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Effect of plasma configuration on carbon migration measured in the inner divertor of JET using quartz microbalance

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Abstract

The deposition of carbon in the louvre area of the inner divertor of JET was measured by means of a Quartz Microbalance diagnostic (QMB) during 806 exposures (total of about 6479 s) in various divertor conditions. Exposure time was controlled by means of a shutter. The overall integrated frequency shift of the deposition crystal from the start of the measurements to the end was 23 640 Hz, corresponding to an average carbon deposition flux of 5.5×10^{-8} g/cm^2 s or 2.8×10^{15} C/cm^2 s. Extrapolating this to the total time of 26.4 hours of divertor plasmas with the MKII GB SRP divertor (gas box divertor with septum replacement plate) yields a total amount of 35.4 g of carbon layers deposited on the louvre region. It was found that the deposition increases significantly with decreasing distance of the strike point position to the louvre entrance. Elmy-H-mode discharges with the strike point on the horizontal target dominate the carbon layer formation on the QMB.

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Keywords: Amorphous films; Co-deposition; JET erosion and deposition; Tritium

1. Introduction

In the present design the divertor of ITER consists of about 100 m^2 of tungsten armour and about 50 m^2 of CFC (carbon fibre composite). 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. In JET the heaviest carbon deposition occurred with the MKIIA divertor. Deposits up to 40 μm thick (which were already starting to flake off) with a deuterium plus tritium ratio of about (D + T)/C = 0.7 were found on the water cooled louvres at the entrance of the inner divertor

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pump duct after a short period of operation in 1996 [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 essential. Thus a quartz microbalance system was developed for JET and installed using Remote Handling techniques in 2001 in the shadowed area of the inner JET divertor in front of the louvres [5].

2. Experimental

The basic element of the quartz microbalance is a flat circular plate with a resonance frequency of 6 MHz 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 crystal, shielded against the particle flux, to compensate the temperature effects when thermal equilibrium is reached [5]. First results based on QMB measurements carried out in the C5 campaign of JET have been published [8]. The QMB technique was applied first

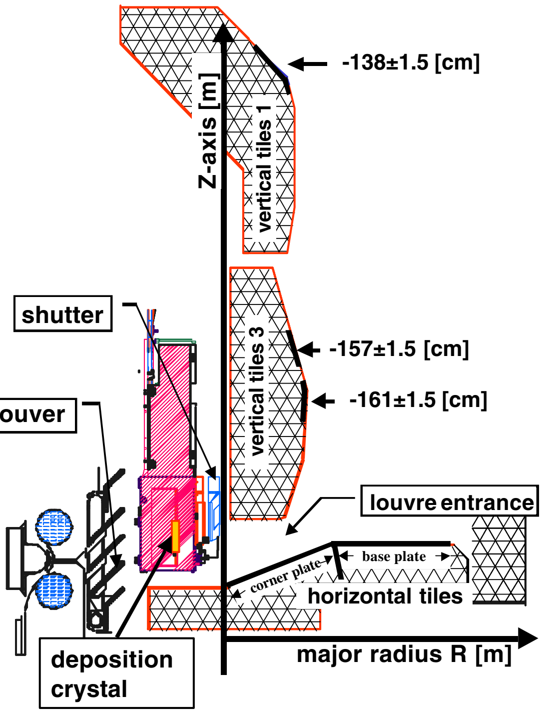

Fig. 1. Cross section of inner divertor at the location of the QMB.

in the Tokamak de Varenne [9] and later in ASDEX [10] and TEXTOR [11]. Fig. 1 shows a poloidal cross section of the inner divertor showing the QMB-system positioned in front of the louvres perpendicularly oriented toward the radial direction and parallel to the toroidal field lines. The exposure time is controlled by a shutter with a time resolution of about 0.1 s. Above 573 °C the piezoelectric quartz crystal (density $\rho_{quartz} = 2.649$ g/cm^3, specific heat $C = 710$ J/kg K) changes its crystalline structure irreversibly from the piezoelectric 'α-quartz' to the non-piezoelectric 'β-quartz'. Also mechanical stress and large thermal stress can destroy the piezoelectric properties. The mass sensitivity was calibrated for carbon to be $S = 1.5 \times 10^{-8}$ [g/Hz cm^2]. The resolution is about 1–2 Hz equivalent to about one monolayer of carbon. More details can be found in [12–14].

3. Results

3.1. Average deposition rates

The results presented in this paper are based on 806 QMB exposures with a total exposure time of 6479 s 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 coincidence of shutter opening and divertor plasma periods. This time is used to calculate the total carbon deposition fluxes, and to extrapolate to the whole operational period. 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 conversion factor $S/XB = 7.1$ to determine the correlation between the D^+ particle fluxes and the measured photon intensity. In January 2003 (# 57934) the reference temperature quartz failed leading to a decreased detection limit from 1 Hz to 2–3 Hz. In January 2004 the deposition quartz crystal finally failed due to overheating. The average deposition 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 March 2001 to 27 January 2004 (campaigns C5–C14). To avoid the effect of temperature drift on the deposition frequency after the temperature compensation crystal failed at # 57934, the frequencies were measured during JET dry runs in the morning when 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 over more than a year of operation. In Fig. 2 the frequencies of the deposition and temperature crystals

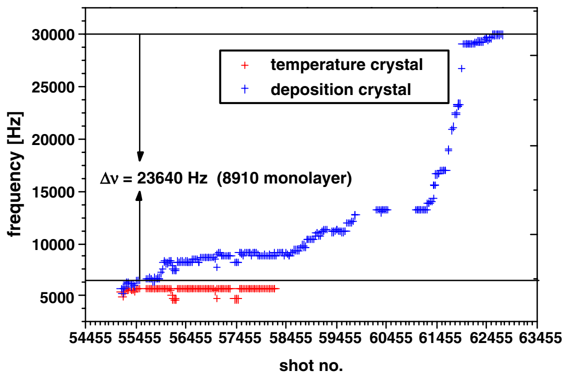

Fig. 2. Total amount of carbon deposition on QMB crystal during operation time.

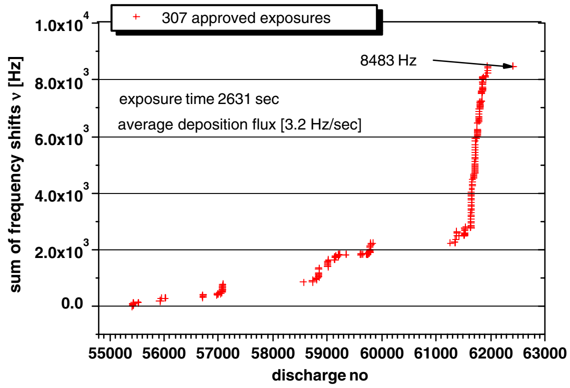

Fig. 3. Sum of individually time resolved measured deposition rates of all evaluated QMB exposures.

are plotted versus the discharge number. During this period 806 QMB-exposures have been carried out with a total exposure time of 6479 s. The corresponding frequency shift of the deposition crystal is 23 640 Hz, giving an average rate of 3.65 Hz/s corresponding to 5.5×10^{-8} g/cm^{2}s, equivalent to 2.8×10^{15} C atoms/cm^{2}s. The flux at the entrance gap (5418 cm^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 35.4 g carbon in the louvre area, considering a divertor plasma time of 26.4 h for the whole operation campaigns C5–C14. The corresponding total D^+ ion fluence into the inner divertor during that time was 2.9×10^{27} giving a carbon co-deposition yield of Y_{C/D^+} of 6.1×10^{-4}. The equivalent value of 3.2×10^{-2} estimated during the MkIIA divertor phase was based on the thickness of carbon films on the louvres and on the shadowed tile surfaces. It was about a factor of 52 greater than the value derived from QMB data, however most discharges during this MkIIA campaign had the strike point on the horizontal tiles.

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 as a function of strike point position. Fig. 3 shows a summary of all these exposures, fixed and swept 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 3.2 Hz/s in a total exposure time of 2631 s resulting in an total frequency shift of 8483 Hz. This value is similar to the 3.65 Hz/s deduced by the integral method shown in Fig. 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 documented [8]. Therefore strike point regions were defined on the vertical target, around the positions of the diagnostic-optimised plasma configurations, DOC-U = −138 ± 1.5 cm, DOC-L = −157 ± 1.5 cm and DOC-LL = −161 ± 1.5 cm as indicated in Fig. 1. Fig. 4 shows the deposition rate of all the selected exposures with strike points on the vertical target as a function of the *Z*-coordinate of the vessel. The same is shown in Fig. 5 for the horizontal base plate, here as a function of the major radius *R*. Fig. 4 reveals a clear increase in the deposition rate depending on the distance to the lower edge of tile 3 (i.e. to the gap into the remote area). Whilst the rates for DOC-U configurations are close to or below the sensitivity limit of the QMB (≈1×10^{15} C/cm^{2}s), much higher values are measured in DOC LL of up to about 1.2×10^{16} C/cm^{2}s and at the edge, where one value of about 3.4×10^{16} C/cm^{2}s was obtained. The data with strike points at the edge are not considered

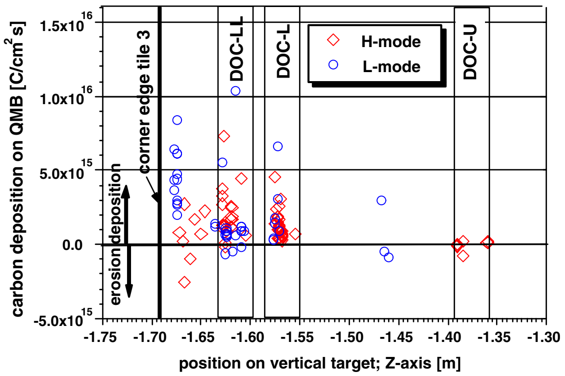

Fig. 4. Deposition rates of QMB exposures with fixed strike point position on vertical target vs. strike point position.

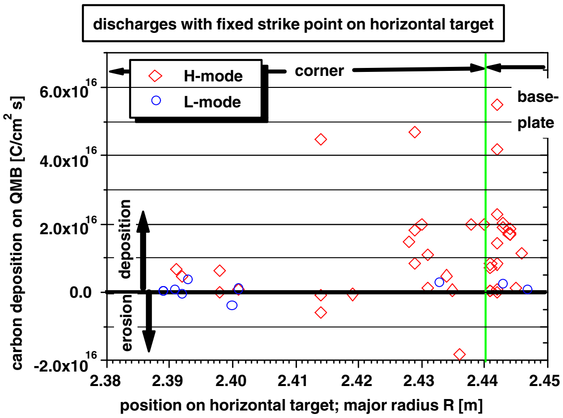

Fig. 5. Deposition rates of QMB exposures with fixed strike point position on horizontal target vs. strike point position.

here in the statistical evaluation, since there is some uncertainty in the determination of the absolute strike point position, and a small error means they may belong rather to the group of discharges on the horizontal target. This group is plotted in Fig. 5 and shows higher values on average with a clear tendency to reach the highest values (about 6×10^{16} C/cm^{2}s) at the change of slope where the base plate becomes the corner plate at $R = 244$ cm. This indicates that this area is a prime zone for intermediate layer formation, from which 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 four 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 shadowed louvre area.

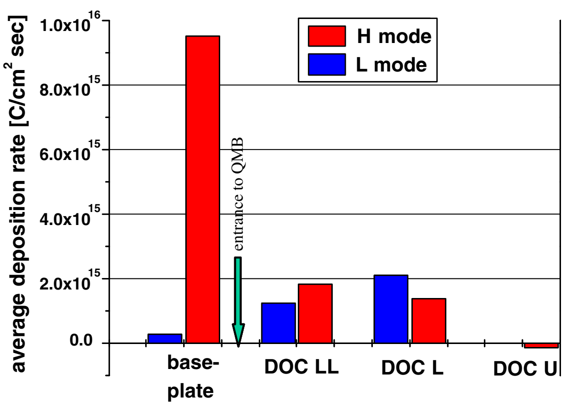

Fig. 6. Average deposition rates of QMB exposures for H- and L-mode discharges depending on fixed strike point position in defined areas of the inner divertor.

4. Summary

The Quartz microbalance deposition monitor was exposed to about 800 discharges throughout the campaigns C5–C12 (total of 6479 plasma seconds) during the divertor phase. The average material deposition rate is 5.5×10^{-8} g/cm^{2}s, corresponding to 2.8×10^{15} C atoms/cm^{2}s 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 35.4 g 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 6.1×10^{-4} related to the total flux of deuterium ions arriving in the inner divertor. The deposition rate in the louvre area is about 1.9×10^{19} C atoms/s.

The most important variable controlling carbon deposition rate is the position of the strike point with respect to the louvre entrance. Whilst the rates for DOC-U configurations are close to or below the sensitivity limit of the QMB of 2–3 Hz, values up to about 1.2×10^{16} C/cm^{2}s are measured with the plasma at the lower vertical target (DOC LL and at the edge). Even higher 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 6×10^{16} C/cm^{2}s) at the change of slope where the base plate becomes the corner plate (at $R = 244$ cm). 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 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 would be deposited on the horizontal tile or escape towards the PFR region. The large amount of carbon observed on the louvres during the MKIIA operations in 1996 was because the strike point was mainly on the horizontal target during this campaign.

The QMB data show also that the material deposition rate is generally much higher when the plasma is moved for the first time onto the horizontal target. The rate then decreases rapidly in subsequent discharges. This indicates a high erosion rate for freshly deposited carbon layers, as also concluded from spectroscopic observations [15] and modelling of the carbon transport. The observed phenomenon and its modelling is described in [16]. More details about this will be published in a forthcoming paper.

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