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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

To promote solutions of key fusion problems like tritium retention, wall erosion and material re-deposition (flake and dust production), more in situ measured data of carbon deposition in remote areas of fusion devices are needed. These data are essential to understand the key processes as well as to model the local and global particle fluxes in present devices which is the basis for predictions for future devices like ITER.

In spring 2000 the development of a new diagnostic, Quartz MicroBalance (QMB), was started to measure quantitatively, in situ and time resolved ($\leq$ 1sec) the material deposition in shadowed areas in the sub divertor region of JET. The QMB was fully installed by Remote Handling (RH) during the October 2001 shut down. Extended calibration work of mass temperature characteristic was done at FZ-Jülich giving a layer mass sensitivity of Γ_{mass} = 7.5*10^{-9}g/Hz and a temperature sensitivity of Γ_{temp}(100°C) $\approx$ 0.09 °C/Hz at the operation temperature. The challenge of the work was to adapt the well known and commercially available QMB technique to the harsh constraints and requirements of JET. After implementation in March 2002 reliable and successful operation was demonstrated during the C5 campaign (~ 1000 plasma pulses). First carbon deposition data for this period are presented.

1. INTRODUCTION AND AIM

Following a 6 month of plasma operation in JET (MkIIA campaign in 1996) a set of divertor tiles was removed for analysis and a visual inspection showed heavy film deposition and flaking on the water-cooled louvers at the corner of the inner divertor. The analysis proved deuterated carbon layers up to about 40µm thickness, with a ratio of D/C = 0.7 build up after 2000 pules and an ion flux into the divertor of 5.5*10^{26}. Assuming toroidal homogeneous deposition on the louvers this would account for 5 – 10% of all the deuterium fuelling into the machine over this period.

The investigation of the fuel inventory in JET revealed nearly all (>90%) of the tritium retained during the DTE1 campaign was stored in those flakes and that at the end of the cleanup after the JET tritium experiment DTE1 6g tritium of 36g injected were still remaining in the vessel [1]. Thus time resolved measurements of the carbon layer growths in the JET divertor intended by the new QMB technique contribute strongly to a more reliable extrapolation of the tritium retention in ITER

Quartz MicroBalance systems (QMB's) with a thickness detection limit and resolution of about 0.1nm provide time resolved measurements and are promising diagnostics to measure material deposition on remote areas in fusion devices.

2. MEASURING PRINCIPLE OF QUARTZ MICROBALANCES

The basis of the QMB measurement is the high sensitivity of the quartz resonator frequencies with respect to mass changes and the accuracy of the frequency readings of resonator circuits in the MHz range. The quartzes are part of electric resonator circuits. They are excited into mechanical vibrations by an alternating electric field applied between their 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 one of the resonators normal modes of vibration and resonance occurs. Near resonance, the amplitude of vibration increases and the otherwise stable resonance frequency does only depend on mass and temperature of the quartz. Any adsorbed layer on the quartz will increase the weight of quartz and lower the frequency [2,3]. The thickness monitoring is made by monitoring this frequency.

The resonators consist of piezoelectric silicon dioxide, SiO_2, precisely dimensioned and oriented with respect to the crystallographic axes optimised for temperature stability and/or layer collection. The density of the crystals is $r_{quartz} = 2.649 g/cm^3$ and the specific heat capacity $C = 710 Jkgm^{-1}K^{-1}$. When the quartz is heated above 573°C its crystalline form changes from the piezoelectric "alpha quartz" to the non-piezoelectric "beta-quartz". This inversion is irreversible. Also mechanical stress and large thermal stress may destroy the piezoelectric feature.

3. DEMANDS ON THE JET/QMB SYSTEM

The aim of the measure and the constraints of the JET operation determine the technical and physical demands on the new diagnostic. In vessel diagnostics are subject to rigid requirements and this excluded commercial available standard QMB-systems to be used. The JET constraints, the requirements for operation, resulting problems and their technical solutions for the QMB design are described below.

3.1 JET IN VESSEL WIRING

The available cables consisted of mineral insulated thermocouple cables of a length of about 6m between the measuring position and the electrical vacuum feed through. They were unsuitable to transmit the 6MHz resonance frequencies of a quartz.

Thus, a new QMB-detector unit (DEU) was developed on the basis of a Printed Ceramic Board (PCB) consisting of suited quartz crystals and electronics. Using An Specific Integrated Circuit (ASIC), working as a frequency mixer, signals below 25kHz are produced which are suited for transmission through the existing wires to a driver unit (DRU) positioned outside the vessel nearby of the electrical feed through. The DRU provides as well lines drivers to the data acquisition systems over a distance of about 120m as well isolated power to run the deposition unit inside the vessel. The DEU system contains the deposition quartz and is placed at the measuring location in front of the louvers of the inner divertor see Fig.1.

3.2 HIGH TEMPERATURE OPERATION

The temperature of the DEU is determined by the surrounding temperature of the divertor tiles (thermal equilibrium). The thermocouples mounted in the direct neighbourhood of the DEU revealed maximum temperatures of about 185°C during vessel baking and 80°C to 190°C during operation. Therefore a DEU version was developed to suit operation at temperatures up to 200°C in steady state. All electronics components including crystals, contacts and the frequency mixer (ASIC) had to meet this temperature.

2

3.3 TEMPERATURE DEPENDENCE OF CRYSTAL FREQUENCIES

The frequencies of a quartz does not only depend on mass changes due to material deposition but also on temperature. Standard QMB's as supplied by various companies are based on water cooled resonators to eliminate the influence of temperature drifts. This technique is not appropriate for JET.

To overcome this problem a so called Temperature Crystal (TC) was added to the DEU nearby the Deposition Crystal (DC) measuring the deposition, see Fig.2. This crystal, placed on the PCB inside the DEU-box, is not open to plasma deposition and its frequency is thus only influenced by temperature. The difference of the frequencies of both crystals represent the measure for the mass change of the deposition crystal under the condition that DC and TC are in thermal equilibrium.

3.4 REMOTE INSTALLATION

Remote installation into the divertor was required since access into the vessel is restricted for safety reasons. Therefore the DEU was designed to be attached manually to the inner carrier of the divertor module 13 which was then installed by remote operation. Correct electrical connection and positioning in front of the louvers was ensured.

3.5 VACUUM COMPATIBILITY

A general rule at JET and other fusion devices is to minimise the outgassing capability of material placed inside the vacuum vessel.

Thus, the DEU was developed on the basis of a Printed Ceramic Board (PCB) carrying quartz crystals and electronic components connected via gold traces to reduce outgassing, see Fig.2.

3.6 TIME RESOLUTION OF QMB MEASUREMENT

A time resolution of the measurement of ≤ 1 second was required to pick up and investigate layer deposition during dedicated parts of discharges.

This was realised by means of an active controlled shutter. A current of 1,5 Ampere is sent through a coil in the presence of the toroidal magnetic field. The resulting Lorentz force lifts the protective shutter and allows deposition on the DC. Without current the shutter drops down by gravity, closes the aperture and interrupts the particle flux to the deposition crystal. Figure 3 shows the whole QMB unit consisting of the deposition unit with the deposition crystal and the protective shutter.

3.7 RADIATIVE POWER FLUX

Radiative power flux from the plasma to the quartz, in particular under large external heating in connection with strike zones on the lower part of the vertical tile or even on the base horizontal tile was recognised as potential failure source. This may lead to destruction of the electronic components inside the DEU-box due to overheating. Even more critical, the quartz crystal, fully unprotected during exposure time, is endangered due to its small heat capacity.

To prevent this possible damage the PCB is triply thermally shielded by lids and housings. Only the DC is freely accessible through the apertures in the housings.

3.8 OTHER POSSIBLE FAILURE SOURCES

Electromagnetic and mechanical impact on the QMB units may always occur during plasma operation. Forces (e.m.f., eddy current, halo current), pick up of voltage during disruptions, pick up of electromagnetic power during plasma heating (ICRH, ECRH) and arcing are beside others the most prominent possible failure sources.

Appropriate shielding, grounding and prevention of electrical loops in the electronics is necessary to overcome this problem. As electrical shielding, a stainless steel mesh, with an optical transparency of 90% is fixed in front of the DC to prevent damage or overheating by arcing.

4. SET UP OF JET/QMB

4.1 DEPOSITION UNIT (DEU):

4.1.1 QUARTZ RESONATORS

The key items of the DEU are 3 resonator crystals. Two of them, the Deposition Crystal (DC) and Temperature Crystal (TC) are disk shaped with 14mm in diameter and 0.29mm in thickness. They are optimised for layer thickness measurements. Front and back side are covered with gold electrodes of about 160nm thickness. Their resonance frequency is close to 6MHz. The third crystal, the Reference Crystal (RC) is embedded in a metallic housing optimised with respect to temperature stability. Special techniques, like the glowing techniques or gold wire (25μm thick) bonding techniques to ensure reliable electrical contacts and fixing of the electronic components and quartzes to the PCB are described in a separate documentation, see [4]. The PCB equipped with all electronics and quartzes is shown in Fig.2.

- *Deposition Crystal (DC)*

The DC is oriented radial towards the divertor. The deposition area is about 0.5cm^2 in the centre of the crystal determined by an aperture of about 8mm in diameter in the thermal shielding of the DEU in front of the DC.

- *Temperature Crystal (TC)*

The frequency of the TC is only influenced by the surrounding temperature since its mounted inside the housing of the DEU and is thus measuring solely the effect of the temperature on the frequency. The difference of the frequencies from DC and TC gives the frequency change due to layer growth on the DC provided temperature equilibrium of both crystals.

- *The Reference Crystal (RC)*

A special temperature stable AT cut type quartz see [5] is used as a Reference Crystal (RC). Its frequency drift due to temperature is ≤ 25ppm for the range 100°C – 200°C. It provides a stable reference frequency of about 5975kHz for subtraction from the frequencies of Dc and TC.

4.1.2 FREQUENCY MIXER

A high temperature compatible (≤ 200°C) application specific integrated circuit (ASIC), see Fig. 2, drives the 3 resonant circuits by means of high precision Pierce oscillators. It also comprises the frequency mixer and thus provides the frequency differences DC-RC and TC-RC which then can easily be transmitted. Stability is achieved by automatic active gain control, for more details see [6].

4.1.3 PROTECTIVE SHUTTER

The protective shutter is controlled by a current of 1,5 Ampere send through a coil in the presence of the toroidal magnetic field. The resulting Lorentz force lifts the protective shutter and allows deposition onto the DC. Without current the shutter drops down by gravity the aperture is closed and the particle flux to the deposition crystal is interrupted. Plasma configuration with the strike zone in the divertor corner which can lead to dangerous power deposition can be avoided by appropriate shutter handling. Figure 3 shows the QMB as a whole as installed in the inner divertor. The shutter is open and the DC is in the position of particle collection.

4.2 PRINCIPLE OF OPERATION

The high primary frequencies of about 6MHz of the DC, $n_{DC,p}$ and TC, $n_{TC,p}$ can't be transmitted to the driver box outside the vacuum vessel due to the limit of the in vessel wiring of about 25kHz. To obtain transmittable frequencies the frequency mixer subtracts the temperature stable reference frequency n_{RC} [a] 5995 kHz from both primary frequencies.

$$\nu_{DC,m} = \nu_{DC,p} - \nu_{RC} \quad \text{and} \quad \nu_{TC,m} = \nu_{TC,p} - \nu_{RC}$$

The resulting measure frequencies $n_{DC,m}$ and $n_{TC,m}$ are then about 5kHz, sufficient small for transmission. Extended calibration measurements of the temperature sensitivity of DC and TC were carried out in the temperature range RT to175°C. The temperature dependence of both crystals were found to be nearly identical. The frequency dependence of the bare DC from temperature can be expressed by the formula

$$\nu_{DC,\ bare} = 0.992 * \nu_{TC,m} + 522$$

and measured deviations from this value are due to layer deposition independent of the operation temperature provided both crystals are in thermal equilibrium.

The actual thickness of a carbon layer ν_{lay} is always determined by

$$\nu_{lay} = \nu_{DC,m} - \nu_{DC,bare}$$

The frequency due to changes of layer mass during a dedicated exposure is given by

$$\Delta\nu_{lay} = \nu_{lay,a} - \nu_{lay,b}$$

with $\nu_{lay,a}$ = frequency due to layer mass after exposure
and $\nu_{lay,b}$ = frequency due to layer mass before exposure.
and the conversion into mass increase of the layer

$$\Delta m_{lay} = \Delta\nu_{lay} * \Gamma_{mass}$$

with $\Gamma_{mass} = 7.5 * 10^{-9}$ g/Hz obtained from laboratory calibration measurements.
Figure 4 shows typical curves of n_{lay} versus JET pulse time. The QMB is usually switched off in the presence of the magnetic field (20sec to 100sec) to minimise the risk of an electronic damage.

That's why the frequency drop due to the temperature excursion is not monitored. The measurement restarts at about 100sec when the frequency already increases due to the cool down of the DC. The signal levels off when the temperature of both crystals, DC and TC, are steady state and in thermal equilibrium. To ensure this, data recording lasts typically till 1200 sec. The difference of ν_{lay} in a series of consecutive pulses of exposure reflect different amounts of layer deposition in the corresponding discharge. For example the discharges 55432 and 55433 both with the inner strike point position far away from the corner (DOC-U) do not show any change in frequency respectively layer deposition with respect to discharge 55431 while discharge 55431 itself with the strike point closer to the inner corner (DOC-LL) shows the most pronounced increase in the series with respect to the previous one 55430.

4.3 *LOCATION OF MEASUREMENT*

Figure 1 shows a schematic of the cross section of the present MKII GB SRP divertor configuration (without Septum). The position of the QMB system in front of the louvers of the inner divertor is marked with a box. Its front side with the aperture for the DC is oriented in radial direction towards the plasma and parallel to the magnetic field.

5. FIRST IN SITU AND ON LINE CARBON RETENTION MEASUREMENT IN THE JET DIVERTOR

In total 979 successful divertor plasma pulses have been performed during the JET-C5 campaign. The integrated divertor plasma time was about 13600 seconds and the total deuterium ion flux into the in the inner divertor during this time was about $2.17*10^{26}$. The latter value is derived from integration of ion currents of Langmuir probes placed on the inner divertor tiles and thus underestimate the flux for conditions where recombination is important The measurement revealed that layer deposition out of the divertor phase could be neglected and only the exposure time during the divertor phase was considered as particle collection time for the data evaluation. The data presented in Fig.5 are based on a selection of 83 pulses with a total exposure time of 776 seconds. The total number of carbon atoms deposited on the QMB per cm^2 is plotted versus the integrated deuterium ion flux into the inner divertor during exposure time. At the maximum $1.33*10^{18}$ C-atoms/cm^2 are collected correlated with an total ion flux into the inner divertor of $3.13*10^{25}$. This value was extrapolated to the area of the gap of the inner pump duct (4518 cm^2). Resulting in $6.04*10^{21}$ deposited C-atoms in the louver area. Thus the ratio of deposited C-atoms to the total D-flux into the inner divertor , the yield for carbon deposition onto the louver area, is about $1.9*10^{-4}$. This is significantly lower compared to the values estimated from the DTE1 of about 4% of D-flux [1]. The total number of collected C-atoms in the louver area during the C5 campaign can be extrapolated to be about ~ $5*10^{22}$ C-atoms, corresponding to ~1.0g.

It will be subject of further research to identify in detail the reasons for the largely decreased carbon deposition on the inner louver area of the 2 campaigns. The most important parameters

seems to be the reduced wall temperature from 300°C to about 180°C which reduced the divertor temperature from about 220°C to 100°C and the different divertor geometry. In MKIIA the strike point was mostly on the horizontal tile with a direct view of the strike point to the louver area whereas it was in C5 always on the vertical tiles with no direct view to the louvers. The pronounced changes in the gradient of the curve in Fig.5 point clearly to the fact that different deposition rates are observed for different plasma scenarios. These questions need to be addressed in coming experiments and the available data will be analysed and published elsewhere.

6. SUMMARY

Aim of the work was to measure in situ and time resolved layer deposition in remote areas of the inner divertor of JET. The challenge was to adapt the standard technique of layer thickness determination based on quartz resonators to the requirements and constraints of JET. The development, set up and first measurements of the new type of Quartz Microbalance (QMB) diagnostic are presented. The QMB was installed fully by remote handling in October 2001 and was put into operation in March 2002. Reliable operation was demonstrated throughout the period of the C5 campaign (about 1000 plasma pulses). For the first time the carbon deposition in remote areas of the JET divertor was measured on a shot by shot basis and first results presented, based on 54 selected discharges, are showing the evolution of the carbon deposition versus the integrated ion flux into the inner divertor region

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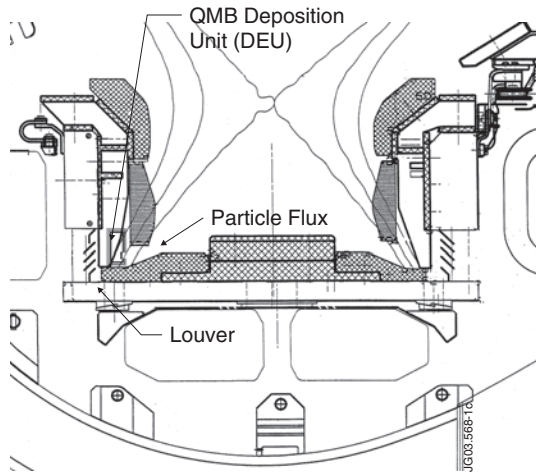
[7]. Rohde ASDEX QMB contributions

Figure1: Cross section of the JET divertor MkII GB SRP, showing the location of the QMB deposition unit in front of the louvers of the inner divertor.
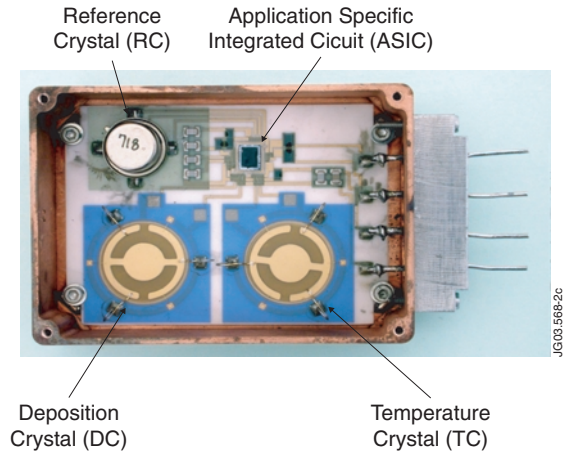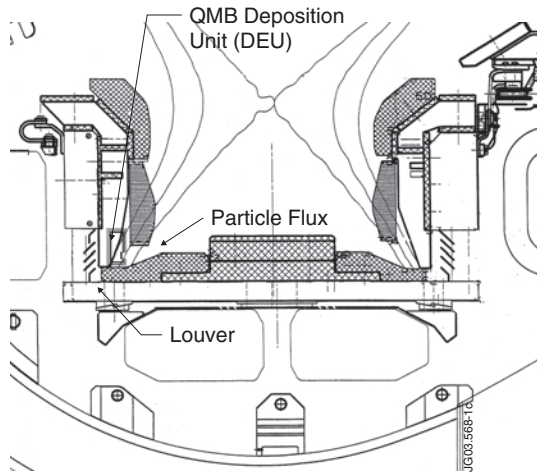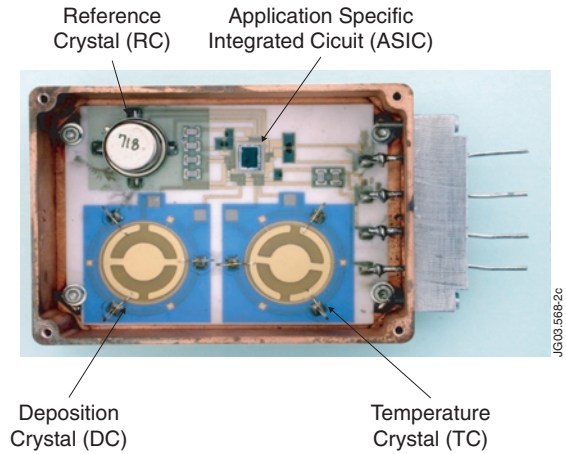

Figure 2: View from the back into the open deposition unit (DEU) showing crystals and ASIC mounted on the PCB connected via gold traces.

8

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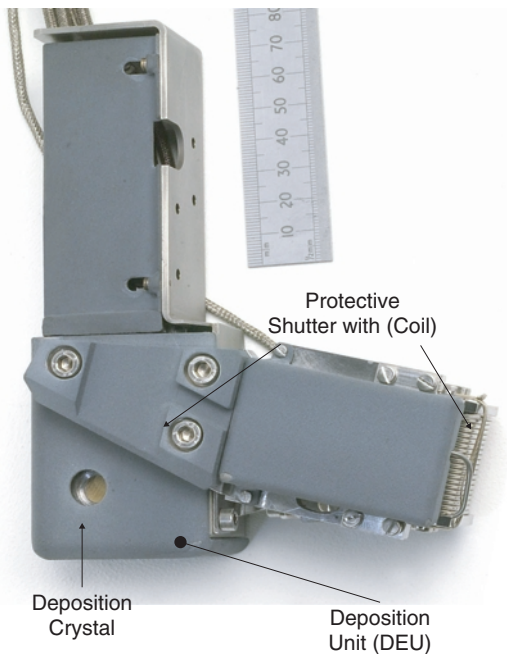

Figure 3: JET Quartz Microbalance;
view onto the complete system including deposition unit and shutter; shutter in open position allows direct view onto the deposition quartz.
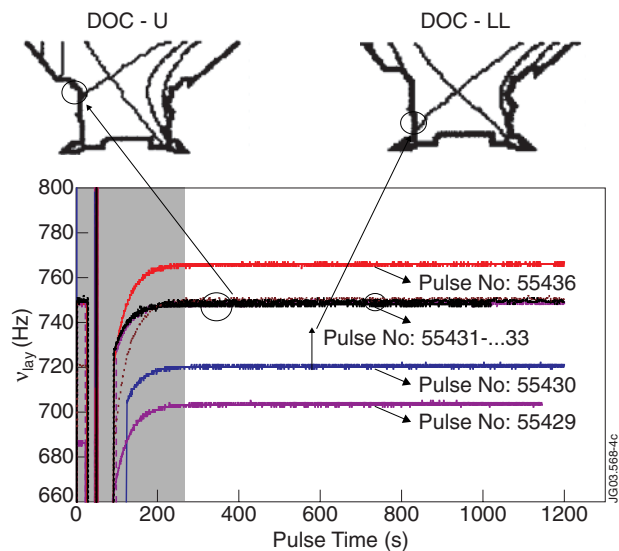

Figure 4: Frequency change of ν_{lay} due to layer deposition; DOC-U strike point positions far away (no deposition) and DOC-LL close to the corner(strongest deposition) of the inner divertor.
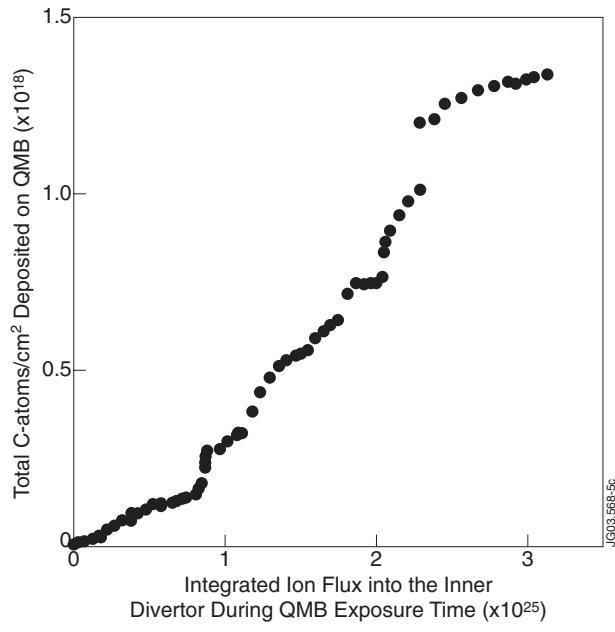
Figure 5: Sum of C-atoms deposited on the inner louver region vs integrated ion flux into the inner divertor; basis 54 JET discharges.