Direct Comparison between the NIST 10V Compact Josephson Voltage Standard and the 2.5 V Programmable Josephson Voltage Standard*

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Abstract

The NIST 10V Compact Josephson Voltage Standard (CJVS) and 2.5V Programmable Josephson Voltage Standard (PJVS) were directly compared at 1.018 V and 2.511 V in February 2007. The difference between the two systems at 1.018 V (i.e. CJVS – PJVS) was -0.09 nV with an expanded uncertainty of 4.72 nV or a relative uncertainty of 4.72×10^{-9} at the 95% confidence level where as the difference between the two systems at 2.511 V was 0.00 nV with an expanded uncertainty of 4.04 nV or a relative uncertainty of 1.61×10^{-9} at the 95% confidence level. These intercomparison results demonstrated the satisfactory performance of the CJVS system handling minor trapped flux in the array and the effectiveness of the "NISTVolt software" to manage step jumps in the measurements.

Keywords: compact Josephson voltage standard CJVS), intercomparison, programmable Josephson voltage standard (PJVS), uncertainty

1. Introduction

The Josephson voltage standard (JVS) is the primary standard of voltage and it is used as the SI representation of the unit Volt. It can be used to calibrate Zener voltage standards, standard cells and digital voltmeters [1-2]. Since all JVSs are based on the same physical principle, the concept of traceability in an unbroken dissemination chain is not applicable to JVSs. The intercomparison between two JVS systems is performed to check their performances and establish some degree of equivalence between them. Since JVS systems are too delicate and bulky for transport, a set of Zener voltage standards is mainly used as a traveling artifact for the intercomparison between the JVS systems. Most of the indirect JVS comparisons are accomplished by transporting Zener standards between the participating labs and have an uncertainty of a few parts in 10^8 at 10V, which is limited by Zener noise, non-linear drift of Zener standards, environmental effects and shipping impact. In order to detect errors of a few parts in 10^8 that are related to the JVS hardware and software and to improve the uncertainty the comparison, the JVS systems are directly intercompared. The direct comparison between two conventional JVS systems that have

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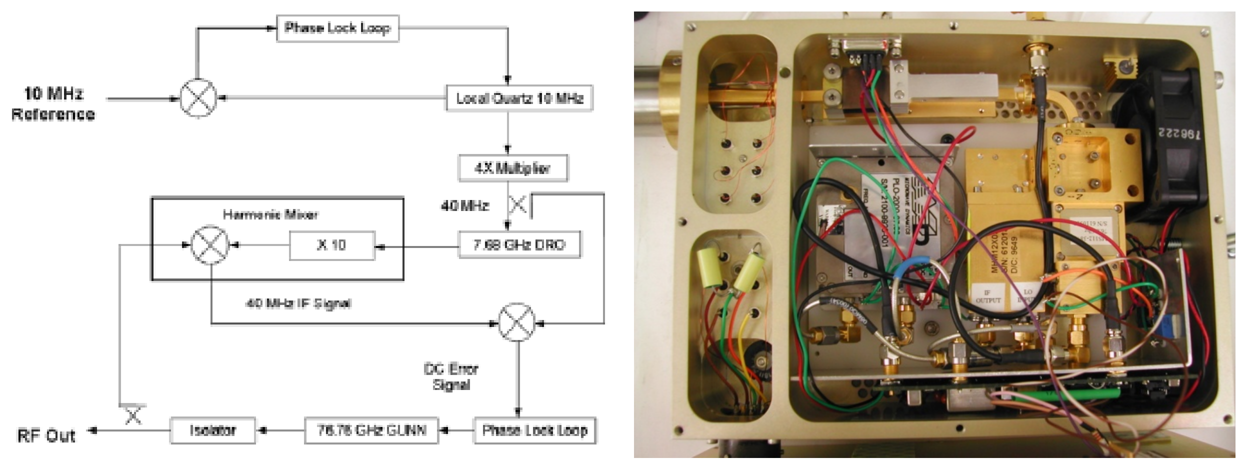
SIS (i.e. Superconductor-Insulator-Superconductor) arrays is a very difficult task due to the noise in the measurement system which results from step jumps during the measurement. These SIS arrays have hysteretic I-V characteristics. These comparisons are usually done manually. The current margin of a SIS array is about 20 µA which makes it very sensitive to electromagnetic interference (EMI) and noise. To overcome the sensitivity issues, arrays using SNS (Superconductor-Normal Metal-Superconductor) junctions have been developed. The SNS arrays have non-hysteretic I-V characteristics, leading to a more stable step environment. The current margin of these SNS arrays is about 2 mA which is about 100 times more immune to noise and EMI than the SIS arrays. The programmable Josephson voltage standard (PJVS) employs the SNS array for near perfect stability and fast programmability. The PJVS works as a stable voltage source just like a Zener reference standard but avoiding the Zener's dependency on its noise and environmental parameters. The PJVS output voltage is immune to these parameters and is a near perfect stable voltage source which can be directly measured by a conventional 10V JVS through the NISTVolt software's automatic mode, appearing like a Zener standard in the measurement circuit. The PJVS and conventional JVS were for the first time directly intercompared in 1997 at NIST and the agreement was 0.5 nV at 1V with a Type A uncertainty of 1.1 nV [3]. Subsequently, the PJVS was deployed in the NIST dc voltage dissemination chain starting in 2000 to accomplish the streamlining of the traceability chain through its replacement of the Primary group of standard cells. Since 2000, the PJVS has been used regularly for the intercomparison of NIST10 and the CJVS to check their compatibility. In 2005, a recent intercomparison between the PJVS and the conventional 10V JVS (i.e. NIST10) was performed and the difference between the two systems was determined to be -0.52 nV at 1.018 V with a Type A uncertainty of 0.0.58 nV or a relative uncertainty of 5.7×10^{-10} at the 95% confidence level. The difference between the two systems also at 2.511 V was found to be -1.44 nV with a Type A uncertainty of 0.55 nV or a relative uncertainty of 2.2×10^{-10} at the 95% confidence level. For North American and international intercomparisons, a special 10 V compact Josephson voltage standard (CJVS) was developed by NIST for easy transportability. The CJVS was constructed by NIST using a fixed microwave frequency at 76.76 GHz. The CJVS system can be transported very easily and can be set up in a remote location within hours. This system has been used for JVS intercomparisons within North America (i.e. the NCSLI JVS ILC 2005), which has resulted in an improvement in the JVS intercomparison uncertainty by a factor of around 10 versus the uncertainty that can be accomplished from transporting Zener standards for a JVS intercomparison. The CJVS is capable of detecting very small errors which cannot be detected through the use of a Zener standard as a transfer artifact [4].

2. NIST 10V Compact Josephson Voltage Standard System (CJVS)

The conventional laboratory JVS is built by the integration of several instruments (such as a digital voltmeter, bias electronics, frequency counter and low thermal scanner etc.), microwave components and cryogenic components into a system. The details concerning the construction and operation of the conventional JVS system have been extensively described elsewhere [1-2]. It is difficult to transport a conventional laboratory JVS to another location for an intercomparison. The CJVS, however, includes four major components: the cryoprobe, bias electronics, a low noise DVM and a laptop computer which makes the system light weight in comparison, weighing only approximately 20 kg (excluding the liquid helium Dewar). It can be easily shipped in two cases and set up in a remote location in a few hours. The CJVS uses the same type of Josephson junction array as the conventional JVS which is based on the superconductor-insulator-superconductor (SIS) design.

The CJVS that was constructed at NIST uses a fixed microwave frequency of 76.76 GHz and integrates the microwave frequency assembly with the cryoprobe. The unique design of the frequency assembly eliminates the frequency counter, thereby reducing the weight of the system. This makes the system compact and transportable. Fig. 1 shows the 76.76 GHz microwave assembly. A local 10 MHz quartz oscillator is phase-locked to a 10 MHz frequency reference from a Global Positioning System (GPS) or Cesium clock. A quadrupler generates a 40 MHz frequency from the 10 MHz signal. Inside the cryoprobe, the 40 MHz signal is supplied as a reference to a Dielectric Resonance Oscillator (DRO) with an internal phase-lock loop (PLL) circuit. The DRO operates at 7.68 GHz. Its tenth harmonic 76.8 GHz is mixed with the 76.76 GUNN Oscillator, creating a 40 MHz intermediate frequency (IF). This 40 MHz IF output is appropriately amplified and mixed with the original 40 MHz quartz signal to provide a dc error signal. The dc error signal is then provided to the GUNN tuning to generate a phase-locked stable microwave frequency at 76.76 GHz for the Josephson array operation. The uncertainty of the fixed frequency 76.76 GHz is determined by the 10 MHz frequency reference and is in the range of a few parts in 10^{12} or better. The entire measurement process is controlled by the "NISTVolt software" which has been developed by NIST to automate the JVS System [4-5]. Fig. 2 shows a photograph of the NIST 10V compact Josephson voltage standard system.



(a) (b)

Fig.1 (a) Block diagram of a 76.76 GHz source for Josephson array operation;
(b) 76.76 GHz microwave assembly built-in cryoprobe.

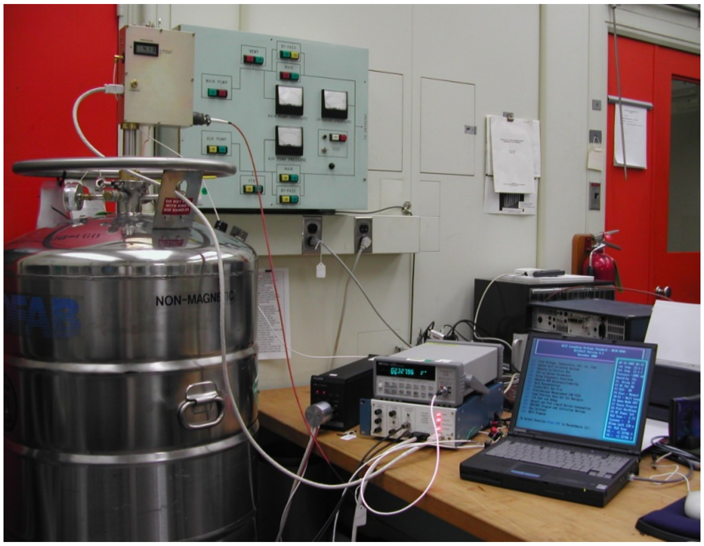


Fig. 2. Photograph of NIST 10V Compact Josephson Voltage Standard.

3. NIST 2.5 V Programmable Josephson Voltage Standard System (PJVS)

The PJVS uses a Josephson junction array that is based on the superconductor-normal metal-superconductor (SNS) junction technology [6-7]. It uses non-zero bias current for the array leading to a non-hysteretic I-V characteristic that has distinct voltage values depending on the bias current. Unless the bias current changes, the voltage output of a junction is set to be stable for an infinitely long time. In this PJVS design, only three bias currents, $-I_n$, 0, $+I_p$, are used, leading to steps of n = -1, 0, or +1 which corresponds to the output voltage of –V, 0, or +V where I_p is the bias current for a positive voltage step and I_n is the bias current for a negative voltage step. In the PJVS, the array junctions are grouped into segments, with all the 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 combinations of bias currents to the various segments (cells). The maximum output voltage of the PJVS depends upon the total number of junctions in the array. The PJVS chip used in the NIST Volt laboratory has 67408 junctions mounted on a two-layer structure which gives a maximum output voltage of 2.511026925 V at 18.014588 GHz. The current margin of the voltage steps of the NIST SNS array is about 2 mA and it is approximate 100 times bigger than that of the conventional zero crossing steps of a conventional SIS array. Therefore, the PJVS is much more immune to noise and electromagnetic interference when compared to the SIS array.

Fig. 3 shows the block diagram for a PJVS system while Fig. 4 shows the photograph of the NIST 2.5V Programmable JVS system. The bias source provides the bias current 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 output voltage required is positive, negative or zero. In order to avoid electromagnetic interference from the AC power coupling to the bias currents, the bias source electronics uses DC power that is supplied by a set of lead-acid rechargeable batteries.

The microwave radiation for the array is 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 [8].

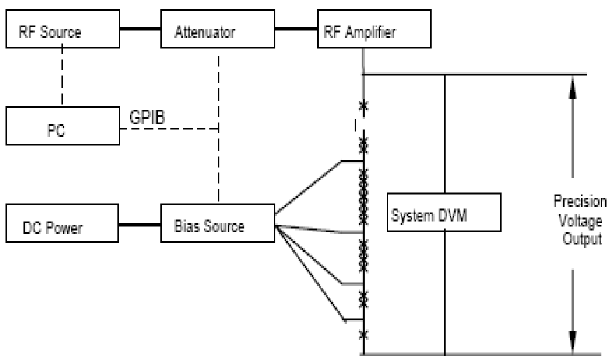


Fig. 3. Block diagram of a PJVS system.

Fig. 4. Photograph of the NIST 2.5V PJVS system.

4. Intercomparison Procedure

For the intercomparison between the CJVS and PJVS, the PJVS was defined as a Device under Test (DUT) in the "NISTVolt software". The polarity of the PJVS was reversed by reversing the bias currents for the selected PJVS array segments. Before connecting the two systems for intercomparison, the PJVS was first initialized using an operating frequency of 18.014588 GHz and the frequency synthesizer set to of 1 dBm RF power. The PJVS array attains its best performance at this frequency and power level. During the initialization process, the optimal bias currents for each segment are determined. This process has been completely automated and is performed by the PJVS instrument control program and completion of this task takes approximately 10 minutes [8].

The PJVS array has 13 segments (or cells) with each segment supplying a different number of junctions. The smallest segment contains 16 junctions while the largest segment contains 8800 junctions. Table 1 shows the construction of the PJVS array used in by NIST for volt dissemination and Table 2 shows the segments combination used to generate output voltages of 1.018 V and 2.511 V, where p is the positive polarity of the segment, n is the negative polarity of the segment and 0 is the segment not selected

Table 1. Construction of the PJVS array and its voltage output at the microwave frequency of 18.014588 GHz.

Segment	Number of junctions	Output voltage (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 2. PJVS array segment combinations and the associated array output voltage.

Nominal output voltage	Actual output voltage	Segments combinations (Sequence from 1 to 13)
+1.018 V	+1.0179999972 V	pp0p0000ppp0n
-1.018 V	-1.0179999972 V	nn0n0000nnn0p
+2.511 V	+2.5110269253 V	ppppppppppppp
-2.511 V	-2.5110269253 V	nnnnnnnnnnnnn

After the completion of the initialization process, the output voltages of the two systems were connected in series opposition as shown in Fig. 5.

The grounding configuration shown in Fig. 5 achieved the best voltage steps with minimum noise. The PJVS itself was not grounded. The shield of the precision output voltage leads of the PJVS, the Dewar and the cryoprobe head were connected together and also connected to the shield of the precision output voltage leads of the CJVS. The Dewar, cryoprobe and shield were connected together and grounded through the AC power cord of the JVS1000 bias controller (i.e. the systems were grounded at CJVS end).

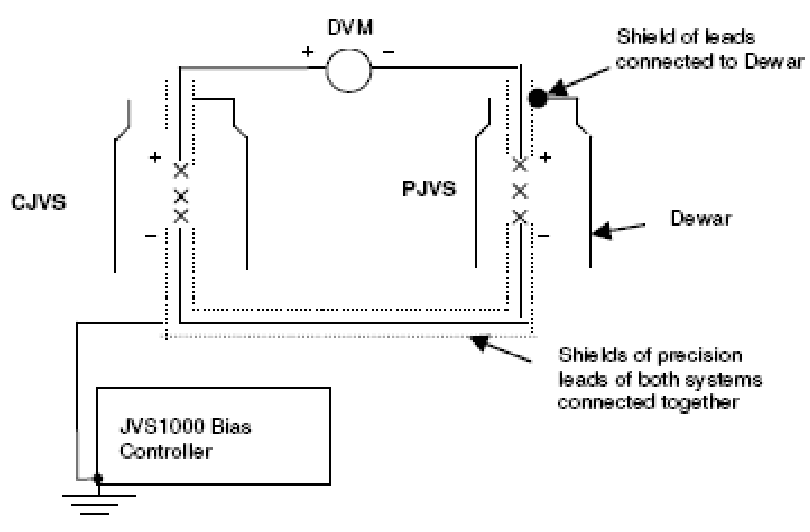


Fig. 5. CJVS and PJVS grounding diagram for the intercomparison

The PJVS was measured by the CJVS using the “NISTVolt” software with the CJVS appearing like a Zener Standard in the measurement circuit. No scanner or reversing switch was used to eliminate the thermal voltages in the measurement circuit. A measurement sequence of + - + - was used where + represents the positive array polarity and – represents the negative array polarity. The thermal EMF and its drift can be largely compensated for by the reversal of the array polarity. The CJVS and PJVS array polarities are controlled by their bias sources electronically. The final result is calculated using a 3 parameter least square fit of the measurements.

5. Data analysis and Results

The difference *D* between the CJVS and the PJVS is computed as the mean of the *N* differences of the paired measurements:

$$D = \frac{1}{N}\sum_{i=1}^{N}(V_{ithpaired}^{CJVS} - V_{ithpaired}^{PJVS}) \tag{1}$$

where $V_{ith\,paired}^{CJVS}$ is the average of a normal and reverse measurement of the PJVS system by the CJVS system. The standard deviation σ and Type A uncertainty u_A of the comparison can be calculated as

$$\sigma = \sqrt{\frac{1}{(N-1)}\sum_{i=1}^{N}\{(V_{ith\,paired}^{CJVS} - V_{ith\,paired}^{PJVS}) - D\}^2} \tag{2}$$

$$u_{\mathrm{A}} = \sigma / \sqrt{N} \tag{3}$$

The combined standard uncertainty u_{c} of the comparison can be calculated by the following equation:

$$u_c = \sqrt{u_A^2 + u_B^{CJVS\,2} + u_B^{PJVS\,2}} \tag{4}$$

The intercomparison between the two JVS systems was carried out using the above configuration. Table 3 shows the estimated 1σ Type B uncertainties for the CJVS and PJVS. Table 4 shows the intercomparison results that were obtained from the measurements. Fig. 6 shows the distribution of the results at 1.018V and 2.511V without any trapped flux in the CJVS array while Fig. 7 shows the distribution of the results at 2.511V with some minor trapped flux in the CJVS array.

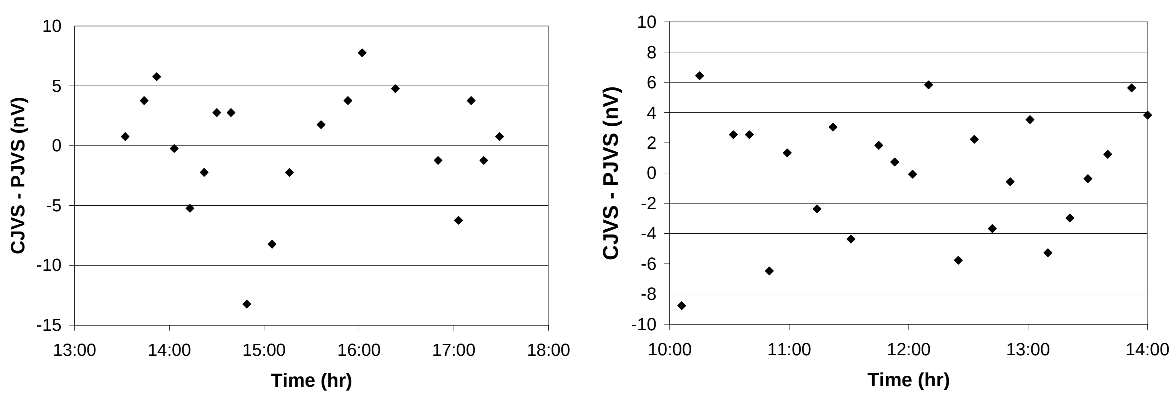
Table 4 lists the results of the three comparisons to illustrate measurement performances of the systems under different conditions. The Type B uncertainty from the PJVS and CJVS includes the contributions of the time base and the leakage of the cryoprobes. Since the PJVS performs like a perfect voltage source, its DVM is used only to monitor its array output voltage and its DVM is not used to measure the voltage difference between the CJVS and PJVS arrays, the DVM gain error of the PJVS DVM is not a component in the direct comparison uncertainty. Since the CJVS DVM is used to measure the voltage difference between the CJVS and PJVS arrays, the CJVS DVM gain error does affect the direct comparison uncertainty and has been included as a component in the comparison uncertainty budget. The effects of the thermal EMFs of the comparison measurements are included in the Type A uncertainty. The combined uncertainty is the RSS of the Type A and Type B uncertainty contributions [9-10].

Table 3. Estimated 1σ Type B uncertainties for the CJVS & PJVS direct comparison at 1.018 V and 2.511V.

Sources of uncertainty	Direct comparison uncertainty (nV)			
	at 1.018 V		at 2.511 V	
	CJVS	PJVS	CJVS	PJVS
Time base	0.006	0.001	0.015	0.003
Leakage	0.081	0.015	0.023	0.038
DVM gain error	1.80	–	1.80	–
Total	**1.802**	**0.015**	**1.811**	**0.038**

Table 4. Intercomparison results

	CJVS - PJVS (nV)	Type A uncertainty (nV)	Expanded uncertainty at 95% CL (nV)	Nominal Voltage (V)	Remarks
1.	-0.09	1.52	4.72	1.018	No trapped flux in the CJVS array
2.	0.00	0.89	4.04	2.511	No trapped flux in the CJVS array
3.	1.51	0.70	3.88	2.511	Trapped flux in the CJVS array



(a) (b)

Fig. 6. Plot of voltage differences between the CJVS and PJVS without trapped flux in the CJVS array (a) at 1.018V (b) at 2.511V .

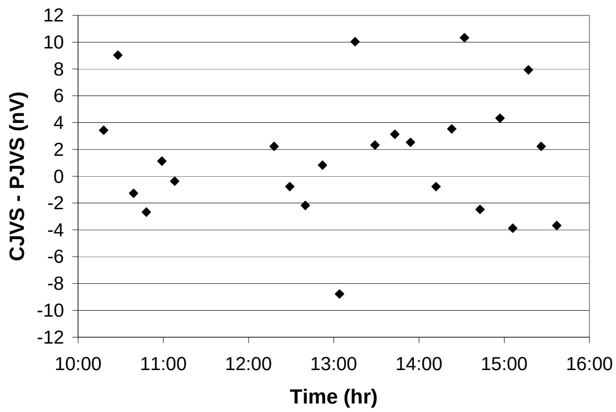


Fig. 7. Voltage differences between the CJVS and PJVS with minor trapped flux in the CJVS array at 2.511V

The agreement between the two systems at 1.018 V was -0.09 nV with an expanded uncertainty of 4.72 nV at the 95% confidence level. The agreement between the two systems at 2.511 V was 0.00 nV with an expanded uncertainty of 4.04 nV at the 95% confidence level. Even with the incident of trapped flux, the CJVS's performance was quite reasonable with the difference only 1.51 nV with an expanded uncertainty of 3.88 nV. Due to the trapped flux in the CJVS array, there were many step jumps, leading to larger offsets and scatter (Type A uncertainty) in the measurement results as shown in Fig. 7. However, the step jumps during the measurement process were ably handled by the NISTVolt software without a significant loss of accuracy.

6. Conclusion

The NIST CJVS was directly intercompared against the PJVS to verify its satisfactory performance. The CJVS system gives its best performance when the precision measurement leads are well shielded. The intercomparisons between the two systems were carried out with and without trapped flux in the CJVS array. The intercomparison results demonstrated the excellent agreement of -0.09 nV at 1.018V and 0.00 nV at 2.511 nV with the expanded relative uncertainty ($k = 2$) from 4.72 to 1.61 parts in 10^9 at these voltages. Even with minor trapped flux in the CJVS array, the result was quite reasonable, proving the CJVS can maintain stable voltage steps. These results definitely verified the satisfactory operation of these two quantum standards whose arrays are based on two different array junction technologies.

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