Vibrating Reed Electrometer With Attocoulomb Charge Resolution and Subattoampere Current Resolution

Article *in* IEEE Transactions on Instrumentation and Measurement · January 2013

DOI: 10.1109/TIM.2012.2212509

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Vibrating Reed Electromer with Attocoulomb Charge Resolution and Sub-attoampere Current Resolution

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***Abstract*— An extremely sensitive vibrating reed electrometer is built, that has aC charge resolution and sub-aA current resolution within a one-minute measurement. The input leakage current of the set-up is typically less than 1 aA with values as low as 0.12 aA, that is less than 1 electron per second. Allan deviation analysis shows that the lowest standard deviation that can be achieved in current measurements is 0.065 aA with a 3-h integration time. Crucial for this extreme sensitivity and low leakage current was the development of an input measurement stage with only vacuum gap capacitors.**

The stability and sensitivity of this new electrometer make it suitable for accurate low-frequency characterization of vacuum gap capacitors as for example used in the electron counting capacitance standard experiment. As a first step towards such a study, the internal vacuum gap feedback capacitor of the electrometer was measured as a function of applied charge and for different heat treatments resulting in changing surface layers of the capacitor plates.

***Index Terms*—current measurement, current, electrometer, capacitance, ionization current, measurement standards**

I. Introduction

A significant uncertainty source in the electron counting capacitance standard (ECCS) is the unknown frequency dependence of the vacuum gap capacitor used in this experiment [1]. This frequency dependence comes into the final measurement value since the single electron transport measurement of the vacuum gap capacitor is performed at an effective frequency of well below 0.1 Hz, whereas the link to the traditional capacitance standards is made at 1 kHz or 1.592 kHz.

So far, only a theoretical estimate is available of the uncertainty contribution due to the frequency dependence of the cryogenic vacuum gap capacitor, since experiments in this direction so far have not been very successful [2, and references therein]. In the theoretical analysis any frequency dependence of a vacuum gap capacitor is expected to come from residual surface layers present on the capacitor plates. From the combined fact that these surface layers are thin and moreover have dielectric properties that freeze out at low temperatures, it is estimated that the frequency dependence of the ECCS vacuum gap capacitor is significantly below 1 part in 10^6 [2].

At VSL, we plan to achieve experimental data underpinning this theoretical estimate by comparing the temperature dependence of the capacitance value of an ECCS vacuum gap capacitor measured at both 1 kHz and 0.01 Hz. If a surface layer is present it will give a frequency dependent contribution to the capacitance value. At one temperature, the exact size of this contribution is extremely difficult to determine since the low frequency measurement would almost inevitably require components for which the frequency dependency must be known. However, since the contribution of surface layers to the capacitance value is temperature dependent, any *difference* in the temperature dependence of the capacitance value measured at 1 kHz and 0.01 Hz will be a signature of the presence of surface layers and thus of a frequency dependence of the capacitor.

A crucial element in the ECCS capacitor frequency dependence experiment is the availability of a sensitive and accurate measurement set-up for capacitance measurements at a frequency of 0.01 Hz. In this paper we describe an electrometer that is developed for this application as part of a European joint research project on realization of a single electron quantum current standard.

First, the principle of the low-frequency capacitance measurement and the vibrating reed electrometer is described, together with the improvements made on an existing electrometer design. Subsequently the results of charge, current, and capacitance measurements with the new electrometer are presented and discussed. In the conclusions, the main characteristics of the electrometer are summarized and furthermore an outlook is given to the applicability of the electrometer for the ECCS vacuum gap capacitor test experiment.

II. Vibrating reed electrometer

The schematic principle of the low frequency capacitance measurement is depicted in Fig. 1. The value of the capacitor under test C_{test} is determined by measuring the charge Q_{test}

Manuscript received March 27, 2012. This work was funded by the Dutch Ministry of Economic Affairs. Additional funding was received from the European Community's Seventh Framework Program, ERA-NET Plus, under Grant Agreement No. 217257.

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when a voltage step ΔV_{test} is applied to the capacitor. The charge Q_{test} is measured with an electrometer based on a vibrating reed capacitor C_{vr} and a feedback capacitor C_{fb}. The electrometer serves as a stable and sensitive charge meter that keeps the central electrode in Fig. 1 at zero potential by appropriately adjusting the feedback voltage V_{fb} across the feedback capacitor C_{fb} until Q_{test} is completely compensated for. When this is the case, the unknown capacitance ratio C_{test} / C_{fb} equals the measured voltage step ratio $\Delta V_{fb} / \Delta V_{test}$.

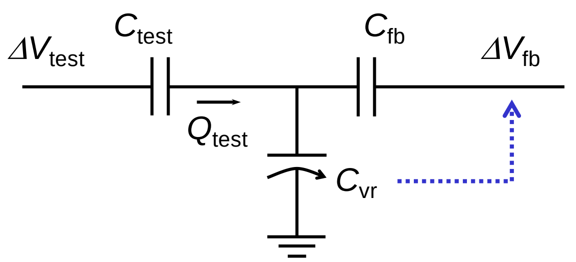

Fig. 1. Schematic low frequency capacitance measurement setup. A vibrating reed charge meter, based on the vibrating reed capacitor C_{vr}, keeps the central electrode at zero potential by adjusting the feedback voltage V_{fb} across C_{vr} until the effect of Q_{test} is compensated.

Fig. 2 gives more details of the actual implementation of the vibrating reed (VR) electrometer [3]. Any dc charge applied to the input generates a dc voltage V_{in} over the vibrating reed capacitor C_{vr}. This induces an ac current, which after passing through C_{fb} is buffered, amplified, and rectified by the lock-in amplifier (LIA). Finally, the output of the LIA is integrated to get an output voltage V_{fb}, which is fed back to C_{fb} via a high-ohmic resistor R_{fb}. The feedback loop changes V_{fb} until the ac signal, and thus the effect of the dc input charge on V_{in}, is nulled.

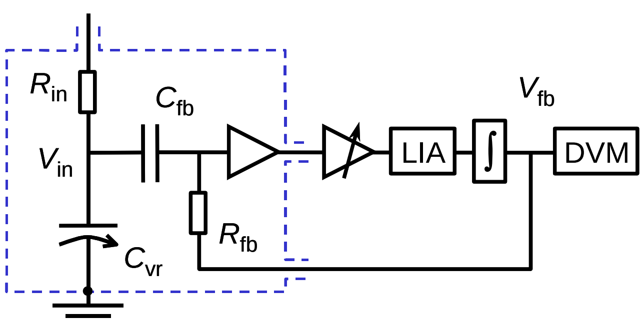

Fig. 2. Schematic of the vibrating reed electrometer. The sensitive-critical input stage is placed in a vacuum chamber indicated by a dashed line.

III. Electrometer Details and Optimization

Reaching low uncertainties in the ECCS capacitance characterization experiment with a setup as depicted in Fig. 1 requires ultimate charge resolution and stability of the charge meter.

In the vibrating reed electrometer, low charge noise together with low input offset currents is achieved by having an input circuit with only capacitors and no active electronic devices like operational amplifiers, and by the use of pure sapphire and other high quality ceramics for mechanically fixing the input elements.

Fig. 3 shows two pictures of the critical elements in the input stage of the vibrating reed electrometer, taken from an old commercial electrometer [9]. They clearly show the configurations of the cylindrical feedback capacitor C_{fb} and the parallel plate vibrating reed capacitor C_{vr}.

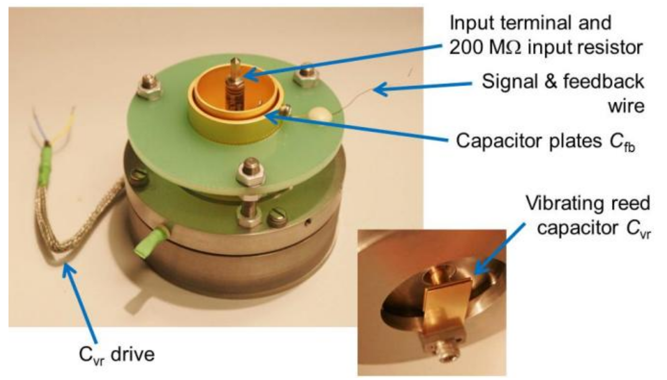

Fig. 3. Crucial parts of the vibrating reed electrometer: the input stage with the cylindrical feedback capacitor C_{fb} and the parallel plate vibrating reed capacitor C_{vr}. The bottom plate in the picture of C_{vr} is the vibrating element, driven by the electromagnetic field of a drive coil (not shown here; see Fig. 4).

The sensitivity of the setup is slightly improved with respect to our old design by decreasing the capacitor plate distance of C_{vr}, hereby increasing the value of C_{vr}. In this way C_{vr} dominates the effective capacitance of the sensitive central island, charged by the applied input charge.

The distance between the vibrating reed capacitor plates $d(t)$ can be described by $d_0 + d_1 \cdot \sin(\omega \cdot t)$, with respectively d_0 the stationary plate distance, d_1 the vibration amplitude, and ω the driving frequency that is selected to be close to the 580 Hz resonance frequency of the vibrating reed element. Having $C_{vr}(t) = \varepsilon_o \cdot A / d(t)$, where A is the surface area of the electrodes, it can be easily derived that the vibrating reed signal increases with increasing ratio d_1/d_0. Decreasing the capacitor plate distance d_0 as mentioned above therefore not only increases the value of C_{vr}, but has the additional effect that less driving signal is needed to achieve a certain ratio d_1/d_0 and thus a certain signal amplitude.

Good stability can only be assured when environmental effects of e.g. humidity on C_{fb} [4] are small. One way to achieve this is to use an external hermetically sealed gas capacitor instead of the internal air capacitor in our first electrometer [3, 4]. However, this requires an extra coaxial cable between C_{vr} and the external C_{fb}. Such a cable will increase the effective capacitance of the sensitive central electrode and therefore will lead to less signal at a certain signal charge. Tests in a prototype set-up indeed confirm that the parasitic capacitance of this cable leads to an unacceptable reduction of the electrometer sensitivity. Therefore, as an alternative solution, it is decided to place C_{fb} in vacuum. To this end a special vacuum chamber is built, that contains the complete input stage of the electrometer as indicated by the dashed line in Fig. 2.

A cross-sectional view of the complete input stage of the electrometer and vacuum chamber is shown in Fig. 4. An input short driven by a reed relay allows for bringing the charge on the input stage to a defined, low value at the beginning of each experiment. The feedback capacitor C_{fb} is surrounded by a grounded metal shield to give a defined, stable influence of stray capacitances on the value of C_{fb}. The sapphire support mechanically fixes the input terminal, the inner electrode of C_{fb}, and the non-vibrating top plate of C_{vr}, and at the same time ensures a very high leakage resistance of these elements to ground.

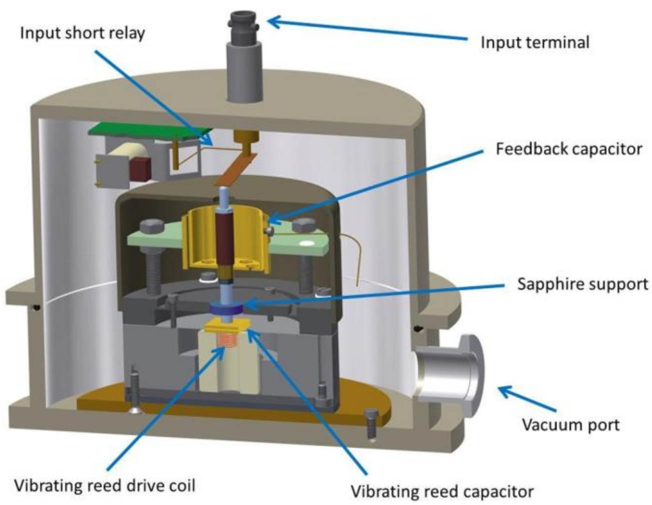

Fig. 4. Cross-section of the complete vibrating reed electrometer input stage, placed in a vacuum chamber.

Placing the complete input stage in vacuum resulted not only in negligible humidity dependence of the input stage capacitors, but it also improved the quality factor $f/\Delta f$ of the resonance frequency of the vibrating reed capacitor with about a factor 10. Apparently in the old electrometer where only the vibrating reed capacitor was in vacuum, this vacuum was not of very high quality. The higher quality factor of the vibrating reed resonance in the new electrometer helped reducing the driving voltage even further.

It is very important to prevent any ground loop in the electrical circuit of the electrometer set-up. The central star point of all ground connections is placed near the low connection of the electrometer BNC input terminal on the case of the vacuum chamber. The star point is connected to a special ground rail in the laboratory and provides the reference null for the amplification and integration electronics depicted in Fig. 2, as well as for the generation and measurement of V_{test} and V_{fb} (see Fig. 1). The 12 V_{DC} supply of the electronics is delivered from the mains by a high-quality, double-shielded supply transformer. The use of isolated BNCs in the vibrating reed electronics prevents ground loops between this electronics and the lock-in amplifier (LIA). The reference output of the LIA is driving the vibrating reed drive coil via a power amplifier. The low of the driving signal is only connected to ground at the LIA, so that the driving current cannot cause unwanted potential differences in the measurement circuit. Finally, the turbomolecular pump maintaining the better than 10^{-4} mbar vacuum in the input stage is electrically isolated from the vacuum chamber by use of plastic rings and clamps in the pumping line.

For achieving low noise in the measurements, not only ground loops should be prevented but the setup must also be well shielded to prevent interference. A very effective precaution was placing the first buffer amplifier of the vibrating reed signal inside the vacuum chamber (see Fig. 2). The output of this amplifier is connected to the main electronics via a shielded 8-wire cable. All other wiring in the setup consists of BNC cables. Pick up from the driving signal is reduced by using a shielded twisted pair cable inside the vacuum chamber for the driving signal (see Fig. 3). A further significant improvement in this aspect is achieved by exciting the vibrating reed capacitor at half its resonance frequency. This in practice reduced the cross talk between the driving signal and the electrometer signal to a completely negligible level. Driving the vibrating reed capacitor at half its resonance frequency is less efficient and thus requires an increase in driving voltage. However, due to the improved quality factor of the resonance and the smaller capacitor plate distance, the driving signal still is a factor 6 smaller than in our previous electrometer.

IV. Charge Measurement

As a first test of the effectiveness of the optimization actions, the electrometer output is monitored without any input signal. Fig. 5 shows two typical results found for the new electrometer. The measurement in the main graph was performed taking one sample every second resulting in a 2.8 μV (k = 1) standard deviation in the voltage measurements, corresponding to a 55 aC standard deviation in charge. This is more than a factor ten better than in our previous electrometer with an air-gap feedback capacitor [3].

In Fig. 5 four voltage steps are seen, with the second and third step occurring only one minute apart at around 80 minutes. These steps are caused by sudden spurious charges in the input stage of the electrometer. The instantaneous response of the electrometer to these charges indicates that the bandwidth of the feedback loop is much faster than the 1 s sampling period of the voltmeter. The sizes of the four voltage steps correspond to charges of 0.59 fC, 0.46 fC, 0.68 fC, and 0.85 fC respectively, with an expanded uncertainty of 0.01 fC, which corresponds to approximately 60 electrons. The voltage steps are visible on a background voltage drift of around 0.6 μV/min, equivalent to an input offset current of -0.2 aA (see also next section).

The inset shows a similar result obtained a few months later, where on the background of a small positive offset current two small charge steps of only 0.35 fC and 0.21 fC are very clearly visible. For clarity, the voltage data in this case have been averaged over 10 s periods.

The origin of the charges causing the steps in the electrometer output voltage is not clear. Typically the charge steps occur about two times per hour, with varying step size. Both frequency and size of the steps slightly decrease over the period of several months. This may indicate that the charges are related to dielectric absorption effects in the isolators of the input stage or to charges released by very small changes in internal stresses inside the electrometer. Another possibility is that the charges originate from ionizing radiation effects, either caused by radioactive contamination inside the electrometer or by background radiation in the laboratory.

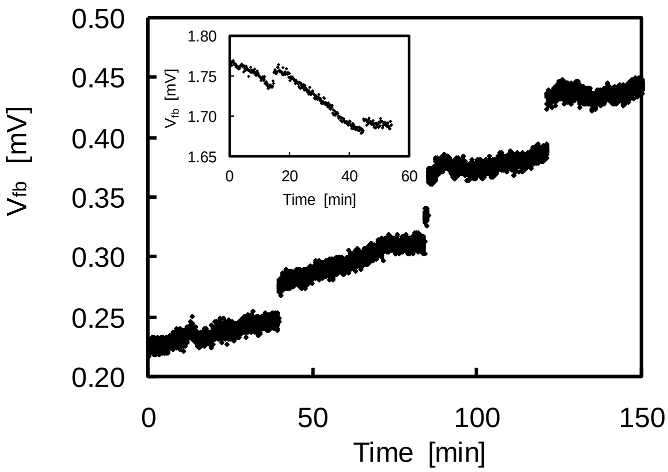

Fig. 5. VR electrometer voltage output as a function of time without any applied input signal, showing four voltage steps originating from sudden charge releases in the electrometer. The slow background drift corresponds to an approximately -0.2 aA input offset current. The inset shows a similar measurement with detection of even smaller charge effects, down to 0.21 fC.

V. Current Measurement

Already from the data in the previous section it is clear that the electrometer has a very small input offset current. This is studied in more detail by measuring the voltage drift in electrometer output with no input connected over several days and by determining every 10 minutes the corresponding offset current. Outliers in the current measurement caused by charges as presented in the previous section where removed. They could be easily detected in the data since they give rise to a large uncertainty in a 10-minute current measurement.

The result with zero feedback voltage across C_{fb} is shown in the first part of Fig. 6, where it can be seen that after a few hours the offset current settles to a value of only -0.12 aA with a 0.25 aA standard deviation in the mean of a single 10-minute measurement. Apparently, where our previous electrometer has an already impressive 8 aA input offset current with 4 aA standard deviation of the mean with a 1-h integration time, in the new vibrating reed electrometer this is reduced by more than a factor 20. Actually, the -0.12 aA offset current corresponds to a current of less than 1 electron per second. Since the internal construction of the two electrometers is very comparable, the very low offset current of the new electro-meter is tentatively attributed to reduced leakage of the (residual) gas in the input stage.

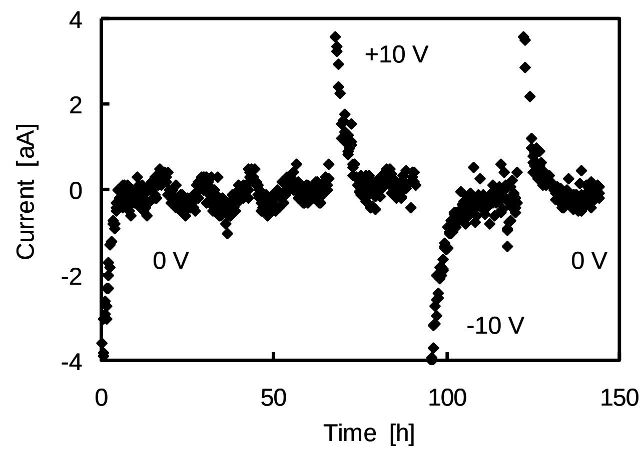

Fig. 6. Offset current of the VR electrometer as a function of time for several voltages across C_{fb}.

After the initial measurement, with still no signal applied to the input, a voltage is put across C_{fb} and the resulting change in input offset current is detected as given in the second part of Fig. 6. After the offset current has settled again, for +10 V and –10 V a current of +0.09 aA and –0.26 aA is measured respectively.

If this change in current with application of voltage to C_{fb} is converted to an effective 'leakage resistance' of C_{fb}, a value $6{\cdot}10^{19}\,\Omega$ is obtained which again proves the excellent capabilities of the new electrometer. The measured resistance of $6{\cdot}10^{19}\,\Omega$ is almost a factor 100 higher than that measured in the old air-gap electrometer. Apparently, in the latter case, the leakage resistance of the feedback capacitor is completely dominated by the presence of air between the capacitor plates. An alternative explanation of this C_{fb} 'resistance' is a voltage and pressure dependent ionization current.

In order to find the ultimate current resolution of the electrometer an Allan deviation analysis was performed on several measurement series, where the current was determined every minute during several days. Fig. 7 shows a typical result obtained in a 2-day measurement. Since the offset current drifted slowly from 6 aA to 2 aA over this particular period, the Hadamard routine was used for calculating the Allan deviation, since this routine corrects for the effect of linear drifts.

Fig. 7 shows that for short integration times the Allan deviation decreases with a slope close to the square root of the integration time. This corresponds to white noise, in which case the Allan deviation is equal to the standard deviation in the measurement. Thus the minimum found in Fig. 7 is the expected standard deviation in a current measurement for an integration time of around 3 hours, which is as low as 0.065 aA (0.3 electron per second). For longer integration times, the Allan deviation increases due to long term instabilities in the electrometer. Other measurement series give the same result as presented in Fig. 7 but only differ in the time at which the Allan deviation starts to increase, which varies between 2000 s and 14000 s.

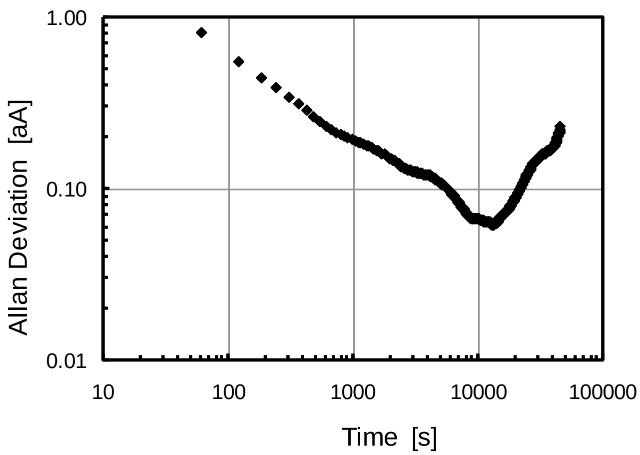

Fig. 7. Allan deviation as a function of integration time for current measurements with the vibrating reed electrometer, calculated with the overlapping Hadamard routine.

VI. Electrometer Calibration

The previous two sections showed the excellent sensitivity of the electrometer. But for making accurate measurements the gain of the electrometer needs to be calibrated. This is similarly true for sensitive commercial picoampere meters that use teraohm resistors to convert the small current to a voltage [6]. The electrometer essentially is a charge meter with a capacitor as feedback element. This is an advantage with respect to picoampere meters, since teraohm resistors are difficult to calibrate accurately given the limited quality and stability of such high-ohmic resistors.

Accurate calibration of the feedback capacitor using a commercial capacitance bridge is difficult since the capacitor does not have a well-defined three- our four-terminal geometry: it consists of two concentric coaxial plates with a grounded screen around it (see Fig. 4). Previous attempts to calibrate the feedback capacitor with a commercial capacitance bridge showed a reproducibility of not better than a few parts in 10^4 [3]. Thus, for most accurate calibrations a setup as depicted in Fig. 1 should be used with a calibrated reference capacitor as C_{test}.

For the calibration voltage V_{test} two sequences have been used: either 0, +V, 0, 0, -V, 0 volt or +V, -V, +V volt. The first sequence allows study of systematic effects, since the capacitance ratio values obtained for positive and negative voltage step should be equal. The second method is faster, so that a lower type A uncertainty can be achieved within a certain measurement period. Changes in V_{test} are applied in a step-wise matter from initial to final value over a time span of 3 seconds. After each change in V_{test}, the feedback voltage of the electrometer was allowed to settle for 6 seconds before measurements were started.

The measurement sequence typically is repeated 10 times for each calibration voltage in order to achieve sufficient statistics. For the second calibration voltage sequence, this takes about 11 minutes. No compensation of the input offset current was done [3], since the compensation scheme results in systematic deviations of a few parts in 10^6, which is significant with respect to the uncertainty level aimed for in the present experiments. However, without offset current compensation, the output of the electrometer slowly drifts due to the offset current until it reaches one of the electronics supply voltages. Since the input connection cable and the reference capacitor generate significant input offset current, in practice the calibration measurements could be run for at most one or two days before the VR electrometer feedback loop needed a reset to zero output voltage.

Fig. 8 shows a typical result for calibration of C_{fb} with a calibrated hermetically sealed 10 pF gas capacitor as reference (model GR1404). The calibrations lasted for 3 days, with one electrometer output reset after 1.5 day. With an effective measurement time of 10 h per calibration charge, a type A uncertainty of 14 μF/F and 2 μF/F was achieved for calibration charges of 10 pC and 80 pC respectively. This is a significant improvement with respect to our previous electrometer [3]. However, it still is slightly worse than expected on the basis of the noise of the bare electrometer as described in the previous sections. It appears that connectors and cables add significant noise and charge instabilities to the experiment.

According to the results of Fig. 8, the calibration value of C_{fb} appears to depend on the applied calibration charge, that is on applied calibration voltage (a 1 V step across the 10 pF reference capacitor generates 10 pC). Below 20 pC no significant effect is seen, as in measurements with the old electrometer [3], but above this charge the effect becomes significant: there is a 30 μF/F difference in value obtained at 20 pC and 80 pC calibration charge respectively. It is not clear whether this is a property of the reference capacitor, of the VR feedback capacitor or an artifact caused by the measurement set-up.

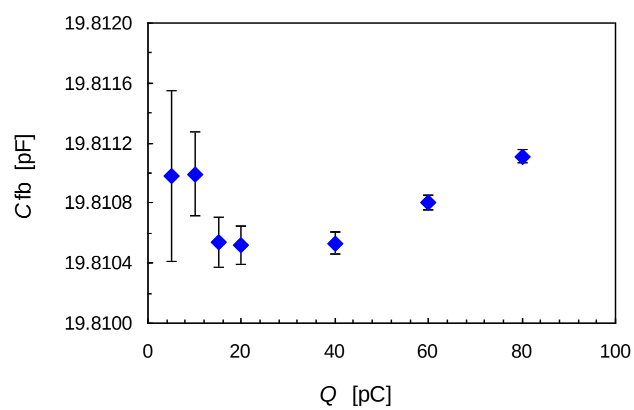

Fig. 8. Calibration values of C_{fb} in the vibrating reed electrometer for different calibration charges Q, using a setup as depicted in Fig. 1 with hermetically sealed gas capacitor as reference instead of the test capacitor. Uncertainties bars indicate $k = 2$ type A uncertainty values.

In the absolute determination of C_{fb} the unknown frequency dependence of the reference capacitor will be the dominant uncertainty contribution. Recent measurements on capacitors with capacitance values of 100 pF to 10 nF indeed show significant frequency dependence [6]. The largest effects are seen for open air-gap capacitors, where humidity effects can be very significant [4, 6], but also hermetically sealed capacitors may suffer from a residual layer of water still present on the capacitor plates after preparation by the manufacturer.

VII. Capacitance Measurement

As a first step towards application of the electrometer in a study of ECCS vacuum gap capacitors as described in the introduction, the 1 kHz and 0.01 Hz value of C_{fb} was measured before and after a heat treatment of C_{fb}.

The 0.01 Hz measurement of C_{fb} was performed with the electrometer set-up and the 10 pF reference capacitor, as described in the previous section. In order to additionally make 1 kHz measurements of C_{fb} possible as well, the input resistor R_{in} was shorted so that the input connector of the electrometer has a direct connection to the inner capacitance plate of C_{fb} (see Fig. 2). Furthermore an extra direct connection was added from the outer capacitance plate of C_{fb} to an additional coaxial connector in the electrometer vacuum housing (not shown in Figs. 2 and 4). Still, the limited definition of C_{fb} does not allow very accurate absolute measurements at 1 kHz, but since the geometry is stable, changes in capacitance can now be measured at 1 kHz with relatively good precision of 2 – 5 μF/F. The fact that R_{in} is shorted hampers the low-frequency measurements, since the 200 MΩ impedance of R_{in} ensures that essentially no vibrating read signal is 'lost' via the input, and furthermore limits negative effects of impedances connected to the electrometer input terminal. With shorted R_{in}, the bare electrometer setup indeed was less sensitive and has about three times more noise than with R_{in} present. Fortunately, this reduction in sensitivity was less pronounced in the capacitance measurement due to the charge effects from connectors and cables.

The heat treatment of C_{fb} consisted of heating the complete electrometer vacuum chamber for three days to a temperature of 65 °C, while continuously pumping the chamber with a turbomolecular pump, after which it was allowed to slowly cool back to room temperature.

An indication of the possible effect of this heating on the surface adsorbants on the gold plates of C_{fb} was obtained by measurement of the work function of the vibrating reed electrometer plates that are similarly gold plated. The work function is determined by applying a dc voltage to the electrometer input terminals via a 100 MΩ resistor, with open electrometer feedback loop, and change this voltage until the LIA signal is zero. In this situation the applied voltage is equal to the work function difference of the two capacitor plates of C_{vr} [8]. For two similarly prepared surfaces the work function difference should be zero, but in practice this is seldom the case since the work function essentially is determined by the outer atomic surface layers and therefore extremely sensitive to adsorbants.

The measured work function difference values for C_{vr} are (13.780 ± 0.005) mV and (11.125 ± 0.005) mV before and after the heat treatment respectively. These values indicate that the vibrating reed electrode surfaces were already quite clean before the heat treatment and that the heat treatment gave a significant, but quite small improvement in the surface cleanliness.

The results of the capacitance measurements at 0.01 Hz are presented in Fig. 9 relative to the value obtained at 1 kHz, both before and after the heat treatment. After the heat treatment, the absolute value of C_{fb} has increased by about 200 μF/F. However, since the effect of surface layers shows up in the *difference* in value obtained at 0.01 Hz and 1 kHz, it is this difference that is presented in Fig. 9.

The data in Fig. 9 show a clearly different calibration charge dependence than presented earlier in Fig. 8. This is tentatively attributed to the fact that R_{in} is removed in the present experiment. The heat treatment does not significantly alter the calibration charge dependence for the present configuration without R_{in}.

Visually, there seems a small decrease in capacitance difference between 0.01 Hz and 1 kHz measurements after heat treatment. This would be in line with the work function measurements, that indicate that a small part of the surface layers – the cause of the difference in 0.01 Hz and 1 kHz capacitance values – are removed in the heat treatment. However, the uncertainty in the capacitance difference values is larger than the size of the changes, so that more explicit conclusions unfortunately can not be drawn.

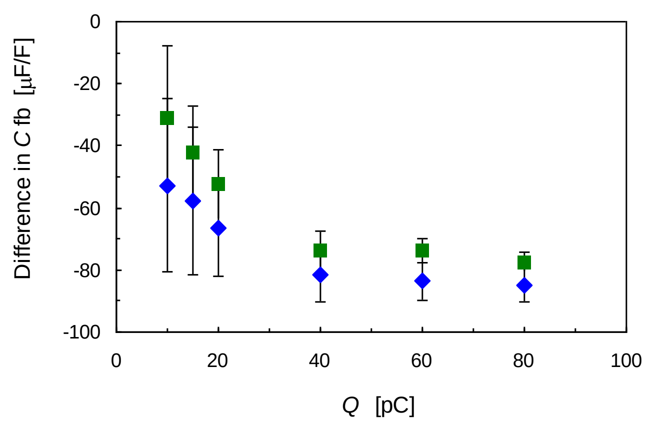

Fig. 9. C_{fb} calibration values obtained for different calibration charges at 0.01 Hz relative to those obtained with a commercial 1 kHz bridge. Measurements before (diamonds) and after (squares) annealing of the electrometer input stage. Uncertainties shown are the $k = 2$ values in the VR measurement.

VIII. Conclusions and Outlook

We have designed and built an optimized vibrating reed electrometer. Several actions, especially putting the complete input stage in vacuum, have improved the sensitivity of the electrometer more than a factor ten with respect to the previous instrument. Charge steps as small as 0.21 fC can now be detected with an uncertainty of 10 aC. The standard deviation in the mean of a single ten-minute current measurement is only 0.25 aA, that is slightly above 1 electron per second. Allan deviation analysis shows that an ultimate standard deviation of 0.065 aA can be achieved in current measurements with a 3-h integration time. The input offset current also is at extremely low levels, typically below 1 aA.

The extreme sensitivity of the new instrument makes it suitable for detection of very subtle charge effects and accurate current measurements, although connecting cables to the input significantly increases offset currents and noise [3]. Still, the value of the VR feedback capacitor could be calibrated using a 10 pF reference capacitor with a type A uncertainty of around 3 μF/F at a test charge of 60 pC and 10 h measurement time.

As a first step towards application of the electrometer in a study of the frequency dependence of ECCS vacuum gap capacitors, the 1 kHz and 0.01 Hz value of the electrometer vacuum gap feedback capacitance was measured before and after a heat treatment of this capacitance. The results of this experiment indicate that the approach taken is viable, even though no significant effect of the heating was found on the difference in capacitance value obtained at both measurement frequencies. This likely is due to the fact that the capacitor plates already were quite clean before the heating, as confirmed by work function measurements.

Future work will include further study on the calibration charge dependence of the electrometer feedback capacitance value in the 0.01 Hz experiment, and especially the application of the new electrometer in frequency dependence studies of ECCS vacuum gap capacitors.

ACKNOWLEDGEMENT

The excellent support of Maurice Heemskerk and André Trarbach of the VSL workshop in the mechanical and electronic design and improvement of the electrometer is gratefully acknowledged.

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