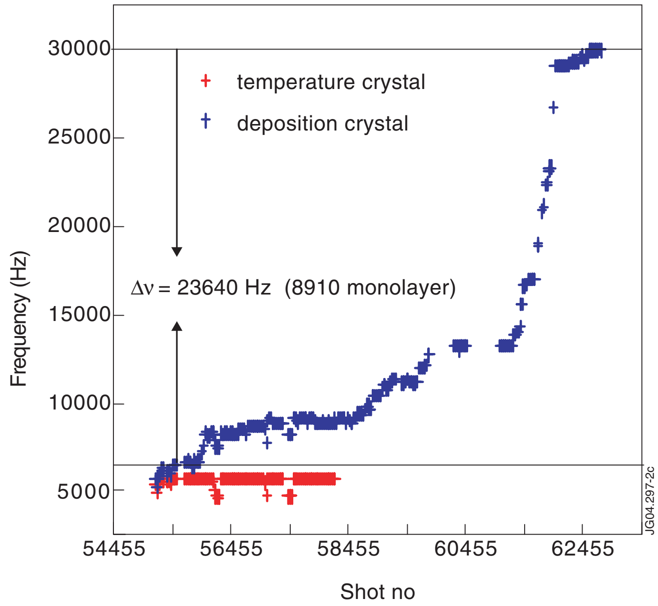

Figure 2: Total amount of carbon deposition on QMB crystal during operation time.

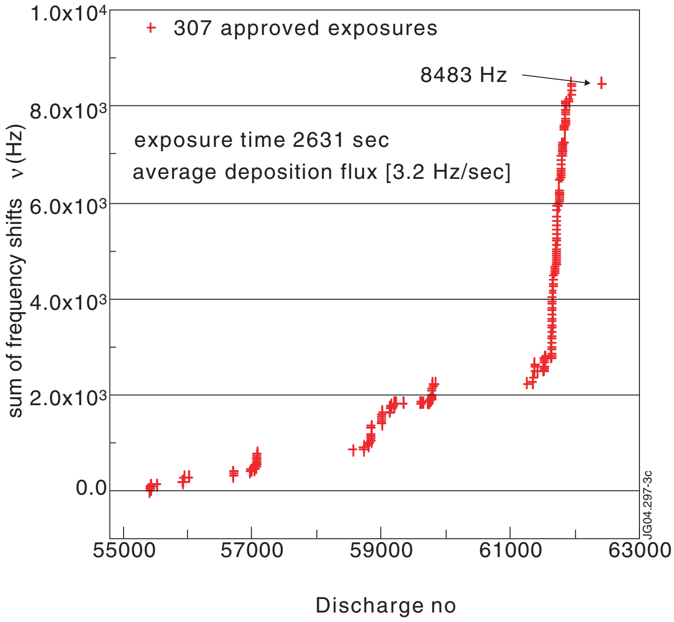

Figure 3: Sum of individually time resolved measured deposition rates of all evaluated QMB exposures.

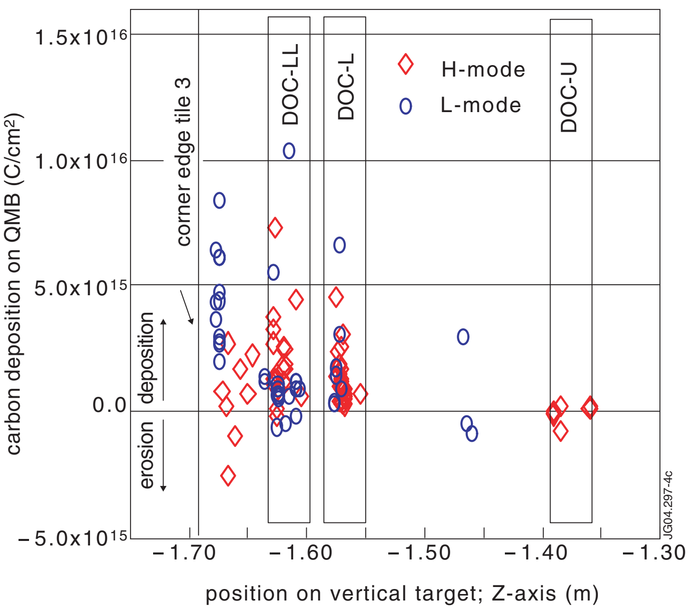

Figure 4: Deposition rates of QMB exposures with fixed strike point position on vertical target vs. strike point position.

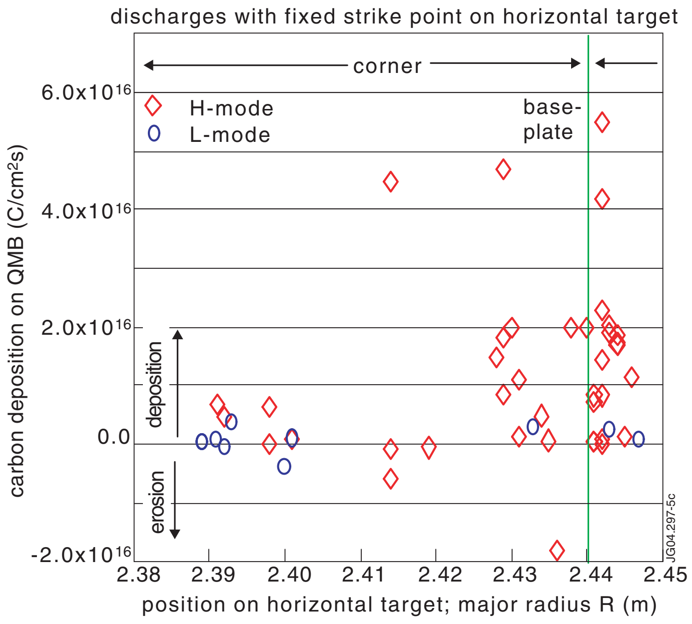

Figure 5: Deposition rates of QMB exposures with fixed strike point position on horizontal target vs. strike point position.

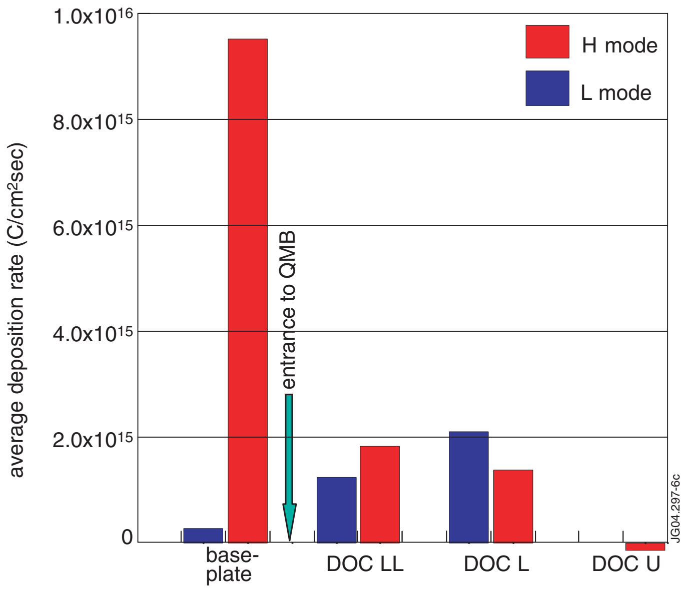

Figure 6: Average deposition rates of QMB exposures for H- and L-mode discharges depending on fixed strike point position in defined areas of the inner divertor.