Analysis of Different Measurement Setups for a Programmable Josephson Voltage Standard

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***Abstract*—The electrical characteristics of two different 1-V binary programmable Josephson arrays, an superconductor/insulator/normal conductor/insulator/superconductor-type Josephson array, and an externally shunted superconductor/insulator/superconductor-type Josephson array, were investigated at ten metrology institutes. Various operational parameters were evaluated and compared using different Josephson array voltage standard setups at microwave frequencies around 70 GHz. The results of the measurements show that both arrays have been working very well and the main differences were not imposed by the arrays themselves, but by the different measurement setups of the laboratories.**

***Index Terms*—Comparison, Josephson arrays, programmable voltage standard, superconductor/insulator/normal conductor/insulator/superconductor (SINIS), superconductor/insulator/superconductor (SIS) Josephson junctions.**

I. Introduction

JOSEPHSON Array Voltage Standards (JAVS) based on programmable Josephson arrays have increasingly gained in importance in recent years. These programmable arrays are superior to SIS arrays used for conventional JAVS, because the steps are inherently stable and any voltage can be set at a high speed limited only by the bias electronics if the array is binary-divided [1], [2]. This ability to set voltages rapidly leads to reduced measurement uncertainties for certain dc applications, such as FRDC measurements on thermal converters [3], [4], resistance calibrations with a double Josephson potentiometer [5], and probably the Watt experiment [6] and the metrological triangle [7]. Furthermore, these programmable arrays have the potential for ac metrology [8], [9]. It is, therefore, anticipated that programmable Josephson arrays will replace JAVS based on conventional SIS arrays over the next few years. In particular, the commercial fabrication of these programmable arrays is under way [10] and they will soon be available on the market.

Nevertheless, there is a concern that errors may exist during practical measurement because the arrays are not operated with zero current. Any current in a series resistance would generate an additional voltage that would hinder useful calibrations. When the programmable Josephson array is binary-divided, an easy self-check can be performed to verify the flatness of the steps of constant voltage and to determine the operating point [11], [12].

The aim of the co-operation presented here was to compare JAVS setups for programmable Josephson arrays. The behavior of the two arrays have been investigated for that purpose within the framework of the ongoing EUROMET project no. 626, coordinated by PTB. In this project, the investigations were focussed on dc measurements. The results obtained with a certain JAVS provide information about special features of the setup used. This information has been made available to every participating laboratory. Therefore, the individual setups can be improved and proper operation of the JAVS based on a programmable array will be ensured.

II. Arrays and Measurement Setups

The two Josephson arrays used in this study have been realized using the reliable superconductor/insulator/superconductor (SIS) array was fabricated at VTT. It consists of 3488 Josephson junctions divided into 5 bits. The junctions are arranged in 16 parallel microwave stripline paths. The 1-V level is achieved at 70 GHz, when the array is operated on the second step. The intrinsically shunted superconductor/insulator/normal conductor/insulator/superconductor (SINIS) array was made at PTB. It has a nominal number of 8192 junctions divided into 6 bits, but the largest bit has a superconductive shorted junction and therefore just 4095 junctions. The shorted junction has no effect on the behavior of the array. The microwave stripline is distributed into 64 parallel paths. A more detailed description of the layouts and the fabrication processes is given elsewhere [13]–[16].

The Josephson arrays were sent from laboratory to laboratory. The time for measuring both arrays was limited to three weeks in

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most cases. The parameters investigated are those related to critical currents, sensitivity to flux trapping, and functionality of all bits, as well as step width as a function of the microwave power and microwave frequency. To perform the measurements, every institute had to mount the arrays to a cryoprobe and to use the equipment of the laboratory's Josephson voltage standard. All participants use an EIP counter to phase lock the frequency, with the exception of IEN. The Gunn oscillators vary in power and frequency, i.e., from 60 to 85 GHz. As various kinds of waveguides were used, with attenuation ranging from 1 dB for oversized circular waveguides to 6 dB for rectangular ones, a wide range of maximum microwave power from about 3 to 50 mW was applied at the finline antenna of the Josephson arrays. In addition, several institutes carried out direct or indirect comparisons with SIS-type, SNS-type, and SINIS-type Josephson arrays to evaluate the calibration capability of the arrays and to verify the quantization of steps.

III. Results

The results obtained for the critical currents and step width are summarized in Fig. 1. Without microwave power applied, the parameters do not differ significantly. For the SINIS array, all measurements of the critical current are within 900 and 1050 μA. For the externally shunted SIS array, all measurements of the critical current are within 180 to 220 μA, with the exception of two unexplained measurements at about 140 μA. All participants used the bias source they would normally use with SIS Josephson arrays, so noise levels are expected to be sufficiently low for the evaluation of the arrays (references or the link to the different articles describing the Josephson measurement setups are found in [17] under *Metrology Area* "Electricity and Magnetism," *Comparison identifier* BIPM.EM-K10.a&b).

Under microwave irradiation, the parameters, such as the maximum step width, vary from one laboratory to the next. This is mainly due to different operating frequencies and/or microwave power available in conjunction with the array's step width dependencies upon frequency and power [17]. Due to these variations, it is necessary to individually determine the optimum operating point for each setup. A Josephson array with a well-known step width in dependence of power and frequency might be useful to establish these conditions. Fig. 2 shows the step width for the SINIS-type array as a function of the applied microwave power at the finline antenna. A large first step has been observed over a wide range of microwave power. As NPL, SP, and NMi used cryoprobes with high attenuation, the resulting maximum step width for the SINIS-type array was found to be smaller than at other laboratories (see Fig. 1). The step width of the shunted array as a function of frequency is shown in Fig. 3. The step width slightly varies over the large microwave frequency range from about 60 to 78 GHz. At high frequencies, the step width decreases.

Special incidents or measurements are very important in this kind of co-operation as they give further information about problems that could appear with the arrays. In contrast to SIS-type Josephson arrays, operated at zero current, the current-voltage characteristic changes with temperature. The bias

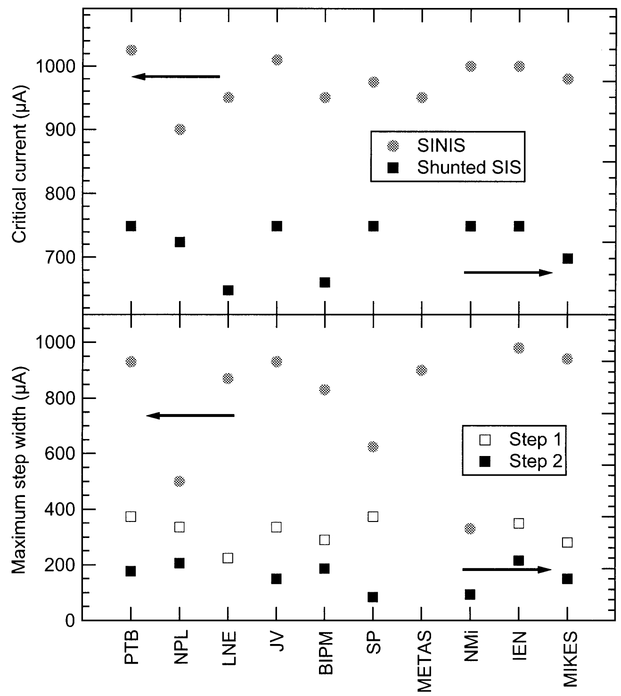

Fig. 1. (Top): Measured critical current of the arrays without microwave irradiation. Arrows to the left indicate the SINIS-type array; arrows to the right the shunted SIS-type array. (Bottom): Measured maximum step width of the first step of the SINIS-type array and of the first and second step of the shunted SIS-type array under microwave irradiation. The step width is measured by detecting a perceptible change of the step voltage to define the step limits (see Fig. 4).

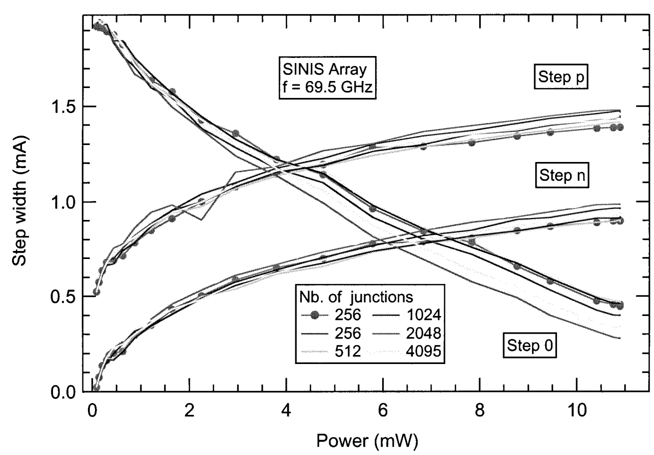

Fig. 2. Step width in dependence upon the microwave power at a frequency of 69.5 GHz for six segments of the SINIS-type array. For clarity, the curves corresponding to the positive steps (step p) have been shifted by 0.5 mA. The measurements were made by METAS.

currents must therefore be adjusted if necessary. For instance, a continuous drift of the step position of an SINIS-type array to higher bias currents is an indication of a falling helium level.

A few institutes observed that the arrays suddenly trapped flux, sometimes without identifiable reason. In one case, it was due to cooling the array too fast. Overall, both arrays showed very small rate of trapped flux.

For measurements with rapidly changing voltages, the choice of filters is a crucial problem. On one hand, large steps are expected to have high immunity to noise that would allow small

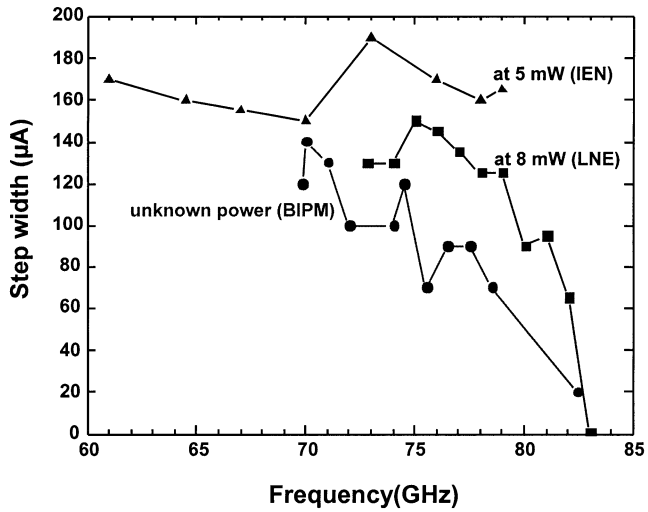

Fig. 3. Step width as a function of frequency for the shunted SIS-type array. The microwave power is estimated at the finline antenna of the array and unknown for the BIPM measurements. The measurements were made by BNM/LNE using an oversized circular waveguide, BIPM using a dielectric waveguide, and IEN using a stainless steel waveguide.

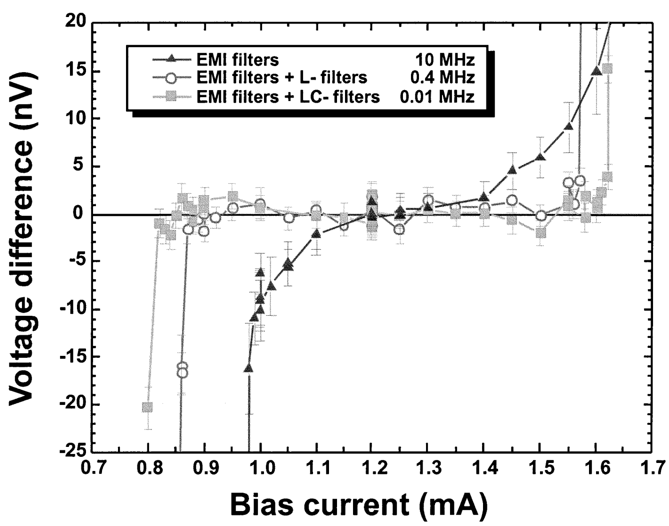

Fig. 4. Flatness of a step of the SINIS-type array measured at the 1-V level using a second JAVS. Removing additional filters between the EM N1a null-detector and the SINIS-type array increases the cut-off frequency of the filter and results in a sloped step. The measurements were made by PTB.

filters to be used. On the other hand, narrow bandwidth filters might support noise-induced phase slippage that might result in sloped steps and very large measurement uncertainties. Fig. 4 shows the flatness of a step of the SINIS array measured by PTB at the 1-V level using a second Josephson voltage standard. Removing additional filters between the EM N1a null-detector and the cryoprobe, a sloped step appeared probably due to phase slippage in the array induced by the noise of the null-detector. The same behavior was found for the externally shunted array. While these measurements indicate that noise immunity and inherent stability of the steps is not the same, i.e., even large steps do not have *per se* a high noise immunity, this problem is easy to overcome by appropriate filtering.

In contrast to conventional JAVS, the steps are inherently stable, but occur at nonzero current. As any small series resis-

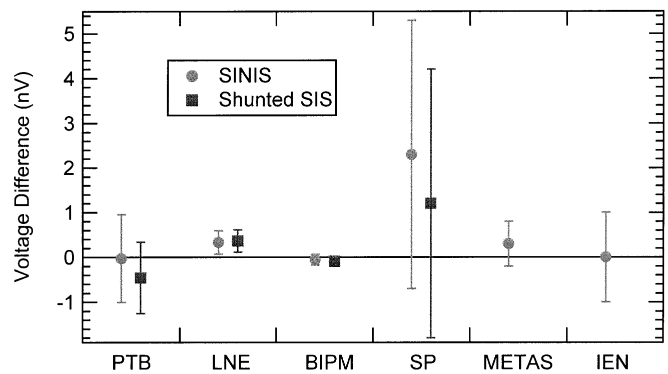

Fig. 5. Comparisons made with both arrays. PTB: direct comparison with another SINIS-type array. BNM/LNE, BIPM, and IEN: direct comparison with SIS-type arrays. SP: indirect comparison with an SIS-type array via Weston cells. METAS: direct comparison with an SNS-type array.

tance within the series arrays could lead to errors, the flatness of the steps has to be verified carefully. This was investigated with self-checks and direct comparisons. Self-checks were carried out at NPL and METAS. Two parts of the array with the same number of Josephson junctions were biased in series opposition. By varying the current on the steps, a slope can easily be found. The voltage difference was measured with a null-detector with sub-nanovolt resolution. To obtain an exact null voltage, the numbers of Josephson junctions need to be equal. Unfortunately, the shorted junction prevented to meet this condition. Thus, the uncertainty was increased to about 1 nV due to the small unbalanced offset voltage.

Fig. 5 shows the indirect and direct comparisons of both arrays with other arrays. All measurements agree very well, e.g., at BIPM, the direct comparisons agree to -0.05 ± 0.12 nV for the SINIS array and -0.09 ± 0.09 nV for the shunted SIS array. The measurement uncertainty corresponds to a one standard deviation of the mean. More details of the comparison procedure at BNM-LNE are given in [18].

IV. Conclusion

Both programmable Josephson arrays were found to be working very well in all laboratories. The main differences in electrical parameters were caused by the different measurement setups of the laboratories. The agreement of the output voltages at the 1-V level between the SINIS-type array or the externally shunted SIS-type array and other Josephson arrays was found to be better than 0.5 nV for all direct comparisons.

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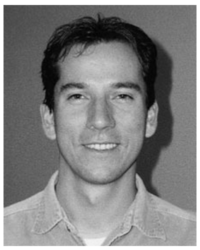

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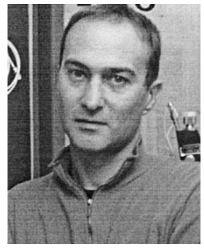

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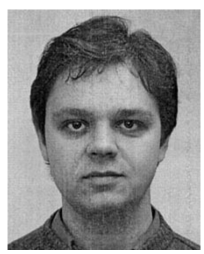

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