

Superconductivity in primary voltage metrology at INRiM

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Abstract – Primary electrical Metrology is among the first and, to date, one of the most active and successful research field for superconducting devices. Voltage standards based on the Josephson effect are in use since few years after its discovery and have enormously reduced the uncertainty of DC voltage calibrations. INRiM the Italian National Metrology Institute has a long tradition in research on the application of superconductivity to electrical standards. This paper is an overview of main results and ongoing activities.

I. INTRODUCTION

Electrical Metrology is one of the first and most successful area of application of superconductivity. Josephson arrays for DC voltage standards, with many thousands of tightly equal junctions, are, to date, among the most relevant achievements of superconductive electronics. Josephson voltage standards hold a peculiar position within superconducting devices, as they are used for high precision voltage Metrology since the early years after the phenomenon was predicted as a consequence of superconductive tunneling.

The extreme accuracy of a Josephson standard follows directly from its physical properties, discovered theoretically in 1962 by B.D Josephson. Indeed, in the paper where the theory of the now eponymic effect was first presented, Josephson doesn't only predict the phenomenon, but describes how it can be used to relate, in some conditions, the constant voltage across a junction with the frequency of the alternate bias current flowing through it. Rather impressively, this is a very concise recipe for a new quantum standard!

For voltage Metrology, the Josephson junction is essentially described by the equation expressing the relationship between frequency and junction voltage:

$$V = \frac{h}{2e} n f$$

where n is an integer, e is the electron charge and h Planck constant. It should be noticed that voltage and frequency are related in the formula by a direct proportionality. Since the coefficient is given in terms of *two fundamental constants* its value is universal. In other words, the Josephson

junction is an ideal frequency-to-voltage converter¹.

As a matter of fact, frequency has the privilege of being the quantity whose standard has the highest accuracy (10^{-13} in the current INRiM official list of capabilities): the advantage of Josephson effect then is to allow an "exact conversion" of voltage into frequency, thus reducing uncertainty by several orders of magnitude.

After Josephson seminal paper and early experiments with single junctions, a great effort was spent in research and development to obtain the practical devices in use today, that allow Josephson standards to reach sub part-per-billion uncertainties. Technical and physical reasons limit the operating frequency of junctions, thus the voltage. Microwave bias frequencies around 70 GHz are typically used, giving junction voltages about $150 \mu\text{V}$. Noise and thermal electromotive forces significantly affect measurements at such low levels.

To achieve the output voltage required for a practical quantum standard, hysteretic Superconductor-Insulator-Superconductor (SIS) technology was successfully adopted, following an idea by Levinsen [1], to fabricate arrays with tens of thousands of highly uniform junctions and output up to 10 V. Primary DC voltage calibrations at 10 V now attain relative uncertainties as low as 10^{-11} .

More recently, voltage standard research has focused on the application of Josephson arrays to AC (programmable devices) [2] and arbitrary signals (pulsed devices) [3]. Programmable Josephson arrays using bias currents to activate/deactivate array sections are, so far, the most successful solution. They are subdivided in sub-circuits with series-connected junctions to generate voltages following a power of two sequence, thus controlling the output voltage as in digital to analog converters semiconductor electronics. This is not the case for SIS junctions used in DC standards, where steps are overlapping.

¹The uncertainty contribution from the values of the fundamental constants in the formula would dramatically increase the total uncertainty balance of the standard. To override this problem, in the current practice the coefficient value is *a priori* defined. This practical approach raises subtle questions, that are beyond the scope of this work.



Fig. 1. The INRiM Josephson DC voltage standard.

II. SUPERCONDUCTIVITY FOR PRIMARY METROLOGY AT INRIM

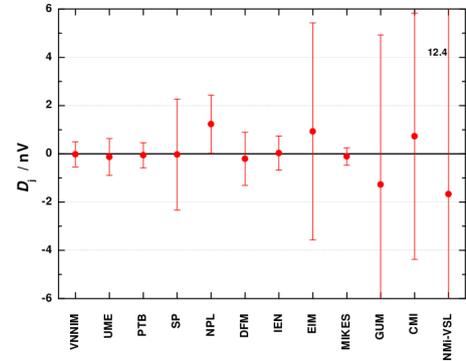
Josephson standards are in use at INRiM (Fig. 1), where they have been studied for several decades, starting from first single junction devices.

The DC national voltage standard is currently maintained and reproduced at 10 V level by means of a Josephson array to calibrate a bank of zener references. In the measurement, the RF frequency is trimmed to obtain an array voltage very close to that of the standard under calibration, then the residual voltage difference is observed over a defined time interval. In every measurement a set of four readings is taken, to reverse position of both the reference under calibration and the detector in order to cancel out any effect of offsets, drifts and thermal e.m.f.s from the results.

International comparisons that guarantee worldwide compatibility can now be performed with Josephson arrays as transfer standards, thus avoiding the strong limitations of electronic references. Such a comparison can verify the capabilities of a Josephson standard, at the highest accuracy level. INRiM participated in the last comparison coordinated by the European metrological association EuraMet, where the consistency of the results was demonstrated at 1.018 V within parts in 10^{10} (Fig. 2).

Primary Metrology cannot be limited to the maintenance of the unit, since calibrations at the highest accuracy are required over a wide interval of values. Voltage calibrations traceable to the primary standard are conducted at INRiM over ranges spanning from millivolt to kilovolt. Again, a Josephson array is used to calibrate voltage ratios and maintain the voltage scale. A set of DVMs (Digital-Volt-Meters) is directly connected to the array whose voltage is varied to span the whole DVM range. A linear fit of the readings vs. the exactly calculable array voltage is then performed. Finally the differences between the actual read-

MEASURAND : DC voltage, Josephson standards
 NOMINAL VALUE : 1.018 V
 Degree of equivalence D_i and expanded uncertainty $U_i (k=2)$



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Fig. 2. Results of Euramet international comparison with a Josephson array transportable standard.

ings and the value given by the fit line, represent the voltmeter nonlinearities. The uncertainty of the nonlinearity profile of DVM after correction is of the order of $0.1 \mu\text{V}$. Two DVMs, with nonlinearities corrected using this technique, can be used to maintain a voltage ratio standard, that allows self-consistency checks [4].

III. CURRENT TRENDS AND ACTIVITIES

A. Toward a helium-free standard

Cryogen-free operation of superconducting devices is crucial for accessibility [5] and bears a special interest for Josephson standards, owing to the potential impact of a new breed of voltmeters with integrated quantum accuracy. The interest of the metrological community in witnessed by the ongoing Euramet project JRP-SIB59, which includes among its tasks the study of a cryocooled standard as for a more user-friendly operation and, even more important, the advantages in reducing uncertainties in the AC Josephson standard. One of the main problems in extending to AC the application of Josephson arrays is due to the need operate open, unterminated, lines. Reducing their length, is then the only way to keep this contribution at a minimum. Cryocooled systems, fitted with shorter cables are currently regarded as the most promising choice.

Reliable cryocooler operation necessitates specific thermal design to cope with problems that are not to be faced with liquid coolants, like minimization of thermal gradients to allow uniform operation of the chip and reduced cooling power. INRiM researchers are contributing to the project with the development of a cryocooler apparatus to study the properties of programmable arrays for AC signals and pulsed standards for arbitrary waveforms (Fig. 3).

Cryocoolers for superconductors operating at liquid helium temperature are, at present, expensive, weighty and



Fig. 3. Test of a cryocooler-refrigerated Josephson array for pulsed bias [6] fabricated at PTB (Euromet project SIB-59): IV curve of the whole array with 4000 junctions.

far from integration inside an instrument case. On the other side, large arrays fabricated with higher critical temperature superconductors, like YBCO or the more recent MgB_2 [7], would allow a significant reduction of cryocooler complexity and costs. Promising results have been achieved using YBCO bi-crystal shunted junctions, with quantized steps above 100 mV measured near 77 K [8]. A relevant issue is thus the operation above 4.2 K of junctions based on low temperature superconductors.

The SNIS (Superconductor-Normal metal-Insulator-Superconductor) junction technology, based on low temperature superconductors but capable of operation above liquid helium temperature, is interesting for application to a cryocooled standard, allowing to set a compromise between device and refrigerator requirements. Furthermore the temperature stability needs of the cryocooler can be relaxed if temperature variations effects on junction behaviour are reduced as in SNIS junctions. This is of interest in applications where a simplified refrigerator is useful such as RSFQ and voltage standards [9].

B. SNIS junctions programmable arrays for cryocooler operation

$\text{Nb}/\text{Al}/\text{AlO}_x/\text{Nb}$ SNIS junctions exhibit some specific properties: the damping in the IV characteristic and the wide range values that can be obtained for critical current density and characteristic voltage through a suitable control of some fabrication parameters [10]. Furthermore, a peculiar feature of SNIS is the temperature stability of its electrical parameters [11], as shown by the comparatively low values in the theoretical calculations of the temperature derivative of $I_c(V_c)$ vs. T . It is in fact possible to minimize this derivative as function of a parameter $\gamma_{eff} = \gamma_{S/N} d_{Al} / \xi_{Al}$ where $\gamma_{S/N} = R_{Nb/Al} / \rho_{Al} \xi_{Al}^*$ with $R_{Nb/Al}$ the product of the interface resistance and its area, and $\xi_{Al}^* = \xi_{Al}(T_c Al / T_c Nb)^{1/2}$.

In particular, we measured in the experiments series arrays devices with segments from 1 to 8192 junctions for

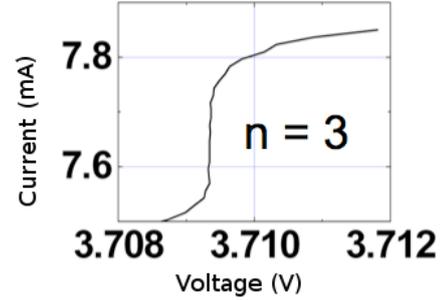


Fig. 4. Third step observed with a SNIS array in liquid helium.

programmable voltage standards [12], fabricated in cooperation with the Physikalisch Technische Bundesanstalt (PTB). The arrays were first tested in liquid helium, and steps up to third order were observable. This behavior is clearly explained by the high critical voltage of the junctions at 4.2 K (Fig. 4). In experiments performed subsequently at temperatures ranging from 3.5 to 6 K, we measured critical current densities from 5 to 20 kA cm^{-2} and V_c from 250 to 500 μV . These parameters were obtained using a thickness of aluminum from 80 to 100 nm, while Nb electrodes were 200 nm. Correspondingly the parameter γ_{eff} varied between 10 and 20.

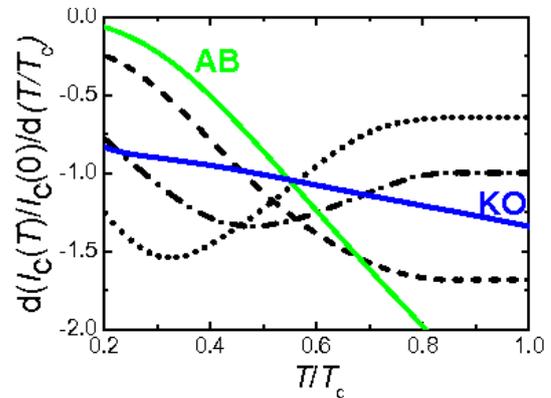


Fig. 5. Temperature derivative of the critical current for SNIS junctions with different values of the aluminum normal layer, compared with typical curves for SIS and SNS Josephson junctions.

From figure 5, we see that this corresponds to a temperature derivative of I_c normalized to $I_c(0)$ from the optimal condition of 0.5, for $T/T_c > 0.7$ for $\gamma_{eff} = 20$, which however becomes about 1.15 at 4.2 K and 1.5 at 3.5 K. On the other hand an almost constant value of 0.75 of the derivative for $\gamma_{eff}=10$, in the experimental temperature range from 4.2 to 7 K is possible. The different conditions outlined represent also different values of characteristic voltage, since there is a univocal relationship linking

the γ_{eff} to this parameter.

First cryocooler experiments have been carried on with both single junction and array devices, checking for the effect of DC current and microwave bias while increasing the number of junctions. The estimated dissipated power ranged between fraction of mW (single junction, step $n=1$, up to 15 mW, 8192 junctions step $n=2$). Quantized steps were observed in segments with a low number of junctions up to temperatures well above 4.2 K. The step width decreased while increasing the number of junctions connected, as expected, from more than 1 mA for $n = 2$, to 0.1 mA for the 1.25 V section [13].

At present we explain this behavior as a combined consequence of a localized temperature raise, due to an insufficient heat exchange between the chip and the cold finger, along with a limited strength of electromagnetic shielding, as shown by the flux-trapping observed more and more frequently with the number of junctions in the section, and last but not least of some degree of nonuniformity of the critical current and microwave field distribution along the array. In next experiments we are going to improve all these factors, allowing the better use of the devices on all the sections at temperature above 4.2 K.

IV. CONCLUSIONS

The activities at INRiM for applications of superconductivity to primary voltage Metrology have been summarized, considering both institutional and research areas. Results obtained in the maintenance of the voltage unit and voltage scale were presented, showing the impressive contribution obtained with arrays in use today, after more than twenty years of development to solve many technical challenges. Particular attention was given to a new junction technology developed at INRiM that has proved very interesting for new AC voltage standards that can be operated in cryocooler, with advantages in terms of both accuracy and ease of use.

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