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High Temperature Quartz Microbalance for the Measurement of Deposition Inside an Experimental Fusion Device

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1. INTRODUCTION

The Joint European Torus (JET) machine has for a number of years been looking at the experimental feasibility of producing fusion energy from isotopes of hydrogen within a magnetically confined vessel called a tokamak. The machine produces plasmas at temperatures of up to 100 million degrees Centigrade in pulses of 10s duration. Conclusions from this project will provide the building blocks for the next machine, which may be the prototype fusionreactor called ITER.

1.1 BACKGROUND TO THE MEASUREMENT

One consequence of the operation of JET is the erosion and re-deposition of wall material, leading to tritium trapping within the re-deposited films on the vessel protection tiles. Tritium is a radioactive isotope of hydrogen for which strict limits are set to the in-vessel inventory for safety reasons. There is a need to understand what factors affect the deposition rates for eroded material, as deposition is the major factor determining the tritium inventory in a fusion reactor. Figure 1 gives the distribution of tritium retention in JET, and shows it is highest on the inner louvres and the photo show large amounts of carbon flaking. Current methods for measuring deposition rely on access to the inside of the machine to remove samples for surface analysis and the intervals when this can be done can be very long (typically one year or more). An online measurement system monitoring deposition on a daily basis would improve our understanding of machine operation. For this reason Quartz Micro-Balance (QMB) technology and high temperature electronics originally developed for the oil well logging business have been combined to develop a measurement system.

2. JET IN-VESSEL INSTALLATION REQUIREMENTS

The design and placement of the QMB, scheduled for September this year has been very much dictated by constraints imposed by the JET machine.

2.1 LOSSY IN VESSEL WIRING

Only lossy or low frequency Sulzer cables, used for thermocouple measurements were available. Typical cable lengths are 6 metres and this factor alone ruled out using commercially available products which operate at frequencies around 7MHz. For comparison, the high temperature BiCMOS ASIC to be used in JET has an output frequency of only 10KHz.

2.2 OPERATING IN TEMPERATURES OF UP TO 200 CENTIGRADE.

The louvre installation site runs continuously at temperatures of up to 200 degrees centigrade. This is one of the cooler parts of the machine and rules out conventional low temperature electronics.

2.3 UHV CONDITIONS

Only low levels of out-gassing are allowed for any equipment installed inside the vessel, since the JET plasma itself weighs no more than about 0.1g. To keep out gassing to an acceptable level the electronic circuit developed for JET is mounted on a ceramic board using wire bonding and epoxy techniques. The amount of epoxy used is about 0.01 of a gram and considered acceptable. Mass loss (mainly hydrocarbons) at 300^{o}C is less than 1%.

2.4 ELECTRICALLY HOSTILE

Plasma currents of 3MA and magnetic fields of 3T are typical for JET. Sometimes this current is rapidly quenched in tens of milliseconds, leading to large induced currents in the vessel. Attention to circuit layout, electrically floating the circuit and screening have been employed to reduce the risk of damage to the circuit caused by induced currents. The QMB is also turned off during plasma operation, as measurements are made in between plasma pulses.

2.5 NEUTRON AND GAMMA RADIATION

The device is not radiation hardened and will have limited life. It is after all a prototype aimed at establishing the measurement technique and further development is envisaged.

2.6 HEAT FLUX FROM PLASMA

Adjacent surfaces to the inner louvres currently receive about $10MW/m^2$, and to minimise these high heat flux levels careful positioning of the device is important. A heat shield and small crystal deposition aperture minimise the heat flux from the plasma.

Flexible mounting of the measurement crystals reduced fracturing. Under these conditions a rigidly mounted wafer crystal would fracture.

Finally an electromechanical shutter is employed to protect the measurement crystal from unwanted plasma shots. The shutter can be held in the closed position electrically, or allowed to open in the magnetic field applied within the JET machine during a pulse.

3. THE QUARTZ MICRO-BALANCE (QMB)

3.1 COMMERCIAL FILM THICKNESS MONITORS

Commercial film thickness monitors are used routinely in controlled laboratory conditions for measuring film growth in vacuum deposition rigs. They are based on a quartz micro-balance and operate on the principal that a resonating circuit containing a thin wafer crystal will change frequency (f_1-f_2) as its thickness (t) increases. To a first order there is a simple ratio between thickness and frequency:

$$t = t_0*(f_1-f_2)/f_1$$

where

$$f_1 = 6MHz \text{ and } t_0 = 0.27mm.$$

The commercial devices are water-cooled and under these conditions are extremely sensitive devices measuring to better than 1nm. They are not suitable to operate inside JET

3.2 A QUARTZ MICRO-BALANCE (QMB) FOR JET

The JET QMB is based on a high temperature BiCMOS ASIC chip [1] originally developed by SINTEF Electronics and Cybernetics for oil well logging of pressure and temperature down a bore hole. This device therefore has similar requirements in terms of the need to survive high temperature and drive long lengths of cable.

A schematic of the device mounted inside the vessel is shown in Fig.2 There are two measurement crystals, one for deposition and one for temperature, with nominally the same operating frequency (5.990MHz), together with a highly stable reference crystal (6MHz). The BiCMOS chip consists of three high precision crystal Pierce oscillator circuits with mixers providing two digital outputs. The outputs provide the difference frequency between reference and deposition crystals, and between reference and temperature crystals, at a low frequency (10KHz). The capture range of the mixer circuit is about 30KHz and this corresponds to a maximum measurement thickness of about 20 microns.

The temperature channel is required to null out the unwanted effect of temperature on the resonant frequency of the crystal. Calibration of the QMB device in a temperature controlled vacuum chamber is still necessary because of slightly different characteristics.

A drive unit just outside the vessel provides isolated power to the QMB, signal isolation and a 50-ohm drive unit for the 100 metre link to data acquisition. Software provides an on screen display of deposition rate.

4. TESTING THE PROTOTYPE

Development times on JET from inception of a new diagnostic being installed and running tend to be long because of the limited access periods to the machine so that an alternative route was needed to test out a prototype system. The facility chosen was a smaller Tokamak, TEXTOR, provided by the IPP EURATOM Association at Forschungszentrum Jülich, as part of the EFDA enhancement contract.

4.1 TEXTOR TESTS

Three experimental periods over the past year were spent looking at how reliable the prototype system performed in a reactor environment. The prototype was fitted on a vacuum interlock system enabling the device to be moved vertically up and down inside the machine.

Of the 5 prototype systems tested failures tended to fall into two areas.

1. Deposition crystal failure due to electrical arcing.
2. Fracturing of crystal caused by high heat flux from the plasma.

In both cases the crystal became damaged and ceased to work as an oscillator. In the first case, the electronics was also destroyed.

The tests did show, however, that with carefully positioning of the device meaningful measurements were possible, but local plasma disruption or loss of plasma position control could easily damage the crystal or electronics. In JET the system is better shadowed from the plasma by fixed structures and so these problems are expected to be less severe.

4.2 DESIGN IMPROVEMENTS

As a result a number of modification were added to the design of the JET system:

1. A more flexible crystal mount to improve heat flux capability and reduce fracturing.
2. Crystals and electronics as one unit to reduce pickup.
3. Wire mesh over the deposition aperture to reduce arcing on the deposition crystal.
4. Added electrical and heat shields for the unit for increased protection.

5. RESULTS FROM TEXTOR

5.1 LABORATORY CALIBRATION OF CRYSTAL WAFER:

To calibrate the JET QMB the quartz crystals were placed in a temperature controlled vacuum chamber and a-C:H (amorphous hydrogenated carbon) was evaporated on to their surface. They were subsequently removed and the frequency change was measured. Results are shown in Fig. 3.

5.2 FREQUENCY CHANGE WITH TEMPERATURE RESULTS FROM TEXTOR

Fig. 4 shows how sensitive the measurement crystals are to temperature changes. The time trace corresponds to an overnight cool down of the device from 90 to 35 Centigrade. The temperature sensitivity of the deposition crystal in this case was determined to be 41Hz/^{o}C, whilst that for the temperature crystal was 58Hz/^{o}C.

5.3 DEPOSITION RESULTS FROM TEXTOR

Despite the sensitivity to temperature the results proved very reproducible so that providing the temperature was allowed to stabilise at the end of a days experiments the deposition could be determined. In the example of Fig.5 a frequency shift of 197Hz was detected from one night to the next (14th and 15th) corresponding to a coating of 22nm during the day of operation. This proved consistent with independent measurements of the film thickness.

CONCLUSIONS

A quartz micro-balance based on high temperature electronics technology has been developed. The prototype QMB been shown capable of measuring deposition of eroded material in the JET magnetic fusion experiment at temperatures up to 200^{o}C.

If the device proves successful in JET there will be a need to develop higher temperature devices for making measurements in other locations (up to 325^{o}C) and to consider development of devices with enhanced resistance to neutron damage.

REFERENCES

[1]. O.Vermesan, ASIC Design for High Temperature Applications HITEN97.

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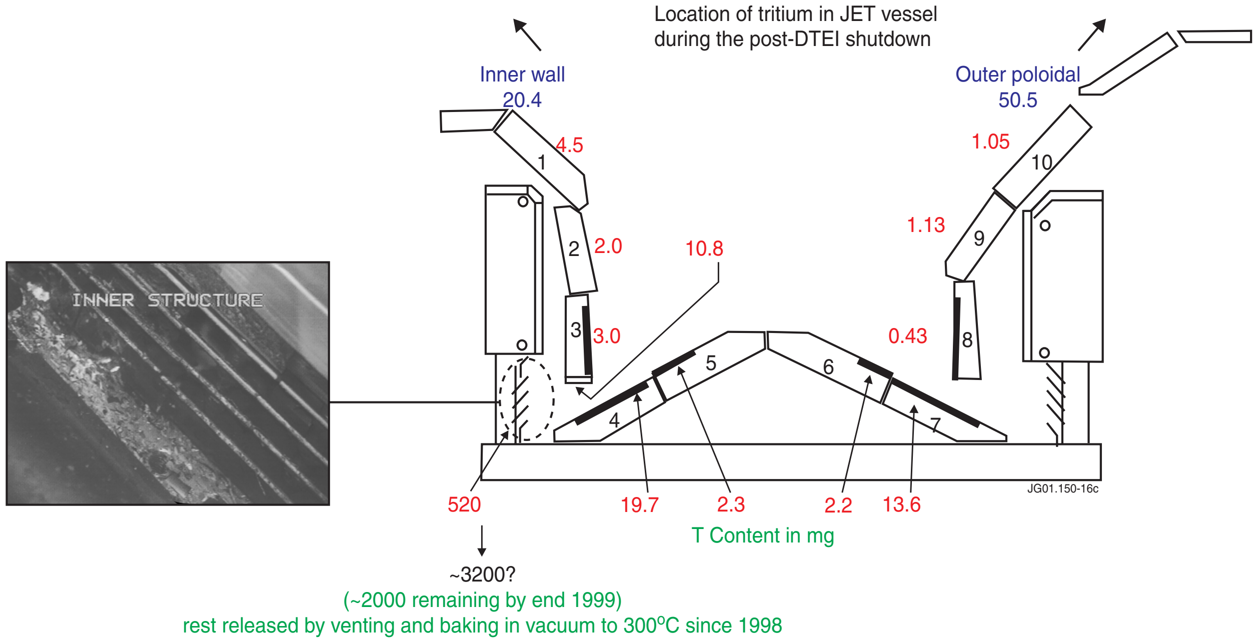
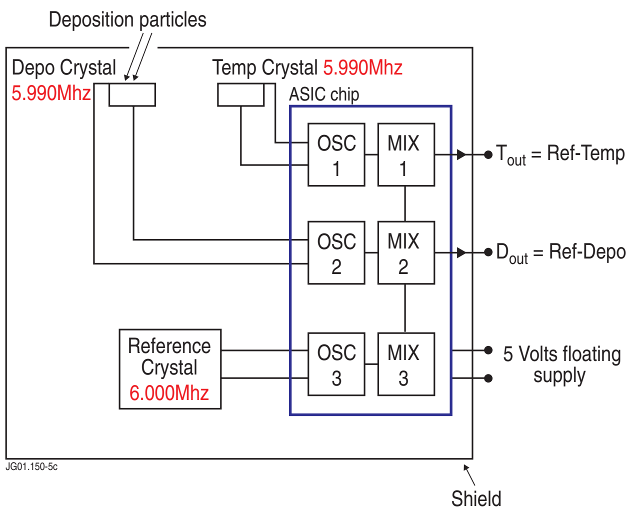


Figure 1:



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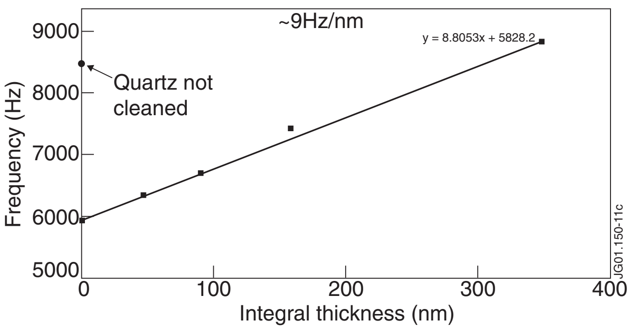

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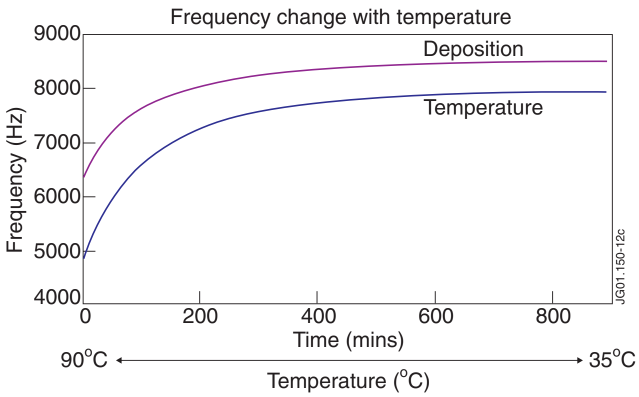

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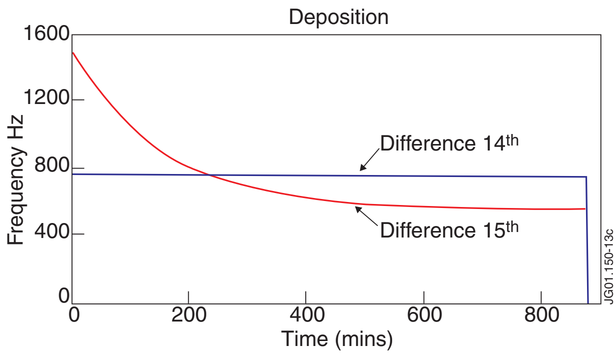

Figure 5: