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*\* See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

**ABSTRACT.**

Quartz MicroBalance (QMB) system was implemented in the inner divertor region of JET in order to measure in situ and time resolved ($\leq 0.1$ sec) material fluxes (mainly carbon) and layer deposition. The system has been developed to operate at temperatures up to $200^{o}$C. The aim is to investigate carbon transport to the remote areas, and hence the tritium retention in dependence on plasma conditions. This question is still a major concern for the ITER operation. The mass sensitivity of the system is $S_m = 7.5 \times 10 - 9 \text{g/Hz cm}^2$. First reliable measurements were made during the C5 campaign (March – May 2002; $\approx 1000$ plasma discharges). The results presented are based on 74 selected exposures under various conditions (strike point positions, input power, gas fuelling, ELM frequency). Most influencing to the carbon flux seems to be the position of the strike zone. In the average a yield of $1.9 \times 10^{-4}$ C-atoms have been deposited related to the $D^+$ flux into the inner divertor.

## 1. MOTIVATION

Carbon erosion and transport to remote areas remains a serious concern in ITER since carbon fibre (CFC) will cover the areas of highest heat fluxes (about $50\text{m}^2$) in the divertor. CFC does not melt but shows chemical and physical erosion and may sublime rather than melt during extraordinary events like giant ELMS and disruptions [1]. Carbon erosion and subsequent formation of amorphous carbon layers in remote areas does not only affect the lifetime of the CFC-tiles but also the tritium accumulation due to co-deposition. The safety limit of 350g of tritium may be exceeded soon. It is challenging therefore to investigate carbon impurity fluxes and deposition rates in-situ in present day machines like JET. The technique was previously applied in the Tokamak de Varenne and ASDEX Upgrade [2,3]. It is based on the very sensitive frequency change of an oscillating quartz crystal due to the mass growing by material deposition onto the surface. The quartz is element of an electrical resonator circuit, and the system is described in more detail in [3]. Before the implementation of QMB systems carbon deposition and tritium retention have been observed in JET in 1996 for the MkIIA divertor. Heavy carbon deposition was found on the inner divertor tiles and on water-cooled louvers, a protection against unacceptable power fluxes to the nitrogen cooled magnetic coil (no such deposition was found at the outer divertor). After about 2000 plasma pulses carbon layers and flakes up to a thickness of 40 mm have been found and a total amount of carbon was estimated to 1g with a deuterium content of D/C $\approx 0.7$. Taking into account the total deuterium ion fluence of $5.5 \times 10$ 26 into the inner divertor a ratio $Y_{C/D+} = 5.2 \times 10^{-2}$ C/$D^+$ is estimated provided toroidal homogeneity. The retained amount of deuterium corresponds to 5-10% of the total amount of deuterium fuelled in and illustrates the consequences to be expected for the ITER operation. Moreover investigations made after the tritium campaign (DTE1) revealed that about 6g tritium of the injected 36g remained still in the vessel [4] despite cleaning. Most of the tritium was stored in those flakes. Observations integrating over long periods of plasma operation can yield average deposition rates and fluxes only and do not discriminate different plasma conditions. It is indispensable therefore to develop techniques, which can measure the impurity fluxes in situ. The introduction of the QMB technique into JET is a first step.

## 2. EXPERIMENTAL SET UP

The Quartz Microbalance was mounted in March 2002 on the divertor carrier module 13 and remotely placed in Octant 8 in front of the inner louver (fig.1). The QMB is equipped with an actively controlled shutter in order to select the exposure time during the running plasma discharge. The time resolution is $< 0.1$ sec and the sensitive area is $0.5 \text{cm}^2$. Figure1 shows the QMB is positioned in front of the louver perpendicularly oriented to the radial direction and parallel to the magnetic toroidal field lines. The principle of measurement with the QMB will only be given briefly here, because the design of the QMB has already been described elsewhere [5,6,7]. The QMB measurement is based on the one hand on the very sensitive dependence of the resonance frequency of an oscillating quartz on the mass and on the other hand on the accuracy of frequency measurements by means of the resonators circuit.

The quartz is part of the electric resonator circuit. It is excited to mechanical vibrations by an alternating electric field applied between its electrodes by means of the piezoelectric effect. The amplitude of vibration is negligibly small except when the frequency of the driving field is in the vicinity of a resonance mode. The resonance frequency depends only on mass and temperature of the quartz. Layers, deposited on the quartz will increase its mass and lower the frequency [6,7]. Above $573^\circ\text{C}$ the piezoelectric quartz crystal (density is $\rho_{quartz} = 2.649 \text{g/cm}^3$ and the specific heat capacity $C = 710 \text{Jkgm}^{-1} \text{K}^{-1}$) changes its crystalline structure irreversibly from the piezoelectric "alpha quartz" to the non-piezoelectric "beta-quartz". Also mechanical stress and large thermal stress may destroy the piezoelectric feature. Its mass sensitivity was found to be $7.5 \times 10^{-9}$ g /Hz cm$^2$.

## 3. RESULTS

During the C5 campaign (March-May 2002) about 1000 plasma pulses were applied with about 13600 sec of divertor plasma time. A total deuterium ion fluence of $\Phi_{D+} \approx 2.6 \times 10^{26}$ into the inner divertor was measured by means of Langmuir probes. The average deuterium ion flux was $\Gamma_{D+} \approx 1.9 \times 10^{22}$ [D$^+$/sec]. For the measurements presented here 74 discharges were selected with QMB exposures to the plasma by use of the control shutter. The total exposure time of the QMB was 694 sec.

### 3.1 FIRST MEASUREMENTS

Fig 2 shows the increase of the carbon deposition on the QMB obtained during the 74 selected exposures given in terms of the deuterium ion fluence FD+ into the inner divertor. The data are plotted in chronological order. Provided the deposited mass is mainly carbon, the values correspond to areal densities given in C/cm$^2$ left hand scale, which can be converted into grams of carbon deposited on remote areas of the inner divertor taking into account the entrance gap width (2.98cm) into the remote area between tile 3 and tile 4 and the toroidal circumference (total area 4518 cm$^2$). The different slopes of the curve correspond to different carbon deposition yields $Y_{C/D+}$. It varies from $3 \times 10^{-5} < Y_{C/D+} < 1.8 \times 10^{-3}$ depending on plasma conditions. The averaged value of $Y_{C/D+}$ is about $1.5 \times 10^{-4}$

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## 3.2 DEPENDENCE ON STRIKE POINT POSITION

The carbon deposition of all 74 selected exposures is plotted in figure 3 to study the influence of the strike point position. During all discharges the strike point was kept on the horizontal tiles but varied between the strike point position $-1.7 < ZSIL[m] < -1.4$ The position of the strike point was found to be most affecting the carbon deposition. Figure 3 shows the deposition rate in units of [g/ cm 2 sec] on the left hand side and [monolayer C/sec] on the right hand side. The strike point position is given by the coordinate ZSIL (Fig.1). H-mode type discharges with a total input power above 8MW (open triangles) create larger deposition than L-mode type discharges (open circles) with total input power below 8MW. At a strike point position of $ZSIL \approx -1.4$m, far away from the entrance gap, the deposition rate is almost negligible compared to the rate found for positions nearer to the gap. However, the large scatter of the deposition rates points to other influencing parameters.

For the following only the data obtained from the region of the strike point position between $-1.59 < ZSIL[m] < -1.63$ are used (lines shown in Fig.3). This corresponds to a region of about 4cm only. Although it seems that the position of the strike zone is the most influencing parameter also other conditions can affect the deposition rate.

## 3.3 DEPENDENCE ON INPUT POWER

Figure 4 shows that the carbon deposition rate increases with the input power. The low input power L-mode shots (open circles) create much lower deposition rates compared to the H-mode shots with a maximum of about 3.6 monolayers/sec. The deposition rate starts to scatter beyond the input power of 8 MW.

## 3.4 DEPENDENCE ON GAS FUELLING

In figure 5 the carbon deposition rate is plotted versus the neutral gas pressure in the sub divertor region. This pressure is mainly determined by gas fuelling during the plasma discharge. Highest deposition rates are observed for unfuelled H-mode discharges while unfuelled L-mode and fuelled H-mode shots show less deposition.

## 3.5 DEPENDENCE ON ELM FREQUENCY

Transient heat loads during ELMS (or disruptions) may strongly influence the carbon erosion and redeposition of the CFC material due to the high power loads. In addition loosely bound deposits grown on the surfaces of the tiles in previous discharges can be heated up to higher temperature and thus contribute significantly to the carbon erosion. Figure 6 shows the measured carbon deposition rate for H-mode discharges versus the ELM frequency. Two groups can be distinguished: shots with an ELM frequency of about 200Hz show less carbon deposition than the ones with frequencies around 25Hz. IR measurements show that the surface temperature of the inner divertor can rise up to 2200K or more[8] for low frequency Type I ELM- discharges. This indicates that carbon is released by thermal decomposition of the films deposited on the inner divertor tiles and transported then to the remote area. It is known that soft carbon films dissolve upon heating up to temperatures

above $200^o$C [9]in a large family of hydrocarbons transporting about 50% of the carbon atoms. It is important to note that no Be was found in the remote areas at the end of the MKIIA divertor campaign[10]. This may indicate that sublimation does not cause the erosion process. Nevertheless this is a working hypothesis, which needs to be confirmed in further measurement. Another possible contribution to the carbon erosion is may be due to the low plasma densities during the unfuelled low ELM-frequency plasma shots.

**SUMMARY AND CONCLUSION**

The measurements show that carbon deposition rates can be determined time resolved and in situ in remote areas of JET. This was the major goal.

The yield of deposited carbon in the inner divertor in front of the louver was found to be $3\times10^{-5} <$ $\mathbf{Y_{C/D}}$++ $<1.8\times10^{-3}$ related to the deuterium ion flow The average value is 1.5x10 -4 . The strike point position on the vertical tiles was found to be most influencing the carbon deposition rate. While for strike point positions on tile 1 (ZSIL $\approx -1.40$m) the rates are almost negligible, they increase with decreasing distance of the strike point position with respect to the to the particle entrance gap into the remote area. If the strike point position is fixed (ZSIL $\approx -1.61\pm0.02$m) the influence of other parameters become obvious like input power, gas fuelling and ELM frequency. The average yield $\mathbf{Y_{Cat/D+}}$ of $1.5\times10^{-4}$ is more than 2 orders of magnitude lower compared to the value $5.2\times10^{-2}$ obtained at the end of the MkIIA divertor phase. This might be due to the fact that during this period the strike zone has been positioned more often on the lower edge of tile 3 and on the horizontal tile 4. It seems that the probability for carbon eroded from those areas to be transported to the louver area is the highest.

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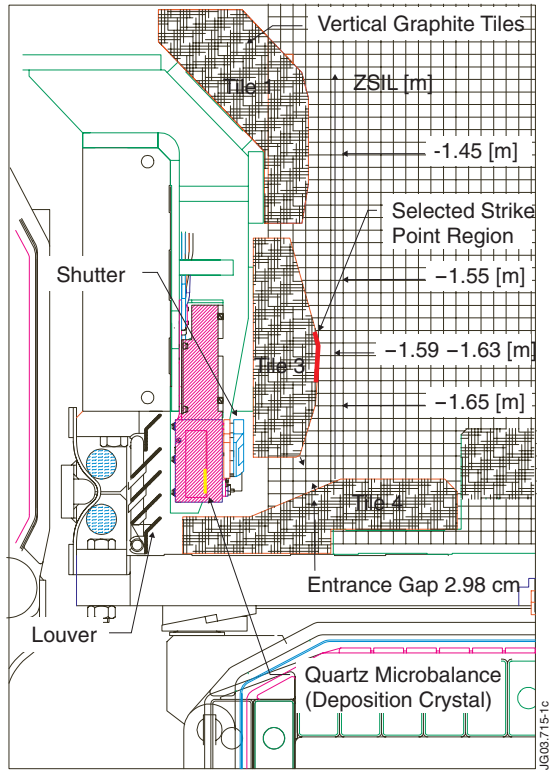[9]. J. Ihde, H.B. Störk, J. Winter, M. Rubel, H.G. Esser et al. J. Nucl. Materials **290-293** (2001) p1180

*Figure 1: Location of the QMB in front of the louver in the inner JET divertor.*
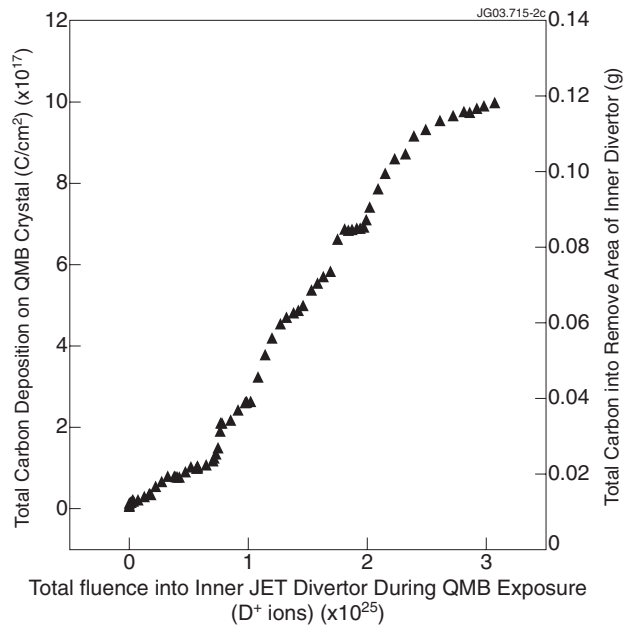


*Figure 2: Increase of carbon deposition on the QMB versus increasing deuterium fluence into the inner divertor.*
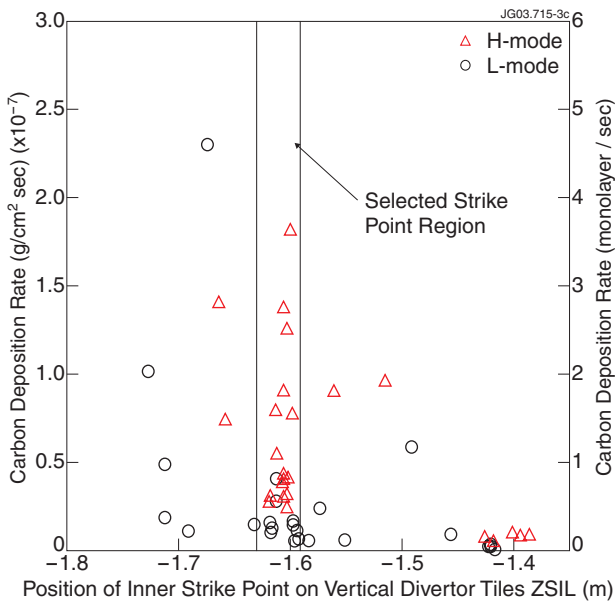


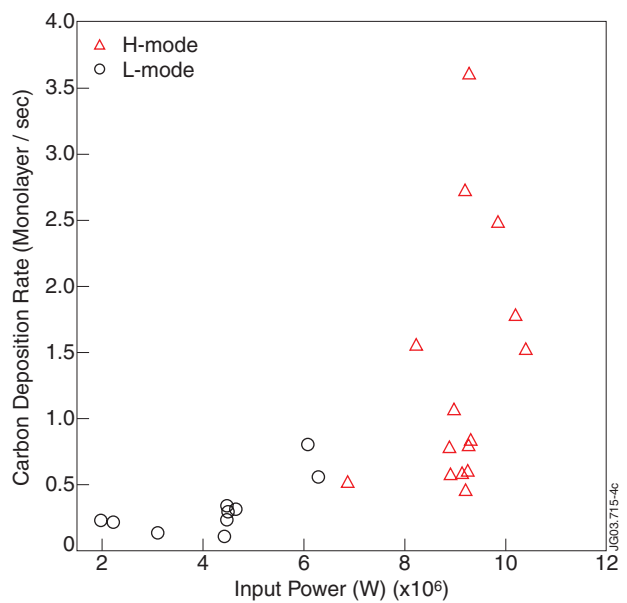*Figure 3: Measured carbon deposition rate as function of the position of the strike point in the inner JET divertor.*



*Figure 4: Measured carbon deposition rate as function of the plasma input power.*
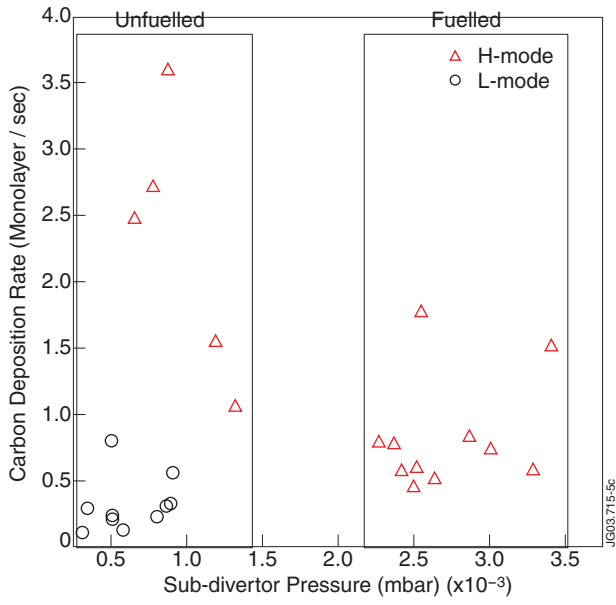
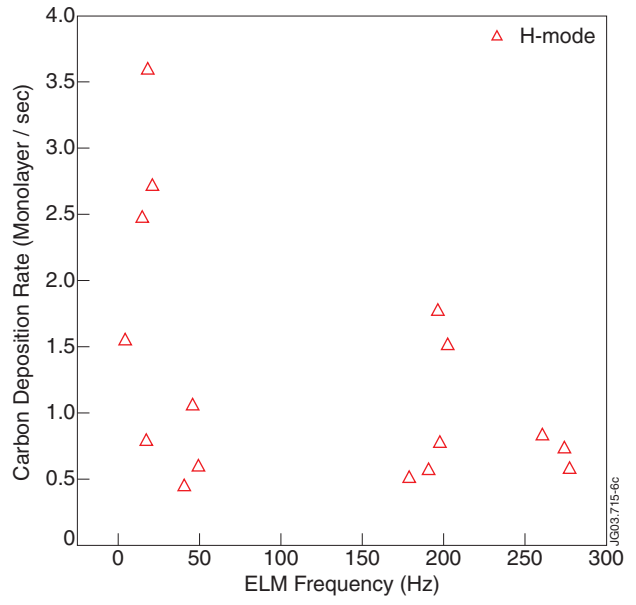*Figure 5: Measured carbon deposition rate as function of neutral gas fuelling.*



*Figure 6: Measured carbon deposition rate as function of ELM frequency.*