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Towards a novel programmable Josephson voltage standard for sampled power measurements

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***Abstract* – The paper deals with recent progress at INRiM towards the setting up and preliminary characterization of a novel programmable Josephson voltage standard (PJVS) operating in a small liquid helium dewar. The PJVS setup is based on a 1-V superconductor-normal metal-superconductor (SNS) binary-divided array of 8192 Josephson junctions. To ensure proper operating conditions of the PJVS chip a custom short cryoprobe was designed, built and successfully tested. The overall system is being developed in the framework of EMPIR project 19RPT01-QuantumPower. The goal is to establish a new quantum voltage standard for sampled power measurement and to gain confidence in running quantum voltage standards for precise calibration of digital sampling multimeters and arbitrary waveform digitizers used in the ac-voltage and power metrology community.**

I. INTRODUCTION

In the era of clean energy transition, the electrical power system is assisting a rapid growth of renewable energy sources with unprecedented levels of integration and rapid decarbonisation of the electricity supply. For stable operation of smart grids, precise and traceable electrical power measurements are required to guarantee stable supply, prevent blackouts, identify the origin and causes of the disturbances, and ensure a fair electricity market. National metrological institutes (NMIs) are working closely with network operators to face the electricity system and grid paradigm shift in response to the EU energy transition and clean energy target.

Presently, in most NMIs, the primary electrical power has traceability to the volt and ampere using a long calibration chain, which involves the use of thermal converters, voltage and current transducers and digitizers. Most recent implementations show that, through a complicated calibration chain, it is possible to achieve sampling-based power measurements with a relative uncertainty ranging from 1 µW/VA to 10 µW/VA (coverage factor k=1) at power-line frequency and at any power factor [1]-[3].

More complex experimental setups aim to integrate ac-quantum voltage standards with sampling power standards [4]- [6] to provide more direct traceability routes of active, reactive and apparent power components to the SI-volt with reduced uncertainty.

In particular, in the framework of the EMPIR project 19RPT01 - QuantumPower, a strong collaboration is taking place between several NMIs to deliver the necessary infrastructure for validated quantum-referenced power measurements and its availability to industry. The initiative brings together the experience gained during the last two decades from the involved NMIs in the field of quantum voltage and electrical power. The project aims to design and build an open-access quantum sampling electrical power standard, which will lead to increased confidence in power measurements used for calibration and validation of standard wattmeters, static energy meters, phantom power sources, power analyzers and new emerging equipment for monitoring and identification of electricity-grid stability parameters where the confidence and traceability are crucial. The new quantum power standard will benefit from the use of quantum voltage standard based on programmable Josephson voltage standard (PJVS) which plays a crucial role in the redefinition of the SI-volt unit.

The research activity being developed at the Istituto Nazionale di Ricerca Metrologica (INRiM) in the framework of 19RPT01 project foresees the integration of two main key components into its modular digital sampling power standard (DSPS) [3]: i) an ac-quantum voltage standard; ii) a synchronous coaxial multiplexer. This will allow to shorten as much as possible the traceability chain employed for the calibration of DSPS constituents by ensuring a direct link of sampled power measurements to the SI-volt, and therefore a reduction in the measurement uncertainty.

The present paper focuses on recent progress towards the development of a novel programmable quantum-based voltage standard which will be integrated into the INRiM modular digital sampling power standard [3].

As the development of such a programmable Josephson voltage standard (PJVS) as a whole is new, it was necessary to carefully design and characterize almost all constituents of the experimental setup. With respect to conventional PJVS, our intent was to develop a compact and transportable experimental bench based on a small liquid helium (LHe) dewar and a home-made short cryoprobe equipped with all essentials parts to ensure suitable operating conditions of the PJVS array.

The maximum output voltage of the PJVS array was chosen to be close to the output voltage level of voltage and current transducers in use at the primary power and energy laboratory of INRiM, which never exceeds 800 mVrms applying nominal quantities to the voltage and current transducers inputs.

II. PJVS SYSTEM DETAILS

It is well known that binary-divided Josephson arrays provide quantized voltages according to fundamental Josephson equation for quantum voltage metrology,

$$U(t) = n\, M(t) \frac{h}{2e} f \tag{1}$$

where n denotes the order of the Shapiro step, M represents the number of Josephson junctions in the "active" state, h and e are the Planck constant and elementary charge, and f the microwave frequency. For proper operation of a PJVS device, two additional conditions must be fulfilled: a) cooling down the array to cryogenic temperatures, e.g. around 4.2 K, and b) rapidly biasing different sub-arrays containing different number of junctions.

At present, both low-frequency current bias and microwave radiation are provided by conventional electronics operating at room temperature, so the connection between the cryogenic environment and room-temperature electronics is performed by using purposely-designed cryoprobes. In the following we report details about the main equipment used for running the PJVS array.

A. Consideration on the small LHe dewar

A LHe dewar designed and manufactured by Precision Cryogenic Systems, Inc. has been used in the proposed experimental setup. The dewar was dimensioned to contain 30 l of LHe and its overall height is about 67 cm. The internal vessel is made of aluminum and the lower inner part is similar to a cylindrical glass with diameter of about 7.73 cm and about 20.3 cm high. This is the useful part dedicated to the experiment and it is wrapped out with a cylindrical AD-MU-80 magnetic shield.

First experiments showed that the small dewar performances in terms of boil-off features and normal evaporation rate are compliant to conventional dewars.

Fig. 1 reports the dewar equipment and the top part of the custom home made cryoprobe.

Fig. 1. Photograph of the dewar with the short cryoprobe inserted end equipment to ensure safety operation during its use.

B. Custom short cryoprobe design

Fig. 2 reports a picture of the custom short LHe-cryoprobe properly designed to host the 1 V PJVS array. Its main support is a low conductivity stainless steel tube with diameter of about 28 mm and length of 700 mm. Internally, an oversized circular waveguide with diameter of about 14 mm and length of 80 mm has been installed. The key parameters of the oversized circular waveguide are: low-microwave loss (attenuation 1 - 3 dB/m at 70 - 75 GHz); low thermal conductivity; temperature operating range from 1 K to 400 K; frequency range from 60 GHz to 90 GHz. The waveguide is plugged at the chip carrier mount flange, see Fig. 2c for details, by a thin polyethylene sheet inserted between the WR-12 flanges.

Since the cryoprobe is significantly shorter than cryoprobes for common higher-capacity dewars, particular attention has to be paid to both its design and the choice of the materials employed for its construction for minimizing the thermal load and, hence, to prevent excessive LHe consumption. The outermost stainless steel hollow tube of the cryoprobe acts itself as an RF shielding and, at the lower end, a 1.5 mm thick magnetic shield made of CRYOPERM 10 is mounted. In fact, in the present setup, the Josephson device is completely shielded to reduce as much as possible electromagnetic interferences, as well as the occurrence of magnetic flux trapping within the Josephson junctions.

Additional key features of the cryoprobe include:

i) top sealed cryoprobe to allow sample cooling using a conventional two-step cooling process leaving the sample inserted in the dewar, i.e. pre-cooling with liquid nitrogen (LN) and then cooling with liquid Helium (LHe) after removing all the LN;

ii) helium gas escapes from the dewar through a plumbing system of ball valve and pressure release valve located on the top of the LHe dewar.

The pressure inside the dewar is kept constant by using either the pressure-released valve or a flow impedance realized with a small diameter hose using gas hose couplings (quick connectors). As a result, variations of thermal electromotive forces (EMFs) and junctions temperature-dependent electrical parameters during operation are largely damped.

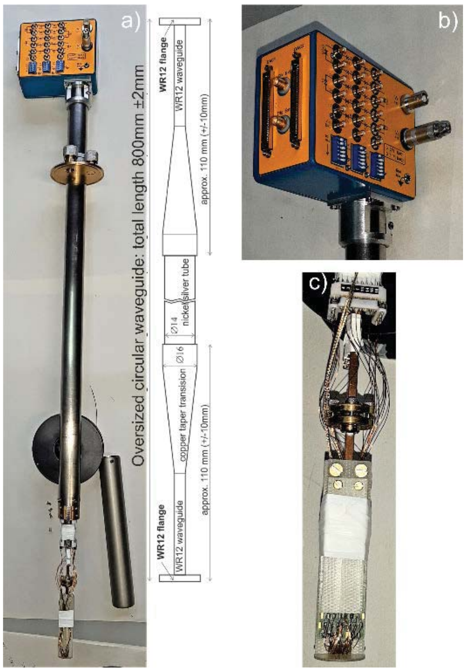

Fig. 2. Home-made short cryoprobe designed for hosting the PJVS chip: a) photograph of the short cryoprobe and cryoperm shield; b) head box with connectors; c) chip carrier with installed PJVS array plugged with WR-12 flange to the oversized waveguide.

C. SNS programmable Josephson array

The PJVS chip is a binary-divided array containing 8192 Josephson junctions fabricated by Supracon[1]. The N-material is an amorphous Nb_xSi_{1-x} alloy near the metal-insulator transitions tuned for operation at about 70 GHz. The array presents quite similar features to those fabricated in the framework of NIST-PTB collaboration [7]. Its main parameters can be summarized as follow:

- $V_C = I_C R_N \approx 160\ \mu V$, with V_C the characteristic voltage, I_C the critical current and R_N the normal resistance, which corresponds to a characteristic frequency of about $f_C = 77$ GHz;
- Critical current $I_C \approx 4.9$ mA at 4.2 K; 0th order Shapiro step width ≤ 4.3 mA; 1st order Shapiro steps width and center for all-subsections ≤ 3.6 mA and ≤ 5 mA, respectively.

The array contains 14 sub-sections of series-connected Josephson junctions, each of which can be independently current-driven to a given quantum step, usually zero and first order. Starting from the low-voltage terminal, the number of junctions in the sub-arrays follows the sequence 32, 16, 8, 4, 2, 1, 1, 64, 128, 256, 512, 1024, 2048, 4096. Two separate single-junction sub-arrays are necessary to perform a highly accurate quantization test and to determine the PJVS quantum operating margins. To this aim, half array (4096 junctions) is current-biased to the $n = +1$ Shapiro step, whereas the second half is biased to the $n = -1$ step. The PJVS output voltage is then exactly zero and is measured with a nanovoltmeter, working as a null-detector.

D. Wiring and connectors

Wiring of the PJVS chip to room temperature electronic instruments requires some precautions to avoid as much as possible phenomena due to flux trapping, electromagnetic interference and electrical noise propagation to the measurement setup. The cryoprobe has been equipped with suitable cryogenic wires as follows:

- 12 twisted-pairs of beryllium-copper (BeCu) wires of 100 μm diameter and 10 Ω/m resistance (independent of temperature) are used for biasing of PJVS sub-sections. Relying on theoretical assumptions, the thermal load of such a twisted-pair cable compared to conventional twisted-pair Cu cable leads to a LHe vaporization rate reduction by a factor of 10.
- The PJVS device is suitably installed on a chip-carrier and bonded on finished gold PCB pads with aluminum wires. 14 pads are used to provide connection of the single sub-sections to the biasing electronics. High (V_H) and low (V_L) voltage Josephson array terminals are bonded on two separate PCB pads. Two ultra-miniature coaxial cryogenic cables with inner conductor of stranded copper isolated in Teflon from its outer conductor, made of braided gold-plated copper, were used to transfer the Josephson quantized voltage from 4.2 K to the room temperature environment. In the first configuration, each coaxial cable has been directly soldered to the PCB pads dedicated to the Josephson voltage. However, it is possible to redefine the connections using the inner conductor of both coaxial cables to bring out the Josephson voltage, which seems the most promising configuration to ensure greater immunity from EMI interferences and phenomena related to the generation

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[1] Brand names are used for identification purposes and such use implies neither endorsement by INRiM nor assurance that the equipment is the best available in the market.

of thermal electromotive forces between the wires and the PCB pads.

- The cryoprobe head is fixed to the main stainless steel tube with a removable sealing mechanism and, in order to avoid the escape of cold helium vapors, its upper side is sealed with a bicomponent epoxy resin. It is equipped with both 16 coaxial SMB connectors and two 68 pin I/O connectors for quick connection to the biasing electronics. A triaxial LEMO connector was used to bring out the Josephson voltage output. Its fixing ensures a good electrically and thermally decoupling from the cryoprobe head, thus avoiding unwanted thermal gradients, which could give rise to thermal electromotive forces.

III. EXPERIMENTAL SETUP FOR ARRAY CHARACTERIZATION

A photograph of the overall experimental setup employed for testing the PJVS array is shown in Fig. 3. It is composed as follows.

Fig. 3. Photograph of the experimental setup for PJVS array characterization.

A. I-V fast monitoring setup

The current-voltage (*I-V*) characteristics of the single sections of the PJVS array, with and without microwave radiation, have been recorded using a fast-tracking fully digital system. The tracking system was used for the first time in the work reported in [8]. Both high-speed digitizers or precision sampling digital multimeters, such as DMM-3458A, can be used for the recording of voltage and current signals.

B. RF-microwave generation and measuring system

During the first experiment run, the array was irradiated using alternatively two Gunn oscillators, capable of covering a frequency range from 70 GHz to about 73 GHz. The microwave power at the input flange of the circular waveguide was about 30 mW, which seems to be a promising value to ensure almost equal width of zero and first order Shapiro steps. Unfortunately, for an unexpected malfunction of the RF frequency counter sensor it was not possible to lock and stabilize the Gunn frequency to the distributed 10 MHz clock reference coming from INRiM atomic clock. Further investigations using non conventional equipment are in progress and details will be matter of future discussions.

IV. RESULTS AND DISCUSSIONS

First characterization of the system and PJVS array concerned the determination of *I-V* characteristics with and without microwave radiation. The *I-V* characteristic of the full array under no microwave radiation is reported in Fig. 5, where it is clearly observed that I_C at 4.2 K spans from – 4.9 mA to +4.9 mA.

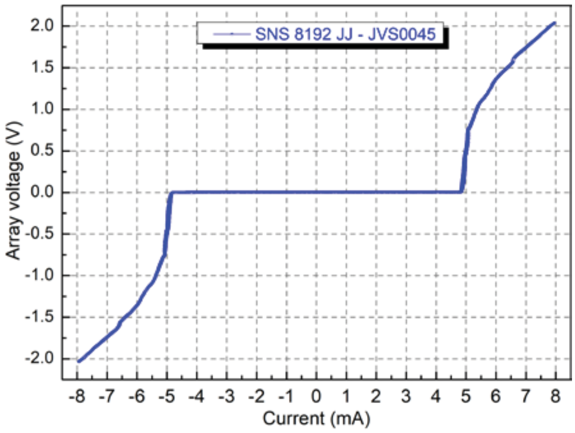

Fig. 4. I-V characteristic for the determination of 1-V PJVS array critical current in in LHe.

The second series of tests were focused on the determination of current-width and flatness of the quantized voltages across each PJVS sub-array. The array has been irradiated from 70 GHz to about 73 GHz.

Fig. 5 reports only the results obtained at 72 GHz.

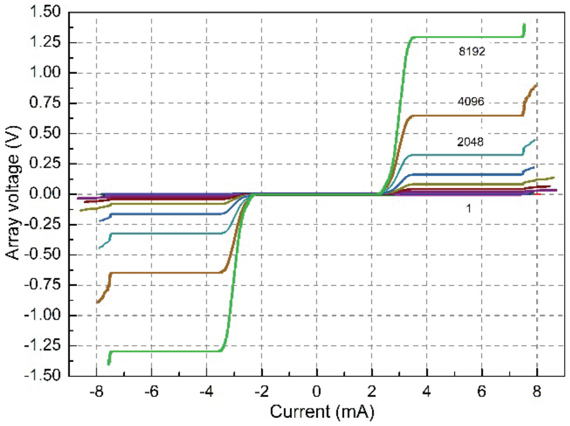

Fig. 5. I-V characteristic of PJVS sub-sections under microwave radiation at about 72 GHz.

As shown, quantized voltage corresponding to $n = -1, 0, +1$ Shapiro steps are clearly visible for all the PJVS subsections. The RF power has been trimmed for ensuring almost similar operational current margins for each section. The operational current margins for Shapiro steps -1, 0 and 1 result to be within 3 mA, which are large enough to simplify proper operations of the array for future experiments on the synthesis of sinusoidal staircase waveforms as required for EMPIR project 19RPT01-QuantumPower

Fig. 6 reports a high-resolution plot as a demonstration of the flatness of n=+1 Shapiro steps.

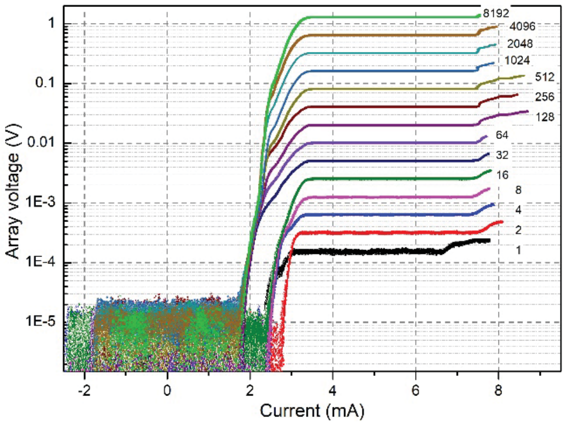

Fig. 6. I-V characteristic of PJVS sub-sections at 72 GHz; logarithmic voltage scale.

The excess of noise observed is due to the fast I-V tracking setup. During the first experiment run, we observed a significant thermal EMF (about 50 µV) superimposed to the Josephson voltage output wired with the cryogenic coaxial cable. Instead, the thermal offset across the BeCu twisted-pair was lower than 1 µV. Further tests have been carried out with a short piece of the same coaxial cable, short-circuited at one end, mounting the same end on the 4 K stage of a pulse-tube cryocooler. The experiment confirmed that large thermal EMF appears, probability due to the different material composition and Seebeck coefficient between center conductor and shield of the coaxial cable.

A. Step flatness quantization test

For demonstrating that the programmable Josephson voltage standard is working properly we perform the so called quantization test.

The test consists of individually biasing the overall binary sub-sections of the PJVS chips under microwave radiation at the first Shapiro step, so that the overall voltage generated by the array is zero. Several biasing sequences were generated and loaded to the biasing electronics. Each sequence corresponds to a well-defined current biasing value chosen in according to the operating margins observed for all subsections as shown in Fig. 6. The biasing current ranging from 4.4 mA to 6.4 mA. The output array was recorded with a digital nanovoltmeter.

The results are reported in Fig. 7. The nanovoltmeter readings at the specific bias current have been corrected by the value of the thermal EMF. It is worth mentioning that after further improvements of the cryoprobe wiring the residual thermal EFM measured at the PJVS output is now reduced by a factor of more than 300 and recent experiments confirm a value of about 153±6 nV.

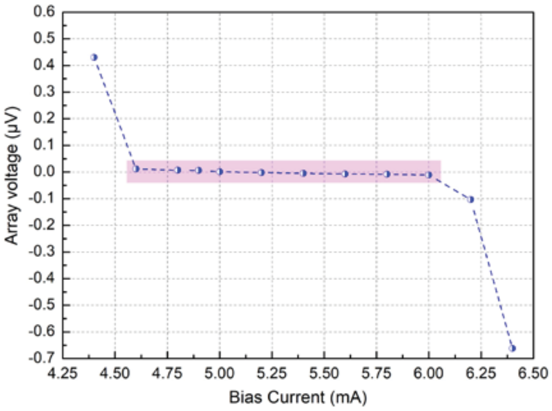

Fig. 7. Step flatness quantization test of the 1-V PJVS SNS chip irradiated at 73 GHz.

B. Synthesis of quantum staircase sine waves

A second round of testing has been conducted in order to validate the experimental setup as a whole, for the direct synthesis of quantum staircase sine waves.

Fig. 8 shows four different sine waves composed of 10 steps at a frequency of about 53 Hz, which differ manly by the bias current used to switch on/off the PJVS sections.

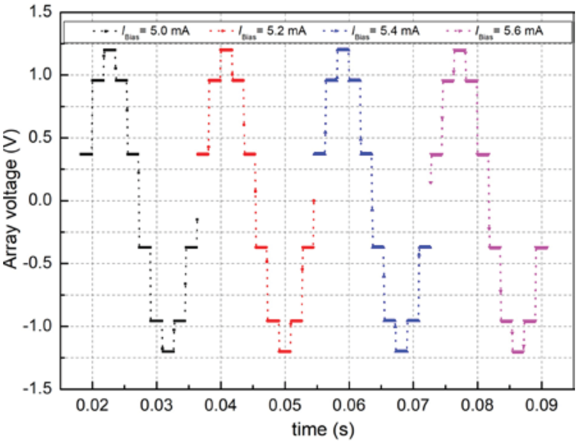

Fig. 8. Staircase sine waves synthesized at different

Comparing the various voltage steps sampled by means of a high precision sampling digital multimeters, e.g. Keysight 3458A, at 10 kS/s and aperture time 90 µS, we found that the relative voltage difference between the quantized voltage steps at different biasing currents are lower than 1 μV/V.

The results obtained confirm once again that the PJVS system is really working and it will be used by INRiM within the 19RPT01 QuantumPower project in the experimental setup of the quantum power sampling standard.

V. CONCLUSION AND FUTURE WORK

We demonstrated the fully operation of a new setup recently employed at INRiM for the generation of quantized voltage steps using a 1-V programmable Josephson array. All the segments of the binary-divided array have been successfully tested without and with microwave radiation at frequencies ranging from 70 GHz to about 73 GHz using a home-made short cryoprobe designed for working in a small liquid helium dewar.

Next experiments will be focused more in detail on the metrological application of the PJVS setup and its full validation against the maintained national dc voltage standard at 1.018 V. A first comparison shown an agreement with 0.4 ppm.

Further extensions of the presented PJVS for the synthesis of staircase approximated waveforms within the 19RPT01-QuantumPower project are planned and the most relevant achievement will be matter of discussion during the conference.

ACKNOWLODGMENTS

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