16. November 2018:

A HISTORIC DAY FOR METROLOGY

16. November 2018:

A HISTORIC DAY FOR METROLOGY

The vision of Max Planck may become true

(2018: 100th anniversary of Nobel Prize for Max Planck)

Ann.Physik 1, 69-122 (1900)

"....with the help of fundamental constants we have the possibility of establishing units of length, time, mass, and temperature, which necessarily retain their significance for all cultures, even unearthly and nonhuman ones."

Welcome to the WEBCAST Session of the 26th General Conference on Weights and Measures (CGPM)

26e CGPM
Versailles
13-16 novembre 2018

10:50 - Start of webcast

Keynote lectures

"The quantum Hall effect and the revised SI"
Klaus von Klitzing (Nobel laureate, Max Planck Institute, Stuttgart)

"The role of the Planck constant in physics"
Jean-Philippe Uzan (*Centre national de la recherche scientifique* (CNRS), Paris)

"Optical atomic clocks – opening new perspectives on the quantum world"
Jun Ye (JILA, Boulder)

"Measuring with fundamental constants; how the revised SI will work"
Bill Phillips (Nobel laureate, NIST, Gaithersburg)

Introduction to the Resolution "On the revision of the International System of Units (SI)"
Martin Milton (BIPM Director)

!!

Voting on Draft Resolution A and closing remarks
Barry Inglis

13:25 - End of session

Draft Resolution A

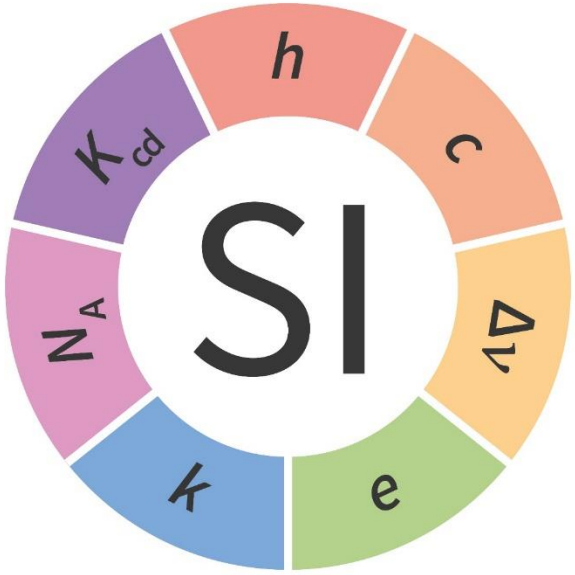
26e CGPM
Versailles
13-16 novembre 2018

On the revision of the International System of Units (SI)

The General Conference on Weights and Measures (CGPM), at its 26th meeting,

decides that, effective from 20 May 2019, the International System of Units, the SI, is the system of units in which:

- the unperturbed ground state hyperfine transition frequency of the caesium 133 atom $\Delta\nu_{Cs}$ is 9 192 631 770 Hz,
- the speed of light in vacuum c is 299 792 458 m/s,
- the Planck constant h is $6.626\,070\,15 \times 10^{-34}$ J s,
- the elementary charge e is $1.602\,176\,634 \times 10^{-19}$ C,
- the Boltzmann constant k is $1.380\,649 \times 10^{-23}$ J/K,
- the Avogadro constant N_A is $6.022\,140\,76 \times 10^{23}$ mol^{-1},



- the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, is 683 lm/W,

Draft Resolution A

26e CGPM
Versailles
13-16 novembre 2018

On the revision of the International System of Units (SI)

The General Conference on Weights and Measures (CGPM), at its 26th meeting,

decides that, effective from 20 May 2019, the International System of Units, the system of units in which:

– the unperturbed ground state hyperfine transition frequency of the caesium 133 atom $\Delta\nu_{Cs}$ is 9 192 631 770 Hz,

– the speed of light in vacuum c is 299 792 458 m/s,

– the Planck constant h is 6.626 [illegible] $\times 10^{-34}$ J/s,

– the elementary charge e is [illegible] $\times 10^{-19}$ C,

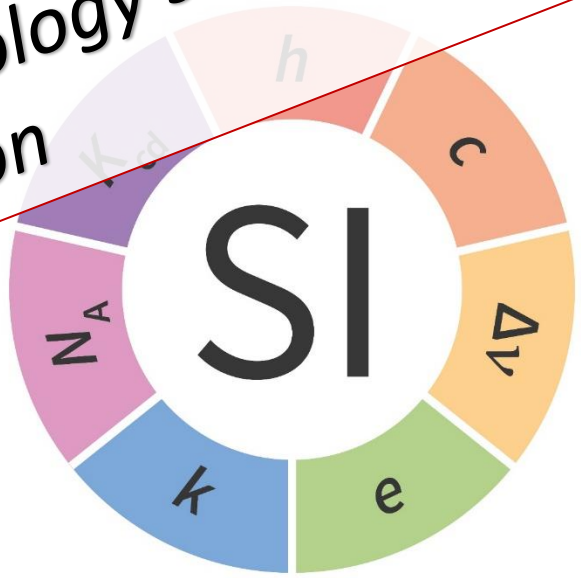
– the Boltzmann constant k is 1.380 649 $\times 10^{-23}$ J/K,

– the Avogadro constant N_A is 6.022 140 76 $\times 10^{23}$ mol^{-1},

– the luminous efficacy of monochromatic radiation of frequency 540 $\times 10^{12}$ Hz, K_{cd}, is 683 lm/W,

The Revised International System of Units

The biggest revolution in metrology since the French Revolution



Our Historically Established *SI* System

26e CGPM
Versailles
13-16 novembre 2018

All measurements can be expressed by our 7 base units
(*SI* units = Système international d'unités)

International system of units (SI units)

second for time

metre for length

kilogram PROTOTYPE

kelvin TRIPELPOINT OF H_2O

ampere FORCE BETWEEN WIRES

candela for luminous intensity

mole for the amount of substance

Official LOGO of Revised SI

26e CGPM
Versailles
13-16 novembre 2018

8 Years Ago !

The new SI: units of measurement based on fundamental constants

From the origins of the metric system,
when the metre was a fraction of the arc of the Paris meridian and the kilogram the weight of a cubic decimetre of water, the ultimate goal has been a system of measurement based on invariant quantities of nature. After more than 200 years we are now within reach of achieving this. While the kilogram is still defined as the mass of a Pt-Ir cylinder kept in a vault in Sèvres, serious plans now exist to redefine the kilogram by fixing the numerical value of the Planck constant h; and the ampere, kelvin and mole by fixed numerical values for e, k and N_A. With the metre already being defined by the speed of light and the second by an atomic microwave transition, but likely soon to be

Publication 2005:

Redefinition of the kilogram: a decision whose time has come

Bottleneck:

Metrology focuses on practical applications "for all time, for all people"

High precision *experimental access* to fundamental constants

The discovery of LASER allowed high precision measurement of velocity of light !
Since 1983 fixed value c = 299792458 m/s for the definition of the length unit „meter"

The Quantum Hall Effect and the Revised SI

length: $\sqrt{\frac{h \cdot f}{c^3}} = 4$

mass: $\sqrt{\frac{h}{\cdot f}}$

time: $\cdot 10^{-43} s$

temperature: $\frac{}{\cdot f} = 3{,}50 \cdot 10^{32} K$

We are ready to introduce a new measurement system based on constants of nature !

Not useful for practical application!

h = Planck constant

f = gravitational constant

c = light velocity

k = Boltzmann onstant

e = elementary charge

Quantum Hall Effect
von Klitzing constant $R_K = h/e^2$

$$\sqrt{\frac{h^2}{e^4}} = 2{,}58 \cdot 10^4 \Omega$$

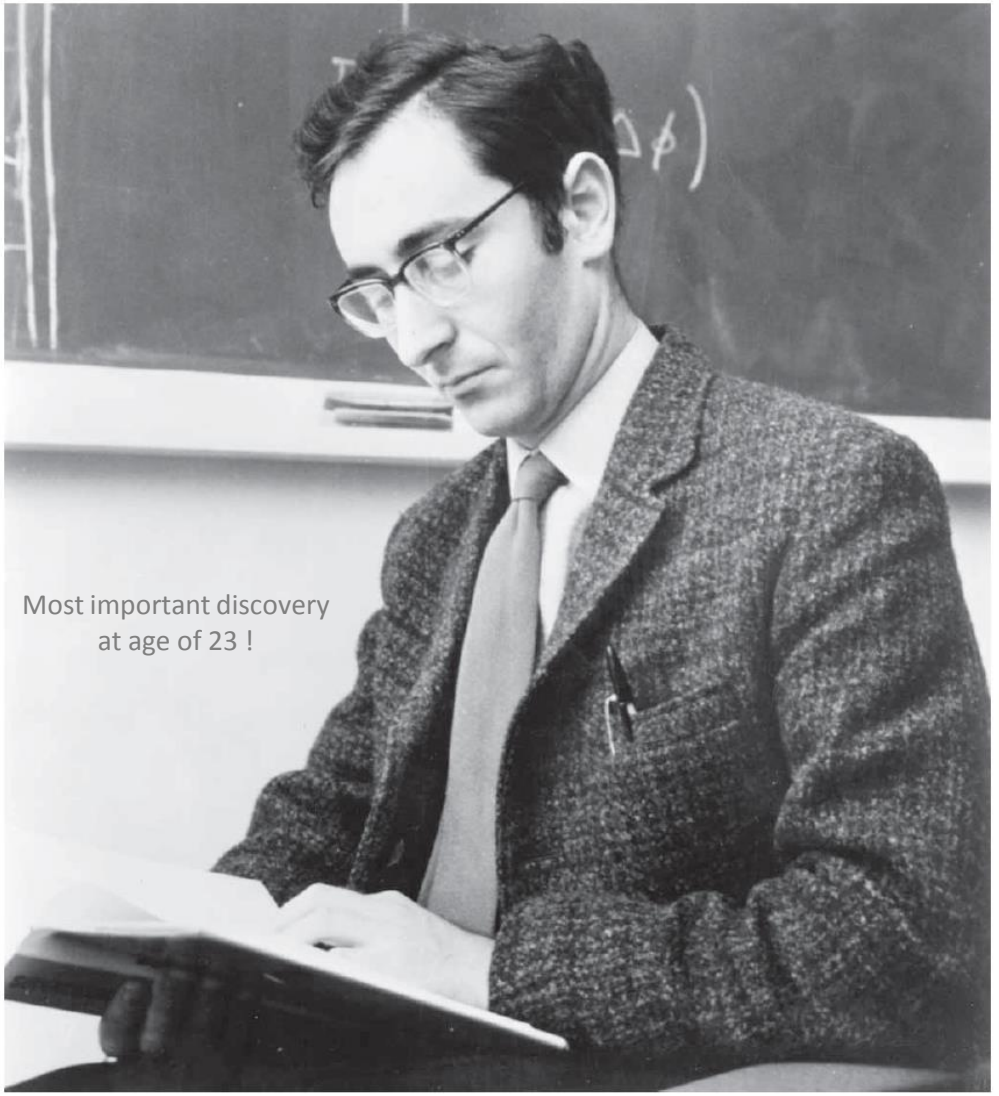
Electrical Units (Quantum Hall Effect, Josephson Effect)

The Driving Force for a New SI Based on Constants of Nature

26e CGPM
Versailles
13-16 novembre 2018

Electrical Quantum Metrology

Pioneering Work of Brian Josephson



Most important discovery
at age of 23 !

Brian Josephson
Cambridge University
1960s

A New Realization of Accurate Voltages

(Theory)

26e CGPM
Versailles
13-16 novembre 2018

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

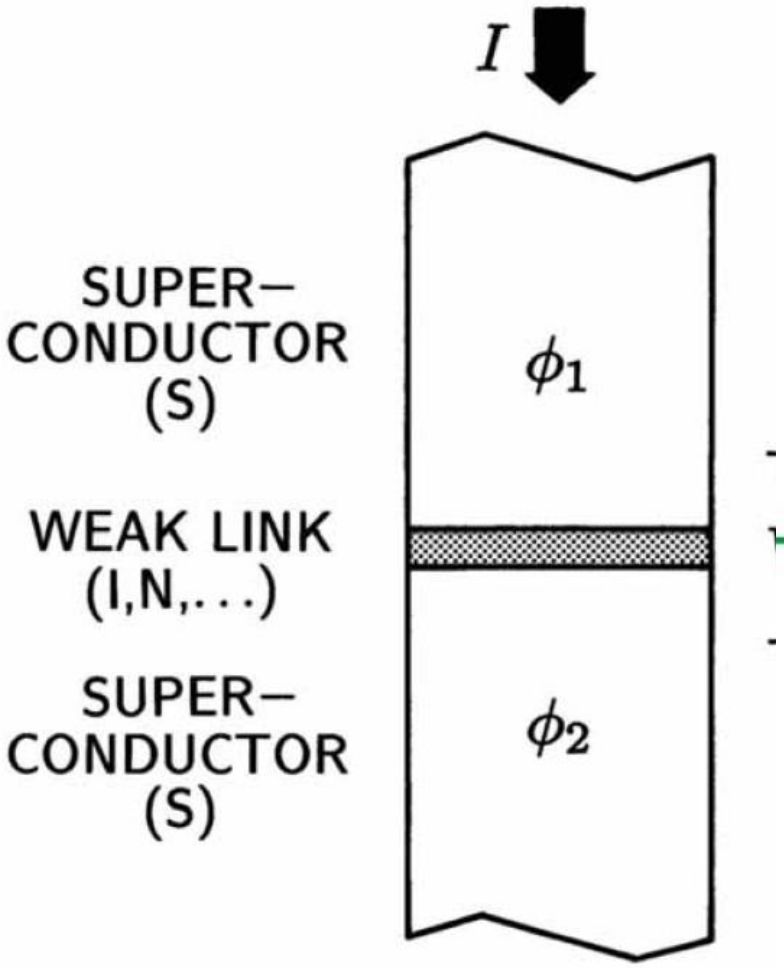
Applied r.f. fields can be treated by noting that the oscillations in V frequency-modulate the supercurrent. Thus if a DC voltage V on which is superimposed an AC voltage of frequency ν is applied across the barrier, the current has Fourier components at frequencies $2eV/h \pm n\nu$, where n is an integer. 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.

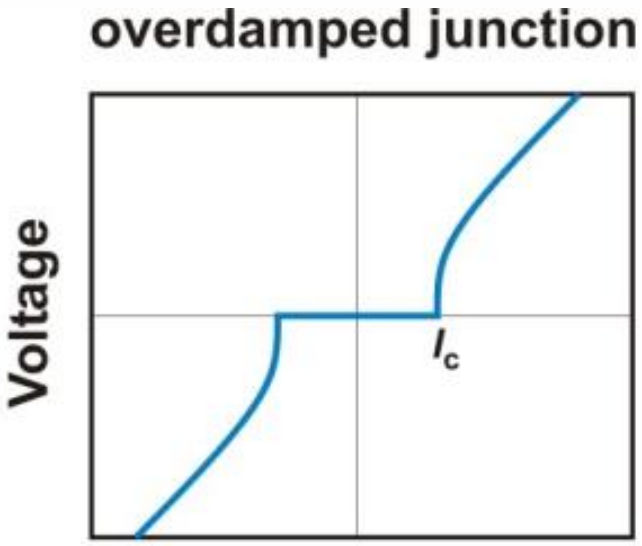
$$V = n\,(h/2e)\,\nu$$

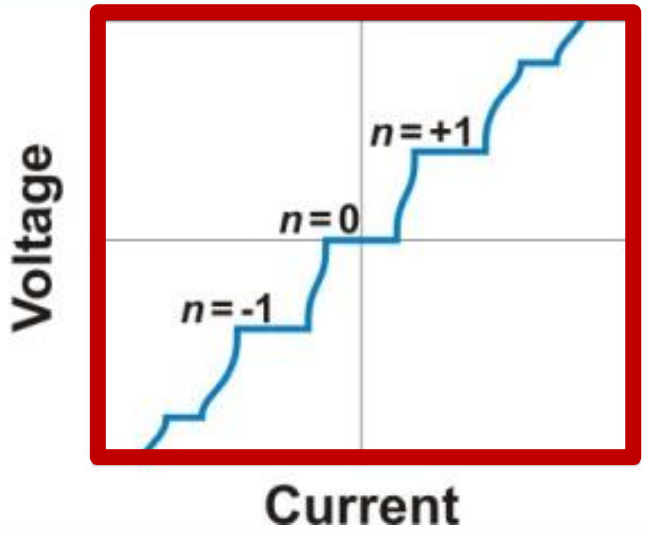
A New Realization of Accurate Voltages

(Experiment)

26e CGPM
Versailles
13-16 novembre 2018







with microwave
E=hν
V=n(h/2e)ν

$$V \leftrightarrow h/2e$$

Universality of Josephson Voltage

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)

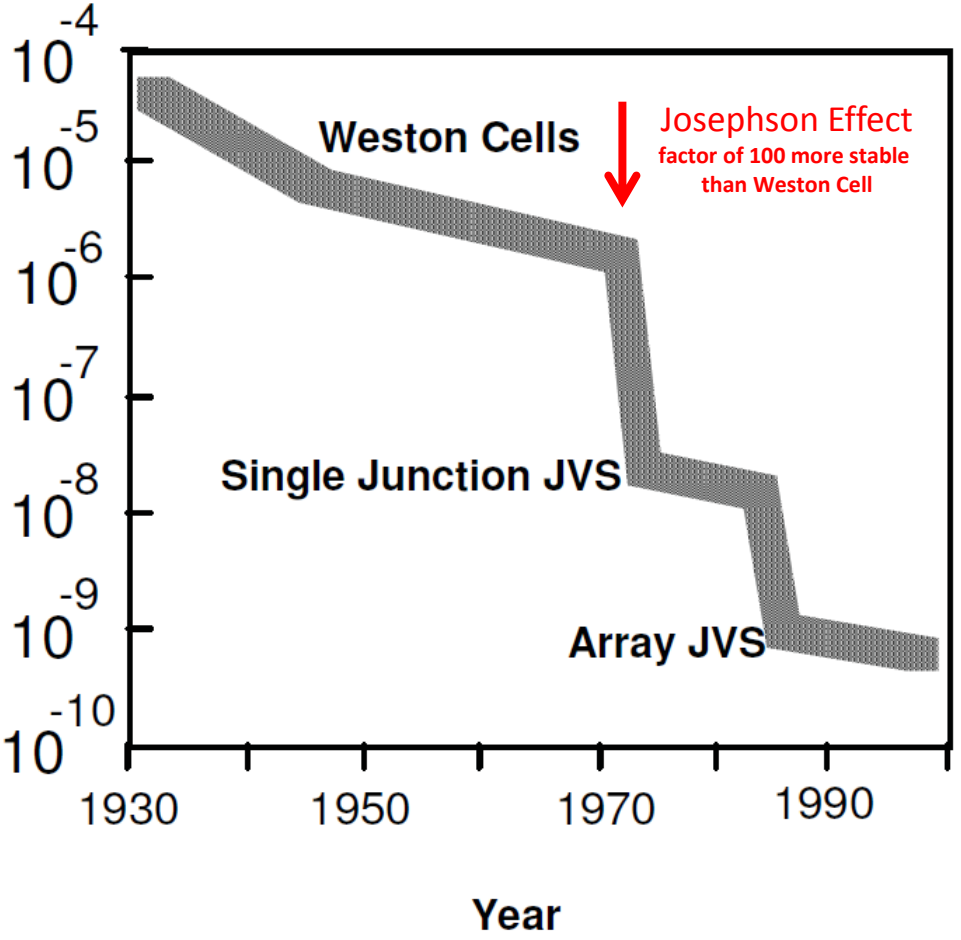
The Josephson voltage-frequency relation has been compared between two quite different (and nonideal) types of Josephson junctions—an indium microbridge and a planar normal-metal barrier junction of niobium with a copper normal region. It is found that the constant of proportionality between voltage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

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

Josephson Voltage Standard (JVS)

Standard Electrochemical Cell
V = 1.018 V

Approximate Level of Agreement in Voltage Measurements among National Standards Laboratories



Metrologia 9, 155-166 (1973)

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

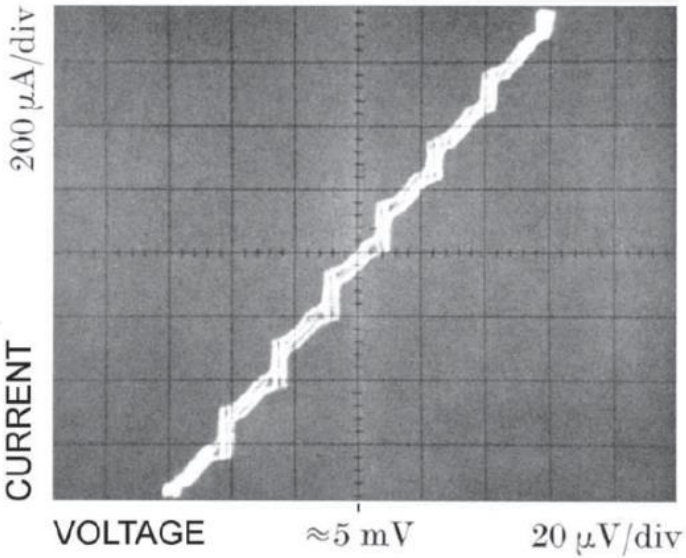
B. F. Field, T. F. Finnegan, and J. Toots

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}.

USA: 2e/h = 483593.420 GHZ/V_{NBS}

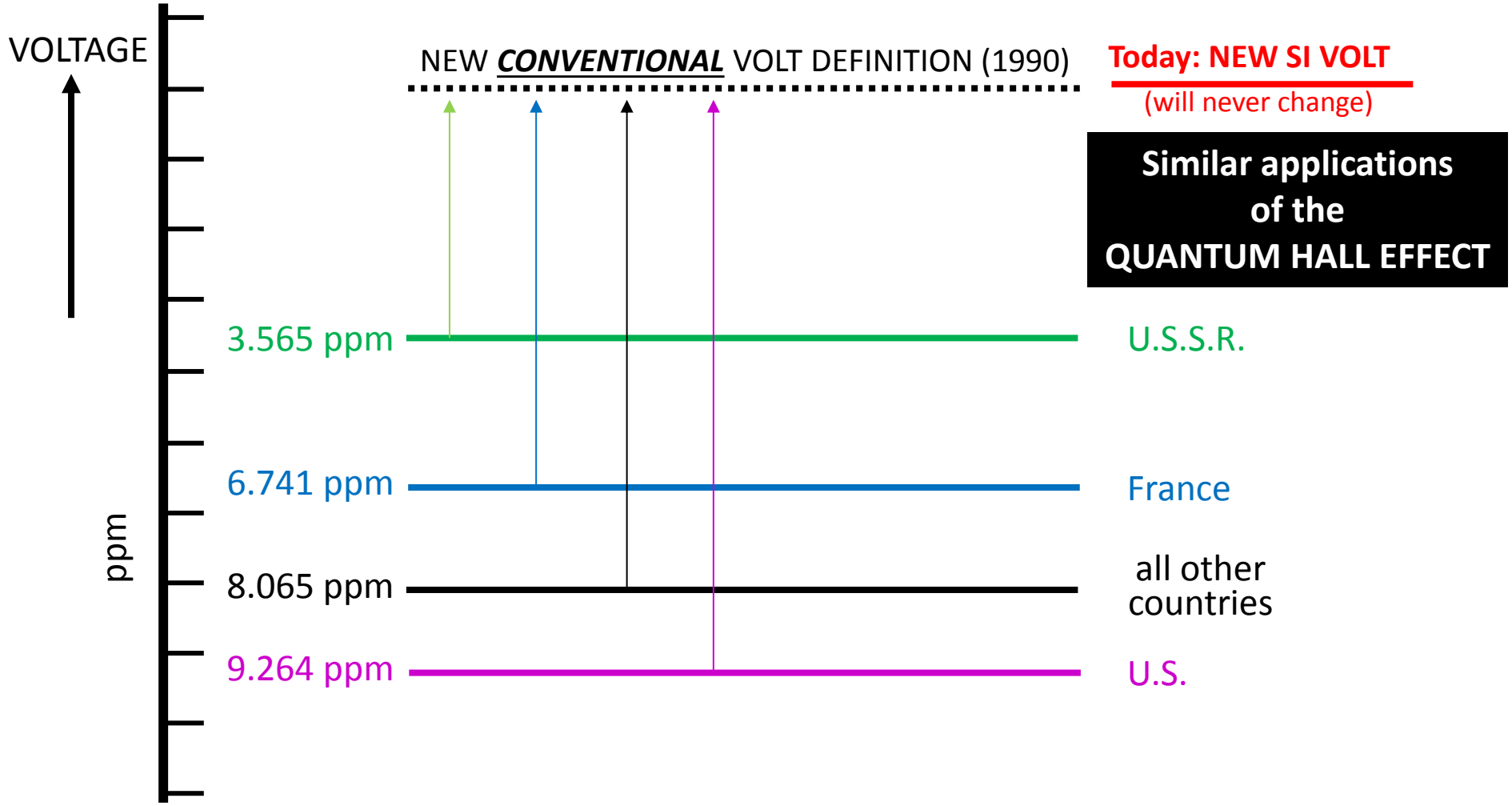


Pb-Pb Junction
Ic = 700 μA
ν ≅ 9 GHz
n ≅ 250

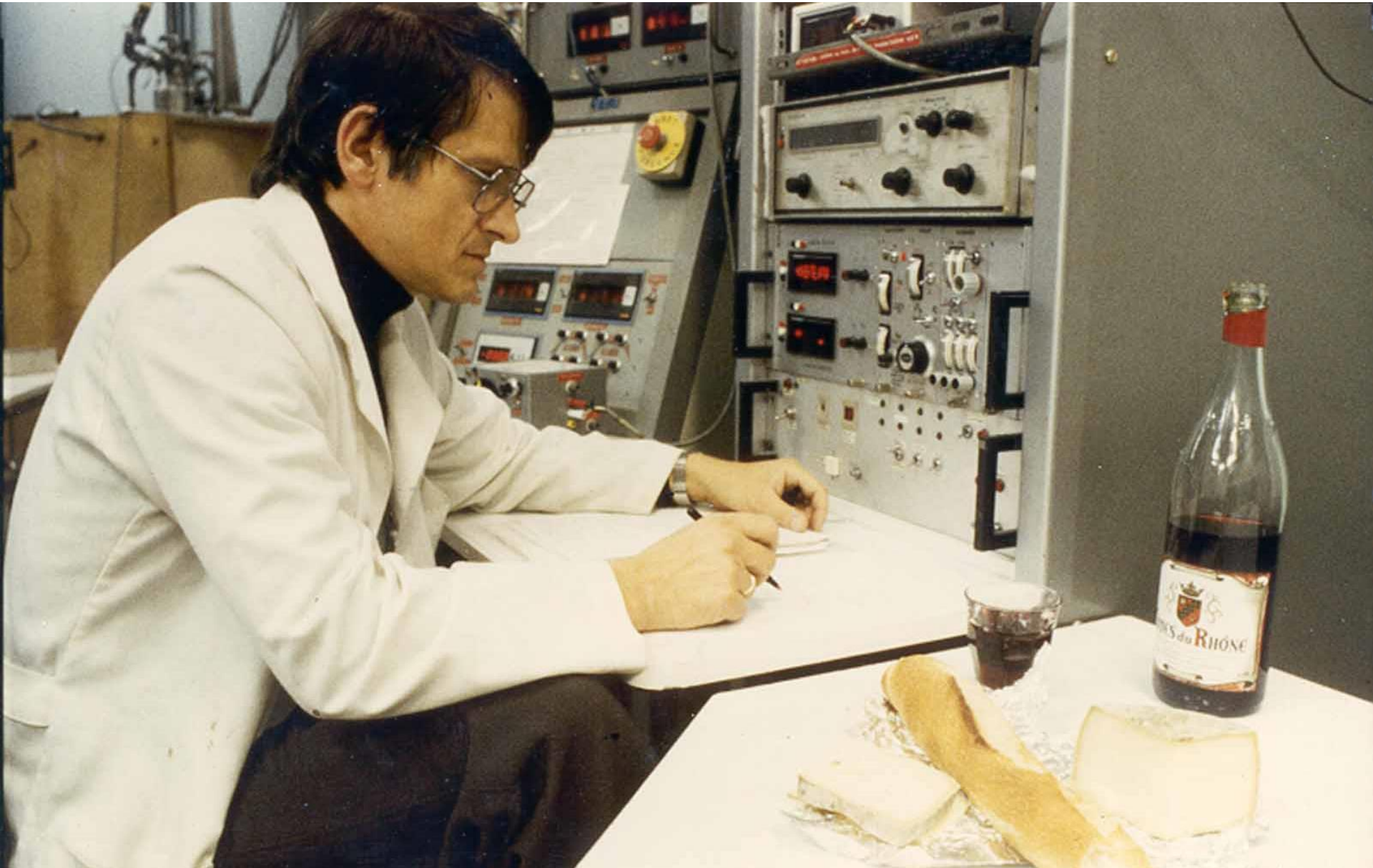
4 different "VOLTS" existed at the time of the Quantum Hall Discovery (1980)

SINCE 1990 A COMMON WORLDWIDE VOLT

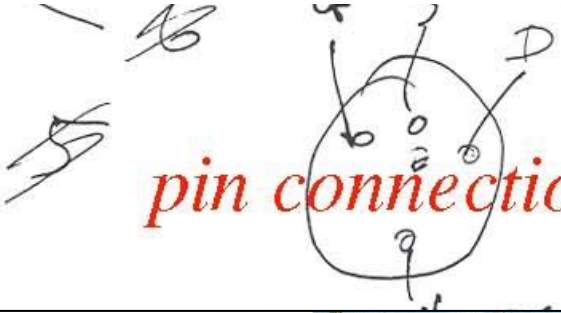
(But Outside the SI System)



Quantum Hall Effect: * 5.2.1980 at 2 a.m. in Grenoble (photo from 1985)



Notes 4./5.2.1980



$$F_L = R_H \cdot B \cdot j = \frac{1}{n \cdot e} \cdot B \cdot \frac{I}{b}$$

$$U_H = \frac{B}{n \cdot e} \cdot I$$

$$U = R \cdot I$$

New type of electrical resistance with a fixed value $h/e^2 \approx 25812\ \Omega$

$\Rightarrow 25813\ \Omega$

notes of the phone call to PTB (5.2.1980)

PTB 531 / 5921 2240

Prof. V. Kose

$\mu_0 = 4\pi \cdot 10^{-9}\ \frac{Vs}{Ac}$

Experimental Fact

All quantized Hall resistances

(different materials like silicon, GaAs or graphene)

show the same value with at least 10 digits

by comparing different devices**!**

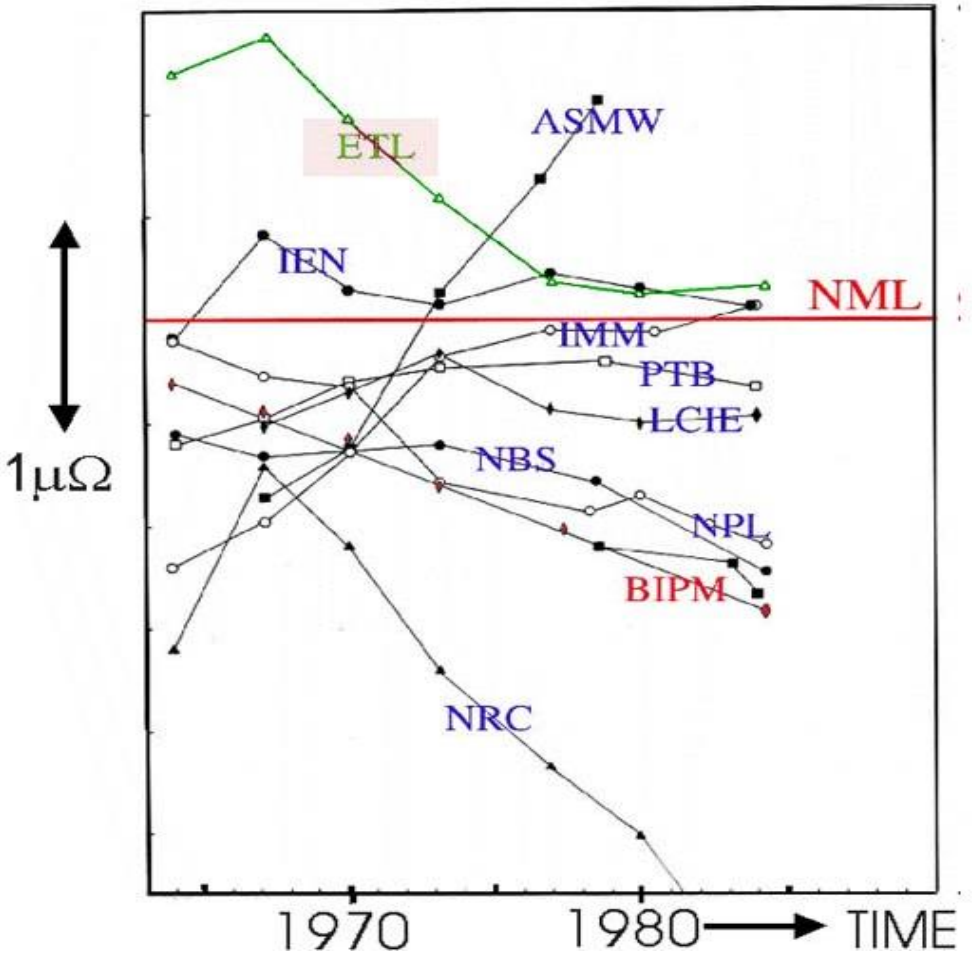
(however only 8 digits can be measured within our present SI system)

Requirement: 2-dimensional electron system and strong magnetic fields

Established Resistance Calibrations at NIMs Before Quantum Hall Discovery

before QHE:
resistance standard represented by wire resistor.

(The NML in Australia was able
to calibrate wire resistors in SI units)



Drift of NBS Ohm

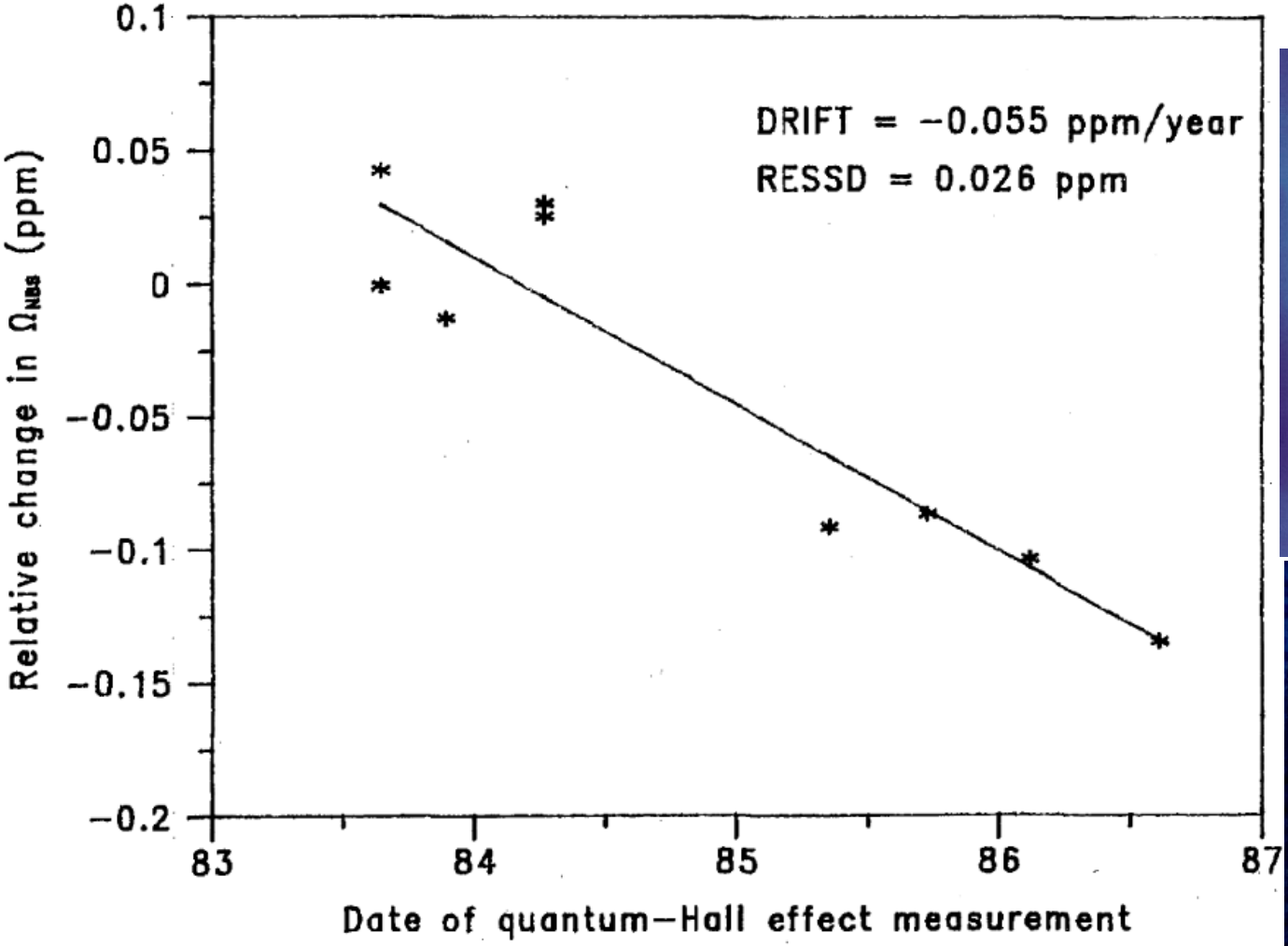
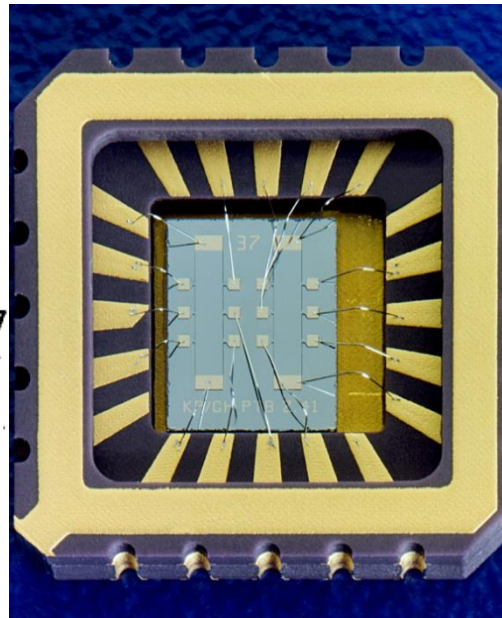
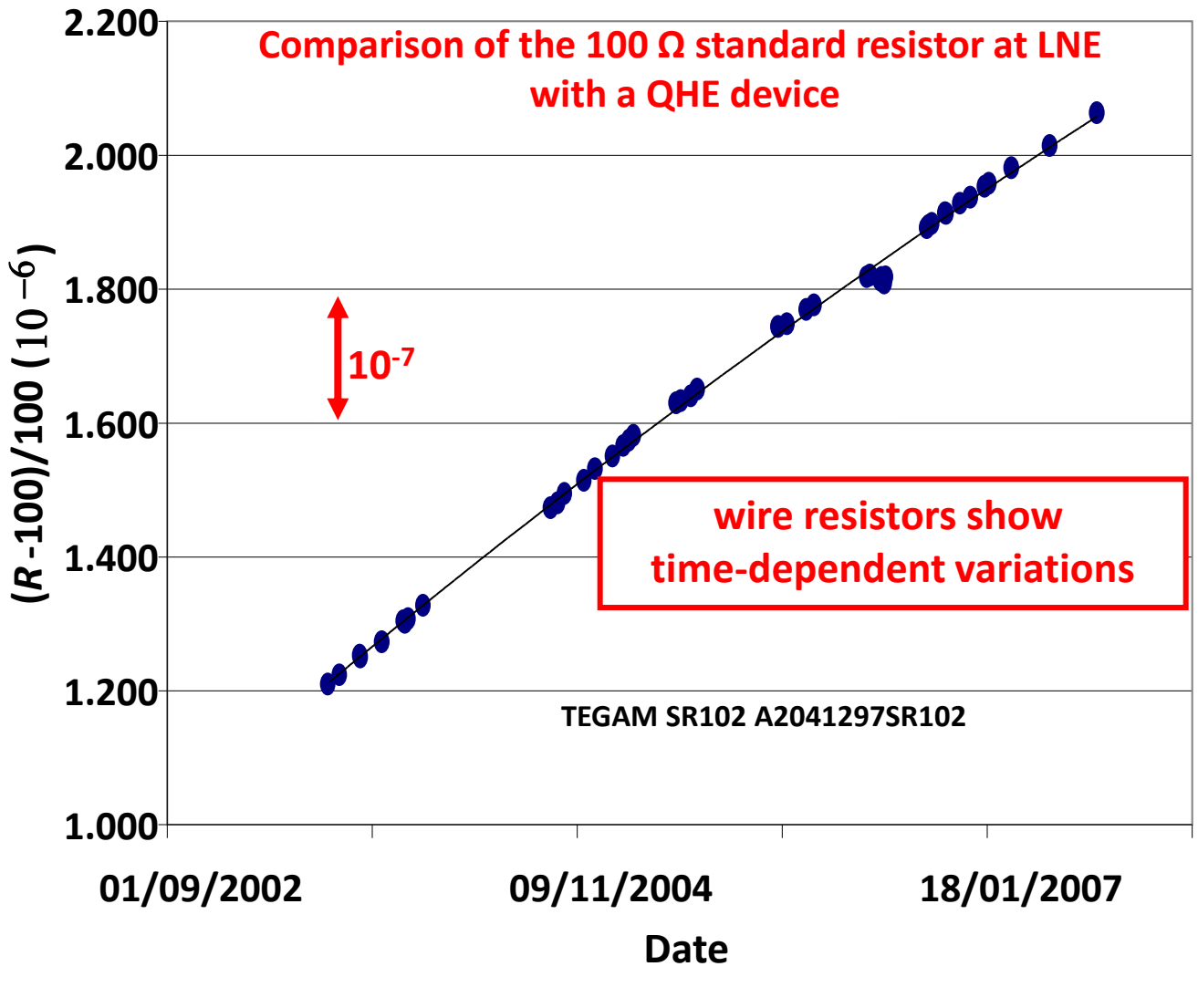


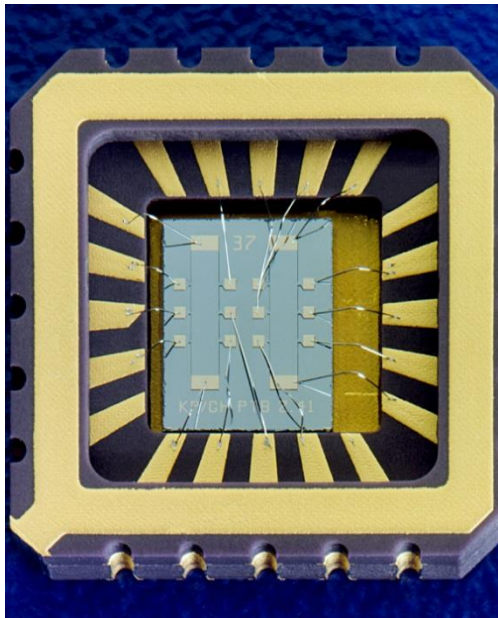
Fig. 1. NBS Ohm drift based on QHE measurements.



VI-A(26)

QHE Against Wire Resistor at LNE





The 18th CGPM, considered (1987):

…that many national laboratories use the Josephson effect and the quantum Hall effect to maintain representations of the volt and of the ohm, as these offer the best guarantees of long-term stability,

that because of the importance of coherence among the units of measurement of the various physical quantities the values adopted for these representations must be as closely as possible in agreement with the SI.

CIPM, 1988: Recommendation 2

The Comité International des Poids et Mesures,recommends

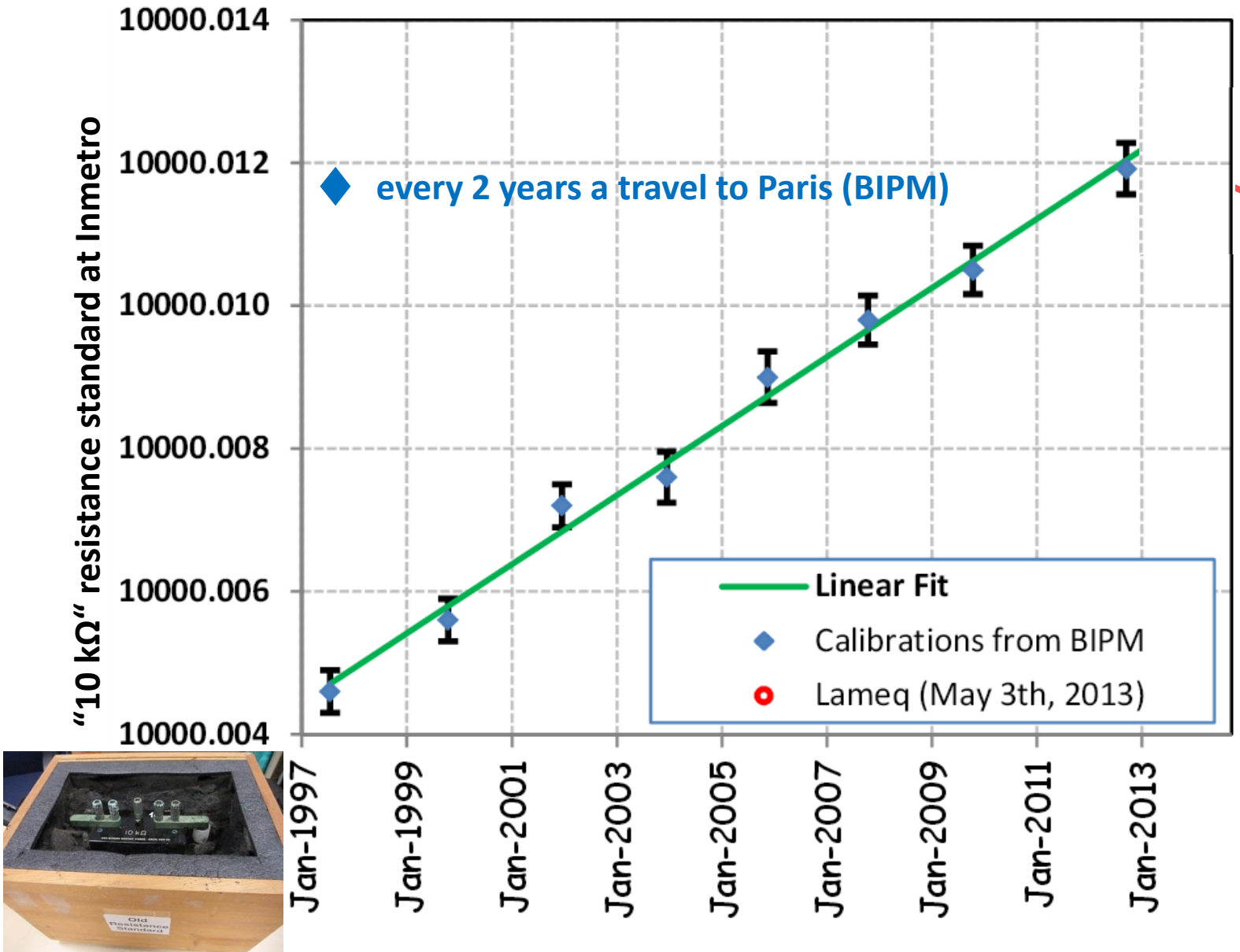
- **that 25 812.807 Ω exactly be adopted as a conventional value, denoted by $R_{K\text{-}90}$, for the von Klitzing constant, R_K,**
- **that this value be used from 1 January 1990, and not before, by all laboratories which base their measurements of resistance on the quantum Hall effect,**
- **that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with $R_{K\text{-}90}$,**

- **and is of the opinion that no change in this recommended value of the von Klitzing constant will be necessary in the foreseeable future.**

The foreseeable future ends today !

(If the vote on draft resolution A is „yes“)

Resistance metrology (NPL)


"10 kΩ" resistance standard at Inmetro
10000.014
10000.012
10000.010
10000.008
10000.006
10000.004
every 2 years a travel to Paris (BIPM)
Linear Fit
Calibrations from BIPM
Lameq (May 3th, 2013)
Jan-1997
Jan-1999
Jan-2001
Jan-2003
Jan-2005
Jan-2007
Jan-2009
Jan-2011
Jan-2013
Calibration with own QHE

Old Resistance Standard

COMMERCIAL QUANTUM STANDARDS FOR VOLT AND OHM

26e CGPM
Versailles
13-16 novembre 2018

Quantum Volt

In cooperation with PTB

Quantum Ohm

In cooperation with NPL

CODATA Internationally Recommended Values of the Fundamental Physical Constants

26e CGPM
Versailles
13-16 novembre 2018

conventional value of Josephson constant

K_{J-90}

Value	483 597.9 x 10^9 Hz V^{-1}
Standard uncertainty	(exact)
Relative standard uncertainty	(exact)
Concise form	483 597.9 x 10^9 Hz V^{-1}

V_{90}

conventional value of von Klitzing constant

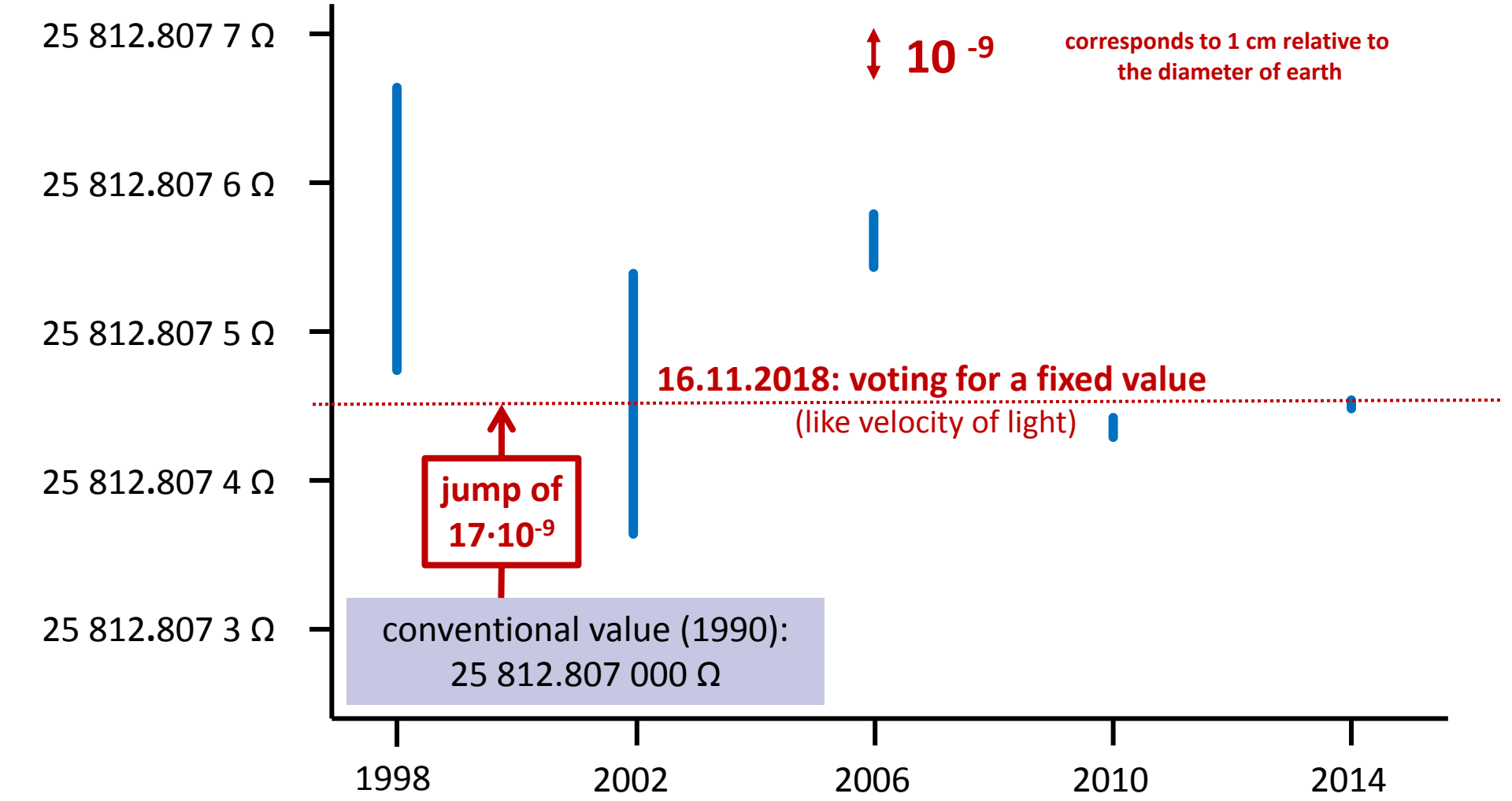
R_{K-90}

Value	25 812.807 Ω
Standard uncertainty	(exact)
Relative standard uncertainty	(exact)
Concise form	25 812.807 Ω

Ω_{90}

von Klitzing constant h/e^2

(CODATA recommended values)



Today we May Celebrate a Funeral and a Marriage Simultaneously

26e CGPM
Versailles
13-16 novembre 2018

Quantum-Units:
A Parallel World in our SI System

26e CGPM
Versailles
13-16 novembre 2018

SI Units

(base and derived)

R_K=25.812,807 450 3045 Ω

kg s m A

$$\Omega = \frac{\mathrm{kg\,m^2}}{\mathrm{A^2 s^3}}$$

adjusted in 1990

Quantum Units

(conventional units outside the official SI units)

$R_{K\text{-}90}$=25.812,807 000 000 Ω

Ω_{90} V_{90} A_{90} C_{90} L_{90} W_{90}

The new SI (which includes *h* and *e*) will unify these two worlds

A Happy Funeral

26e CGPM
Versailles
13-16 novembre 2018

Your vote today:

GOOD NEWS:
The value of $R_K=h/e^2$ will be a FIXED number compatible with the new SI system

– the decision to adopt the conventional values of the Josephson constant K_{J-90} and of the von Klitzing constant R_{K-90} taken by the CIPM (1988, Recommendations 1 and 2) at the request of the CGPM (18th meeting of the CGPM, 1987, Resolution 6) for the establishment of representations of the volt and the ohm using the Josephson and quantum Hall effects, respectively,

is abrogated.

Proposal for a New SI System

26e CGPM
Versailles
13-16 novembre 2018

THE DEFINING CONSTANTS OF THE INTERNATIONAL SYSTEM OF UNITS

Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta\nu_{Cs}$	9 192 631 770	Hz
speed of light in vacuum	c	299 792 458	m s^{-1}
Planck constant*	h	$6.626\,070\,15 \times 10^{-34}$	J Hz^{-1}
elementary charge*	e	$1.602\,176\,634 \times 10^{-19}$	C
Boltzmann constant*	k	$1.380\,649 \times 10^{-23}$	J K^{-1}
Avogadro constant*	N_A	$6.022\,140\,76 \times 10^{23}$	mol^{-1}
luminous efficacy	K_{cd}	683	lm W^{-1}

fixed values without uncertainties

*These numbers are from the CODATA 2017 special adjustment. They were calculated from data available before the 1st of July 2017.

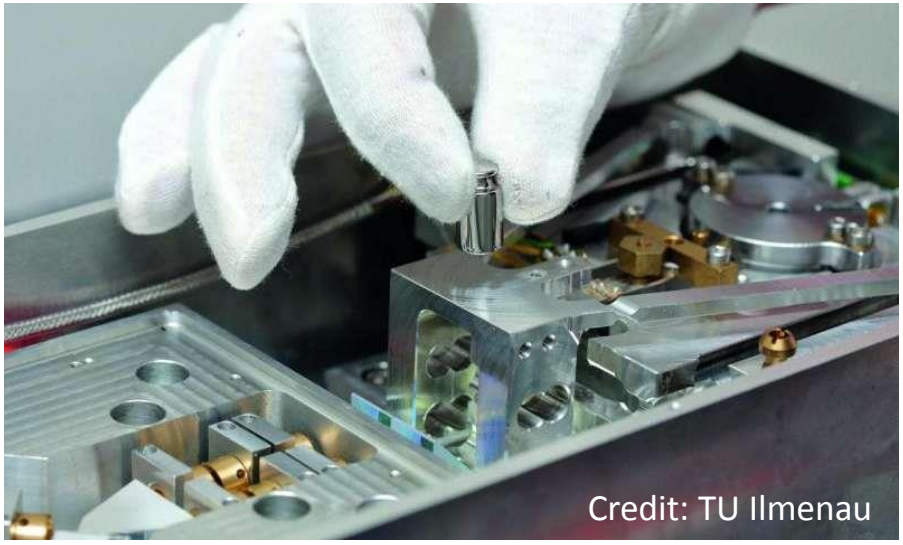
h/e^2 = 25812,807 459 304 506 660 045 516 706 087 443 042 457 273 221 403 421 768 329 716 073 228 965 768 572 716 532 282 171 634 884 319 000 217 144 421 378 765 742 75.. Ohm

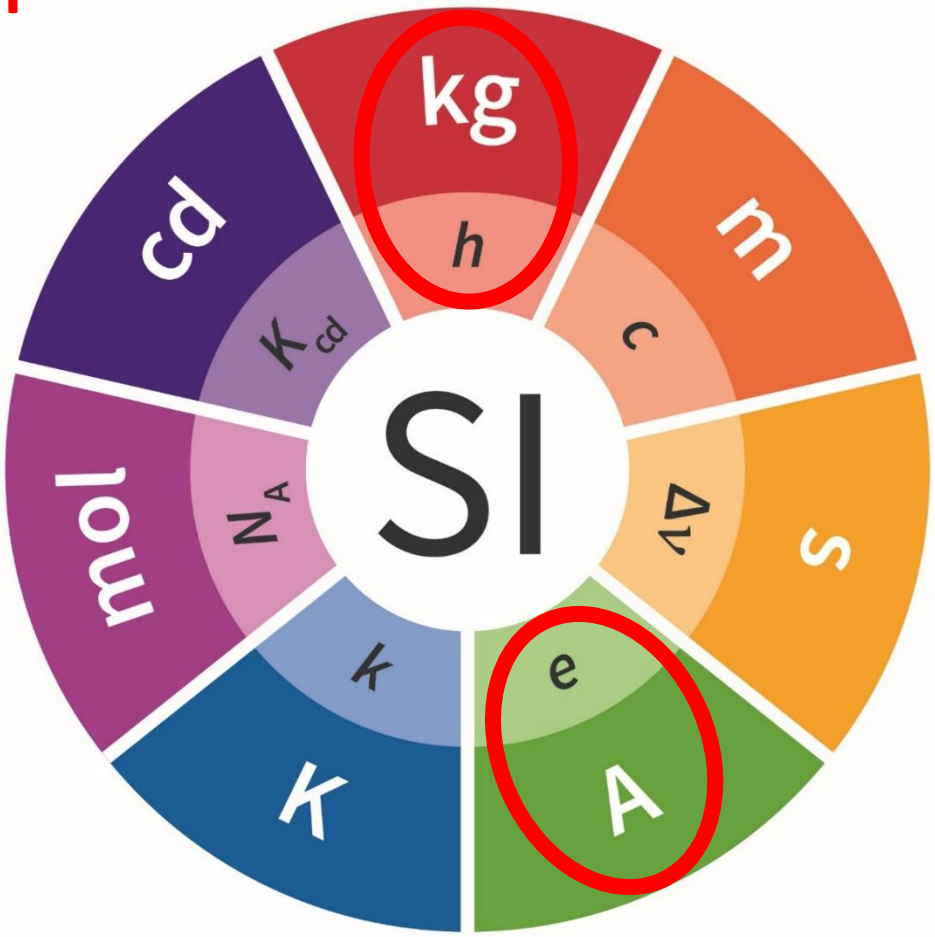
The Scientific Community is in Favour of the Revised SI

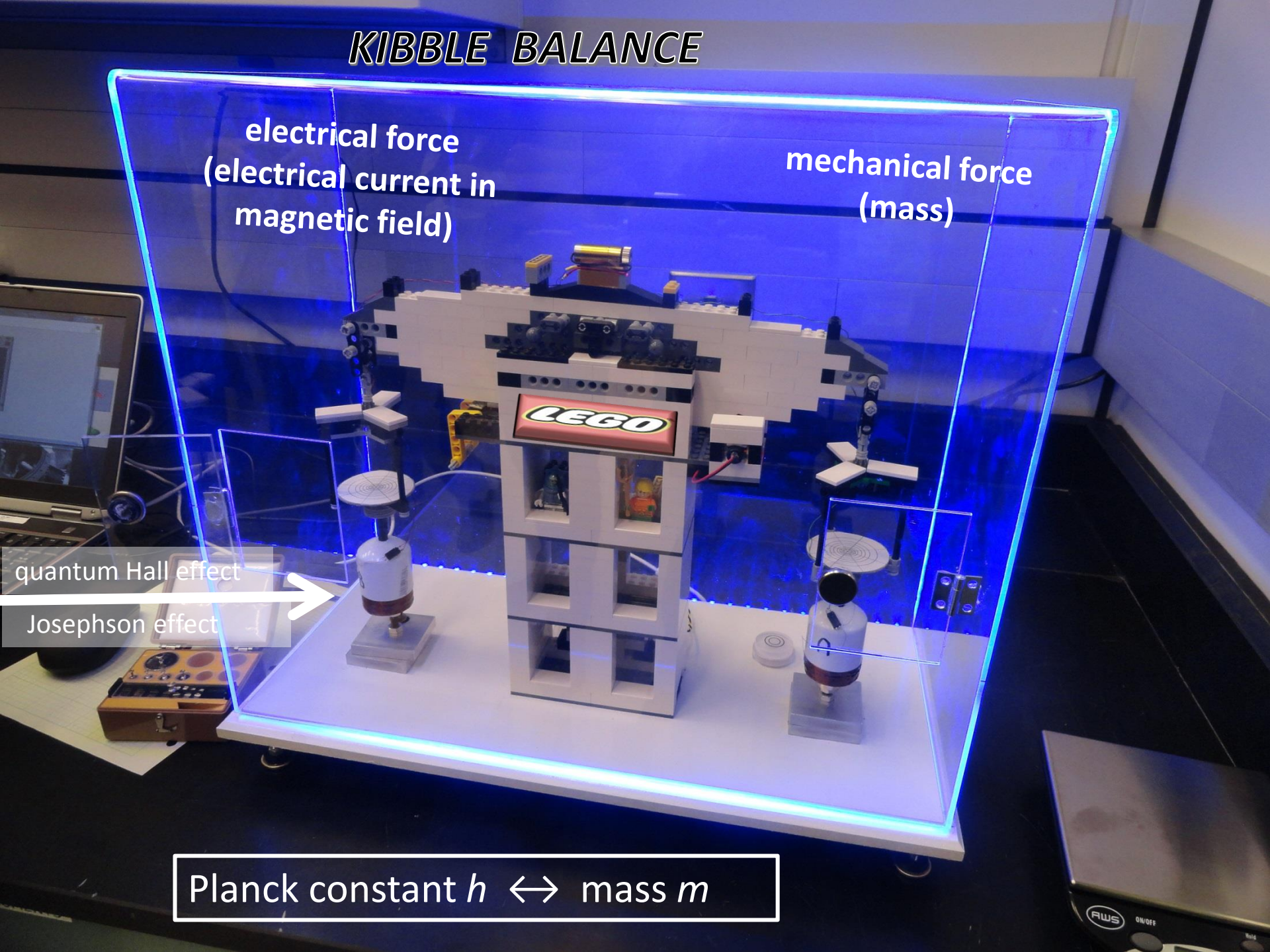
26e CGPM
Versailles
13-16 novembre 2018

An unexpected application of electrical quantum units:

Realization of an electronic kilogram based on a fixed value for h



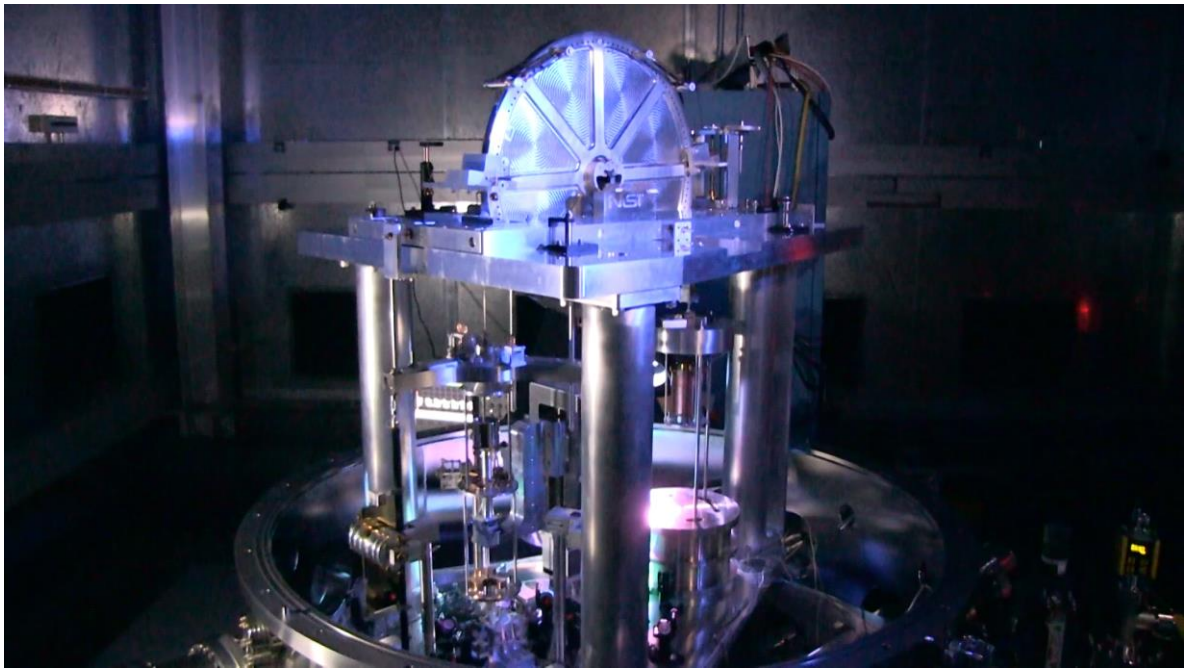



KIBBLE BALANCE
electrical force
(electrical current in
magnetic field)
mechanical force
(mass)
LEGO
quantum Hall effect
Josephson effect
Planck constant h ↔ mass m

Redefinition of the Kilogram

26e CGPM
Versailles
13-16 novembre 2018

Le Grand K
The artifact Kilogram



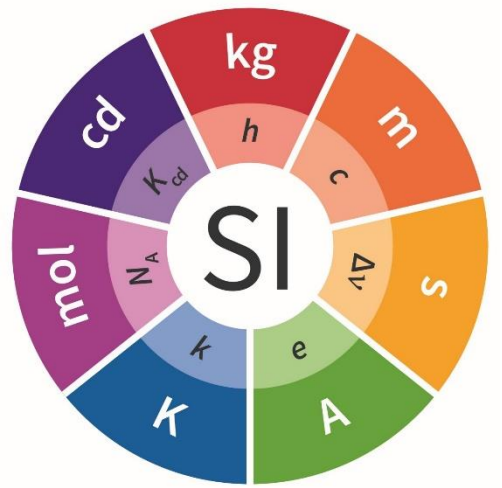
The Kibble Balance
The electronic Kilogram (The NIST-4 Watt Balance)

QUANTUM HALL EFFECT:
Not only important for electrical standards
but also for the realization of the kilogram

CONCLUSION

I look forward for the
vote on draft resolution A

Constants of nature are the most stable basis for an universal system of units *"for all time, for all people"*

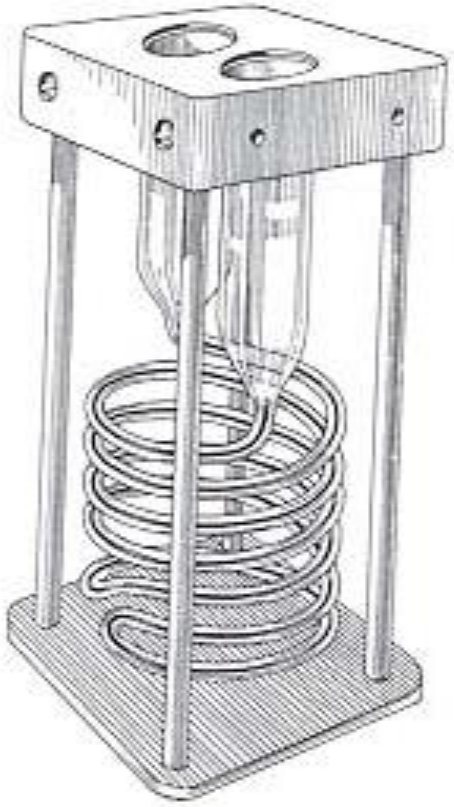


Thank you for your attention!

Official LOGO of Revised SI

1960: Introduction of SI System

Practical unit of electrical resistance (international Ohm until 1948):
Since 1884: column of mercury with diameter 1 mm² and length 106.0 cm
Since 1893: column of mercury with diameter 1 mm² and length 106.3 cm



$$1\ \Omega_{int} \longleftrightarrow 1\ \Omega_{abs}$$

up to 1990: resistance standard represented by wire resistor

since 1990:
conventional value for the quantized Hall resistance ≡ 25812,807 Ohm (fundamental constant)

recommends

- that 25 812,807 Ω exactly be adopted as a conventional value, denoted by R_{K-90}, for the von Klitzing constant, R_K,
- that this value be used from 1st January 1990, and not before, by all laboratories which base their measurements of resistance on the quantum Hall effect,
- that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with R_{K-90},
- that in the use of the quantum Hall effect to establish a laboratory reference standard of resistance, laboratories follow the most recent edit[illegible] measurements of [illegible] Comité Consultatif d'El[illegible]tional des Poids et Mesures,

THE FUTURE IS NOW!

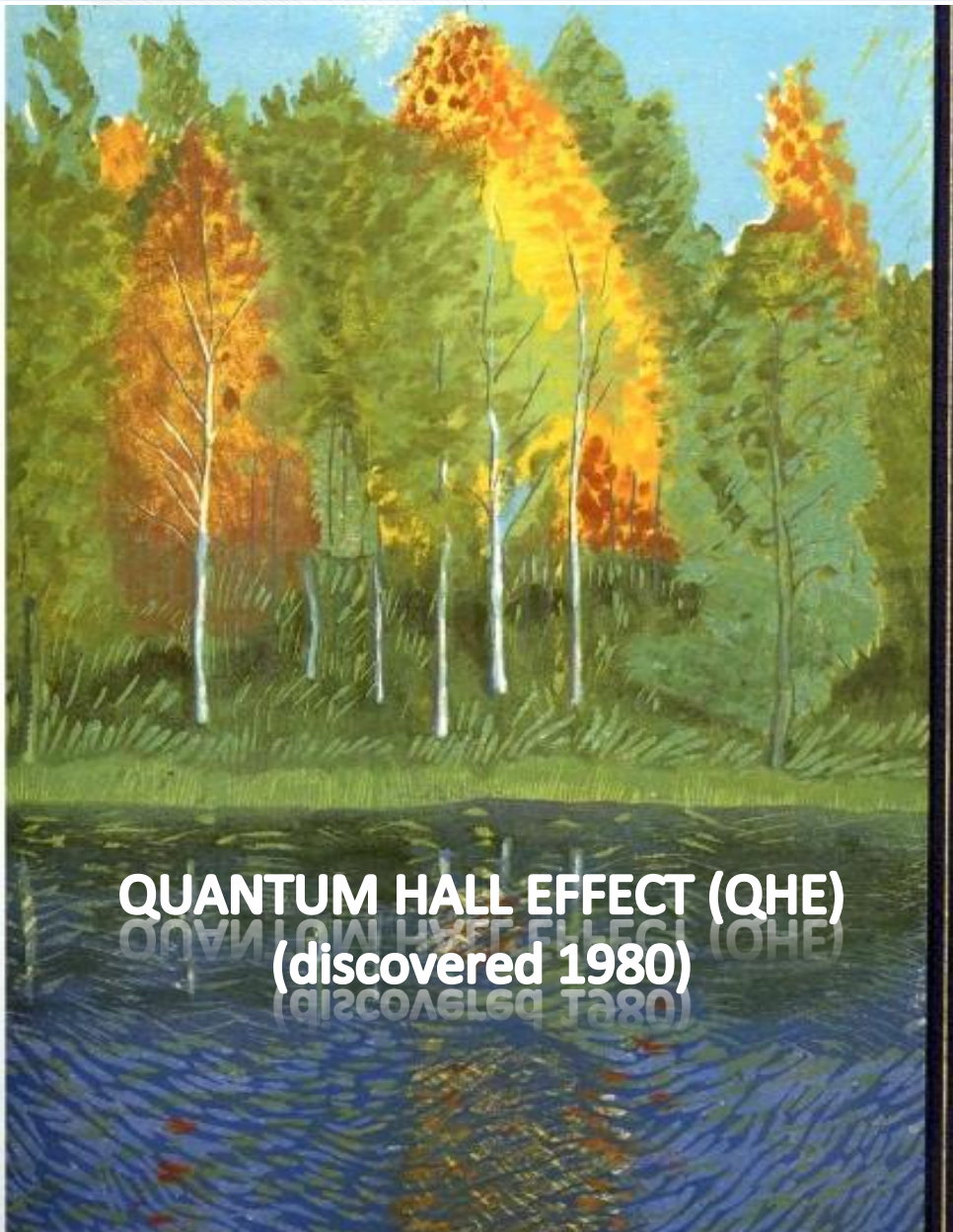
and is of the opinion

- that no change in this recommended value of the von Klitzing constant will be necessary in the foreseeable future.

Nobel Prize in Physics 1985

Kungliga
Svenska Vetenskapsakademien
har den 16 oktober 1985 beslutat att med det
NOBELPRIS
som detta år tillerkännes den
som inom fysikens område
gjort den viktigaste upptäckten eller
uppfinningen belöna
Klaus von Klitzing
för upptäckten av den kvantiserade
Halleffekten

STOCKHOLM DEN 10 DECEMBER 1985



QUANTUM HALL EFFECT (QHE)
(discovered 1980)

Historical Remarks to our Present SI System

26e CGPM
Versailles
13-16 novembre 2018

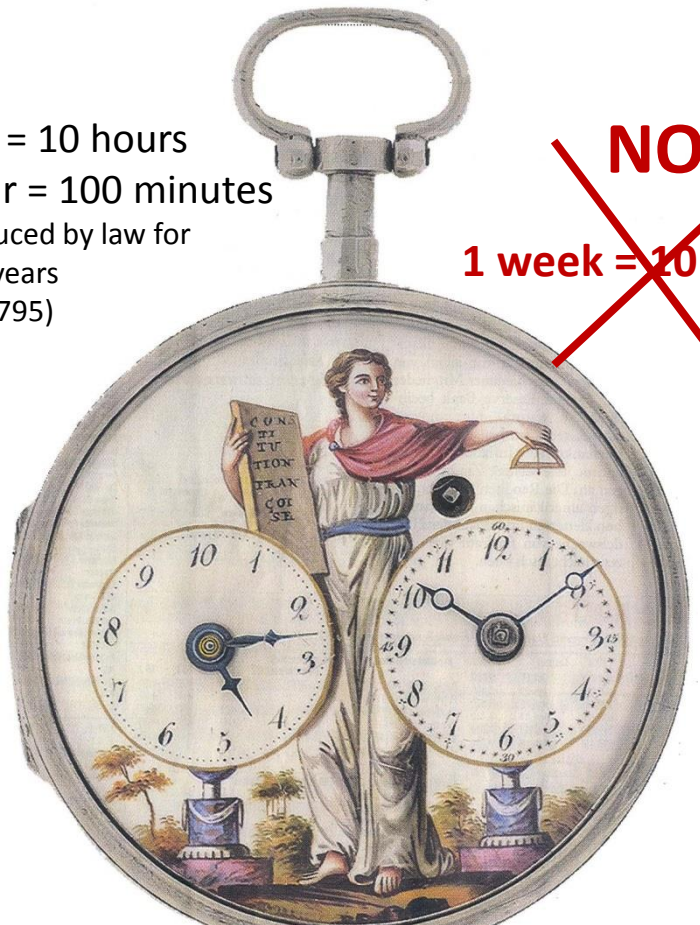
22.8.1790: Working Group for an
UNIVERSAL SET OF UNITS

Introduction of „Metric System“ by French Academy of Science …1, 10, 100, 1000, …

1 day = 10 hours
1 hour = 100 minutes
(introduced by law for only 2 years 1793-1795)

NO

1 week = 10 days



New International Electrical Reference Standards Based on the Josephson and Quantum Hall Effects

B N Taylor[1] and T J Witt[2]

Metrologia, Volume 26, Number 1

Metrologia 26, 47–62 (1989)

metrologia

New International Electrical Reference Standards Based on the Josephson and Quantum Hall Effects

B. N. Taylor [a] and **T. J. Witt** [b]

[a] National Institute of Standards and Technology, Gaithersburg, MD 20899, USA
[b] Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92312, Sèvres Cedex, France

Received: November 17, 1988

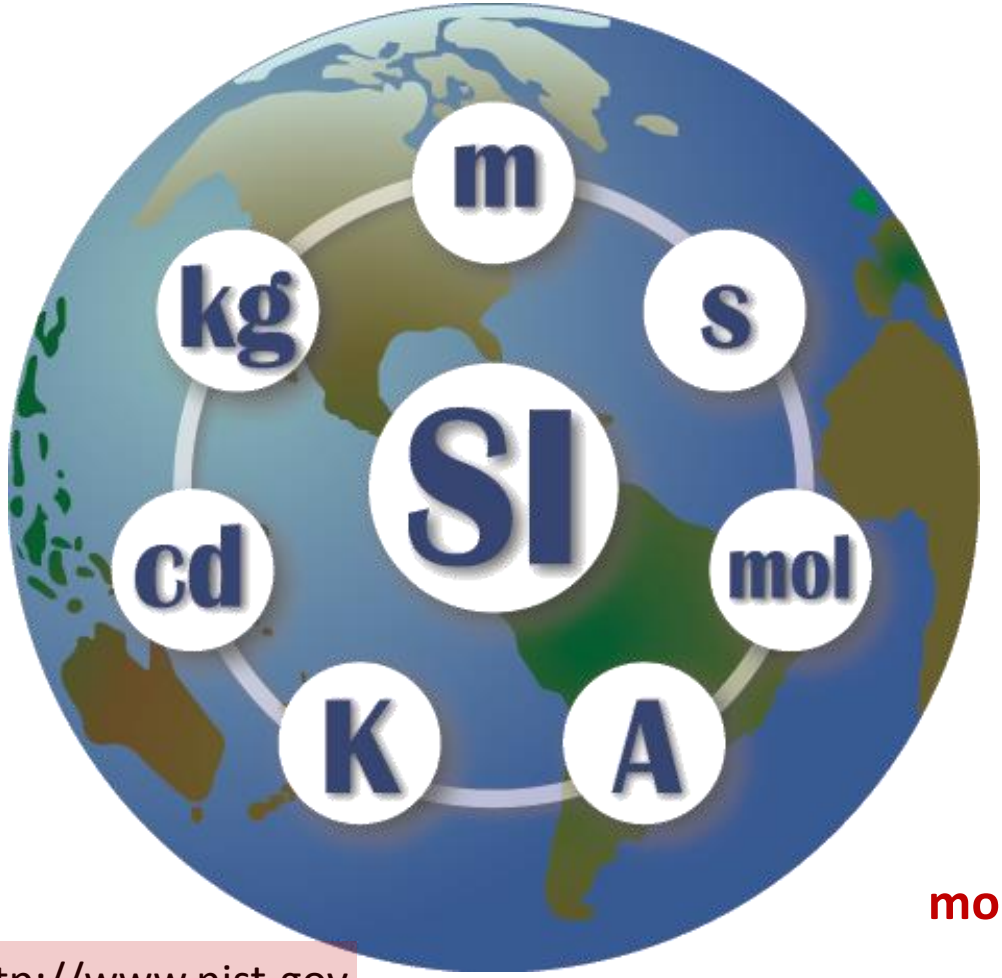
METROLOGY

= Science of Measurements

26e CGPM
Versailles
13-16 novembre 2018

All measurements can be expressed by our 7 base units

(SI units = Système international d'unités)



International system of units (SI units)

second for time

metre for length

kilogram PROTOTYPE

kelvin TRIPELPOINT OF H_2O

ampere FORCE BETWEEN WIRES

candela for luminous intensity

mole for the amount of substance

http://www.nist.gov

Diploma work at Royal Academy, London

Welcome to the WEBCAST Session of the General Conference on Weights and Measures (CGPM)

26e CGPM
Versailles
13-16 novembre 2018

10:50 - Start of webcast

Keynote lectures

"The quantum Hall effect and the revised SI"
Klaus von Klitzing (Nobel laureate, Max Planck Institute, Stuttgart)

"The role of the Planck constant in physics"
Jean-Philippe Uzan (*Centre national de la recherche scientifique* (CNRS), Paris)

"Optical atomic clocks – opening new perspectives on the quantum world"
Jun Ye (JILA, Boulder)

"Measuring with fundamental constants; how the revised SI will work"
Bill Phillips (Nobel laureate, NIST, Gaithersburg)

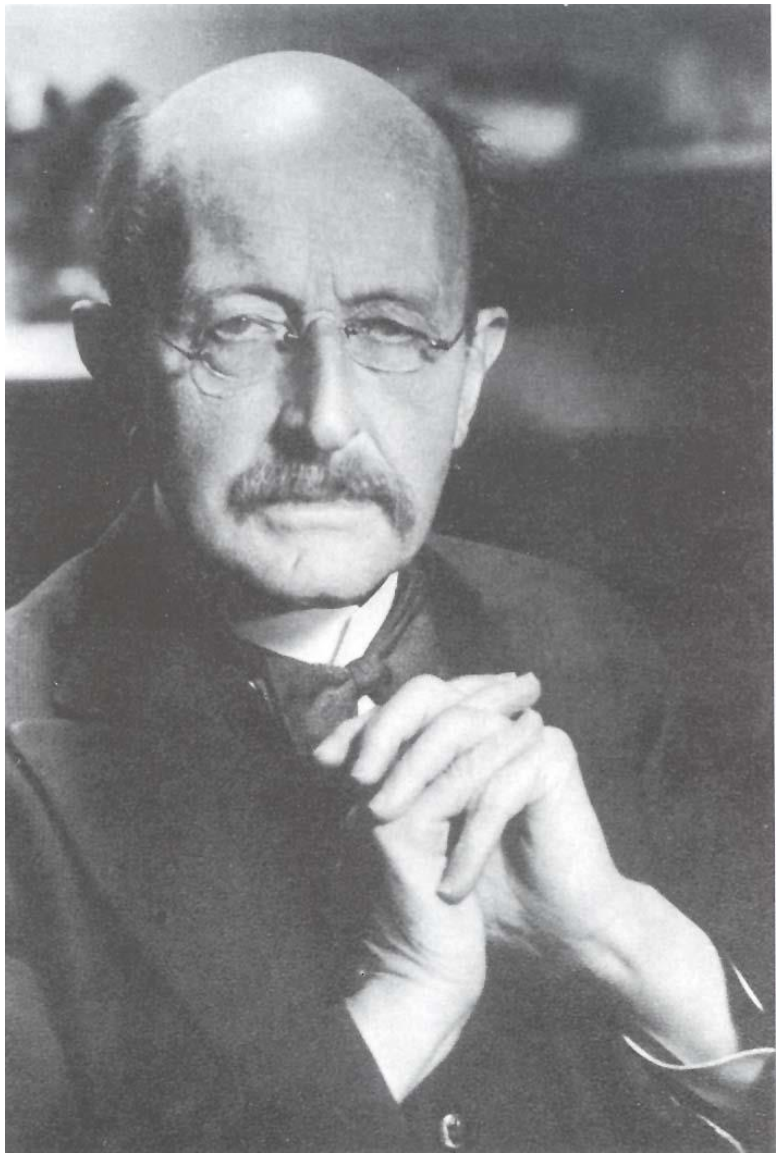
Introduction to the Resolution "On the revision of the International System of Units (SI)"
Martin Milton (BIPM Director)

Voting on Draft Resolution A and closing remarks
Barry Inglis

13:25 - End of session

100th Anniversary of Nobel Prize for „ENERGY QUANTA“

26e CGPM
Versailles
13-16 novembre 2018



The Nobel Prize in Physics 1918
Max Planck

Share this: 47

The Nobel Prize in Physics 1918

Max Karl Ernst Ludwig Planck
Prize share: 1/1

The Nobel Prize in Physics 1918 was awarded to Max Planck *"in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta".*

Max Planck received his Nobel Prize one year later, in 1919. During the selection process in 1918, the Nobel Committee for Physics decided that none of the year's nominations met the criteria as outlined in the will of Alfred Nobel. According to the Nobel Foundation's statutes, the Nobel Prize can in such a case be reserved until the following year, and this statute was then applied. Max Planck therefore received his Nobel Prize for 1918 one year later, in 1919.

Result of the Performance 23.4.1938

26e CGPM
Versailles
13-16 novembre 2018

Present for Max Planck at his 80th birthday

(23.4.1938)

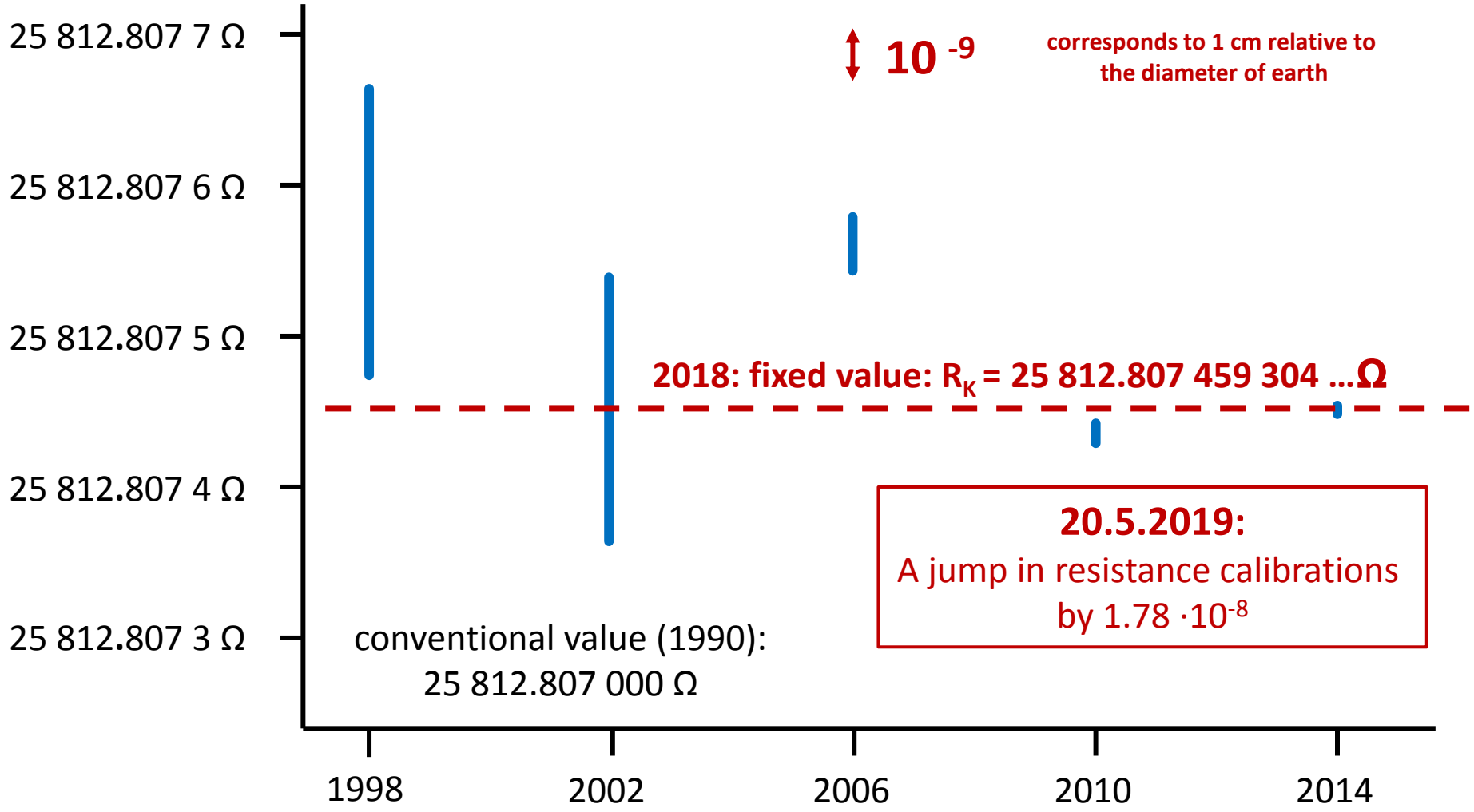
$$h \equiv 6{,}543210 \cdot 10^{-27} \text{ erg sec}$$

A real birthday gift for Max Planck 80 years later (2018)

2018: $h \equiv 6{,}626\,070\,15 \cdot 10^{-34}$ **kg** $m^2 s^{-1}$

von Klitzing constant

CODATA recommended values)



The Expected Value of VON KLITZING CONSTANT (from "*mises en pratique*")

26e CGPM
Versailles
13-16 novembre 2018

h/e^2 = 25812,807 459 304 506 660

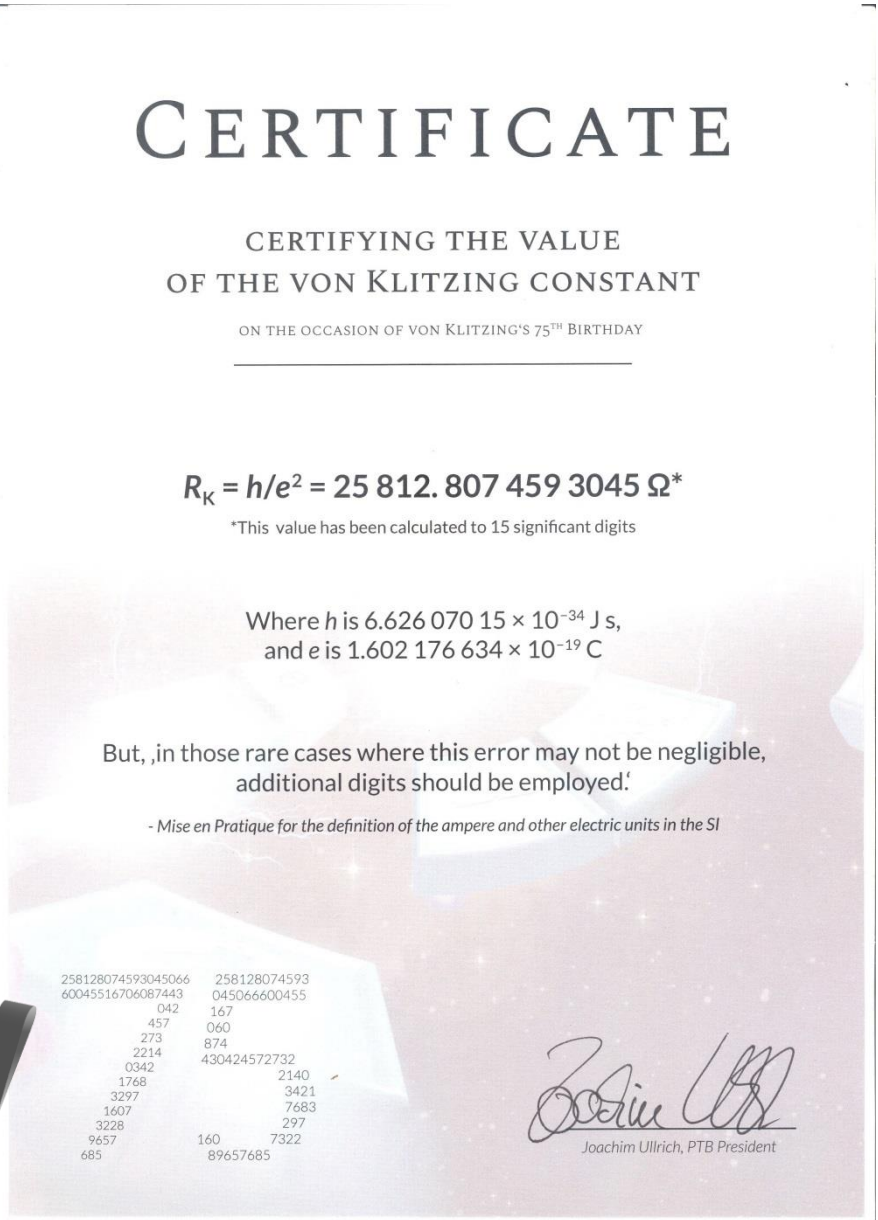
045 516 706 087 443 042 457 273

221 403 421 768 329 716 073 228

965 768 572 716 532 282 171 634

884 319 000 217 144 421 378 765

742 75.. Ohm



CERTIFICATE

CERTIFYING THE VALUE
OF THE VON KLITZING CONSTANT

ON THE OCCASION OF VON KLITZING'S 75TH BIRTHDAY

$R_K = h/e^2 = 25\,812.807\,459\,3045\ \Omega^*$

*This value has been calculated to 15 significant digits

Where h is $6.626\,070\,15 \times 10^{-34}$ J s,
and e is $1.602\,176\,634 \times 10^{-19}$ C

But, ‚in those rare cases where this error may not be negligible, additional digits should be employed.'

- *Mise en Pratique for the definition of the ampere and other electric units in the SI*

258128074593045066 258128074593
600455167060874 045066600455
042 167
457 060
273 874
2214 430424572732
0342 2140
1768 3421
3297 7683
1607 297
3228 160 7322
9657 89657685
685

Joachim Ullrich, PTB President

Thank you for your attention!

– the decision to adopt the conventional values of the Josephson constant K_{J-90} and of the von Klitzing constant R_{K-90} taken by the CIPM (1988, Recommendations 1 and 2) at the request of the CGPM (18th meeting of the CGPM, 1987, Resolution 6) for the establishment of representations of the volt and the ohm using the Josephson and quantum Hall effects, respectively, is abrogated.

18th CGPM Meeting (1987)

26e CGPM
Versailles
13-16 novembre 2018


www.bipm.org

How my Nobel Prize Contributed to this Development

Final Statement

26e CGPM
Versailles
13-16 novembre 2018

Fundamental constants (***h, e, c,*** k_B, N_A) form the most stable basis for a new international system of units. They will replace our present ***SI system*** in the near future, the member of the 'The General Conference on Weights and Measures') have the chance to decide, that this future starts today!

The Biggest Revolution in Metrology Since the French Revolution


Bureau
International des
Poids et
Mesures
www.bipm.org