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# Present and Future of High-Temperature Superconductor Quantum-based Voltage Standards

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## Abstract

This paper presents a brief overview of the current state-of-the-art of Josephson junctions for Quantum-based Voltage Standards fabricated with High-Temperature Superconductors (HTS). A short introduction on the history and technical evolution of Low Temperature Superconductors (LTS) technology is provided for non-specialists. Then HTS technology is summarized and discussed in the context of quantum voltage standard applications. Finally, the two most promising technologies: bicrystal and Focused Helium-Ion Beam junctions are discussed with more detail, analyzing strength, limitations and perspectives in both cases.

## Introduction

The application of quantum effects to electrical metrology in the last decades has brought an extraordinary improvement in the accuracy of primary standards. As an example, the volt, the unit of electromotive force, can be nowadays reproduced with an accuracy better than one part per billion. This is a breakthrough change in the primary metrology of electrical units following the possibility of directly linking, through quantum phenomena, the value of the following standards to the fundamental constants of physics: Josephson effect for the volt and quantum Hall effect for the unit of resistance, the ohm. At the same time, the latest achievements in science and industry radically changed the instrumentation technology. In modern production, high-precision digital measuring systems are being used everywhere. Due to these factors, the requirements to the accuracy of the calibration equipment have increased. Thus, it becomes very important to create standards and references of physical quantities on the basis of quantum effects for the practical metrology too.

The basis for using the Josephson effect [1] in quantum metrology is the fact that under the influence of an external electromagnetic field with a frequency  $f$  on the current-voltage characteristic (IVC) of the junction, current steps occur at voltages

$$V_n = nf / K_J, \quad (1)$$

where  $K_J \equiv 2e / h$  is known as Josephson constant and since the revision of SI system of units in 2019 has value of  $483\,597.848\,4 \text{ GHz} / \text{V}$  [ii],  $h$  is the Planck constant,  $e$  is the elementary charge and  $n$  is the integer.

The validity of relation (1), its independence from the experimental conditions (materials, temperature, type of Josephson contacts) and, therefore, its fundamental nature is a principal condition for the use of Josephson junctions (JJ) in metrology. In the most accurate experiments [iii], it was shown that  $KJ$  in various low temperature superconductors (LTS) at the liquid helium temperature  $T = 4.2 \text{ K}$  coincides with relative uncertainty better than  $3 \times 10^{-19}$ . Thus, the dc voltage  $V_J$  is determined only by quantum constants and the irradiation frequency. Currently, other physical effects that could compete with the Josephson effect in quantum metrology in the accuracy of reproducing a voltage unit are not known.

Large arrays of tens of thousands synchronized LTS Josephson junctions with output voltages up to  $U_{JLTS} = 10 \text{ V}$  are used in different types of dc and ac voltage standards. Readers interested in the detailed operation of such systems are referred to the review the state of the art performance, best practices, and current impact of these standards on voltage metrology<sup>iv</sup>.

The discovery in 1986 [v] of high-temperature superconductors (HTS) and the subsequent discovery [vi] of superconductivity in yttrium-barium ceramics  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  (YBCO) at temperatures above the boiling point of liquid nitrogen (77 K) initiated work on the creation of Josephson contacts from these materials [vii]. HTS Josephson contacts are of considerable interest for use in quantum voltage metrology due to their higher operating temperature. The state-of-the-art HTS technology junction circuits allows the fabrication of the arrays containing hundreds JJs with an output quantum voltage up to  $0.1 \text{ V}$  [viii]. About nanojunctions

Here we present a quick overview of the current state-of-the-art of Josephson junctions for Quantum-based Voltage Standards fabricated with HTS. A short introduction on the history and technical evolution of LTD technology is provided to ease reading of non specialists, then HTS technology is summarized and discussed in quantum voltage standard applications. Finally, the two most promising technologies: bycrystal and Focused Helium-Ion Beam junctions are discussed with more detail, analyzing strength, limitations and perspectives in both cases.

## **Low-temperature superconductor Josephson junctions and their application in quantum-based voltage standards**

Josephson Voltage Standards based on LTS JJs have evolved sufficiently from the initial development in the early 70s. The first standards were based on a single junction, or a short number of junctions individually biased. These systems could generate voltages of 10 mV at most, and required specifically designed resistive dividers to compare with the best voltage standards at that time, the Weston cells.

The quantized voltage (1) arising on one Josephson junction is usually smaller than 150  $\mu\text{V}$ . To increase the output voltage, JJs are connected in series and a common bias current is passed through them. The parameters of the contacts and the conditions of their operation are adjusted so that the voltage (1) arises on each junction, and the total voltage is equal to

$$U = NV_J, \quad (2)$$

where  $N$  is the number of JJs. Relation (2) imposes strict uniformity restrictions on the spread of normal resistances  $R_n$  and critical currents  $I_c$  of JJs as well as high requirements for the uniformity of their irradiation with an external signal with a frequency  $f$ . At the same time characteristic voltage of the junctions  $f_c = K_J I_c R_n$  should be adjusted basing on  $f$ ,  $I_c$  and  $R_n$ .

State of the art technologies of LTS JJs, as well as advances in design of microwave and millimeter wave integrated circuits for applications in the voltage standards, have allowed to develop the conventional Josephson voltage standard (CJVS), programmable Josephson voltage standard (PJVS) and the Josephson arbitrary waveform synthesizer (JAWS), also known as the ac Josephson voltage standard (ACJVS), which differ both in the type of LTS Josephson junctions used and in the way they are synchronized with external microwave signal. Below we will briefly discuss various voltage standards built on integrated superconductor circuits from LTS Josephson junctions.

### ***dc Josephson voltage standard***

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The first practical voltage standards were based on the arrays of superconductor – isolator – superconductor (SIS) junctions with hysteretic IVC. A major progress in increasing the number of synchronized junctions connected in series was obtained after the idea of exploiting the so called “zero crossing steps” [ ]<sup>ix</sup>, i.e. voltage steps whose value is quantized over a range of currents that covers positive and negative values, including the condition of zero direct current (dc) bias. These zero-current-crossing voltage-steps allowed the junction uniformity problem to be circumvented by biasing the array at, or near, zero dc current.

The elaboration of the technology of the Superconductor-Isolator-Superconductor (SIS) Josephson junctions Nb / Al-AlO<sub>x</sub> / Nb [ ]<sup>x</sup> with hysteretic IVC in 1982, as well as the proposed [ ]<sup>xi</sup> integration of arrays of such junctions in a microstrip line with a fin-line antenna, provided synchronization of a large number series connected JJs by electromagnetic radiation of the millimeter wave range. As a result, the first large scale superconducting integrated circuits with  $N = 14000$  SIS niobium junctions, each working on  $n \approx 5$  step were developed. Such circuits are used in dc conventional Josephson voltage standards with output voltages up to  $U = 10$  V with step current margins about  $\Delta I \cong 20$   $\mu$ A and combined relative uncertainties  $(1-5) \times 10^{-9}$ . DC voltage standards are commercially available [ ]<sup>xii</sup>.

At present, the quantum LTS dc voltage standards are widely used in National Metrology Institutes (NMIs) to reproduce dc volt, to calibrate directly the new solid state voltage standards (Zeners) at 1 V and 10 V and precision digital voltmeters as well as they replaced the former “artifact” primary standards based on Weston cells [ ]<sup>xiii</sup>, [ ]<sup>xiv</sup>. They formed the base of the Recommendation 1 (CI-88) which established the new representation of the volt based on the Josephson effect and, joint to the development of the quantum Hall resistance standards, began the process to the redefinition of the SI ampere [ ]<sup>xv</sup>.

### ***ac Josephson voltage standards***

Despite the world recognition of the dc voltage standards based on SIS junctions with precisely quantized zero crossing steps they suffer serious limitations. Several steps with different number  $N$  are possible for a given level of a small bias current and microwave

excitation. Consequently, spontaneous jumps between steps due to the system noise can occur, resulting in the instability of the output voltage. At the same time it was impossible to quickly provide the setting of the Josephson output voltage which was highly desirable for the calibration, for example, of digital-to-analog and analog-to-digital converters.

A big effort has been made in the last decades to overcome these limitations, with the development of new arrays where it was possible to control the junctions voltage by means of bias signals, making them capable of generating ac voltage, with two widely different approaches: programmable Josephson voltage standard (PJVS)<sup>xvi</sup> and ac Josephson voltage standard (ACJVS)<sup>xvii</sup>. The new arrays consist of thousands of Superconductor – Normal Layer – Superconductor (SNS) junctions or stacks with single valued non-hysteretic IVCs. The typical materials used for manufacturing SNS JJs are Nb-Nb<sub>x</sub>Si<sub>1-x</sub>-Nb], [1].

In order to be driven by the same bias current and irradiation signal for the first constant voltage step ( $n=1$ ), the junctions should have very small spread of  $R_n$  and the characteristic frequency  $f_c \cdot f$ . In this case the quantized voltage  $V_j$  will appear at each junction of the array biased to the first step ( $n = 1$ ) obtaining the series combined sum equal to (2) [1]<sup>xviii</sup>. Moreover, for the stable and immune to noise exploitation of the ac standards voltage steps with current margins larger than 2 mA are highly desirable. Taking into account the most used irradiation frequencies approximately equal to 20 GHz and 70 GHz the normal resistances of the junctions should be adjusted to small values ranging from 0.02  $\Omega$  to 0.08  $\Omega$ .

PJVS consists of many thousands of junctions, arranged in individually biased sub arrays in binary progression (1,2,4,8...). Junctions bias currents are used to activate/deactivate array sections and, combining sections, it is possible to source binary programmed voltages in a way very similar to the technique used in semiconductor digital-to-analog converters. Presently, PJVS are the most successful attempt to extend metrological applications of Josephson standards beyond dc. PJVS have been proved effective in many applications such as traveling standards for international comparisons, in a watt balance, in quantum impedance and power standards. They provide dc and ac peak voltages in excess of 10 V, up to several kHz. PJVS systems are commercially available<sup>xix, xxe</sup>.

AC Josephson Voltage Standard (ACJVS) consist of a single array driven by a frequency modulated pulsed radio frequency (RF) signal. JAWS can generate spectrally pure ac signals up to 2 V and 1 MHz. It has been shown that the use of short pulses instead of a sinusoidal RF signal allows to effectively modulate the signal over a wide range of

frequencies, keeping junctions on a quantized step [1]. The output voltage is then exactly determined by the knowledge of the pulse repetition rate.

The LTS Programmable Josephson AC Voltage Standards and pulse-driven AC Josephson Voltage Standard are replacing thermal voltage converters used to reproduce the AC volt in terms of DC volt, especially at lower frequencies (<10 kHz) [21], [22], [23] where the determination of metrological parameters of thermal converters is troublesome [24]. However, the thermal converters will still play an important role in AC voltage metrology, at least in the next decade, in particular above 100 kHz [25], [26].

### ***Cryocooling methods***

The LTS JJs used in quantum voltage standards operate around 4 K, i.e. the temperature of boiling  $^4\text{He}$ . In general, two cooling methods are used to achieve such low temperatures: passive or active. In the former, the JJ is immersed in a bath cryostat in the form of Dewar container filled with liquid helium. Unfortunately, high cost and short supply of helium make the operation of passive-cooled LTS quantum voltage standards expensive. The active method uses cryocoolers [27]. The systems used to cool down the LTS JJs are predominantly Gifford-McMahon or pulse-tube regenerative cryocoolers using helium as working gas [28]. Lately, an extensive work was performed to model and optimize the operation of the LTS cryocoolers [29], [30]. However, operation at 4 K requires expensive and energy consuming compressors (typically a few kW), and requires to master difficult cryogenic techniques. Completely different landscape would be provided by HTS arrays operating at 77 K, the liquid nitrogen boiling temperature. Cryocoolers operating at 77 K are much smaller, and consume less energy (about few W), such as it would be possible to include a quantum standard for AC and DC into e.g. a commercial voltmeter. This argument alone is sufficient to show the enormous impact from the development of HTS Josephson arrays.

### **High-temperature superconductor Josephson junctions and their application in quantum-based voltage standards**

For the wide application of HTS Josephson junctions in cryoelectronics, both the development of the technology for deposition of thin HTS epitaxial films and the technology for fabrication Josephson junctions were necessary. An important step in the development of basic and applied research was the development of the deposition technology of epitaxial films of the most used high-temperature superconductor YBCO. This technological success,

as well as the subsequent demonstration of very low microwave losses in YBCO thin films, initiated the development of thin-film passive microwave devices that are currently used in nuclear magnetic resonance or magnetic resonance imaging (receiving coils), in mobile communication systems (resonators filters) and other passive microwave devices [Seidel]. In contrast to the technologies of passive devices of superconducting electronics, the technology of active devices is poorly developed in comparison with the technology of LTS Josephson junctions based on niobium and its compounds.

For the fabrication of a Josephson junction, it is necessary to create a weak link between two superconducting electrodes. As the material for the weak link, dielectrics, normal metals, or superconductors with a lower critical temperature compared to electrodes can be used. The length of this connection,  $L$ , is limited by several coherence lengths  $\xi$ , in the ideal case  $L \leq 3\xi$ . Unlike low-temperature superconductors, HTS are characterized by strong anisotropy of superconducting properties. Mainly used YBCO single crystal films with orthorhombic crystallographic structure have a coherence length  $\xi_{\text{YBCO}}$  equal to 1.5 nm in  $ab$  plane parallel to the substrate. This coherence length is much shorter as compared with  $\xi_{\text{Nb}}$  value for Nb which is equal to 40 nm. A very small coherence length  $\xi_{\text{YBCO}}$  is a most important limitation in the development of Josephson junctions technology. The traditional methods for creating weak links, which are widespread in the manufacture of Josephson junctions from LTS, such as niobium, are practically difficult to implement. In particular, the HTS SIS junctions with hysteretic IVC were not demonstrated up to now. Additional restrictions on technology are imposed by the need to create arrays of Josephson junctions with a small spread of  $I_c$  and  $R_n$ . Moreover the performance parameters,  $I_c$ ,  $R_n$  and  $f_c$  should be adjusted for the specific applications at elevated temperatures, e.g. higher than 55K, where a small scale cryocooler can be used.

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***Bicrystal Josephson Junctions and their application in present and future HTS dc and ac voltage standards***

HTS arrays of bicrystal Josephson junctions used in DC voltage standards is structured on yttria-stabilized-zirconia (YSZ) bicrystal substrates of size  $10 \times 10$  mm, thickness of about 0.5 mm and misorientation angle  $24^\circ$ . An epitaxial film of high-temperature YBCO superconductor with the thickness of 120 nm is grown in temperature  $665^\circ\text{C}$  on these substrates. Next, the layer is covered with a thin layer of gold with a thickness of 30 nm. A two-layer film structure is used to create series arrays of shunted HTS junctions. Junction

shunting is necessary to reduce the spread of  $R_n$ , which is one of the conditions for the realization of equation (2).

The Josephson junctions are formed at the intersection of the bicrystal grain boundary with thin-film bridges of HTSs with a width  $w = 6 \mu\text{m}$ . The width of the meander, i.e. the size of the meander in the direction perpendicular to the electric field vector is chosen to be  $\lambda_{\text{eff}}/2$ , where  $\lambda_{\text{eff}}$  is the effective wavelength in the YSZ substrate with dielectric constant  $\varepsilon = 26$ . Thus, each strip of the meander forms an external electromagnetic field with a half-wave resonator at a frequency of about 75.2 GHz with RF current maximum at its center in the region of the Josephson junction [klushin 2008].

With this optimal design and quasioptical method of irradiation of the arrays [xxxxii] a maximum first step at a Josephson voltage of about  $U_{\text{JHTS}} \cong 0.1 \text{ V}$  on the array of 620 bicrystal junctions at temperature of 79 K and frequency of  $f = 77.465 \text{ GHz}$  was achieved (Fig. 2). The resulting characteristic frequency  $f_c \approx 60 \text{ GHz}$  was smaller as  $f$  is optimum for the observation of the first voltage step under mm-wave irradiation. Enlarged portions of the I-V curves demonstrate the amplitude and the steepness of the step with nV resolution. Sub-arrays containing 62 junctions each were also synchronized at the same frequency and power. Steps from 0.01 V to 0.1 V were observed. It is important to note that the average critical current is  $I_c = 0.55 \text{ mA}$  with a standard deviation of  $19 \mu\text{A}$  or 3.5%. The average resistance of one shunted junction is about  $0.18 \Omega$  with a standard deviation of  $2.5 \text{ m}\Omega$  or less than 1.5%. These parameters approach the best results typical of the advanced technology of LTS (Nb, NbN) Josephson junction arrays. Hence, the arrays of bicrystal junctions are challenging for application in a dc and ac programmable voltage standards.

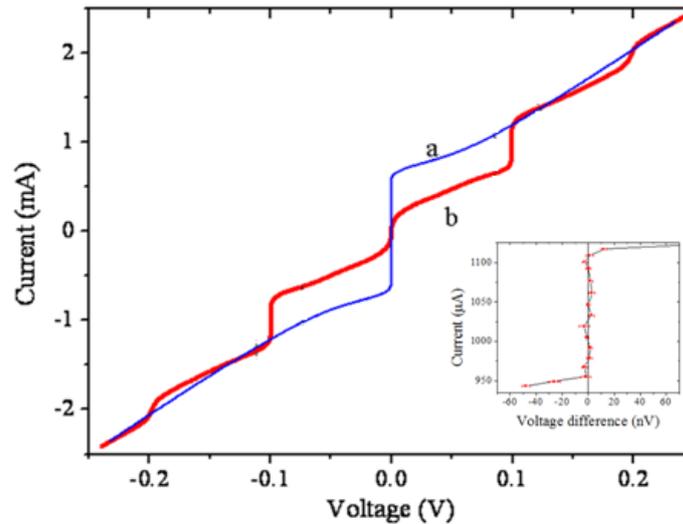


Fig. 1. The current-voltage characteristics of the first JJ array of 620 junctions at 79.2 K without (a) and with (b) the external electromagnetic wave irradiation at a frequency of 77.465 GHz. Enlarged portions of the I-V curves demonstrate the amplitude and the steepness of the step with 2 nV resolution at voltage of about 0.1 V.

### ***Metrology application of bicrystal junctions arrays at present***

A commercially available table top dc voltage standard N4-21 based on the successful development of the arrays of high-temperature superconductor bicrystal Josephson junctions with dry nitrogen temperature of about 77 K and Zener diodes is shown in Fig. 2 [Klushin 2019].

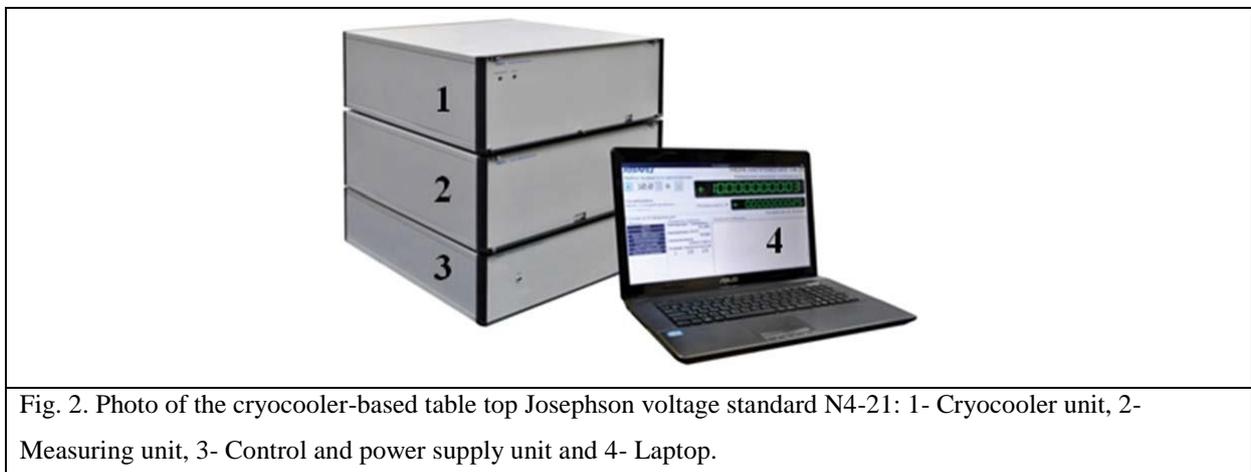


Fig. 2. Photo of the cryocooler-based table top Josephson voltage standard N4-21: 1- Cryocooler unit, 2- Measuring unit, 3- Control and power supply unit and 4- Laptop.

It has output voltages from  $-10$  to  $10$  V in steps of  $0.1$  V and the nominal voltages  $\pm 1.025$  V. The voltage standard N4-21 includes four units: 1) cryocooler unit; 2) measuring unit; 3) control and power supply unit; and 4) laptop. The required output voltage of the N4-21 is formed by the precision dividers, which are automatically calibrated against  $V_J \approx 25$  mV. The turnkey standard N4-21 is powered by 220 V or 110 V ac voltages. The HTS Josephson

junctions array is located in a cryostat and cooled by a small cryocooler. The array is irradiated by a compact 68-78 GHz synthesizer.

The measured relative standard type A uncertainties between output voltages of N4-21 and the primary state voltage standard of Russia is only a few parts in  $10^8$ . Such low uncertainties are sufficient for the application of voltage standard N4-21 in the highest-level metrology. The implementation of the link between Josephson junctions and Zener diodes largely eliminates the uncertainty contributions associated with Zeners nonlinear drift, environmental effects, and the impact due to shipping.

***Metrology application of bicrystal junctions arrays in the future: programmable Josephson voltage standard (PJVS).***

As it was mentioned above, the PJVS uses LTS niobium junction arrays with three constant voltage steps,  $n = 0, \pm 1$  [5]. The array for an  $m$ -bit PJVS was divided into  $m$  sections containing the Josephson junctions sequence equal to 1, 2, 4, 8  $2^{m-1}$ . The total number of junctions in the array was  $N^{2^{m-1}}$ . By applying bias currents to the appropriate set of sections, arbitrary voltages with amplitudes not exceeding in steps of  $Nf/K_J$ , were obtained.

In contrary to the niobium arrays, the HTS arrays demonstrate only two quantum steps,  $n = \pm 1$ . The utilization of two instead of three quantum steps requires a new slightly different series array circuit design [ ]<sup>xxxiii</sup>. In this case the  $N^{2^m}$  junctions in the array are divided into  $m + 1$  segments (bits). The number of junctions in the first  $m$  segments, including the most significant bit (MSB) of the array corresponds to the binary code (1, 2, 4, 8...). The last ( $m+1$ ) segment consists of only one junction. Zero voltage can be achieved if the MSB is biased oppositely to all the remaining segments. By changing the code of the first bits, one can get any desired voltage in steps of  $2Nf/K_J$ . The sign of the output voltage is defined by the MSB, and the additional bit has the opposite sign. It is important to note, that in this case the maximal step amplitude can be equal to  $\Delta I_{1\max} = 1.16I_c$  in contrary to the case with three stable states in which  $\Delta I_{1\max} = 0.54I_c$ .

***A promising alternative: high- $T_c$  Josephson junctions made by Focused Helium-Ion Beam for quantum-based voltage standards.***

In high- $T_c$  compounds, the superconducting order parameter which describes the fundamental properties of the quantum condensate has a  $d$ -wave symmetry, as opposed to most of the conventional superconductors. As a consequence, any crystallographic defect acts as a

“depairing center”, *i.e.* a place where superconducting properties are weakened. An increasing density of defects lowers the superconducting critical temperature  $T_c$  and, beyond a threshold, makes the material metallic, and even insulating at large dose, because the crystalline structure of the material is too altered to keep its metallicity. It is therefore possible to fabricate a Josephson junction, which is a weak link between two superconducting reservoirs separated by a non-superconducting material, by locally disordering the high  $T_c$  material on a scale which is on the order of a few tens of nanometers, to keep phase coherence across the junction.

Ion irradiation has been used to create such a local disorder. High-energy ions (typically 100 keV oxygen) are sent onto a high  $T_c$  (very often YBCO) channel made as a thin film (50 to 150 nm thick) which is protected by a resist, except in its central part, where a tiny aperture (20-40 nm) lets the ions penetrate the sample and locally increase the defect density. For a proper dose in the range of a few  $10^{13}$  oxygen ions/cm<sup>2</sup>,  $T_c$  is depressed and the Josephson coupling is observed below a temperature  $T_J$ , which depends on the irradiation conditions. Such a JJ displays nice characteristics [ ]<sup>xxxiv</sup>, which have been used in different applications such as dc SQUIDs, high frequency (400 GHz) mixers or RF magnetometers. This technique used to create high  $T_c$  JJ is interesting for applications which require a large number of JJs, and rather complex design. However, the Josephson characteristic voltage  $I_c R_n$  is moderate (in the range of a few 100  $\mu$ V) which is too low for some applications, and the spread in parameters (in the 10% range for  $I_c$  and  $R_n$  ) a bit large for very demanding applications.

Recently, S. A. Cybart and his collaborators at University of California San-Diego developed a parent technique [ ]<sup>xxxv</sup>, where the local ion irradiation is performed directly on the thin film in a Zeiss-Orion ion microscope. This advanced Focused Ion Beam (FIB) system allows the direct patterning of JJ by introducing the defects with of a sub-nanometer 30 keV helium beam. Because helium is light, ion straggling in the YBCO thin film is reduced, and the resolution of the defect density profile is much better than with the high energy oxygen irradiation technique. Since the ion energy is rather low, and therefore the range of the ions in matter limited, thinner YBCO films must be used with typical thickness of 50 nm or lower. Cybart and co-workers convincingly demonstrated that high- $T_c$  JJ can be fabricated with this technique [Cybart 2015], which  $T_J$ ,  $I_c$  and  $R_n$  can be adjusted with the He dose.

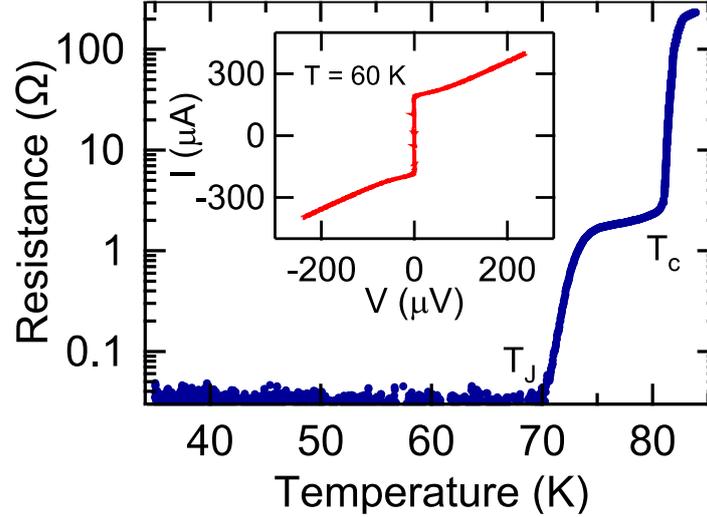


Fig.3. Resistance versus temperature curve of a JJ irradiated with 400 ions/nm. The critical temperature of the reservoirs  $T_c$  and the Josephson coupling temperature  $T_J$  are shown. Insert : Current-Voltage characteristic of the JJ measured at  $T = 60$  K.

In the first series of experiments, they made two types of JJ, depending on the ion dose. For low dose, typically  $2 \cdot 10^{16}$  ions/cm<sup>2</sup>, the irradiated part is essentially a normal metal (N) above  $T_J$ , with a decreasing resistance as the temperature is lowered. The JJ is therefore of “SNS” type, with a critical current  $I_c$  rising up quadratically below  $T_J$  as expected, and an I-V characteristics very close to the conventional Resistively Shunted Junction (RSJ) model. For higher dose, beyond  $6 \cdot 10^{16}$  ions/cm<sup>2</sup>, the disordered material shows an insulating (I) behavior with an increasing resistance at low temperature. This “SIS” type JJ has a linearly increasing  $I_c$  at low temperature, and does not display hysteresis because of its very small capacitance. In this tunnel junction, the dynamical resistance  $dV/dI$  displays a gap like feature which is reminiscent of the gap opening in the density of states of a superconductor below  $T_c$ . A BCS like temperature dependence is reported, with a zero-temperature gap value of around 30 mV.

Recent experiments performed by the ESPCI Paris team confirm that the He FIB technique produces interesting and versatile high- $T_c$  JJ [xxxvi]. In these experiments, standard high-energy ion irradiation technique is used to fabricate a 4  $\mu$ m wide YBCO channel in a 50 nm thick YBCO film. The JJ is then created by mean of a 0.7 nm diameter He ion beam at 30 kV scanned across the channel. Fig. 4 shows the resistance as a function of temperature of a junction made with a dose of 400 ions/nm introduced in a single scan. Below the critical temperature  $T_c$  of the reservoirs, a resistance plateau develops till Josephson coupling takes place at  $T_J$ . Below this temperature, the I-V characteristics of the JJ follows closely the standard RSJ model (inset in Fig. 3).

One advantage of these JJ is the wide range of parameters accessible by changing the ion dose, as compare to high energy ion irradiated ones. For a 4  $\mu$ m wide channel,  $I_c$  can vary

from 1  $\mu\text{A}$  to more than 1 mA,  $R_n$  from a few hundred  $\text{m}\Omega$  to 10  $\Omega$ , and the  $I_c R_n$  product can reach almost 1 mV at low temperature [ ]<sup>xxxvii</sup>.

Another decisive advantage of these He FIB made JJs is the possibility of placing several junctions at nano-metric distances of each other, to make compact 1D arrays with very good characteristics. Experiments conducted by L. Kasaei *et al.* on the superconductor  $\text{MgB}_2$  showed that JJ arrays made by He FIB have the lowest spread in critical current ( $\sim 3.5\%$ ) ever recorded in this material [ ]<sup>xxxviii</sup>. Correlatively, they obtained flat giant Shapiro steps under microwave irradiation at 12 GHz for 60 JJ in series, well synchronized, which is mandatory for voltage standards applications. Preliminary results on YBCO in the ESPCI Paris group point towards the same direction.

Clearly, arrays of YBCO JJ made by the He FIB technique have great advantages to make high- $T_c$  AC voltage standard such as Programmable Josephson Voltage Standard (PJVS) and Josephson Arbitrary Waveform Synthesizers (JAWS), or Quantized Voltage Noise Source (QVNS)<sup>xxxix</sup>. The latter application require a moderate number of JJ, but are demanding in terms of RF design since for their operation bias currents produced by short pulses instead of a sinusoidal RF signal are used. The He FIB JJ technique allows the fabrication of compact and complex 1D and 2D circuits that fit these specificities. The large flexibility in the JJ parameters is an asset as well. For instance, QVNS circuits require high critical current (up to 2 mA) with low  $I_c R_n$  product (20 to 40  $\mu\text{V}$ ) at the same time, which is difficult to achieve with other fabrication techniques as Grain Boundary JJ for example. It is also possible to tune the parameters of each individual JJ in the array, which opens new and unique perspectives for advanced design of short JJ arrays for metrological applications. Finally, the possibility of placing JJ at very short distances gives access to new synchronization schemes that may have a great interest for those applications.

## Conclusions

For the development of LTS Voltage standards, the tremendous effort spent in research has lead from single junction devices to the development of a sophisticated superconductive technology that made arrays with thousands of junctions available in many laboratories as quantum accurate dc voltage standards. Successively, the development of programmable standards and, more recently, of pulsed standards, ac quantum volt metrology has become a reality at acoustic frequencies for both sinewaves and arbitrary signals, and is about to reach the RF domain.

Recent results obtained with arrays of HTS Josephson junctions operating at liquid nitrogen temperature make possible to overcome issues related to liquid helium cryogenics, and can even work with closed-cycle refrigeration systems of limited size, low consumption and low cost. Thanks to these characteristics, a HTS Josephson quantum voltage standard being integrated in a widely used equipment, like a digital multimeter, is now foreseeable. A first prototype of compact cryocooled DC Josephson standard is in fact nowadays available on the market [], yet many relevant problems are still to be solved to fully take advantage of the potentialities of HTS voltage standards.

It seems that the further research should be concentrated on two fronts: the investigation of possible effects of the superconducting materials and novel technologies at unprecedented accuracies; the development of new sophisticated methods to apply HTS standards in fundamental metrology. An example of such devices, which look promising for metrological applications, are the high- $T_c$  Josephson junctions made using the low energy helium Focused Ion Beam microscope. The accurate control of the individual junction parameters on the one hand, and the large freedom to design complex and compact 1D or 2D short arrays on the other hand, open new perspectives to fabricate ac voltage standards and noise sources with high- $T_c$  superconductors. Also, the future applications of the HTS arrays in PJVS are discussed.

## References

- [] W. Nawrocki, *Introduction to Quantum Metrology: The Revised SI System and Quantum Standards*, 2nd ed. Springer, 2019.
- [] <https://physics.nist.gov/cgi-bin/cuu/Value?kjos>
- [] A. Klushin, W. Prusseit, E. Sodtke, S. Borovitskii, L. Amatuni and H. Kohlstedt, "Shunted bicrystal Josephson junctions arrays for voltage standards", *Applied Physics Letters*, vol. 69, no. 11, pp. 1634-1636, 1996.
- [] RECOMMENDATION 1 (CI-2002): "Revision of the practical realization of the definition of the metre," 91st Meeting of the CIPM, pp. 194 – 204. <https://www.bipm.org/utis/en/pdf/CI-2002-1-EN.pdf>
- [] S. Benz and C. Hamilton, "Application of the Josephson effect to voltage metrology", *Proceedings of the IEEE*, vol. 92, no. 10, pp. 1617-1629, 2004.
- [] C. Hamilton, "Josephson voltage standards", *Review of Scientific Instruments*, vol. 71, no. 10, p. 3611, 2000.

- [] T. Lipe, J. Kinard, Y. Tang, S. Benz, C. Burroughs and P. Dresselhaus, "Thermal voltage converter calibrations using a quantum ac standard", *Metrologia*, vol. 45, no. 3, pp. 275-280, 2008.
- [] M. Schubert et al., "An AC Josephson Voltage Standard up to the Kilohertz Range Tested in a Calibration Laboratory", *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 6, pp. 1620-1626, 2015. Available: 10.1109/tim.2015.2416454.
- [] O. Kieler, R. Behr, R. Wendisch, S. Bauer, L. Palafox and J. Kohlmann, "Towards a 1 V Josephson Arbitrary Waveform Synthesizer", *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 3, pp. 1-5, 2015.
- [] M. Grzenik and M. Kampik, "Determination of Frequency-Independent Component of AC–DC Transfer Difference of SUT Calculable AC Voltage Standards", *IEEE Transactions on Instrumentation and Measurement*, vol. 68, no. 5, pp. 1515-1521, 2019.
- [] M. Grzenik and M. Kampik, "Calculable AC Voltage Standards for 10 kHz-1 MHz Frequency Range", *IEEE Transactions on Instrumentation and Measurement*, vol. 66, no. 6, pp. 1372-1378, 2017.
- [] M. Grzenik and M. Kampik, "Determination of AC–DC Transfer Difference of Calculable Thermal Voltage Converters in 1–30-MHz Frequency Range", *IEEE Transactions on Instrumentation and Measurement*, vol. 68, no. 6, pp. 2072-2077, 2019.
- [] G. Walker, *Cryocoolers*. New York: Plenum Press, 1983.
- [] P. Durandetto, *Josephson devices for ac quantum voltage standard. From dry-cooling to metrological application*. Doctoral Dissertation. Politecnico di Torino, Turin, Italy, 2019.
- [] A. Sosso and P. Durandetto, "Experimental analysis of the thermal behavior of a GM cryocooler based on linear system theory", *International Journal of Refrigeration*, vol. 92, pp. 125-132, 2018.
- [] J. Bednorz and K. Muller, "Possible high  $T_c$  superconductivity in the Ba-La-Cu-O system", *Zeitschrift fur Physik B Condensed Matter*, vol. 64, no. 2, pp. 189-193, 1986.
- [] M. Wu et al., "Superconductivity at 93 K in a new mixed-phase Y-Ba-Cu-O compound system at ambient pressure", *Physical Review Letters*, vol. 58, no. 9, pp. 908-910, 1987.
- [] P. Chaudhari et al., "Direct measurement of the superconducting properties of single grain boundaries in  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ ", *Physical Review Letters*, vol. 60, no. 16, pp. 1653-1656, 1988.

- [] N. Bergeal, X. Grison, J. Lesueur, G. Faini, M. Aprili and J. Contour, "High-quality planar high- $T_c$  Josephson junctions", *Applied Physics Letters*, vol. 87, no. 10, pp. 102502, 2005. Available: 10.1063/1.2037206.
- [] S. Cybart et al., "Nano Josephson superconducting tunnel junctions in  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  directly patterned with a focused helium ion beam", *Nature Nanotechnology*, vol. 10, no. 7, pp. 598-602, 2015.
- [] B. Müller et al., "Josephson Junctions and SQUIDs Created by Focused Helium-Ion-Beam Irradiation of  $\text{YBa}_2\text{Cu}_3\text{O}_7$ ", *Physical Review Applied*, vol. 11, no. 4, 2019.
- [] L. Kasaei et al., "Reduced Critical Current Spread in Planar  $\text{MgB}_2$  Josephson Junction Array Made by Focused Helium Ion Beam", *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 5, pp. 1-6, 2019.
- [] A. Klushin, M. He, S. Yan and N. Klein, "Arrays of high- $T_c$  Josephson junctions in open millimeter wave resonators", *Applied Physics Letters*, vol. 89, no. 23, pp. 232505-232505-3, 2006.
- [] A. Klushin, M. He, M. Levitchev, V. Kurin and N. Klein, "Optimization of the coupling of mm wave power to arrays of high- $T_c$  Josephson junctions", *Journal of Physics: Conference Series*, vol. 97, pp. 012268, 2008.
- [] S. Khorshev et al., "Voltage Standard Based on Dry-Cooled High-Temperature Superconductor Josephson Junctions", *IEEE Transactions on Instrumentation and Measurement*, vol. 68, no. 6, pp. 2113-2120, 2019.
- [] A. Klushin et al., "Toward a programmable HTS Josephson voltage standard: recent results", *IEEE Transactions on Instrumentation and Measurement*, vol. 48, no. 2, pp. 274-278, 1999.

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<sup>i</sup> Josephson

<sup>ii</sup> <https://physics.nist.gov/cgi-bin/cuu/Value?kjos>

<sup>iii</sup> Lukens

<sup>iv</sup> Rufenacht 2018

<sup>v</sup> Bednorz

<sup>vi</sup> Chu

<sup>vii</sup> Applied Superconductivity: Handbook on Devices and Applications, ed. P. Seidel, John Wiley & Sons, 2015, ISBN 3527670653, 9783527670659

<sup>viii</sup> A. Klushin, M. He, M. Levitchev, V. Kurin and N. Klein, "Optimization of the coupling of mm wave power to arrays of high- $T_c$  Josephson junctions", *Journal of Physics: Conference Series*, vol. 97, pp. 012268, 2008.

<sup>ix</sup> Levinsen

<sup>x</sup> Gurvitch

<sup>xi</sup> Niemeyer

<sup>xii</sup> Hypres

<sup>xiii</sup> Calibration Weston cells 1

<sup>xiv</sup> Calibration Weston cells 2

<sup>xv</sup> SI

<sup>xvi</sup> Hamilton

<sup>xvii</sup> Benz

<sup>xviii</sup> Borovitsky 1985

<sup>xix</sup> Supracon

<sup>xx</sup> NIST commerz

<sup>xxi</sup> ??

<sup>xxii</sup> ??

<sup>xxiii</sup> ??

<sup>xxiv</sup> ??

<sup>xxv</sup> ??

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xxvi ??

xxvii Cryocooler

xxviii ??

xxix ??

xxx ??

xxxi Likharev 1979

xxxii A. Klushin, M. He, S. Yan and N. Klein, "Arrays of high- $T_c$  Josephson junctions in open millimeter wave resonators", *Applied Physics Letters*, vol. 89, no. 23, pp. 232505-232505-3, 2006.

xxxiii A. Klushin et al., "Toward a programmable HTS Josephson voltage standard: recent results", *IEEE Transactions on Instrumentation and Measurement*, vol. 48, no. 2, pp. 274-278, 1999.

xxxiv N. Bergeal, X. Grison, J. Lesueur, G. Faini, M. Aprili and J. Contour, "High-quality planar high- $T_c$  Josephson junctions", *Applied Physics Letters*, vol. 87, no. 10, pp. 102502, 2005. Available: 10.1063/1.2037206.

xxxv S. Cybart et al., "Nano Josephson superconducting tunnel junctions in  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  directly patterned with a focused helium ion beam", *Nature Nanotechnology*, vol. 10, no. 7, pp. 598-602, 2015.

xxxvi ESPCI Paris 2019 ?

xxxvii B. Müller et al., "Josephson Junctions and SQUIDs Created by Focused Helium-Ion-Beam Irradiation of  $\text{YBa}_2\text{Cu}_3\text{O}_7$ ", *Physical Review Applied*, vol. 11, no. 4, 2019.

xxxviii L. Kasaei et al., "Reduced Critical Current Spread in Planar  $\text{MgB}_2$  Josephson Junction Array Made by Focused Helium Ion Beam", *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 5, pp. 1-6, 2019.

xxxix S. Benz