A Compact 14-Bit Cryogenic Current Comparator

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Abstract — **A cryogenic current comparator with an overall of 17,252 turns and windings including numbers of turns ranging from 2^0 to 2^{13} has been realized. This system offers the possibility of resistance calibration at increased magnetic flux levels and allows for a direct calibration of 1 Ω to 100 MΩ normal resistors against the quantum Hall effect. Besides that, the very low-current measurements at PTB will benefit from the availability of this additional setup. Such applications include the use of this comparator as a current amplifier as well as for calibration of highly-stable transimpedance amplifiers.**

Index Terms — **Bridge circuits, calibration, electrical resistance measurement, precision measurements, superconducting devices.**

I. Introduction

The cryogenic current comparator (CCC) is an established tool in resistance calibration with ultimate accuracy. As the core part of a measurement bridge, it can provide a fixed current ratio I_1/I_2 equal to N_2/N_1, the reverse ratio of the numbers of turns of the CCC windings, through which these currents flow. For that operation, a SQUID serves as the magnetic field sensor (null-detector) in a feedback loop taking control of one of the current sources.

Both the coils with N_1 and N_2 turns can be composed of several CCC windings (algebraic sum of the numbers of turns taking into account the respective orientation). Obviously, it is the set of available windings – with numbers of turns N_i ranging from N_{min} to N_{max} and summing up to N_{tot} – that determines the maximum current ratio equal $(N_{tot} - N_{min})/N_{min}$. Also, it depends on this set how close the ratio of the resistances to be compared can be approached by $(I_1/I_2)^{-1} = N_1/N_2$, a point which is of concern especially for the calibration of normal resistors with decade nominal values against the 12.906,403,5 kΩ quantum Hall resistance (QHR) at filling factor 2. Finally, the N_i set defines the frame within which the same numbers-of-turns ratio can be realized involving different N_1 and N_2 numbers: As soon as the SQUID sensor's intrinsic noise significantly contributes to the measurement uncertainty, the numbers N_1 and N_2 have – if possible – to be increased (of course, without changing their ratio). This has to be considered in experiments at low current levels or – to be more precise – low levels of the magnetic fluxes coupled into the SQUID loop resulting from the currents I_1 and I_2.

In the recent years we have used a 12-Bit CCC, i.e. with N_i from $N_{min} = 1$ to $N_{max} = 2{,}048$ in powers of 2 and an overall of $N_{tot} = 4{,}647$ for the 18 windings. [1] Here we describe our new 14-Bit CCC with $N_{tot} = 17{,}252$ in, again, 18 windings.

II. Design of the 14-Bit Comparator

As the 12-Bit version, the 14-Bit CCC is designed for operation in a liquid helium storage dewar with 50 mm flange. This has been achieved by reducing the wire diameter by a factor of two (from 50 µm / 70 µm without or with insulation, respectively, to 25 µm / 35 µm), a change, which makes the manufacturing considerably more demanding. The wire is a single-filament NbTi superconductor in Cu matrix. The Type-I CCC's lead screen overlaps about 2.9 times. Inner and outer diameter of the torus are 18.0 mm and 32.5 mm, respectively, and the comparator's so-called chimney is about 226 mm long. It ends in the contact board's volume in the upper part of the probe's cold head (see Fig. 1). This upper part is separated from the lower part by a 12 mm thick cylindrical Nb plate acting as a superconducting screen. The whole lower part – with the CCC torus and the SQUID at its bottom end – is placed in a 210 mm high Nb-made superconducting screening cup of 44 mm and 46 mm inner or outer diameter, respectively. The screening is completed by an outer cup of Cryoperm, a high-permeability material suitable for low-temperature applications.

The two room-temperature interfaces of the probe provide separate access to the CCC windings and to the SQUID. Among the 18 windings to be selected by means of a windings selector box plugged onto the CCC interface are 14 with numbers of turns from $2^0 = 1$ to $2^{13} = 8{,}192$ (14-Bit-CCC). In addition there are four more windings available with numbers of turns 1, 17, 78 and 773.

III. Measurement Results

A. Noise Spectrum

First we determined the flux linkage sensitivity of the new CCC plus SQUID system obtaining 11.1 (µA·turns)/Φ_0 with Φ_0 denoting the superconducting flux quantum. Then the noise spectrum shown in Fig. 2 has been recorded for the system without connecting the current sources. The spectrum displays a wide peak at about 200 Hz resulting from the CCC self-resonance when damped by an *RC* series array (2 kΩ and 900 nF, both placed on one of the contact boards) in parallel with the winding of highest inductance, i.e. the one with 8,192

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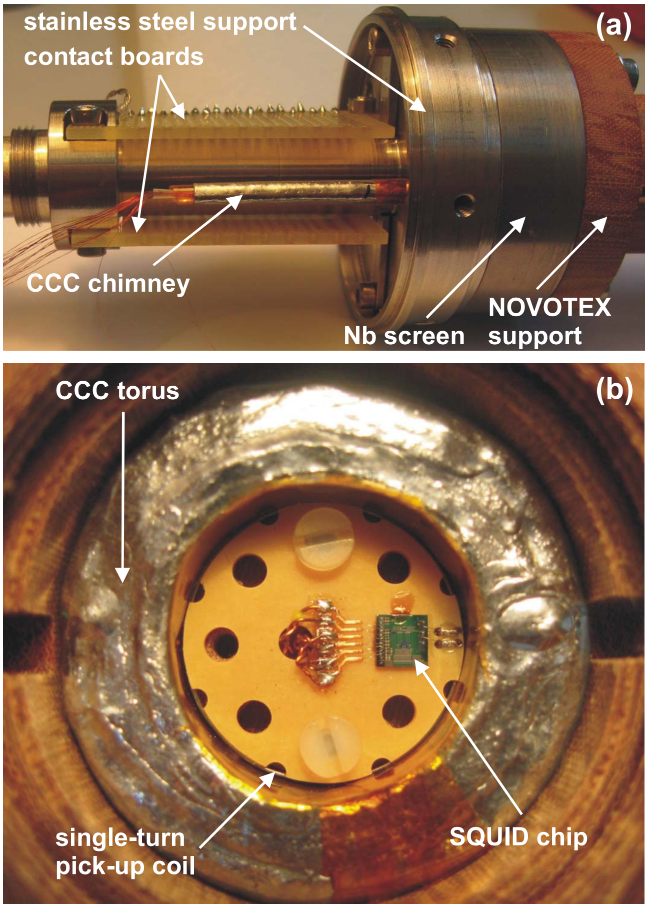

Fig. 1. Photographs of the CCC probe's cold head during manufacturing with (a) displaying the upper part when the probe is in horizontal position and (b) the lower end seen from the bottom in absence of more NOVOTEX (Tufnol) parts used for fixing the torus and of the Nb and Cryoperm-made screening cups.

turns. Note that the decrease of the resonance frequency by almost an order of magnitude compared with the 12-Bit-CCC [1] corresponds to a reduced bandwidth limit.

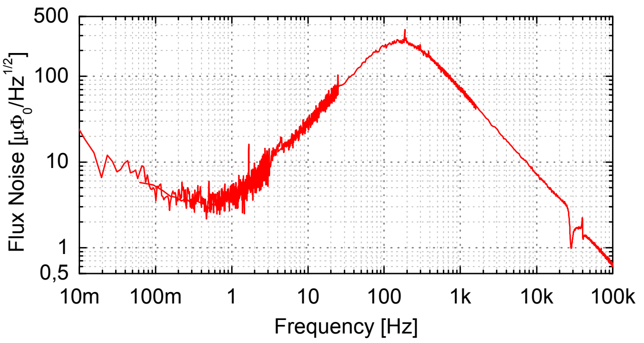

Fig. 2. Spectrum of the SQUID's flux noise when mounted to the CCC probe. For an input coil with 17,000 turns, the flux noise level in the 0.1 Hz to 1 Hz range corresponds to an equivalent input current noise of about 3 fA/Hz$^{1/2}$.

B. Exemplary Resistance Comparisons

In combination with the recently completed CCC electronics, the new probe has been tested for resistance calibration. For the first time, we could directly compare normal resistors with nominal values of 1 Ω and of 100 MΩ with the QHR. The chosen N_1/N_2 ratios of 12,906 : 1 for the QHR to 1 Ω or 15,496 : 2 for the 100 MΩ to QHR comparisons, respectively, have not been available before. For example, in the case of the 100 MΩ to QHR comparison, this measurement has the potential to replace the previous practice, namely a chain of three calibrations using a CCC (QHR → 100 Ω →10 kΩ →1 MΩ) followed by two calibrations using a direct current comparator (1 MΩ →10 MΩ and 10 MΩ →100 MΩ). The measurement results for the deviation of the 100 MΩ resistor from its nominal value, (37.67 ± 0.43) or (38.3 ± 2.0) parts in 10^6 obtained with the new or the established way of calibration, respectively, are in excellent agreement. Also the calibration of a 100 Ω normal resistor against the QHR with N_1/N_2 ratio 16,133 : 125 provided a result which is consistent with the calibration at ratio 4,001 : 31 using the 12-Bit-CCC. However, in this case, there is not much benefit from the increased numbers of turns, because already for the 12-Bit-CCC experiment, the Type-A uncertainty is no longer dominated by the contribution related to the SQUID noise. Of course, all these experiments involved an auxiliary CCC winding of one turn in the primary circuit of the measurement bridge for achieving good balance [2].

IV. Conclusion and Outlook

First promising measurements with a 14-Bit-CCC probe suggest interesting applications, especially in experiments where the current levels are very low. Examples include investigations of the fractional quantum Hall effect, the direct use of a CCC as a current amplifier [3] or alternative approaches with the CCC being used for an amplifier's calibration [2].

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