1:30 000 Cryogenic Current Comparator With Optimum SQUID Readout

Gert Rietveld, Elena Bartolomé, Javier Sesé, P. de la Court, Jaap Flokstra, Conrado Rillo, and Agustín Camón

Abstract—We have developed a 1:30000 winding ratio cryogenic current comparator (CCC) for measurement of small currents, e.g., generated by a single electron transport device. A dedicated low-noise SQUID is used for the readout, which allows reaching a sensitivity close to ideal, that is without loss of sensitivity in the flux transformer coupling the CCC and the SQUID. The CCC-SQUID equivalent current input noise using a 1:30 000 winding ratio is 2.1 fA/Hz$^{1/2}$, measured down to 0.1 Hz. Room temperature impedance measurements on CCCs appear to be a useful method for the determination of the screening by shields surrounding the CCC as well as for the detection of internal CCC resonances.

Index Terms—Cryogenic current comparator (CCC), current measurement, dc SQUID, inductance measurement, single electron transport (SET).

I. INTRODUCTION

THE future establishment of a quantum standard for electrical current relies on the precise amplification of the very small quantized current (1 to 10 pA) provided by a single electron transport (SET) device, with the help of an ultra-sensitive, large-ratio cryogenic current comparator [1] with SQUID readout. The current quantum standard can then be combined with the existing resistance and voltage quantum standards to close the quantum metrological triangle of electrical units [2], [3]. The final current resolution of the cryogenic current comparator (CCC)-SQUID system (provided that all external sources of noise can be properly shielded) depends on the SQUID noise, and the efficiency of the coupling between the CCC and the SQUID. Usually, the CCC overlapped tube is coupled to the SQUID via a superconducting flux transformer. We have shown [4] that perfect coupling can be achieved connecting the tube directly to the SQUID input coil, in which case an optimal current noise is achieved

$$\left\langle I_P^2 \right\rangle^{1/2} = \frac{1}{N_{\mathrm{CCC}}} \sqrt{\frac{8\varepsilon}{k_{\mathrm{sq}}^2 L_{\mathrm{CCC}}}}.$$

Here, ε is the intrinsic energy resolution of the SQUID, and k_{sq} is the coupling constant between the SQUID washer and input coil. To minimize $\left\langle I_P^2 \right\rangle^{1/2}$, the CCC should have a large
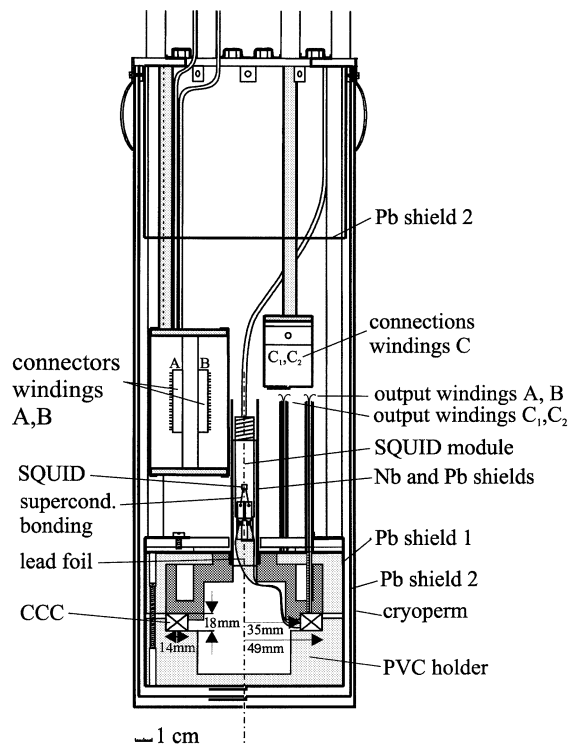
Fig. 1. Schematics of the lower part of the cryogenic insert containing the large ratio CCC with SQUID and the electrical and magnetic shields.

number of primary turns N_{CCC} and maximal self-inductance L_{CCC}. Furthermore, the SQUID should have minimum energy resolution ε and input coil inductance L_i close to L_{CCC}. In this paper, we present the integration and characterization of a complete 1:30 000 CCC with optimal SQUID readout.

II. EXPERIMENTAL SETUP

A schematic view of the cryogenic part of the system is shown in Fig. 1 [5]. The CCC, with one turn overlap, contains the following sets of windings: 1, 1, 2, 4, 4, 10, 10, 20, 20, 40, 40, 100, 100, 200, 400, 400, 1000, 1000, 2000, 4000, 4000, 10 000, and 10 000 turns. Thus, the maximum amplification ratio available is 1:33 350. The windings are made of 70-μm-thick insulated Cu wire. The CCC has an inner diameter of 70 mm and a width and height of 14 and 18 mm, respectively.

The CCC is completely surrounded by a Pb shield. Due to the image effect, the inductance L_{CCC} of the CCC becomes an effective inductance $L_{\mathrm{CCC,eff}}$ smaller than that of the unshielded CCC. The size of this effect is measured at room temperature with an LCR meter using a dummy CCC without windings and an overlapping tube of the same dimensions as that of
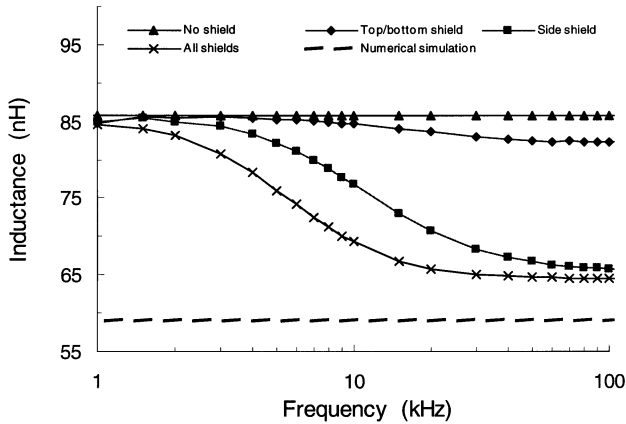
Fig. 2. Inductance of a dummy CCC without windings as a function of frequency for different configurations of the shields surrounding the CCC. The measurements were performed at room temperature using a commercial LCR meter.
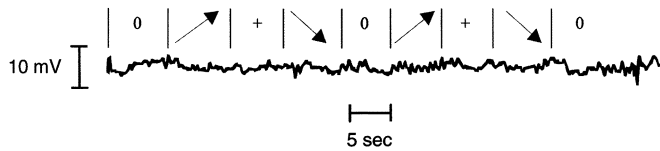

Fig. 3. SQUID output signal as a function of current applied to two 1000 turn windings placed in series with opposite polarity. The arrows indicate the up- and down-ramping of the 26-μA current. No error signal is detected within the noise of about $10^{-4}\,\Phi_o$, which indicates a ratio error F of less than 8.7×10^{-9}.

the 1:30 000 CCC [6]. The results are given in Fig. 2, where the inductance values have been corrected for the zero of the LCR meter. The low frequency value of the inductance is that of the unshielded CCC whereas at frequencies above 10 kHz, L_{CCC} is affected by eddy currents in the surrounding shield. As expected, the effect of the side shield is larger than that of top and bottom shield. For the complete shield, the value measured by the LCR meter, 64 nH, compares very well with the numerically calculated value at dc for superconducting shields (all shields present) of 59 nH [7].

A home-made Nb/Al dc SQUID [5], [8] with input coil inductance $L_i = 45$ nH close to $L_{\mathrm{CCC,eff}}$ is used. The noise of about $7\,\mu\Phi_o/\mathrm{Hz}^{1/2}$ in the white noise region is dominated by that of the SQUID commercial readout electronics; at low frequencies, however, the noise is essentially that of the SQUID sensor and amounts only to approximately $11\,\mu\Phi_o/\mathrm{Hz}^{1/2}$ at 1 Hz. Annealed Nb wires, wedge bonded to the SQUID input coil pads, and spot welded to the SQUID module Nb blocks are used to connect SQUID input coil and mounting Nb blocks. A very low inductance (<1 nH/m) lead foil is used to connect the SQUID module to the CCC [6]. The SQUID module is shielded by two concentric Nb and Pb shields.

Only nonmagnetic materials are used in the construction of the CCC support system. The whole CCC-SQUID is fixed at the end of a rigid insert and surrounded by a second lead and cryoperm shield of an inner diameter of 135 mm and a height of 400 mm (Fig. 1). Finally, the complete cryostat is placed in a high-permeability iron can. The wires carrying small (C_1, C_2) and high (A, B) currents are separated to avoid possible cross talk. Two 10-MΩ resistors are soldered in series with the C_2

winding to facilitate applying a small current. At room temperature, the A and B windings are available at two 20-pin Lemo connectors, while the C_1, C_2 windings are connected to triax connectors. A battery-powered current source is used to manually apply a variable current of either 0 to 26.4 μA or 0 to 11.8 pA to the windings.

III. MEASUREMENTS ON THE 1:30 000 CCC

First of all, the characteristics of the SQUID directly connected to the CCC has been measured. The period of the SQUID output voltage V in the $V - \Phi$ curve corresponding to 1 Φ_o of feedback flux is 5.5 V, an intermediate situation between having the SQUID input coil leads open or shorted, giving 4.5 or 9 V per Φ_o, respectively. In contrast to the normal direct $V - \Phi$ curve, the demodulated $V - \Phi$ curve is affected by superimposed large high-frequency signals. This behavior results from the appearance of LC-resonances in the multi-turn CCC, excited by the 500-kHz modulation frequency signal of the SQUID readout electronics, that couples back to the flux transformer. The demodulated $V - \Phi$ curve and the noise spectrum thus contain all the excited resonant peaks corresponding to the different windings, with dominance of a peak at approximately 1.7 kHz coming from the largest coil. The resonant phenomena make the system extra sensitive to vibrations and acoustic noise, but do not prevent the operation of the SQUID readout electronics in internal feedback mode.

The current sensitivity of the CCC is found to be $S_{\mathrm{CCC}} = 2.3\,\mu$A · turn$/\Phi_o$. This is close to the theoretical ideal value, being twice the current sensitivity of the SQUID of 1.1 μA$/\Phi_o$. The ratio error of the CCC has been measured by applying a current, reversed approximately every 5 s between 0 and 26.4 μA, to two 1000-turn windings connected in series opposition (see Fig. 3). No error signal can be detected within the SQUID noise of $10^{-4}\,\Phi_o$, which corresponds to a ratio error of less than $8.7 \cdot 10^{-9}$ [5].

The noise of the SQUID connected to the CCC as measured in flux locked loop (FLL) is given in Fig. 4 (upper curve). At high frequencies, the system noise spectrum shows the resonant behavior already commented, with the main peak at 1.7 kHz. The broad peak in the region of 10 to 100 Hz is due to vibrations. In this particular experiment, the noise in this area is extra large, due to the fact that several of the plastic screws clamping the CCC (Fig. 1) had been broken during cool down. The noise in this region is also large when several of the wires connected to the CCC windings are broken and thus are allowed to move relatively easily upon vibration excitation. The peak at 100 Hz is caused by the mains supply in the SQUID readout electronics and disappears when this electronics is run on battery supply. At frequencies lower than 10 Hz, a flat noise level of about $27\,\mu\Phi_o/\mathrm{Hz}^{1/2}$ is measured, corresponding to a noise current spectral density $\langle I_P^2\rangle^{1/2}$ (for a 1:30 000-turn winding ratio) of approximately 2.1 fA/Hz$^{1/2}$. The 1/f noise of the SQUID (lower curve in Fig. 4) dominates below the corner frequency of about 0.1 Hz, and it seems that connecting the CCC does not add significant 1/f noise. To measure the noise at very low frequencies, the FLL output filtered at 1 Hz is recorded during 6 min and a current standard deviation of $\sigma_I = 2.3$ fA was obtained.
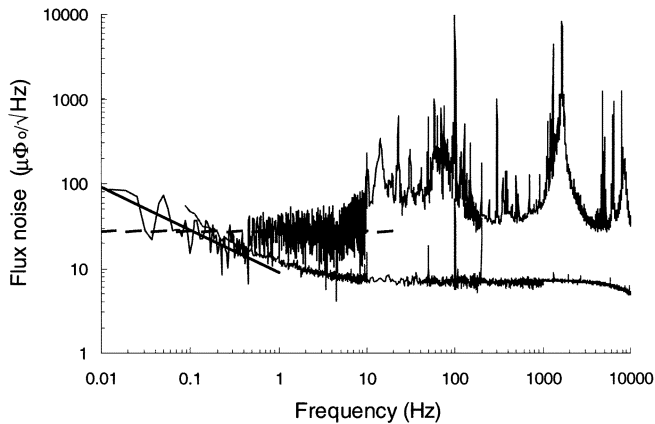
Fig. 4. Flux noise of the 1:30 000 CCC (upper curve) and the bare SQUID (lower curve). The peak at 1750 Hz in the spectrum of the CCC is the internal resonance of the CCC; the broad peak in the region of 10 to 100 Hz is due to vibrations. The dotted line indicates the 27 $\mu\Phi_o/\mathrm{Hz}^{1/2}$ noise of the CCC system in the 0.1 to 10 Hz range.

Fig. 6. Inductance of the three different CCCs examined in this study. The curve of the 1:30 000 CCC shows a clear resonance peak at 1.1 kHz, whereas the CCC with internal Cu shields has a damped resonance around 1.4 kHz.
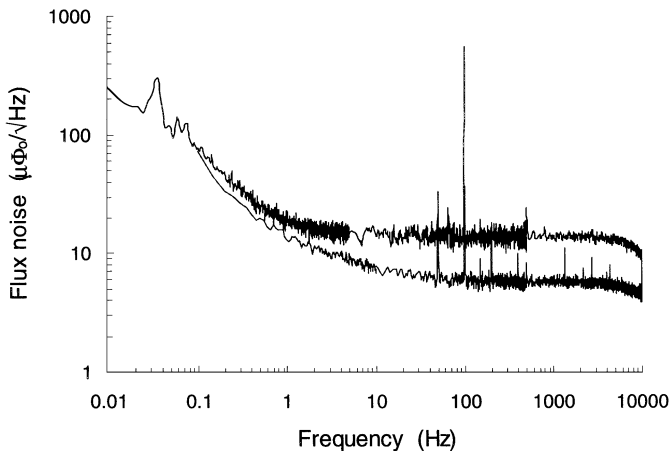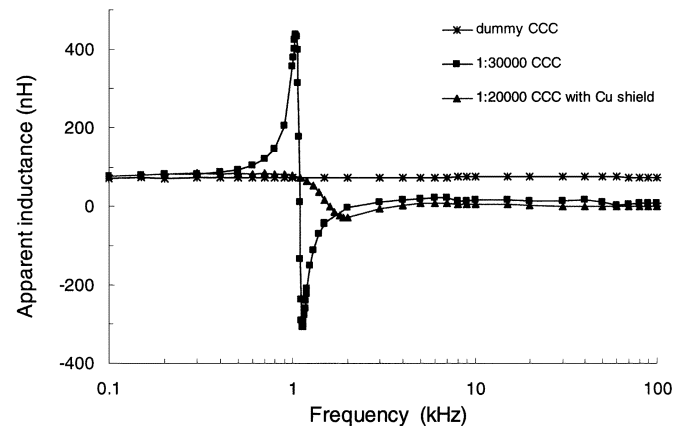

Fig. 5. Flux noise of the bare CCC (upper curve) compared with that of the bare SQUID (lower curve). The peaks at 50 and 100 Hz are caused by the SQUID readout electronics.
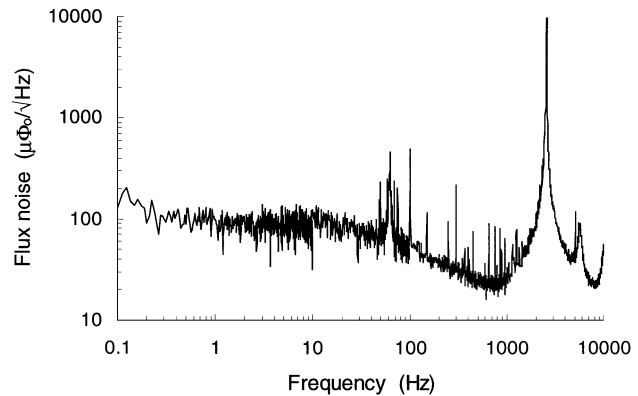

Fig. 7. Flux noise of the CCC with internal Cu shields. The internal resonance is still present at 2.5 kHz. The low frequency noise is relatively high and amounts to 90 $\mu\Phi_o/\mathrm{Hz}^{1/2}$.

IV. MEASUREMENTS ON A DUMMY CCC

The accuracy of the final CCC setup is directly related to the noise as e.g., given in Fig. 4. Since the noise spectrum of the 1:30 000 CCC shows the dominant presence of the internal resonance, we have performed a similar experiment with the dummy CCC used in the impedance measurements shown in Fig. 2. The result of the measurements is given in Fig. 5 and is compared to the spectrum of the bare SQUID. The spectrum is essentially smooth, with a peak at 100 Hz caused by the SQUID electronics and a small peak at 50 Hz from mains interference. The white noise is 15 $\mu\Phi_o/\mathrm{Hz}^{1/2}$, which is only a factor two more than that of the bare SQUID.

The flux locked loop of the SQUID readout electronics is extremely stable during the measurements since the CCC has no windings inside. The low noise values and the clean noise spectrum indicate that our present electrical and magnetic shielding is sufficient. The extra noise seen in the noise spectrum might still be introduced by external sources or by the movement of frozen flux lines inside the CCC.

V. MEASUREMENTS ON A CCC WITH INTERNAL CU SHIELDS

The internal resonance of the 1:30 000 CCC is a major source of extra noise and instability and therefore deserves further study. The resonance is caused by the large inductance of the 10 000 windings, $L_{10\,000} = N^2 \cdot L_{\mathrm{CCC,eff}} \approx 6\,\mathrm{H}$, combined with its internal capacitance $C_{10\,000}$. Given the value of the resonance frequency and the value of $L_{10\,000}$, we find a value of $C_{10\,000} \approx 1.4\,\mathrm{nF}$. Similar values for internal capacitances were found by F. Gay [9]. In order to affect this internal resonance of the CCC, a 1:20 000 winding ratio CCC was made where between every 2000 windings a single Cu layer was placed. Each Cu shield formed a 0.95 turn in order to not short the CCC transformer.

Fig. 6 shows the results of room temperature impedance measurements on all three CCCs, without shields. The dummy CCC gives an essentially constant value, as expected. The 1:30 000 CCC has a clear resonance at 1.1 kHz, but the resonance of the 1:20 000 CCC seems to be quite effectively damped by the internal Cu shields. Since the resonance of the 1:20 000 CCC is around 1.4 kHz, the shields apparently do not significantly reduce C_{winding}. This can be understood from the fact that the main capacitance contributing to C_{winding} will be between successive layers of windings and there is only one Cu shield every

8 layers of windings. All Cu shields were connected together, but isolated from the overlapping tube. The impedance spectrum did not change when the shields were grounded or not.

At 4.2 K, using this CCC, the noise spectrum of Fig. 7 is obtained, from which it becomes clear that the resonance peak is still present at low temperatures. If the damping at room temperature is caused by eddy current dissipation in the Cu shields, this effect is smaller at low temperatures due to the lower resistance of the copper; it may be that other material, like, e.g., manganin, should have been used instead. Like for the impedance measurement, the noise spectrum does not depend on whether the Cu shields were grounded or not. The cause for the increase of noise below 700 Hz is still unclear. The noise levels there are much higher than what is found with the 1:30 000 CCC. This will be the subject of future work.

VI. CONCLUSION

We have developed a 1:30 000 winding ratio CCC for the measurement of small (e.g., SET) currents. A dedicated low-noise SQUID is used for the readout, which allows reaching a sensitivity close to ideal, that is without loss of sensitivity in the flux transformer coupling the CCC and the SQUID. The CCC-SQUID equivalent current input noise using a 1:30 000 winding ratio is 2.1 fA/Hz$^{1/2}$, measured down to 0.1 Hz. Measurements on a dummy CCC have revealed that the electrical and magnetic shielding of our cryogenic system is good, and that in the insert mechanical fixing of the wires connecting the CCC windings is very important. A test with a 1:20 000 CCC with internal Cu shields did not result in lower current noise, even though at room temperature these shields damp effectively the internal resonances of the CCC.

Room temperature impedance measurements on CCCs appear to be a useful tool for the determination of the screening by shields surrounding the CCC as well as for the detection of internal CCC resonances.

We can estimate the current uncertainty that can be reached in the measurement of a SET current with our present 1:30 000 CCC, based on the measured noise current spectral $\left\langle I_P^2 \right\rangle^{1/2} \approx$ 2.1 fA/Hz$^{1/2}$. Assuming that the SET current can be reversed at a frequency $f_{S1} \approx f_c = 0.1$ Hz, assuming a measurement bandwidth of 0.1 Hz and an averaging over 720 measurement cycles (2 h measurement time), the standard deviation of the mean current would be 25 aA. In the measurement of a 1 pA to 10 pA SET current this would correspond to a relative uncertainty of approximately $3 \cdot 10^{-5}$ to $3 \cdot 10^{-6}$, respectively. If surface acoustic wave devices were available that can give accurate quantized currents of the order of 1 nA, a relative uncertainty less than 10^{-7} might be reached.

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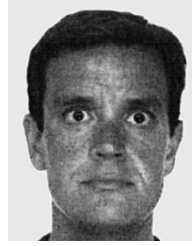
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