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REVIEW OF SCIENTIFIC INSTRUMENTS **77**, 093501 (2006)

On the use of a capacitive diaphragm gauge for dust detection in next-step fusion devices

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The technology underlying a ceramic capacitive diaphragm gauge (CDG) manometer has been investigated for use as a microbalance for measurement of dust accumulation in next-step fusion devices such as ITER. Initial trials have confirmed in principle the use of CDG devices as dust microbalances and both the gauge head and electronics have been adapted to address the environmental constraints. Remote electronics, capable of controlling the gauge at a distance of 30 m, have been developed and a prototype device has been tested in the laboratory, where a sensitivity of 500 $\mu g/cm^2$ and dynamic range of at least 10^3 were demonstrated. The work shows that this approach is a promising contender to measure dust accumulation in next-step fusion devices. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2338296]

I. INTRODUCTION

Dust arising from plasma-wall interactions within the harsh environment of a next-step fusion device such as ITER could represent a significant safety hazard in off-normal situations. As a result, all next-step devices are likely to have stringent dust inventory limits and the requirement for dust measurement and assessment of techniques for the measurement of dust and erosion are current high priority research tasks for ITER.[1] These measurements, however, represent a significant challenge to traditional technologies in this area.

Gravimetric techniques have been used for some time to measure both erosion and deposition in plasma processing devices, but invariably these have been accomplished with a quartz crystal microbalance (QMB). This is a well developed technology used throughout the industry for microgram scale measurement and has been adapted over the last few years for use in the tokamak environment. QMBs have been installed successfully in the ASDEX Upgrade, JET, and TEXTOR machines.[2–4] While it cannot yet be ruled out that a QMB could be developed to be compatible with the ITER-like design environment, it is certainly not suitable in its current form. The high frequency electronics used to drive the piezoelectric crystals at the heart of a QMB are usually closely coupled to the crystal but are only tolerant of a cumulative radiation dose of $\sim 10^4$ Gy. They will therefore certainly not survive the dose received on any ITER carrying component (typically $10^4 - 10^5$ Gy per operational day) for the minimum component replacement lifetime of 2 yr. More seriously it has yet to be demonstrated that the crystals themselves can withstand this radiation dose without failure or significant changes in their characteristics.

By contrast the capacitive diaphragm gauge (CDG), shown schematically in Fig. 1, is a gravimetric device that can measure the cumulative weight of dust, flakes, or film growth on the surface of a diaphragm by determining the change in capacitance caused by its deflection relative to a fixed plate. The CDG concept is conventionally used for manometers (in which case the volume behind the diaphragm is evacuated) in the range up to ~ 100 Torr and the most sensitive commercially available gauges operate with a full scale deflection of around 0.1 Torr. When used as microbalances, these devices are potentially far more robust to neutron fluxes than piezoelectric crystals and can be operated using remote drive electronics. The principles of this application were reported in Ref. 5. The work described here explores their potential for dust measurement and tests their performance with remote electronics.

II. DUST LOAD, ENVIRONMENT, AND SENSOR SELECTION

The proposed inventory limits for accumulated dust in ITER[6,7] are currently around 10 kg for beryllium dust on the hot surfaces of the divertor dome and baffle (80 m^2) and around 400 kg for tungsten, carbon, and beryllium dust on the remaining divertor surfaces (200 m^2), under the dome (40 m^2) and in the subdivertor region (200 m^2). Estimates for the dust production rate in ITER[6,7] are subjected to large uncertainties; however, extrapolations from existing devices and analysis of erosion mechanisms, such as sputtering, melt layer loss, and so on, coupled with assumptions about the average dust dimensions indicate that the dust inventory limit may be reached in around 5000 shots.

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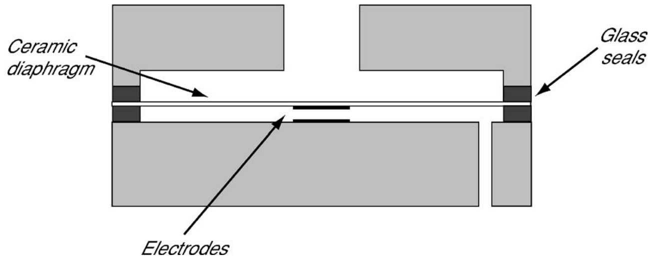

FIG. 1. Schematic of a capacitance diaphragm gauge (CDG).

If all the dust is uniformly distributed, then dust deposition is close to 1 kg/m^2 or 100 mg/cm^2 over the 5000 shots or 20 μg/cm^2 per shot. It is, however, more likely that dust will accumulate in localized regions (swept there by plasma action and vibration) and may reach 10 kg/m^2 or 200 μg/cm^2 per shot.

Current commercial 1 Torr CDG manometers have a dynamic range of $\sim 10^4$ and can in theory resolve to an accuracy equivalent to a central point load of ~ 200 μg. For a 1 cm opening to the diaphragm, a CDG microbalance based on the same gauge is therefore on the edge of the sensitivity for a shot by shot basis. The working life of a diagnostic component must be at least as long as the expected replacement time of the carrying component, and the minimum time between these replacements varies between 2 and 7 yr, depending on the component. With a sensitivity equivalent to the dust deposition in about one shot and a dynamic range of 10^4, the gauge would last around 10 000 shots before requiring refurbishment or replacement. This is at least 3–5 yr on current estimates of the shot rate in ITER. The trade between the sensor dynamic range, overall sensitivity, and accuracy, together with the machine application, will determine the final sensor parameters.

During preliminary analysis of the sensor application the following key environmental constraints were identified: (i) radiation—electronic damage and nuclear heating, (ii) thermal plasma load—sensitivity to plasma loading on sensor surface, (iii) temperature—operational levels and thermal gradients, (iv) electrostatic and magnetic effects—all fusion machines have inherently high levels of electric and magnetic fields and associated disturbance, and (v) mechanical vibration—the close proximity of high heat flux cooling systems will generate vibration.

A program of modeling and preliminary testing was undertaken at the Department of Materials Engineering at The Open University to evaluate the performance of CDGs acting as a microbalance and to gain an insight of their performance against some of the above constraints. Modern capacitance manometers utilize ceramic diaphragms for increased sensitivity and dynamic range. Such a manometer is manufactured by Inficon Ab, Finland and was modified for use as a microbalance by removing the dust guard normally protecting the diaphragm from unwanted dust accumulation and opening the gettered region at the rear of the diaphragm to avoid pressure differentials.

The diaphragm is so sensitive that, aside from fluctuations in applied force (weight or pressure), even the smallest change in operating environment can likewise affect the capacitance spacing and hence the sensor output. To minimize such effects, CDG manometer manufacturers pay great attention to the materials used and thermal expansion effects are minimized in the Inficon gauge by fabricating all parts out of alumina ceramic. For a fusion environment, this material of choice has the important added benefit of providing demonstrated compatibility with high levels of radiation. Estimates of the likely radiation dose for a gauge mounted in the lower regions of the ITER divertor cassette (likely to be a significant dust accumulation area) range from 10^4 to 10^5 Gy/o.d. (operational day), which is within tolerable limits for alumina ceramic in a fusion environment.[8] This dose is, however, two or three orders of magnitude higher than conventional electronics can handle over a typical lifetime for the gauge. Drive electronics for the CDG must therefore be kept remote from the gauge by at least 0.5 m radially away from the plasma, where the level reduces to ~ 10 Gy/o.d., and preferably by greater than 1.5 m (behind radiation shielding), where levels reduce to 10^{-1} Gy/o.d.

III. CONCEPT MODELING AND FEASIBILITY

Preliminary work was undertaken at The Open University to gain an understanding of the behavior of the CDG manometer when modified for use as a microbalance. This involved modeling of the diaphragm movement and tests of its sensitivity, noise immunity, and thermal drift. Engineering models were applied to predict changes in diaphragm shape in response to point loading (as compared to the uniform loading which would result from a pressure differential across the diaphragm), as well as the impact of self-load and orientation. The CDG sensor tested, a modified Inficon CR090 1 Torr manometer with a 0–10 V output, was predicted to have an equivalent central point load full scale deflection of 2.28 g (equivalent to ~ 4.4 V/g output), with a resolution of 228 μg. In addition, the sensitivity of the CDG to ambient temperature change was modeled and compared with quoted sensor specifications. Operation of the CDG was demonstrated in air and vacuum. Electronic noise with the as-supplied drive electronics (which are closely coupled to the sensor) was found to cause signal variations equivalent to ±45 μg of uniform load.

The sensor response to central point loads was measured by inserting calibrated copper wire weights onto the diaphragm through the manometer gas inlet port. The response was found to be linear over the full dynamic range at around 4 V/g (Fig. 2), close to the predicted value of ~ 4.4 V/g. The sensitivity was also measured using individual, 500 μm diameter silicon dioxide particles, with calibrated weights of around 4 mg. The distribution of these relatively coarse particles was limited to the diaphragm center by the close spacing between the inlet port and the diaphragm, and, as a result, the measured sensitivity was identical to the copper wire central point load tests. However, when a 260 mg aliquot of sodium chloride particles, with diameters of around 100–500 μm, was poured into the inlet and allowed to settle a sensitivity of 2.6 V/g was determined. This reduced sensitivity was due to the inevitable spreading of the finer particles across the diaphragm surface within the CDG (an ef-

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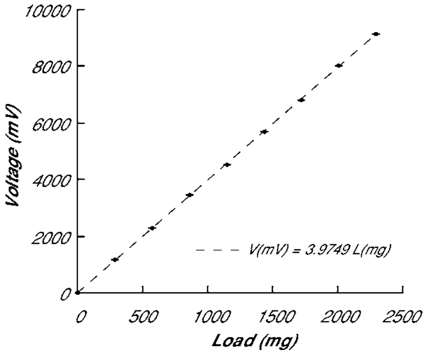

FIG. 2. Calibration of the modified Inficon CR090 manometer using copper wire weights applied close to the center of the diaphragm. Data are solid symbols, dotted line is a linear least squares fit.

fect confirmed photographically). The value was less than the theoretical minimum sensitivity of 1 V/g for a uniform load, since some of the coarser particles were still confined near the diaphragm center.

When the sodium chloride particles were inserted in four separate aliquots of 65 mg, however, an anomalous result was revealed. The output voltage steps with each added aliquot were not uniform (Fig. 3) and the corresponding sensitivities did not lie in the range bounded by the expected central point and uniform load cases. In particular, the first aliquot added resulted in a step of 0.52 V—a factor of 2 larger than the 0.26 V expected for a cental point load (the theoretical maximum sensitivity). The other three aliquots produced steps of either 0.06 or 0.08 V—close to the 0.065 V expected for a uniform load. The effect was repeatable over several experiments using different aliquots. These results cannot be explained only by redistribution of the particles across the diaphragm with each added aliquot, although that may play a part. One hypothesis is that static electric charges carried on the sodium chloride particles might have built up on the diaphragm, affecting measurement of the capacitance between the electrodes. Although no quantitative estimate for charging of the particles through triboelectric effects or the impact of charge build up on the diaphragm was made, modifications to the CDG design to eliminate this electrostatic effect (see Sec. IV) proved completely successful (see Sec. V), adding support for the hypothesis.

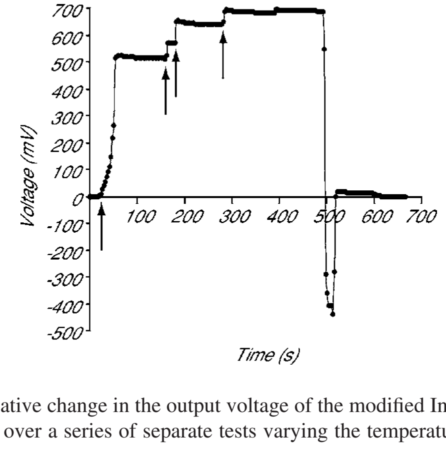

FIG. 3. Relative change in the output voltage of the modified Inficon CR090 manometer over a series of separate tests varying the temperature at the top of the sensor.

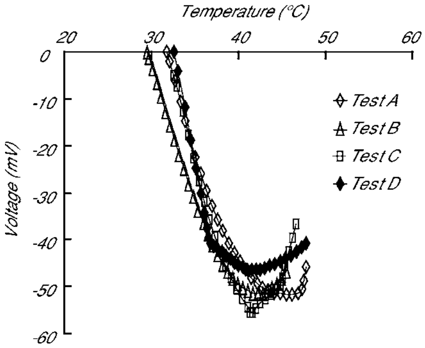

FIG. 4. Response of the modified Inficon CR090 manometer to sodium chloride particles added in four aliquots of 65 mg each at the times indicated by the arrows. The sensor is inverted, to clear the particles, at 500 s resulting in the negative output signal.

When the CDG was heated by a water jacket attached to the top of the sensor, a temperature rise of 1 °C changed the output by an equivalent 1–3 mg central point load. This was repeated in several tests on two separate gauges and was a factor of 10 greater than the effective quoted specification for the original manometer, probably because the heating was applied at one end only giving rise to thermal gradients in the CDG. Although nonlinear, as shown in Fig. 4, this temperature behavior was repeatable in each case and there was no hysteresis, providing the potential for compensation if required. The curvilinear upturn at the end of the plots may be a direct result of the temperature gradients across the CDG and/or an increase in sensitivity due to diaphragm flexure arising from those gradients.

IV. SENSOR DEVELOPMENT

The preliminary tests conducted at The Open University demonstrated the scope for use of the CDG as a microbalance. The subsequent design and development then focused on the following issues: (a) utilizing existing CDG sensor technology wherever possible, (b) removing all electronic components to provide remote measurement via standard cabling, and (c) incorporating a reference capacitance and virtual ground screening within the sensor head to minimize temperature drift and electrostatic effects, respectively.

A. Sensor head

The development optimized the existing Inficon CDG manometer design to address (b) and (c). Two design improvements were simultaneously evolved. The first adapted the standard ceramic housing and diaphragm to provide a reference cell. Initial designs considered a separate reference cell in either a back-to-back or a side-by-side arrangement.[5] Both, however, would have required significant changes to the ceramic and glass bonding of the original manometer. An alternative hybrid design shown, in Fig. 5, was therefore developed by Inficon which uses different electrode patterns to provide both measuring and reference capacitances on the same diaphragm. Full metallization on the front of the diaphragm, tied to the ground plane of the sensor, was also added to the design to provide a virtual Faraday cage to

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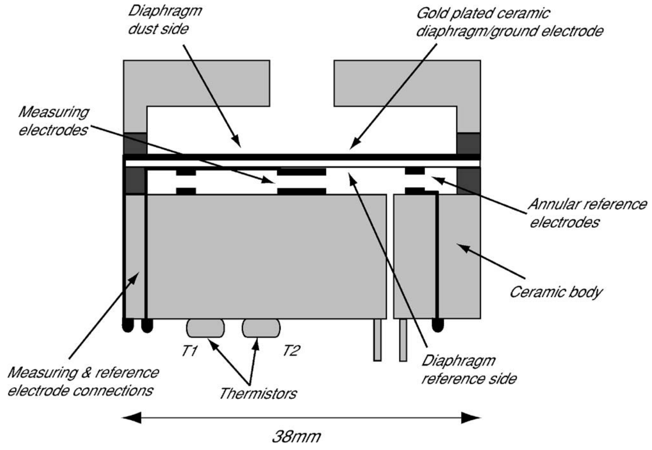

FIG. 5. Hybrid design of dust sensor showing the measuring and reference electrodes together with the ground Faraday shielding.

shield against stray electrostatic fields. At the rear of the sensor, two thermistors were mounted to provide 25 W back heating and temperature measurement.

The advantage of this design is that modification to the existing CDG fabrication is restricted to just the electrode metallization and feedthroughs. Linear expansion effects can be easily accommodated, as both the measuring and reference capacitances will change equally with temperature. Measurement errors due to differential expansion arising from local thermal gradient effects will, however, remain. To minimize thermal gradients, therefore, the CDG was mounted in a close-fitting "isothermal" shell. Copper was chosen for the shell material in the prototype sensor because of its high thermal conductivity and ease of manufacture. For ITER, copper might need to be replaced by a material more compatible with the high neutron flux environment.

B. Electronic bridge circuit

Various methods have been used in the past to measure the change in capacitance of a diaphragm, ranging from parallel resonance to phase locked loop electronics that track the resonant frequency. All had been developed, however, for single electrode devices. The inclusion of a matched reference electrode into the CDG sensor design allowed development of an attractive "bridge circuit" alternative, which determines the difference in capacitance between the measuring and reference capacitances. This approach has the advantages of simple, robust electronic design, low frequency drive signal (a few 100 Hz compared to several megahertz in the QMB), use of twisted pair cable or coaxial feeds, and remote drive electronics—no components within the CDG body. As discussed earlier, the electronics need to be at least 1.5 m remote to survive and preferably behind the shield wall—many tens of meters.

The circuit shown in Fig. 6 consists of a bridge circuit driven from a signal generator. A high gain instrumentation amplifier, giving a measure of the difference in capacitance, amplifies the difference in amplitude at the "null point" of the bridge. The capacitance of the measuring electrode and reference cell is 15 pF while that of the cable (30 m) is ap-

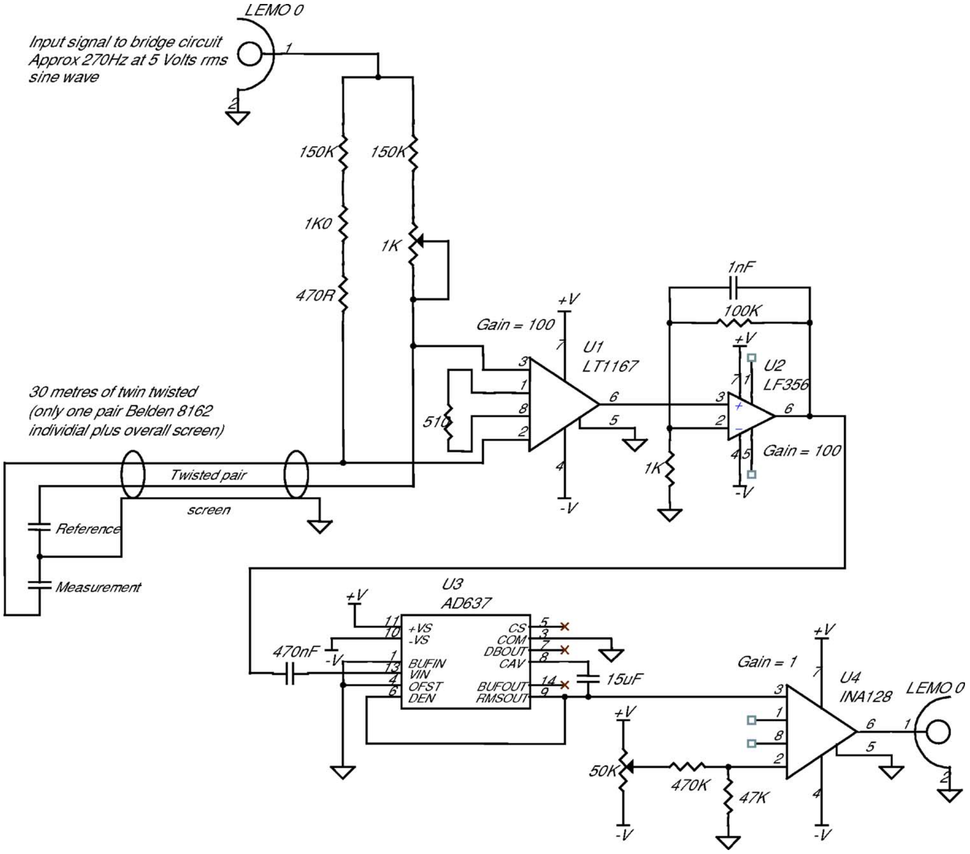

FIG. 6. Schematic of the remote drive electronics for the hybrid sensor.

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proximately 2 nF, so the cable capacitance dominates. The change in the capacitance of the diaphragm is of the order of a few picofarads.

Because the "difference signal" is small compared to the amplitude of the signal generator, an amplifier with a very high common rejection ratio (>120 dB, 10^6) was required. The null point of the bridge is connected to an instrumentation amplifier U1 having a gain of ×100 to give the best common mode rejection ratio. This is followed by a further gain stage U2 and then ac coupled to a rms to dc converter U3. The resulting dc voltage is further amplified by output stage U4 to provide a dc output voltage corresponding to the change in value of the trimmer capacitor. The drive to the bridge, provided by a signal generator, was set at a level of 20 V peak to peak and frequency of 90 Hz. The output voltage of the test circuit varied from 0.1 to 10 V depending on the trimmer capacitor's value. During load tests, the input signal frequency to the bridge circuit was increased to 270 Hz as this was found to increase the amplitude of the response.

With this circuit connected over a 30 m long twisted pair cable to the CDG, changes in the output voltage could be measured to better than 10 mV, corresponding to a point load of ~500 μg, with a load of ~500 mg being applied before saturation of the output of the bridge circuit and amplifier occurred (the dynamic range being slightly better than 10^3). The prototype remote drive electronics over a 30 m cable therefore had a sensitivity around a factor of 2 worse than the close-coupled CDG manometer drive electronics used in the initial tests and about five to ten times worse dynamic range (mostly the result of electronic noise). It is anticipated that future developments to the remote electronics (for example, better screening for electrical pickup) will allow the specifications to approach those of the close-coupled system.

V. RESILIENCE TO THERMAL AND ELECTROSTATIC EFFECTS

The hybrid CDG sensor head was mounted in an oven at temperatures between 20 and 70 °C, both with and without a load, and connected to the electronic bridge circuit (outside the oven) via 30 m of twin twisted Belden 8162 cable. The oven temperature was increased at around 1 °C/min, slow enough for the isothermal shell of the CDG to remain in equilibrium with the oven. The initial tests using a standard CDG manometer (described in Sec. III) had shown equivalent central point load thermal sensitivity between 1 and 3 mg/°C. The results, shown in Fig. 7, for the hybrid gauge and remote electronics surprisingly revealed a similar thermal sensitivity, together with some hystereses which had not been observed in the earlier tests. This hysteresis was identified as the result of thermal gradients across the CDG, as much as 6 °C, during heating and cooling of the oven leading to flexure or differential expansion of the diaphragm and ceramic assembly. The gradient was an unanticipated consequence of preferential thermal leakage to the isothermal shell, which was clamped to the CDG at the front face only. It is likely that this effect was also responsible for the thermal sensitivity, which had been expected to reduce significantly with incorporation of the reference cell. This observation highlights the need to maintain thermal isolation of the ceramic CDG body from the external isothermal housing in future designs. Repetition of these tests awaits implementation of these design changes.

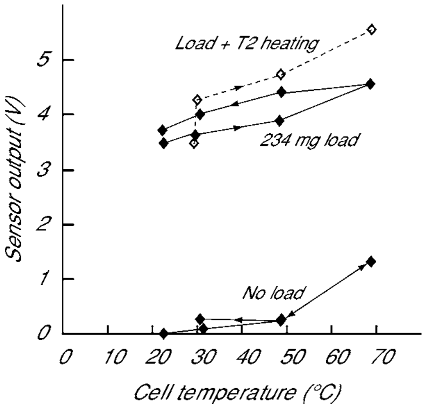

FIG. 7. Thermal sensitivity of the hybrid sensor when heated in oven cell.

A simple test was carried out to check the electrostatic resilience of the hybrid CDG sensor. A pulse generator was capacitively coupled to the copper isothermal shell of the dust sensor with the shell floating and the step response observed at the output of the detector. This decayed on a time constant of approximately 1 ms. As expected, with the shell grounded, no change in the output was observed.

To check for electrostatic charge effects, some additional measurements were taken by first loading the diaphragm with lengths of copper wire of calibrated weight and then with aliquots of sodium chloride particles of similar mass, as described in Sec. III for the initial tests. In the earlier work the addition of sodium chloride particles gave anomalous results compared to those observed when wire weights were used, this effect being attributed to electrostatic charge buildup on the diaphragm from the particles. With the hybrid sensor head, however, no anomalous effects were observed. The output voltage steps with each added aliquot of sodium chloride particles were uniform and in line with the sensitivity determined from the wire weight tests, indicating that the diaphragm metallization and grounding were having the predicted effect of preventing unwanted charge buildup.

VI. DISCUSSIONS

This work has demonstrated that the design for a capacitance diaphragm gauge manometer can be successfully modified to a gravimetric dust sensor, in principle suitable for use in a fusion reactor. Incorporation of a reference cell, matched in capacitance to the measurement cell, enables a sensitive bridge network to be constructed and allows all associated electronics to be remote from the sensor. Operation of the sensor over 30 m of standard twisted pair cabling has been demonstrated without significantly degrading the performance (both twisted pair and coaxial cables compatible with the ITER environment are under development by the ITER team). The sensitivity of the prototype sensor and remote electronics is better than 500 μg/cm^2, with a dynamic range of better than 10^3. Some differential thermal

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effects still appear to be significant even after compensation for linear expansion of the CDG is made with the reference cell, and this is being addressed with improvements to the isothermal shield. Faraday shielding of the CDG diaphragm by metallization successfully eliminates anomalous electrostatic effects observed in earlier tests. The work completed to date shows that a CDG-based microbalance is an appropriate candidate for dust measurement of the dust loads expected in regions of future tokamak reactors.

ACKNOWLEDGMENTS

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[1] ITPA High Priority Research Tasks 2004–2005, ITER Website: www.iter.org/priorities04.htm
[2] V. Rhode, M. Mayer, and the ASDEX Upgrade Team, J. Nucl. Mater. **313–316**, 337 (2003).
[3] H. G. Esser, V. Philipps, M. Freisinger, P. Coad, G. F. Matthews, G. Neill, and JET EFDA Contributors, Phys. Scr., T **T111**, 129 (2004).
[4] J. von Seggern, P. Wienhold, T. Harai, V. Philipps, and H. G. Esser, J. Nucl. Mater. **313–316**, 439 (2003).
[5] G. F. Counsell and C. H. Wu, Phys. Scr., T **T91**, 70 (2001).
[6] S. J. Piet *et al.*, Proceedings of the 17th IEEE/NPSS Symposium on Fusion Energy, San Diego, 6–10 October, 1997 (unpublished).
[7] G. Federici *et al.*, Nucl. Fusion **41**, 1967 (2001).
[8] T. Shikama, Nucl. Fusion **43**, 517 (2003).

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