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Characterization and calibration of a capacitive diaphragm gauge manometer for the measurement of dust particles in vacuum

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ABSTRACT

A capacitive diaphragm gauge (CDG) has been modified to measure the amount of accumulated in-vessel dust in tokamaks. In order to pin point the mass load on the CDG, aluminum dish is used. Calibrations show that the CDG has a measurement range from 2.2 g to 6.7 g with a minimum detection mass of 30 mg. Long term stability of measured signal is obtained at least more than 12 h operation with the atmospheric pressure and under vacuum. The CDG will be installed in KSTAR (Korea Superconducting Tokamak Advanced Research) device in 2012 campaign to measure the amount of in-vessel dusts.

1. Introduction

The characterization and removal of dust particles have been emerging issues in advanced tokamaks such as KSTAR (Korea Superconducting Tokamak Advanced Research) device and ITER (International Thermonuclear Experimental Reactor). Dust particles may be radioactive if they contain tritium or activated metals, and can be toxic and/or chemically reactive with steam and air [1–4]. High particles and energy fluxes during edge localized modes (ELMs) and unipolar arcs will enhance the erosion of plasma facing components (PFCs) leading to the in-vessel dust production [5]. Dust is strongly accelerated, it has the potential to damage vacuum vessel and diagnostic equipment [6–8]. Chemical composition, distribution and production rate of dust particles have been studied in detail, but the data is mostly from vessel samples that have been collected after device operations [5,6].

The ITER limit on the amount of mobilized cold dust is 670 kg based on public safety considerations [1–4,7]. Therefore, it is crucial to measure the amount of in-vessel dust in next generation devices as accurate as possible, and dust may have to be removed on a daily basis or even between shots to keep within the safety limit [1–4,7]. To know when the removal of dust particles is required, production should be monitored in real time.

In order to detect and measure the dust, several methods and device have been developed using laser, grid type device and capacitive diaphragm [9–12]. The capacitive diaphragm gauge (CDG) manometer was suggested by Counsell et al. for ITER, since it can be configured for dust detection in harsh environments, including high neutron fluxes, due to the rugged all-ceramic construction [11,12]. Other merits include low cost and easy of modification. Before applying a CDG manometer to ITER and KSTAR, it must be calibrated for sensitivity, reliability and reproducibility. We have modified and calibrated a CDG dust detector under vacuum state that may be suitable for use in ITER.

2. Modification of CDG for dust measurements

The CDG manometer was originally manufactured by Leybold company and was modified by Counsell et al. [11,12]. The diaphragm gauge is 38 mm in diameter and 5 mm thick. For the modification of the CDG manometer, the mounting structures, housing and measurement circuits were disassembled, including the dust guard that protects the diaphragm from dust accumulation within the inlet of the manometer (Fig. 1). Reference vacuum sealing for the pressure measurement located at the bottom of the CDG was removed to set the vacuum difference across the diaphragm to zero.

CDG manometer maintains capacitance between three electrodes: the reference electrode, measurement electrode, and the ground. Each has a circular metallized coating at the center of a thin circular ceramic diaphragm. A sinusoidal input waveform with variable frequencies is applied to the reference electrode by a function generator, and as a result the electric potential on the electrode oscillates. The measurement electrode is fixed and the capacitance due to the gap between two electrodes is measured.

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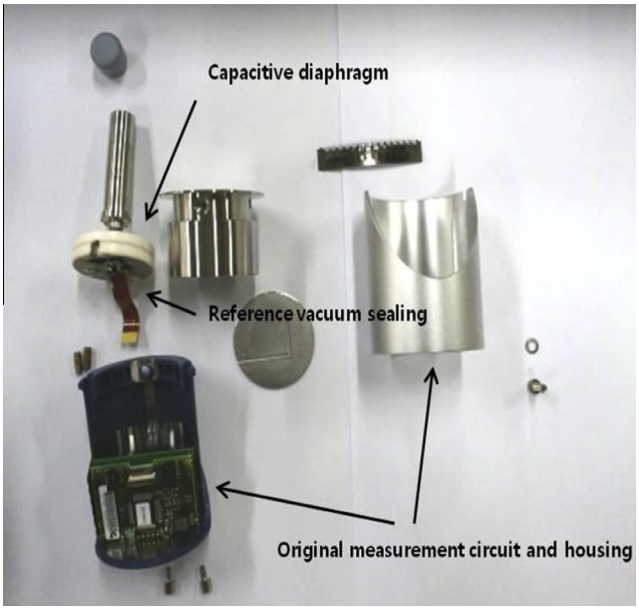

Fig. 1. Disassembled capacitive diaphragm gauge manufactured by Leybold.

If a certain amount of weight is accumulated and applies pressure to the reference electrode, the gap between the reference and measurement electrodes become smaller, which results in a change in the capacitance. Note that the deflection of diaphragm is not a linear function of the force, but is proportional to the square of the deflection. Also, the response from the CDG is sensitive to the position where the mass load occurs. Therefore, it is very important to carefully locate the mass load on the diaphragm. For this purpose, we have manufactured an aluminum dish-shaped tray with a shaft and the center of the diaphragm is the contact point for the shaft. For the application to KSTAR, we have not attached any forced cooling system, but it would be needed for the higher power machine like ITER or longer operation of KSTAR with higher plasma current, since higher power radiation would deform the tray and the gap of the electrodes. Or, with higher heat load, this Al-tray would be replaced by a better material, which is stronger than Al in terms of heat and/or radiation resistance, such as alumina or boron nitride.

Fig. 2 shows the new mount, and housing for in-vessel dust measurements in KSTAR. The aluminum dish has the same diameter as the diaphragm (38 mm) and the length of the shaft is 40 mm. The CDG is mounted to a 6 in. flange along with a housing that protects the CDG from direct contact with the plasma, the housing also provides a stable vertical support for the shaft.

3. Calibration and characterization procedures

Fig. 3a shows a schematic of the CDG calibration procedure. The CDG is connected to a function generator via a 1 m BNC cable. Signals of the generator are sinusoidal waveforms with a fixed peak to peak voltage of 10 V and the frequency of the signal is varied to find the best response to the mass load. The measurement electrode is also directly connected to oscilloscope through 1 m BNC cable, but without a preamplifier for assuring intrinsic properties. The initial tests of the mass load show that the detection limit

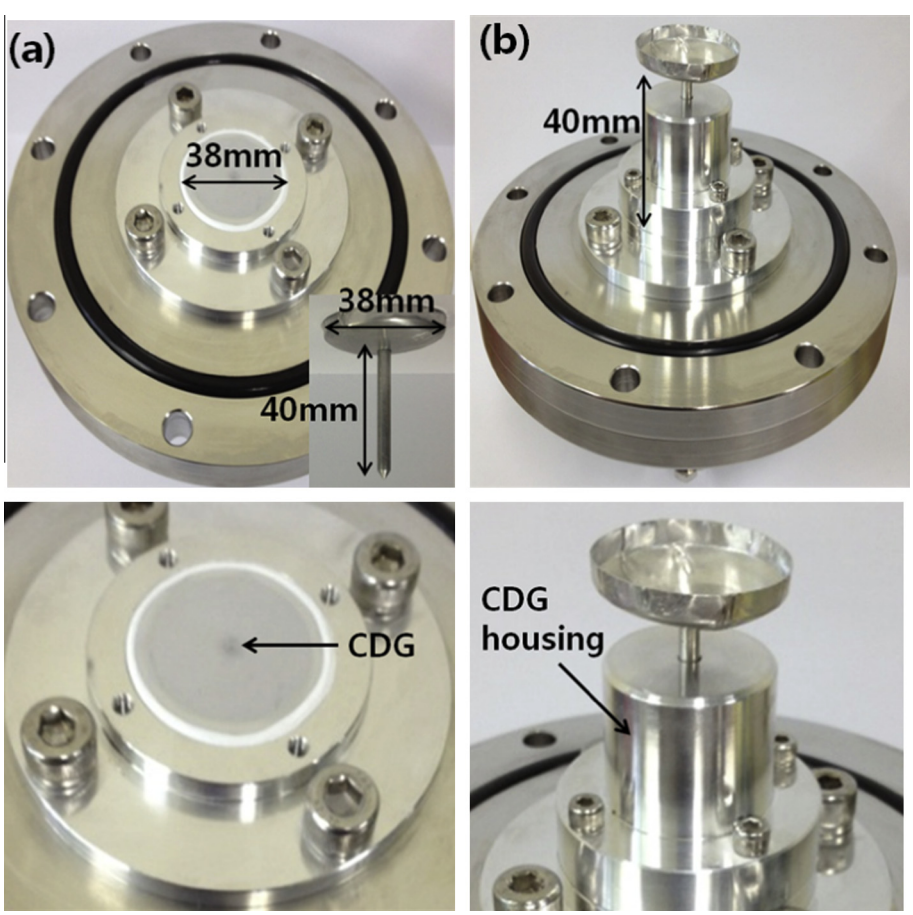

Fig. 2. Modified and mounted CDG (a) CDG without housing (b) CDG with housing.

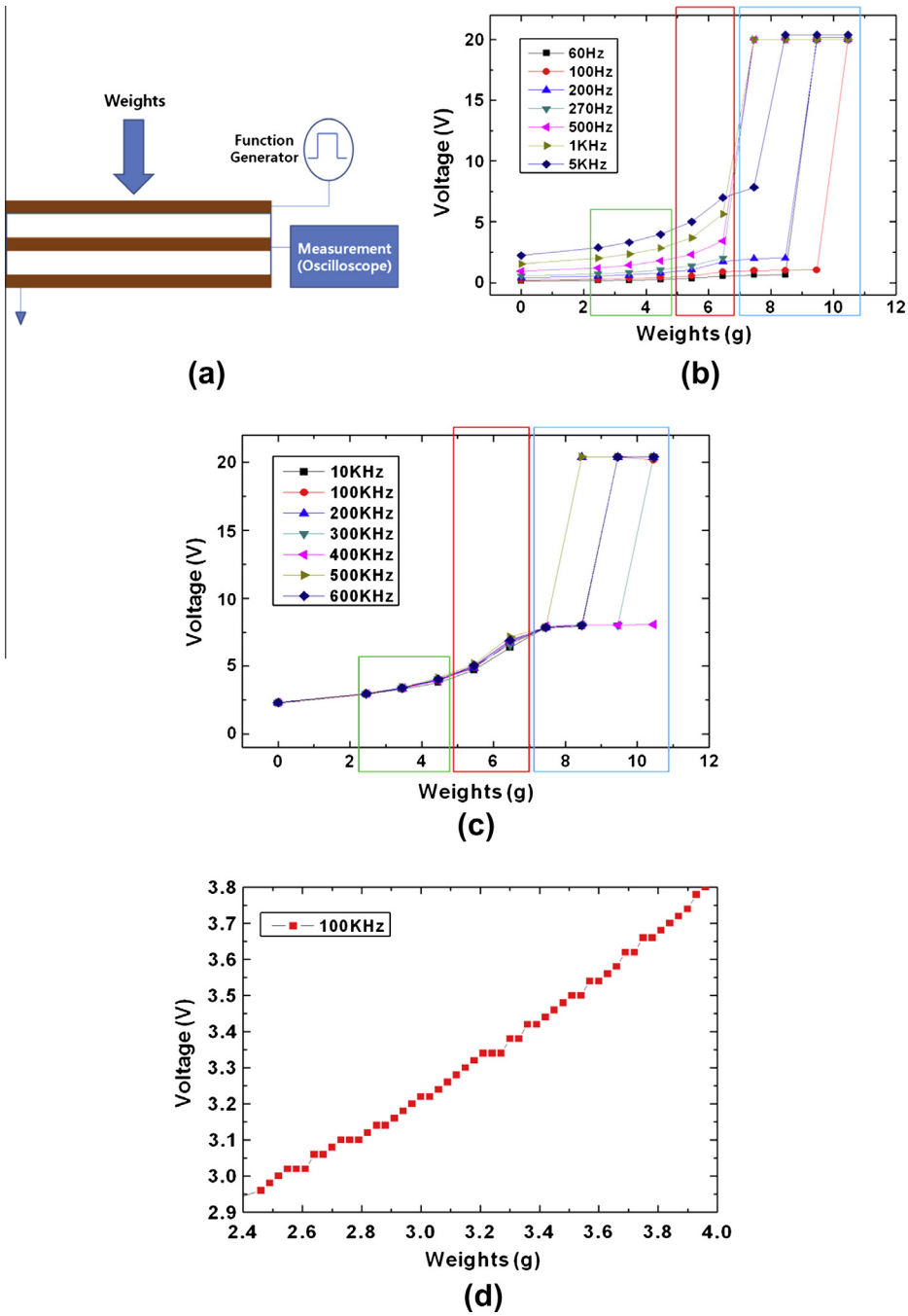

Fig. 3. (a) Schematic drawing of CDG measurement. (b) CDG response to mass load with input signal at higher frequency. (c) CDG response to mass load with input signal at lower frequency. (d) CDG response to mass load from 2.4 g to 4 g with mass load step of 30 mg.

of this configuration is 30 mg (Fig. 3d) and so we have used small metal balls with an individual mass of 30 mg for the calibration. We have measured the response of the CDG via peak to peak voltage of the measurement electrode (V_{pp}) and found that the amplitude of V_{pp} depends strongly on the frequency of the input signals to the reference electrode. At lower frequency under 10 kHz, the variation of V_{pp} by mass load is small and 30 mg mass load is not clearly detectable, as shown in Fig. 3b. At higher frequency, e.g. over 10 kHz, the response is much better so that the 30 mg mass load is clearly seen and distinguishable, which have been shown in Fig. 3c. As we have mentioned above, the deflection of the diaphragm is not linear with the mass load. This is why we have a nonlinear response as a function of mass shown in Fig. 3b and c. The response can be divided into three regions (Fig. 3b). The first region identified by the green[2] rectangular box is the small mass region where the response is ~0.02 V_{pp} to a 30 mg mass load. The measurement range starts at ~2.2 g which is corresponding to the mass of aluminum tray, and reach up to ~5 g. In this small mass load region, the response approximately is linear, as shown in Fig. 3d. Afterwards, the response is 0.06 V_{pp} from a 30 mg mass load up to ~6.5 g, and it becomes strongly nonlinear. The response of the CDG to a mass load larger than ~6.5 g indicates the saturation of the signal at the level of ~20 V_{pp}.

[2] For interpretation of color in Fig. 3, the reader is referred to the web version of this article.

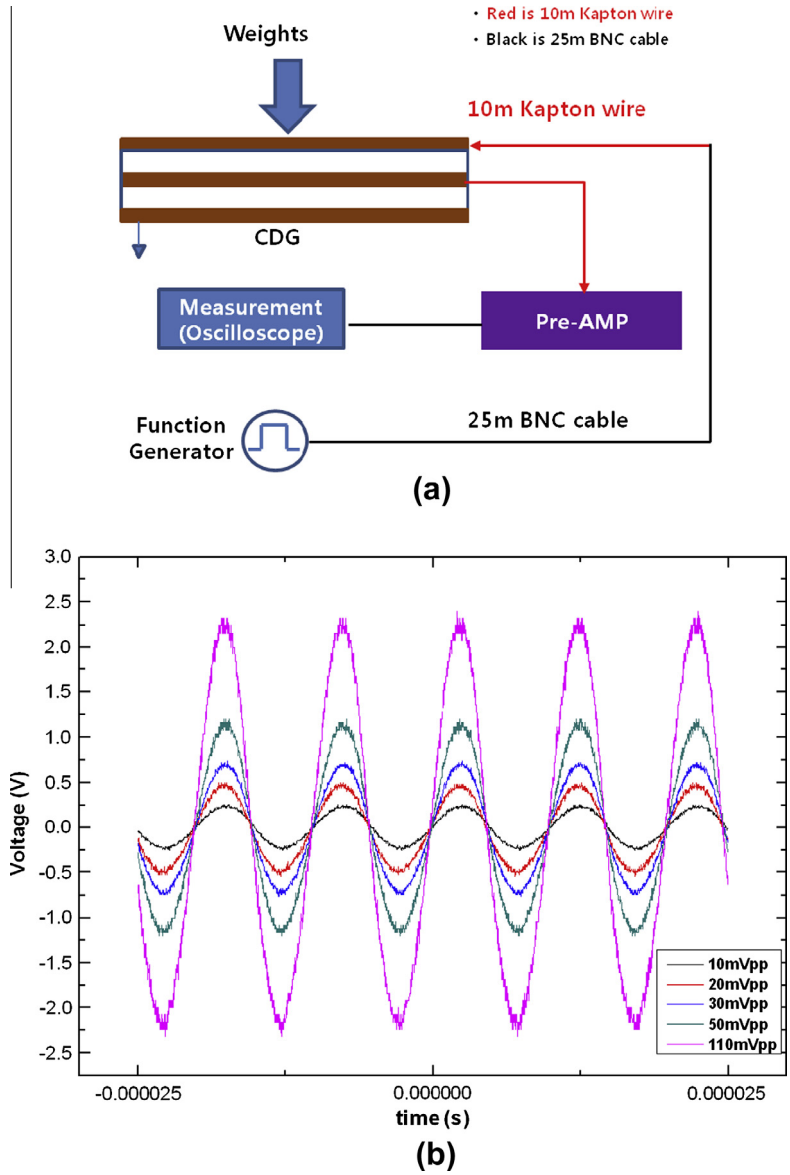

Fig. 4. (a) Schematic representation of experimental set up for KSTAR installation and (b) output signal from CDG with various input V_{pp} at a frequency of 100 kHz.

4. Preparation for KSTAR installation and testing under vacuum

In order for the modified CDG to be applied to in-vessel dust measurement in KSTAR and/or ITER, the connection cable lines should be up to 35 m long, connecting 25 m coaxial cable to 10 m of Kaptone wire (MDC Corporation, Part Number 680503), as shown in Fig. 4. A schematic view of the component connections is shown in Fig. 4a. Signals from the CDG are recorded by a remotely controlled TDS 2014B oscilloscope (Tektronix Corporation) with Labview Signal Express. Due to a long transmission line, the signal from the measurement electrode decreases significantly. The amplitude of the measurement signal for an input signal of 10 V_{pp} without a preamplifier, is approximately reduced to 20 mV_{pp} as shown Fig. 4b. In order to compensate for the loss of the signal amplitude, signals from the measurement electrode should be obtained through a preamplifier (S1A2201). This gives reasonable amplification to 120 mV_{pp} for the output from the measurement electrode, but starts to cause distortion above this value.

Before the installation of the CDG to a KSTAR port, the housing was mounted onto a 6 in. flange and tested for one day under vacuum condition (4–5 m torr). The aim of the test was to check the reliability and long term stability of the measurements under vacuum. As mentioned above, two different measurement regions exist: 2.2–5 g and 5–6.5 g. To test the CDG in both regions separately, two different trays were applied with a mass of 2.2 g and 5.7 g. The test was performed several times, over the duration of 12 h. The masses loaded onto the trays were 30 and 60 mg, respectively. Table 1 shows the results from the test.

Table 1
Amplitudes of CDG signals depend on weights. It is possible to measure vacuum state and 0.03 g of sensitivity in 4×10^{-3} torr.

Type of tray	Weight (g)	Pressure (torr)	$V_{peak-peak}$ (V)	Standard error
Tray 1	2.184	Atmospheric	0.8374	9.054×10^{-5}
Tray 1	2.184	5×10^{-3}	0.8360	0.836×10^{-5}
Tray 1 + 1 metal ball	2.214	4×10^{-3}	0.8366	2.390×10^{-4}
Tray 1 + 2 metal ball	2.244	4×10^{-3}	0.8518	1.329×10^{-4}
Tray 2	5.697	Atmospheric	1.2120	1.303×10^{-4}
Tray 2	5.697	4×10^{-3}	1.2089	1.943×10^{-4}
Tray 2 + 1 metal ball	5.727	4×10^{-3}	1.2188	2.747×10^{-4}
Tray 2 + 1 metal ball	5.757	4×10^{-3}	1.2180	3.854×10^{-4}

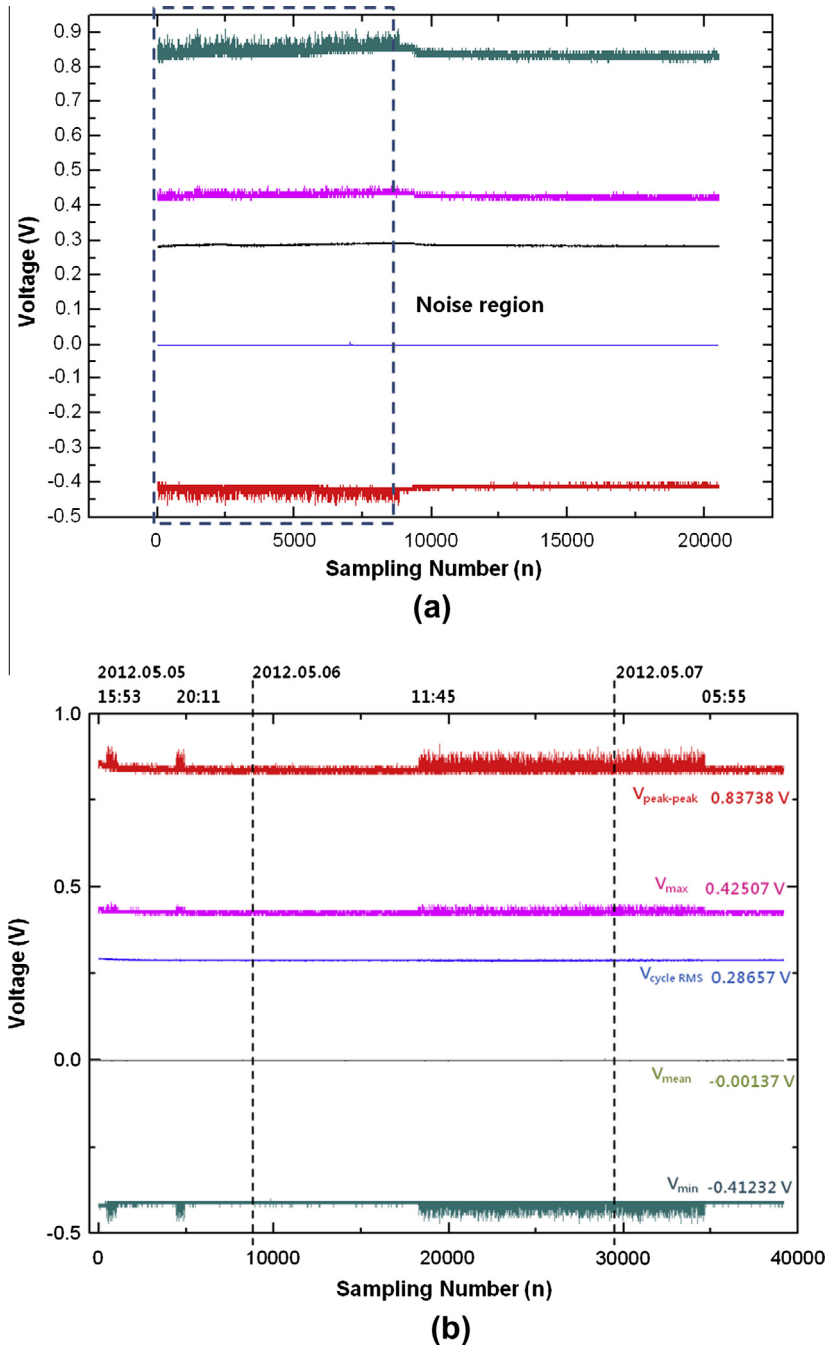

Fig. 5. Long term stability measurements under vacuum for about ~12 h (a) and 22 h (b).

The initial values of the CDG response to the mass load of the trays at atmospheric pressure are 0.8374 V_{pp} and 1.2120 V_{pp}, respectively. Under vacuum pressures of approximately 5×10^{-3} torr, the deflection of the diaphragm is slightly affected by the drop in pressure, i.e. the response indicates a reduction in mass in both cases, thus V_{pp} decreases (see Table 1). In the small mass response region, the average increase in V_{pp} is 0.0006 V_{pp} per 30 mg, and in the high mass region it is 0.0099 V_{pp} per 30 mg.

Fig. 5 shows the long term stability of the measurements for about ~12 h (Fig. 5a) and 22 h (Fig. 5b). Although it can be clearly seen that the ground noise affects the measurements, it is confirmed that the long term measurements shows very stable response indicating the CDG will deliver correct values to dust mass load in long term scale, i.e., daily or during the KSTAR campaigns.

5. Conclusions

We have modified the CDG from the design of Counsell et al. for ITER for the purpose of monitoring the production of tokamak dust. It has a measurement range from 2.2 g to 6.7 g with a minimum detection mass of 30 mg. The CDG is calibrated and tested at atmospheric pressure and under vacuum, which gives the sensitivity, reliability and reproducibility in short and long term time scale. The modified CDG will be installed in KSTAR to measure dust production during 2012 campaign.

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