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APPLICATIONS OF THE PROGRAMMABLE JOSEPHSON VOLTAGE STANDARD IN VOLTAGE METROLOGY

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Abstract: A new type of Josephson junction array using current biased voltage steps can provide highly stable and accurate voltages. The superior voltage stability of such a Josephson voltage standard has many applications in dc voltage metrology. This paper describes the working principle of the programmable Josephson voltage standard (PJVS) using this new array technology and a few examples of its applications.

Keywords: Josephson voltage standard comparison; programmable Josephson voltage standard (PJVS); voltage dissemination; uncertainty

1. INTRODUCTION

The Josephson voltage standard (JVS) has been widely used in many national metrology institutes around the world to maintain and disseminate voltage to the end user, such as calibration laboratories, instrument manufacturers and scientific researchers. In North America, especially in the United States, the JVS is also used in many industrial, military and government laboratories. The JVS is based on the physical law that an ac current of frequency f applied to a Josephson junction generates a dc voltage V_n at the quantized values

$$V_n = nhf/2e \qquad (1)$$

where n, the step number, is an integer and the value used for $2e/h$, is the value of K_{J-90} = 483 597.9 GHz/V which is the conventional value of the Josephson constant adopted worldwide on January 1, 1990 [1].

In order to establish confidence in the JVS operation, the comparison between JVS systems in different laboratories is a common practice. Most of the JVS comparisons use Zener standards as transfer standards. An array to array direct comparison may achieve smaller uncertainty. However, this type of comparison sometimes is difficult to carry out due to the intrinsic instability of zero current biased voltage steps. A voltage step jump from either JVS system during the comparison requires restarting the data acquisition process. A new type of programmable Josephson junction array uses a current biased voltage step which has the same accuracy provided by the zero current biased Josephson junction array and is based on the same quantum phenomenon described by Eq. (1). The voltage steps of a programmable Josephson junction array are highly stable because these voltage steps are biased at different currents with high current margins. This unique property of the step accuracy and stability can achieve better uncertainty and is more efficient and easier to operate. This paper describes the working principle of a programmable Josephson voltage standard (PJVS) and presents a few examples of the PJVS applications.

2. WORKING PRINCIPLE OF PJVS

The programmable Josephson voltage standard (PJVS) was developed in 1997 at NIST using the Superconductor-Normal metal-Superconductor (SNS) junction [2]. The disadvantage of the zero current biased Josephson junction array, shown in Figure 1(a), is the step number n cannot be uniquely specified by any operating parameter in the system. Hence, the output voltage can exhibit spontaneous jumps triggered by noise in the measurement circuit or electromagnetic interference from the surrounding environment. By contrast, the PJVS is biased at non-zero current, leading to a non-hysteretic junction that has distinct voltage values depending on the bias current, as shown in Figure 1(b). Unless the bias current changes, the voltage output of a junction is set to be stable for an infinite time period. In the present PJVS design, only three bias currents, $-I_n$, 0, $+I_p$ are used, leading to steps of n = -1, 0, or +1, which implies a voltage output of –V, 0, or +V. In the PJVS, the array junctions are grouped into segments, with all junctions in a segment being biased by a common bias current, and each segment having a number of individual junctions taken from a binary sequence. Hence, each segment can be individually programmed to one of the three operating states by setting its bias current. Thus, the output voltage of the full array can be digitally programmed by applying the appropriate combination of bias currents to the various segments.

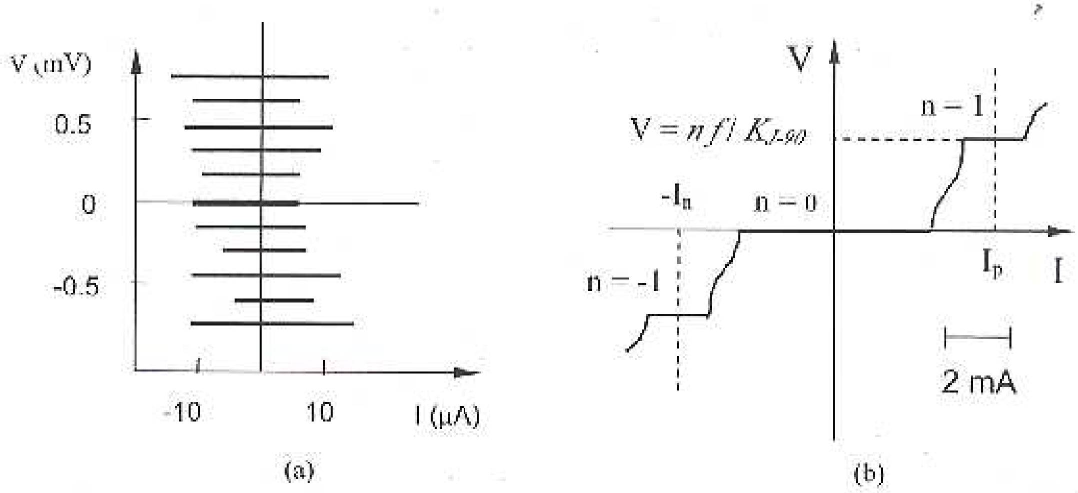

Figure 1. Voltage steps of (a) zero current biased Josephson junction array, (b) programmable Josephson junction array.

The PJVS can be programmed to provide a stable output anywhere between $-V_{Max}$ and $+V_{Max}$ where V_{Max} is determined by the total number of junctions in the array. The resolution of the voltage output is determined by the number of junctions in the smallest segment. A state-of-the art array design can contain more than 67 000 junctions on a two-layer structure with 16 junctions in the smallest segment [3]. Table 1 shows the construction of a programmable Josephson junction array used in the NIST Voltage Laboratory. By programming a combination of segments and their bias currents, a stable voltage up to 2.6 V can be generated.

Figure 2 shows the block diagram of a PJVS system. The bias source provides bias currents for each of the segments in the array. The bias current for an individual segment can be positive, negative or zero depending on whether the voltage output required is positive, negative or zero. In order to avoid electromagnetic interference from ac power coupling to the bias circuits, the bias source electronics uses dc power supplied by lead-acid rechargeable batteries. Microwaves for the array are provided by a microwave source with an attenuator and RF amplifier to obtain the optimum RF power level for array operation. A PC controls all the electronics through a GPIB interface.

Segment	Number of junctions	V (mV)
1	8800	327.810
2	8800	327.810
3	8798	327.736
4	8800	327.810
5	8794	327.587
6	8800	327.810
7	8792	327.512
8	3888	144.833
9	1296	48.278
10	16	0.596
11	48	1.788
12	144	5.364
13	432	16.093

Table 1. Construction of a programmable Josephson junction array and its voltage output with microwave frequency 18.014588 GHz.

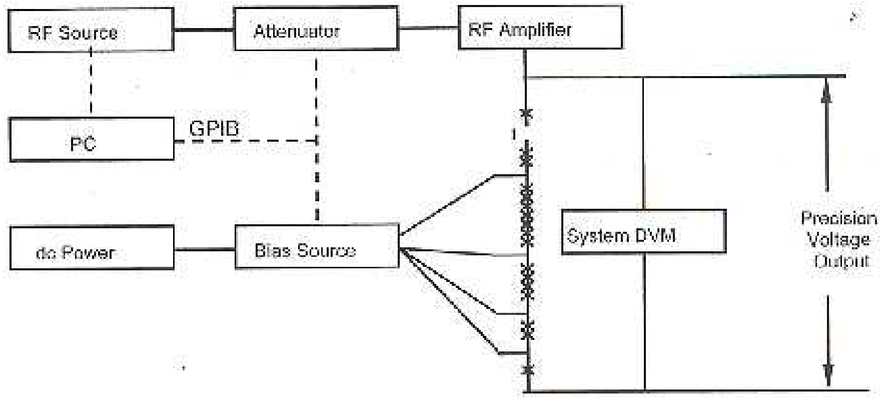

Figure 2. PJVS block diagram.

3. Characterization of PJVS

Before a PJVS can be used for calibrating a device under test (DUT), it must be optimized for its operation. This includes finding the best operating microwave frequency and power level, and characterizing the working parameters for each segment such as bias current, step margin etc. The operating frequency for the programmable array is designed to be between 15 GHz to 18 GHz. The optimum operating frequency range is determined by scanning the frequency and finding the maximum current margin for the voltage steps. Figure 3 is an example of array frequency characteristics, which shows that the best operating frequency is between 17.82 GHz and 18.03 GHz. The current margin corresponding to the frequency varies between 1.7 mA and 2.0 mA. The rich structure is unique to each array chip and is due to interference between the 8 microwave transmission lines that distribute microwave power to the junctions. Since the frequency characteristics vary from array to array, it is necessary to characterize the frequency response for each array to ensure the best performance of its voltage output.

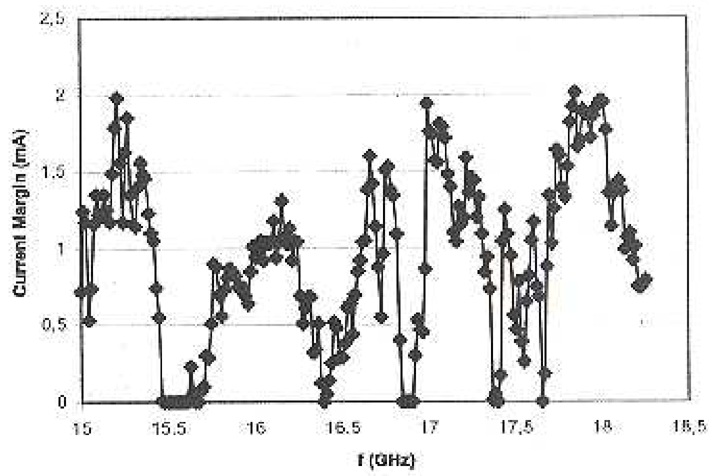

Figure 3. Frequency characteristics of a programmable Josephson junction array.

In order to maintain a stable voltage step, the segments must be biased at the center of the steps as shown in Figure 1(b). The optimal bias current for each segment is slightly different, and each optimal current can be slowly shifting due to the changes in the liquid helium level in the Dewar. It is important to characterize the PJVS at the time of use to determine the bias currents for each segment. This process is completely automated and is performed by an instrument control program and takes approximately 10 min to complete. Table 2 lists the parameters of a programmable Josephson junction array containing 13 segments, where I_p is the bias current for a positive voltage step, I_n is the bias current for a negative voltage step, pHEIG is the current margin of a positive voltage step, nHEIG is the current margin of a negative voltage step, and zHEIG is the current margin of a zero voltage step. For example, if segment 1 is chosen, the bias current for a positive voltage output is 13.22 mA.

Table 2. Bias currents and voltage step margins. All currents in mA.

Segment	Number of junctions	I_p	I_n	pHEIG	zHEIG	nHEIG
1	8800	13.22	-13.22	2.11	8.27	2.11
2	8800	12.84	-12.77	2.18	6.97	2.17
3	8798	13.40	-13.39	1.95	8.48	1.96
4	8800	13.14	-13.05	2.14	8.32	2.15
5	8794	13.15	-13.12	1.91	7.75	1.90
6	8800	13.03	-13.02	2.22	8.22	2.24
7	8792	12.67	-12.64	1.87	6.34	1.86
8	3888	12.92	-12.93	2.31	8.74	2.30
9	1296	12.79	-12.80	2.38	9.05	2.37
10	16	12.13	-12.19	3.16	9.72	3.16
11	48	12.59	-12.67	2.74	10.14	2.77
12	144	12.73	-12.81	2.95	9.93	2.95
13	432	12.82	-12.87	2.78	10.09	2.80

Uncertainty sources of the PJVS come from the frequency reference, leakage resistance of the cryoprobe, thermal voltage fluctuation in the leads, RF induced offset and noise in the measurement circuit. The uncertainty in voltage measurement caused by the frequency reference is proportional to the noise of the frequency reference, which can be measured using the Allan variance deviation. For most frequency standards, such as a cesium clock, disciplined GPS or other types of high performance frequency references, the Allan variance deviation is between a few parts in 10^{11} and few parts in 10^{12}. The measured leakage resistance between the two precision leads is $6.5 \times 10^{11}\ \Omega$. With a lead resistance of about 10 Ω, the uncertainty caused by the leakage resistance is negligible. We have also measured the combined uncertainty contributed by the thermal voltages in the leads, RF induced offset and the noise in the measurement circuit. In approximately 15 min, the standard deviation of the short measurements at the operating frequency and power level of the PJVS was found to be 3.9 nV. This is the most significant component in the PJVS uncertainty budget. The total uncertainty of the PJVS at 1 V is thus 3.9 nV or 3.9 nV/V. Table 3 summarizes the uncertainty of the PJVS for a 1 V output. When the PJVS is used for calibrating Zener standards or standard cells, other uncertainty components such as the thermal voltages from the switches should be included.

Table 3. PJVS uncertainty at 1 V.

Component	(nV)
Time base	0.001
Leakage	0.015
Leads thermal voltage, RF induced offset and noise in the circuit	3.9
Total uncertainty	3.9

4. Applications of PJVS

The superior stability and accuracy of the PJVS have found many important applications in voltage metrology and scientific research. At NIST we routinely use PJVS for array to array direct comparisons to establish confidence in our JVS operations. We are in the process of implementing a PJVS as a replacement for the primary standard cell groups that have played an important role in voltage dissemination in the last 70 years. A PJVS is now being used for voltage measurement in the electronic mass experiment to improve the uncertainty of the voltage transfer by a factor of 6 compared to uncertainty of the transfer using a Zener standard.

4.1 Direct array to array comparison

A convenient way to make a JVS comparison is to use Zener standard as transfer standard. A majority of the JVS comparisons are carried out by shipping Zener standards from one laboratory to another. The uncertainty of such comparisons is limited by the characteristics of the Zener standards used as transfer standards. These characteristics include *1/f* noise floor, environmental effects on the Zeners and the shipping impact on the Zeners during transit. In the last several NCSLI[1] JVS interlaboratory comparisons, the uncertainty has been in the range of a 20 nV/V. The error sources in this range are therefore not obvious in these comparisons. To improve the comparison uncertainty, an array to array direct comparison between JVSs is used. BIPM has carried out many direct array comparisons over the last decade [4]. The array stability is critical in the array to array direct comparison. A step jump of the zero current biased array of either system during the measurement requires starting the data acquisition process again.

The highly stable voltage steps of the PJVS can make array to array direct comparison feasible for future JVS comparisons. At NIST, comparisons between a

[1] National Conference of Standards Laboratories (NCSL) expanded its membership and was renamed as NCSL International (NCSLI) in 2000.

conventional JVS using the zero current biased array and a PJVS using a programmable Josephson junction array, are routinely performed to establish confidence of array system operation. The difference between the two voltages can be measured by a low noise DVM. Figure 4 shows the result of such a comparison at 1.018 V. The difference between the two systems is 0.09 nV with an expanded uncertainty of 0.83 nV/V at 95 % confidence. Such comparisons are carried out at the 1 V or 2 V level due to the limit of the PJVS maximum voltage output. Several national metrology institutes are putting much effort into array development to raise the maximum PJVS voltage to 10 V. The uncertainty of a JVS comparison using the PJVS at the 10 V level is expected to achieve a few parts in 10^{11}.

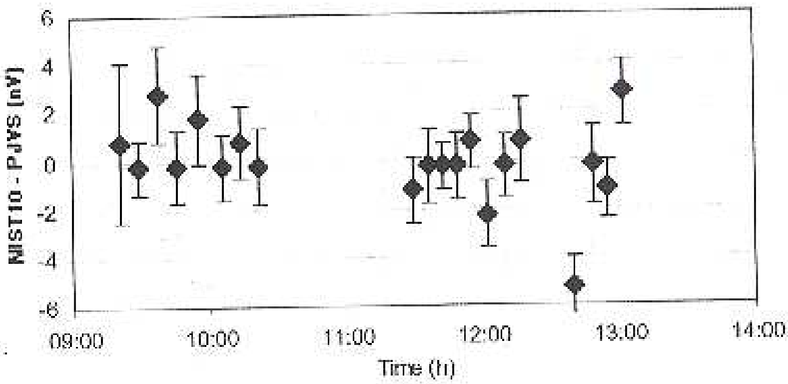

Figure 4. Direct comparison between the zero current biased array and the programmable Josephson junction array at 1.018 V.

4.2 PJVS implementation in NIST volt dissemination

The NIST dissemination chain for dc voltage is illustrated in Fig. 5 [5]. The primary standard cell groups are used to perform the daily calibrations of a working cell group and the standard cell calibration workload. The primary standard cell groups at NIST have been well maintained in enclosures with very stable temperature control. The variation or noise of these cell groups is smaller than the noise of Zener standards. The cell groups exhibit very linear drift characteristics so their output value at the time of use can be predicted very accurately between transfers from the NIST JVS systems. For the last three decades, since the advent of Josephson-based voltage references, the NIST primary standard cell groups have continued to play a critical role in disseminating the volt to calibration customers. The cells in the NIST primary cell groups are aging and some can exhibit erratic behavior, which requires reconfiguration of the cell groups to exclude poorly performing cells. The supply of high quality standard cells around the world is very limited and is decreasing. Hence, finding a suitable backup or replacement for the NIST primary standard cell groups has become a high priority task that must be completed to maintain a healthy national dissemination system.

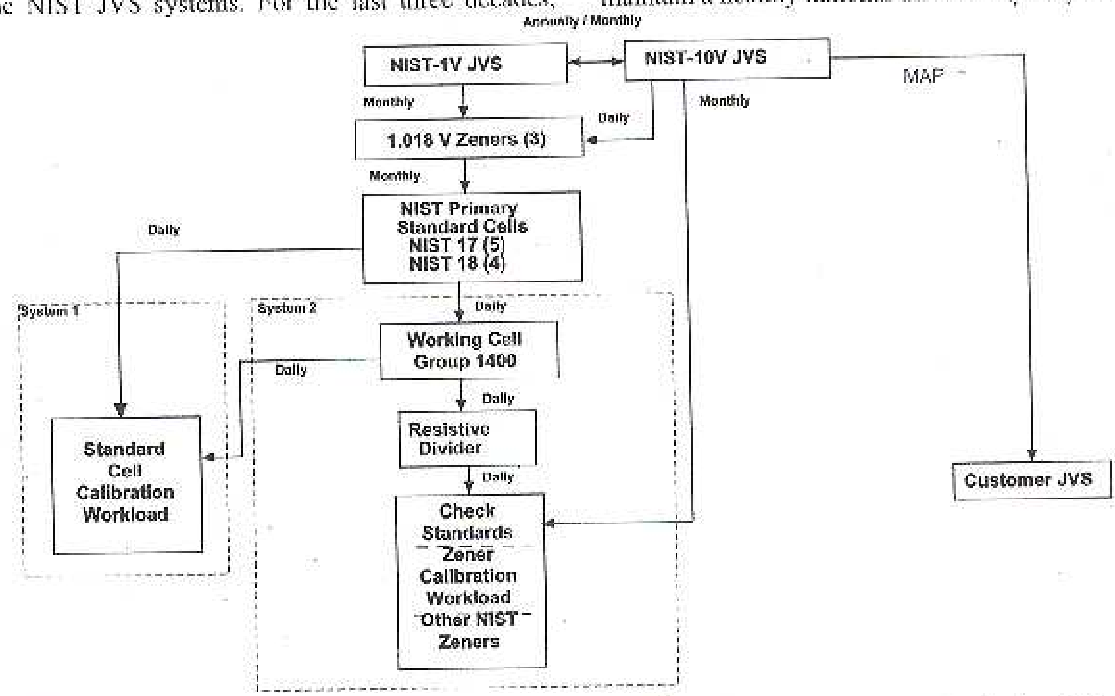

Figure 5. NIST voltage dissemination chain. The primary standard cell groups play an important role in transferring the volt from the JVS and disseminating the volt to calibration customers.

The superior stability of the voltage output from the PJVS makes it an attractive backup and potential replacement for the NIST primary standard cell groups. Figure 6 shows the streamlined NIST voltage dissemination chain. Several steps in the dissemination chain shown in Figure 5 are eliminated. The PJVS can make direct calibrations at 1.018 V for a Zener standard or a standard cell. The PJVS can also calibrate a ratio divider from 1.018 V up to 10.18 V, which provides for the calibration of 10 V Zener standards.

The new dissemination chain improves the reliability, efficiency and uncertainty of the voltage disseminat... process. In all these measurements, the uncerta... PJVS is negligible compared to the short-term noise of the DUT. The streamlined voltage dissemination chain reduces the calibration uncertainty by reducing the required number of voltage transfer steps between the primary reference and the DUT.

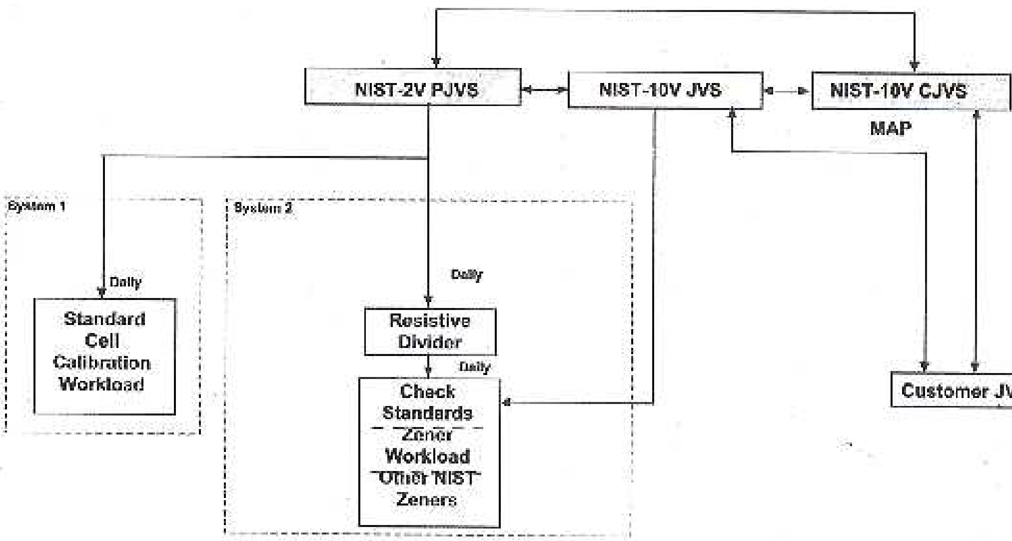

Figure 6. Streamlined NIST volt dissemination chain.

There are other advantages obtained by incorporating the PJVS into the dissemination chain to replace the primary standard cell groups. Because a large temperature change in the enclosure for the primary standard cells can cause a permanent voltage shift, strict temperature control and 100 % reliability of laboratory power are essential to maintain a stable working environment. These requirements can be reduced in the streamlined dissemination chain. A stable temperature is still required in general for making satisfactory measurements, but excursions do not lead to permanent problems.

4.3 PJVS in the NIST electronic mass experiment

The NIST electronic mass experiment relates the kilogram to the Josephson voltage standard and the quantum Hall resistance standard. The experiment measures the Planck constant precisely and provides a scientific basis for redefinition of the Kilogram, the last artifact in the SI unit system. The experiment consists of two separate modes proposed first by Kibble [6]. In the force mode a coil carrying a current I in a magnetic field generates a force that balances the gravitation force of a standard mass in local gravity g. A geometric factor can be calculated from the quotient mg/I. In the velocity mode the same coil is moving in the magnetic field with velocity v, generating an induced voltage V. The same geometric factor is calculated by the quotient V/v. So long as the magnetic field profile is steady, by taking the ratio of two quotients, the ratio of mechanical to electrical power is calculated. Thus the artifact mass standard can be related to the Planck constant through the quantum electrical standards for voltage and resistance.

Before a PJVS was incorporated in the electronic mass experiment, the voltage measurements in the force mode had been made by a voltage drop across a 100 Ω reference resistor with a constant current source. This voltage was calibrated against a Zener voltage standard. Figure 7(a) shows the voltage measurements in the force mode. In the velocity mode the voltage generated by the moving coil was measured by comparing with a Zener voltage standard directly. The Zener standard in turn was calibrated against a zero current biased JVS. The uncertainty from the voltage measurement is about 30 nV/V, largely determined by the Zener noise characteristics. The uncertainty of the voltage measurement was the third largest contribution to the total uncertainty budget with the two largest being the index of refraction and alignments. The conventional JVS is not suitable to measure the voltages directly in the electronic mass experiment because of the voltage step jump caused by electromagnetic interference in the measurement circuit. The voltage step margin of a PJVS is in the range of 2 mA, about 100 times larger than that of the conventional JVS. This property makes it possible to use PJVS for the voltage measurement directly without using a Zener standard transfer. The uncertainty contribution from Zener transfer is thus eliminated. A PJVS has been incorporated for the voltage measurements since 2003 as shown in Figure 7(b). The present uncertainty using PJVS for all voltage measurements is now reduced to 5 nV/V, a factor of 6 improvement. A further reduction in the uncertainty for the voltage measurement is expected [7].

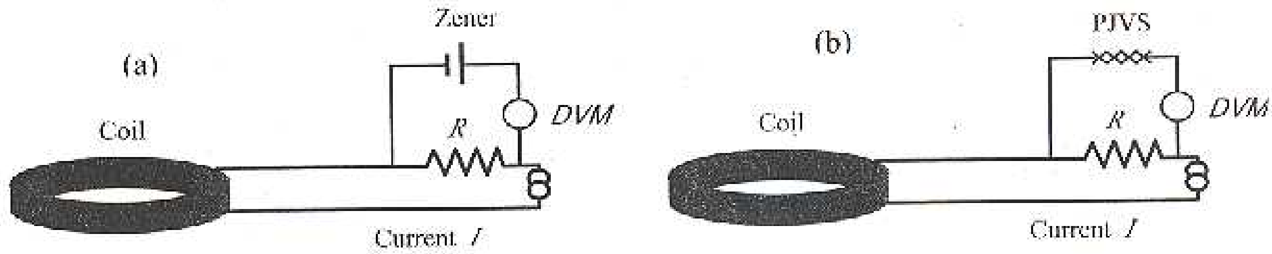

Figure 7 Voltage measurement in the force mode of the electronic mass experiment (a) via Zener standard, (b) against a PJVS directly.

5. Summary

The new programmable Josephson junction array, which is based on current biased junctions, provides substantial advantages compared to the traditional zero current biased arrays, primarily due to the stability of its voltage steps. A PJVS using the current biased array has been used for array to array direct comparisons because no spontaneous step jump can occur in the PJVS. A PJVS is also being implemented into the NIST voltage dissemination chain to replace the primary standard cell groups. The new dissemination chain will have improved reliability and efficiency. PJVS also has an application in the NIST electronic mass experiment. The implementation of the PJVS reduces the uncertainty of the voltage measurement via Zener transfer by a factor of 6. At the present time, the programmable Josephson junction array works at 1 V to 2 V. Using multi-layer array technology may raise the voltage limit up to 10 V in a few years. A 10 V PJVS is expected to find more applications in future voltage metrology.

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