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Towards a quantum ampere with dual-Shapiro steps in ultrasmall Josephson junctions

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***Abstract*—Microwave-driven ultrasmall Josephson junctions integrated in high-impedance environments exhibit quantized current plateaus, dual of the Shapiro steps observed in conventional Josephson junctions. Dual Shapiro steps were found to agree with the theory in parts in 10^3, and research is now ongoing with the aim of increasing the plateau currents and robustness, favoring the adoption of dual Josephson devices as primary quantum current standards. This work presents the development of an experimental setup optimized to achieve accurate quantum current plateaus. The setup includes a dry dilution refrigerator equipped with properly filtered DC and microwave lines for the minimization of noise and interferences, targeting the traceable characterization of dual Shapiro steps with uncertainties down to the 10^{-6} level.**

***Index Terms*—Josephson effect, Josephson junctions, current measurement, International System of Units**

I. Introduction

Primary voltage standards are based on the inverse AC Josephson effect: a microwave-driven Josephson junction (JJ) produces constant voltage plateaus (Shapiro steps) whose value is determined by the microwave frequency f, the Planck constant h and the elementary charge e. The quantum-mechanical nature of the Josephson effect has long suggested the possibility of achieving under proper conditions quantized current plateaus (dual Shapiro steps), manifesting the so-called AC Coherent Quantum Phase Slip (AC-CQPS) effect.

Recent research has revealed dual Shapiro steps in a device composed of ultrasmall JJs (UJJs) surrounded by much larger JJs. A current plateau at $1.3\,\mathrm{nA}$ and $4\,\mathrm{GHz}$ agreeing with $I = 2ef$ within 1 part in 10^3 was demonstrated [1]. In [2], quantized currents up to $3\,\mathrm{nA}$ were achieved by driving UJJs at $6\,\mathrm{GHz}$. Dual Shapiro steps up to $8.3\,\mathrm{nA}$ were also demonstrated in a superconducting nanowire driven at $26\,\mathrm{GHz}$ [3].

In addition to its fundamental interest in the physics of superconducting systems, AC-CQPS is of considerable practical importance, as it could form the basis of future quantum current standards, thus completing the missing piece needed to realize the fully-coherent quantum metrology triangle [4]. In recent years, several devices capable of generating quantized currents through the controlled transfer of single electrons have been developed. Among the most advanced are single-electron pumps, which achieve currents on the order of $1\,\mathrm{nA}$; however, scaling up this current exploiting a coherent and inherently accurate effect, further remains a challenge, making AC-CQPS devices a promising alternative for developing quantum current standards, as foreseen within the ongoing AQuanTEC European Partnership on Metrology (EPM) project.

II. Quantum Phase Slip in Josephson junctions

Quantum mechanical duality dictates that the phase φ and the charge Q in a JJ are quantum conjugate variables. Because of this incompatibility, suppressing the variance of one of these operators causes an increase in the variance of the other. The balance between φ and Q fluctuations is determined by the ratio of two energy scales, namely the Josephson energy $E_\mathrm{J} = \hbar I_\mathrm{c}/2e$ and the charge energy $E_\mathrm{C} = \hbar e^2/2C$, being I_c the JJ critical current, C its capacitance, and $\hbar$ the reduced Planck constant. A large $E_\mathrm{J}/E_\mathrm{C}$ ratio is required for Josephson voltage standards, where an almost classical behavior of φ is needed. In this regime, the dynamics of a JJ is described by the well-known tilted-washboard potential: by applying a microwave tone, the potential is tilted periodically and a quantum flux $\Phi_0 = h/2e$ is transferred across the JJ at each period, resulting in quantized voltage steps.

Conversely, in the $E_\mathrm{J}/E_\mathrm{C} \lesssim 1$ limit, φ fluctuations increase, allowing Q to become the quasi-classical variable. A microwave drive is then expected to produce the dual of Shapiro steps: here the cyclic slope of a periodic charge potential (the lowest Bloch band [1]) can modulate the transport of Cooper pairs across the JJ, thus resulting in quantized current steps at multiples of $I = 2ef$.

Although an UJJ has an $E_\mathrm{J}/E_\mathrm{C}$ ratio smaller than 1, its behavior is strongly influenced by the surrounding environment, causing Q localization to be hampered by both thermal and quantum fluctuations. To avoid this, the UJJ has to be integrated within a high-impedance environment [5], [6]. In particular, the impedance of the environment must be larger than the quantum resistance $R_Q = h/4e^2$, whereas thermal fluctuations can be suppressed by cooling the environment down to the mK range.

III. Experimental Setup

The overall experimental setup is schematically reported in Fig. 1. The device tested in this work, referred to as a Bloch array hereafter, consists of a superconducting quantum interference device (SQUID) formed by two UJJs surrounded

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by two linear JJ superinductances, realizing the required high-impedance environment with non-dissipative elements and thereby preventing issues associated with self-heating and thermally induced fluctuations. Arranging two UJJs within a SQUID enables the magnetic tuning of the device critical current I_c. The Bloch array consists of Al/AlO_x/Al JJs in a micro-stripline geometry, fabricated by using the shadow evaporation technique and electron beam lithography on a fused silica wafer [1]. The Bloch array is installed within the mixing chamber of a dry dilution refrigerator, with a base temperature of 20 mK.

The dilution refrigerator is configured to enable simultaneous RF and DC measurements. The RF section comprises two input lines (A_1, A_2) and two output lines (B_1, B_2), mutually coupled at the mixing-chamber stage by means of two directional couplers (DC_1, DC_2). The input lines provide a total attenuation of approximately, 55 dB arising from a combination of cryogenic attenuators and coaxial-cable losses, which reduces the thermal noise incident on the device below vacuum fluctuations. Infrared filters (IR_1, IR_2) are also installed along the input lines to suppress residual infrared radiation. On the output side, a pair of two-stage amplification chains, each composed of a high-electron mobility transistor (HEMT) amplifier at the 3 K plate and a room-temperature low-noise amplifier (LNA), is employed together with a pair of triple-stage isolators (IS_1, IS_2) to prevent back-propagation of amplifier noise towards the Bloch array. After DC blocks, the RF input and output lines are connected at room temperature to a vector network analyzer (VNA) with accessible receivers. In this setup, two single-pole six-throw electromechanical switches (SW_1, SW_2) allow traceable calibration of the device scattering matrix by acquiring the response of a set of short-open-line-reciprocal (SOLR) calibration standards connected to their ports [7]. A variable temperature source (VTS) is also available between a pair of ports, allowing to determine the absolute power incident on, and scattered from, the Bloch array. The device can be DC-biased via two bias-tees (BT_1, BT_2). The bias current is generated at room temperature using a voltage-divider network whose lowest-resistance element is thermally anchored to the mixing-chamber stage; the current is RC-filtered prior to entering the cryostat, and further filtered by two π filters (π-F) and a infrared filter (IR_3). The bias current is measured by the voltage across a 500 Ω resistor placed between the pair of π filters.

IV. Conclusion and Outlook

Different measurement schemes and an optimized experimental setup will be exploited to obtain robust dual Shapiro steps in the (1–10) nA range within an UJJs operated at 20 mK in a dry dilution refrigerator. Both flatness and absolute value of the quantized currents will be evaluated, ultimately aiming for agreement with theory at the 10^{-6} level. Further details and complete experimental results will be presented at the conference.

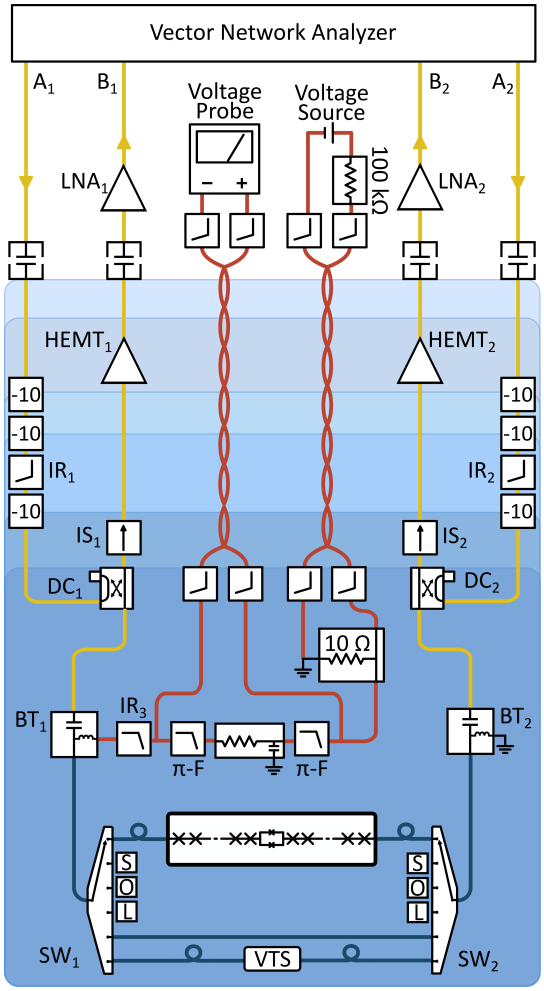


Fig. 1. Schematic representation of the measurement setup. The light-blue box highlights the cryogenic environment and its temperature stages. RF lines are shown in yellow, DC lines in red, and combined RF+DC connections in blue.

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