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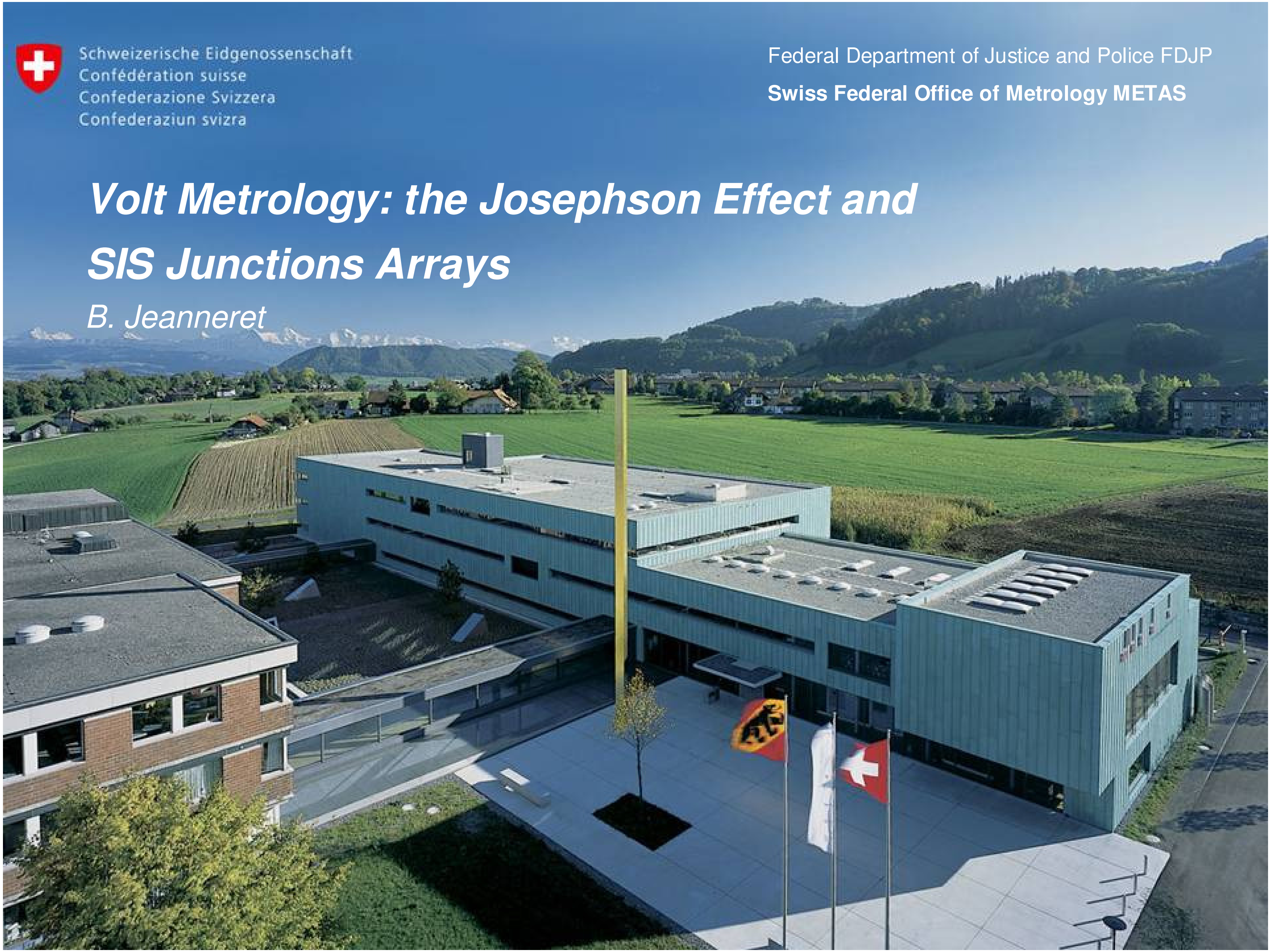
Volt Metrology: the Josephson Effect and SIS Junctions Arrays

B. Jeanneret



Volt Metrology: the Josephson effect and SIS Arrays

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B. Jeanneret
Swiss Federal Office of Metrology (METAS)

Outline

- Voltage unit: Definition, Realization, Representation
- Superconductivity: a rather quick overview
- The Josephson Voltage standard
    - Josephson effect
    - Josephson junction array
    - The primary standard
- Applications
    - Zener calibration
    - DVM Linearity
    - Watt Balance, Metrological triangle
- Conclusions

Voltage Unit: Definition

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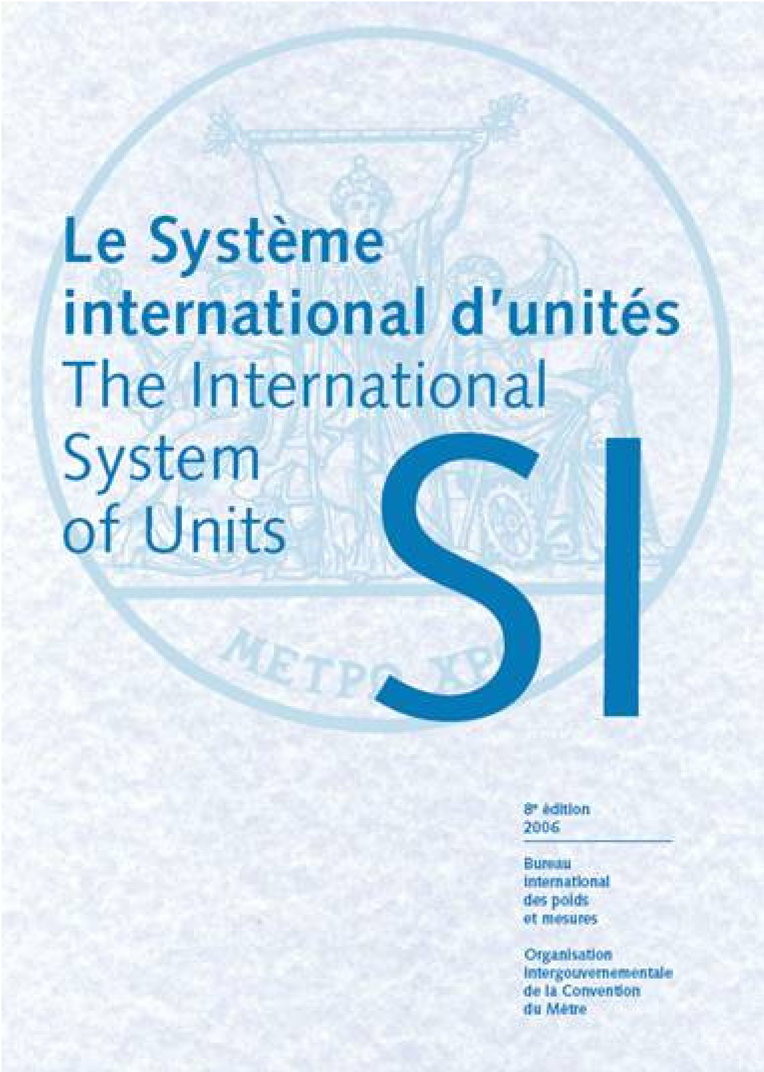

9ème CGPM, 1948:

Le volt est la différence de potentiel électrique qui existe entre deux points d'un fil conducteur transportant un courant constant de 1 ampère, lorsque la puissance dissipée entre ces points est égale à 1 watt.

$$1\ \mathrm{V} = 1\ \mathrm{W/A} = 1\ \mathrm{m^2\ kg\ s^{-3}\ A^{-1}}$$

Voltage Unit: Realization with Hg electrometer

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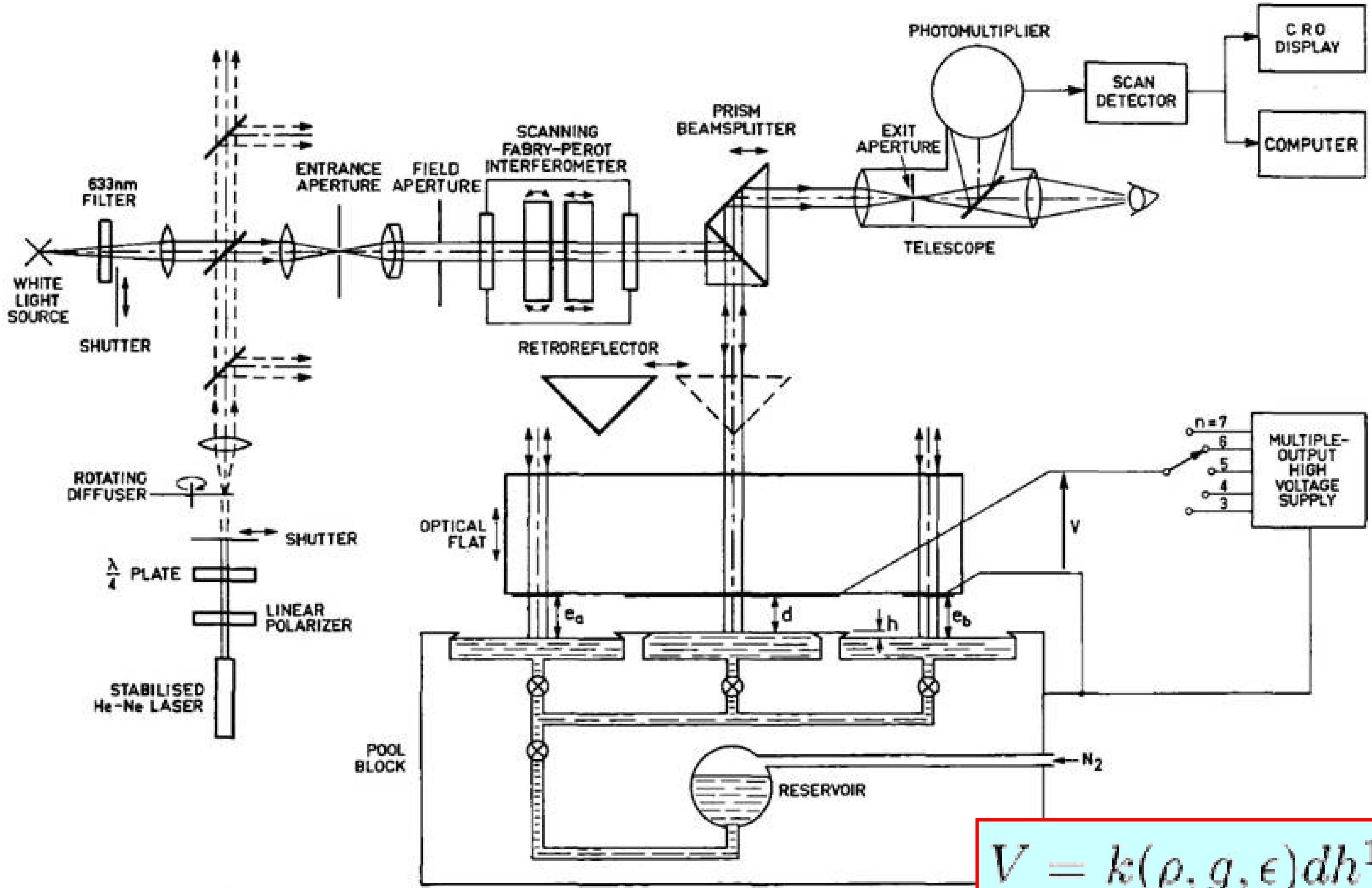


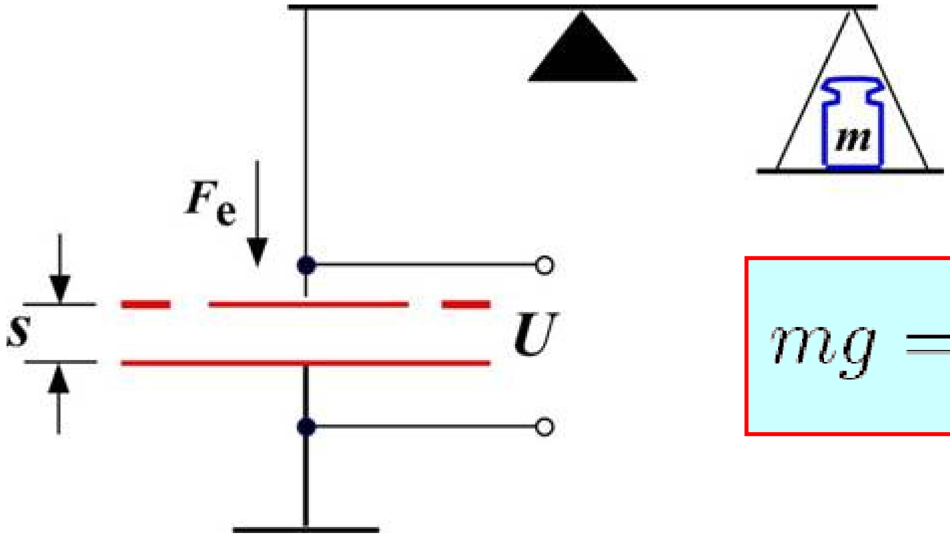
Fig. 1. Schematic of absolute liquid electrometer and optical measuring system

$$V = k(\rho, g, \epsilon) d h^{1/2}$$

Clothier et al, Metrologia 26, 9 (1989).

Uncertainty: 0.27 ppm

Voltage Unit: Realization with a Voltage Balance



$$mg = \frac{1}{2}U^2\frac{dC}{ds}$$

T. Funck et al. , IEEE Instr. Meas. 40-2, 158, 1991.

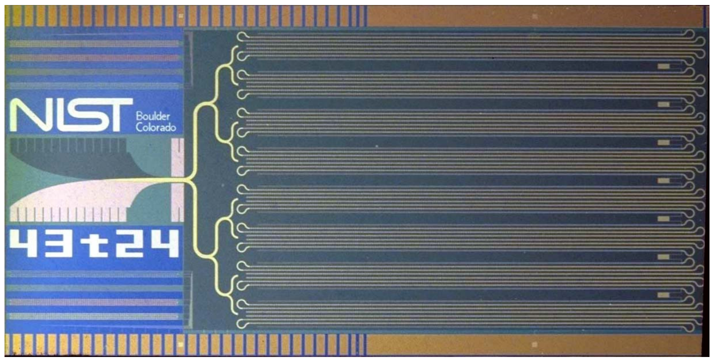
Uncertainty: 0.31 ppm

Summary:

The SI volt is realized with an uncertainty of 0.3 ppm

Voltage Unit: Representation

- 1794: A. Volta, First electrochemical cell, current source
- 1836: Daniell, Zn-Cu cell as the first stable voltage standard
- 1883: Clark cell (Zn-Hg) as a standard to maintain the unit volt
- 1908: Weston cell (Cd-Hg), U = 1.018 V, *International Unit* realization
- 1948: Introduction of *Absolute Units*
  → Weston cells became only a representation of the volt
- 1960: Introduction of the SI
- 1962: Discovery of the Josephson effect
- 1972: Single junction voltage standard (few mV)
  → Weston cell became obsolete
- 1985: 1 V Josephson junction array
- 1987: 10 V Josephson junction array, **uncertainty < 0.001 ppm**



Voltage Unit: Representation

- 1908: Weston cell (Cd-Hg), U = 1.018 V, *International Unit* realization
- 1948: Introduction of *Absolute Units*
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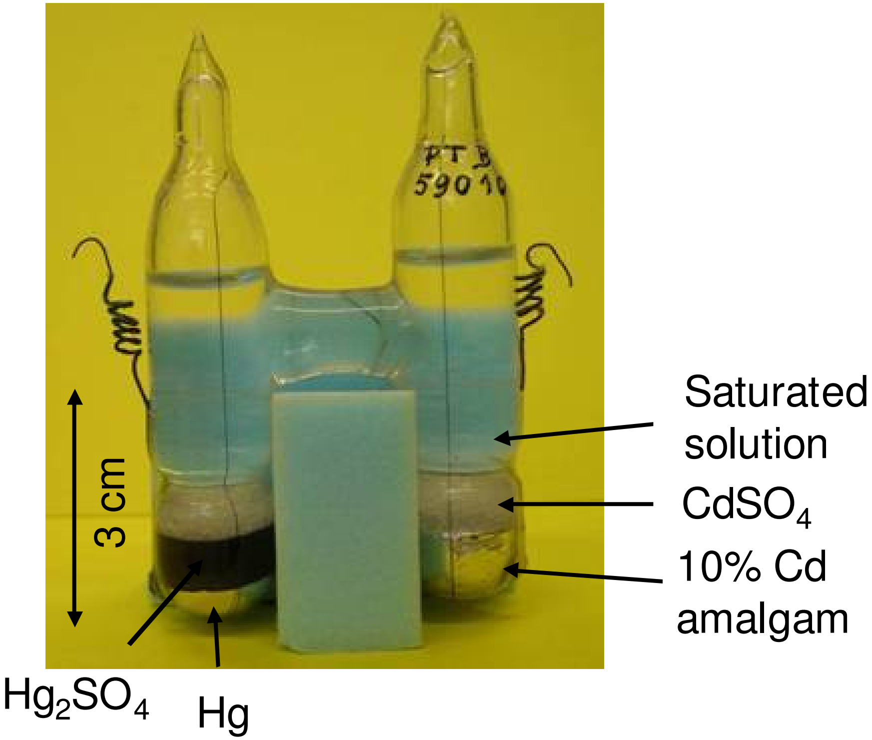

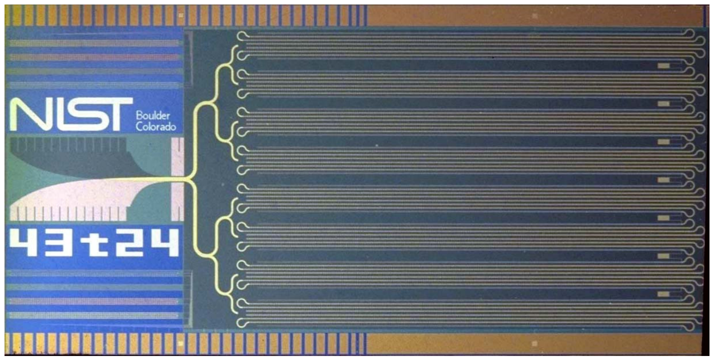

Voltage Unit: 1990 Conventional value

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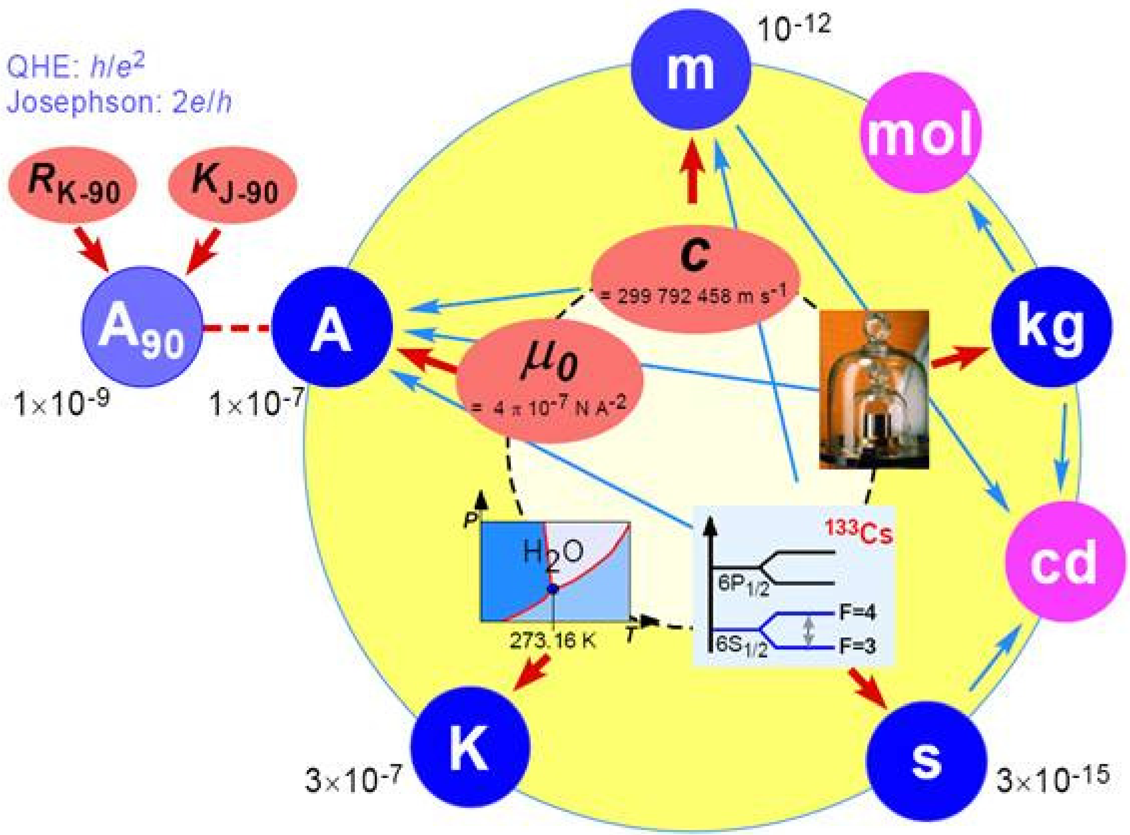

$$V = \frac{h}{2e} f = K_{\mathrm{J}}^{-1} f$$

$$K_{\mathrm{J-90}} = 483'597.9 \mathrm{GHz/V}$$

Uncertainty in the SI: 0.4 ppm

Voltage Unit: Representation

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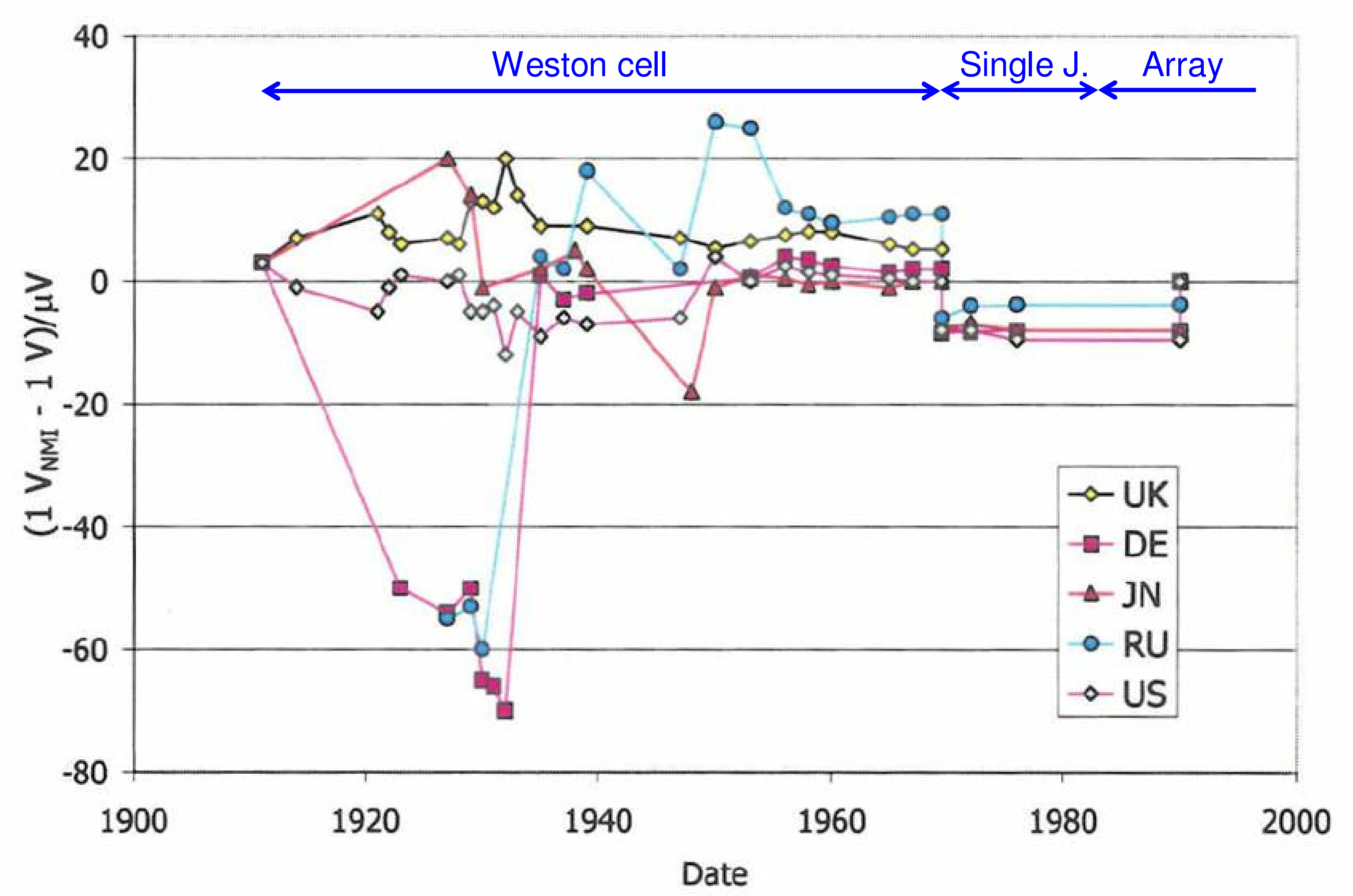

Voltage Unit: Representation

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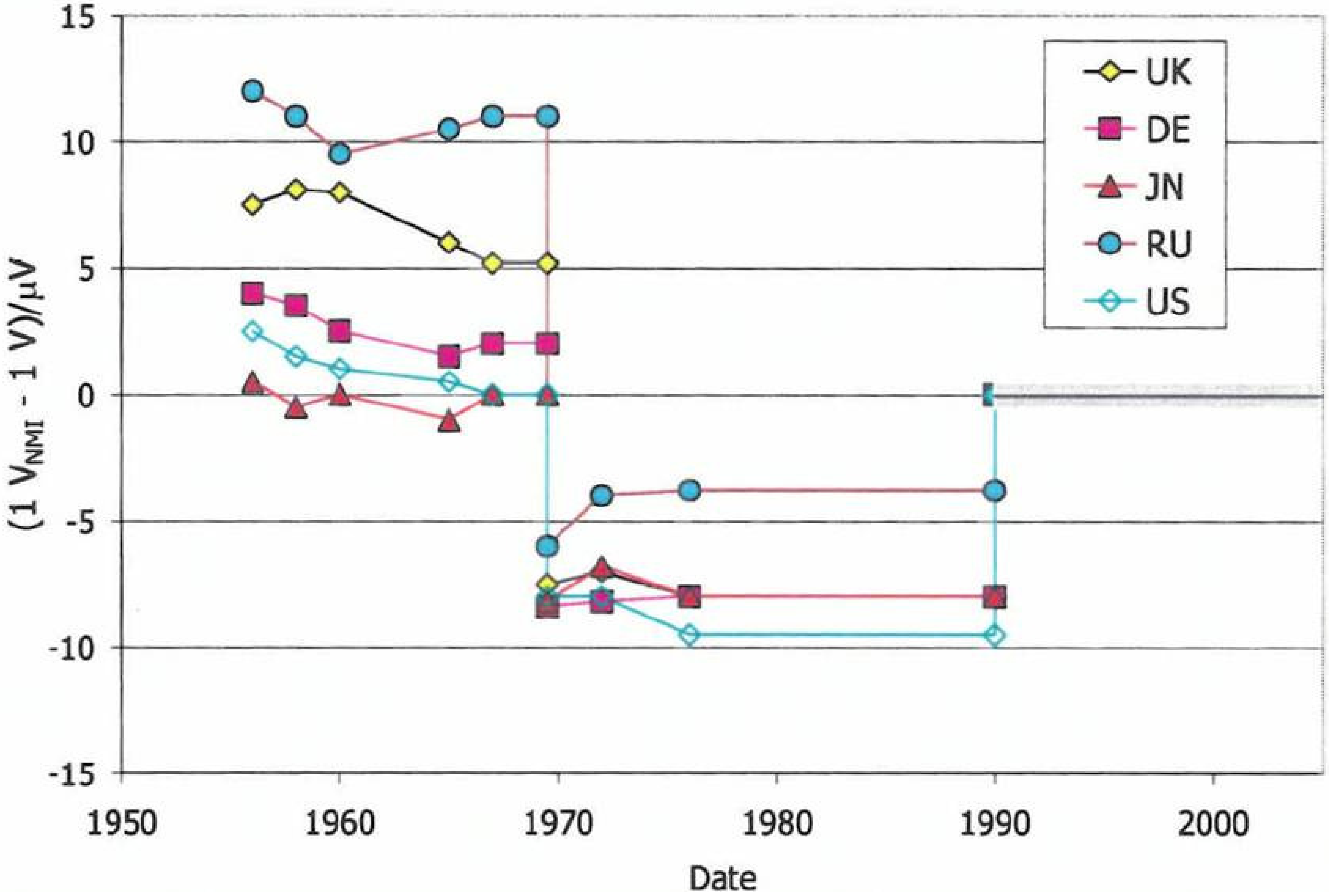

Superconductivity: BCS Theory (Nobel Prize 1972)

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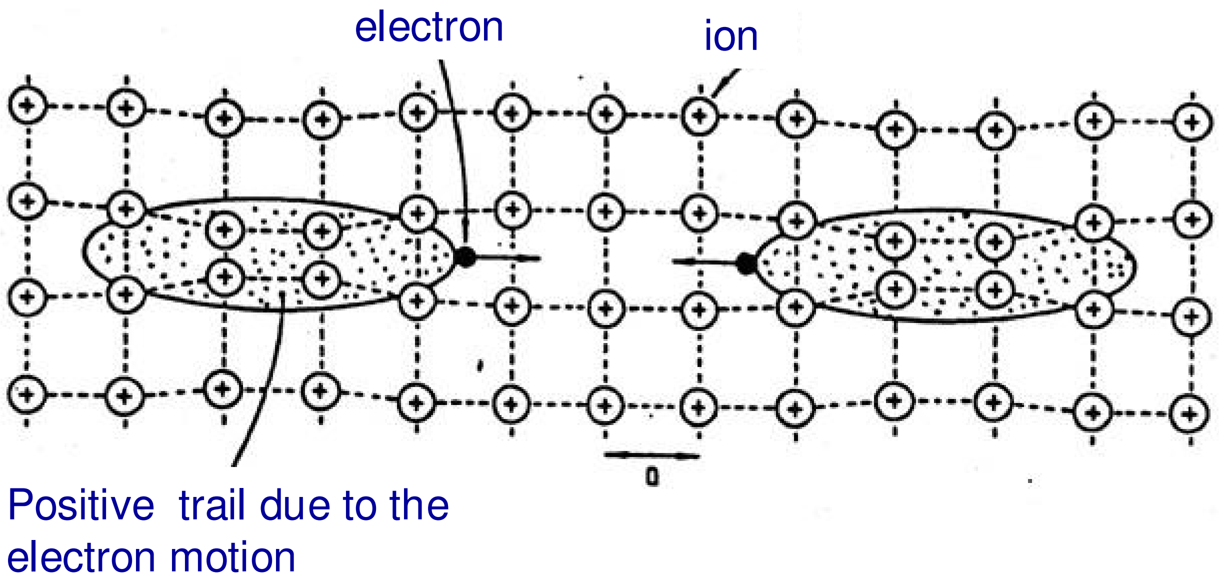
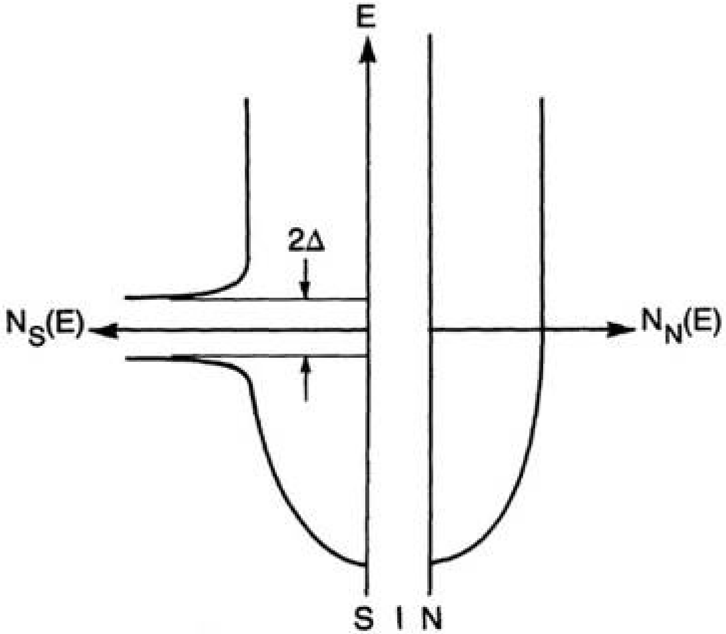


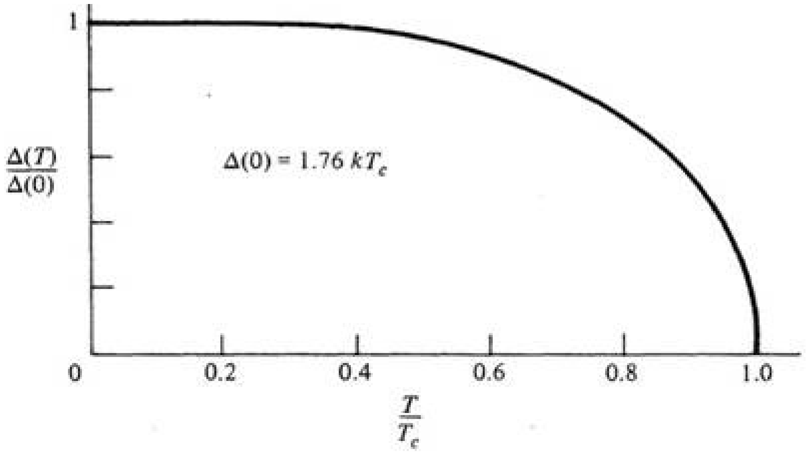
- Electrons feel an attractive potential $E_g = kT_c$ → **Cooper pairs**
- Correlated motion→ Phase coherence over macroscopic distances
- Bose condensation in a single macroscopic quantum state
- Macroscopic wave function

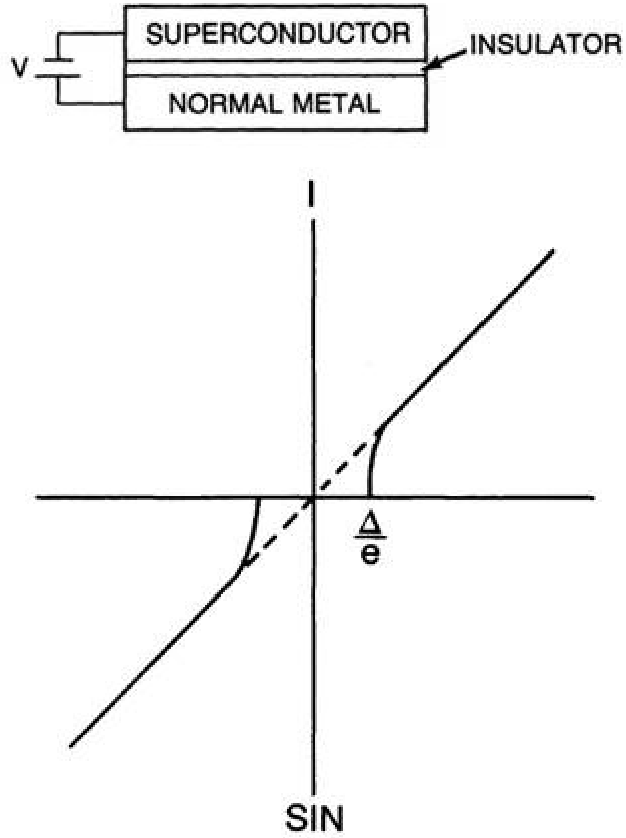
$$\Psi = |\Psi| e^{i\varphi}$$
$$n_s = |\Psi|^2$$

Superconductivity: Energy Gap

- The Bose condensation opens a gap in the DOS: $\Delta \sim kT_c$







The Josephson effect

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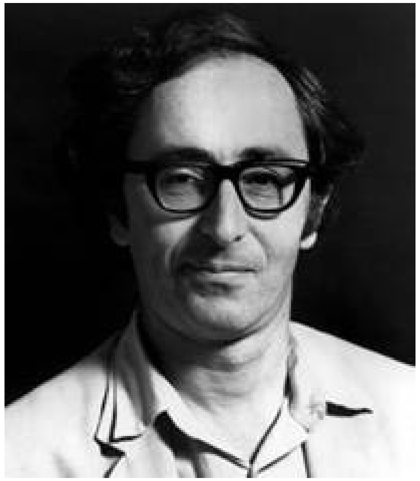
Volume 1, number 7 PHYSICS LETTERS 1 July 1962

POSSIBLE NEW EFFECTS IN SUPERCONDUCTIVE TUNNELLING *

B. D. JOSEPHSON
Cavendish Laboratory, Cambridge, England

Received 8 June 1962

We here present an approach to the calculation of tunnelling currents between two metals that is sufficiently general to deal with the case when both metals are superconducting. In that case new effects are predicted, due to the possibility that electron pairs may tunnel through the barrier leaving the quasi-particle distribution unchanged.



Brian D. Josephson
1940 -

Two pages → Nobel prize in 1973

THE NOBEL LAUREATE VERSUS THE GRADUATE STUDENT

In 1962, Brian Josephson, a 22-year-old research student at Cambridge University, suggested a new and surprising effect. A supercurrent, he argued, can tunnel through a thin insulating barrier.[1] University of Illinois theorist John Bardeen disagreed, and that mattered. At age 54, Bardeen was the most celebrated solid-state theorist of his time. He had shared the 1956 Nobel Prize in Physics with William Shockley and Walter Brattain for the invention of the transistor. He would share a second Nobel prize in 1972 with Leon Cooper and Robert Schrieffer for their 1957 solution (the BCS theory) of the long-standing riddle of superconductivity.

John Bardeen, the leading condensed matter theorist of his day, was quite wrong when he dismissed a startling prediction by the unknown Brian Josephson.

Donald G. McDonald

Bardeen publicly dismissed young Josephson's tunneling-supercurrent assertion in a "Note added in proof" to a 1962 article in *Physical Review Letters*:

> *In a recent note, Josephson uses a somewhat similar formulation to discuss the possibility*

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with a numbe
Anderson, Coo
Phillips, Robert
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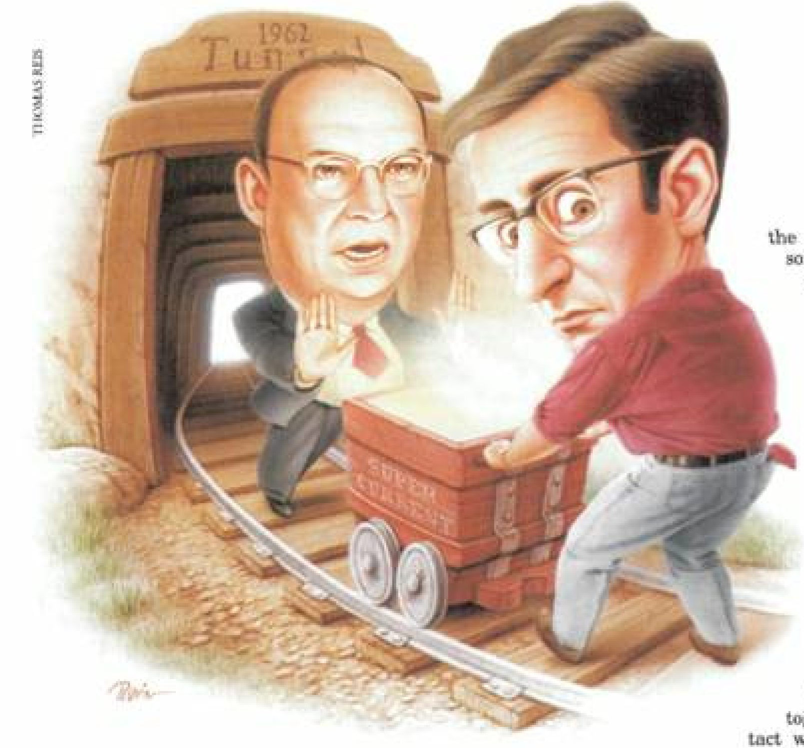
THOMAS REIS

science make of that?

The story of Josephson's discovery has been told by his mentor Philip Anderson (PHYSICS TODAY, November 1970, page 23), his thesis adviser Brian Pippard,[3] and by Josephson himself.[4] In those retellings, however, the role of Bardeen has been largely ignored.



the phase. Meanwhile, Josephson was studying various different formulations of the theory.[4] His mantra became: The phase is "real enough to produce . . . flux quantization." How can I make it more explicit in experiments?

The third discovery was published in 1960 by Hans Meissner in a paper entitled "Superconductivity of Contacts with Interposed Barriers."[10] Meissner's experiments used superconducting wires of tin, coated with a thin layer of a normal metal such as copper. Bringing two such wires together, he found that the contact was superconducting despite

Physics Today, July 2001, p. 46-51

The Josephson effect: Tunnel junction

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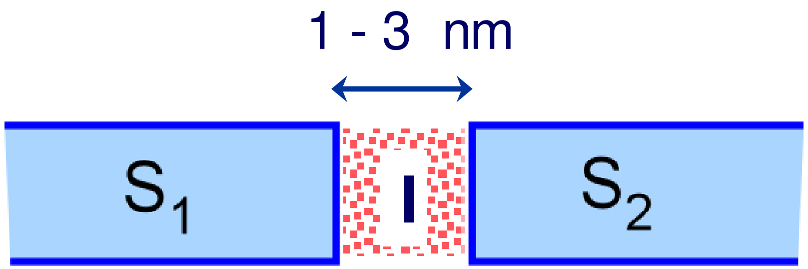
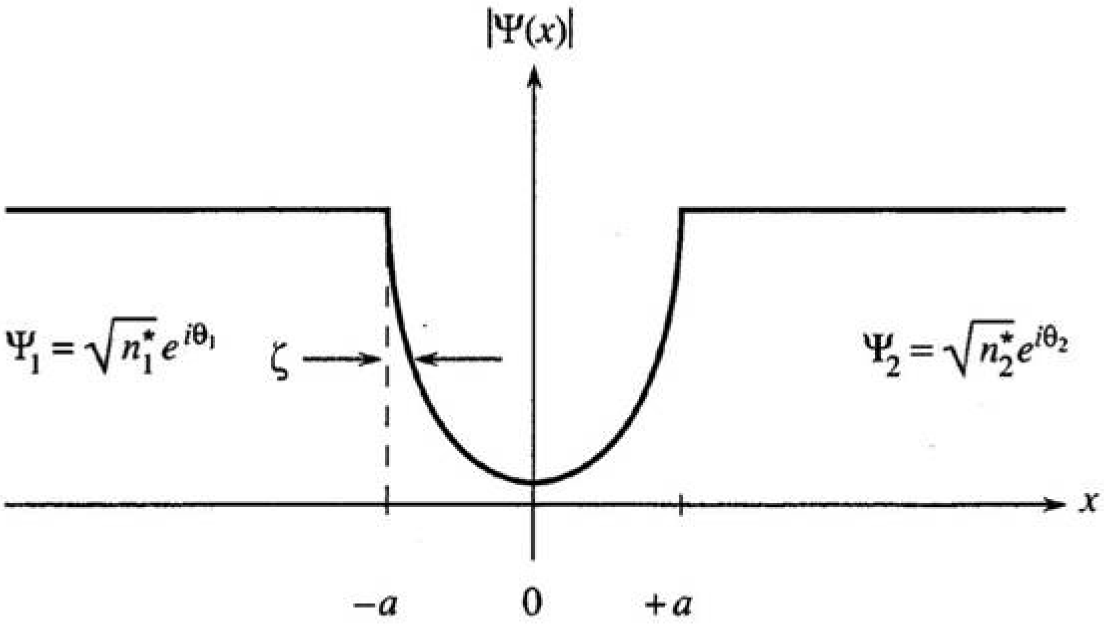




Josephson equations:

$$I = I_c \sin \Delta\varphi$$

$$V = \frac{\hbar}{2e} \frac{d}{dt} \Delta\varphi$$

$$\Delta\varphi = \varphi_2 - \varphi_1$$

Critical current: I_c

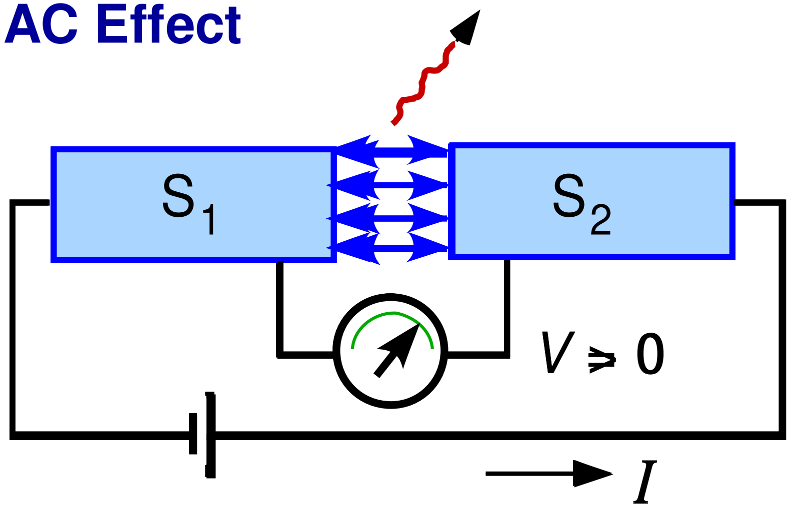
Josephson effect: Coherent tunneling of Cooper pairs through the junction

The Josephson effect:

$$I = I_c \sin \Delta\varphi$$

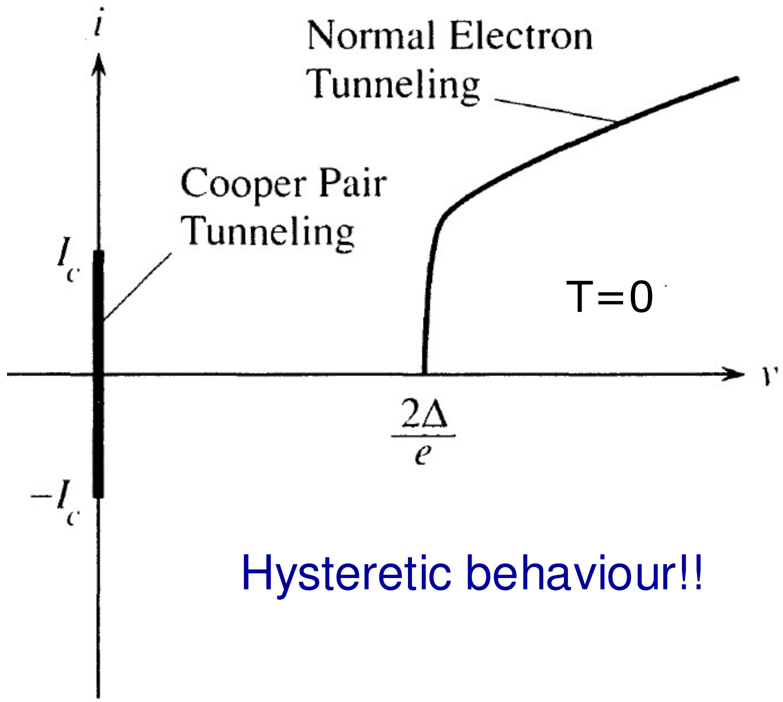
$$V = \frac{\hbar}{2e}\frac{d}{dt}\Delta\varphi$$

AC Effect



EM Radiation:

$$f_J = \frac{2e}{h}V$$



Hysteretic behaviour!!

The Josephson effect: AC Effect

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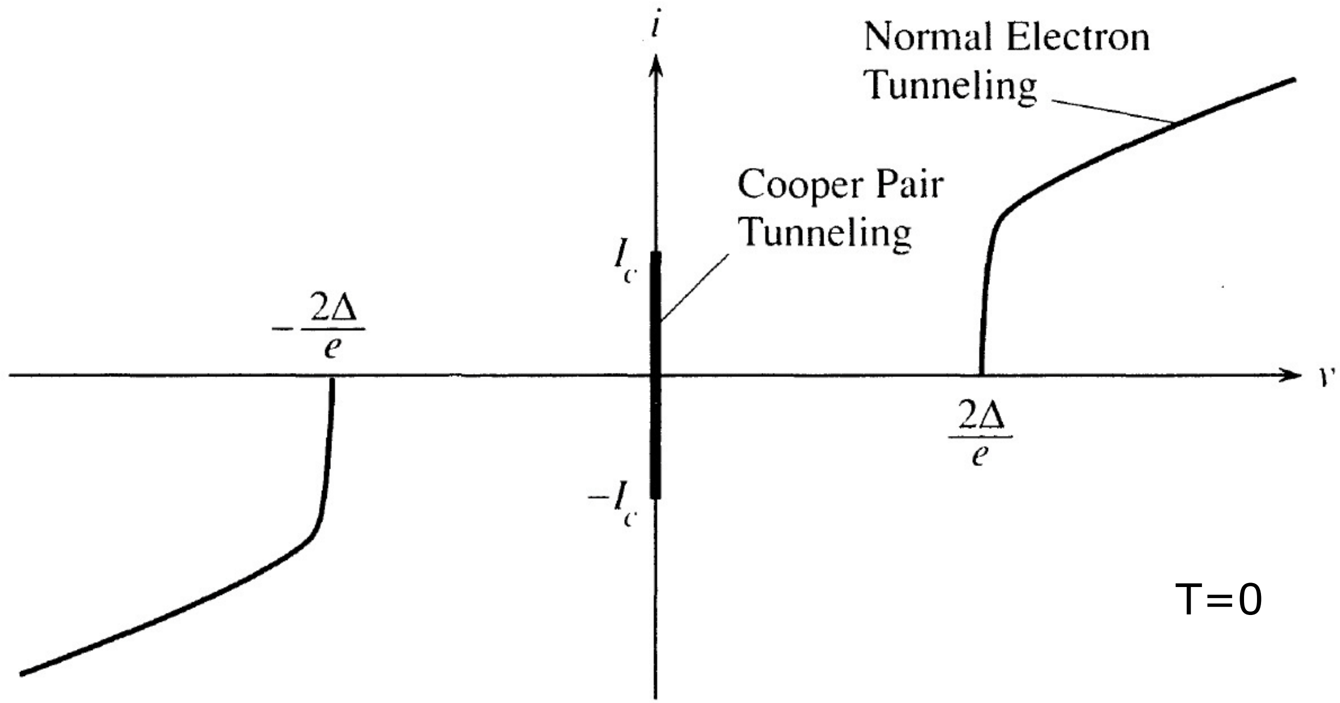


Josephson Voltage Standard: Single Junction

metas

Irradiation with microwave:

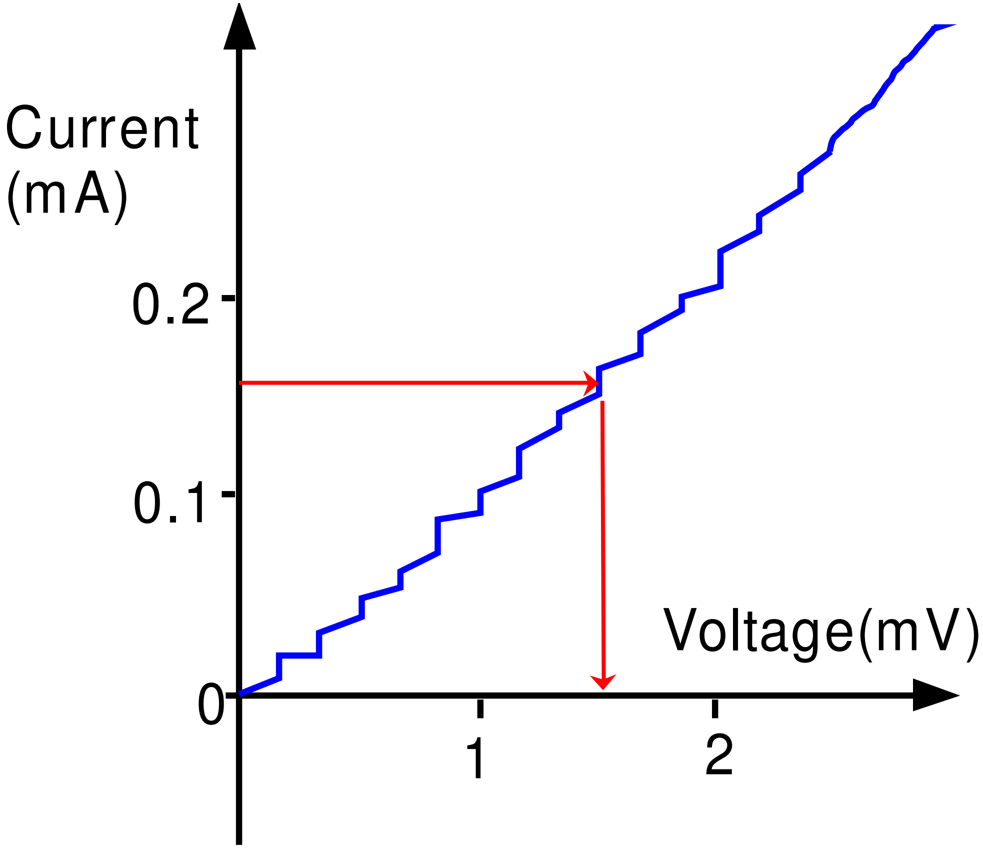
- Cooper pairs synchronize with radiation

- Voltage steps appear

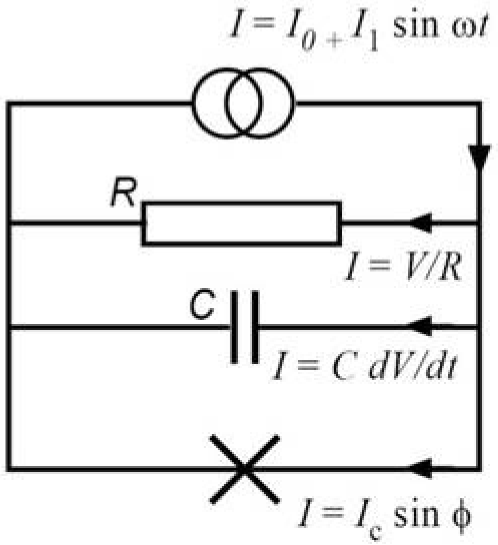
$$V_n = n\frac{h}{2e}f$$

Shapiro step, 1963

V_1 ~ 145 µV @ 70 GHz



Josephson Voltage Standard: RCSJ Model



Small angle: $L_J = \hbar / 2eI_c$

Mc Cumber parameter:

$$\beta_c = \frac{\tau_{RC}}{\tau_J} = \frac{R^2 C}{L} = \frac{2e}{\hbar} I_c R^2 C$$

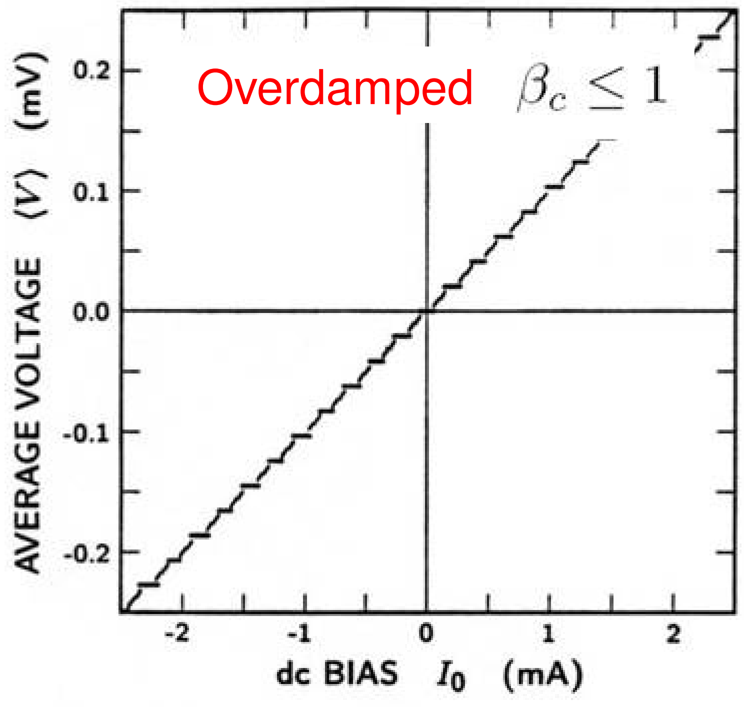
$$\frac{\hbar C}{2e}\frac{d^2\phi}{dt^2} + \frac{\hbar}{2eR}\frac{d\phi}{dt} + I_c \sin\phi = I_0 + I_{rf}\sin(\omega t)$$

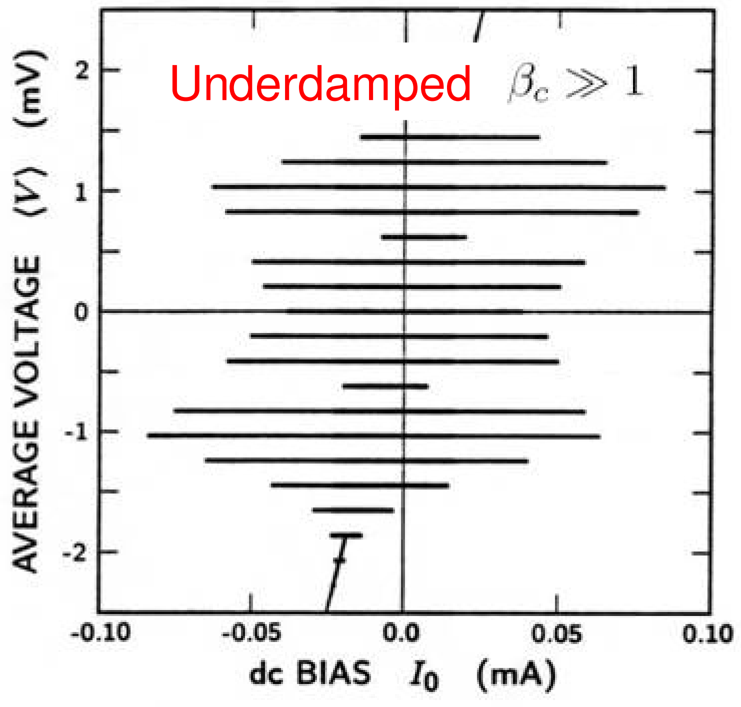
Non linear, second order equation (Pendulum): **CHAOS**

Voltage Step ⟷ **Phase lock to microwave**

Josephson Voltage Standard: Single Junction

metas





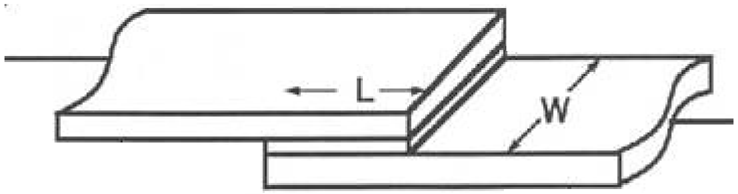
Problems:

- Voltage limited to 2.5 mV (gap Nb)
- Impossible to make large arrays → Bias scheme

→Zero crossing steps (Levinsen 1977)

Josephson Voltage Standard: Step stability (R. Kautz, 80’s)

metas



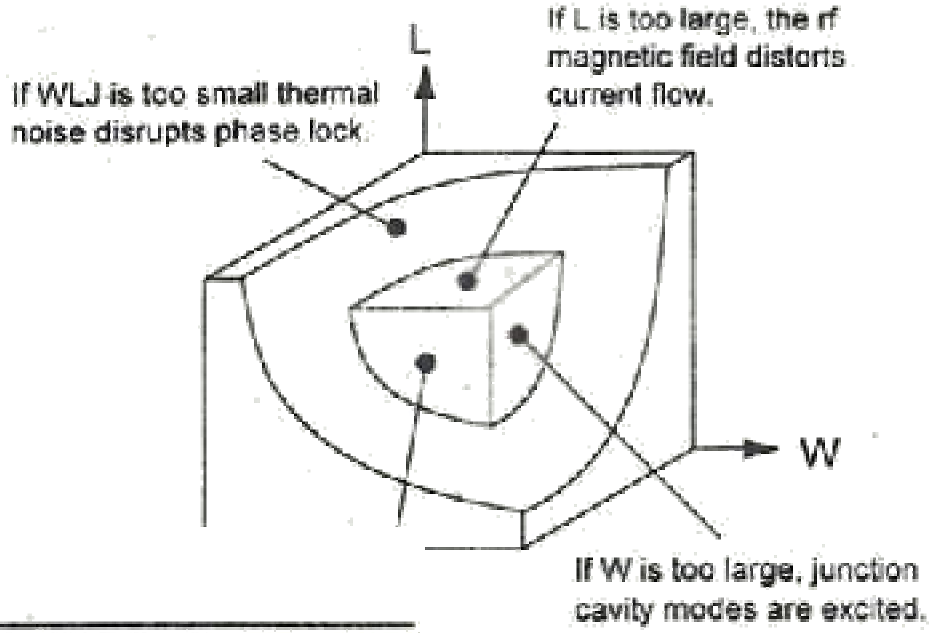


TABLE I. Junction design parameters.

Junction materials	$Nb/Al_2O_3/Nb$
Critical current density J	20 A/cm^2
Junction length L	18 μm
Junction width W	30 μm
Critical current I_0	110 μA
Plasma frequency f_p	20 GHz
Lowest resonant cavity mode	175 GHz
Rf drive frequency f	75 GHz

Hamilton, 2000

Josephson Voltage Standard: Power distribution

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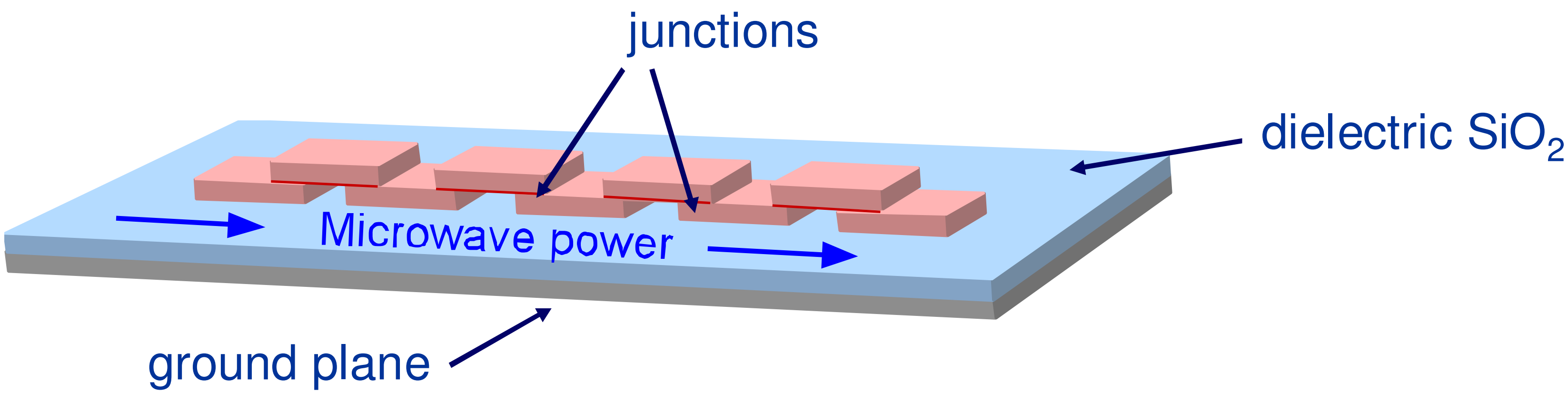
- Homogeneous distribution of microwave power to all junctions
  → Stripline geometry



- Strip line impedance: 2-5 Ω
- Junction capacitive impedance: 1 mΩ

→ Attenuation: 1 mdB/ junction

→ Stripline with 5000 junctions, uniformity ±1.5 dB

Josephson Voltage Standard: Arrays

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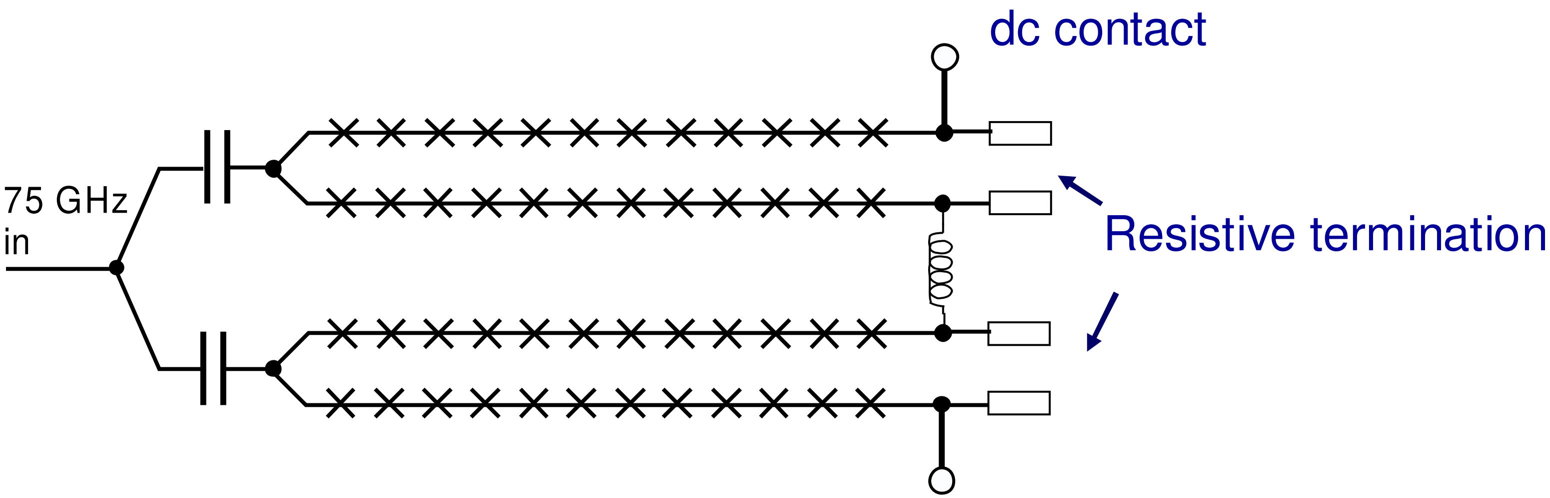
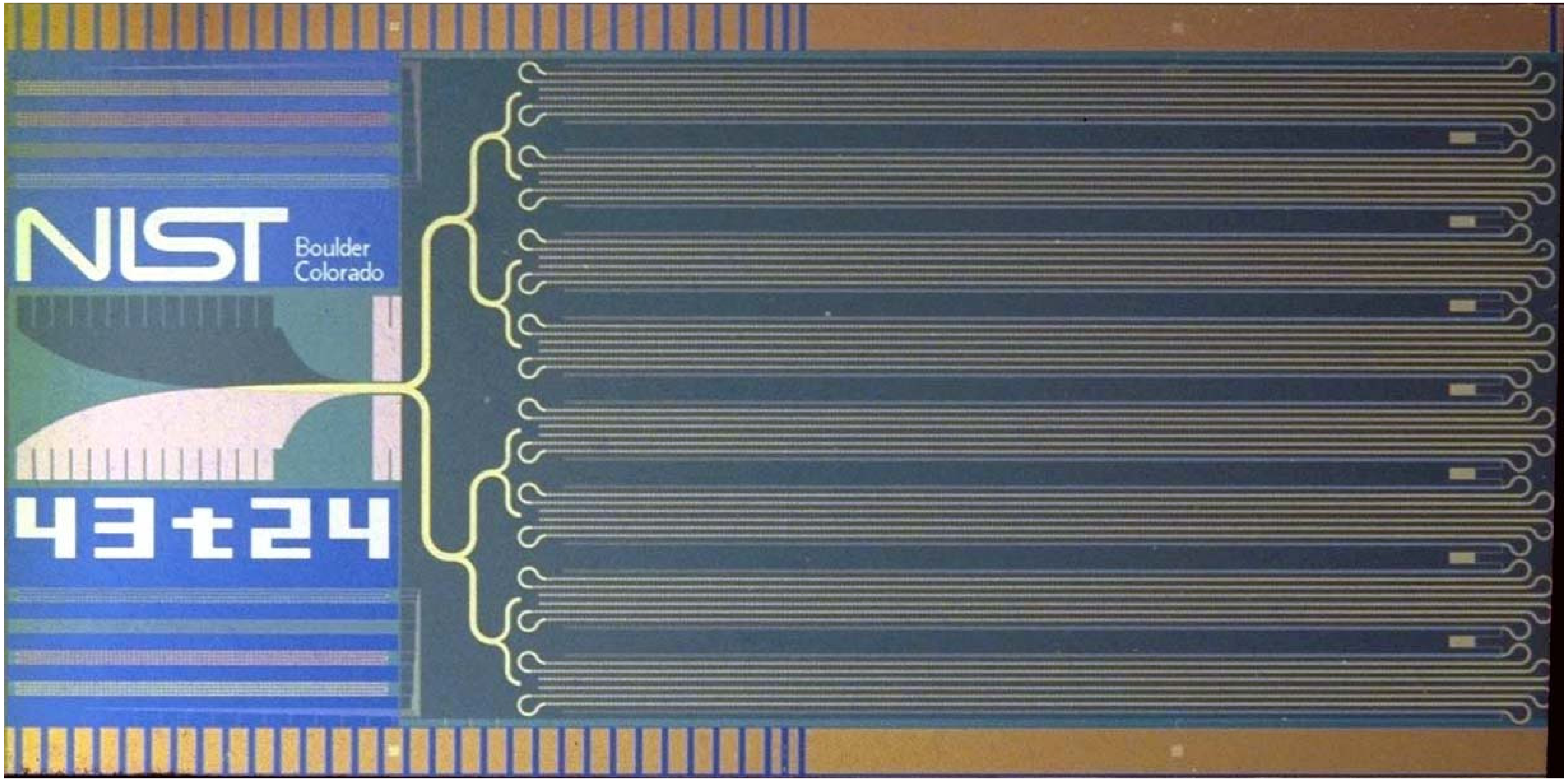
- Fabrication of large junction arrays with little variation in parameters



- 1985: first 1 V arrays, 1'400 Pb junctions, Niemeyer (PTB), Hamilton and Kautz (NIST)
- 1987: 10 V array, 14'484 Pb junctions, NIST
- 1991: METAS 1V array from NIST
- 1998: METAS 10V array, 20'208 Nb/Al_2O_3/Nb junctions, Hypres

Josephson Voltage Standard: Arrays



Josephson Voltage Standard: Accuracy

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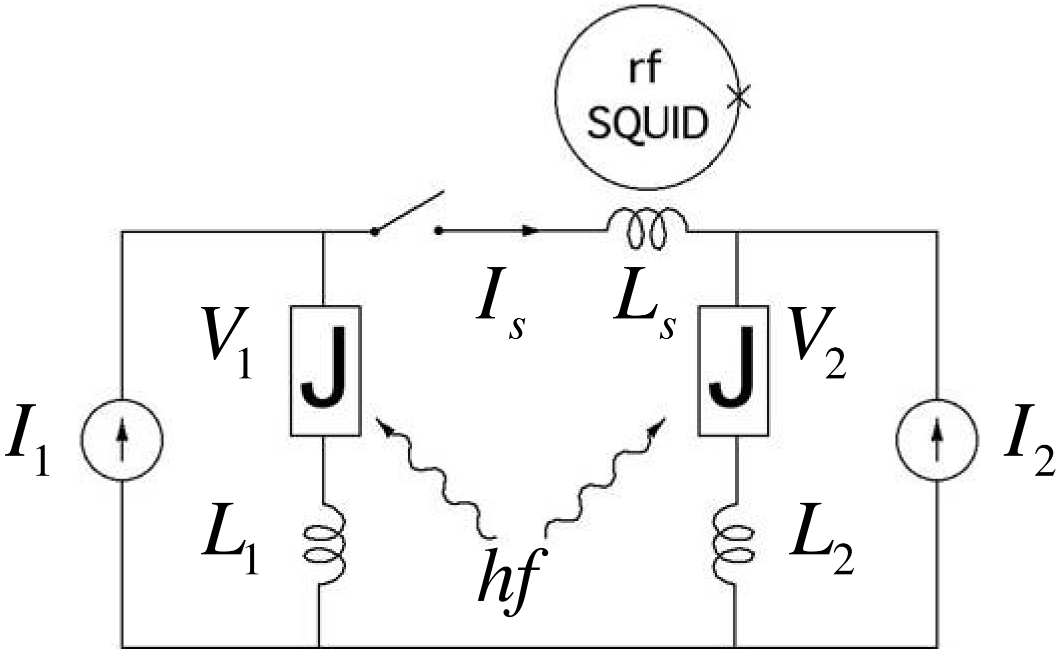
$$V_n = n\frac{h}{2e}f = nK_J^{-1}f$$

- How accurate is the Josephson relation?
- High precision comparison required!



$$I_s = \frac{1}{L}\int (V_1 - V_2)dt$$

$$L = L_s + L_1 + L_2$$

→ Extremely sensitive method

Josephson Voltage Standard: Accuracy

metas

- 1983: Comparison between two single junctions: $\Delta V / V < 2 \cdot 10^{-16}$

  J.S Tsai, A.K. Jain, J.E. Lukens, *Phys. Rev. Lett. 51*, 316, (1983).

- 1986: Comparison between two 1V arrays: $\Delta V_{step} / V_{step}(30\mu A) < 7 \cdot 10^{-13}$

  J. Niemeyer et al., *IEEE Electron Device Lett. EDL-7*, 44, (1986).

- 1987: Comparison between two 1V arrays: $\Delta V / V < 2 \cdot 10^{-17}$

  R.L. Kautz, F.L. Lloyd, *Appl. Phys. Lett. 51*, 2043, (1987).

- 1987: Comparison between two single junctions: $\Delta V / V < 3 \cdot 10^{-19}$

  A.K. Jain, J.E. Lukens, J.S. Tsai, *Phys. Rev. Lett. 58*, 1165, (1987).

- 2001: Comparison between two 0.6V SINIS arrays: $\Delta V / V < 1.2 \cdot 10^{-17}$

  I.Y. Krasnopolin et al., *Supercond. Sci. Technol. 15*, 1034, (2001).

→ "it shows that gauge invariance is exact!" P.W. Anderson (87)

Josephson Voltage Standard: The system

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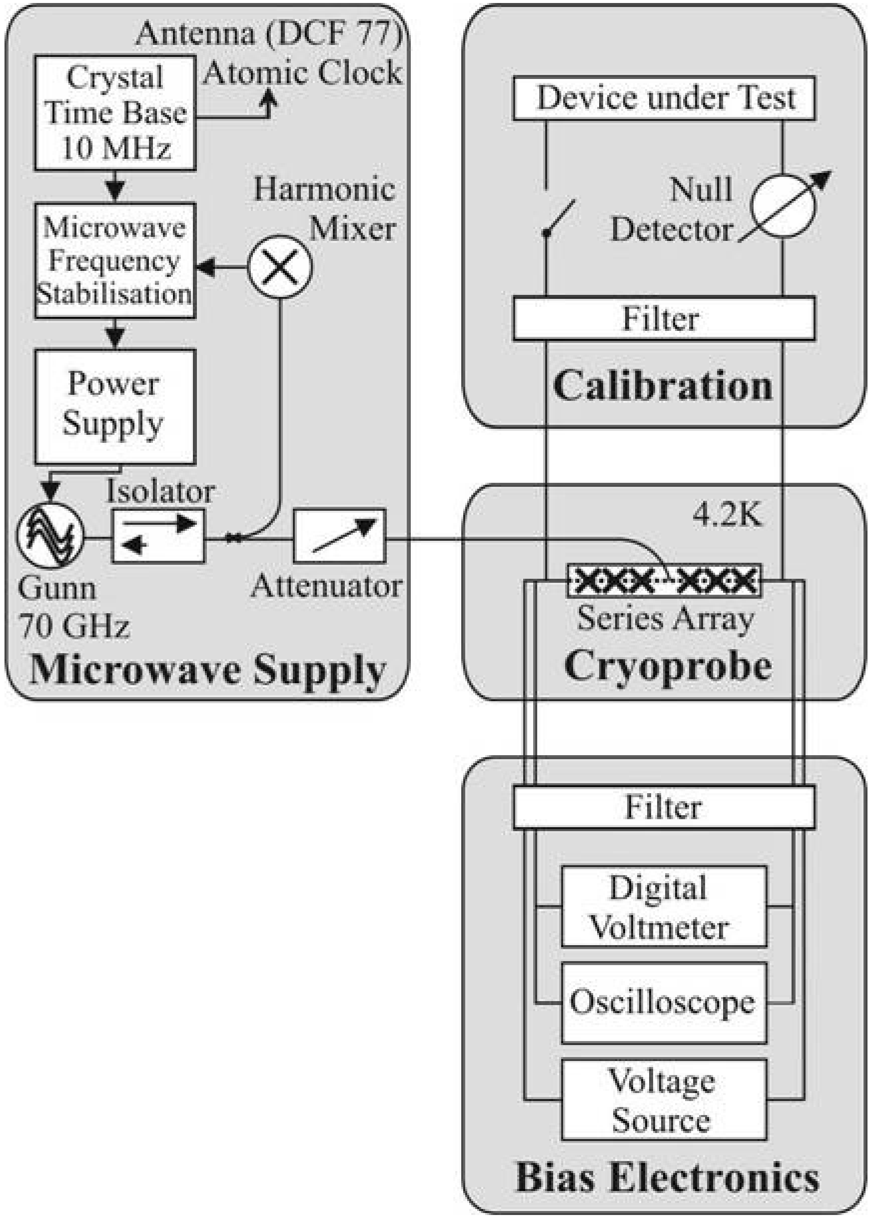

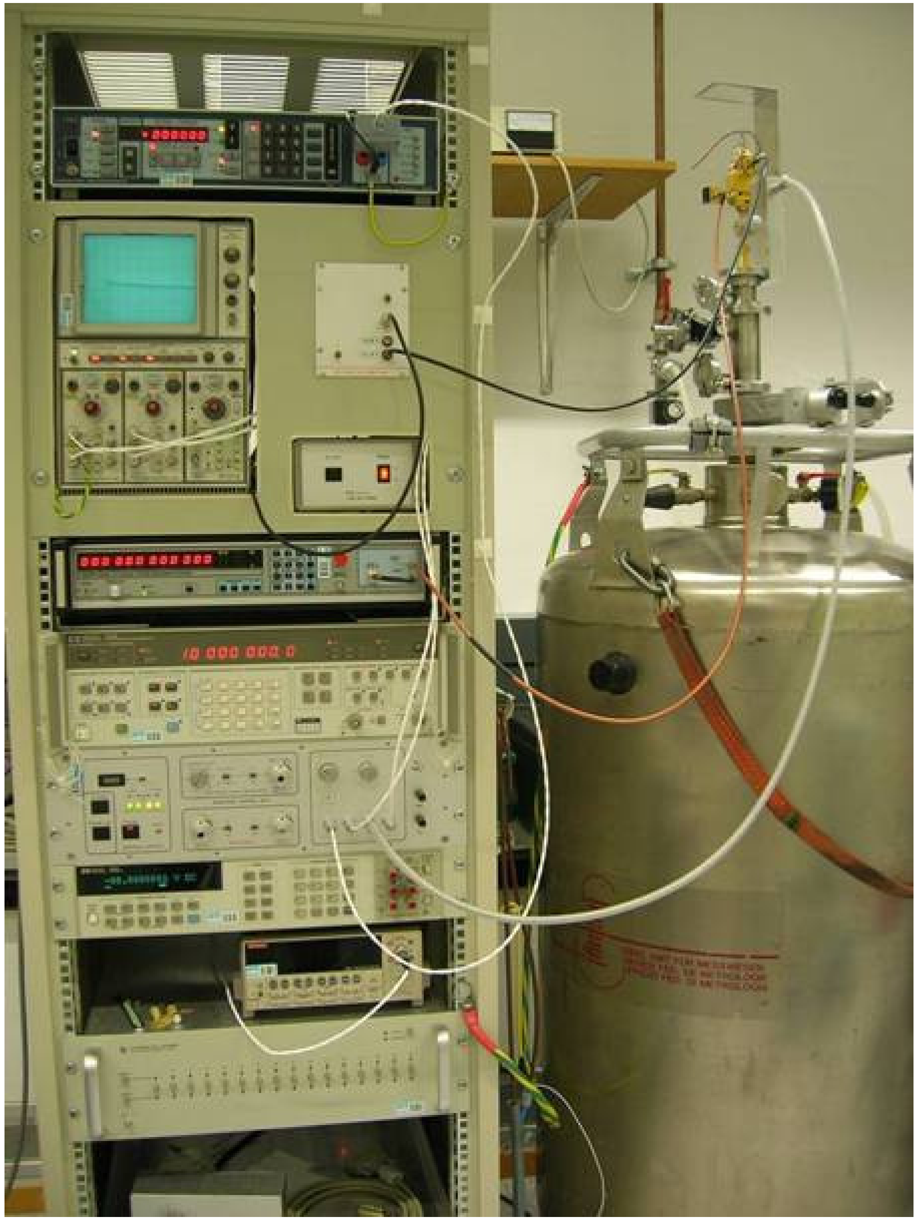

Josephson Voltage Standard: The system

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PRIMARY VOLTAGE STANDARD SYSTEM

The HYPRES Primary Voltage Standard System is a complete, computer controlled system to implement a variety of voltage calibration functions. Using this system, secondary voltage standards and voltmeters can be calibrated automatically. A properly used Josephson Standard is correct by definition because of its realization of a quantum physics phenomenon, and the adoption of that phenomenon as the basis of the SI Volt representation.

The HYPRES Primary Voltage Standard System is a commercial implementation of the system suggested by the US National Institute of Standards and Technology (NIST). The microwave components and voltage sensing electronics are specifically designed and manufactured for this application.

The NISTVolt™ for DOS operating software for controlling automatic calibration of secondary standards and voltmeters was developed by NIST. HYPRES' PROVolt system software is designed for a WINDOWS operating system and contains the same algorithms as NISTVolt™.

The HYPRES Primary Voltage Standard System is available in two system configurations. The electronic equipment rack is provided for both system configurations and contains:

- JBS-501 Josephson Bias Source
- EIP-578 Frequency Locking Counter
- Hewlett Packard Digital Voltmeter
- PC w/monitor
- Hewlett Packard Laser Jet Printer (not shown)
- I/V Oscilloscope

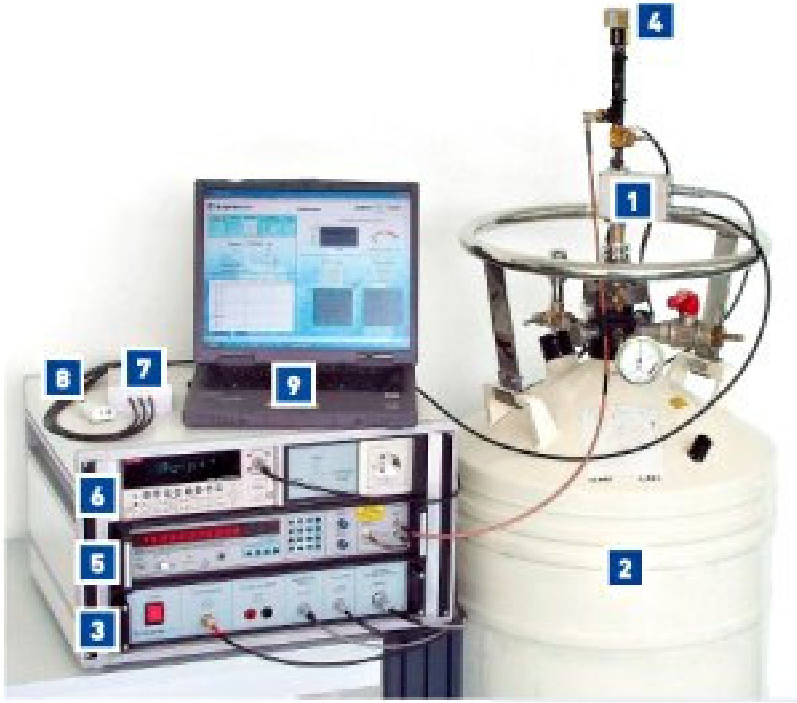
The Primary Voltage Standard circuits were commercialized in a project with NIST under sponsorship of the US Army.

HYPRES is a state-of-the-art facility encompassing design, fabrication, packaging and testing of superconducting ICs. Since its inception in 1983, HYPRES has been the leading company devoted to the commercialization of thin-film superconducting technology. Its fabrication foundry supplies universities, companies and national laboratories around the world. Other products include A/D converters, shift registers, memory, IR Sensors and SIS mixers.

A liquid helium based system allows 6 weeks of continuous operation on one 100 liter dewar of liquid helium. A Cryoprobe with magnetic & RF shielding, waveguide loss<3dB @ 75 GHz, RF filtering 60dB above 100kHz and 100dB above 1 MHz and a 75 GHz Gunn diode RF source with 1 GHz mechanical tuning, 100 MHz electronic tuning, 60 mW minimum output power are provided.

A closed-cycle refrigerator based system allows continuous operation and eliminates the liquid helium requirement. This system configuration is ideal for laboratories where liquid helium is not readily available or is cost prohibitive. A completely integrated waveguide, RF source and an RF filter are built into the closed-cycle refrigerator package.

HYPRES



JVS 10 V systems commercially available:

- Hypres (USA): NIST array technology
- SupraCon (Germany): PTB array technology

Josephson Voltage Standard: Uncertainty budget

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List of the uncertainty components:

1) Reference frequency offset and noise
2) Leakage currents in the measurement loop
3) Detector gain error
4) Detector bias current
5) DVM offset, input impedance, non linearity and noise
6) Uncorrected thermal voltages
7) Rectification of the reference frequency current
8) Electromagnetic interference
9) Sloped steps (bias dependent voltage)

} Do not depend on voltage

→ evaluation by measurement of a short circuit

C.A. Hamilton, Y.H.Tang, *Metrologia 36*, pp. 53-58, (1999).

Josephson Voltage Standard: Uncertainty budget

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Component	*Type*	*Unc. (nV)*
Frequency	*B, 1σ*	*0.7*
Leakage current	*B, 1σ*	*1.0*
DMM gain error	*B, 1σ*	*0.6*
Repeatability HP3458	*A, 1σ*	*5.0*
Combined	*1σ*	*5.2*

At a level of 10 V: 5.2×10^{-10}

With nDVM < 10^{-10}

Josephson Voltage Standard: BIPM Comparison

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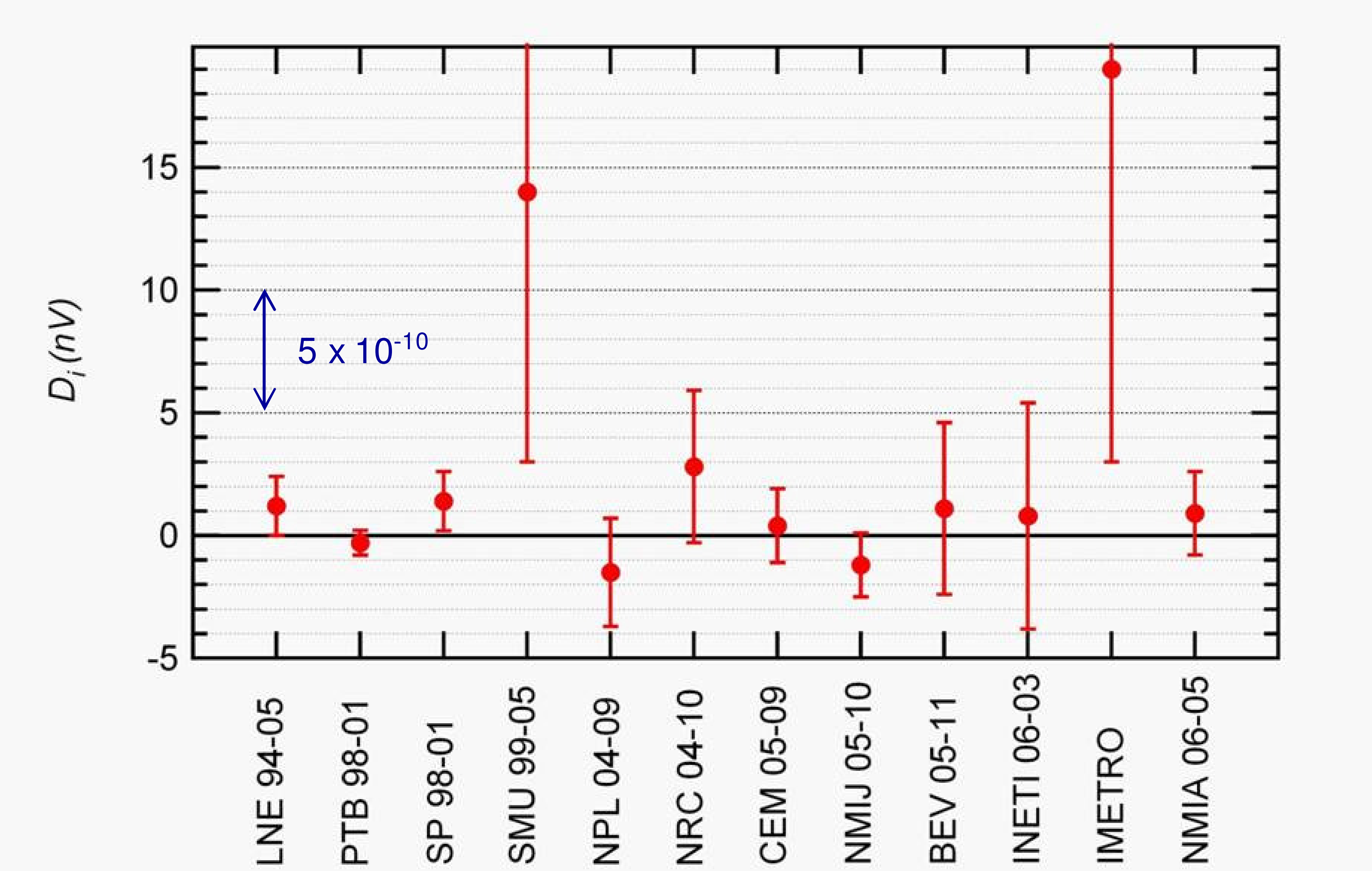

Voltage Scale: Zener voltage reference

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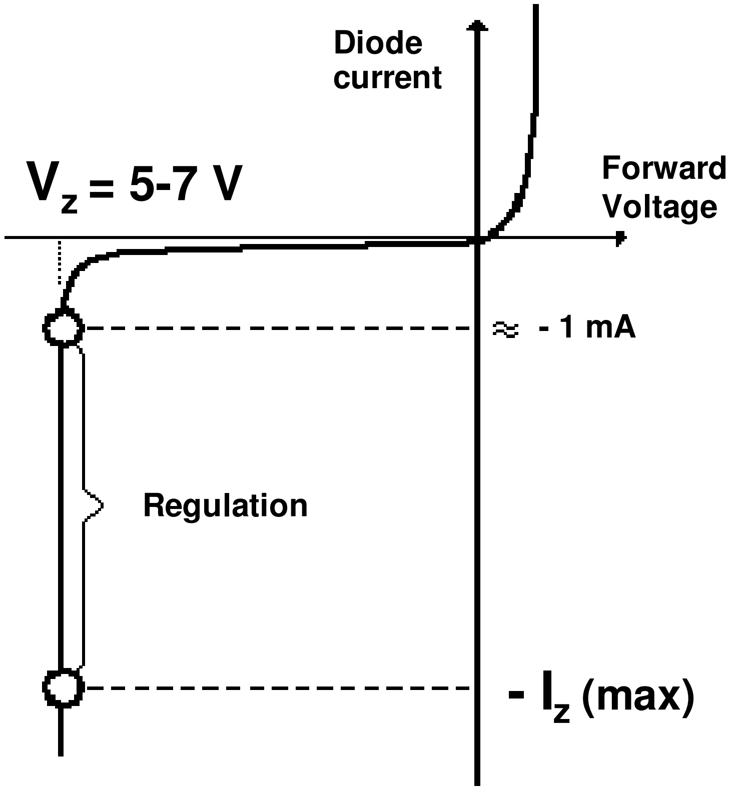
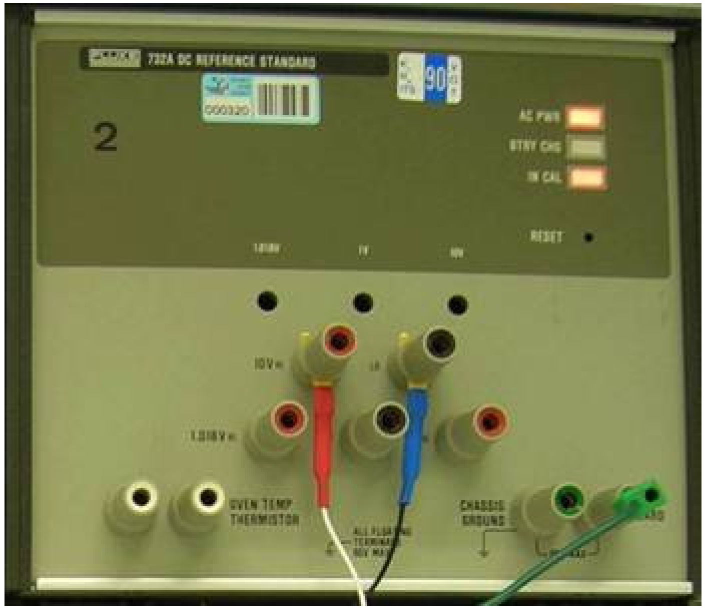
p-n junction: Zener effect (1934)



Voltage reference:
- Regulation electronics
- Temperature control
- Output: 10V, 1.018V



Voltage Scale: Zener voltage reference

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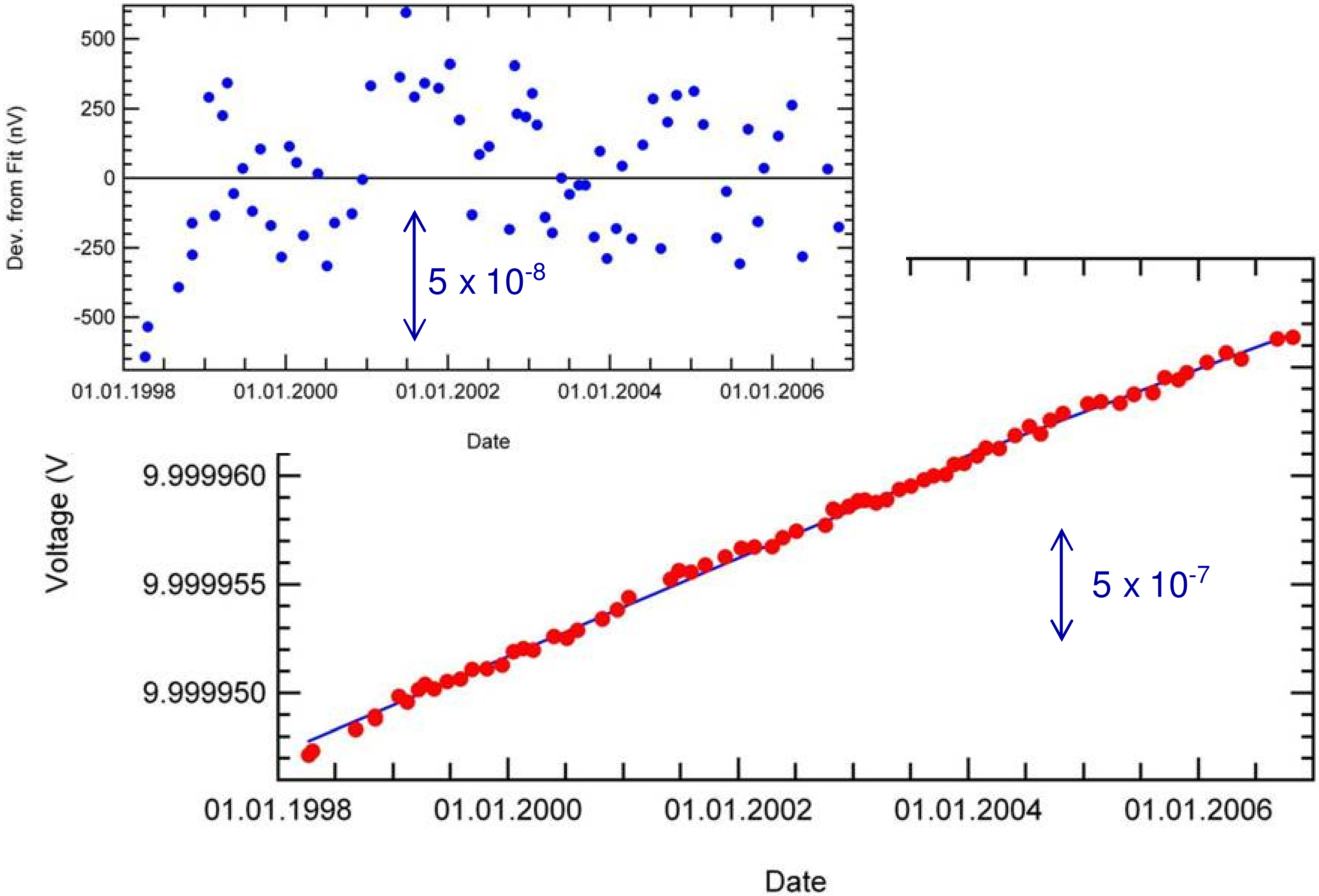

Voltage Scale: Zener voltage reference

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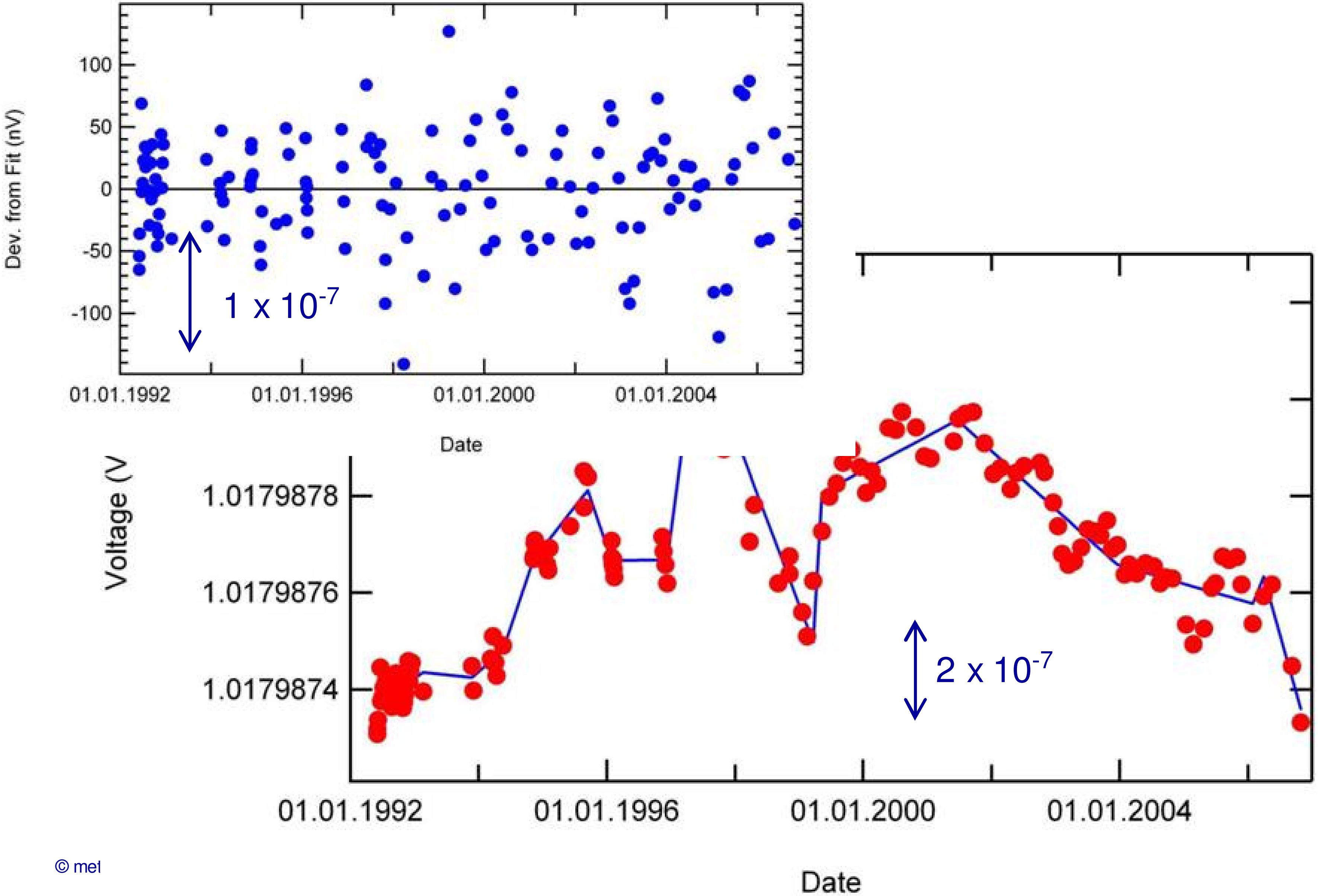
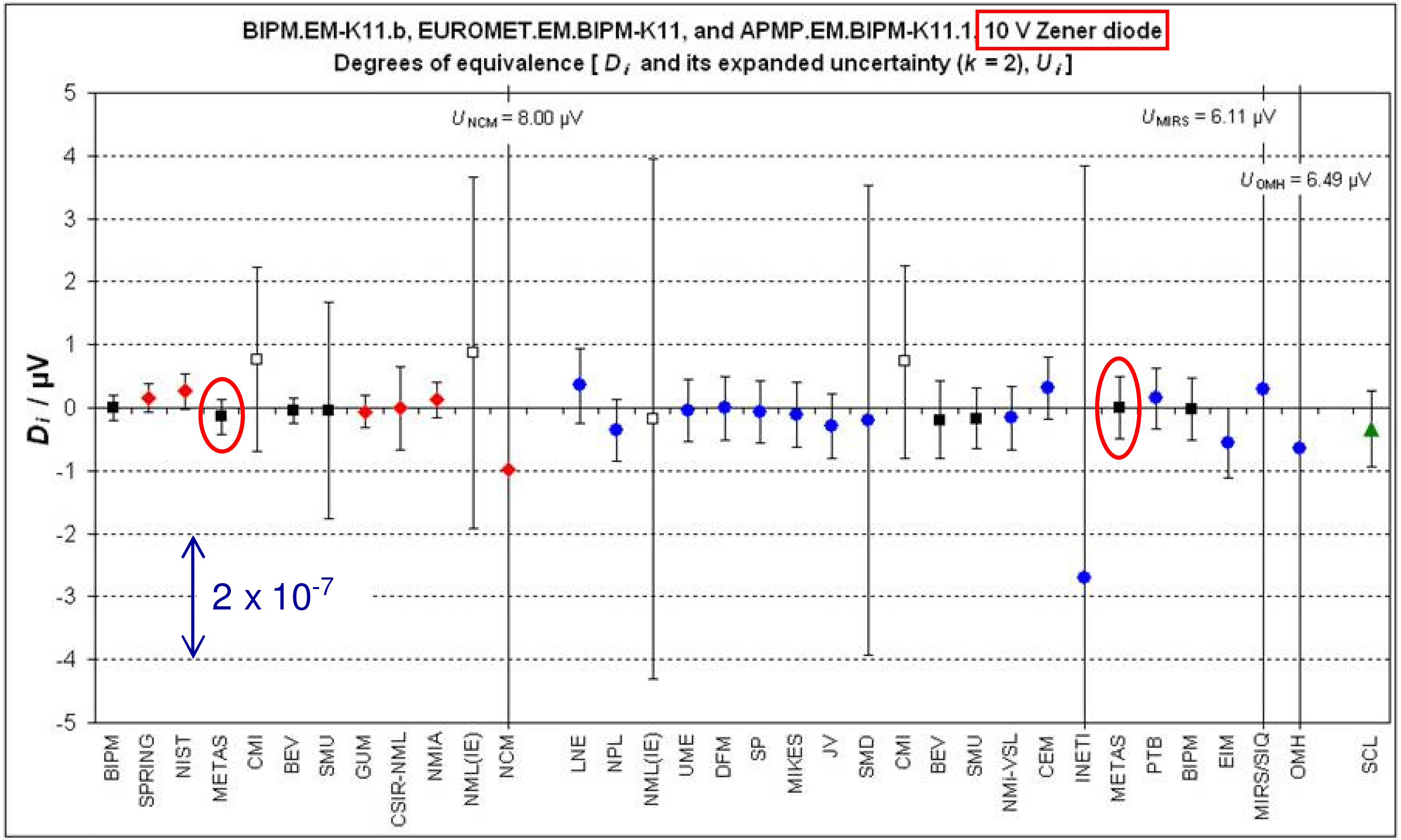


Voltage Scale: Zener BIPM Comparison

metas



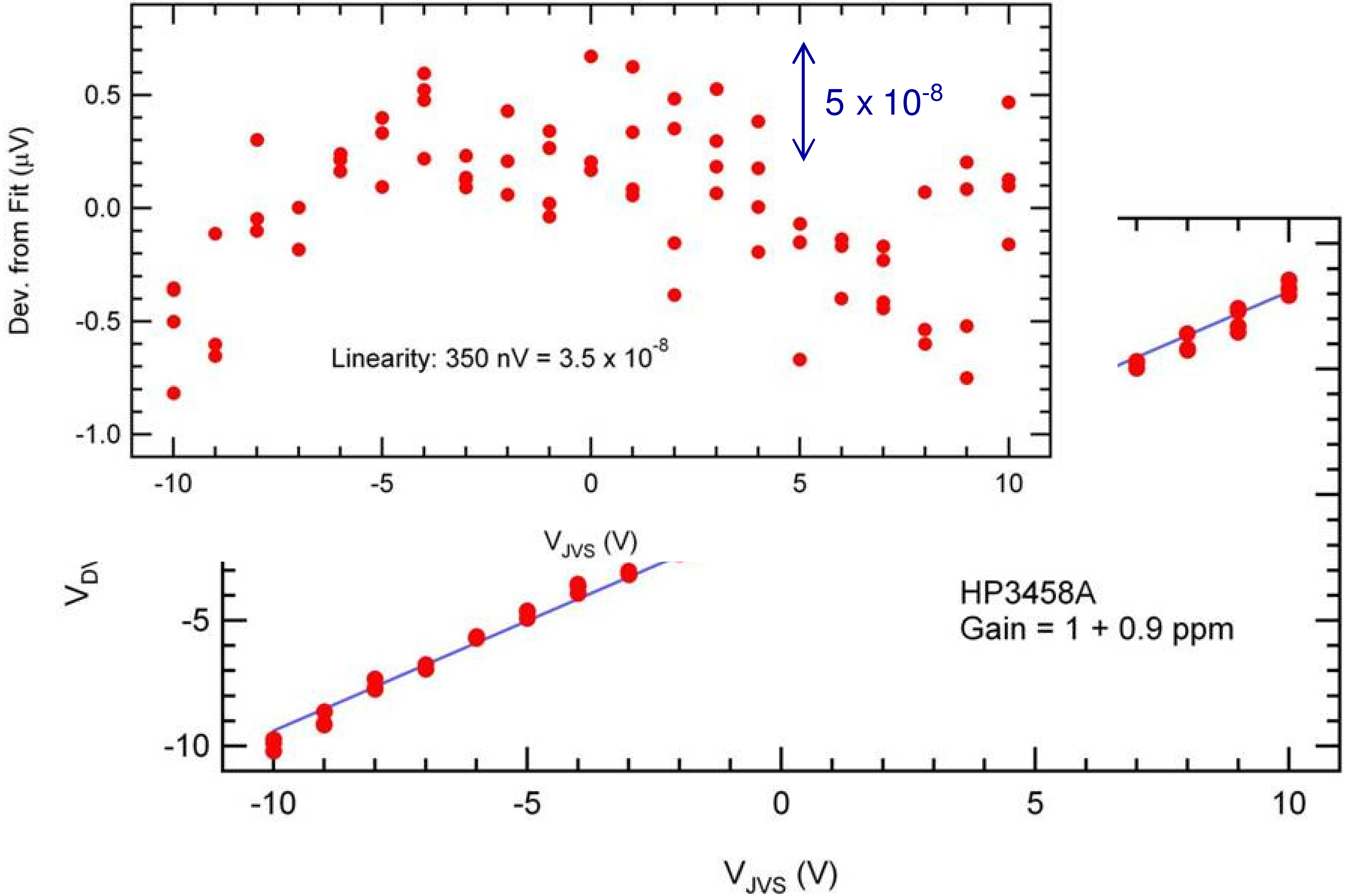
Red diamonds: participants in BIPM.EM-K11.b only

Blue circles: participants in EUROMET.EM.BIPM-K11 only

Green triangle: participant in APMP.EM.BIPM-K11.1 only

Black squares: common participants in BIPM.EM-K11.b and EUROMET.EM.BIPM-K11 (filled up in black: laboratories used to compute the link)

Voltage Scale: DVM Linearity

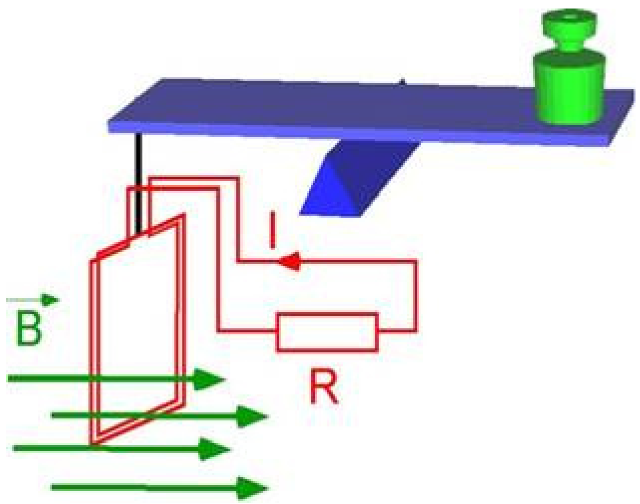


metas

Replacement of the kilogram: Watt balance

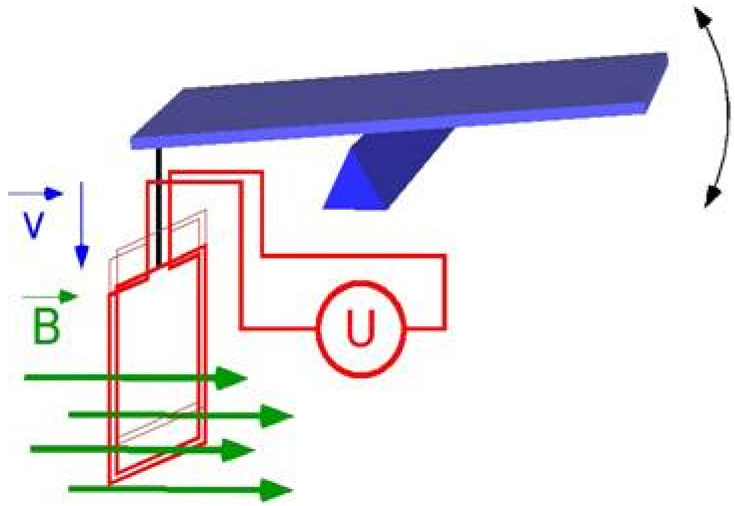
metas

Force measurement



$$I\int Bdl = mg$$

Speed measurement

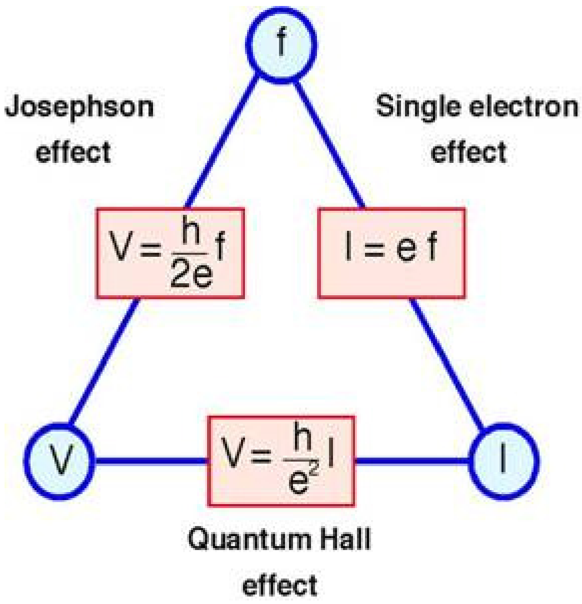


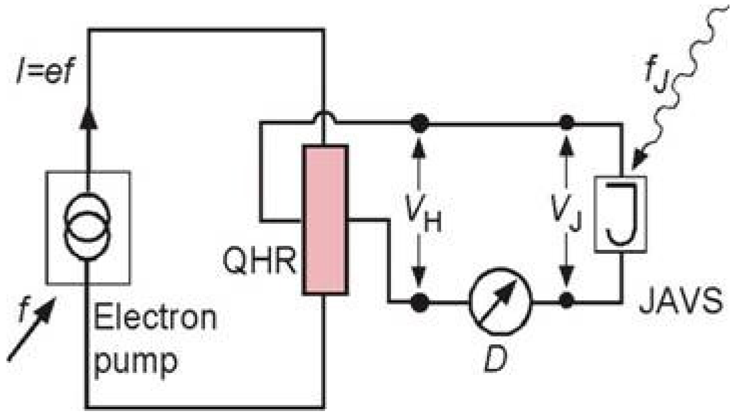
$$U = v\int Bdl$$

$$UI = mgv$$

Metrological triangle

metas





N. Feltin, Next Thursday

- Modified version: charging a capacitor
- Primary capacitance standard

  M. Keller, Next Wednesday

Conclusions

- The Josephson effect is used world wide as the representation of the voltage unit.
- Large SIS array produces voltage up to 10 V with unprecedented uncertainty:

→	SI Volt realization:	3×10^{-7}	
→	Josephson junctions:	3×10^{-19}	@ mV,
		2×10^{-17}	@ 1V
→	Josephson Voltage Standard:	1×10^{-10}	@ 10V

- New development for AC voltage metrology → S. Benz NIST