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RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

Establishing of Quantum Voltage Standard in Cryogenic Cooler at TÜBİTAK UME

TÜBİTAK UME'de Kriyojenik Soğutucuda Kuantum Gerilim Standardının Kurulumu

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Abstract

This paper describes the implementation of a programmable Josephson voltage standard in a cryogenic cooler at the National Metrology Institute of Türkiye (TÜBİTAK Ulusal Metroloji Enstitüsü). This work includes the installation of a 10 V Josephson array in the cryostat, installing the devices necessary for its operation, preparing software for system control and optimization, and testing the installed system.
Keywords: Josephson effect, PJVS, Voltage standard, Metrology, SI system

Öz

Bu makalede, TÜBİTAK Ulusal Metroloji Enstitüsü'ndeki kriyojenik soğutucuda programlanabilir bir Josephson gerilim standardının kurulumu anlatılmaktadır. Bu çalışma, 10 V Josephson dizisinin kriyojenik soğutucuda montajını, dizinin çalışmasını sağlayacak cihazların kurulumu, sistemin kontrolü ve optimizasyonu için yazılımların hazırlanmasını ve kurulan sistemin test edilmesi sürecini içermektedir.
Anahtar kelimeler: Josephson etkisi, PJVS, Gerilim standardı, Metroloji, SI sistemi

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1. INTRODUCTION

Quantum voltage standards are intrinsic standards based on the Josephson Effect and produce voltages defined solely by the ratio of natural constants: Planck's constant h, the electron charge e, and frequency [1]. These are known as Josephson Voltage Standards (JVS), and they have been continuously improved over the past four decades, significantly increasing the accuracy of electrical measurements.

Earlier standards, known as conventional standards, were only suitable for DC voltage due to the hysteretic behavior of junctions in Josephson arrays. Recently, substantial efforts have been made to improve these standards so that they can also be used for AC voltage. However, the practical realization of AC voltage is still based on the calorimetric method, which cannot meet all the requirements of modern measurement technology. As a result, two types of Josephson arrays/systems have been developed: the Programmable JVS (PJVS), which can produce step-approximated AC voltages [2] [3], and the pulse-driven JVS, which can produce pure sine waves up to MHz frequencies, also known as the Josephson Arbitrary Waveform Synthesizer (JAWS) [4][5].

TÜBİTAK UME, as the legal scientific authority for national measurement standards in Türkiye, adopted a conventional 10V JVS in 1997 [6] and demonstrated its expertise through several international comparisons [7].

The increasing demand for dynamic measurements and participation in international collaborations led TÜBİTAK UME to initiate a project to establish a PJVS capable of meeting emerging needs. Although such a standard can be purchased today, the manufacturer's built-in software, designed for basic system functions, makes it nearly impossible to use for more complex measurements that typically involve synchronization with external devices. One example is the UME Kibble Balance [8], a complex system in which the PJVS is a subsystem that must be synchronized with other subsystems. To have full control over the process, a unique PJVS with customizable software was designed to meet the specific needs of the Kibble balance setup [9]. This system uses liquid helium to provide the cryogenic environment for Josephson array operation.

As part of this project, the implementation of another UME PJVS is planned, which will be optimized for the calibration of semiconductor voltage standards and the testing of digital converters. Although more challenging, it was decided to build the new system into a cryogenic cooler (or cryocooler) due to practical difficulties in using liquid helium and the growing availability of cryogenic cooler technology.

The following paragraphs present the details of the construction and testing of the new system.

2. SYSTEM DESCRIPTION

The main components of the UME PJVS in cryocooler (CPJVS) are: Josephson Array, bias electronics, cryogenic system, and software. Details of each component are given below.

2.1. Josepson Array

The Josephson array is produced by Supracon AG [10] and has the basic characteristics given in Table 1. The array is fabricated using NbSiX technology with Superconductor-Normal Metal-Superconductor (SNS) layers and contains 69,630 Josephson junctions (JJs) subdivided into 18 segments with a nearly binary sequence.

Table 1. Characteristics of the PJVS Array

Parameter	Value
Number of Josephson Junctions	69630
Operating Frequency	69,6 GHz
Maximum Output Voltage	±10,02 V
Bias Current	3,1 mV
1st Shapiro Step Width	1 mA
Resolution	144 μV (17 bit)
Operating temperature	3,7 K

Figure 1a shows the array, with a small antenna on the right for receiving microwave energy. The array is glued to a small board that has the bias current input connections. During operation, the array generates more than 100 mW of heat, which is not critical when operating in liquid helium but is quite important for array operation in the cryocooler. To maximize heat transfer between the array and the cryocooler cold stage, a special thermal interface [11] was installed by the array provider (Figure 1b).

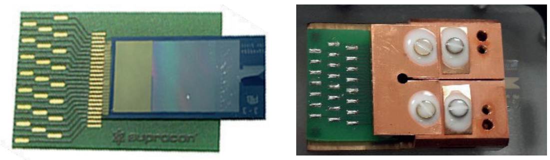

Figure 1. Josephson Array (a) with Thermal Interface (b)

2.2. Cryogenic Cooler

2.1.1. Crycooler Setup

The CPJVS array is cooled by a customized closed-cycle, two-stage pulse tube cooler (PTC) from TransMIT GmbH [12]. The PTC is driven by a 7 kW air-cooled CSA-71A Helium compressor, which requires a three-phase 200 V power supply provided through a special three-phase transformer. The available cooling power is approximately 700 mW at 4,2 K and 500 mW at 3,7 K, the operating temperature of the CPJVS array. The power input to the compressor is around 6,5 kW. Due to noise and heat released during operation, the compressor is installed in a separate room. The temperature of the first stage is 44 K, and the second stage achieves 2,2 K without load. The cold stage temperature increases slightly after installing the array and its wiring. Optimum array operation requires a stable temperature. The cryocooler used dampens the intrinsic temperature oscillations caused by the periodic compression/expansion of the Helium working gas in the PTC by condensing liquid helium into the pot installed at the second stage. As a result, the peak-to-peak temperature oscillations at the array carrier are dampened by about 10 mK, providing sufficient working margins.

The cooler is equipped with three temperature sensors and two heaters, which are used in conjunction with the Lakeshore 335 temperature controller to set the proper operating temperature.

2.1.2. Installation and Wiring of the Array in the Crycooler

The array is mounted to the second stage of the cooler on a special finger designed to fit the thermal interface of the array, shown in Figure-2. The interface is screwed onto the finger, and the thermal contact between the finger and the interface is ensured by a layer of Apiezon N grease [13].

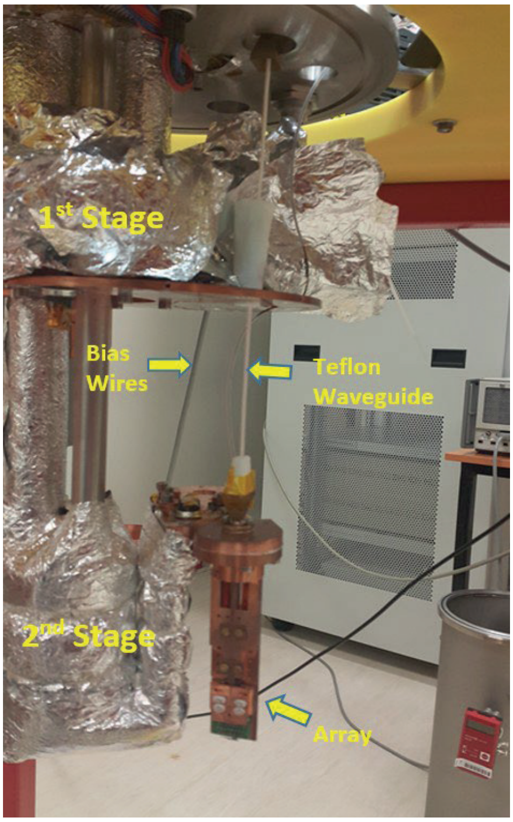

Figure 2. Array and Wiring Inside the Cryocooler

To block the inflow of heat from the outside, the electrical connections to the bias source are made with insulated manganin wires (0,125 mm diameter), tightly twisted together. The voltage output from the chip is made with a twisted pair of thin isolated copper wires (40 µm diameter). All wires are thermally anchored to the surfaces of the first stage. Microwave bias is transferred to the array via a Teflon waveguide inserted between the WR-12 waveguide line using two horn antennas [14]. The finger with the array is magnetically shielded with a Cryoperm cylinder cup. Finally, the second stage with the array is protected by a copper cylinder wrapped in several layers of Mylar foil to ensure maximum protection from thermal radiation.

All connections from the array to the outside are made via vacuum-proof connectors on the top side of the cooler chamber. For the WR-12 microwave connector, a window is made from a thin epoxy layer that can sustain a vacuum of 10^{-5} mbar under microwave radiation.

2.3. Bias Electronics

For the PJVS to operate properly, two signals need to be fed into the array: an RF microwave signal with a known frequency to produce a reference voltage, and a bias current to ensure that the array operates in a flat quantum region.

2.3.1. Current Bias

As already mentioned, the array used has 18 segments in series, each of which is independent. When biased, each segment produces a voltage proportional to the number of its Josephson junctions. The total voltage produced by the array is the sum of the voltages from all the biased segments.

For current biasing, a National Instruments PXIe-6738[1] 32-channel board, mounted in the NI 1082DC PXI chassis, is used. Since this device operates in voltage mode, it is necessary to know the resistance of each segment's path in order to calculate the voltage that produces the required current. As this board has very low source resistances (0,2 Ω), additional resistors were added to each segment's path to keep the applied voltages within regions where the board is more stable. The resistors used have very low inductance, ensuring a fast transition of applied voltages, which is especially important when the PJVS operates in AC mode. Measurements with a high-speed oscilloscope show that the transition time between two voltage steps of this setup is below 2 µs. The resistors are placed in an isothermal box to ensure the stability of the applied current. The array's segment parameters and the total resistance of the connecting paths are given in Table 2.

[1] Commercial instruments are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by TÜBİTAK UME

Table 2. Array Parameters

Segment	JJs	Resistance(Ω)	Voltage @ 69,6 GHz Bias
1	34.814	35,3	5,01047390 V
2	17.408	111,36	2,50538087 V
3	8.704	111,42	1,25269044 V
4	4.352	110,89	0,62634522 V
5	2.176	110,83	0,31317261 V
6	1.088	111,25	0,15658630 V
7	544	111,31	7,8293152 mV
8	272	111,15	3,9146576 mV
9	136	111,06	1,9573288 mV
10	1	111,84	143,9212 µV
11	1	110,91	143,9212 µV
12	1	111,13	143,9212 µV
13	2	111,10	287,8424 µV
14	4	111,30	575,6849 µV
15	8	111,49	1,151370 mV
16	17	111,53	2,446661 mV
17	34	111,94	4,893322 mV
18	68	111,07	9,786644 mV

The bias system is isolated from ground by powering the PXI chassis with a battery, and its communication with the computer is achieved via a fiber-optical connection.

2.3.2. Microwave Bias

Microwave bias is provided by a compact synthesizer produced by the TeraHertz Laboratory, a branch of the TÜBİTAK MAM Institute [15]. The synthesizer can produce up to 200 mW of CW power at frequencies between 69 and 71 GHz, with a resolution of 4 kHz. It is locked to a rubidium frequency standard and controlled by the PC via an isolated RS-232 link. To avoid introducing unnecessary energy into the system, it has been determined that 90 mW is the minimum power the synthesizer should send for optimal array operation. Approximately 40 mW is directly radiated into the array, and the rest is dissipated or reflected along the microwave path.

2.4. Software

The control software is developed using the NI LabVIEW platform. It features several windows with an intuitive graphical user interface, providing the user full control over the system. The main window, "Array Parameters," allows users to set all array parameters, such as the number of segments, the number of Josephson junctions (JJ) in each segment, path resistances, and bias currents. There is also a function that automatically measures the bias current of all segments, but the user also has the option to optimize this parameter manually.

For any selected output voltage of the CPJVS, the program automatically calculates the voltages applied to all 18 bias channels of the array, based on the microwave frequency and array parameters. The output voltage is measured by a high-resolution voltmeter, Keysight 3458A, which is connected to the computer via the GPIB interface.

The user can also access other windows for measurement procedures, such as calibrating a DC voltage standard or determining the linearity of a high-resolution voltmeter. In addition, there are specific subprograms for AC applications, which are more specialized and depend on the instrument under test and its synchronization capabilities with the PJVS.

It should be noted that the UME CPJVS supports clock-in and trigger-out connections with external devices, which is included in each of the specific programs.

2.5. System Operation

The complete system is shown in Figure 3. Before operating the cryocooler, the vacuum chamber with the built-in cold stages is pumped to a pressure of less than 10^{-3} mbar. The cryocooler reaches its final temperature of about 3 K in approximately 8 hours. The cooling process can be monitored through the software, which records the cooling chart.

Once the system has cooled down, the bias electronics are powered on, the software is started, and the system is optimized for operation. This includes tuning the RF generator and determining the optimal bias currents for each segment. When the array enters the optimal operating mode, its I-V characteristics are as shown in Figure 4 (for segments 4-8, for clarity). The flat voltage regions correspond to the quantum-defined voltages of each segment. The widths of the bias currents that induce quantum voltage are important parameters, as they indicate the operating margins of the system.

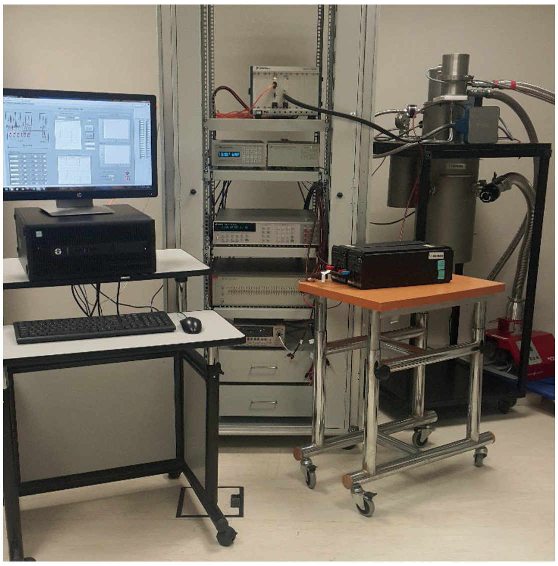

Figure 3. UME CPJVS

In the UME CPJVS, these currents range from 0,6 mA for the four largest segments to about 1 mA for the smaller ones. The bias currents, which are set to the middle of the quantum voltage regions in the software, act as the operating points for each segment. These currents cluster around 3,1 mA, with a maximum variation of 0,3 mA, depending on the segment, which is consistent with the manufacturer's specifications for the array. The optimal bias currents generally do not change during the same cryogenic operating cycle, and any changes are more likely related to trapped currents (or flux) within the array. This phenomenon occurs when external electrical noise is injected into the chip while it is in the superconducting state via cables. It usually manifests as very narrow or non-existent flat voltage regions in the I-V characteristics of one or more segments.

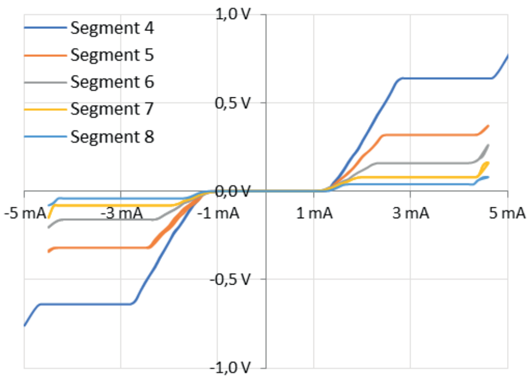

Figure 4. I-V characteristics of Segments 4-8

In such cases, the array can be heated to exit the superconducting state using the temperature controller and heater installed between the first and second cooling stages. When the temperature sensor on the second stage reads 12 K, maintaining this temperature for about 10 minutes is sufficient to clear the trapped current.

Once the bias currents are optimized, the system is ready for use. In the first stage, a high-resolution voltmeter is used to test the system at several voltages. During this process, the optimal bias currents are deliberately varied (dithered) to confirm that the chip is operating in the quantum regime. This practice is also applied for other measurements. If it is observed that the width of the voltage step is below the specified criterion, the chip heating procedure is performed.

3. SYSTEM TEST

3.1. DC Voltage

As previously mentioned, TÜBİTAK UME has been using a DC conventional JVS since 1997, proven in several international comparisons. These comparisons typically use a DC standard with a known drift as a traveling standard. The UME CPJVS was compared to the existing system using the same approach. For comparison, a Fluke 732B DC standard, calibrated periodically with the UME JVS for over 25 years, was used. This ultra-stable DC source has outputs of 1,018 V and 10 V. During the measurement, the DC standard is connected in reverse series with the UME CPJVS, adjusted as close as possible to the DC standard output, and their difference is measured using a Keithley 2182A nanovoltmeter.

To remove offsets and thermal voltages in the loop, the measurement is performed in two stages, forward and reverse polarity mode. A special low-thermal switch is used to connect the DC standard, which has a fixed polarity, unlike the CPJVS, which can be easily reversed by software. The actual output of the DC standard is calculated as the sum of the CPJVS voltage and the measured difference. The measurement results show that the difference between the measured and predicted value at 10 V is about 20 nV, which is far below the uncertainty of the DC standard calibration. The excellent agreement between the two systems can be seen in Figure 6, which shows the long-term drift trend of the DC standard along with the measurements of both systems.

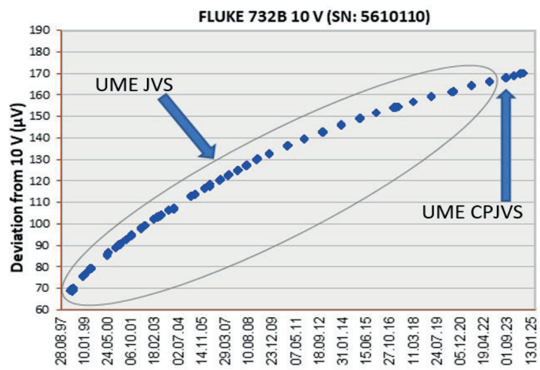

Figure 5. Long-term Drift of the DC Standard

3.2. AC Voltage

PJVS systems can generate voltages very quickly due to their non-hysteretic array. This feature allows for the creation of time sequences of voltages with arbitrary shapes, which requires synchronization and timing of all segments of the array, i.e., bias channels. As previously mentioned, the UME CPJVS uses a multichannel board as a bias current source, and all channels are synchronized directly on the board. Additionally, the board can be synchronized with external devices through timing and trigger connections.

The rms accuracy of the PJVS synthesized signals is limited by the transition time between steps, which depends on the wiring and bias electronics. However, the steps of the generated waveform are intrinsic quantum voltages and are suitable for use with digital converters. As an example, the synthesis and application of a sine signal, commonly used in AC applications, is shown here.

3.2.1. System Description

Figure-7 shows the schematic of the system used for testing a digitizer (Keysight 3458A) in dynamic mode using the UME CPJVS.

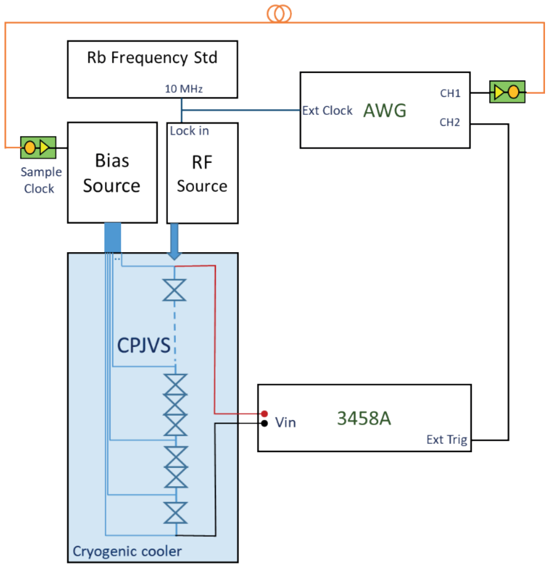

Figure 6. System for Testing Digitizer Using UME CPJVS

The digitizer used has a 28-bit integrative DAC and allows full control over its measurement functions, such as resolution, timing, and sampling parameters. It is synchronized to the UME CPJVS using an arbitrary waveform generator (AWG) locked to a rubidium frequency standard. The other channel of the AWG is connected to the CPJVS bias source via fiber-optic electro-optical converters to keep the system in floating mode.

3.2.2. Measurement Procedure

The test signal applied by the CPJVS is a 20-step approximated sine wave with a 2 Vpp amplitude at a frequency of 62,5 Hz. The system software automatically calculates each of the 20 step voltages and loads them to the bias source. Since 20 steps are used for each period of the signal, the AWG Channel 1 will set the clock signal for the bias source to 62,5 × 20 = 1250 Hz. Channel 2 of the AWG is adjusted to the frequency at which the digitizer will sample the signal, in this case, 50 kHz, i.e., 800 points per period will be measured. The sampling parameters of the digitizer are set as follows: voltage range: 1 V, DCV digitizing mode, integration time: 3 *μs, and trigger mode: external. The measurement performed with these parameters over five successive periods is shown in Figure-7. There are small transition regions between the steps due to the finite transition time, where the measured voltages are not defined (zoomed-in circle). In this example, only one point is visible due to the relatively low sampling frequency, but at higher frequencies, more points will fall into the transition region. These points are discarded, and the remaining data is used to calculate the average voltages of each step and the dynamic gain of the digitizer at the given frequency.*

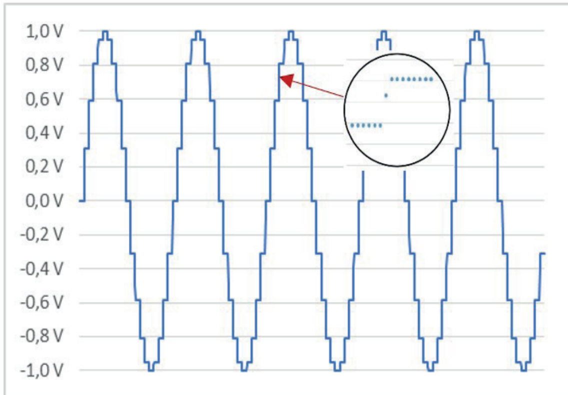

Figure 7. UME CPJVS Step-Approximated Sine Wave Measured by Digitizer

To determine whether the operation of the UME CPJVS in AC mode is regular, the same measurement was repeated by applying each step as a DC voltage and measuring it with the digitizer set to the same sampling parameters as for AC. The difference in voltages measured in the two different modes at each step was smaller than the standard deviation of the measurement, which proves that the system operates in a regular quantum state.

4. CONCLUSION

The establishment of the TÜBİTAK UME CPJVS system was presented. Full control over the system and user-friendly operation in the cryogenic cooler were the main goals of the project, and these goals were successfully achieved. The tests performed show that the system is capable of producing a reference voltage for the calibration of DC voltage standards and can also be used in the calibration of digital converters.

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