Scaling the current from a GHz electron pump using a CCC

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***Abstract* — We demonstrate the scaling of the current from a tunable-barrier electron pump using a cryogenic current comparator (CCC) with a turns ratio of 1:22592. The amplified current flows in a calibrated 100 kΩ resistor, and the voltage drop across this resistor is directly compared against a binary Josephson array. The experimental setup constitutes a prototype realization of the metrology triangle proposed more than 15 years ago.**

***Index Terms* — Electron pump, current standard, small current, primary electrical standard.**

I. Introduction

Comparison of the current, of order 100 pA, from an electron pump with reference currents derived from the Josephson voltage and quantum Hall resistance standards is a challenging scaling problem. The most accurate direct measurements to date have relied on calibration of high-value resistors [1]-[3] and in the case of [3] also a resistance ratio [4], using cryogenic current comparators (CCCs). Additional assumptions concerning the power dependence of those resistances and / or ratios are required. A proposal to use a cryogenic current comparator directly to scale the pump current by a factor of more than 10^4 [5] has so far only been implemented using metallic pumps [6] with relatively small (< 20 pA) output currents and a highly specialized setup with the CCC incorporated into the same cryostat as the electron pump.

II. Measurement circuit

Here, we investigated the feasibility of comparing an electron pump current with a reference current using three existing building blocks: a semiconductor tunable-barrier electron pump, a high-turns-ratio CCC mounted in a cryogen-free refrigerator, and a binary Josephson junction array. These three cryogenic components were connected as shown schematically in Fig. 1. The electron pump was driven at a frequency f_P, generating a current $I_1 \approx ef_P$ when tuned to the one-electron plateau, where e is the charge on the electron. I_1 is carried to the CCC along an ≈ 8 m long co-axial cable and passed through N_1 = 45184 turns. An extra series resistance of 17 kΩ was found necessary to suppress SQUID flux jumps. A second current I_2 was generated by a DAC in series with resistance $R_C + R$, carried to the CCC along a ≈ 30 m long screened twisted-pair cable, and passed through N_2 = 2 turns. The current I_2 could be

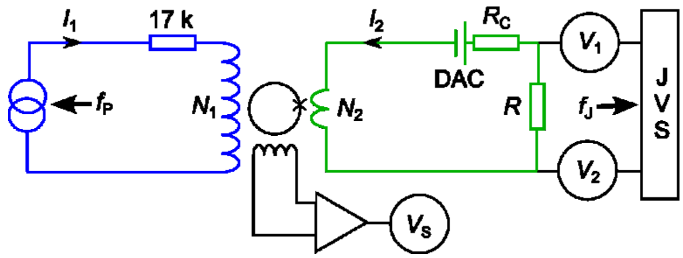

Figure 1 Schematic diagram of the measurement circuit. The electron pump driven at frequency f_P is represented as a current source at the left, and the binary Josephosn voltage standard (JVS) is at the right. Control of the JVS biasing is not shown. R is a 100 kΩ standard resistor calibrated against the quantum Hall resistance, and R_C is an extra current-scaling resistor

measured by comparing the voltage across standard resistor R = 100 kΩ (calibrated with standard uncertainty 0.04 μΩ/Ω) with the voltage developed across a binary Josephson array driven at frequency f_J. The SQUID control electronics produces an output voltage $V_S = k(N_2I_2 - N_1I_1)$, with $k \approx [(0.07\ \mathrm{V}/\Phi_0)\ /\ (6.4\ \mu\mathrm{A\ turns}/\Phi_0)]$ calibrated to 0.1% accuracy using conventional current sources. V_1 and V_2 were measured with 16-bit ADCs, and we define the voltage difference $V_{\mathrm{diff}} = V_1 - V_2$.

III. Experiment and results

As an initial feasibility test, the DAC was turned off (I_2 = 0) and only I_1 was passed through the CCC. An additional pico-

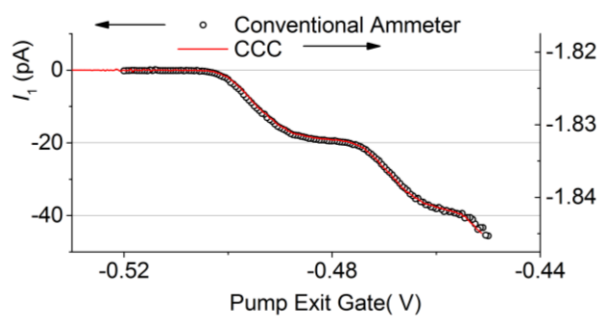

Figure 2 Current measured using a conventional ammeter (points, left axis) and SQUID output voltage (solid line, right axis) as the exit gate voltage of the electron pump is swept. The right axis is scaled using the CCC sensitivity, calibrated to 0.1 % accuracy in a separate experiment.

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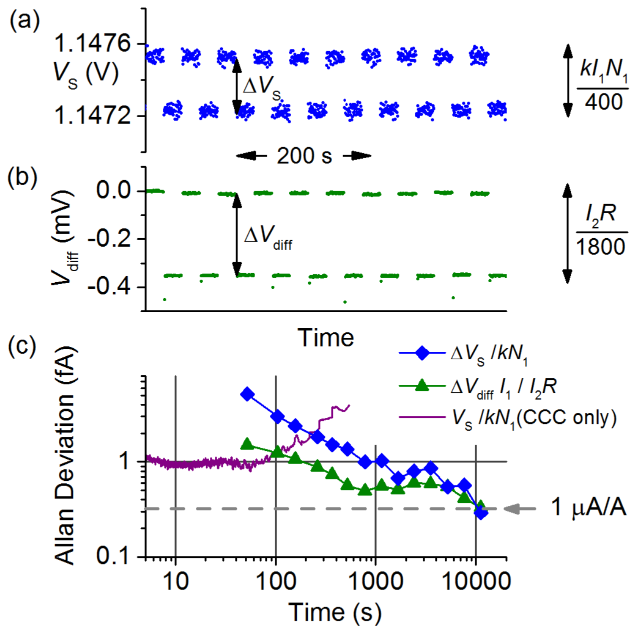

Figure 3 (a): A section of raw SQUID output data from a measurement run of 1200 on-off cycles. 10 cycles are illustrated. (b) raw voltage difference data from the same part of the run. In (a) and (b), a fraction of the full scale signal is illustrated by vertical arrows to the right of the plot. Vertical arrows in the middle of the plot indicate the difference signals ΔV_S and ΔV_{diff} extracted from the data. (c) Allan deviations of ΔV_S and ΔV_{diff} from this run, expressed as current noise in the large winding. The Allan deviation of V_S measured with the stand-alone CCC is also shown (solid line). A horizontal dotted line indicates 1 µA/A type A uncertainty for a pump current of 320 pA.

ammeter (not shown in Fig. 1) was inserted into the circuit to provide an independent measurement of I_1. For this test, an NPL-designed GaAs electron pump was used, with f_P = 125 MHz yielding $ef \approx 20$ pA. The pump was at the relatively high temperature of 4.2 K, and zero magnetic field. As shown in Fig. 2, the CCC output is stable on the time-scale of the measurement and reproduces the conventional measurement.

For subsequent high-resolution measurements, a silicon electron pump [7] at a temperature of 1.3 K was used, driven at $f_P = 2$ GHz. This yields the approximate experimental parameters $I_1 = 320$ pA, $kI_1N_1 = 158$ mV, $I_2 = 7.2$ µA and $I_2R = 0.72$ V. The JVS was set up with 22400 junctions driven at $f_J = 15.592$ GHz. Previous characterization of the pump had shown a tiny slope (0.1 µA/A per mV of exit gate voltage) to the quantized current plateaus at this relatively high frequency, and in the initial measurements reported here we focused just on the stability and noise aspects of the overall setup. The currents were switched on and off with a cycle time of 50 s.

Figures 3 (a),(b) show a section of raw data from a 17-hour experimental run with 1200 on-off cycles. During this run, the SQUID experienced only 11 flux jumps. The Allan deviation of the SQUID difference signal ΔV_S and the voltage difference ΔV_{diff} is shown in Fig. 3(c). The DAC stability affects V_{diff} for times > 1000 s, but for determining I_2 it only needs to be stable on the time for one cycle. The CCC has the largest contribution to the system noise, and a type A standard uncertainty of 0.1 µA/A would be reached after an averaging time of around 11 days. We also measured V_S without any cables connected to the CCC (solid line in Fig. 3c). This shows firstly that to avoid the $1/f$ noise corner of the SQUID, the on-off cycle time should be 10 seconds or less, and secondly there are noise sources external to the CCC (for example, triboelectric currents generated in the connecting cables) which increase the noise by at least a factor 2 when the full circuit is connected.

IV. Conclusion

We have connected a high-current electron pump to a high-turns-ratio CCC, and demonstrated stable operation of the CCC. We demonstrated 1 µA/A resolution of a 320 pA current with a 10^4 s averaging time. Foreseeable improvements will increase the resolution by a factor of 4, and a total uncertainty of <0.1 µA/A can be achieved in a 'metrology triangle' type experiment with a few days averaging time.

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