Accepted Manuscript

Characterization of a Josephson array for pulse-driven voltage standard in a cryocooler

A. Sosso, P. Durandetto, B. Trinchera, O. Kieler, R. Behr, J. Kohlmann

PII: S0263-2241(16)30542-5
DOI: http://dx.doi.org/10.1016/j.measurement.2016.09.039
Reference: MEASUR 4356

To appear in: *Measurement*

Received Date: 14 March 2016
Accepted Date: 22 September 2016

Characterization of a Josephson array for pulse-driven voltage standard in a cryocooler

A. Sosso[a,], P. Durandetto[a], B. Trinchera[a], O. Kieler[b], R. Behr[b], J. Kohlmann[b]

[a]*I.N.Ri.M. - Istituto Nazionale di Ricerca Metrologica*
Strada delle Cacce, 91 - 10135 Torino, Italy
[b]*Physikalisch-Technische Bundesanstalt (PTB)*
Bundesallee 100, D-38116 Braunschweig, Germany

Abstract

Pulse-driven Josephson junctions allow the synthesis of very precise both spectrally pure and arbitrary waveforms with frequencies up to the megahertz range. We investigated the properties relevant for metrological applications of series arrays with 4000 Josephson junctions fabricated at PTB in cryocooler and liquid helium. DC electrical parameters were evaluated and Shapiro steps dependence on operating conditions was studied. Both cooling techniques provided similar results for all relevant parameters. In particular, we were able to observe Shapiro step widths of more than 1 mA in cryocooler. Yet, we found that some specific effects related to the different thermal conditions must be taken into account for proper operation in cryocooler.

Keywords: Josephson effect, quantum voltage standard, quantum waveform synthesis, measurement techniques, measurement uncertainty, precision measurements, uncertainty.

Email address: a.sosso@inrim.it (A. Sosso)

1. Introduction

Arrays with several thousands of Direct Current (DC henceforth) Josephson junctions have been used for many years as voltage standards with ultimate accuracy (up to few parts in 10^{11} [1]). Junction technology for these arrays is based on insulating barrier (Superconductor-Insulator-Superconductor technology) and they are operated with sinusoidal radio frequency (rf henceforth) signals. Using short pulses instead of a sinusoidal rf signal makes it possible to effectively modulate the rf period while keeping junctions phase locked over a wide range of frequencies [2]. The working principle is based on flux quantization inside the junction: if a high-speed digital code is fed to a Josephson array, the magnetic flux quanta crossing the junctions can be used to generate arbitrary voltages with quantum accuracy. Fundamental accuracy thus follows from the control of the flux quanta transferred through the junctions by the pulse signal. The output voltage is then exactly calculable from fundamental constants if the pulse repetition rate is known [3]:

$$V_n = \Phi_0 \cdot N \cdot n \cdot f \tag{1}$$

where $\Phi_0 = h/2e \simeq 2.07$ fWb is the magnetic flux quantum, N is the number of junctions in the array and n is the Shapiro step number. With N and n fixed, the voltage depends only on the frequency f.

This principle is used in the Josephson Arbitrary Waveform Synthesizer (JAWS), where the pulse repetiton rate of the rf bias is modulated. This is equivalent to control the frequency as a function of time and allows the synthesis of arbitrary waveforms with quantum accuracy and voltage signals with very high spectral purity [4][5][6], making use on the sigma-delta technique for digital to analog conversion developed for electronics.

Josephson voltage standards have been developed and used for many years with liquid helium (LHe) cooling, yet cryogen-free operation is now regarded as crucial to widen the range of applications of quantum standards, with a technological impact epitomized by a foreseeable helium-free system run by technicians with no experience in cryogenic liquids management [7]. Cryocooler operation with pulsed standards is particularly interesting because of the expected significant impact in voltage Metrology with quantum standards approaching radio frequencies. Furthermore, cryocooler-based systems may provide a solution to the most relevant uncertainty contribution when the signal frequency is increased, namely the loading of the array due to cables, whose length can be significantly reduced in helium-free systems.

In this paper we report our measurements performed on arrays with 4000 Josephson junctions fabricated at PTB, using a cryocooler for cooling down to temperatures around 4.2 K. We first obtained parameters typical of DC effect (critical current I_c and normal resistance R_n) and then we measured Shapiro steps under irradiation. Measurements in liquid helium were also performed to compare results in different environments.

2. Chip fabrication technology and properties

JAWS arrays are presently realized with Superconductor - Normal metal - Superconductor (SNS) Josephson junctions. Different materials have been studied in the past for the barrier of these overdamped junctions, e.g. HfTi

[8] or Nb_xSi_{1-x} [9]. The resistivity of the barrier material should be rather high in order to realize suitable characteristic voltages $V_c = I_c R_n$, (the value where the optimal step width *vs.* rf power is obtained), or equivalently, from (1), a characteristic frequency f_c around 15 GHz for typical clock frequencies in this range.

The work presented here uses arrays of Josephson junctions realized by PTB with Nb_xSi_{1-x} as barrier material, in order to achieve higher characteristic frequencies and lower current densities (20-30 kA/cm^2 [10]) with respect to the previously adopted HfTi barrier [11]. One of the main problems in further increasing the output voltage of a JAWS circuit is that the number of junctions is limited by the requirement that all junctions must receive the same amount of rf power to assure correct operation [12]. PTB overcame this problem by fabricating arrays with double and triple-stacked junctions [13], thus realizing arrays with up to 6000 and 9000 junctions, respectively [6].

Our JAWS samples consist of two arrays, with 4000 junctions each, integrated on a 10 mm×10 mm silicon chip. For each array, junctions are arranged in double stacks and are embedded into the center line of a 50 Ω coplanar-wave- guide (CPW) which ensures a suitable propagation of pulses [10], that are characterized by large harmonic content with respect to a continuous microwave signal. The JAWS chip is mounted onto a chip carrier 23 mm×40 mm made on Rogers RO30061. Two conducting CPW paths made of copper with a 2 µm gold layer on top (without nickel) are used for pulse transmission to the arrays. The CPW lines of this carrier are connected to two PCB-SMA launchers for connection to coaxial cables [14]. The carrier

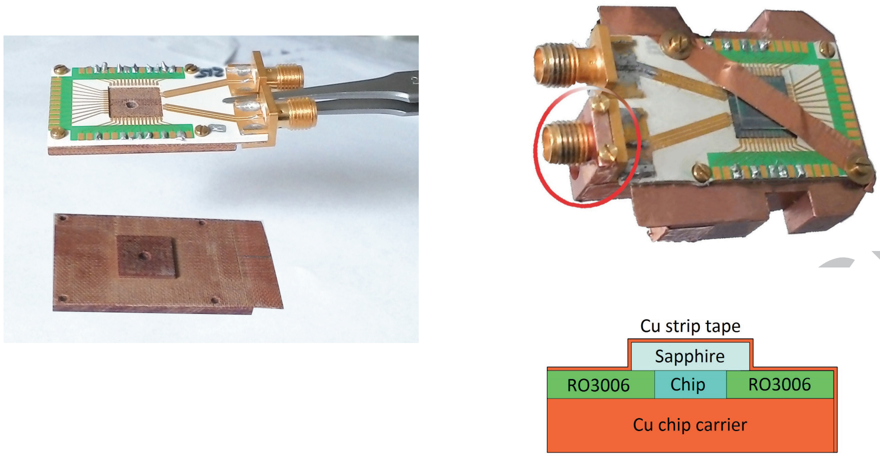

Figure 1: Original LHe (left) and modified (right) JAWS chip sample holder showing modification for proper thermalization of the junctions using a cryocooler. The Al spring to press the chip against the substrate was removed for clarity. The red circle highlights an L-shaped copper block for thermal anchoring the stainless steel coaxial cable to the coldplate, as explained in the text. Bottom right figure shows a schematic sectional representation of the holder structure.

was designed for LHe operation, so it was not suited for cryocooler operation in vacuum: a carrier properly redesigned was then used in our experiments and will be described in the following.

3. Experimental and Cryocooler Set-up

Our measurements were performed with a Gifford-McMahon closed-cycle refrigerator[1] with top loading sample assembly, minimum (no load) temper-

[1]Leybold Coolpower 4.2. Brand names are used for identification purposes. Such use implies neither endorsement by the authors nor assurance that the equipment is the best

ature achievable of about 2.9 K, and nominal cooling power of 1 W at 4.2 K. The cool down time is about 2 hours. The cold finger top was fitted with an additional disk retaining inside a deep-set thermometer that, along with a heater wire wound around it, allows fine temperature monitoring and control. A second thermometer close to the chip was used to better estimate the array operating conditions and detect unwanted thermal gradients [15].

When a Josephson array is irradiated by rf continuous waves, as in Programmable Josephson Voltage Standards, or by trains of short pulses, as in JAWS, it unavoidably warms up due to the Joule effect. Heating rises the local temperature and consequently worsen the array's operating margins [[16]], since the critical current I_c and consequently Shapiro steps amplitude decreases as the temperature raises. Also DC bias currents contribute to the Joule heating effect of the chip. All heat has to be transferred from the substrate to the cryocooler's cold head through a series of suitable thermal links with high thermal conductivity [17].

The sample holder was designed for LHe operation, where thermal conduction to the chip is not an issue, since the array is totally immersed into the cooling liquid. The original bakelite chip support was unsuitable for the required high thermal conduction from the coldplate to the array substrate, so we replaced it with a newly designed, made in Oxygen-free (OFHC) copper (bottom of Fig. 1). Our first attempt was to realize a good contact between the chip and the copper holder by fastening it with special silver-based glues, but we observed a significant decrease of effectiveness after a few

available.

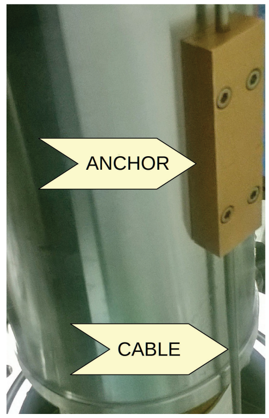

Figure 2: Copper block for thermal anchoring the coaxial cable to the cylindrical first stage shield of the cryocooler

thermal cycles and the chip eventually detached from the carrier. In order to solve this problem we realized an Al (ergal) spring needed for pressing the chip against the carrier and transferring the heat generated within the junctions to the cold head. In addition, to avoid any electrical contact to the Nb films, we positioned a 0.5 mm thick sapphire substrate between the chip and the spring, since sapphire is a good thermal conductor as well as an electrical insulator. Heat transmission through the ergal spring was not as high as expected, and was then further increased adding a thin copper strip tape with both ends screwed to the copper chip carrier and pressed in the middle by the spring against the sapphire substrate (see Fig. 1).

It should be taken into account that also the coaxial cable for rf pulse transmission considerably affects the minimum achievable temperature, since it connects the cold region to the outer stages of the cryocooler and to the laboratory environment. To reduce this source of thermal loading, we adopted a 0.5 m long cable made in stainless-steel and thermally anchored at two points: first to the first stage shield of the cryocooler at around 40 K (see. Fig. 2), then to the cold plate, where the coax cable is tightened to the sample holder connector. The thermal loading of the cold plate doesn't significantly affect its temperature, since the dissipated power is well within the cryocooler capabilities.

4. Cryocooler and LHe measurements

The first set of measurements performed on the samples consisted in the DC electrical characterization at different temperatures T, both in liquid helium bath and cryocooler. The observed IV characteristics are shown in Fig. 3.

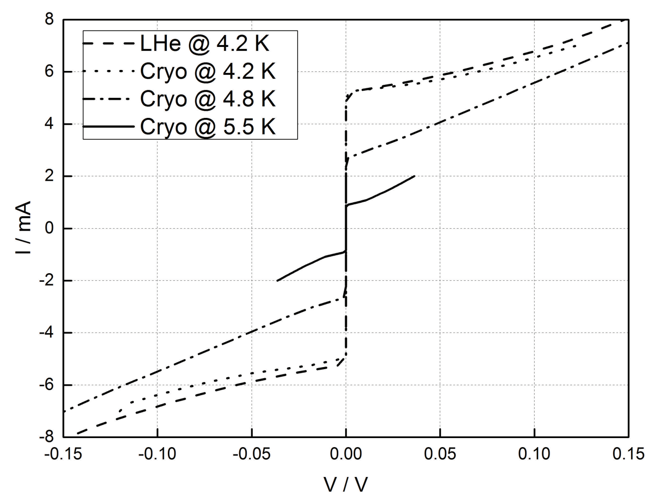

Figure 3: DC-IV characteristic of JAWS chip at different temperatures in liquid helium bath and cryocooler.

It can be seen that the value of critical current I_c is similar in both conditions, for a given measured temperature: 4.6 mA at 4.2 K in cryocooler and 4.5 mA in LHe. This demonstrates that the temperature of the junctions in cryocooler is almost equal to the temperature in helium bath, consistently with the values measured by the thermometers, hence the sample is correctly thermalized to the cold plate.

It is well known [[7]] that mechanical cycling in cryocoolers, particularly in those based on GM technology, induces thermal fluctuations in the experiment, that can be observed as oscillations in the value of I_c. In our case, the amplitude of I_c oscillations was about 0.5 mA, corresponding to a $\pm$100 mK fluctuation of temperature. As shown in the following, if array operating conditions are suitably set, the effect of I_C fluctuations on the generated signal can be reduced to negligible values.

A first evaluation of the metrological properties can be obtained by irradiating the array with a continuous sine wave signal (CW), that in our case was supplied by a synthesizer[2]. The first characterization has been made in LHe setup: in this case rf heating is easily dissipated and the effective junctions temperature is the same of the helium bath.

It should be noted that the array we tested was designed for a Pulse Pattern Generator (PPG) model with 15 GHz maximum operating frequency (Return to Zero (RZ) pulses). Consequently (as shown by the I_c in Fig. 3, considering the 5 mΩ R_n value), the junctions characteristic frequency f_c at 4.2 K was set to 11 GHz and the wide steps observed with the 10 GHz irradiation are motivated by the operating conditions close to this optimal

[2] HP-83711

value.

It was not possible to reach such high frequency values in pulse bias tests of the array, as they are higher than we could obtain with the PPG we used[3]. In our case, the maximum clock frequency is 12.5 GHz: since our PPG generates NRZ-pulses (Non Return to Zero), the maximum frequency of data pulses is about 6 GHz (realized by setting a 10101010... output pattern).

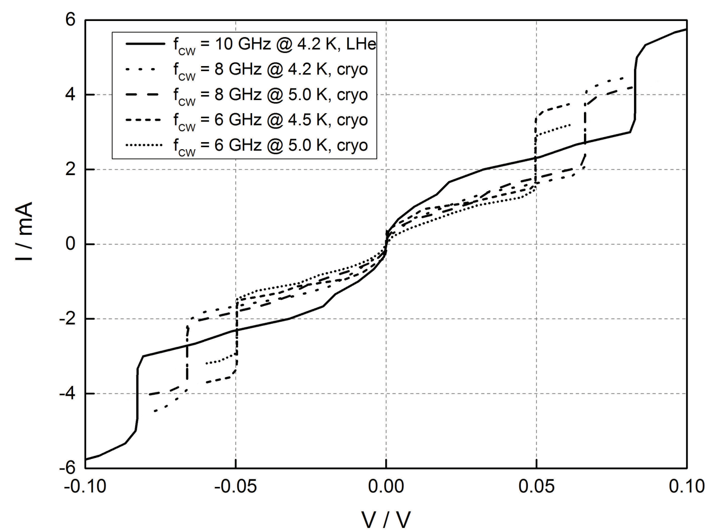

Figure 4: AC-IV characteristic of JAWS chip at different temperatures and f_{CW} values in liquid helium and cryocooler

On the other side, when operating in cryocooler one has to consider that the resistance of thermal links reduces the thermal dissipation of chip and increases its temperature when irradiated [16]. The effective junctions I_c under irradiation may then be lower, with a corresponding reduction of f_c

[3] Anritsu MP1763C

that partially counterbalances the higher fabrication value. It is not possible to directly measure the effective chip operating temperature: to study the combined effect of both contributions in our measurements in cryocooler we first analyzed the step properties with CW irradiation at different temperatures and operating frequencies. For each frequency value, the temperature and rf power was optimized for maximum width of $n = 1$ Shapiro step. The results, shown in Fig. 4 (along with LHe steps, for ease of comparison) indicate that by properly setting the operating temperature, suitable steps can be observed at 6 GHz. From the graphs one can also see that, despite the expected increase of junctions temperature discussed above, the optimal operating temperature in cryocooler at the frequencies of interest is still above 4.2 K, a value easily obtained with the He-free refrigerator.

After proving that the sample was working well with CW irradiation and the electrical parameters were suited to the PPG in use, we tested its response when irradiated by trains of pulses. A comparison between IV curves obtained with CW as well as PPG irradiation at the same frequency and temperature (6 GHz, $T \simeq 4.5$ K) is represented in Fig. 5. It is clearly seen that Shapiro steps with identical properties are observed in both cases and step width is always well above 1 mA.

Finally we tested the cryocooled JAWS array in the generation of a pure tone sinewave. The ≈-80 dBc (Fig. 6) value of the ratio between the fundamental and the highest harmonic tone were obtained at center of the operating margins, where the sensitivity to the operating conditions, including the effect of thermal fluctuations in the cryocooler, is very low. To investigate the influence of the cryocooler on measurements, we compared our results to

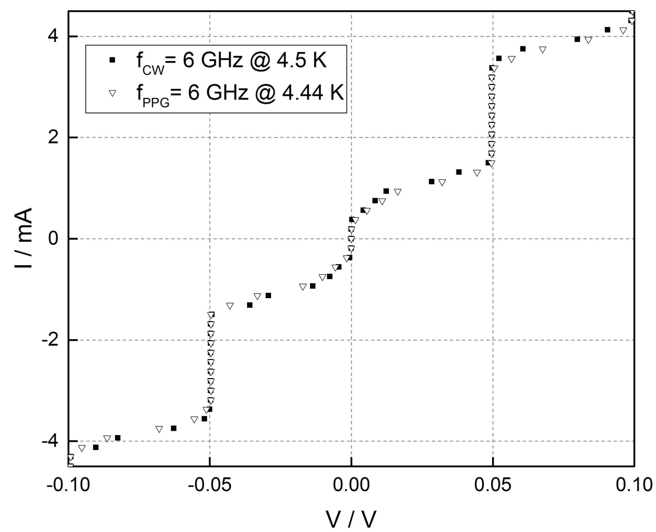

Figure 5: AC-IV characteristics of JAWS chip at $T \simeq 4.5$ K and with f_{CW}= f_{PPG}= 6 GHz in cryocooler.

the spectra observed with the array cooled in LHe. Both cases are shown in figure 6: no relevant difference can be seen in the harmonic content. The 2–5 mW of microwave power required for operation is then effectively dissipated on the coldplate, without significant consequences in the behavior of the array.

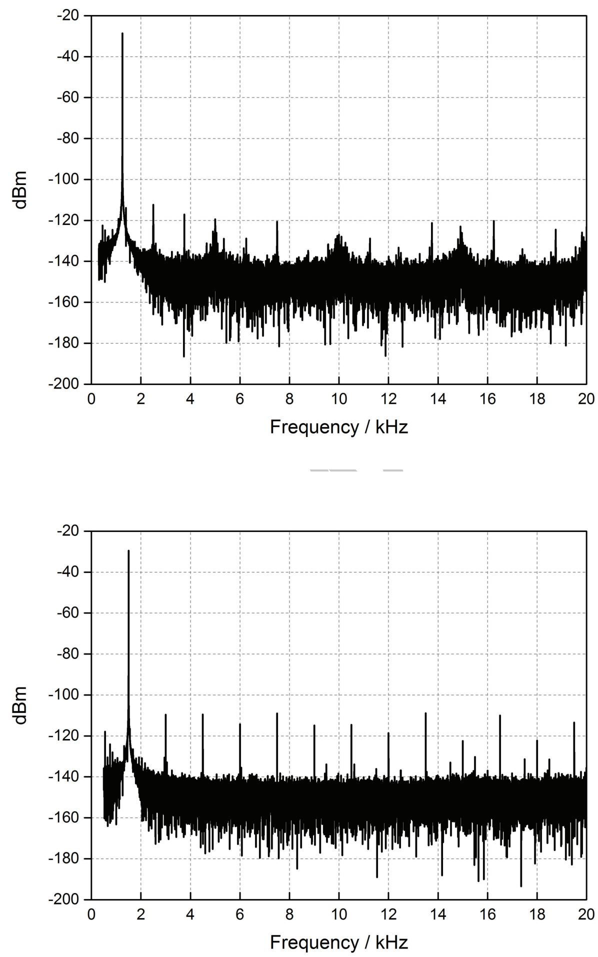

Figure 6: Spectra of a synthesized sinewave in cryocooler (top) and liquid He (bottom). The rms value, modulation amplitude and amplitude of the highest harmonics were 5.84 mV, 20%, -84 dBc and 5.26 mV, 15%, -79 dBc respectively.

5. Conclusions

We analyzed the DC and AC electrical properties of arrays with 4000 Josephson junctions for metrological application to a pulse-driven arbitrary voltage quantum standard, both in LHe and cryocooler to investigate the effects related to closed cycle device cooling. A special stainless steel coaxial cable 0.5 m long was used for rf transmission, thus limiting thermal loads on the experiment. Both cooling techniques provide very similar results for all relevant parameters. In particular, we were able to observe Shapiro step widths of more than 1 mA in cryocooler and synthesize sinewaves with spectral purity in excess of -80 dBc. Our result is promising for the development of a totally He-free JAWS apparatus capable of reducing the electrical loading on the array from output cable by means of a second stainless steel cable, that will reduce the length of the output line by about a factor of two with respect to the systems currently in use. We expect then a significant reduction of presently the major source of uncertainty. The additional heat loading during operation of the JAWS arrays, however, will require a careful study of thermal issues.

Acknowledgements

The authors gratefully acknowledge the contribution of D. Serazio for designing and manufacturing several parts the cryogenic apparatus.

This work was partly carried out with funding by the European Union within the EMRP project JRP SIB59 Q-WAVE. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

References

[1] B. Wood, S. Solve, A review of Josephson comparison results, Metrologia 46 (6) (2009) R13–R20.
URL http://stacks.iop.org/0026-1394/46/i=6/a=R01

[2] J. Kim, A. Sosso, A. Clark, Dynamics of overdamped Josephson junctions driven by a square-wave pulse, J. Appl. Phys. 83 (6) (1998) 3225–3232.

[3] S. Benz, C. Hamilton, A pulse-driven programmable Josephson voltage standard, Appl. Phys. Lett. 68 (22) (1996) 3171–3173.

[4] S. Benz, P. Dresselhaus, C. Burroughs, N. Bergren, Precision Measurements Using a 300 mV Josephson Arbitrary Waveform Synthesizer, IEEE Trans. Appl. Supercond. 17 (2) (2007) 864–869. doi:10.1109/TASC.2007.898138.

[5] C. Urano, M. Maruyama, H. Nobu-Kaneko, H. Yamamori, A. Shoji, M. Maezawa, Y. Hashimoto, H. Suzuki, S. Nagasawa, T. Satoh, M. Hidaka, S. Kiryu, Operation of a Josephson arbitrary waveform synthesizer with optical data input, Superconductor Science and Technology 22 (11) (2009) 114012.
URL http://stacks.iop.org/0953-2048/22/i=11/a=114012

[6] O. Kieler, R. Behr, R. Wendisch, S. Bauer, L. Palafox, J. Kohlmann, Towards a 1 V Josephson Arbitrary Waveform Synthesizer, IEEE Trans. Appl. Supercond. 25 (3) (2015) 1–5.

[7] A. Sosso, B. Trinchera, E. Monticone, M. Fretto, P. Durandetto, V. Lacquaniti, Temperature Stability of SNIS Josephson Arrays Between 4.2 K and Critical Temperature in Cryocooler, IEEE Trans. Appl. Supercond. 25 (3) (2015) 1–4. doi:10.1109/TASC.2014.2383173.

[8] R. Behr, O. Kieler, J. Kohlmann, F. Müller, L. Palafox, Development and metrological applications of Josephson arrays at PTB, Meas. Sci. Technol. 23 (12) (2012) 124002.

[9] B. Baek, P. Dresselhaus, S. Benz, Co-sputtered amorphous Nb_xSi_{1-x} barriers for Josephson-junction circuits, IEEE Trans. Appl. Supercond. 16 (4) (2006) 1966–1970.

[10] J. Kohlmann, O. Kieler, R. Iuzzolino, J. Lee, R. Behr, B. Egeling, F. Muller, Development and investigation of SNS Josephson arrays for the Josephson Arbitrary Waveform Synthesizer, IEEE Trans. Instrum. Meas. 58 (4) (2009) 797–802. doi:10.1109/TIM.2008.2007033.

[11] O. Kieler, R. Behr, D. Schleussner, L. Palafox, J. Kohlmann, Precision comparison of sine waveforms with pulse-driven Josephson arrays, IEEE Trans. Appl. Supercond. 23 (3) (2013) 1301404.

[12] J. Kohlmann, F. Müller, O. Kieler, T. Scheller, B. Egeling, R. Wendisch, R. Behr, Josephson series arrays with NbSi barrier for ac voltage standards, in: Precision Electromagnetic Measurements (CPEM 2014), 2014 Conference on, IEEE, 2014, pp. 466–467.

[13] P. Dresselhaus, Y. Chong, J. Plantenberg, S. Benz, Stacked SNS Joseph-

son junction arrays for quantum voltage standards, IEEE Trans. Instrum. Meas. 13 (2) (2003) 930–933. doi:10.1109/TASC.2003.814151.

[14] O. Kieler, T. Scheller, J. Kohlmann, Cryocooler operation of a pulse-driven AC Josephson voltage standard at PTB, World Journal of Condensed Matter Physics 3 (2013) 189–193.

[15] A. Sosso, M. Fretto, V. Lacquaniti, E. Monticone, R. Rocci, D. Serazio, B. Trinchera, Tests of SNIS Josephson Arrays Cryocooler Operation, Journal of Supercond. and Novel Magnetism 28 (3) (2015) 1181–1184.

[16] A. Rufenacht, L. Howe, A. Fox, R. Schwall, P. Dresselhaus, C. Burroughs, S. Benz, Cryocooled 10 V Programmable Josephson Voltage Standard, IEEE Trans. Instrum. Meas. 64 (6) (2015) 1477–1482. doi:10.1109/TIM.2014.2374697.

[17] L. Howe, C. Burroughs, P. Dresselhaus, S. Benz, R. Schwall, Cryogen-free operation of 10 V programmable Josephson voltage standards, IEEE Trans. Appl. Supercond. 23 (3) (2013) 1300605. doi:10.1109/TASC.2012.2230052.