Operation of compact cryocooled 2V programmable josephson voltage standard at NIM

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Abstract *– In the past, most of worldwide Josephson voltage standard systems use liquid helium to cool down the Josephson junction chips. Due to the liquid helium shortage, the cost of operating liquid helium based Josephson voltage standards rises year by year.Therefore there is an increasing need for a compact cryocoooled Josephson voltage standard which has no need of liquid helium. This paper presents a domestic liquid-helium-free dc programmable Josephson voltage standard (PJVS) operating on a cryocooler at 4K or 10 K. In this work, the performance of a NIST-fabricated two volt Josephson junction array (JJA) and a NMIJ-fabricated two volt JJA operating in a cryopackage around the Gifford-McMahon (GM) cryocooler is presented. The JJA chip has been shown to operate successfully with the domestic cryopakage. Stable quantum steps with operating margin greater than 1.4 mA was obtained. Differences in behavior of the NIST-fabricated JJA in liquid helium and on the cryocooler are also discussed.*

Keywords *– Cryocooled Josephson voltage standard, cryocooler, dc-voltage, liquid helium free.*

I. INTRODUCTION

Josephson Voltage Standard (JVS) systems are mainly used to provide the volt unit realization. They are able to provide the very low uncertainty around several parts in 10^9 to 10^{10} for dc voltage calibration. These JVS systems often operate at temperatures of about 4K. They normally use liquid helium to cool down the JJA chip to 4.2K. However, liquid helium is a very scarce resource all over the world. The total amount of liquid helium dissipation for a PJVS system is approximately 4~5 liter per day. Rising costs and difficulties in obtaining liquid helium in many areas of the world provide requirements for liquid helium free PJVS systems. National Institute of Standards and Technology (NIST), Hypres and US Army Research Laboratory jointly developed a cryocooled conventional Josephson voltage standard in 1997. In 2013, NIST developed a liquid helium free 10 V programmable Josephson voltage standard [1]. National Metrology Institute of Japan (NMIJ) developed a 10 volt cryocooled PJVS system operating at temperature of 10 K[2]. Such a cryocooled system would allow Josephson voltage standard to be used more broadly applied to areas where liquid helium is not available.

Limited by the micro-nano electronic fabrication technology in China, we start to research on Josephson voltage standard since 1991. One volt and ten volt conventional dc Josephson voltage standard was established at National Institute of Metrology (NIM, China) in 1993 and 1999. In 2009, one volt PJVS system was developed at NIM. About two years ago, we started to research on the cryocooled PJVS system. The biggest challenge is to realizing the equilibrium between the heat dissipated and the cooling capacity of the cryocooler. We also focus on reducing the electromagnetic interference coming from the cryogenic system, such as high-power compressor (with rated power of 10 kW), water chilling unit, molecular pump, and so on, which may cause the measurement inaccuracy or flux-trapping for Josephson junction array.

II. CRYOGENIC PACKAGE

The cryogenic package is built around a domestic two-stage G-M cryocooler. It provides a temperature floor of around 3.5 K with 1.5 watt @4.2 K cooling capacity. The layout of the cryopakage is schematically shown in Fig. 1. The whole system is consist of a cryocooler, a cold plate, coaxial cables for microwave transmission, low thermoelectric leads for bias current and voltage transmission, a heater, two thermosensors, a magnetic-field shield, a thermal-radiation shield, a vacuum enclosure, cables and electrical connectors. A

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programmable Josephson array chip is mounted on a cold plate (copper block) which is used to extract the heat generated by the Josephson chip. Electrical connections from the bias current source to the chip are via 48 copper dc bias leads which are divided into two groups. A heater and two thermometers mounted on the second stage are used for temperature control. A cylindrical permalloy magnetic shield is used as the thermal shield for the second stage. A thermal-radiation shield mounted on the first stage for heat insulation protects the chip from the interference coming from terrestrial magnetic field and stray magnetic field. A stainless-steel jacket as vacuum enclosure is used to keep the cryostat under vacuum. Stainless-steel coaxial cables and SMA connectors are employed to deliver the 16 GHz ~ 20 GHz microwave.

Two kinds of cold plate are designed to mount two types of programmable Josephson array chip: one kind is a NIST-fabricated two volt superconductor-normal metal-superconductor (SNS) Josephson array which works at temperature around 4.2 K, another kind is NMIJ-fabricated two volt NbN-based programmable Josephson array which works at temperatures around 10 K. The cryostat, which has a multipoint temperature control system, is designed to work at temperatures around 4.2 K and around 10 K. This kind of design is suitable for two kinds (4.2 K and 10 K) of Josephson chips mentioned above. As an aluminum nitride (AlN) slice is set between JJA chip and the cold plate for electrical isolation, the temperature on the JJA chip is a bit higher than the temperature measured on the cold plate by the thermosensor. For instance, the cold plate is usually set to 3.5 K~3.7 K in order to get the same critical current (Ic) [1] as the same chip operating in liquid helium.

Table Ⅰ shows the technical specifications of the refrigeration system. We have never researched on cryocooler based PJVS system before, so a relatively large power cryocooler is employed in order to provide enough cooling capacity.

Table Ⅰ Technical specifications of the refrigeration system

Cryocooler		
Cryocooler Type	Two Stage Gifford-McMahon cooler	
Lowest Temperature:	< 3.5K	
Cooling Capacity (50Hz):	First Stage	Second Stage
	35W @ 50K	1.5W @ 4.2K
Cooldown Time (2nd stage):	< 60min.(4.2K)	
Weight:	Coldhead	Compressor unit
	19 kg	118 kg
	Compressor	
Power Consumption(50Hz)	Steady	Cooldown
	6.5kW	7.2kW
Cooling Type	Water	

Fig. 2 shows the typical load map of KDE415 cryocooler. Fig. 3 shows the diagram of the domestic two-stage G-M cryocooler with NMIJ-fabricated Josephson chip mounted on the cold plate.

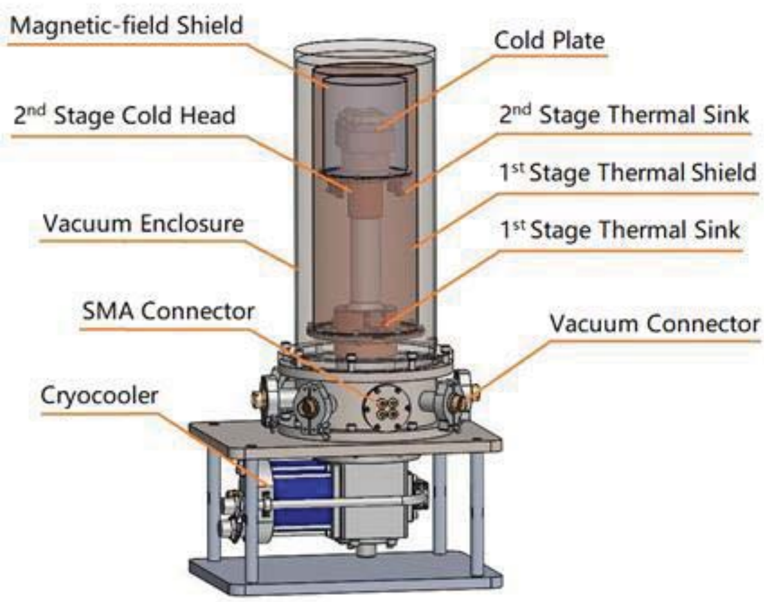

Fig. 1 Cryopakage Layout

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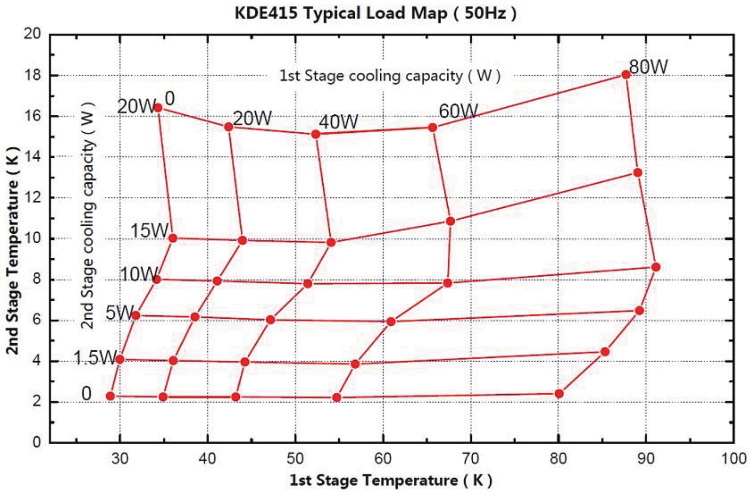

Fig. 2 Typical load map of KDE415 cryocooler

Fig. 3 Two-stage G-M cryocooler with NMIJ-fabricated Josephson chip mounted on the cold plate

III. PROGRAMMABLE JOSEPHSON ARRAY

Two kinds of programmable Josephson chips are used in this system.

NIST-fabricated two volt superconductor-normal metal-superconductor (SNS) Josephson array works at temperature around 4.2 K. It consists of 12 available subarrays (Table Ⅱ). Bias current operated on each subarray may make the output of the junctions be positive, negative, or zero quantum voltage step.

At 18.0 GHz, the minimum voltage output of 0.0000744420 V may be generated by positively biasing the subarray 1 (with 8800 Josephson junctions) at the positive quantum voltage step, while as negatively biasing the subarray 3 (with 8798 Josephson junctions) at the negative quantum voltage step. As shown in Table 2, when positively current biasing subarray 1 to subarray 12, with totally 67408 Josephson junctions, the output quantum voltage of the JJA chip is 2.1815233534 V which is the maximum voltage output of this chip. Fig. 4 shows the NIST-fabricated two volt Josephson chip mounted on the cold plate within the cryostat.

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Table Ⅱ Configuration of NIST-fabricated two volt SNS programmable Josephson Array

Subarray	Number of junctions subarray	Positive step (1st Shapiro step) at microwave frequency of 18.0 GHz (V)
1	8800	0.3275448816
2	8800	0.3275448816
3	8798	0.3274704396
4	8800	0.3275448816
5	8796	0.3273959976
6	8792	0.3272471135
7	3888	0.1447152841
8	1296	0.0482384280
9	16	0.0005955361
10	48	0.0017866084
11	144	0.0053598253
12	432	0.0160794760
Total	58610	2.1815233534

According to Josephson effect, the PJVS circuit and its subarray are commonly operated on the voltage corresponding to the first Shapiro step (n=1) of each junction. Fig. 2 shows the I-V curve of the programmable Josephson array. The array voltage is given by:

$$U = n\frac{h}{2e}f = n\frac{f}{K_{J-90}{}^{*}} \quad (1)$$

Where n is the number of Josephson junctions, f is the microwave frequency, e is the electron charge and h is the Planck constant.

* $K_{J\text{-}90}$ (483597.9 GHz*V) is the fixed conventional value of Josephson constant since 1990. With the redefinition of SI base units this year (2019), the Josephson constant has an exact value of K_J=483597.8484…. GHz*V, which will take place of the conventional value $K_{J\text{-}90}$ later in China.

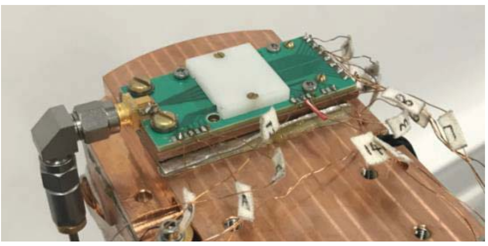

Fig. 4 NIST-fabricated two volt Josephson chip mounted on the cold plate

NMIJ-fabricated two volt NbN-based programmable Josephson array works at temperatures around 10 K. I It consists of 16 available subarrays (Table Ⅲ). Bias current operated on each subarray may make the output of the junctions be positive, negative, or zero quantum voltage step.

At 16.077 GHz, the minimum voltage output of 0.0010638261 V may be generated by positively biasing the subarray 1 (with 32 Josephson junctions) at the positive quantum voltage step. As shown in Table 3, when positively current biasing subarray 1 to subarray 16, with totally 65536 Josephson junctions, the output quantum voltage of the JJA chip is 2.1787157975 V which is the maximum voltage output of this chip. Fig. 5 shows the NMIJ-fabricated two volt Josephson chip mounted on the cold plate within the cryostat.

TableⅢ Configuration of NMIJ-fabricated two volt NbN-based programmable Josephson Array

Subarray	Number of junctions subarray	Positive step (1st Shapiro step) at microwave frequency of 16.077 GHz (V)
1	32	0.0010638261
2	32	0.0010638261
3	64	0.0021276521
4	128	0.0042553043
5	256	0.0085106086
6	512	0.0170212172
7	1024	0.0340424343
8	2048	0.0680848687
9	4096	0.1361697373
10	8192	0.2723394747
11	8192	0.2723394747
12	8192	0.2723394747
13	8192	0.2723394747
14	8192	0.2723394747
15	8192	0.2723394747
16	8192	0.2723394747
Total	65536	2.1787157975

Fig. 5 NMIJ-fabricated two volt Josephson chip mounted on the cold plate

IV. CRYOCOOLED PROGRAMMABLE JOSEPHSON VOLTAGE STANDARD

Fig. 6 shows the framework of the domestic

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liquid-helium free programmable Josephson voltage system. Multi-channel bias current source is used to provide bias current for Josephson chip mounted on the cold plate. It is connected to a 25-pin vacuum connector on the cryostat. Voltage output of Josephson chip can be accessed via a 19-pin connector on the cryostat. Microwave source is used to provide 16 GHz to 20 GHz microwave for Josephson chip. 10 MHz frequency reference coming from a rubidium clock is a time base for the commercial microwave source. A cryogenic temperature controller and assorted heater are employed to control the temperature in the cryostat. Digital Volt Meter (DVM) is used as a null detector when measuring the dc voltage reference standard under test. An automatic reversing and multi-selecting system is utilized to change the polarity of the Device Under Test (DUT). It also has 24 channels which are used to select DUT. Fig. 7 shows the cryocooler based PJVS system.

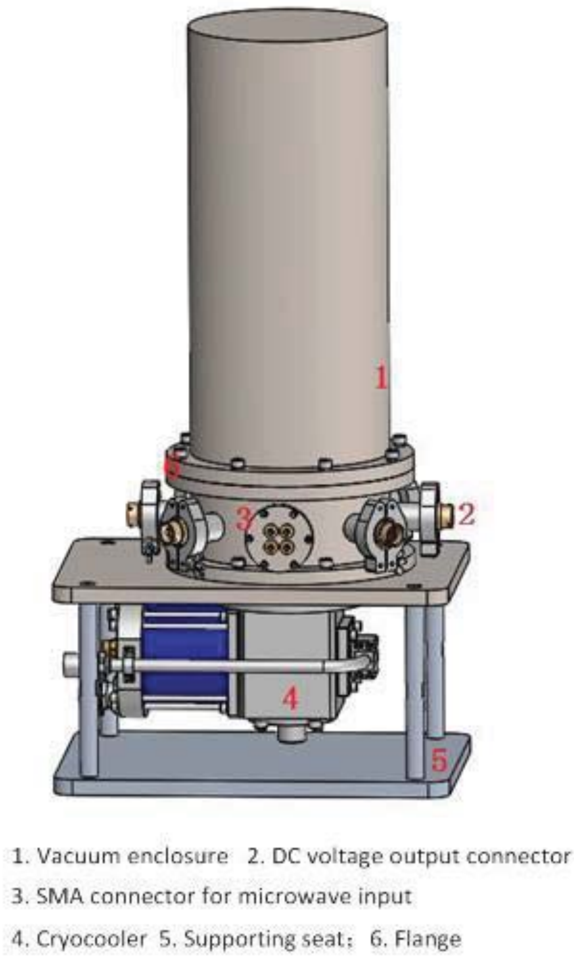

Fig. 6 Framework of liquid-helium free programmable Josephson voltage system

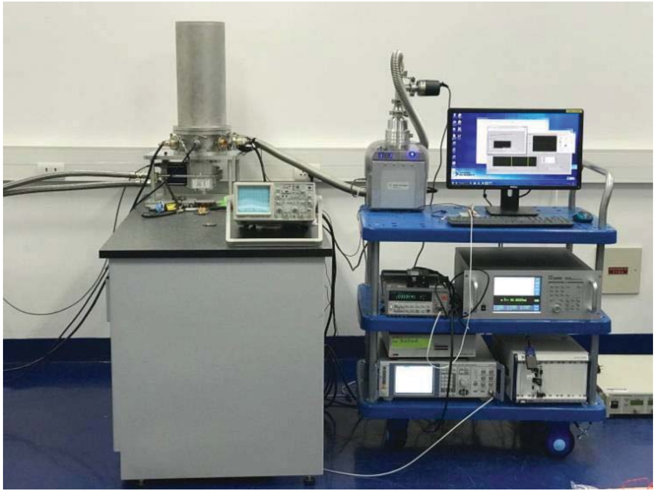

Fig. 7 Liquid-helium-free programmable Josephson voltage system

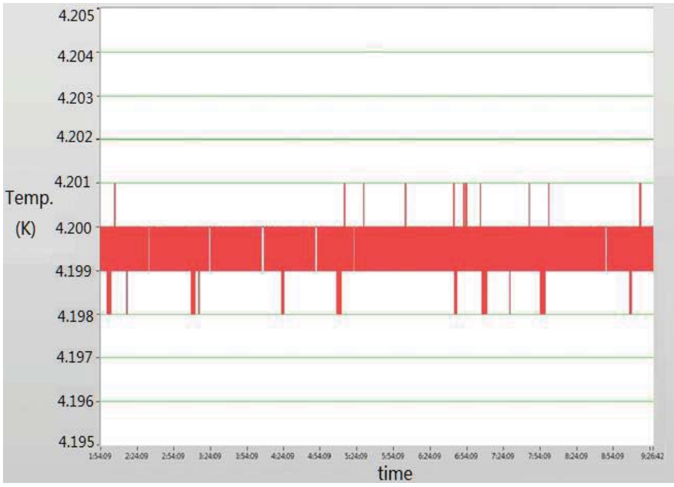

Fig. 8 Temperature stability measurement result

V. EXPERIMENTAL RESULTS AND ANALYSIS

A. Temperature Stability

Cryostat temperature stabilization is one of the most important issues for a cryocooler based PJVS system. Temperature oscillations and temperature gradient may cause the instability of the quantum voltage step generated by the Josephson chip. A low-pass thermal filer and shim with high thermal impedance are used to minimize the temperature oscillations. Pressed Indium foils with synthetic low-temp grease are placed on the contact surfaces between Josephson array chip, AlN isolator and cold head. The temperature measured by the thermos sensor placed on the second stage cold head was recorded in order to observe the temperature stability. Fig. 8 shows the temperature stability measurement result.

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B. Margin measurement

The ideal current-voltage curve of programmable Josephson array driven by a microwave ac signal can be demonstrated as Fig 9. Positive and negative operating margins are also shown in Fig. 9. Margin means the dc bias current range over which the output of Josephson junction arrays does not vary with the bias current and the output value only depends on the microwave signals. Positive margin is defined as the positive quantum voltage on the first Shapiro step (*n*=1). Negative margin is defined as negative quantum voltage on the first Shapiro step (*n*=-1). After measuring the width of positive margin (positive_width), the width of zero step (zero_width) and the width of negative margin (negative_width) for each subarray, a margin table with the specifications of quantum voltage steps could be generated. Positive and negative bias current for each subarray can be finally set to the center of positive margin (positive_bias), the center of zero step (zero_bias), or the center of negative margin (negative_bias). The wider the margin, the more stable quantum voltage step obtained.

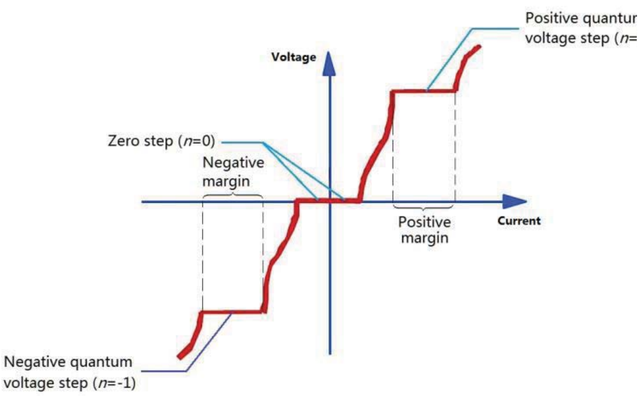


Fig. 9 Ideal current-voltage curve of programmable Josephson array

Fig. 10 shows the measured voltage-current curve of the NMIJ-fabricated programmable Josephson chip with Keysight 34420A voltmeter (subarray 5 with 256 junctions as shown in Table 3). The operating temperature of the second stage cold head is around 10 K. The cold plate temperature measured by the thermosensor is 10.1 K. The microwave frequency for the Josephson chip is 16.04 GHz with power of 23 dBm. Fig. 11 shows the positive margin and negative margin measurement results. The width of both positive and negative quantum voltage steps are larger than 1.0 mA, which ensures the stable performance of chip in our domestic cryocooled PJVS system.

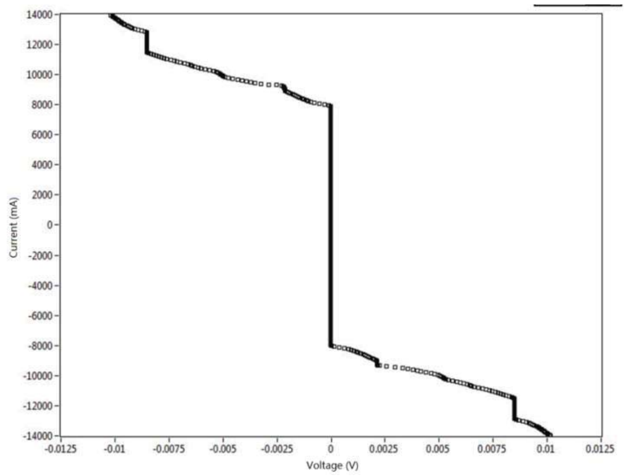
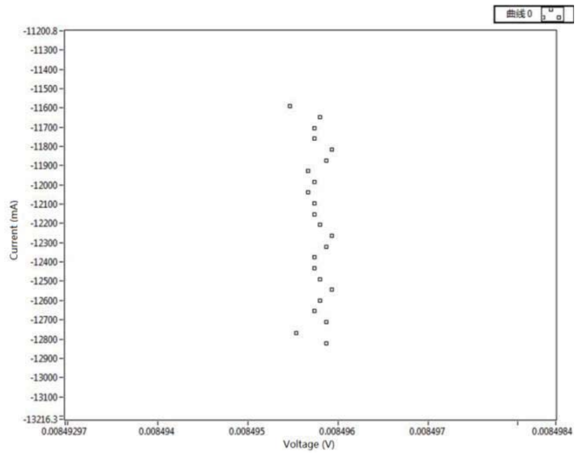
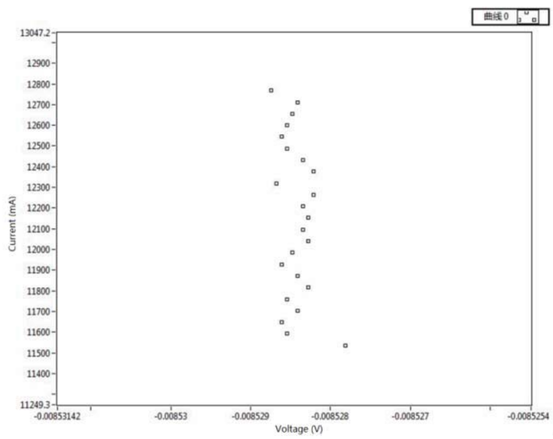


Fig. 10 Voltage-current curve of the NMIJ-fabricated programmable Josephson chip (subarray 5 with 256 junctions)



(a)Positive margin



(b) Negative margin

Fig. 11 Positive margin and negative margin of the NMIJ-fabricated programmable Josephson chip (subarray 5 with 256 junctions)

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Table Ⅳ shows the margin measurement result of NIST-fabricated programmable Josephson chip recorded by Keysight 34420A voltmeter. The microwave frequency is 18.00 GHz with microwave power of 23 dBm. The cold plate temperature measured by the thermosensor is 3.5 K. The width of all the quantum voltage steps (positive_width, zero_width, and negative_width) is more than 1.5 mA. All the measured margin width of each subarray in this cyrocooled Josephson voltage system is a little bit smaller than that in the liquid helium Josephson voltage system (with the same microwave frequency and power). The measured critical current (Ic) is almost the same as in liquid helium system.

Table Ⅳ Margin measurement result of NIST-fabricated programmable Josephson chip with microwave frequency of 18.00 GHz and microwave power of 23 dBm

Subarray	Number of Junctions	Positive_bias	Negative_bias	Positive_width	Zero_width	Negative_width	Ic
1	8800	12.90 mA	-12.88 mA	2.56 mA	11.26 mA	2.56 mA	10.91 mA
2	8800	12.94 mA	-12.93 mA	2.12 mA	10.76 mA	2.22 mA	10.85 mA
3	8798	12.58 mA	-12.69 mA	1.94 mA	10.00 mA	1.84 mA	10.16 mA
4	8800	12.70 mA	-12.77 mA	1.64 mA	10.26 mA	1.80 mA	10.45 mA
5	8796	12.41 mA	-12.48 mA	2.04 mA	9.70 mA	1.94 mA	10.46 mA
6	8792	12.12 mA	-12.15 mA	2.46 mA	8.92 mA	2.30 mA	10.48 mA
7	3888	11.92 mA	-11.97 mA	3.00 mA	9.36 mA	3.10 mA	10.47 mA
8	1296	12.08 mA	-12.08 mA	2.64 mA	9.52 mA	2.64 mA	10.60 mA
9	16	11.32 mA	-11.30 mA	4.10 mA	10.10 mA	4.20 mA	10.61 mA
10	48	12.08 mA	-12.13 mA	3.68 mA	12.04 mA	3.70 mA	10.95 mA
11	144	11.89 mA	-11.88 mA	3.88 mA	10.62 mA	3.86 mA	10.87 mA
12	432	12.19 mA	-12.18 mA	3.56 mA	11.72 mA	3.50 mA	10.81 mA

C. DC voltage standard measurement

This system is successfully used to calibrate 1.018 volt output of the Fluke 732B dc voltage reference standard. A domestic automatic Reversing and multi-selecting system is used to carry out the dc voltage reference standard calibration. The type A uncertainty of 12 measurements is 3.6×10^{-9} V.

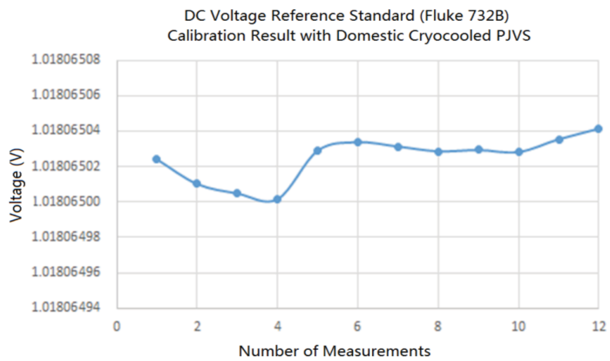

Fig. 12 DC voltage reference standard calibration result

VI. CONCLUSION AND FUTURE WORK

This paper demonstrated a domestic liquid helium free dc programmable Josephson voltage standard (PJVS) operating on a cryocooler at 4K or 10 K. The margin measurement results of a NIST-fabricated two volt Josephson junction array (JJA) and a NMIJ-fabricated two volt JJA are presented. Both of these two kinds of Josephson chip have been shown to operate successfully in the domestic cryopakage. The measured operating margins of all NIST fabricated subarrays are greater than 1.5 mA was obtained. The dc voltage reference standard calibration result with the type A uncertainty of 3.6×10^{-9} V shows a high accuracy of this cryocooled PJVS system.

ACKNOWLEDGMENT

This work is supported by National Key R&D Program of China under Grant No. 2016YFF0200401 and National Natural Science Foundation of China under Grant No. 51307156, and 51477159.

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He Qing was born in Beijing, on August 10, 1965. He graduated in Tsinghua University and got a bachelor degree in 1988. In 1999 he got the master degree from Beijing University of Chemical Technology. In 2009 he got a doctor degree from Harbin Institute of Technology. He joined NIM in 1988 and worked on the establishment of Chinese QHR standard. His current research interests are the joule Balance, ac quantum Hall resistance (ACQHR) and quantum device fabrication.

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