Towards a programmable quantum current generator

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***Abstract*—We report on the development of a programmable quantum current generator (PQCG) based on quantum voltage and resistance standards. First measurements with a digital amperemeter in the 100 μA range demonstrate the linearity of the generated current as a function of the theoretical current, linked to the electron charge, with a relative uncertainty of 2.7×10^{-7} ($k = 1$). To overcome the detector limits and validate the PQCG as a practical realization of the ampere in the new SI, accurate quantization measurements with a target combined uncertainty of a few parts in 10^8 are in progress.**

***Index Terms*—Current measurement, metrology, quantum standards.**

I. Introduction

The future revision of the SI will have a strong impact on the electrical units. Indeed, by fixing the exact numerical values of the Planck constant h and the elementary charge e, the quantum electrical standards based on the Josephson and the quantum Hall effects will become the practical SI realizations of the volt and the ohm with the best accuracy, assuming the exact relations for the Josephson constant, $K_{\mathrm{J}} = 2e/h$, and the von Klitzing constant, $R_{\mathrm{K}} = h/e^2$, respectively. Another issue will concern the practical realization of the ampere which could be directly related to quantum effects by using single electron devices or by applying directly the Ohm's law to the quantum standards [1]. Single electron devices have driven big research efforts over the last decades [2] and recently there has been a significant improvement of the accuracy of single-electron sources reaching 2 parts in 10^7 at 90 pA [3]. On the other hand, application of the Ohm's law to voltage and resistance standards calibrated in terms of K_{J} and R_{K} is mainly used by National Metrology Institutes (NMIs) for the current tracability chain, however the accuracy claimed in their calibration and measurement capabilities is in practice not better than 1 part in 10^6. The original implementation of the Ohm's law we propose with the programmable quantum current generator (PQCG) allows to directly benefit from the ultimate accuracy of the quantum electrical standards and should lead to an improvement of the current traceability in particular in the range from 1 μA to 10 mA.

II. Description of the experimental set-up

The PQCG shown in Fig.1 consists in an external current source locked to a programmable quantum current standard (PQCS) described in detail in [4]. The PQCS is a closed loop formed by a programmable Josephson voltage standard (PJVS), generating quantized voltage steps $V_{\mathrm{J}} = n_{\mathrm{J}}(h/2e)f_{\mathrm{J}}$

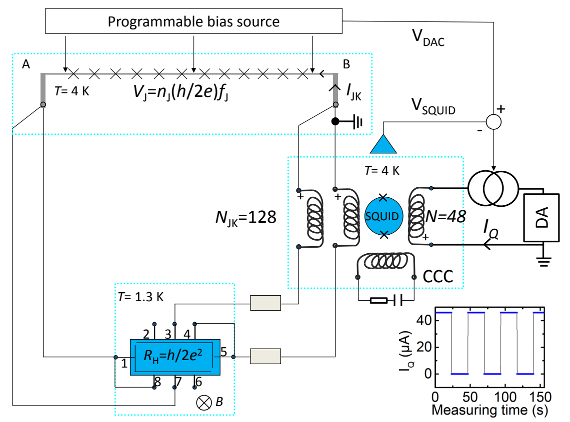

Fig. 1. Schematic of the PQCG. The double connection circuitry has been improved by implementing a triple local connection that reduces further the correction due to the cable resistances. A RC damping circuit was placed on a separate winding of 1600 turns to reduce the effect of the CCC resonance. The digital amperemeter (DA) readings I_Q are shown in the inset, it illustrates a measurement cycle of two ON/OFF/ON sequences used to determine the value of $\overline{I_Q}$. The measuring time in each state (ON or OFF) is 24 s, and the waiting time after the state change is 2s.

(where n_{J} is the number of Josephson junctions and f_{J} is the Josephson microwave frequency) and a quantum Hall resistance standard (QHR) of value $R_{\mathrm{H}} = h/2e^2$. A multiple connection (see Fig.1) is used between the two superconducting pads of the Josephson array to the QHR terminals. It ensures that the current I_{JK} circulating through the PJVS is equal to the ratio $\frac{V_{\mathrm{J}}}{R_{\mathrm{H}}}(1-\varepsilon)$ where ε is a relative correction related to the cable resistances. Here, the latter have been measured and the correction has been calculated to $(1.16 \pm 0.03) \times 10^{-7}$ [4]. I_{JK} can be rewritten as $I_{\mathrm{JK}} = n_{\mathrm{J}} e f_{\mathrm{J}}(1-\varepsilon)$ showing the direct link of the generated current with the electron charge. In order to measure this current which feeds the multiple connection to the QHR, two windings of a cryogenic current comparator (CCC) of equal number of turns $N_{\mathrm{JK}}(=128)$ are inserted on the low potential side of the circuit. A third CCC winding of $N(=48)$ turns is connected to an external current source controlled by the feedback voltage of a DC SQUID coupled to the CCC. This feedback current nulls the ampere-turn value in the CCC. Finally, the current source is locked to I_{JK} and generates a quantized current $I_Q^{theo.}$ theoretically equal to $\frac{N_{\mathrm{JK}}}{N} I_{\mathrm{JK}}$. The PJVS we have used is based on a binary divided 1V SINIS array manufactured at PTB [5] with 8191 Josephson junctions. Each Josephson junction can be biased on the center of the Shapiro steps $n = 0$

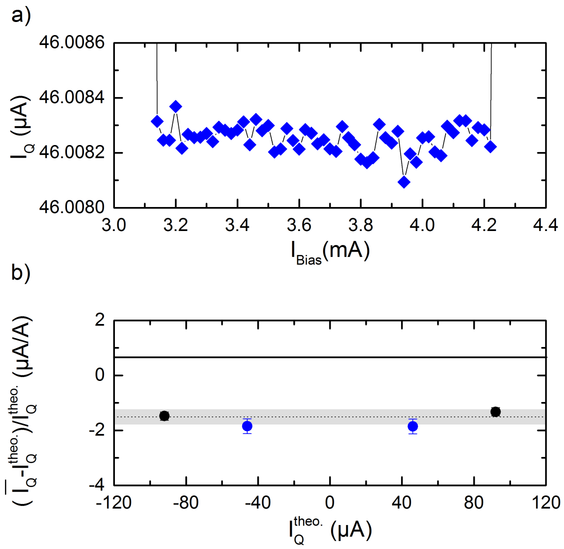

Fig. 2. **a,** Current measured directly at the output of the PQCG with a HP 3458A as a function of I_{Bias} for the segment with $n_{\rm J}$ =1536. **b,** Relative deviation between $\overline{I_Q}$ and $I_Q^{theo.}$ on the 100 μA range. Black and blue dots represent respectively the current generated for $n_{\rm J}$ =3072 and 1536. Error bars show type A standard uncertainties (k = 1). The dashed line at -1.63 μA/A and the shaded area represent the average of the four measurements and the experimental deviation of ± 0.27 μA/A respectively.

or $n = \pm 1$ using a home-made programmable bias source (battery powered and optically decoupled from the computer). The amplitude of these steps are about 1.2 mA and 1 mA respectively at the working frequency $f_J = 70.111$ GHz and the first step is centered at $I_{Bias} = \pm 3.6$mA for all segments. The current $I_{\rm JK}$ has been kept below 40 μA, well within the current margins of the voltage steps. The programmable bias source also commands the home-made external current source such that it nominally cancels the flux in the SQUID caused by $I_{\rm JK}$ in order to lower the demand on the open-loop gain of the SQUID electronics. The array is grounded at cryogenic temperatures to reduce possible errors due to leakage current [4]. The QHR is based on a Hall bar patterned in a GaAs/AlGaAs heterostructure (LEP 514), placed at 1.3 K and 10.8 T. The Hall resistance is quantized to $R_{\rm K}/2$ within one part in 10^9 up to feeding currents of 80 μA. The number of turns ratio of the CCC is known with a relative uncertainty better than 10^{-10}. The current sensitivity of the CCC is equal to 8 $\mu\mathrm{A.turn}/\phi_0$. The CCC is equiped with a SQUID having a white noise level of 3 $\mu\phi_0/\mathrm{Hz}^{1/2}$ and a 1/*f* corner frequency at 0.3 Hz. A digital amperemeter HP3458A (DA) measures the current I_Q generated by the PQCG. The DA was adjusted using a calibrated 10 kΩ resistance standard and a 10 V Zener standard.

III. Results

We test the independence of the current I_Q generated by the PQCG directly as a function of the Josephson bias current I_{Bias}. Fig. 2.a) illustrates this behaviour for the segment $n_{\rm J}$ = 1536 of the PJVS. It shows a wide current plateau, flat within 2.10^{-6} peak to peak, at a value close to 46 μA for I_{Bias} between 3.2 mA and 4.2 mA. This 1 mA wide current plateau reflects the current width of the $n = 1$ Shapiro step at $V_{\rm J} = 0.22$ V. To perform a preliminary test of the PQCG accuracy, we measure $\overline{I_{\rm Q}}$ which results from data averaging from eight measurement sequences, each one consisting in switching ON/OFF/ON for offsets subtraction. Measurements were performed for $n_{\rm J}$ = 1536 and $n_{\rm J}$ = 3072 at $I_{Bias} = \pm 3.6$ mA. Relative deviations of $\overline{I_{\rm Q}}$ to $I_Q^{theo.}$ as a function of $I_Q^{theo.}$ are reported in Fig. 2.b). The four data values are aligned with the average value at -1.63×10^{-6} within the experimental standard deviation of 2.7×10^{-7}. The observed offset between the measured value and the theoretical value is due to the accuracy limitation of the calibration procedure of the DA. Nonetheless, this result shows the excellent linearity of both the PQCG in terms of $V_{\rm J}$ and the DA on this range. The nonlinearities of the PQCG and the DA might cancel by chance, however similar results on the ranges 1 μA and 10 μA tend to rule out such an hypothesis. Here we would like to emphasize that the experimental standard deviation is in agreement with the DA noise figure, but well above the few 10^{-8} estimated from [4] for the present experiment parameters. Therefore a different experiment is required to demonstrate such an accuracy.

IV. Conclusion

A programmable quantum current generator, linked to the electron charge, was successfully implemented. Measurements show that the current generated in the 100 μA range scales linearly with the Josephson voltage within a few parts in 10^7. The accuracy of the present measurements was clearly limited by the digital amperemeter. To go beyond this limit in order to test the predicted accuracy, we propose to compare the voltage drop developed by the current of the PQCG across a resistance standard to the voltage of a second PJVS. Considering the noise of the set-up, we expect demonstrating the accuracy of the PQCG with a relative uncertainty of a few 10^{-8} for currents up to a few mA.

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References

[1] Draft *mise en pratique* for the ampere and other electric units in the International System of Units (SI), Draft 1, CCEM/09-05. [http://www.bipm.org/cc/CCEM/Allowed/26/CCEM-09-05.pdf].

[2] J. P. Pekola, O.-P. Saira, V. F. Maisi, A. Kemppinen, M. Möttönen, Y. A. Pashkin, and D. V. Averin, "Single-electron current sources: Toward a refined definition of the ampere", *Review of Modern Physics*, vol. 85, p. 1421, 2013.

[3] F. Stein, D. Drung, L. Fricke, H. Scherer, F. Hohls, C. Leicht, M. Götz, C. Krause, R. Behr, E. Pesel, K. Pierz, U. Siegner, F. J. Ahlers, and H. W. Schumacher, "Validation of a quantized-current source with 0.2 ppm uncertainty", *Applied Physics Letters*, vol. 107, p. 103501, 2015.

[4] W. Poirier, F. Lafont, S. Djordjevic, F. Schopfer and L. Devoille, "A programmable quantum current standard from the Josephson and the quantum Hall effects", *Journal of Applied Physics*, vol. 115, p. 044509, 2014.

[5] R. Behr, O. Kieler, J. Kohlmann, F. Müller, and L. Palafox, "Development and metrological applications of Josephson arrays at PTB", *Measurement Science and Technology*, vol. 23, p. 124002, 2012.