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Operational Experience with a Remote Radiation Hard Quadrupole Residual Gas Analyser

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1. Introduction

JET(Joint European Torus) is the world's largest fusion experiment with the main aim of investigating the scientific feasibility of nuclear fusion with a Tokamak reactor. Tokamak reactors operate with magnetic confinement of heated plasmas in a toroidal shaped vacuum vessel. The present generation of Tokamak machines operate primarily with Deuterium plasmas. It is expected that JET will be the first Tokamak to operate extensively with Tritium/Deuterium plasma in 1996 resulting in significantly more fusion reactions than with Deuterium plasma. The energetic neutrons, given off from the plasma, will create an ionizing radiation environment around the vessel which will be particularly hostile to electronic components such as those used in residual gas analyzers (RGA).

2. Requirements for mass spectrometers on JET

During plasma operation the Torus vessel is maintained at 300 °C by electric and gas baking and pumped by four turbo molecular pumps giving a total pumping speed of approximately 8500 mbar l s^{-1} (Protium). It is normal to achieve a base pressure in the low 10^{-7} mbar range (hydrogen) and impurities in the 10^{-9} mbar range following vessel conditioning. RGA are required for the analysis of Torus vacuum as well as for the peripheral vacuum vessels of the neutral beam injectors and the pellet injectors. At JET RGA are primarily used as diagnostic tools for the detection of leaks, other problems with the vacuum and for confirming the purity of gases to be introduced into the plasma. Leaks from inert gas filled interspaces and from coolants such as water and Freon and dielectric sulphur hexafluoride must be detected. The overall air leak rate must be controlled to less than 1 X 10^{-6} mbar l s^{-1} [1], hence major air leaks must be diagnosed. These are recognised primarily by the cracking pattern for nitrogen since oxygen is gettered by the hot graphite and beryllium protection tiles on the vessel wall. RGA with a secondary electron multiplier can not be used due to the avalanche effect caused by Tritium decay. The basic requirement of JET is therefore for faraday cup quadrupole RGA that are able to scan mass ranges 1 - 100 atomic mass units (amu) with good mass resolution and have good sensitivity to low partial pressures.

3. Environmental considerations.

The neutron fluence experienced by an item on the Torus will depend on the experimental programme ultimately performed. The reference fluence which has been used for design purposes is 4.7 X 10^{16} equivalent 1 MeV neutrons cm^{-2}. The availability of radiation damage data for high neutron fluences is somewhat limited. It has been predicted that for semiconductors materials neutrons may cause 100 times more damage than gamma radiation [2]. The new RGA has been developed to withstand a dose of 1 X 10^{8} rad based upon test data for mixed neutron/gamma irradiation [3]. At this dose unacceptable degradation would occur for example in semiconductors, electrolytic capacitors, carbon resistors and Teflon insulation. It is however expected that insignificant degradation would occur in vacuum tubes, mica capacitors, metal film resistors and polyimide insulators.

During the actual generation and heating of plasma on JET there is no requirement for data from the RGA. The RGA must however be able to withstand the unfavourable conditions generated during a plasma pulse. The worst conditions occur in the event of a high current disruption in the plasma wherein the plasma current is suddenly lost due to instability. Under these conditions the vessel to which the RGA is connected can become charged to several hundred volts, and simultaneously be subject to considerable mechanical forces and large transient electromagnetic fields. In locations on the Torus where RGA could be placed vibration levels of up to 100 ms^{-2} and magnetic fields of up to 3 Tesla may be experienced during plasma discharges.

4. Reasons for development of a new RGA

The Torus is positioned in a large hall with 2.8 m thick concrete walls which constitute the biological radiation shield. It is not practical to provide local shielding at the RGA head locations on account of access and spacial constraints. The size and arrangement of available junction boxes dictates that cable runs from the Torus to electrical cubicles located outside the biological shield are in the region of 100 m. The decision to develop a radiation resistant quadrupole RGA followed a survey which revealed that all commercially available RGAs had radiation sensitive components in close proximity to the quadrupole head. One manufacturer has recently removed sensitive components 15 m from the RGA head. This is an interesting development but does not cope with the distance required by JET.

5. The design and experience of the new RGA.

The new RGA system was designed to conform to the JET Control and Data Acquisition System (CODAS) [4]. The basic control and data acquisition for each RGA is microprocessor based. Most of the innovative parts of the design are based around being able to operate under the harsh environmental conditions, particularly the radiation environment. The electronics of the design combined a radiation hard section, at the quadrupole head, with a semiconductor based section placed away from the high levels of radiation. The two sections have been designed to operate at a cabling distance of approximately 100 m apart. A block diagram showing the outline of the RGA system is given in Fig 1 . The experience gained, by operation of the three most novel sections of the design, is detailed below.

5.1. The quadrupole head

The head is of similar design to most conventional analytical quadrupoles except for the provision of high voltage isolation between the filter system and the flange mounting. The requisite isolation was initially provided for by mounting the lens system on a Macor ceramic ring. This was however found to be too brittle and following a failure, was replaced with three Vespel pillars, which proved to be much more durable.

5.2. The RF generation and control

The mean amu of the ions forming a stable path through the filter of a quadrupole is determined by the geometry of the head and the frequency and voltage of the alternating voltage applied to the rods. The new RGA uses a 2 MHz alternating voltage which is varied in amplitude in proportion 2.224 times the amu. The accuracy of the RF voltage applied to the head critically influences the effectiveness of the instrument. The RF transmission technique adopted requires only a transformer, several capacitors and a triode valve to be located at the head [5]. Radiation hard versions of all these components were sourced. The RF generator is of conventional semiconductor design and drives the 100 m coax cable through a transformer. The feedback from the rectifying triode facilitates the accurate control of the RF voltage at the head.

The RF transmission technique generally worked well. At 100 amu the power required was approximately 15 Watts with the transmission line impedance matched to the source and the impedance of the head tuned. The vacuum tube feedback did exhibit a slight non-linearity causing up to 0.5 of an amu inaccuracy in the peak position over the mass range. In order to obtain constant sensitivity the ratio of DC to AC voltage at the head should be constant. With linear DC and slightly non linear AC there is therefore a small error in the relative sensitivities across the mass range. This does not cause any particular problem for JET applications but ways of solving this problem are being sought.

5.3. The Electrometer

A partial pressure of 1 X 10^{-11} mbar would produce a ion current of 5 Femto amperes with a typical head sensitivity of 5 X 10^{-4} A mbar^{-1}. The design used to sense this current, at a distance of 100 m, featured two vacuum tube tetrodes positioned at the head. These are incorporated into the feedback loop of an integrated circuit differential amplifier outside of the radiation environment. One tetrode is used as a reference, the other as a very high gain current amplifier. The highest gain setting uses a 100 Giga ohm feedback resistor giving a closed loop gain for the pre-amplifier of 1 X 10^{-11} V A^{-1} . The main components at the head end are the tetrodes and metal film resistors which are radiation hard. A relay is also used at the head end for reducing the gain of the electrometer for higher pressure measurements. The radiation hardness of the relay has yet to be confirmed.

Good design practice for low noise Femto ampere measurements had to be employed. The electrometer's performance was further improved for the highest gain setting by the addition of a 4th order low pass filter to remove 50 Hz noise. The resulting noise constant sensitivity the ratio of DC to AC voltage at the head should be constant. With linear DC and slightly non linear AC there is therefore a small error in the relative sensitivities across the mass range. This does not cause any particular problem for JET applications but ways of solving this problem are being sought.

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Good design practice for low noise Femto ampere measurements had to be employed. The electrometer's performance was further improved for the highest gain setting by the addition of a 4th order low pass filter to remove 50 Hz noise. The resulting noise level in the Torus environment was equivalent to less than 5 X 10^{-15} A peak to peak related back to the faraday cup signal.

When initially setting up the RGA, offsets in the electrometer are tuned out using the control grids of the tetrodes. It was observed that during plasma operations an offset in the electrometer output was produced after some plasma pulses. The offsets did not drift or decay away and were only changed by another offending pulse. The offsets induced could be positive or negative but over a reasonable number of pulses had a mean of zero. The worst offsets resulted from high current plasma disruptions. Experiments were done, away from the Torus environment, where the electrometer was subjected to simulated alternating magnetic fields and vibrations but it was not possible to emulate the aforementioned offsets. In the main, the offsets presented a problem only at the highest gain settings. A manual trimmer was introduced, at the control end, so that the offsets could be tuned out. If the cause of the offsets can not be identified and eliminated then an electronic solution for their mitigation will be reasonably straight forward to implement.

6. Results from operational experience with RGA

Experience of the prototype analyser was first gained with the head installed to a small ion pumped vacuum system. A number of teething problems, associated with the prototype nature of the equipment, occurred during these initial tests. Once these had been cured the RGA was installed on the JET vacuum vessel and connected up using the JET standard cabling arrangement. The RGA was operated during plasma operations for a period of over 6 months. Over this test period no component failures were experienced however various improvements were made to the control side of the RGA to improve it's performance.

A typical mass spectrum of the Torus vacuum during plasma operations is given in Fig. 2. It displays good resolution and peak definition. The masses in the range 12 to 32 result mainly from deuterated species of methane, water, acetylene, and ethylene.

The low pressure performance of the RGA is demonstrated by the mass spectrum of the Torus vacuum as shown in Fig. 3 taken with the RGA on its maximum gain setting of 1 X 10^{14} V A^{-1}. Peaks in the region of 1 X 10^{-11} mbar can be discerned within the noise . The peaks in the range 35 to 39 are mainly due to chlorinated components. The ion current for the head with the resolution shown was 5 X 10^{-4} A $mbar^{-1}$; this was obtained with the ion source set up with an electron current of 1 mA, an electron potential of 70 V and an ion injection energy of 12.75 eV. It can be seen that high head sensitivity is very important for the low pressure performance of the system. Reductions in head sensitivity can be caused by mechanical misalignments in the head [6] or contamination of the filter system [7]. The mass spectrum shown (Fig. 3) was made towards the end of the long test period and shows that even after possible degradation in the head sensitivity it was still at an acceptable level to give the desired low pressure performance.

Both mass spectra shown are made at the prototype's slowest speed. The filter voltages are increased and the ion current sampled 10 times amu^{-1} leading to a scan speed of approximately 2 amu s $^{-1}$. The production system will be designed to give 32 increments amu^{-1} giving a slowest speed of approximately 0.8 amu s^{-1}. It is expected that this will enhance the visibility of the mass spectra particularly at lower pressures.

7. Conclusions and future plans

The extensive testing of a prototype radiation hard RGA on JET has validated the precepts of the design by demonstrating that mass spectra of good resolution and with high sensitivity can be obtained. As a result of lessons learned, during the testing, certain design enhancements will be incorporated in the production units. These will be procured and commissioned ready for service during the next operating period of JET. Five radiation hard RGA will be operated along side the conventional ones already installed on JET. As confidence in the new RGA grows they will be used in preference to the conventional units in order to obtain as much operating experience as possible prior to the JET Active Phase.

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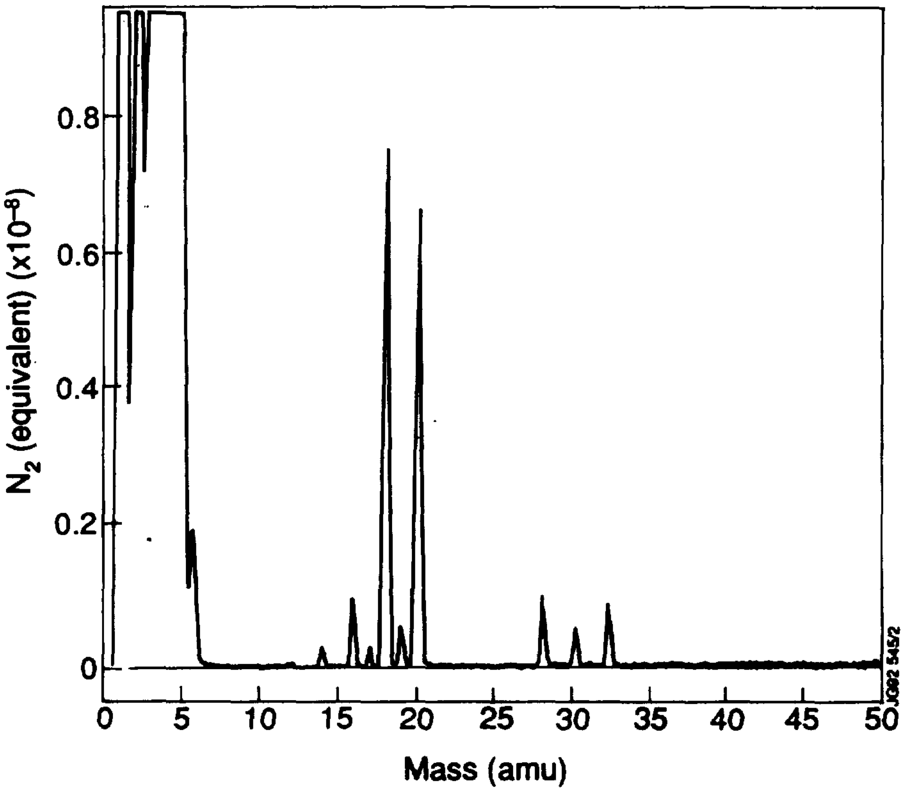

Fig.2 : Typical mass spectrum of Torus Vacuum using the prototype radiation hard RGA.

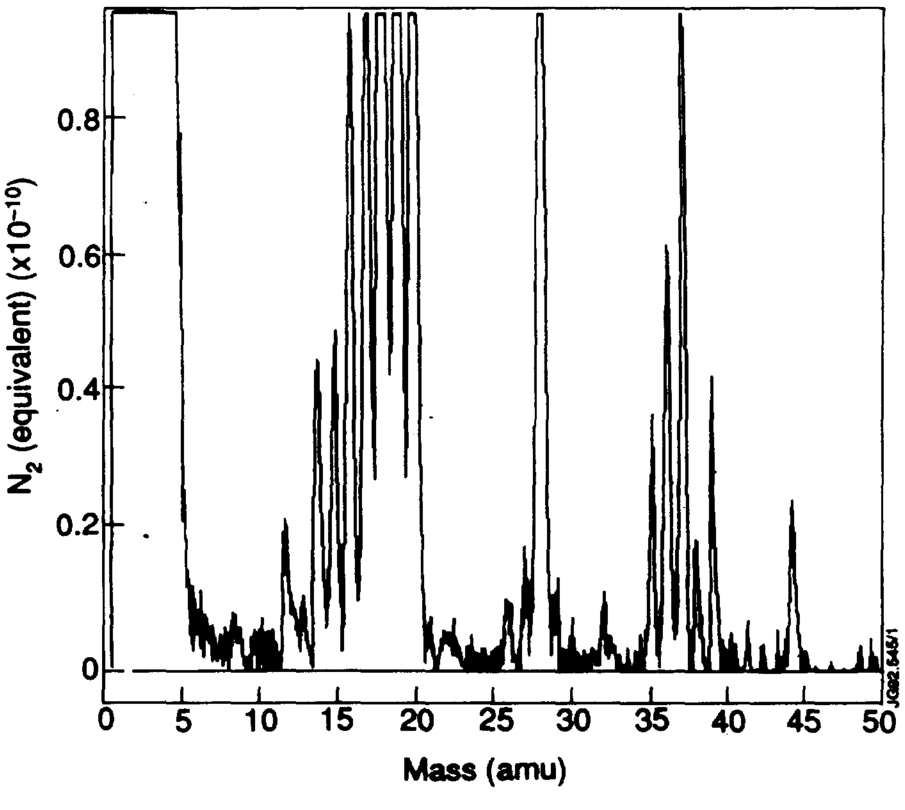

Fig.3 : Mass spectrum of Torus vacuum obtained with prototype radiation hard RGA on maximum gain setting.

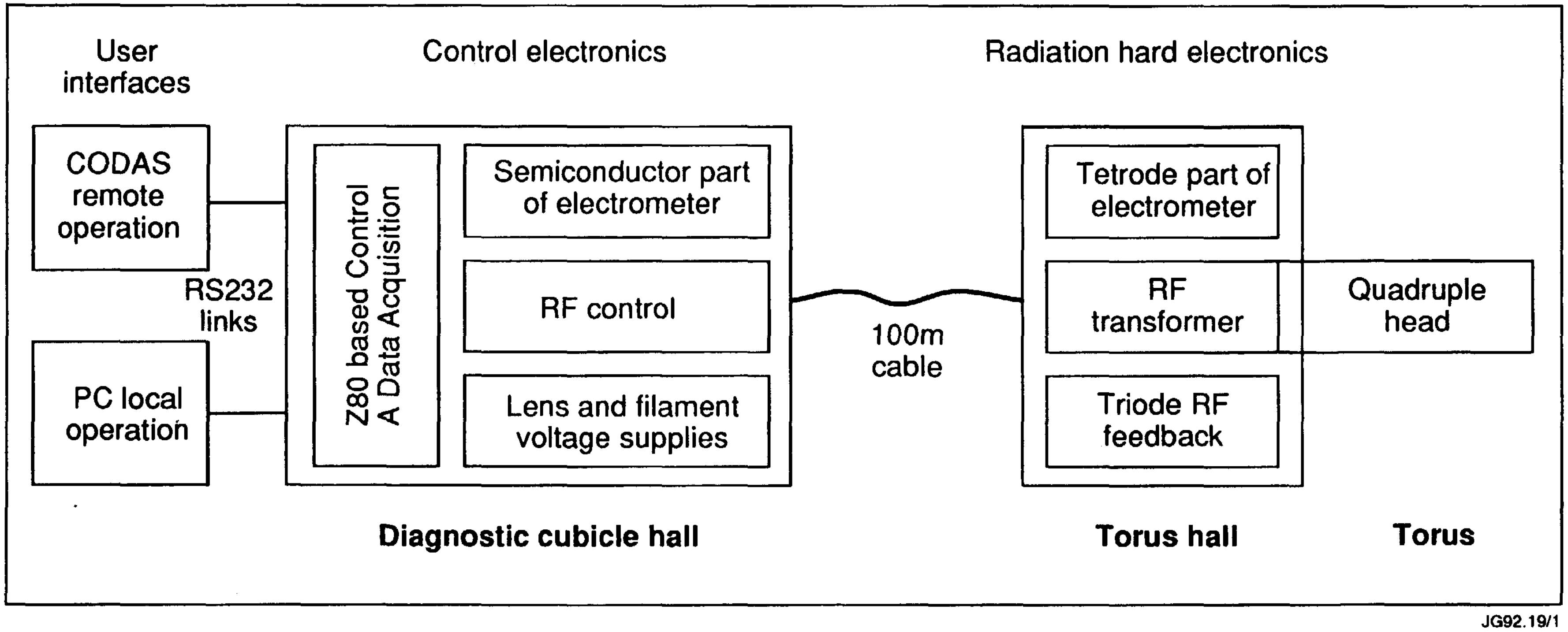

Fig.1 : Block diagram of radiation hard residual gas analyser (RGA)

Appendix I

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