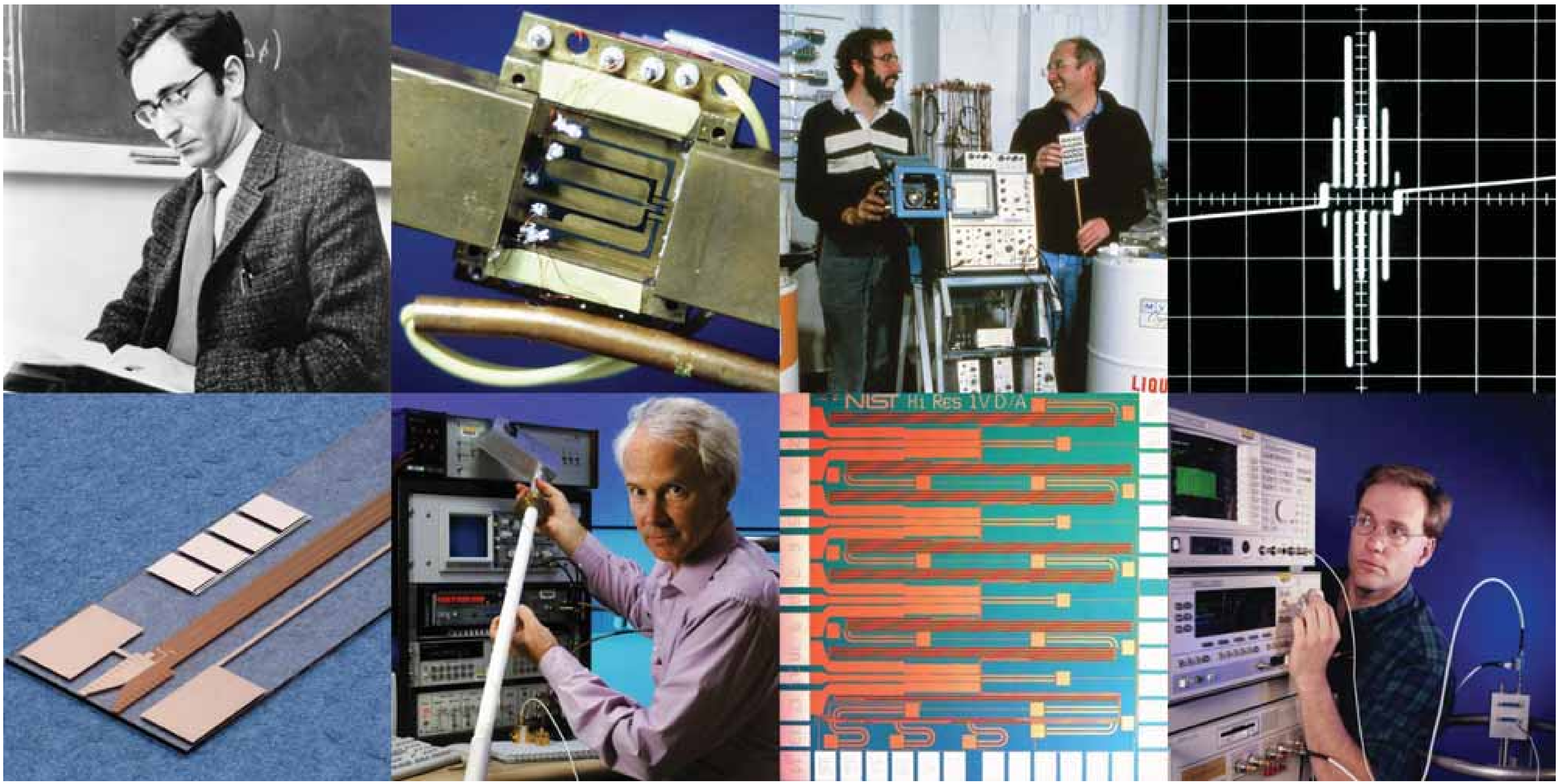
The Josephson Volt

The First Quantum Electrical Standard



Brian Josephson
Cambridge University
1960s

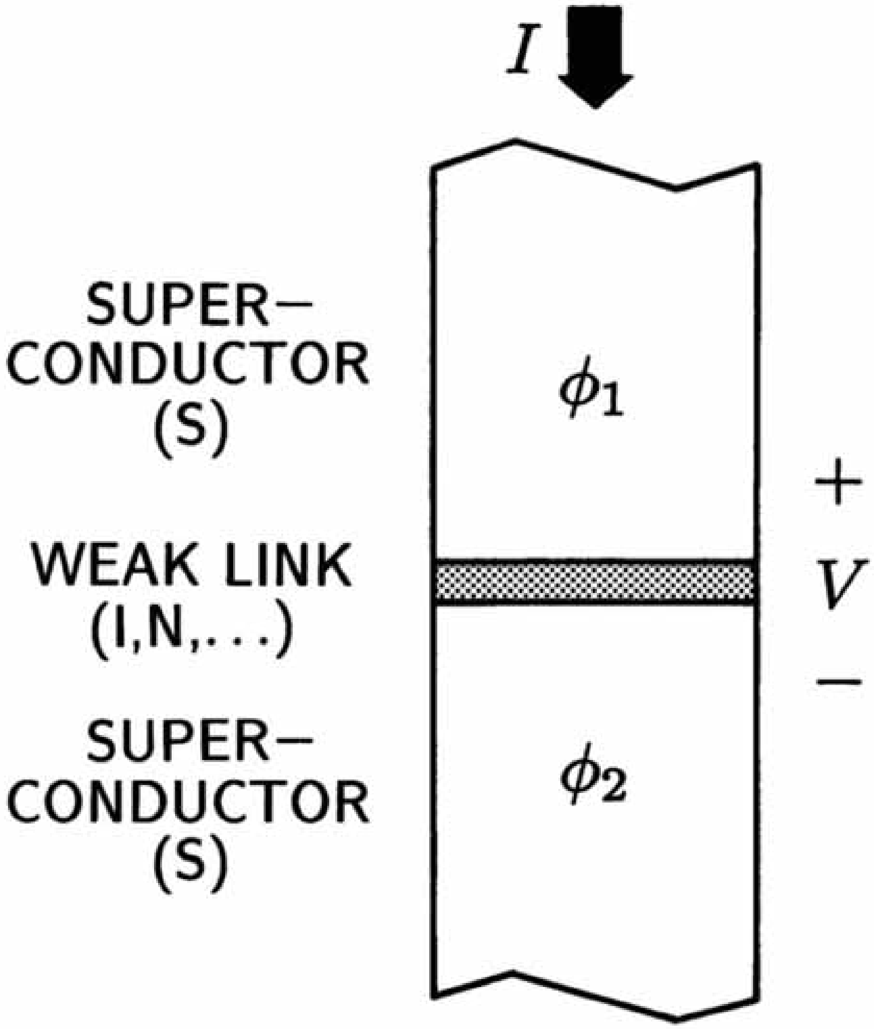
POSSIBLE NEW EFFECTS IN SUPERCONDUCTIVE TUNNELLING *

B. D. JOSEPHSON
Cavendish Laboratory, Cambridge, England

Received 8 June 1962

Applied r.f. fields can be treated by noting that the oscillations in V frequency-modulate the supercurrent. Thus if a DC voltage V on which is superimposed an AC voltage of frequency ν is applied across the barrier, the current has Fourier components at frequencies $2eV/h \pm n\nu$, where n is an integer. If for some n, $2eV/h = n\nu$, the supercurrent has a DC component dependent on the magnitude and phase of the AC voltage. Hence the DC characteristic has a zero slope resistance part over a range of current dependent on the magnitude of the AC voltage.

$$V = n\,(h/2e)\,\nu$$



MACROSCOPIC WAVEFUNCTION

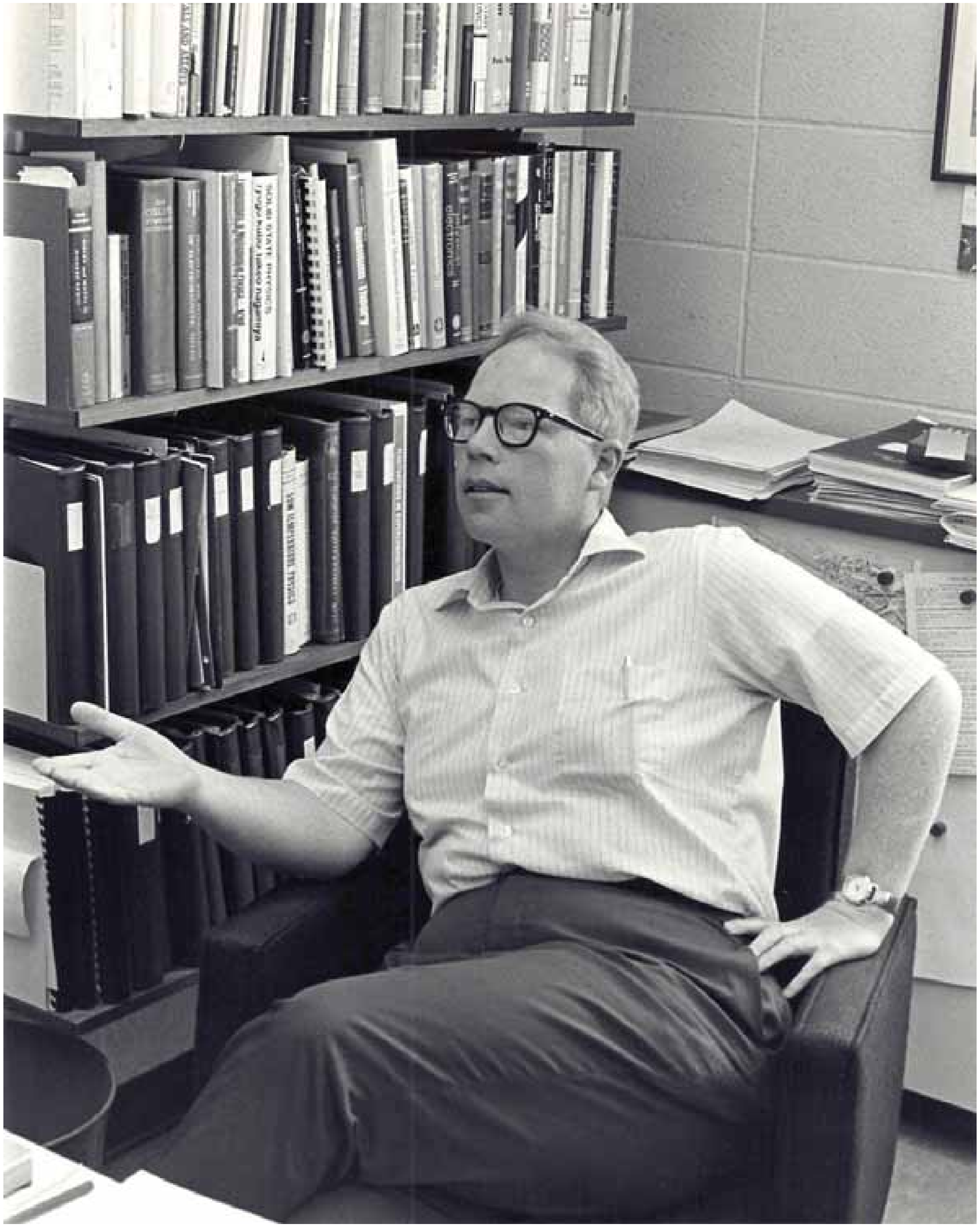
$$\psi_1 = |\psi_1|\, e^{i\phi_1}$$

JOSEPHSON EQUATIONS

$$I = I_c \sin\phi$$

$$V = \left(\frac{\hbar}{2e}\right)\frac{d\phi}{dt}$$

$$(\phi = \phi_1 - \phi_2)$$



Sidney Shapiro
University of Rochester
1970s

JOSEPHSON CURRENTS IN SUPERCONDUCTING TUNNELING: THE EFFECT OF MICROWAVES AND OTHER OBSERVATIONS*

Sidney Shapiro
Arthur D. Little, Inc., Cambridge, Massachusetts
(Received 13 June 1963)

ν = 9.3 GHz

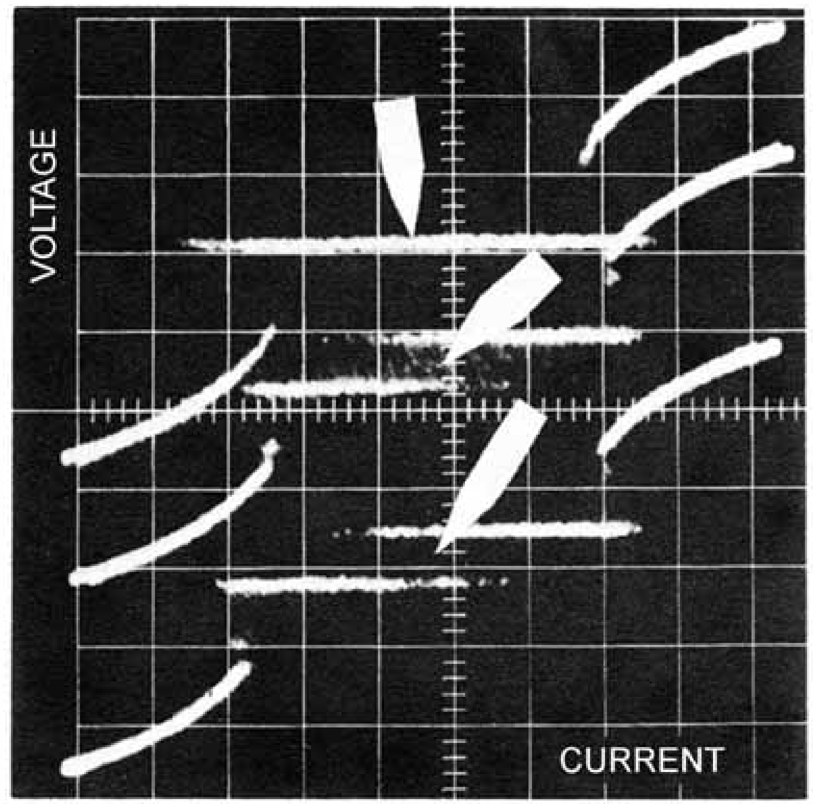


FIG. 2. Initial effect of microwave power. Pointers mark origin, which becomes noisy and vanishes as zero-slope regions at $\pm h\nu/2e$ appear. Note negative resistance at origin. Vertical scale 58.8 μV/cm, horizontal scale 13 nA/cm.

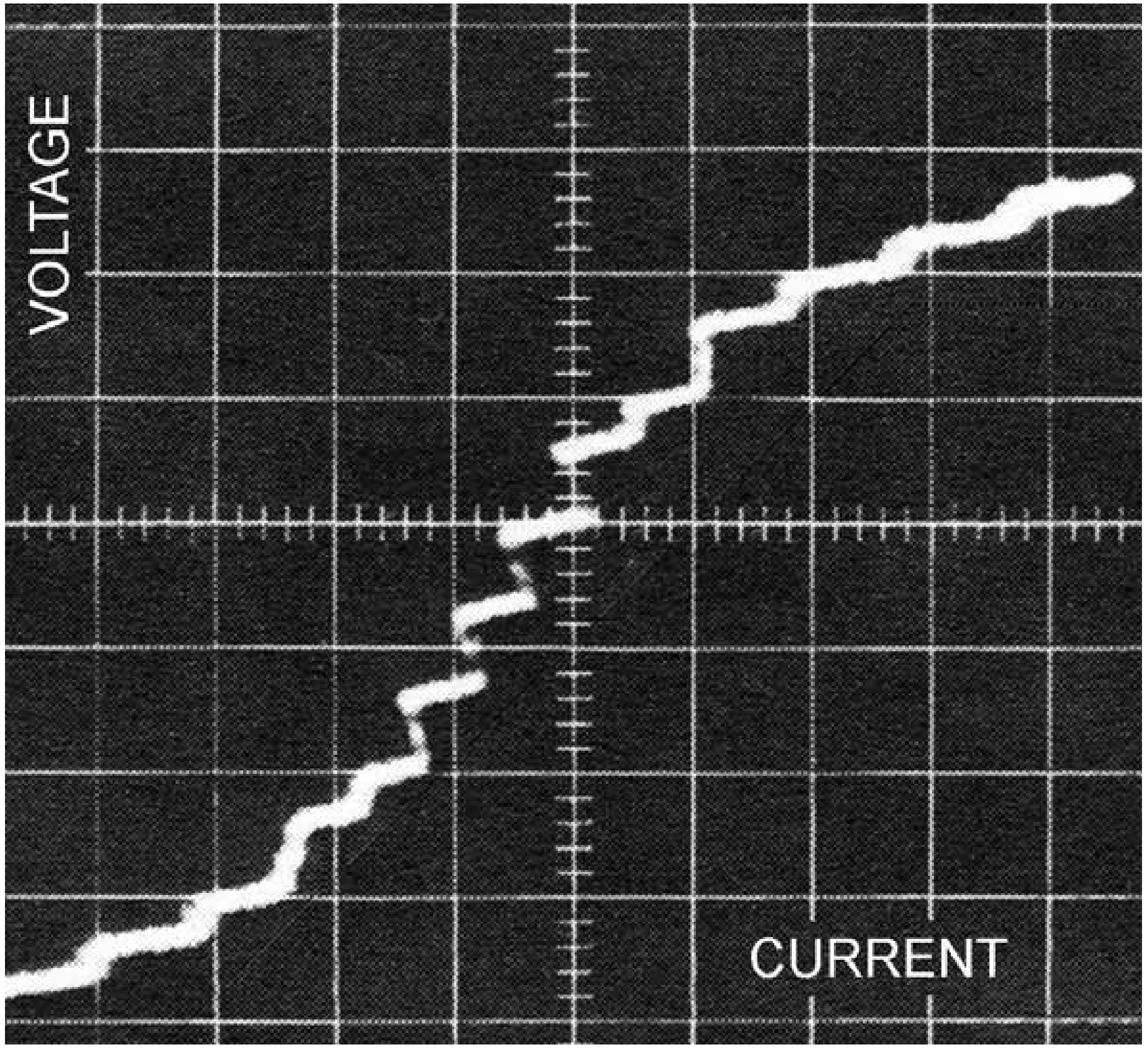
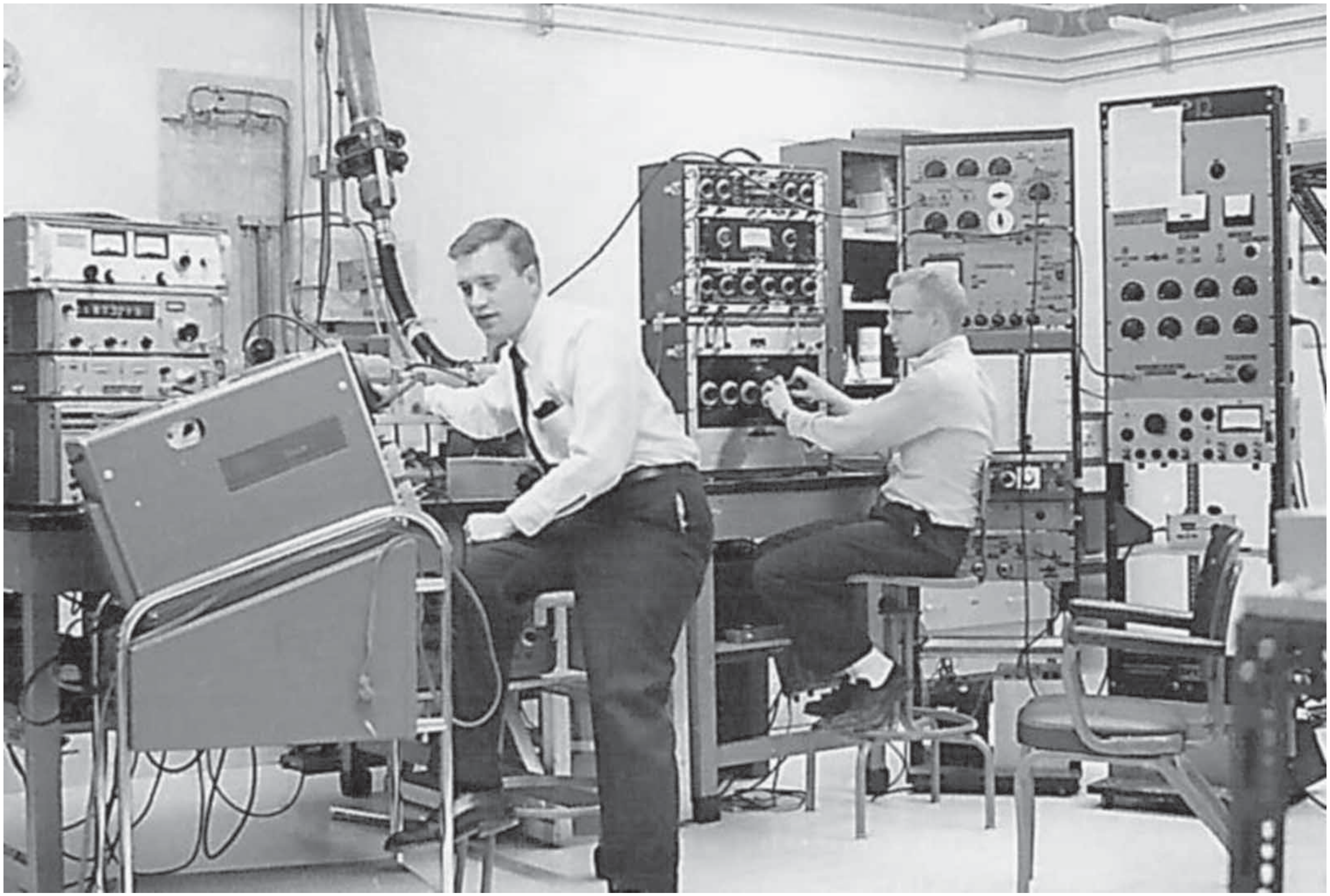


FIG. 3. Microwave power at 9300 Mc/sec produces many zero-slope regions spaced at $h\nu/2e$ or $h\nu/e$ $= 38.5\ \mu V$. Vertical scale is $58.8\ \mu V/cm$; horizontal scale is 67 nA/cm.

STANDARD
ELECTROCHEMICAL
CELL
V = 1.018 volt



Barry Taylor
Bill Parker
University of
Pennsylvania
ca. 1968

PHYSICAL REVIEW VOLUME 150, NUMBER 1 7 OCTOBER 1966

Experimental Test of the Josephson Frequency-Voltage Relation*†

D. N. LANGENBERG, W. H. PARKER, AND B. N. TAYLOR‡
Department of Physics and Laboratory for Research on the Structure of Matter, University of Pennsylvania, Philadelphia, Pennsylvania
(Received 31 May 1966)

The measured frequency-voltage ratio in this case was equal to the currently accepted value of $2e/h$ to within an experimental accuracy of 0.006% (60 ppm). The frequency-voltage ratio was also found to be independent of the type of junction used, temperature, magnetic field, harmonic number, voltage polarity, microwave power, and frequency to within the 10-ppm precision of the measurements.

John Clarke
Cambridge University
ca. 1967

EXPERIMENTAL COMPARISON OF THE JOSEPHSON VOLTAGE-FREQUENCY RELATION IN DIFFERENT SUPERCONDUCTORS*

John Clarke
Inorganic Materials Research Division, Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 8 July 1968; revised manuscript received 14 October 1968)

Using the ac Josephson effect we have demonstrated experimentally that $2e/h$ is identical in lead, tin, and indium to within 1 part in 10^8.

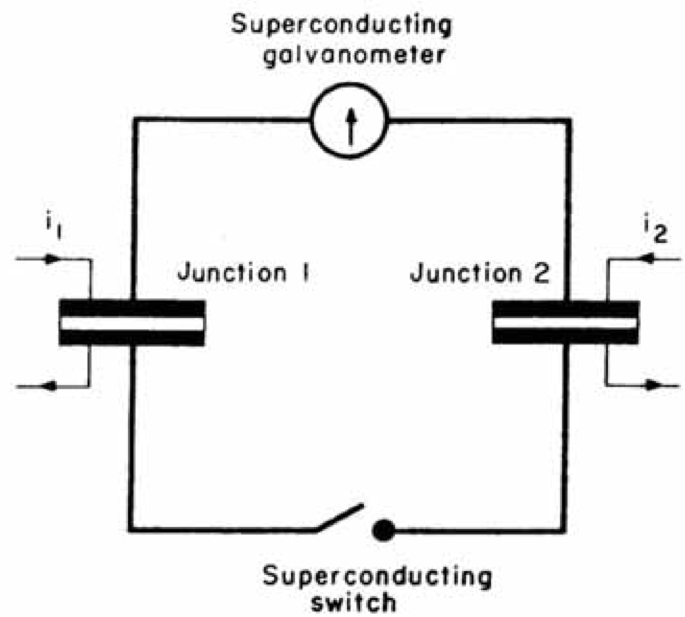


FIG 2. Circuit used both for measuring the differential resistance of the induced steps and for comparing the voltages developed across two junctions made from different superconductors. The currents i_1 and i_2 are adjusted to bias each junction on the same order current step.

$\Delta V/V < 1\text{x}10^{-8}$

Tom Finnegan   Arnold Denenstein

Bill Parker   Barry Taylor   Don Langenberg

University of Pennsylvania
Group

International Conference
on Precision Measurement
and Fundamental Constants

NBS, Gaithersburg
August 1970

PHYSICAL REVIEW B VOLUME 4, NUMBER 5 1 SEPTEMBER 1971

ac-Josephson-Effect Determination of e/h: A Standard of Electrochemical Potential Based on Macroscopic Quantum Phase Coherence in Superconductors*

T. F. Finnegan,† A. Denenstein, and D. N. Langenberg
Department of Physics and Laboratory for Research on the Structure of Matter, University of Pennsylvania, Philadelphia, Pennsylvania 19104

The Josephson frequency-voltage relation was shown experimentally to be independent of magnetic field, temperature, and Josephson-device bias voltage or induced step number to within the accuracy of the final result. The final experimental result and its one-standard-deviation uncertainty are $2e/h = (483.593\,718 \pm 0.000\,060)$ $\mathrm{MHz}/\mu V_{\mathrm{NBS}\,69}$ (0.12 ppm) referred to the volt as maintained by the U. S. National Bureau of Standards after January 1, 1969.

First-Generation Josephson Standards

Laboratory	Josephson Junction	Junction Voltage	Voltage Divider Ratio	Divider Calibration Method	Detector
BIPM, France	2 x Pb-Pb Ox 9 GHz	10 mV	100:1	(R) SPIR (Hamon)	PGA
CSIRO, Australia	Nb-Nb (PC) 8.75 GHz	1 mV	1000:1	(C) Current Comparator	SQUID
ETL, Japan	2 x Pb-Pb Ox 9.3 GHz	10 mV	100:1	(R) Hamon 10 x 45Ω 15 x 45Ω	PGA
IEN, Italy	Pb-Pb Ox	10 mV	Current Ratio	(C) Current Comparator 100:1	SQUID
LCIE, France	2 x Nb-Nb Ox 9 GHz	10 mV	100:1	(R) Hamon SPIR 10 x 100Ω	PGA
NBS, USA (1) (2)	Pb-Pb Ox 9GHz	10 mV 5.2 mV	100:1 196:1	(R) SPIR Hamon (C) Current Comparator Up to 15:1	SQUID
NPL, UK (1) (2)	Pb-Pb(PC) 36 GHz Pb-Pb Ox 9.2 GHz	1.2 mV 2.5 mV	900:1 400:1	(C) SPIR Hamon (C) Current Comparator	SLUG SQUID
NRC, Canada	Sn-Sn Ox Pb-Pb Ox 9.75-10.75 GHz	2.54 mV	400:1	(R) 100Ω: 0.25Ω 10 x 10Ω Hamon	PGA
PTB, FRG (1) (2)	2 x Nb-Nb (PC) 70 GHz Pb-Pb Ox 70 GHz	3 mV 3 mV	320:1 320:1	(R) 32Ω: 0.1Ω 8 1/3 Hz (C) Current Comparator	SQUID SQUID
VNIIM, USSR	2 x Pb-Pb Ox 8.64 GHz	2.3 mV	Up to 512:1	(R) Bootstrap Potentiometer 1:1:2:4:8,.....:512	PGA

B. W. Petley, in *Quantum Metrology and Fundamental Physical Constants* (Plenum, 1983) p. 293.

Metrologia 9, 155—166 (1973)

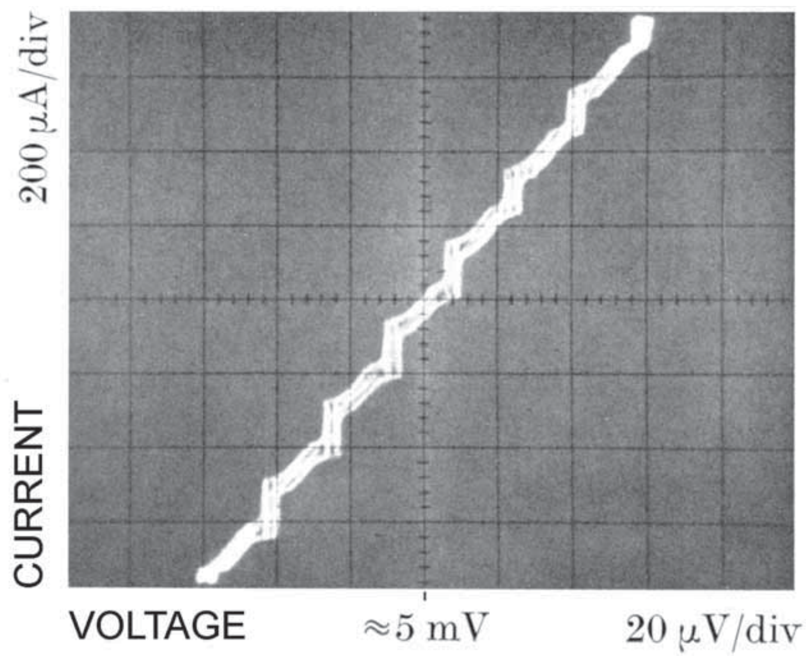
Volt Maintenance at NBS via $2e/h$: A New Definition of the NBS Volt*

B. F. Field, T. F. Finnegan, and J. Toots

Institute for Basic Standards, National Bureau of Standards, Washington, D.C. 20234, U.S.A.

Abstract

This paper describes in detail the procedures, methods and measurements used to establish a new definition of the U.S. legal volt via the ac Josephson effect. The adopted value of $2e/h$ is 483593.420 GHz/V_{NBS}.

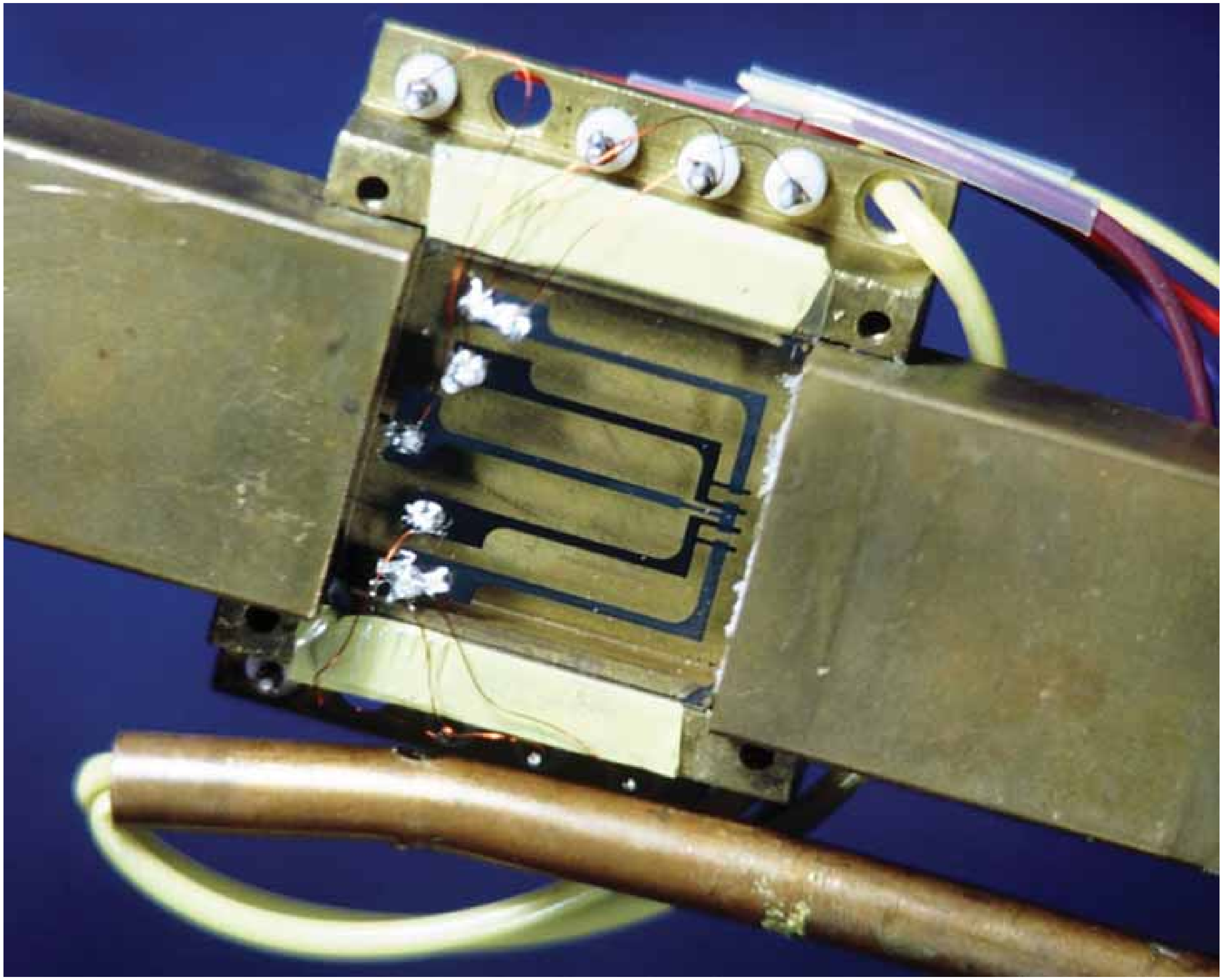


Pb-Pb Junction

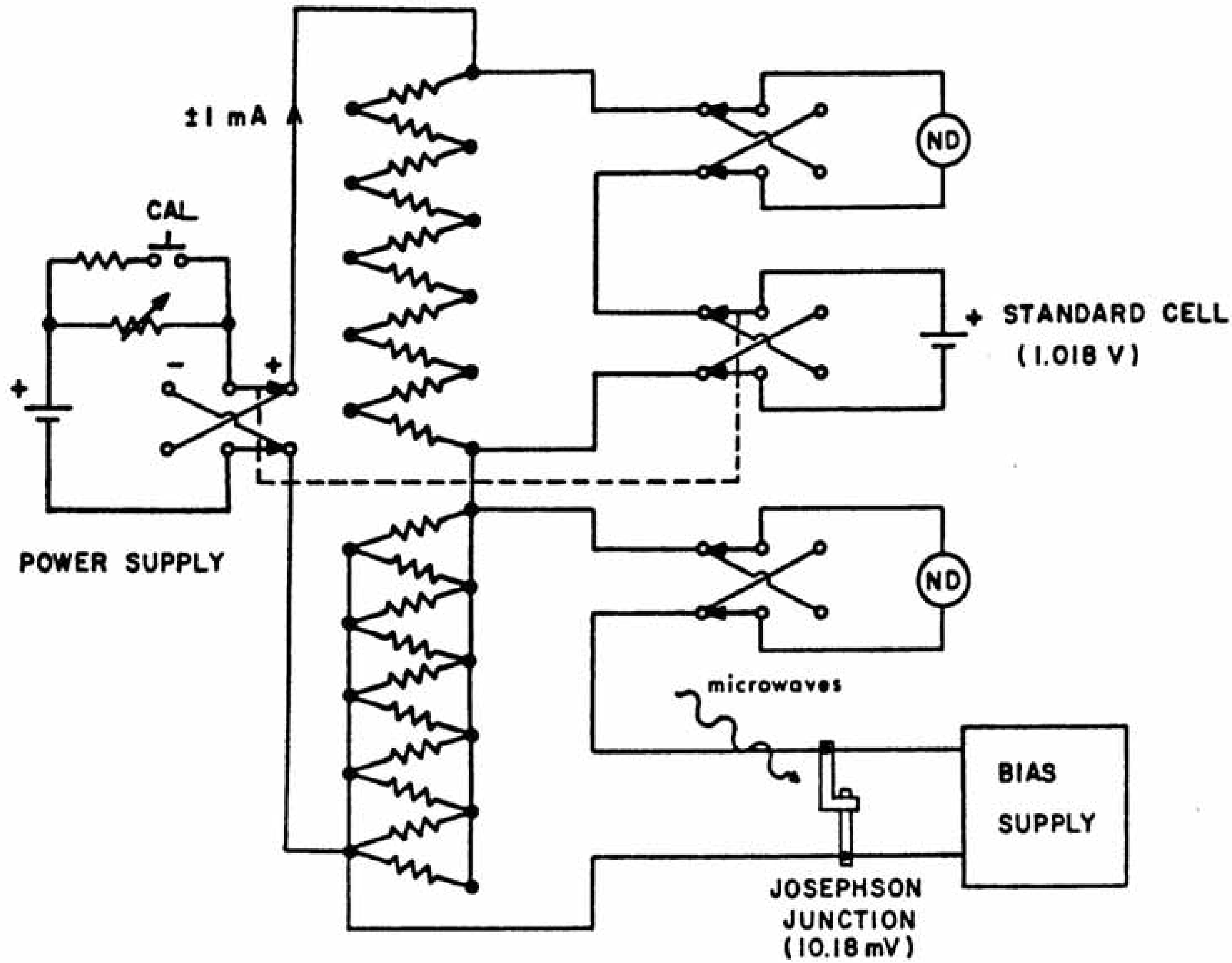
Ic = 700 μA

ν ≅ 9 GHz

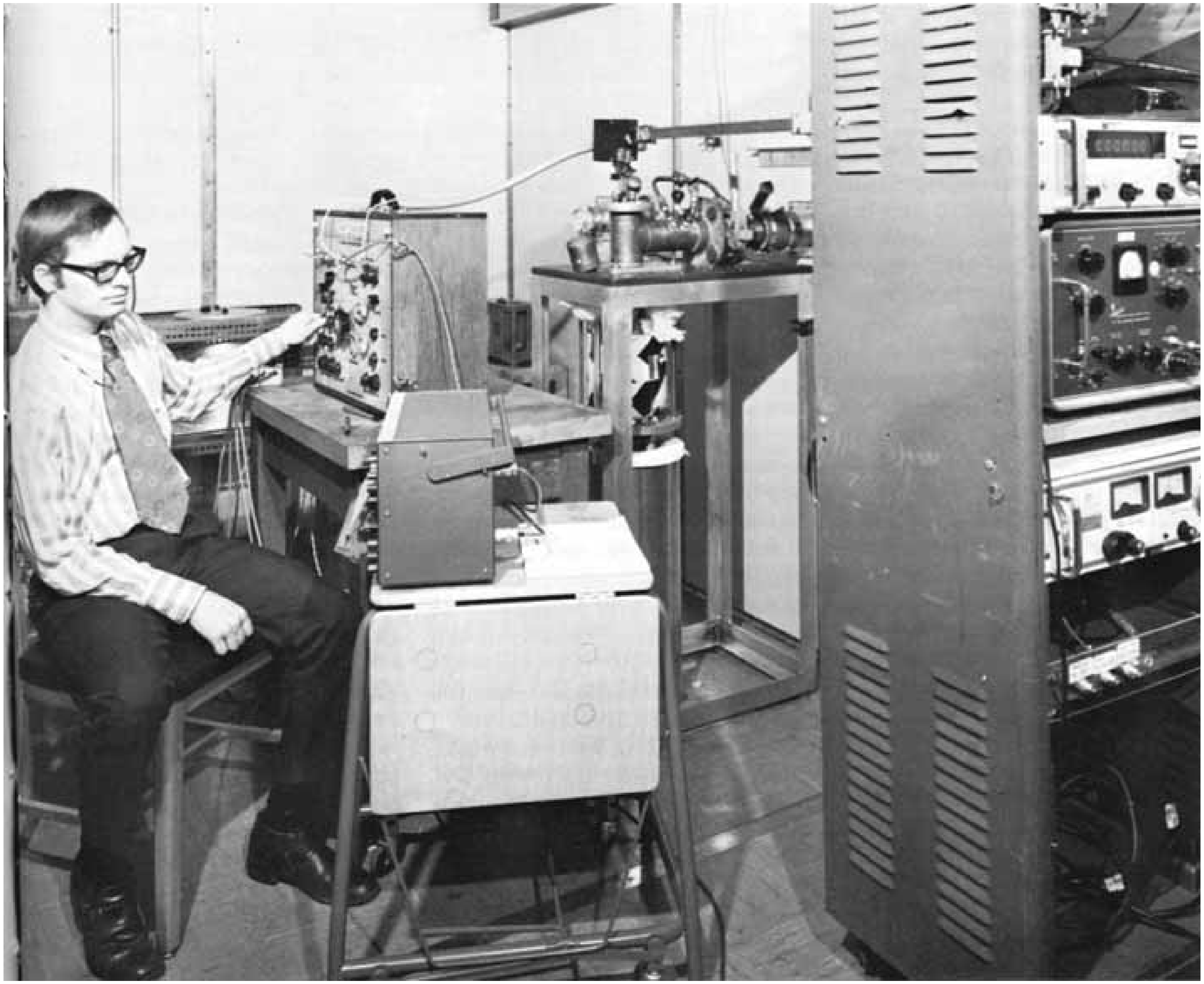
n ≅ 250



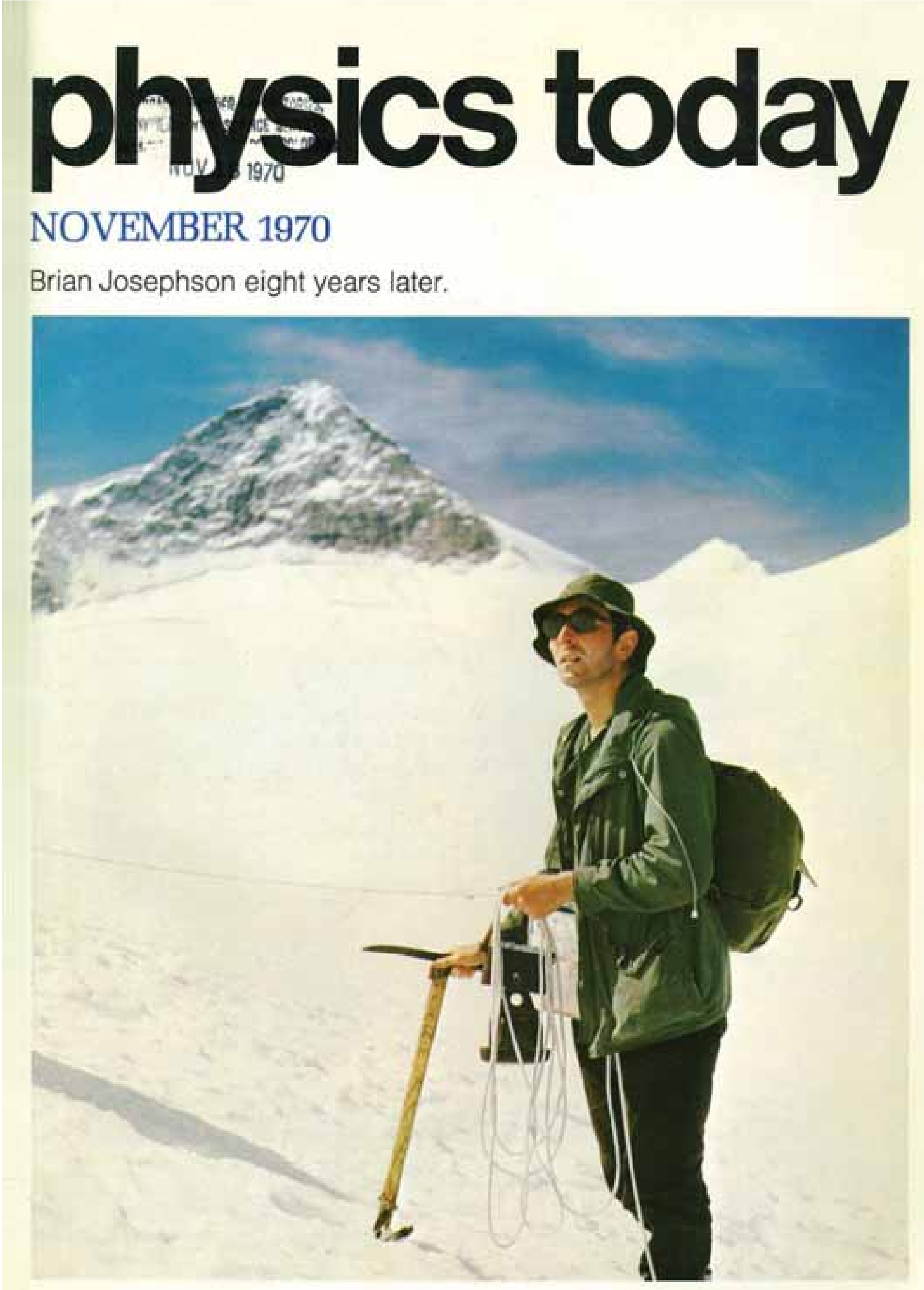
10-mV Standard
2 Pb-Pb junctions
NBS, Gaithersburg
ca. 1972



Simplified circuit diagram of series-parallel voltage comparator



Bruce Field
10-mV Josephson
Standard
NBS, Gaithersburg
1972



Brian Josephson
1973 Nobel Laureate

Aloke Jain Shen Tsai Joe Sauvageau Jim Lukens

Lukens Group
Stony Brook University
ca. 1983

VOLUME 51, NUMBER 4 PHYSICAL REVIEW LETTERS 25 JULY 1983

High-Precision Test of the Universality of the Josephson Voltage-Frequency Relation

Jaw-Shen Tsai,[a] A. K. Jain, and J. E. Lukens
Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794
(Received 11 May 1983)

The Josephson voltage-frequency relation has been compared between two quite different (and nonideal) types of Josephson junctions—an indium microbridge and a planar normal-metal barrier junction of niobium with a copper normal region. It is found that the constant of proportionality between voltage and frequency is the same in both the junctions to at least 2 parts in 10^{16}.

$$\Delta V/V < 2\mathrm{x}10^{-16}$$

VOLUME 58, NUMBER 12 PHYSICAL REVIEW LETTERS 23 MARCH 1987

Test for Relativistic Gravitational Effects on Charged Particles

A. K. Jain, J. E. Lukens, and J.-S. Tsai[a]
Department of Physics, State University of New York, Stony Brook, New York 11794
(Received 14 November 1986)

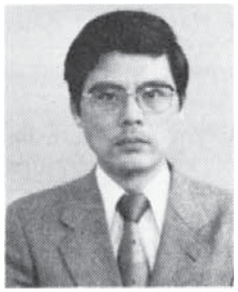
Experimental results are presented which provide the first measurement of the effects of a gravitational field on charged particles, equivalent to the red shift for photons. Two Josephson-effect batteries ($V \simeq 300\ \mu$V) having a vertical separation of 7.2 cm are connected in opposition by superconducting wires. A voltage difference of 2.35×10^{-21} V is maintained between these batteries by means of the gravitational red shift. The emf around this loop is, however, measured to be less than 1×10^{-22} V, consistent with the predicted invariance of the gravito-electrochemical potential along the wires.

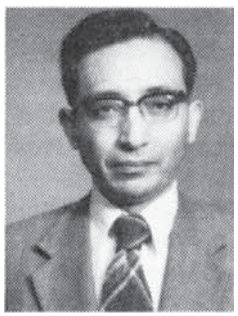
$$\Delta V/V < 3\mathrm{x}10^{-19}$$

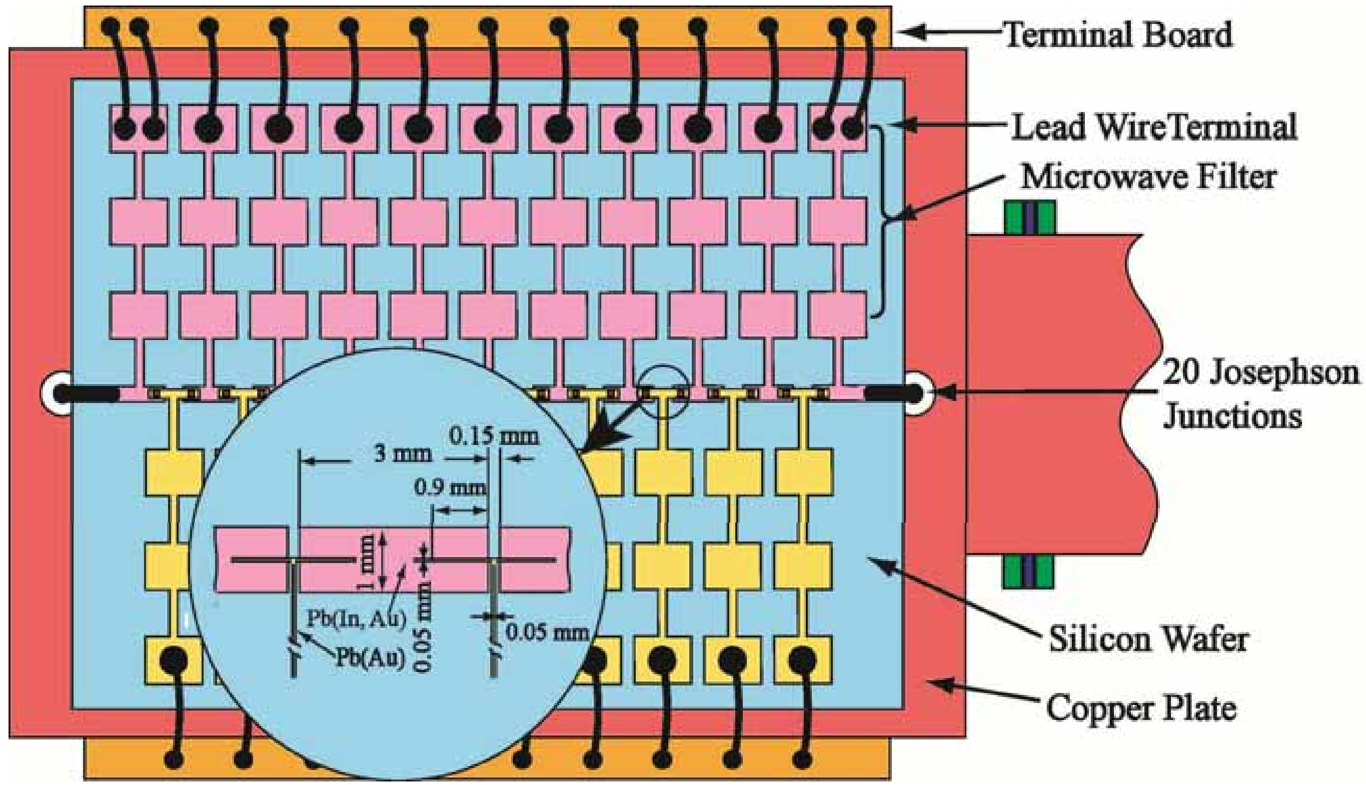
IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. IM-32, NO. 1, MARCH 1983

High-Accuracy Josephson Potentiometer

TADASHI ENDO, MASAO KOYANAGI, AND AKIRA NAKAMURA
Electrotechnical Laboratory, 1-1-4 Umezono Sakura-mura, Niihari-gun, Ibaraki 305, Japan

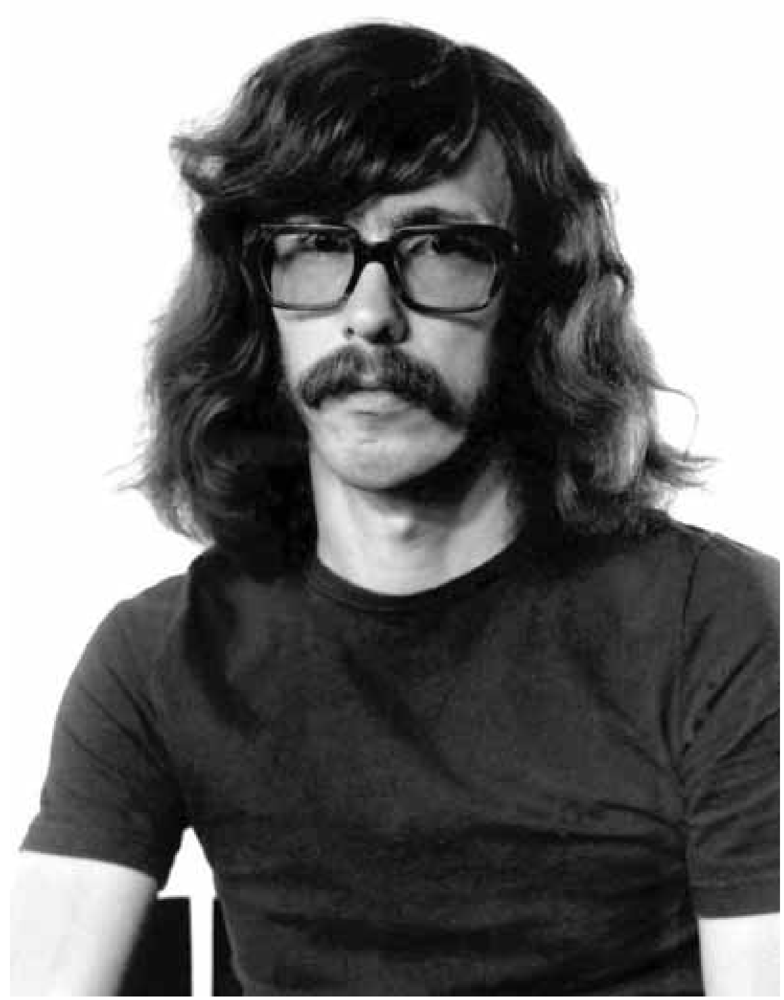






V =100 mV

Don Sullivan
NBS, Boulder
1985



Mogens Levinsen
University of Copenhagen
ca. 1977

Applied Physics Letters, Vol. 31, No. 11, 1 December 1977

An inverse ac Josephson effect voltage standard

M. T. Levinsen

Physics Laboratory I, H.C. Ørsted Institute, University of Copenhagen, Universitetsparken 5, DK 2100 Copenhagen Ø, Denmark

R. Y. Chiao, M. J. Feldman, and B. A. Tucker

Department of Physics, University of California, Berkeley, California 94720
(Received 6 September 1977; accepted for publication 28 September 1977)

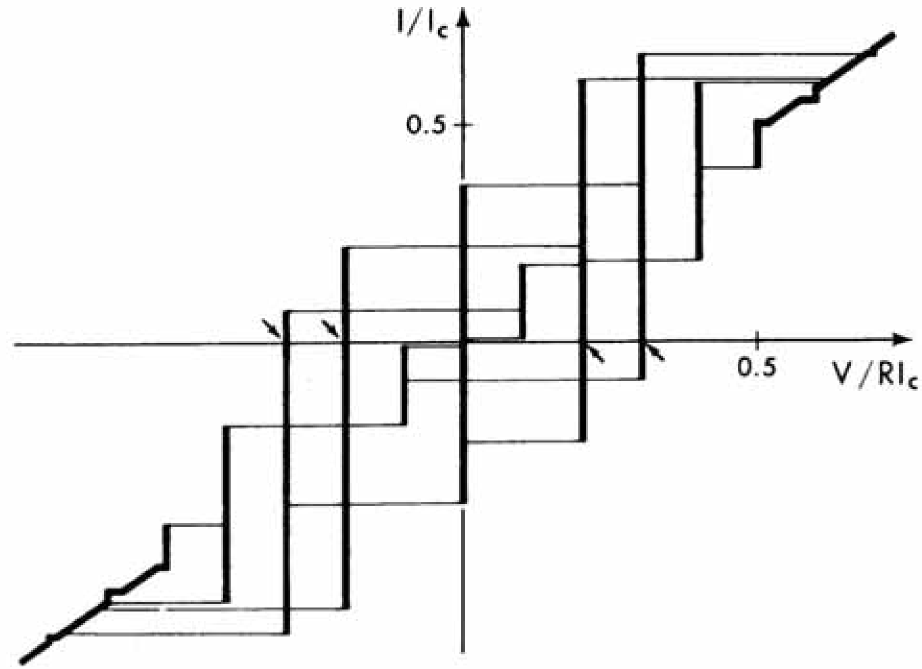
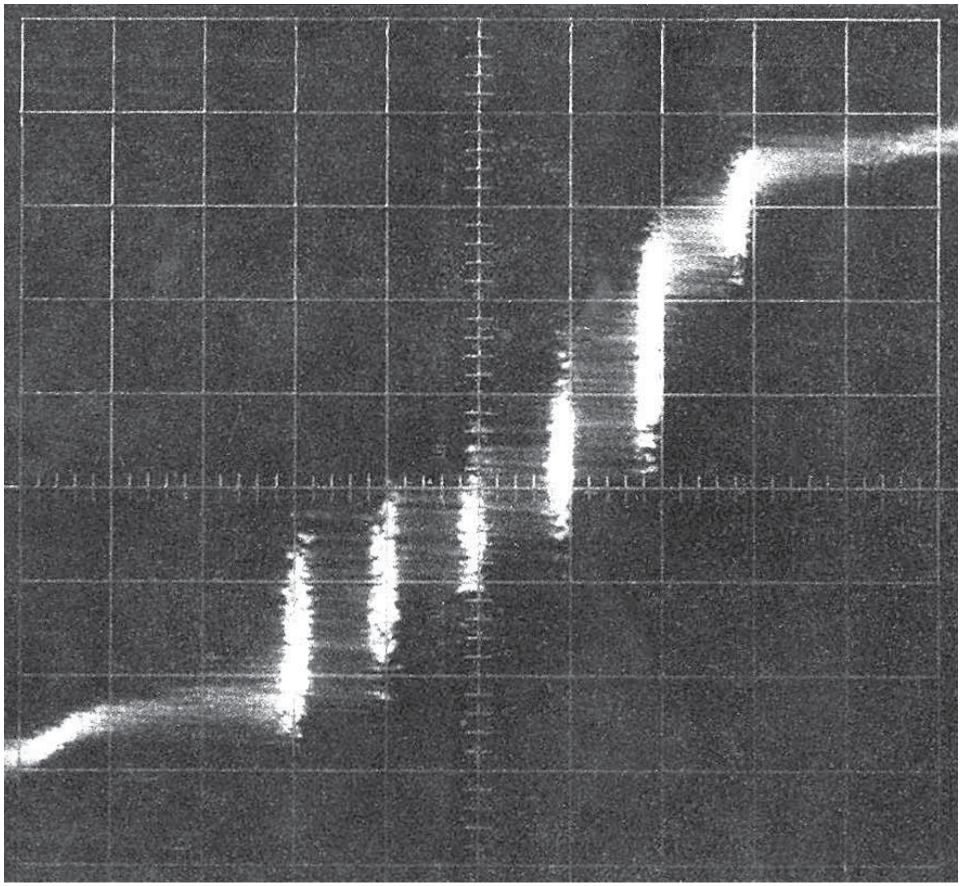


FIG. 1. Multiple tracing of the I–V curve of the analog Josephson simulator.

ν = 11.88 GHz

Ic = 170 μA

CURRENT 1 μA/cm



VOLTAGE 50 μV/cm

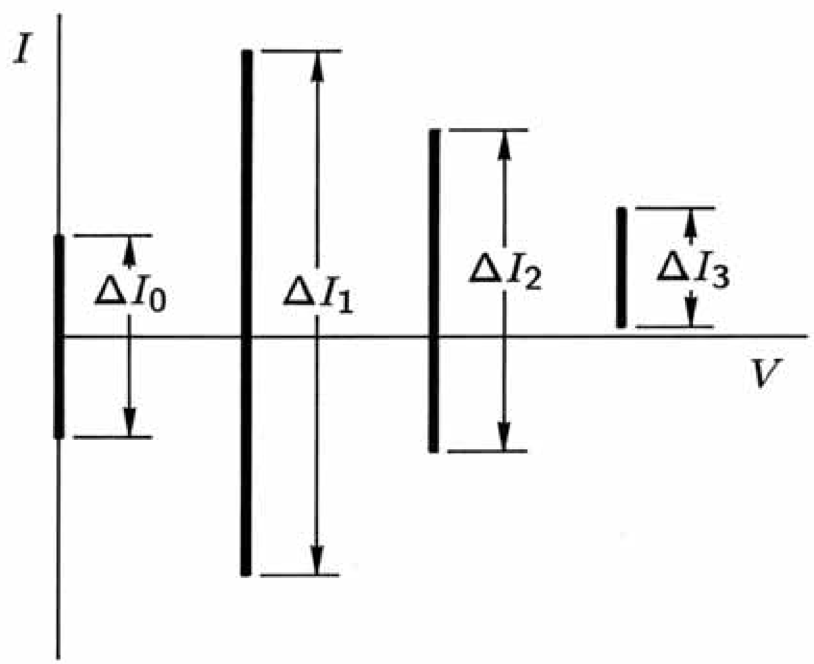
Lead-Alloy Junction
September 1977

Reviews of Modern Physics · January 1964

Effect of Microwaves on Josephson Currents in Superconducting Tunneling*

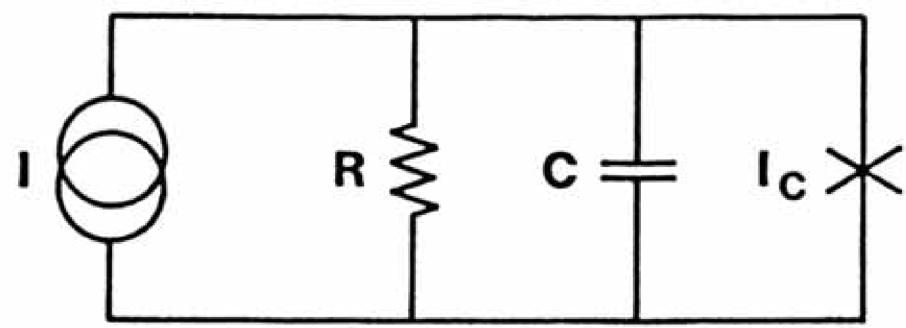
SIDNEY SHAPIRO,† ANDRE R. JANUS, and SANDOR HOLLY
Arthur D. Little, Inc., Cambridge, Massachusetts

STEP AMPLITUDES FOR MICROWAVE VOLTAGE BIAS

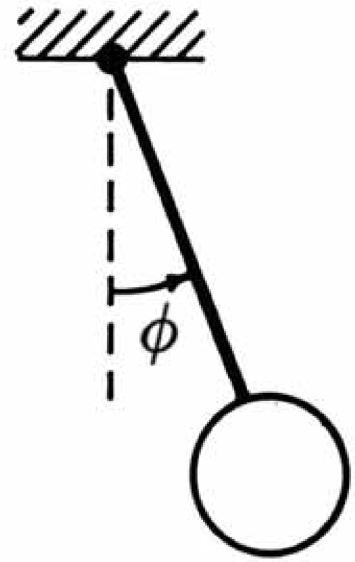


$$\Delta I_n = 2I_c|J_n(2eV_{rf}/hf)|$$

MICROWAVE – BIASED JUNCTION



DRIVEN DAMPED PENDULUM



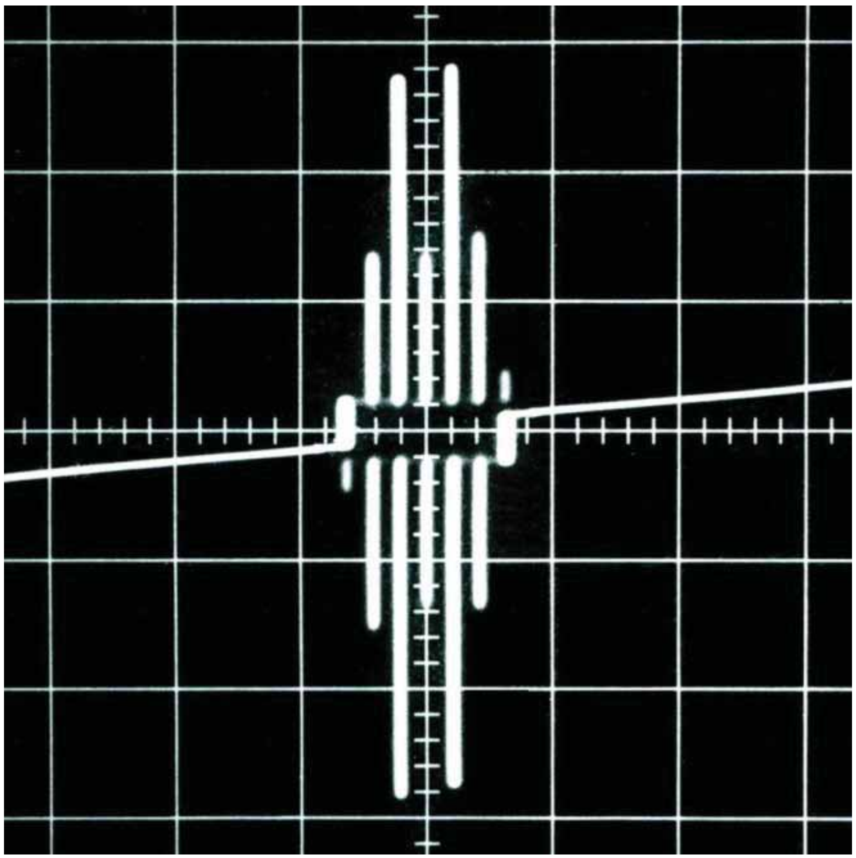
$$\frac{d^2\phi}{dt^2} + \sigma\frac{d\phi}{dt} + \sin\phi = i_0 + i_1 \sin\omega t$$

$$\omega = \nu/\nu_p$$

Appl. Phys. Lett. **36**(5), 1 March 1980

On a proposed Josephson-effect voltage standard at zero current bias

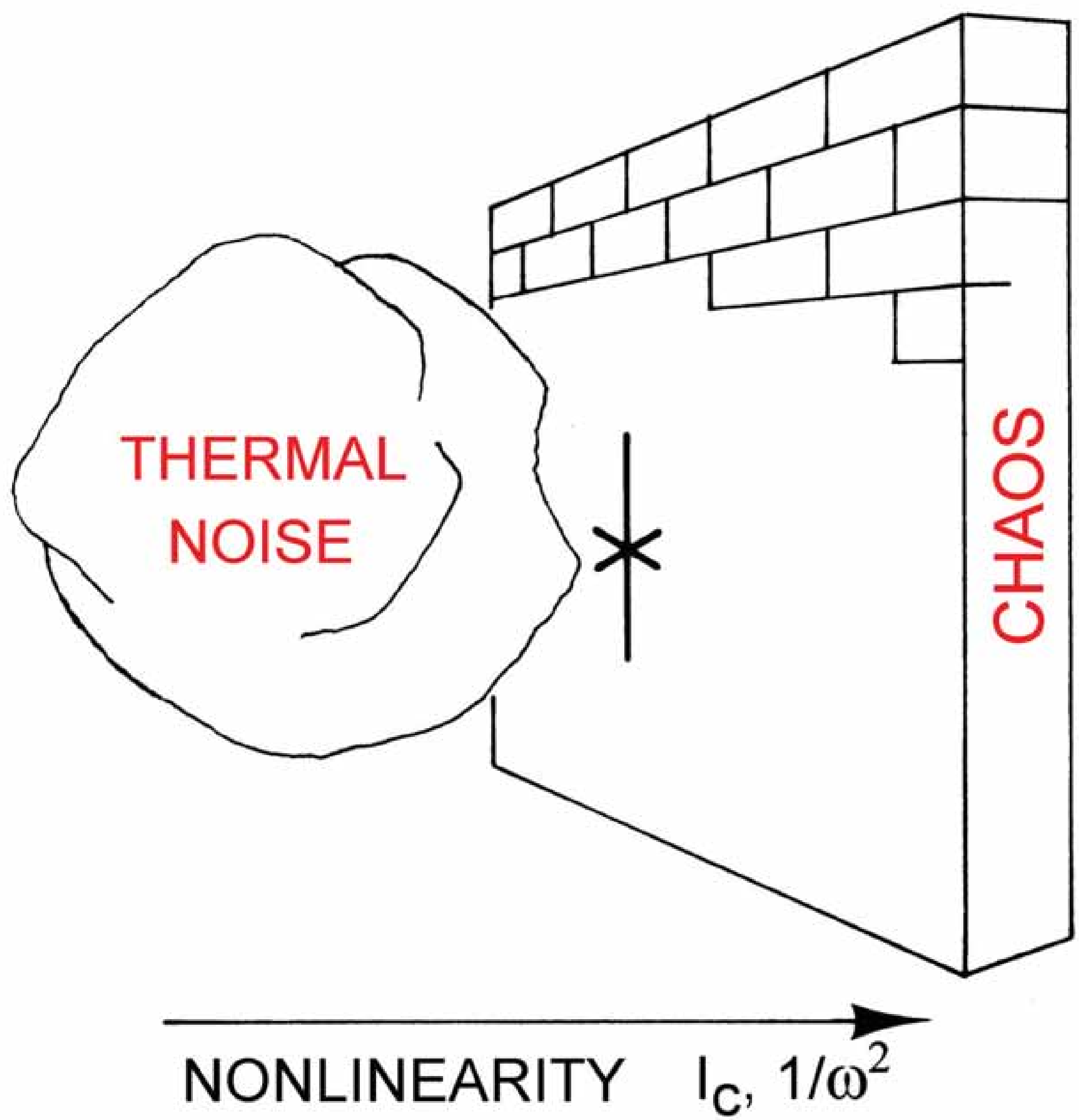
R. L. Kautz
Electromagnetic Technology Division, National Bureau of Standards, Boulder, Colorado 80303

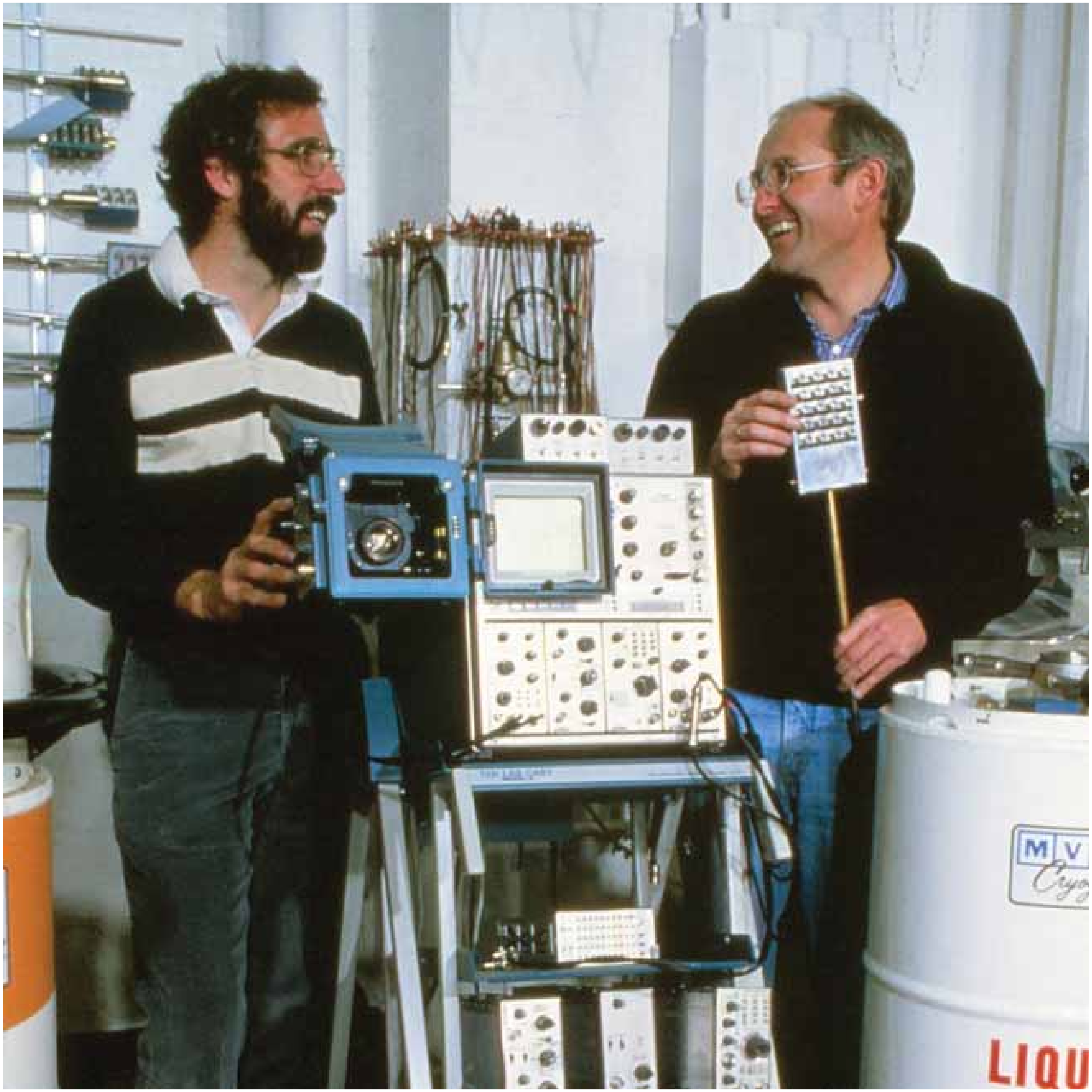


CURRENT 20 μA/cm

VOLTAGE 200 μV/cm

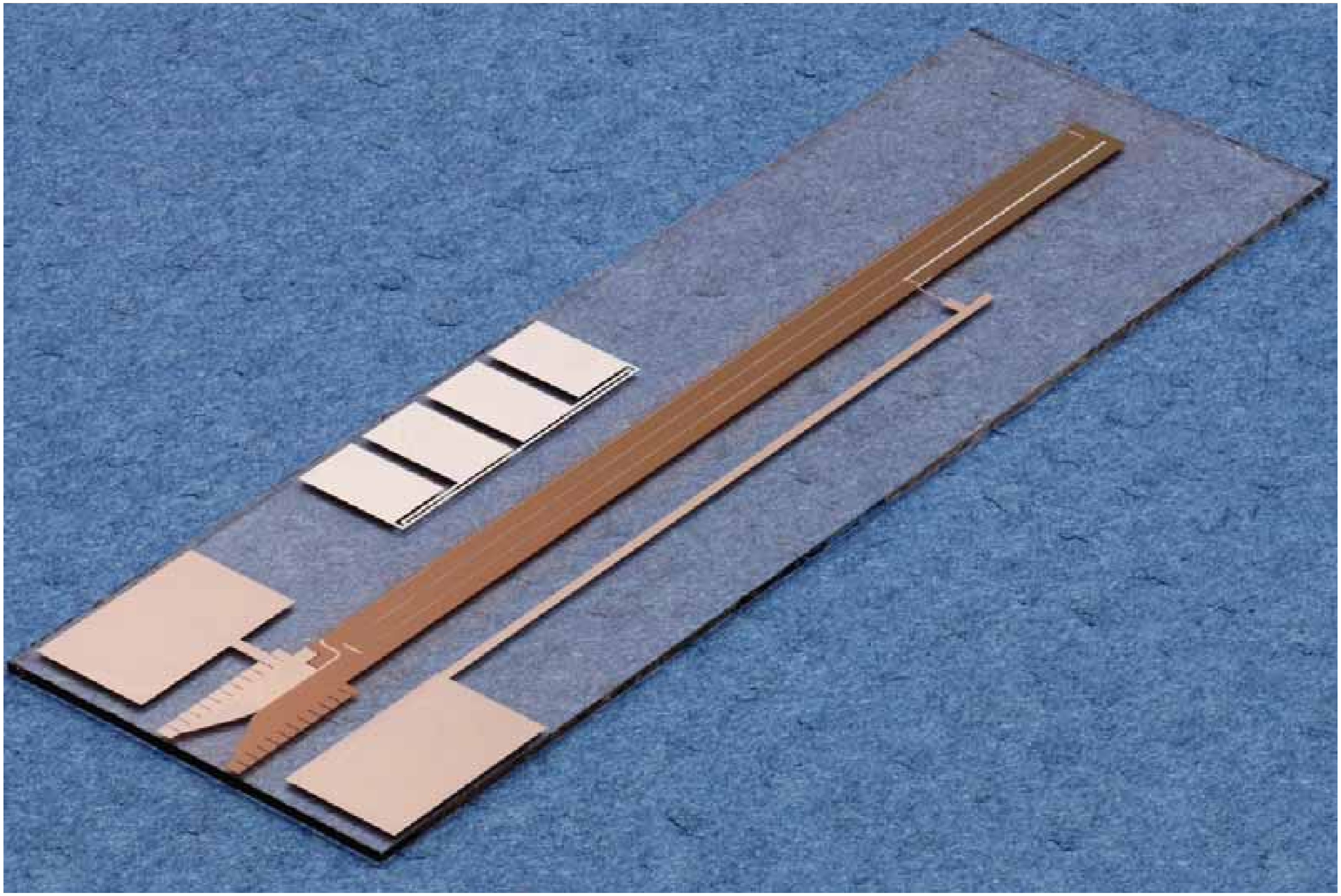
Nb-Pb Junction
Ic = 98 μA
ν = 20.35 GHz
(ω = 1.4)
July, 1979


THERMAL NOISE
CHAOS
NONLINEARITY I_C, $1/\omega^2$



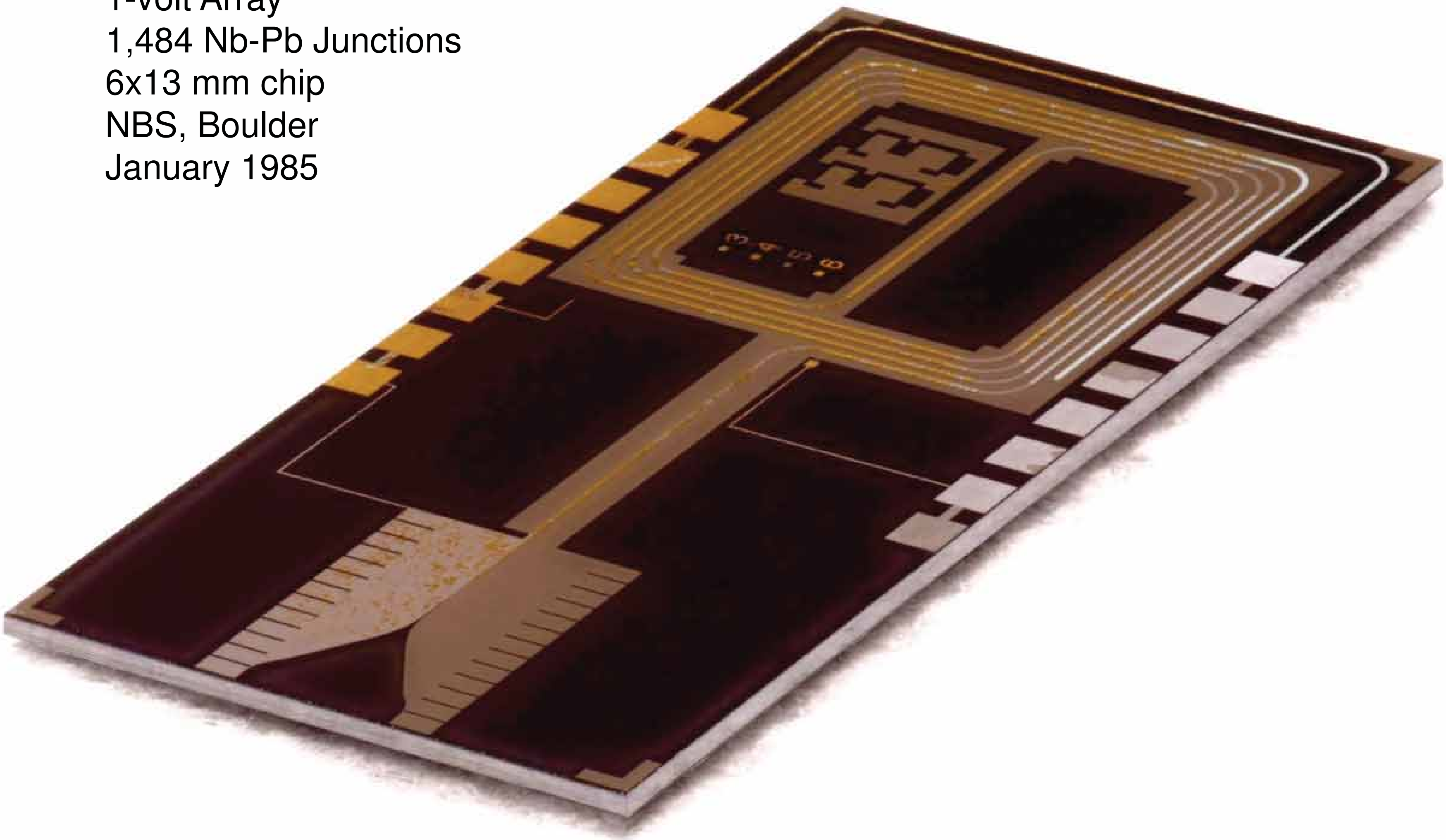
Richard Kautz
Jurgen Niemeyer
NBS, Boulder
March 1984

PTB/NBS 1-Volt Array 1984



1,474 Pb-alloy
junctions
10x30 mm chip
ν = 90 GHz

1-volt Array
1,484 Nb-Pb Junctions
6x13 mm chip
NBS, Boulder
January 1985

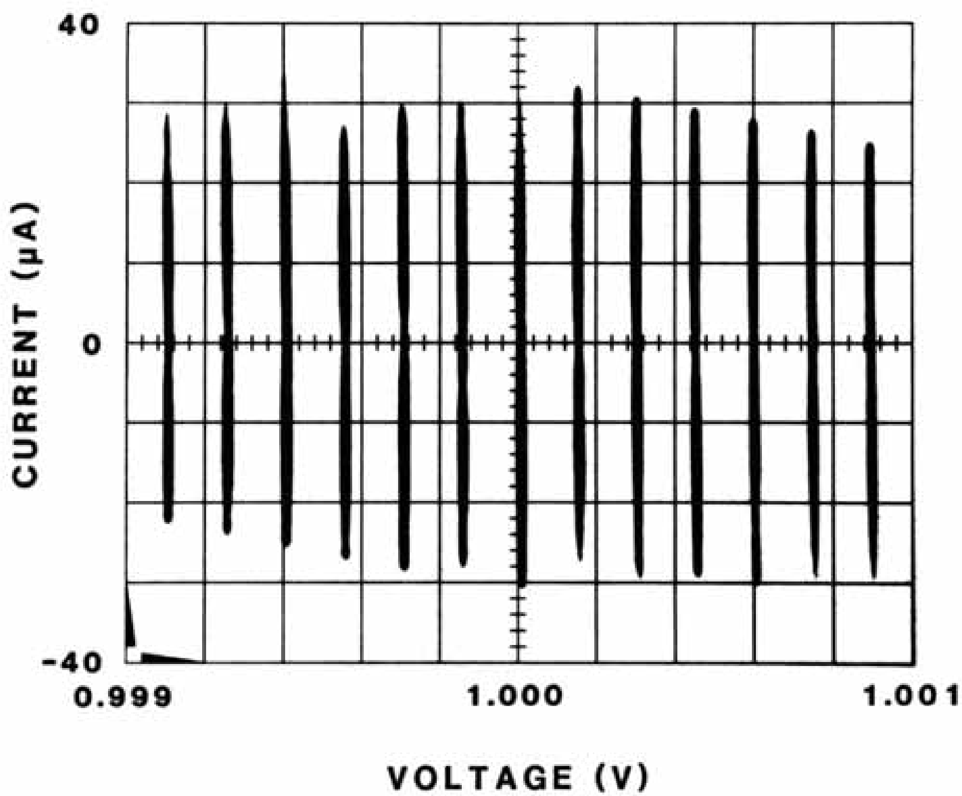


Clark Hamilton
NBS, Boulder
ca. 1982

IEEE ELECTRON DEVICE LETTERS, VOL. EDL-6, NO. 12, DECEMBER 1985

A Practical Josephson Voltage Standard at 1 V

C. A. HAMILTON, MEMBER, IEEE, R. L. KAUTZ, R. L. STEINER, AND FRANCES L. LLOYD



$\nu = 72$ GHz

Appl. Phys. Lett. 47 (11), 1 December 1985

Stable Josephson reference voltages between 0.1 and 1.3 V for high-precision voltage standards

J. Niemeyer, L. Grimm, and W. Meier
Physikalisch-Technische Bundesanstalt, Bundesallee 100, 3300 Braunschweig, Federal Republic of Germany
J. H. Hinken and E. Vollmer
Institut für Hochfrequenztechnik der Techn. Universität Braunschweig, P. O. Box 3329, 3300 Braunschweig, Federal Republic of Germany

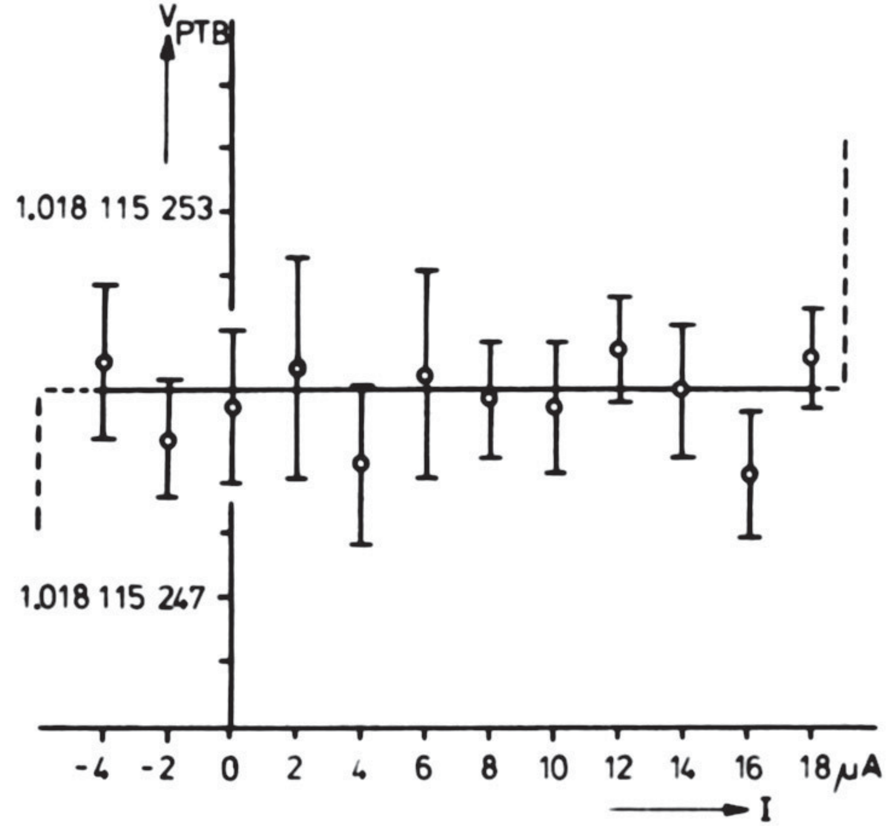


FIG. 3. Voltage of the 7000 th constant voltage step relative to a Weston cell as a function of bias current. The stable step amplitude is 22 μA, the average critical current of the array 120 μA. The uncertainty bars denote 2 s (s: experimental standard deviation of a single measurement). Standard deviation of the mean: $\sigma = s/\sqrt{n} = 3\times 10^{-10}$ V, $n = 12$.

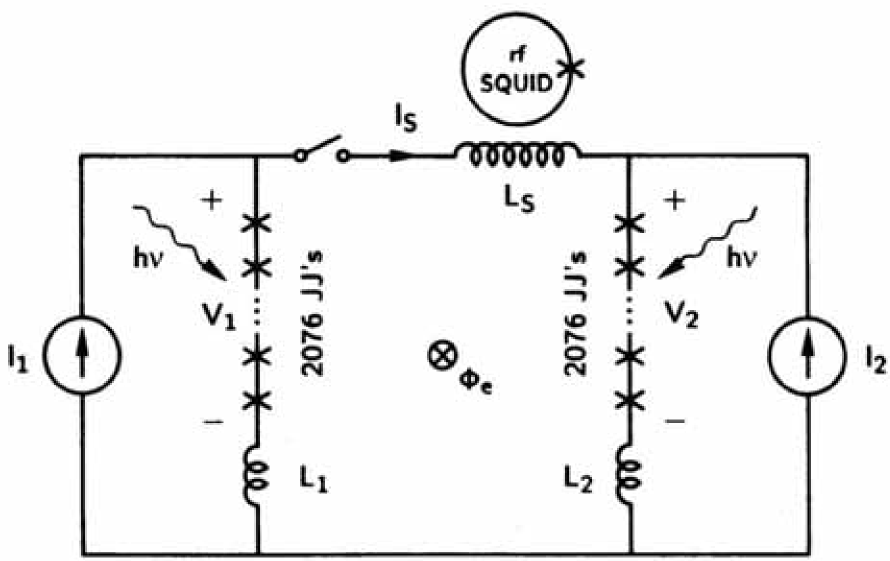
Appl. Phys. Lett. **51** (24), 14 December 1987

Precision of series-array Josephson voltage standards

R. L. Kautz and Frances L. Lloyd
National Bureau of Standards, Boulder, Colorado 80303

(Received 7 August 1987; accepted for publication 9 October 1987)

Comparison of two series-array Josephson voltage standards operated at over 1 V shows that they differ in voltage by less than 2 parts in 10^{17}.



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

$\Delta V/V < 2\text{x}10^{-17}$

Shin Kosaka Jurgen Niemeyer Akira Shoji

PTB/ETL Collaboration

JAPANESE JOURNAL OF APPLIED PHYSICS
VOL. 25, NO. 5, MAY, 1986, pp. L343–L345

Nb/Al-oxide/Nb and NbN/MgO/NbN Tunnel Junctions in Large Series Arrays for Voltage Standards

Jürgen NIEMEYER,† Yasuhiko SAKAMOTO, Eckhard VOLLMER,†† Johann H. HINKEN,††
Akira SHOJI, Hiroshi NAKAGAWA, Susumu TAKADA and Shin KOSAKA

Electrotechnical Laboratory (ETL), 1-1-4 Umezono, Sakura-mura, Niihari-gun, Ibaraki 305
†Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 3300 Braunschweig, F. R. Germany
††Institut f. Hochfrequenztechnik, Technische Universität Braunschweig,
P. O. Box 3329, 3300 Braunschweig, F. R. Germany

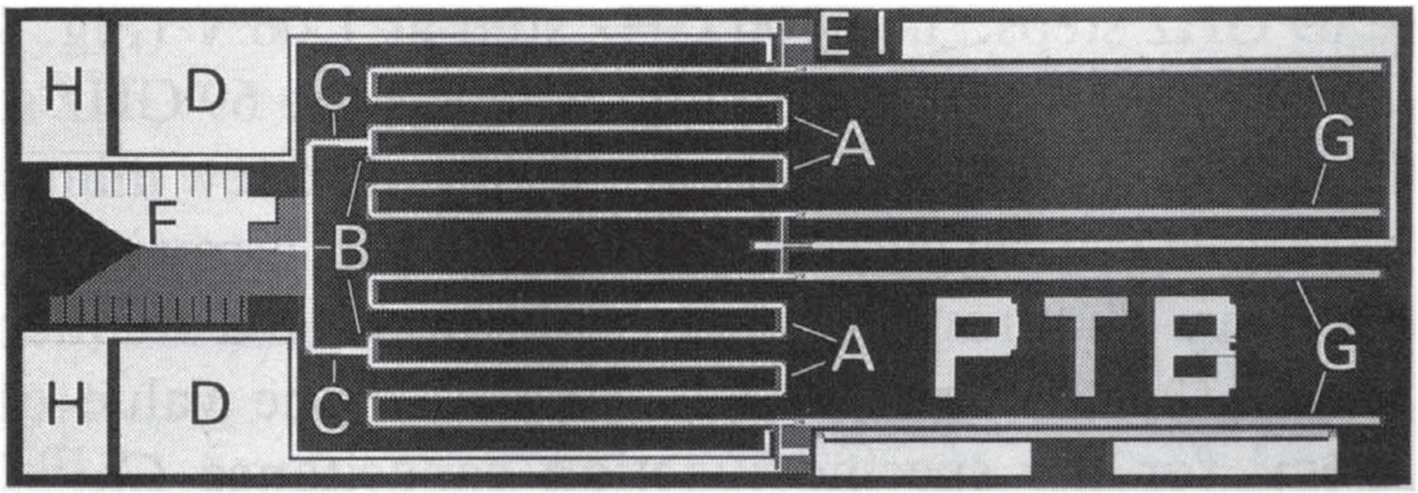


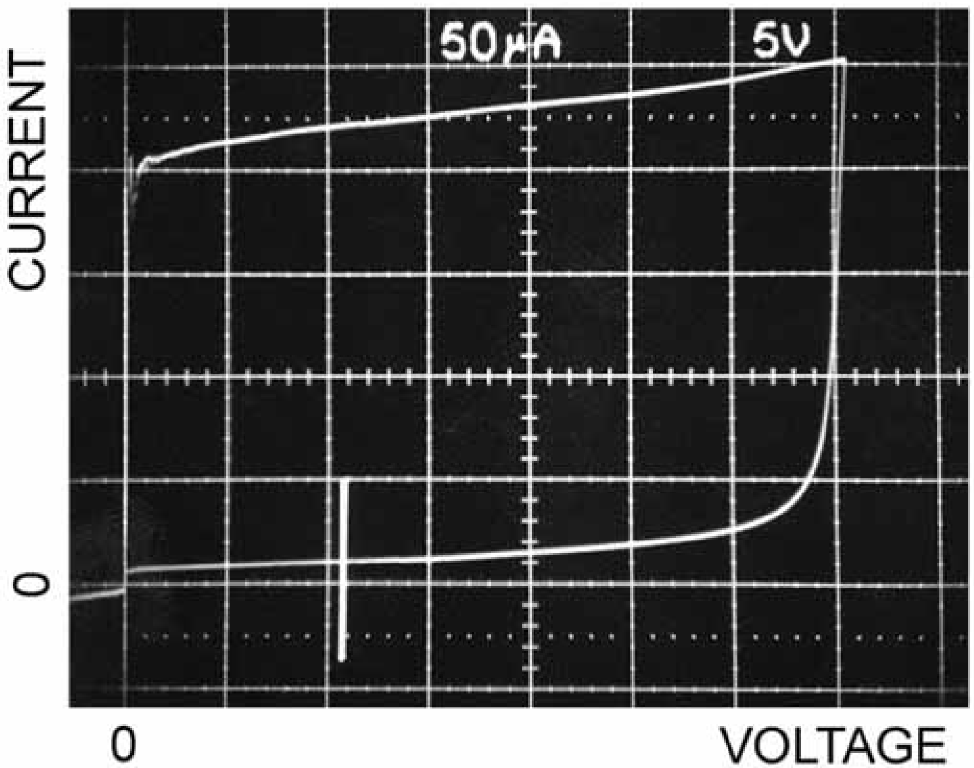
Fig. 1. Micrograph of a series-parallel array of 1440 Josephson tunnel junctions. 4 series arrays (A) are connected in parallel to the microwave supply by three power dividers (B) and two dc-blocks (C), and in series to the dc-connections (D) over bandstop filters (E). The circuit is matched to a 70 GHz waveguide by a tapered fine-line (F) and terminated by 4 matched loads (G). (H) denotes single junction electrodes and (I) a center electrode.

Dick Harris
Frances Lloyd
Jim Beall
Clark Hamilton
Dick Kautz
NIST, Boulder
May 1989

IEEE ELECTRON DEVICE LETTERS, VOL. EDL-8, NO. 10, OCTOBER 1987

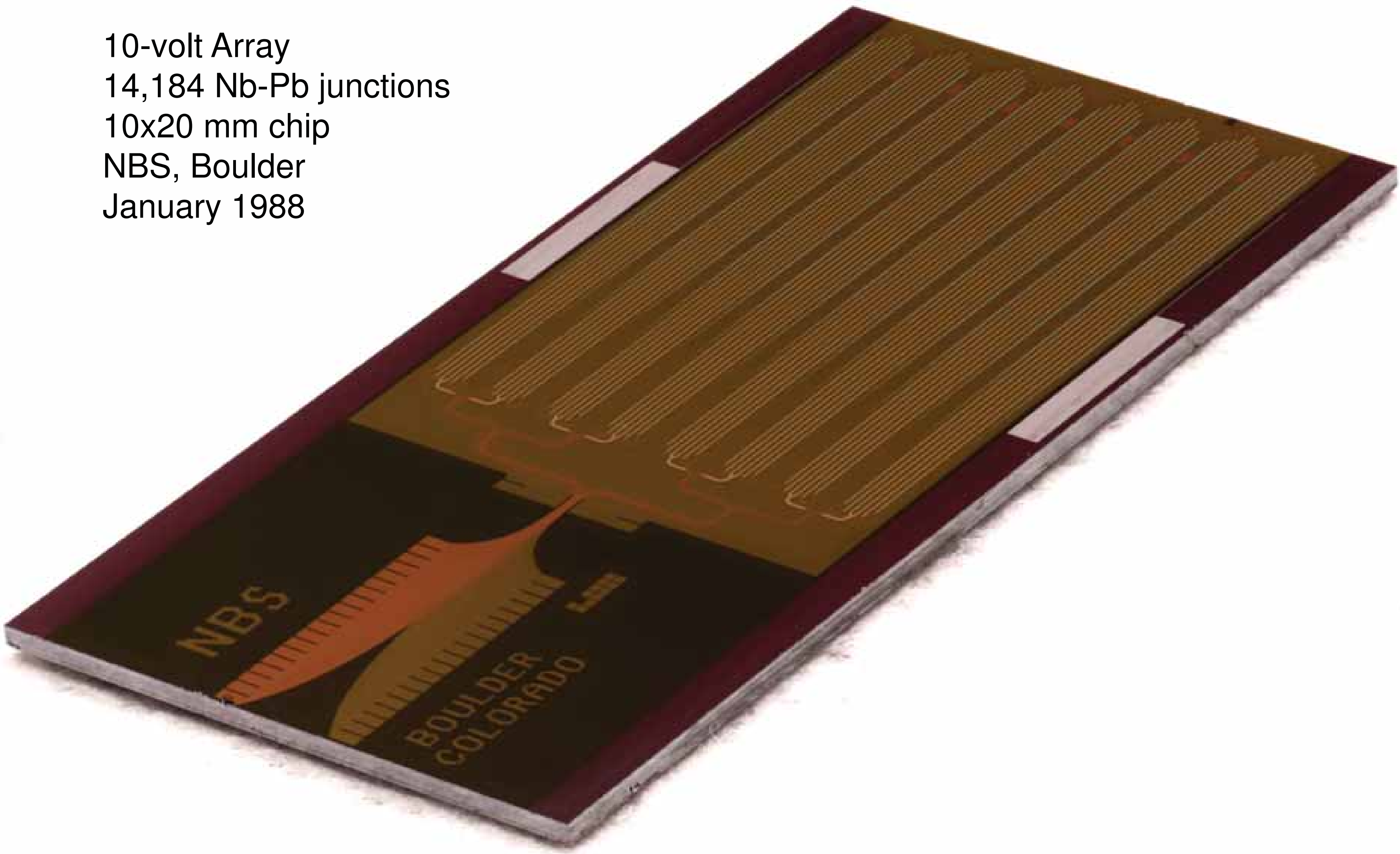
A Josephson Array Voltage Standard at 10 V

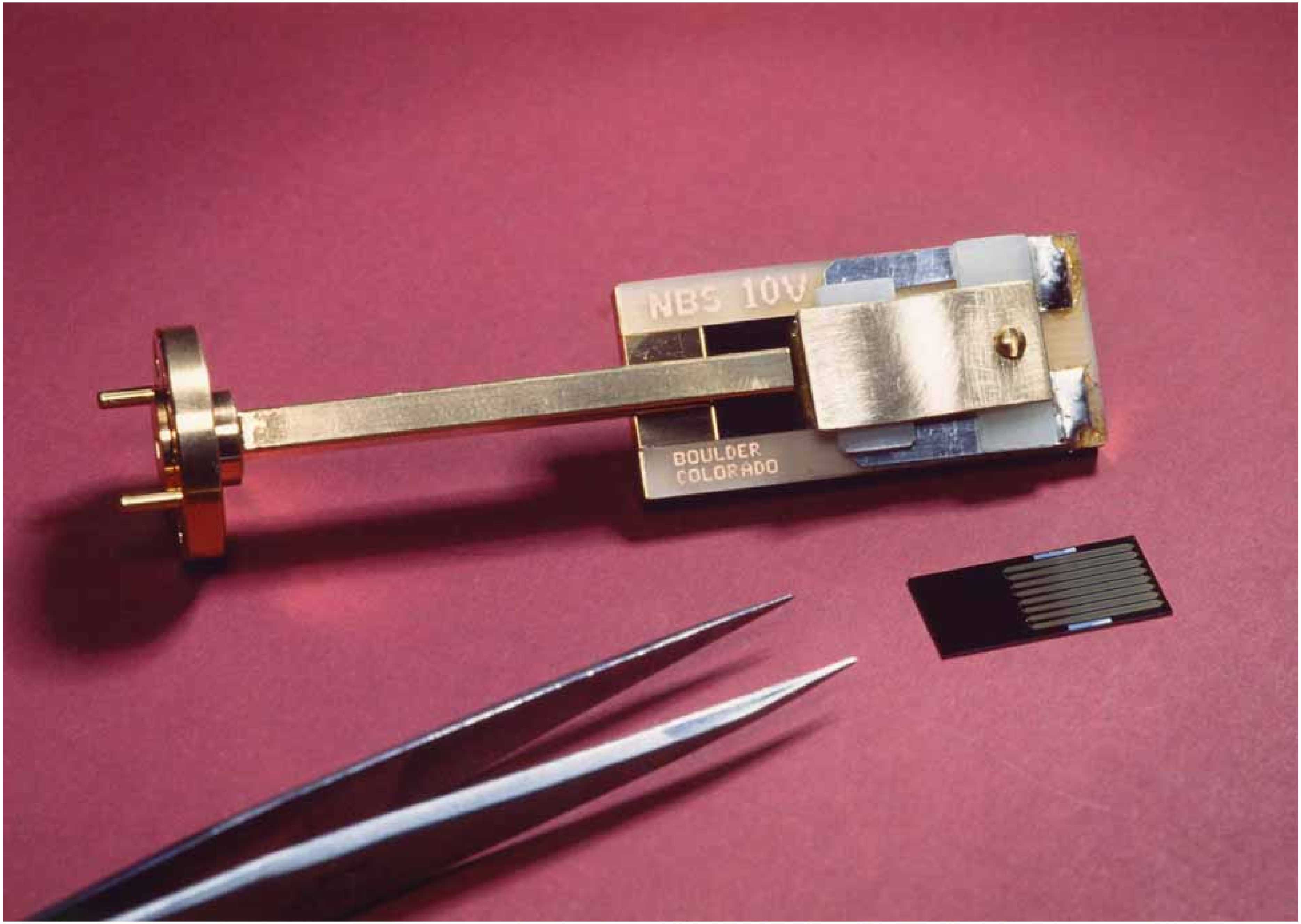
FRANCES L. LLOYD, CLARK A. HAMILTON, MEMBER, IEEE, J. A. BEALL, DIANE GO, R. H. ONO, AND RICHARD E. HARRIS, MEMBER, IEEE



14,184 Nb-Pb Junctions
ν = 87 GHz
January 1988

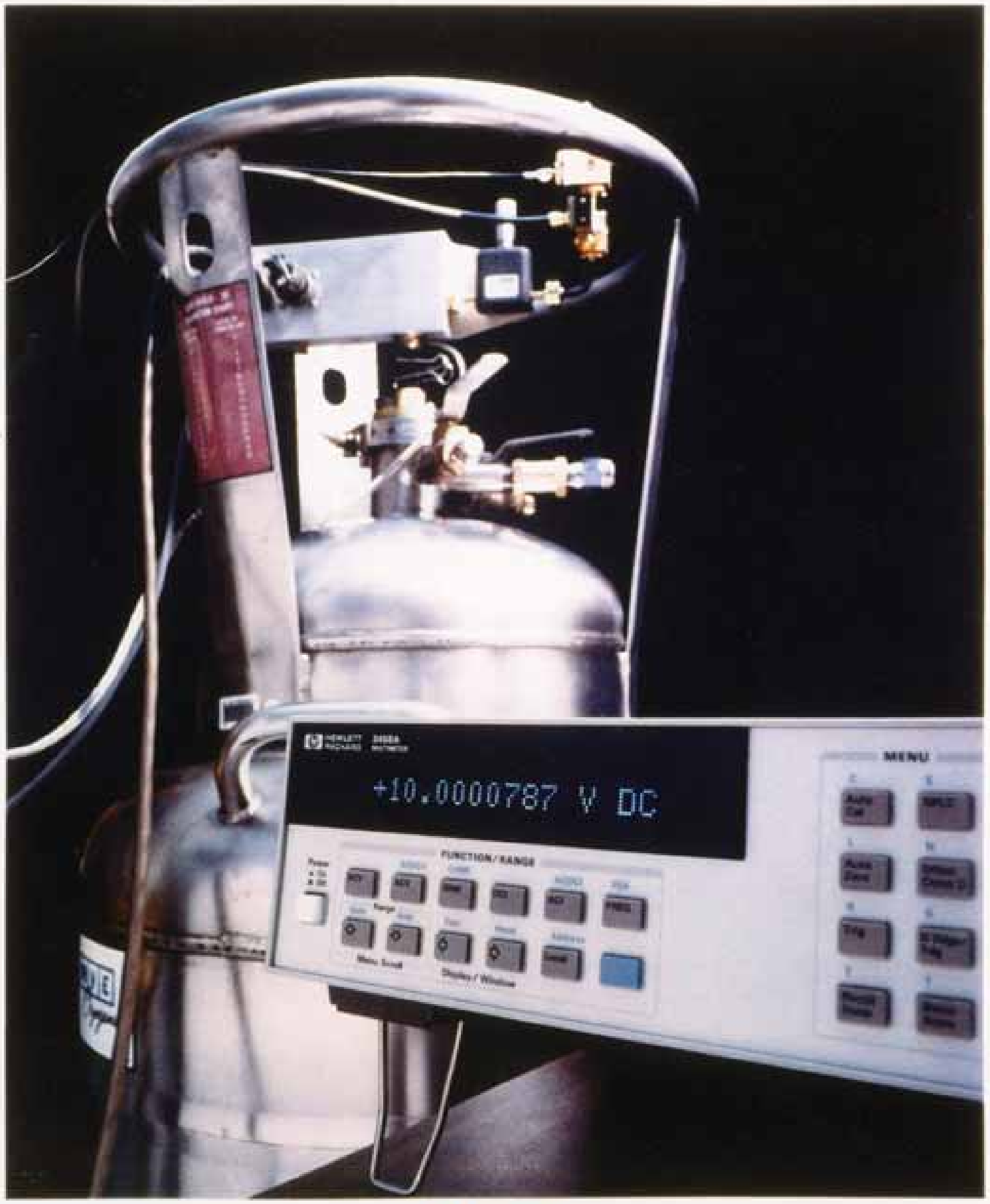
10-volt Array
14,184 Nb-Pb junctions
10x20 mm chip
NBS, Boulder
January 1988




NBS 10V
BOULDER
COLORADO

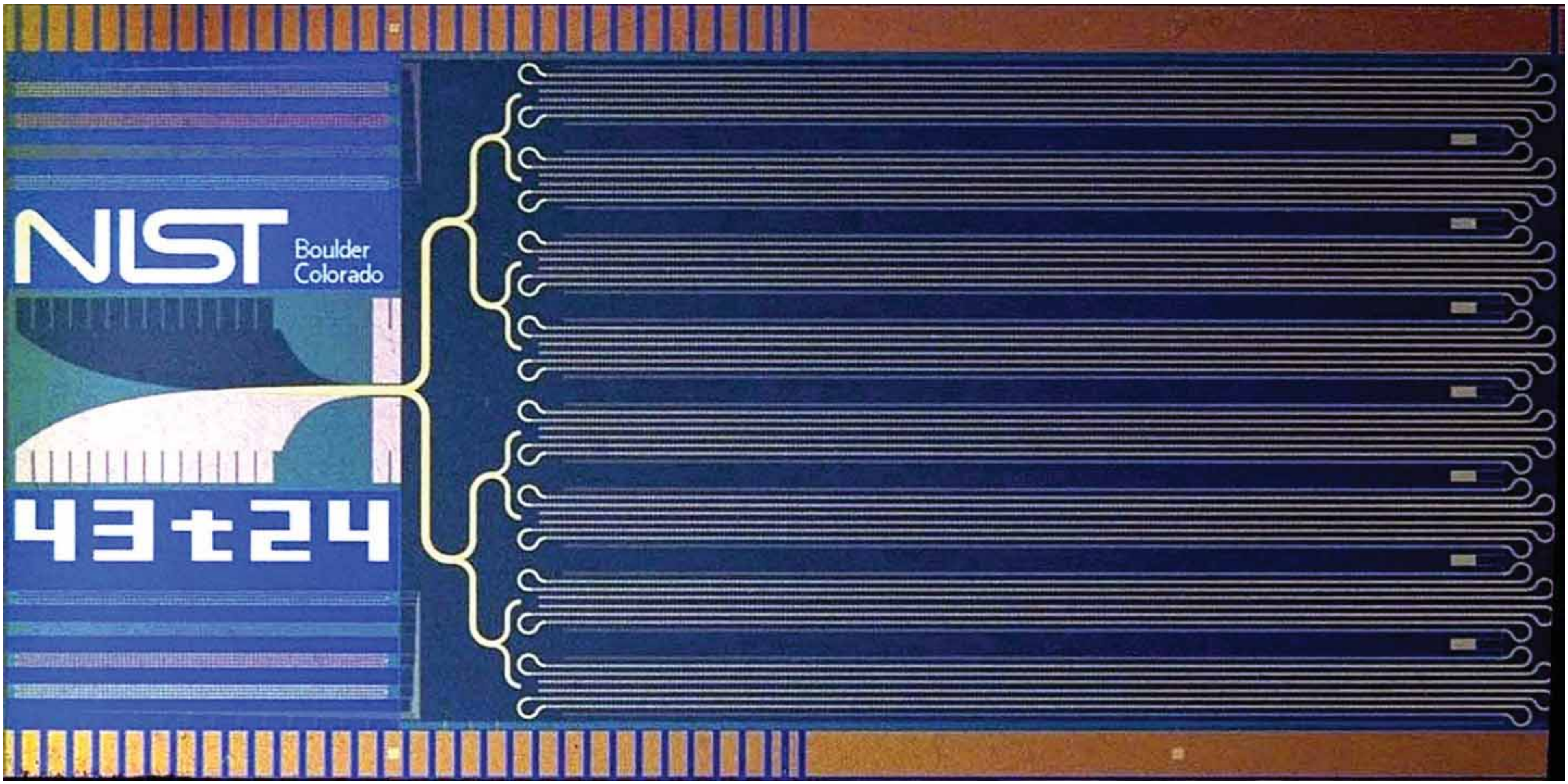
HEWLETT-PACKARD
JOURNAL

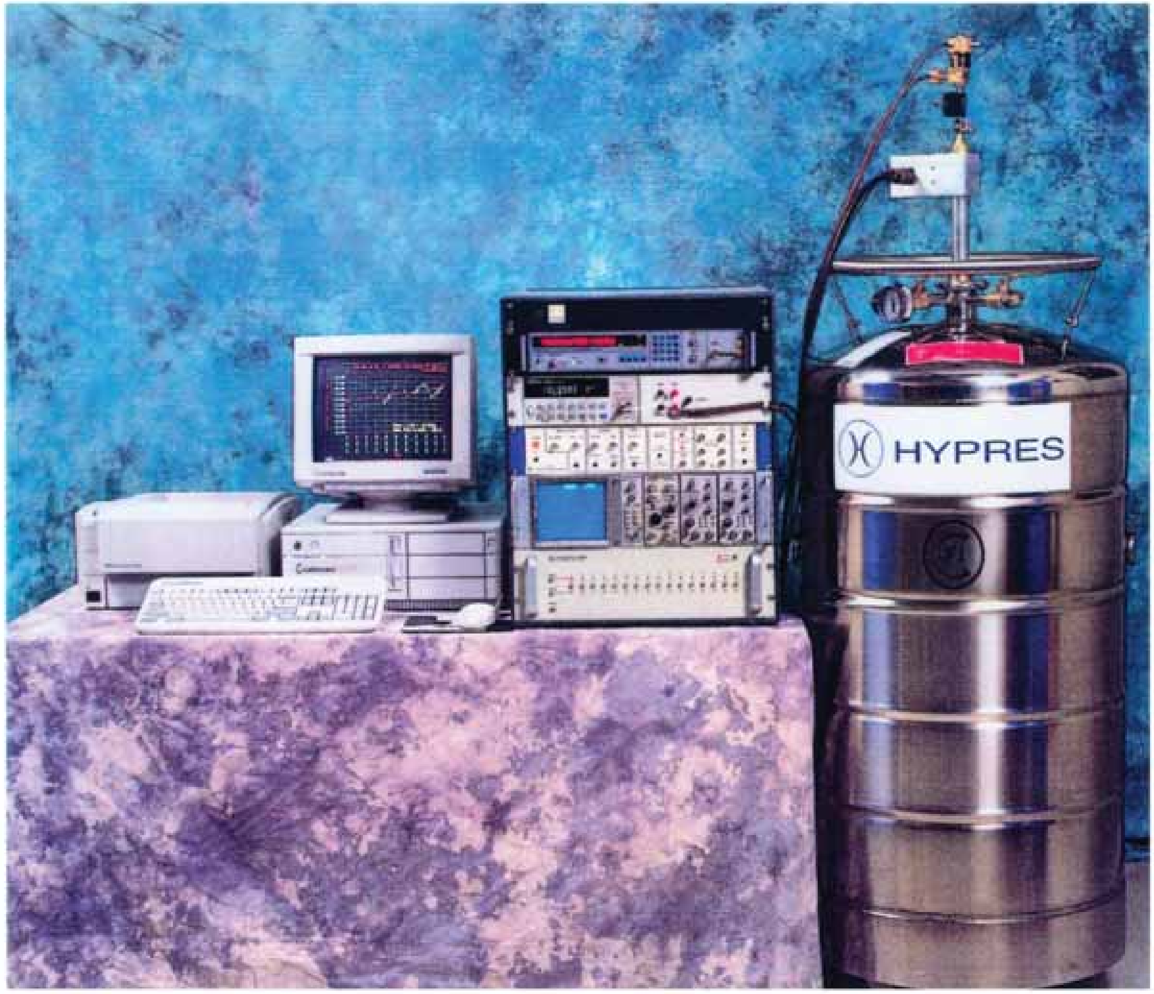
APRIL 1989



HEWLETT
PACKARD

10-volt Array
20,208 Nb-AlO-Nb Junctions
NIST, Boulder, 1992
10x20 mm chip





The HYPRES 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 automatically calibrated.

Since this system implements the International Standards Organization (ISO) definition of the volt, it never requires recalibration.

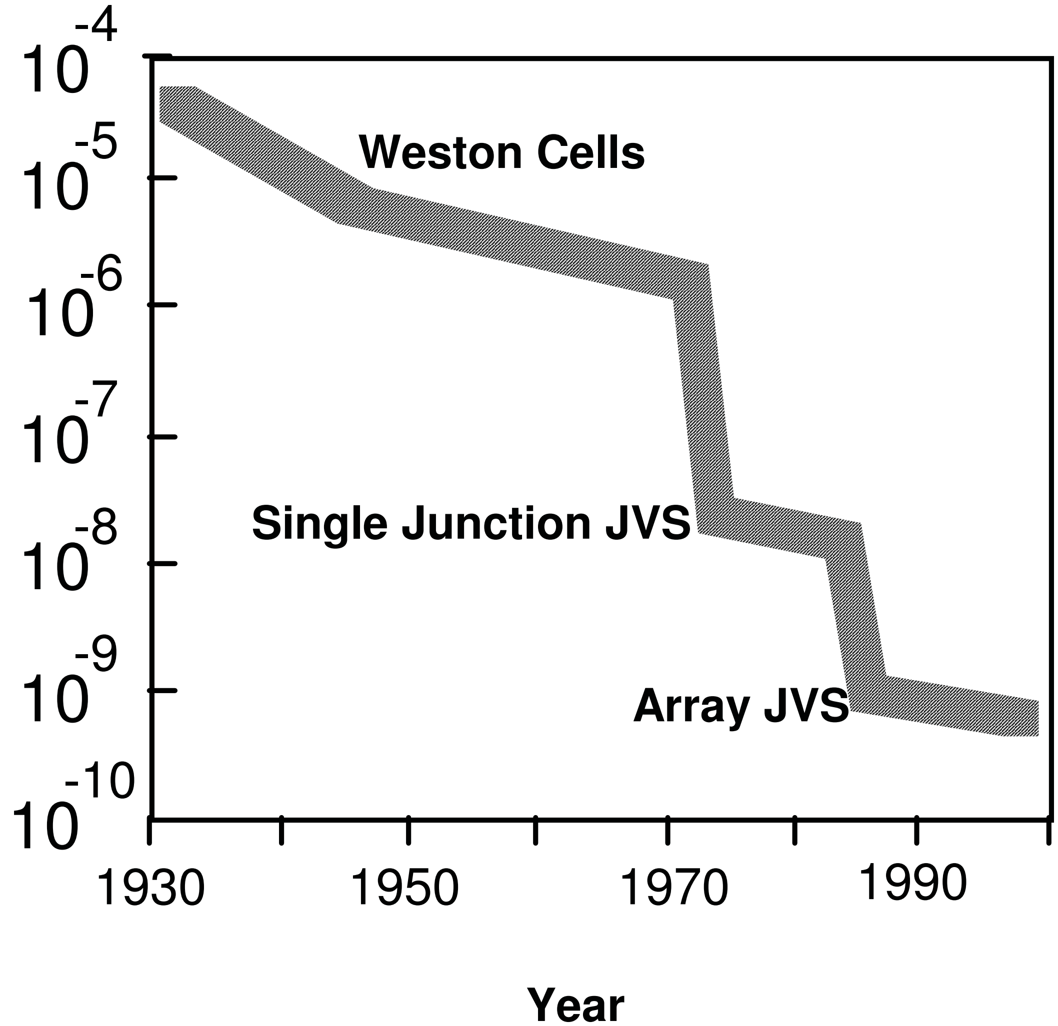
The HYPRES Primary Voltage Standard System is a commercial implementation of the system developed by the U.S. National Institute of Standards and Technology (NIST). The specialized microwave components and voltage sensing electronics are manufactured according to NIST specifications.

HYPRES

Setting Tomorrow's Standards Today

SECOND-GENERATION JOSEPHSON STANDARDS

APPROXIMATE LEVEL OF AGREEMENT IN VOLTAGE MEASUREMENTS AMONG NATIONAL STANDARDS LABORATORIES



THIRD-GENERATION JOSEPHSON STANDARD

IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. 44, NO. 2, APRIL 1995

Josephson D/A Converter with Fundamental Accuracy

C. A. Hamilton, C. J. Burroughs, and R. L. Kautz

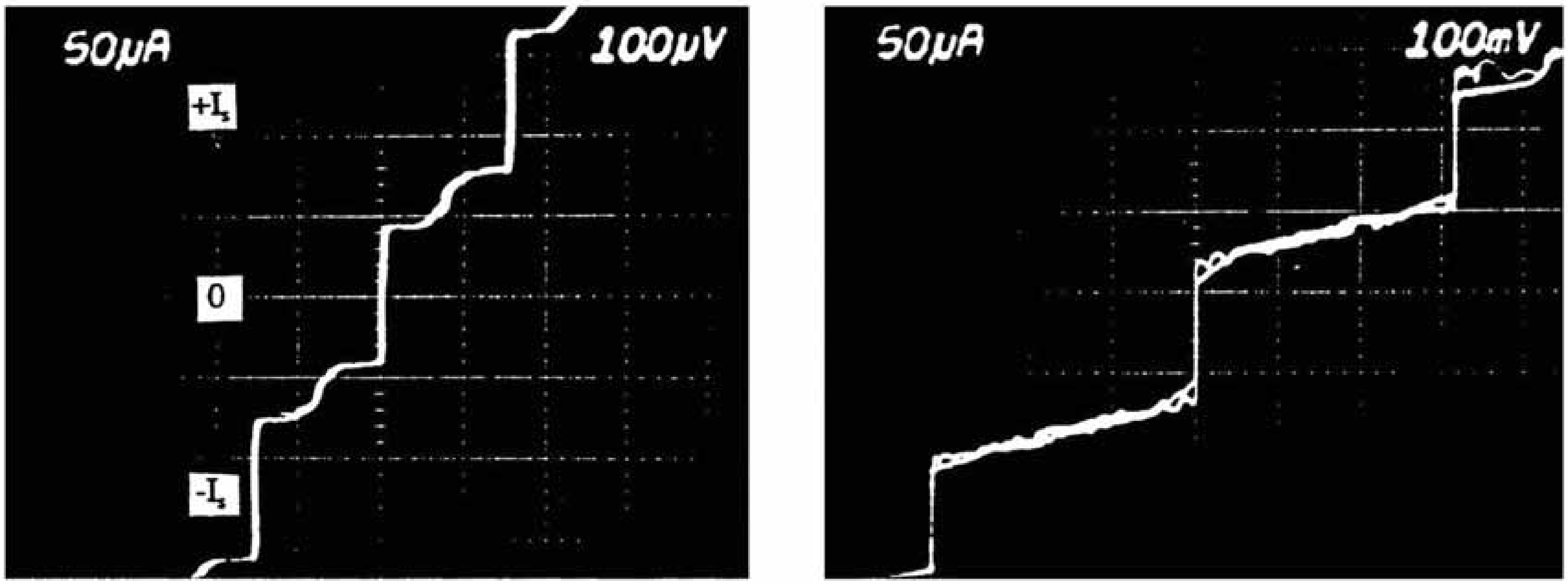


Fig. 1. (a) The I–V curve of a single shunted junction driven at 75 GHz and (b) the I–V curve for an array of 2048 junctions.

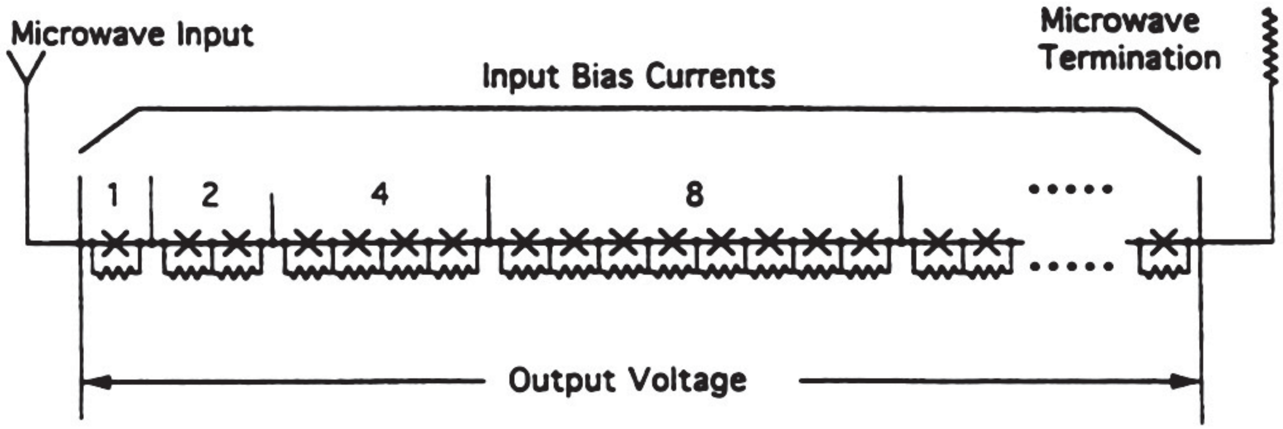


Fig. 2. A Josephson D/A converter based on a binary sequence of shunted junction arrays.

Programmable Array
511 externally shunted SIS JJs
75 GHz

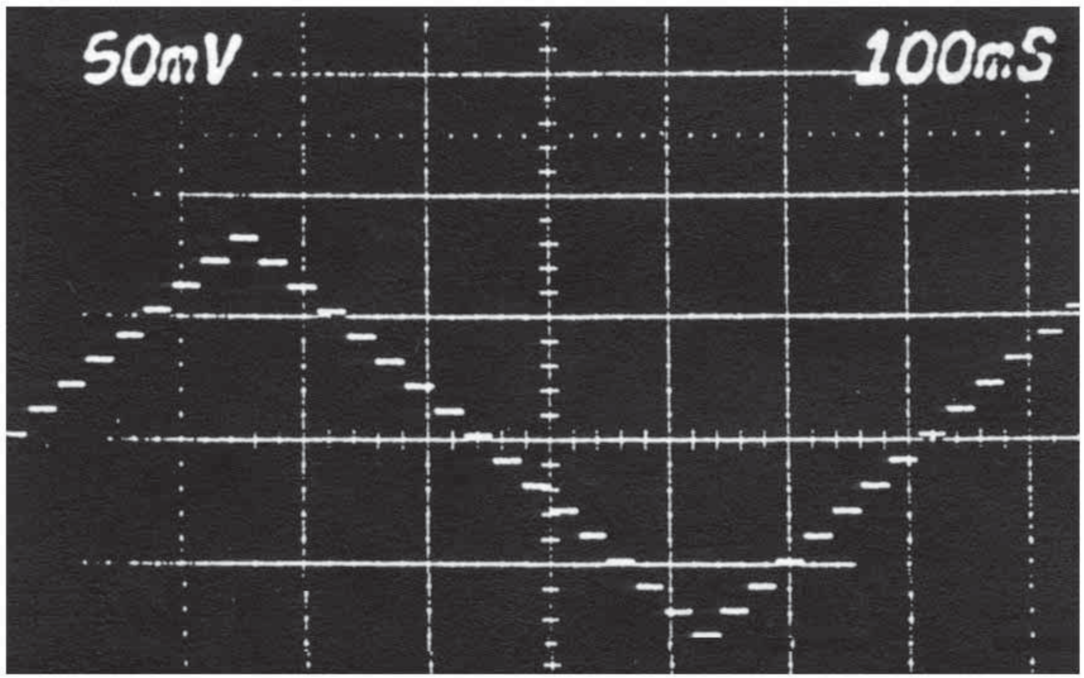
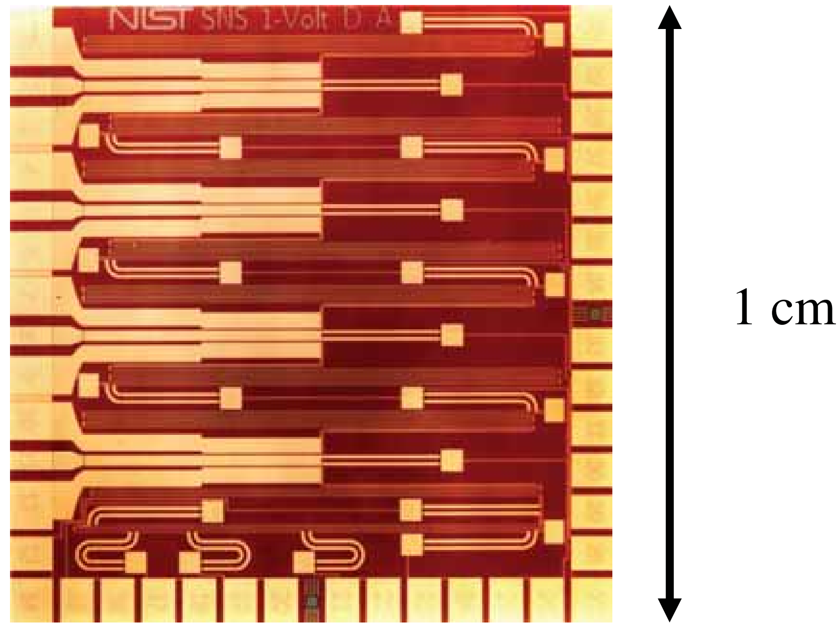


Fig. 3. Synthesized triangle wave using the 4 most significant bits of the Josephson D/A converter.

Stable Programmable DC Standard System (1997)

- 1 V chip
- 32,768 Nb-PdAu-Nb junctions
- 16 GHz drive



Charlie Burroughs

- Intrinsically stable voltage steps
- Programmable from +1.1 to -1.1 V
- 1 μs settling time
- Fully automated
- High noise immunity allows direct connections

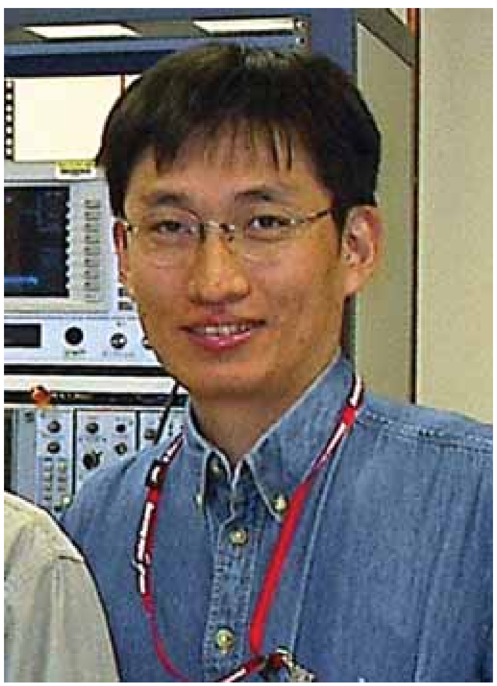
APPLIED PHYSICS LETTERS **88**, 042503 (2006)

10 V programmable Josephson voltage standard circuits using NbN/TiN_x/NbN/TiN_x/NbN double-junction stacks

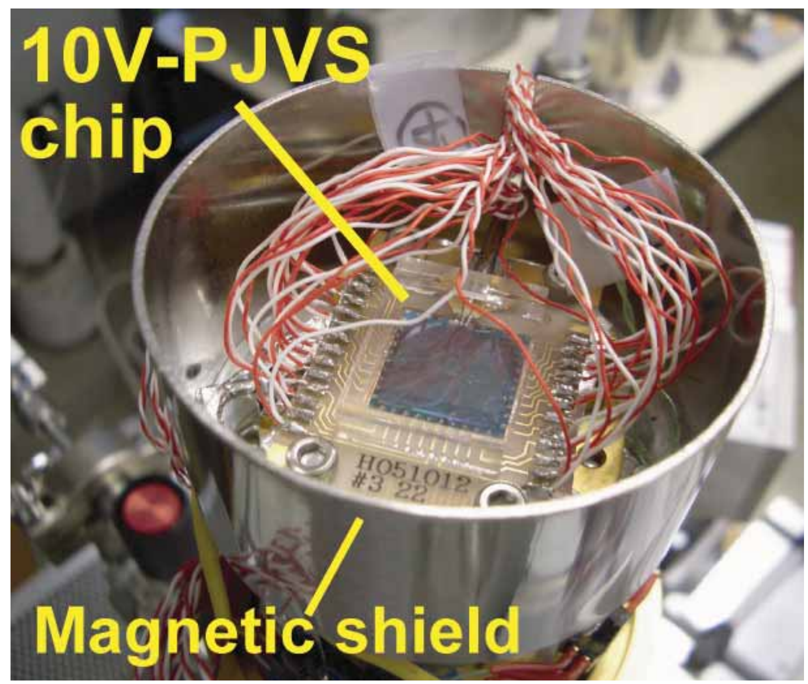
H. Yamamori,[a] M. Ishizaki, and A. Shoji
National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba 305-8568, Japan

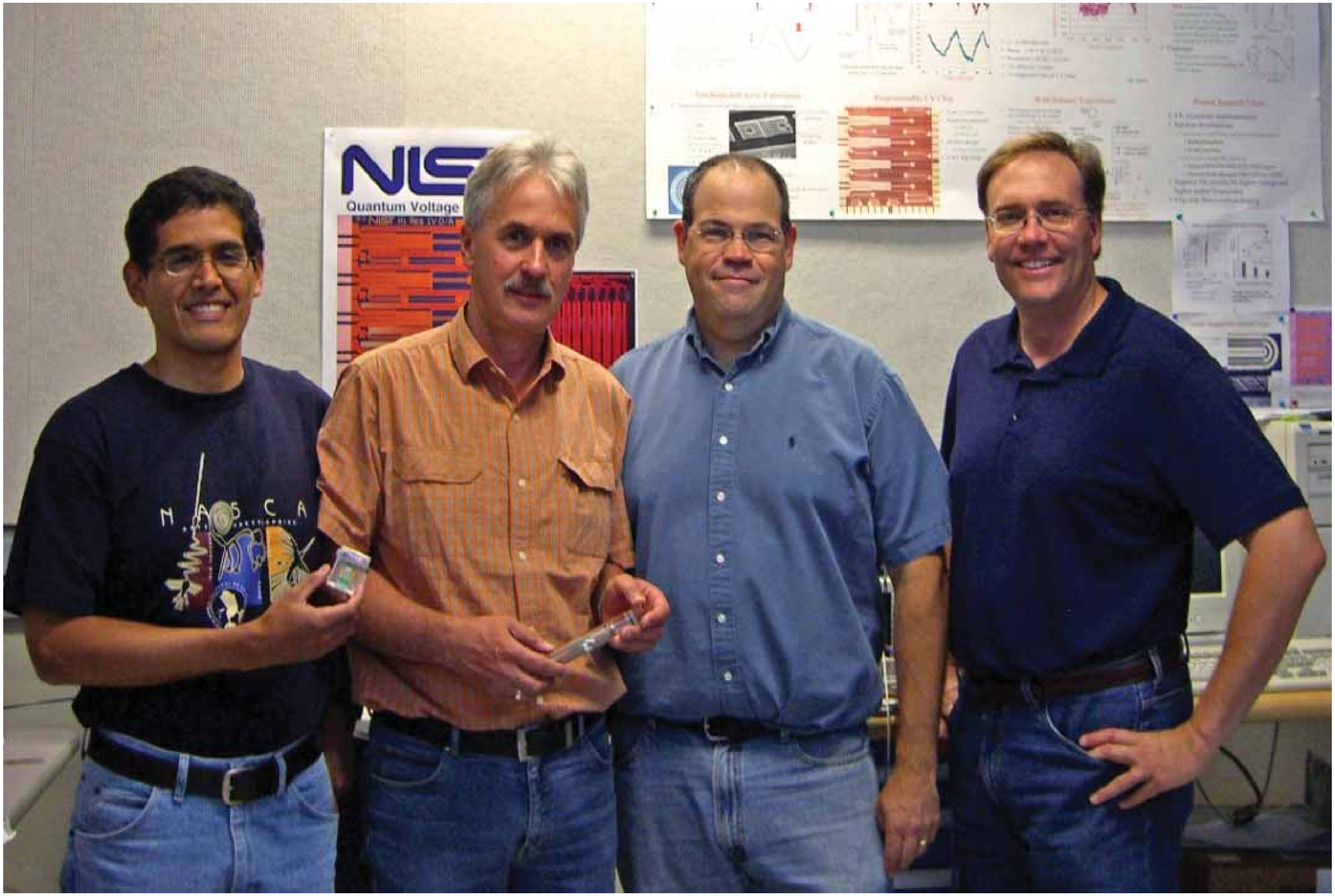
P. D. Dresselhaus and S. P. Benz
National Institute of Standards and Technology, Boulder, Colorado 80305-3328

Using NbN/TiN_x/NbN/TiN_x/NbN double-junction stack technology we have demonstrated a programmable Josephson voltage standard chip that operates up to 10.16 V output voltage cooled with a two-stage Gifford–McMahon cryocooler. The circuit uses double-junction stacks, where two junctions are fabricated in each stack, in order to integrate 327 680 junctions into a 15.3 mm × 15.3 mm chip.



Hirotaki Yamamori





David Olaya Franz Mueller Paul Dresselhaus Sam Benz

PTB/NIST Collaboration
Boulder, Colorado, 2008

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 19, NO. 3, JUNE 2009

1 V and 10 V SNS Programmable Voltage Standards for 70 GHz

F. Mueller, R. Behr, T. Weimann, L. Palafox, *Senior Member, IEEE*, D. Olaya, P. D. Dresselhaus, and S. P. Benz, *Senior Member, IEEE*

69,632 Nb-NbSi-Nb Junctions

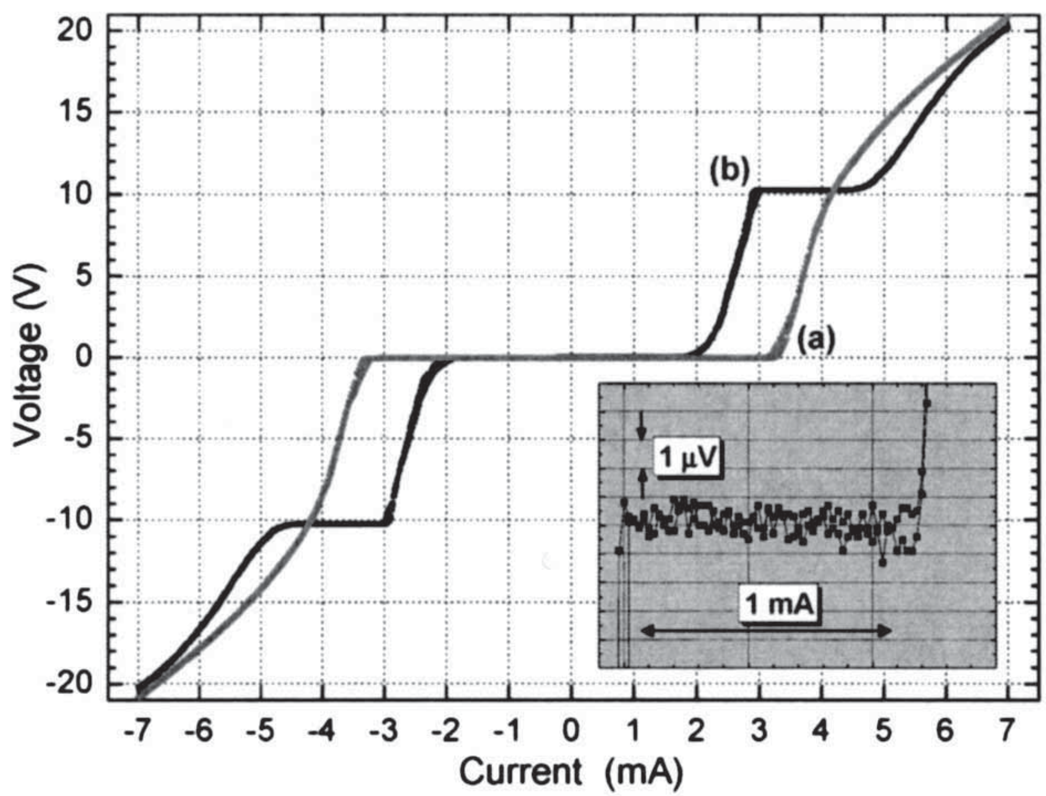
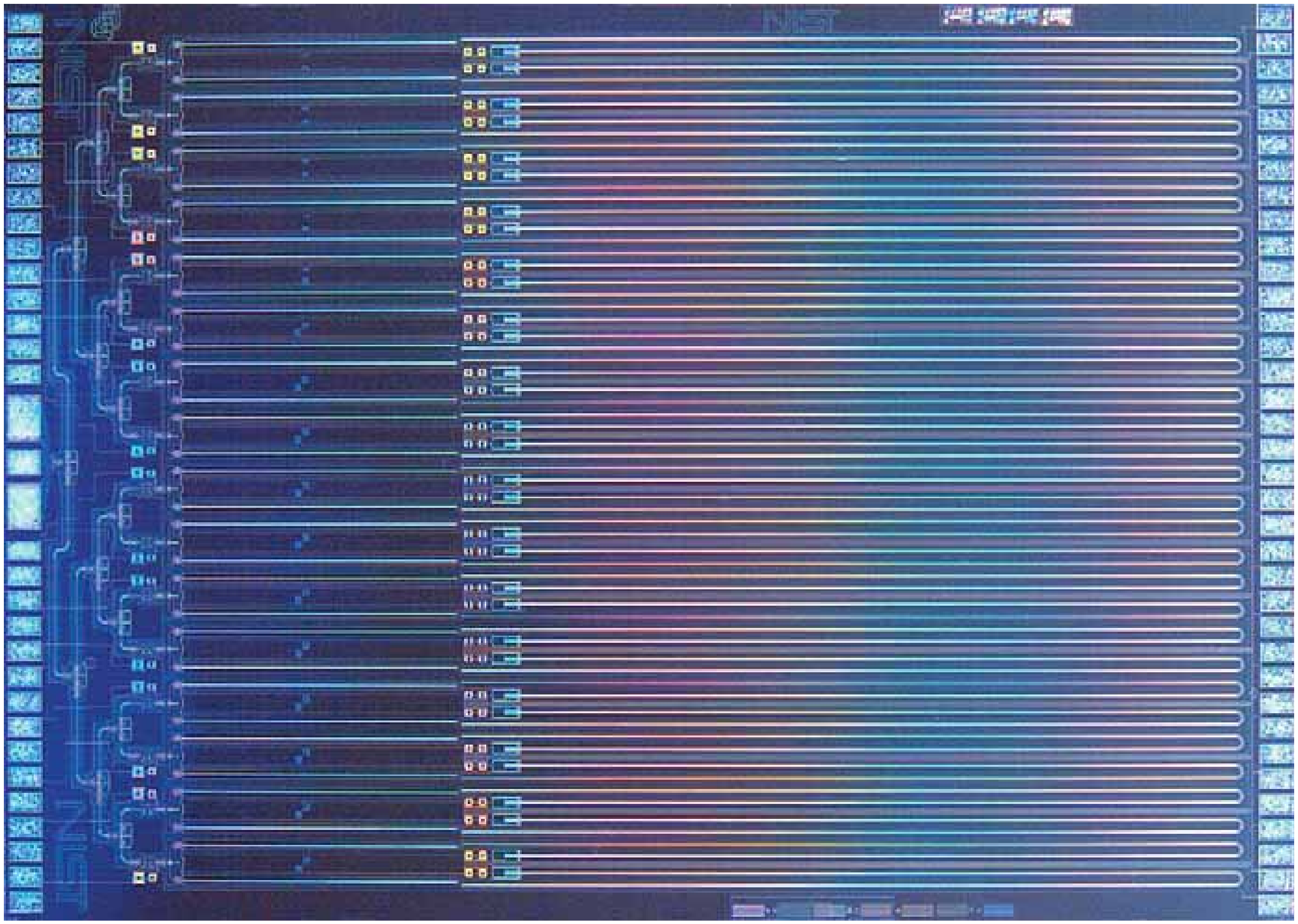


Fig. 4. IVC of a 10 V PJVS with 69 632 SNS junctions, (a) without microwaves, (b) with microwaves at 71.28 GHz and 50 mW at antenna. The inset inset shows the 10 V step with high resolution. Junction parameters: $I_c = 3.05$ mA, $I_c R_n = 150\ \mu$V (at $2I_c$).



Programmable 10-V Array
300,000 Nb-NbSi-Nb JJs
12x17 mm chip
NIST, Boulder
2011

FOURTH-GENERATION JOSEPHSON STANDARD

Appl. Phys. Lett. **68** (22), 27 May 1996

A pulse-driven programmable Josephson voltage standard

S. P. Benz and C. A. Hamilton
National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80303

(Received 12 February 1996; accepted for publication 29 March 1996)

A voltage standard based on a series array of pulse-biased, nonhysteretic Josephson junctions is proposed. The output voltage can be rapidly and continuously programmed over a wide range by changing the pulse repetition frequency. Simulations relate the circuit margins to pulse height, width, and frequency. Experimental results on a prototype circuit confirm the expected behavior.

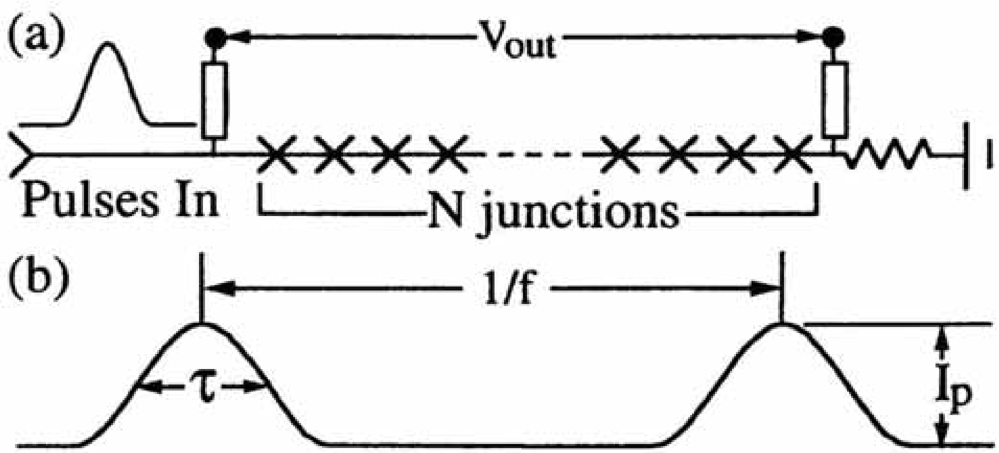


FIG. 1. (a) Circuit schematic, (b) pulse-drive waveform.

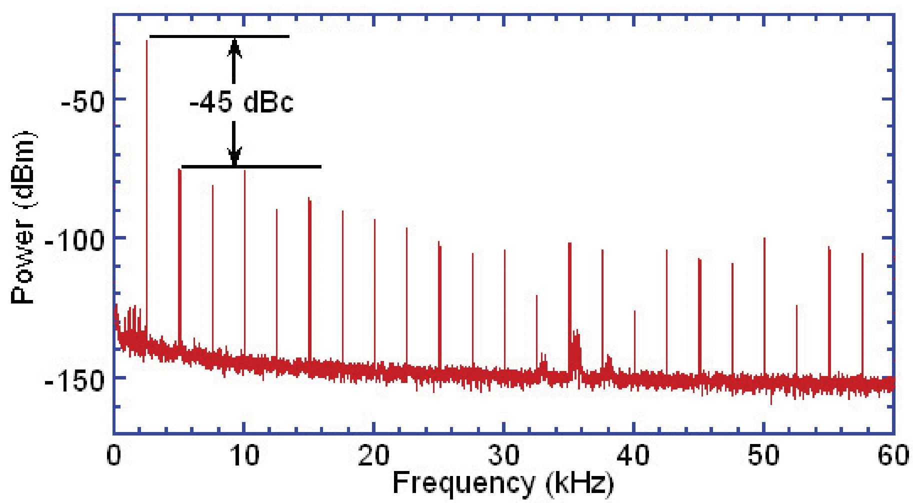
Josephson Arbitrary Waveform Synthesizers

- Features
  - Quantum-based calculable ac voltage source
  - Stable ac voltages
  - Programmable arbitrary waveforms
  - Combine dc, ac and arbitrary wave-form functions in a single standard
- Applications
  - Metrology standards
    - AC & DC intrinsic standard
    - Programmable harmonic source
      - » Spectrum analysis

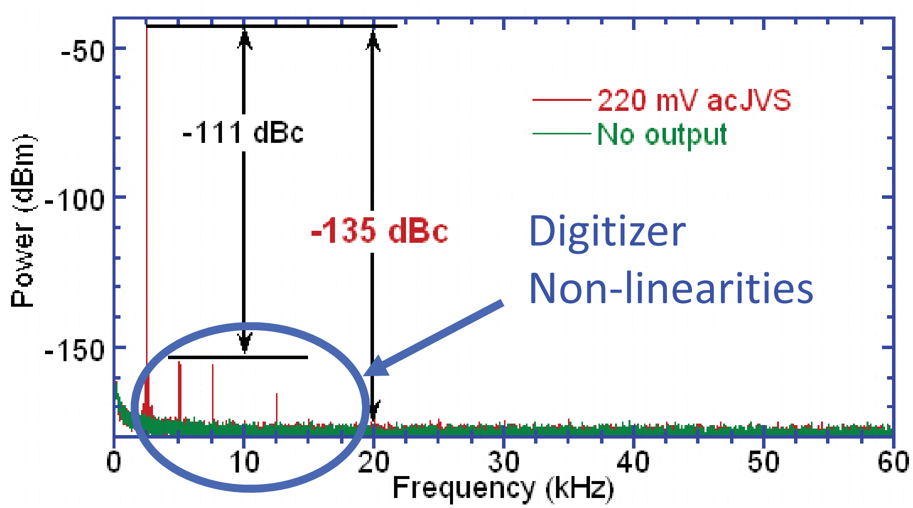
Sam Benz

Perfect Quantization Demonstration

Semiconductor Code Generator Output



Josephson Junction Array Output



- Sine Wave Synthesis
  - 2.5 kHz tone
  - 4,00,000 bit code length
  - 15 GHz sine, 10 GHz clock
- Semiconductor code generator
  - **-45 dBc** Harmonic distortion
- 2 ac-coupled arrays in series
  - 10,240 junctions
  - 220 mV rms voltage
  - **-135 dBc** Harmonic distortion

Perfect quantization produces intrinsically accurate waveforms

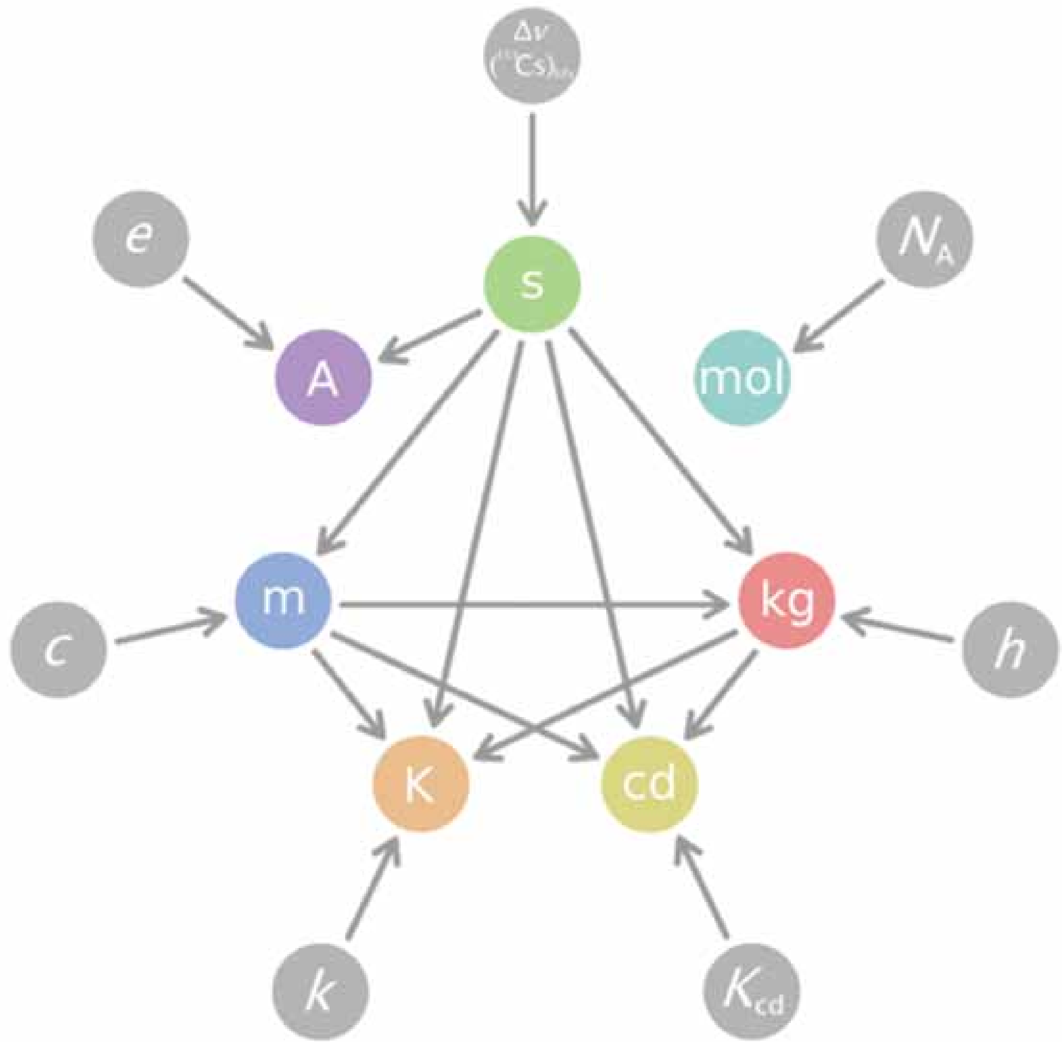
Proposed new SI units (2010)

The 7 base units

- SECOND
- MOLE
- KILOGRAM
- CANDELA
- KELVIN
- METER
- AMPERE

derive from 7 defined fundamental constants

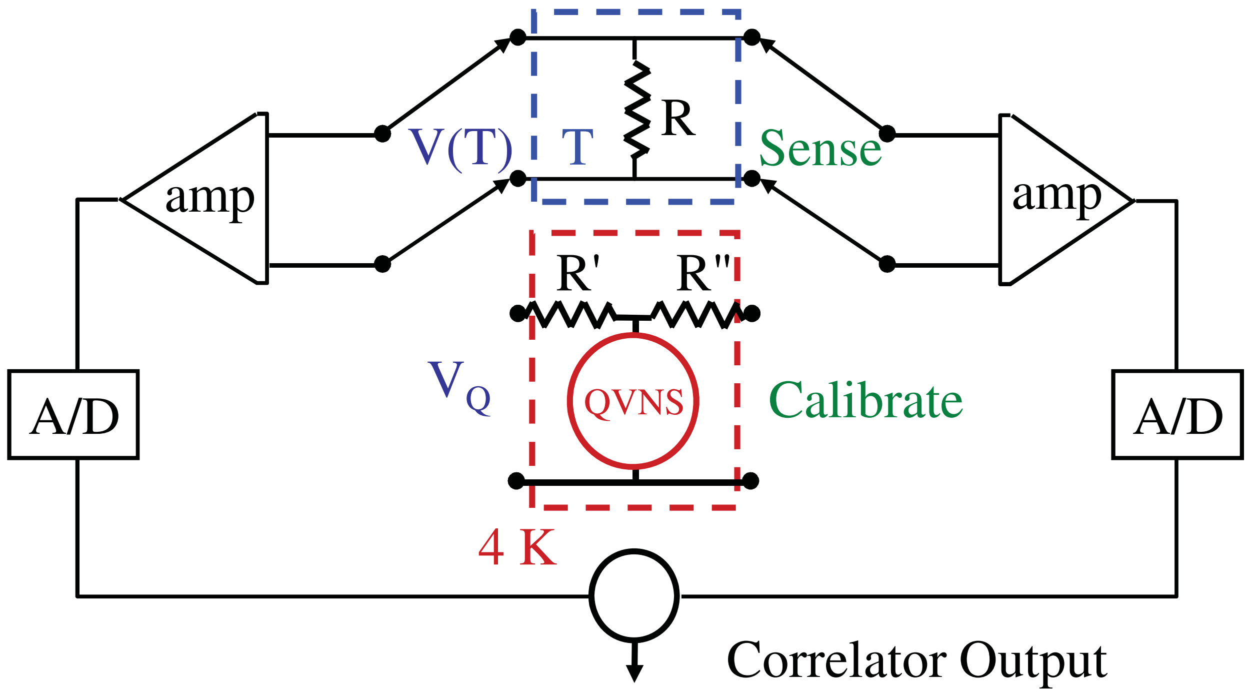
- $\Delta\nu$ = Cs hyperfine splitting
- N_A = Avogadro constant
- h = Planck constant
- K_{cd} = Candela constant
- k = Boltzmann constant
- c = speed of light
- e = elementary charge



Johnson Noise Thermometry with a Quantized Voltage Noise Source

- Calculable pseudo-noise waveform
- Absolute temperature calibration

$$\left\langle V^2(T) \right\rangle = 4kTR\Delta f$$



Measured Boltzmann constant of 1.380 651(17)x10^{-23} J/K will contribute to 2010 CODATA and 2014 SI redefinition.

Electronic Kilogram

Josephson volt and quantum Hall resistance yield electrical power.

$$P_E = V^2/R$$

Gravitational force and velocity yield mechanical power.

$$P_M = mgv$$

The Watt balance yields mass.

$$m = V^2/Rgv$$

NIST Watt Balance