Redefinition of the International System of Units

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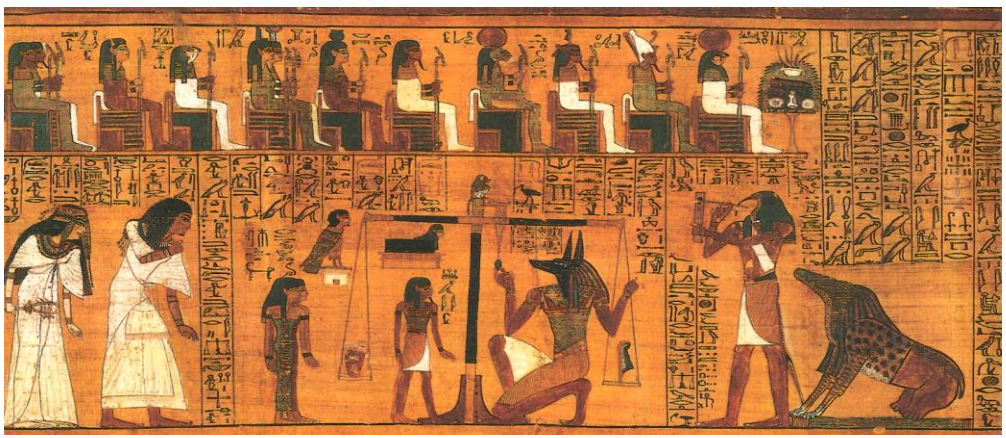
- **Introduction - SI history**
- The need for change of SI units
- Preparations for change
  - the mole
  - the kilogram
  - the ampere
  - the kelvin
- Consequences for users
- RF electrical quantities
  - CMI national standards
  - future “quantum realizations”

- various units used for thousands of years, some of systems stable over time
- mostly based on nature or human body measures (which were thought to be constant)
- English system (England up to 1826 - teaspoon, pint, gallon, etc.); Imperial system (post-1824, British Empire)



source: Wikipedia

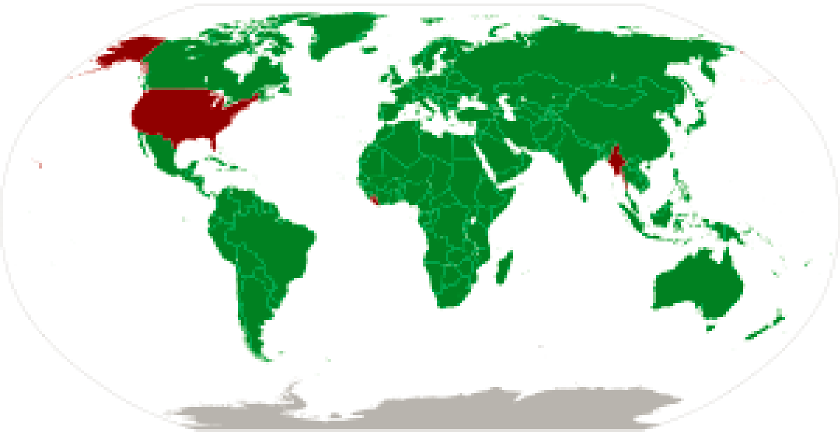
credit: D. Pisano, Flickr

- 1875 – Metre convention, signed by 17 countries (only the metre and the kilogram), a set of 30 prototypes of the metre and 40 prototypes of the kilogram made from 90% Pt and 10% Ir alloy manufactured in 1889

source: Wikipedia

- 1960 - the 11th CGPM synthesised a set of 16 resolutions, the system was named the International System of Units (Le Système International d'Unités, **SI**)
- the metre, kilogram, second, ampere, degree Kelvin, and candela (+ mole in 1971)

- base units derived from **invariant constants of nature** (e.g. speed of light in vacuum), **triple point of water** and one **artefact** (kilogram)
- derived units - defined in terms of base units or other derived units (e.g. $1\ \mathrm{Pa} = \mathrm{kg}\cdot\mathrm{m}^{-1}\cdot\mathrm{s}^{-2}$, $1\ \Omega = \mathrm{kg}\cdot\mathrm{m}^{2}\cdot\mathrm{s}^{-3}\cdot\mathrm{A}^{-2}$ etc.)



nowadays, SI units officially used almost everywhere except USA, Myanmar and Liberia

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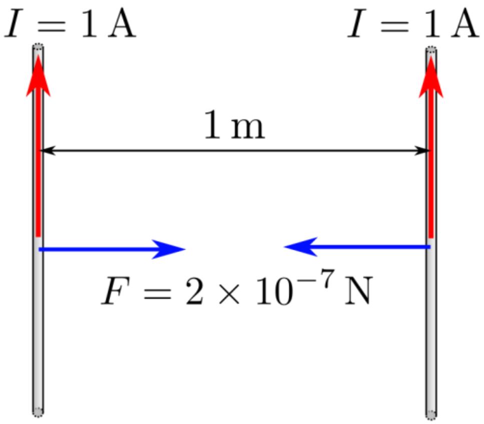
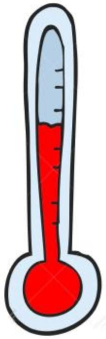
- main motivation for change of SI
  - the prototypes of **the kilogram** change their weight (~tens of μg relative to the 1889 values due to contamination (+) and cleaning (-))
  - **the ampere** is defined by means of an idealized and unrealistic measurement setup
  - **the kelvin**, triple point of water influen-ced by impurities and by the isotopic composition of the water; as temperature is not an additive quantity, additional definitions are necessary in order to expand the temperature scale beyond the triple point of water





source: Wikipedia

- former SI: values of the fundamental constants specified; our measurement capabilities are reflected in these values
- new SI: the seven base units are defined by determining seven "defining constants" that contain these units

Current SI		New "Quantum" SI	
Base quantity	**Base unit**	**Base quantity**	**Defining Constant**
Time	second (s)	Frequency	$\Delta\nu(^{133}Cs)_{hfs}$
Length	meter (m)	Velocity	c
Mass	kilogram (kg)	Action	h
Electrical Current	ampere (A)	Electric Charge	e
Therm. Temperature	kelvin (K)	Heat Capacity	k
Amount of Substance	mole (mol)	Amt of Substance	N_A
Luminous intensity	candela (cd)	Luminous intensity	K_{cd}

- the idea not new – already in 1870, James Clerk Maxwell was concentrating more on atomic quantities to provide a definition of the units

"If, then, we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them NOT in the dimensions, or the motion, or the mass of our planet, but in the wave-length, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules."

Address to the Mathematical and Physical Sections of the British Association

- 1900 – Max Planck made use constants when he formulated his law of radiation

"On the other hand, it should not be without interest to say that the use of the two [...] constants a and b offers the possibility of establishing units for length, mass, time and temperature which necessarily maintain their significance for all times and for all cultures (this also includes extraterrestrial and non-human cultures) – independent of special bodies and substances – and which can, therefore, be called "natural mass units."

Ann. Physik 1, 69 (1900)

Planck mass	$m_p = \sqrt{\frac{\hbar c}{G}}$	$= 2.176 \cdot 10^{-8}$ kg
Planck length	$l_p = \sqrt{\frac{\hbar G}{c^3}}$	$= 1.616 \cdot 10^{-35}$ m
Planck time	$t_p = \frac{l_p}{c}$	$= 5.391 \cdot 10^{-44}$ s
Planck temperature	$T_p = \frac{m_p \cdot c^2}{k}$	$= 1.417 \cdot 10^{32}$ K

h = Planck's constant

c = speed of light

G = gravitational constant ("Big G")

k = Boltzmann constant

The need for change of SI units

- the quantities chosen as defining constants are quantities that can be measured with great precision in the old SI (relative uncertainties ideally around 10^{-8})
- the gravitational constant is not one of these quantities, as it is known only with a relative uncertainty of 10^{-4}

$$F = G \cdot \frac{m_1 \cdot m_2}{r^2}$$

- definition of the second via the cesium frequency was kept (present-day caesium clocks rel. uncertainty $\sim 10^{-16}$, optical atomic clocks with Yb or Sr even have stabilities of 10^{-18}, yet none has proven to be clearly superior)

source: NPL

- the SI revision does not pretend to be for daily use
- milestone in the history of civilization – from the Middle Ages until 18th and 19th centuries the units were used regionally
- the numerical values of seven unit-related constants – the "defining constants" – are to be specified exactly
- the seven base units (s, m, kg, A, K, cd, mol) will no longer be directly but indirectly defined
- numerical values of constants **may still change** if such changes are necessary due to improved experimental results
- even a Martian could understand what a kilogram is

The need for change of SI units

- the new “quantum” SI

26ᵉ CGPM
Versailles
13-16 novembre 2018

- The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.
- The metre, symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum c to be 299 792 458 when expressed in the unit m/s, where the second is defined in terms of $\Delta\nu_{Cs}$.
- The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be $6.626\,070\,15 \times 10^{-34}$ when expressed in the unit J s, which is equal to kg m^2 s^{-1}, where the metre and the second are defined in terms of c and $\Delta\nu_{Cs}$.
- The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge e to be $1.602\,176\,634 \times 10^{-19}$ when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{Cs}$.

https://www.bipm.org/utils/common/pdf/CGPM-2018/26th-CGPM-Resolutions.pdf

- the new "quantum" SI

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- The kelvin, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant k to be 1.380 649 × 10^{-23} when expressed in the unit J K^{-1}, which is equal to kg m^2 s^{-2} K^{-1}, where the kilogram, metre and second are defined in terms of h, c and $\Delta \nu_{Cs}$.
- The mole, symbol mol, is the SI unit of amount of substance. One mole contains exactly 6.022 140 76 × 10^{23} elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A, when expressed in the unit mol^{-1} and is called the Avogadro number.
- The amount of substance, symbol n, of a system is a measure of the number of specified elementary entities. An elementary entity may be an atom, a molecule, an ion, an electron, any other particle or specified group of particles.
- The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540 × 10^{12} Hz, K_{cd}, to be 683 when expressed in the unit lm W^{-1}, which is equal to cd sr W^{-1}, or cd sr kg^{-1} m^{-2} s^3, where the kilogram, metre and second are defined in terms of h, c and $\Delta \nu_{Cs}$.

https://www.bipm.org/utils/common/pdf/CGPM-2018/26th-CGPM-Resolutions.pdf

- SI history
- Measurement traceability
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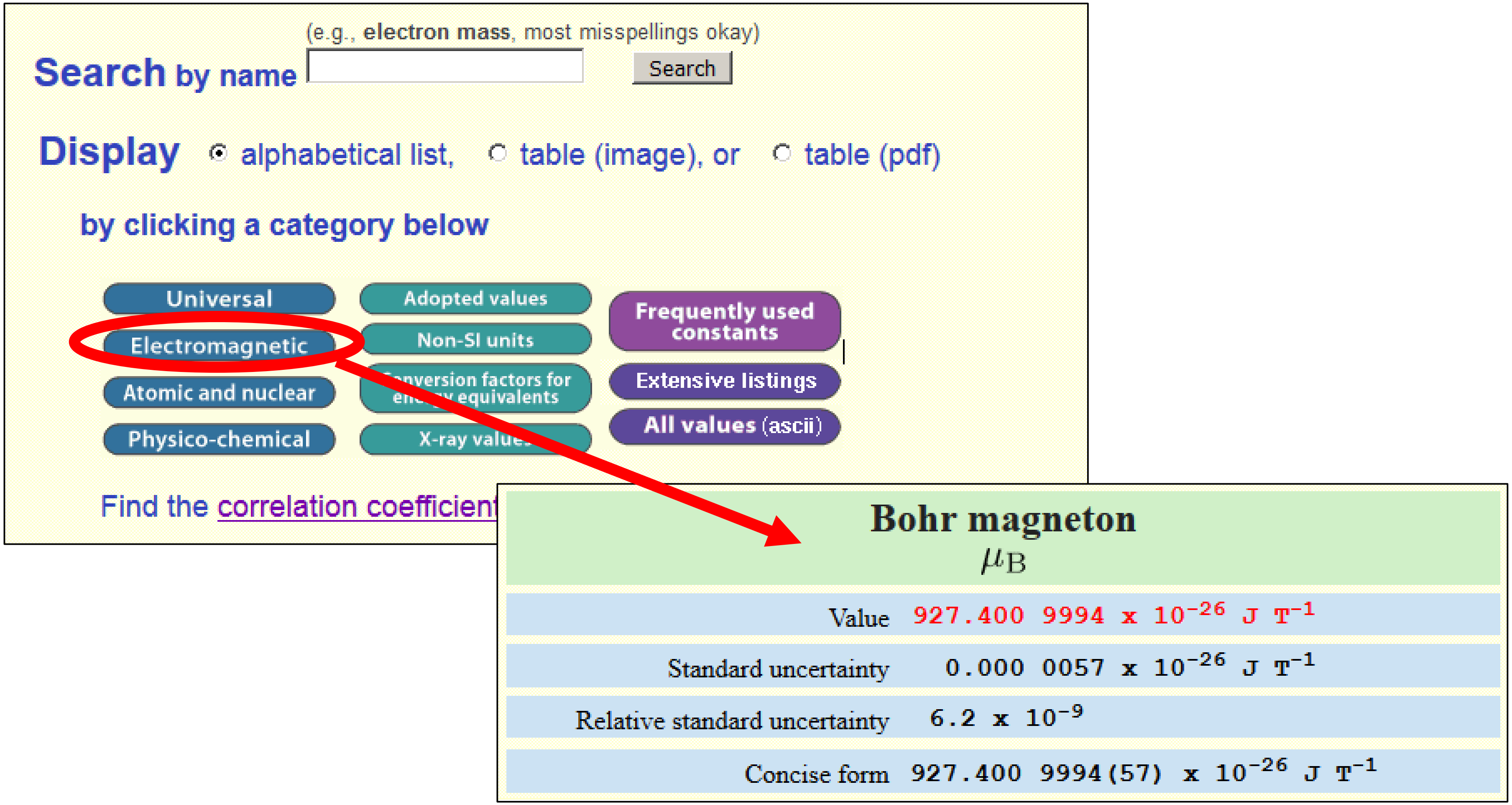
- Consequences for users
- Further reading

- **how to realize** “new” SI units?

- for the second and the metre (and derived units the ohm and the volt) – extremely precise measurement procedures exist (caesium atomic clock, light propagation and the quantum Hall effect/Josephson effect), traceable directly to $\Delta\nu_{Cs}$, c, h and e
- for the kilogram, the mole, the ampere and the kelvin, it was necessary to develop measurement procedures of comparable precision
- CODATA – provides set of internationally recommended values of physical constants; target relative uncertainty from different experiments must be consistent
- **20 May 2019** – the implementation day of the “new” SI units (world day of metrology)

- CODATA internationally recommended values of fundamental physical constants
  https://physics.nist.gov/cuu/Constants/index.html



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- attempts to determine Avogadro constant using silicon (3 isotopes) since 2003
- in highly enriched silicon, isotopes ^{29}Si and ^{30}Si are just impurities which can be determined by mass spectroscopy; approx. 5 kg single silicon crystal used for experiments
- 2011 – rel. uncertainty $\sim 2\times 10^{-8}$ achieved under extreme experimental challenges
- number of atoms in a 1 kg silicon sphere counted
- the Avogadro's constant and Planck's constant determined in one experiment
- at least 3 independent experiments required by 2018

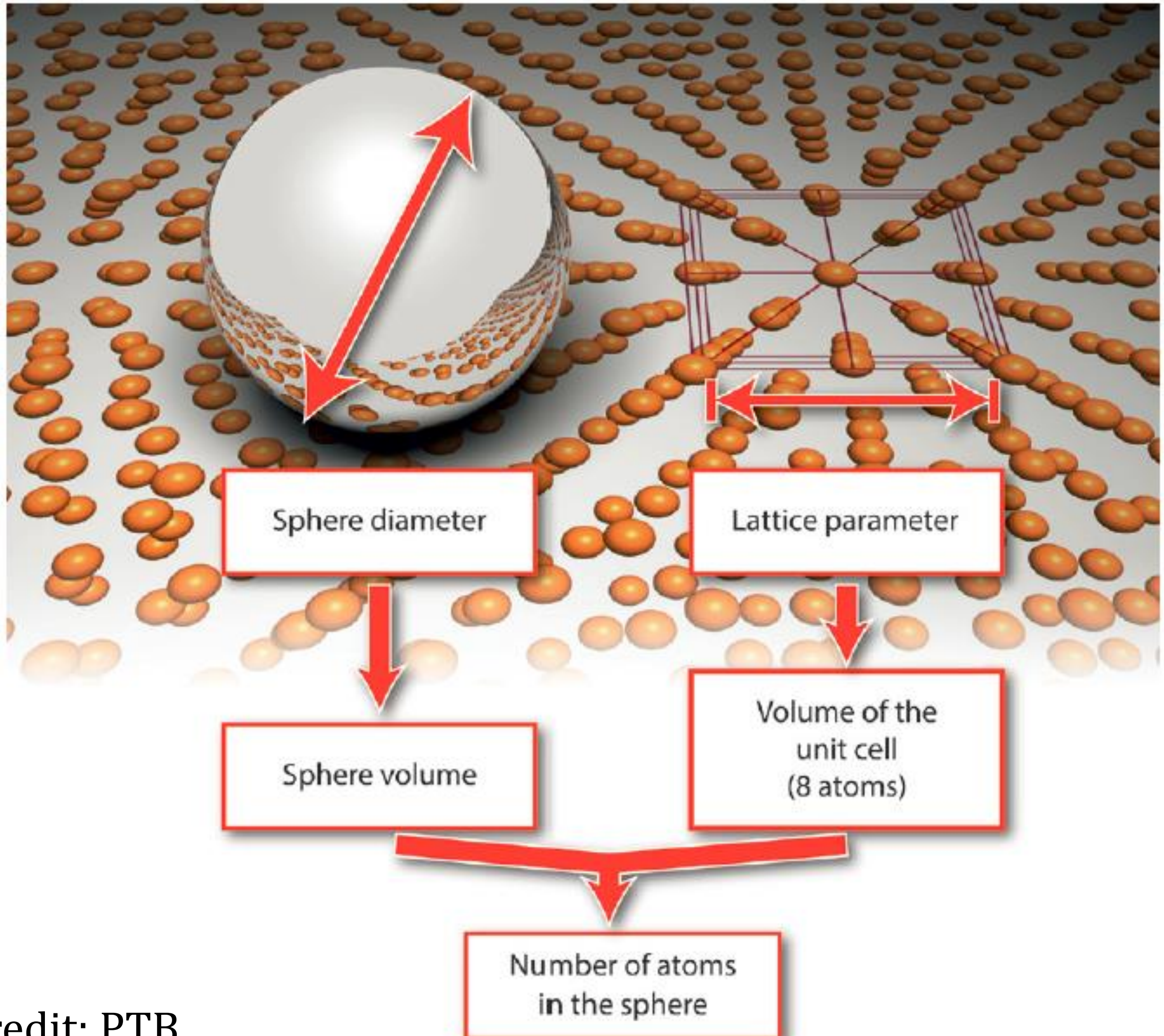
- Avogadro's constant N_A and Planck's constant h related via molar Planck's constant $N_A h$ = 3.9903127110(18)×10^{-10} Js/mol (rel. measurement uncertainty of 4.5 × 10^{-10})

$$N_A h = \frac{M_u \, c\alpha^2}{2R_\infty} A_r^e$$

M_u = molar mass constant
α = fine-structure constant
R_∞ = Rydberg constant
A_r^e = relative atomic mass of electron

- Rydberg constant, speed of light and fine-structure constant determined with much higher accuracy than Planck's constant

- number of atoms in a silicon sphere



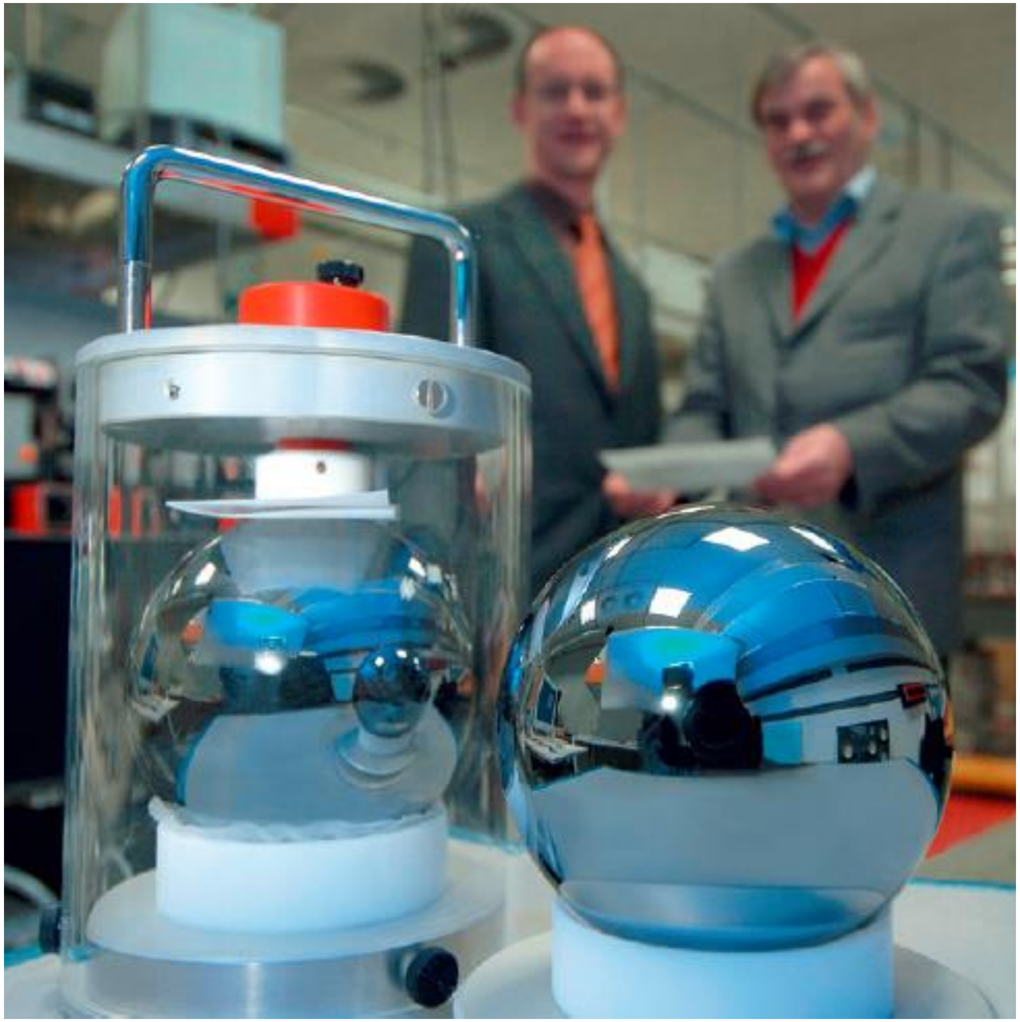
credit: PTB

1). number of atoms determined from sphere volume and volume of the unit cell
2). sphere weighed once, determining the mass of a silicon atom

Problems:

- disturbing SiO_2 “coat”
- crystal temperature to be known within 0.001 K (lattice expansion)
- atomic masses of ^{28}Si, ^{29}Si and ^{30}Si must be linked to ^{12}C, the reference value for atomic masses (Penning trap)

- international Avogadro project (2004 – 2011)



credit: PTB

- impurities: X-ray interferometry
- oxidized surface: X-ray fluorescence analysis and many other techniques
- sphere volume: optical interferometry using spherical waves (e.g. PTB Germany) or plane waves (e.g. NMIJ Japan)
- sphere mass: both air and vacuum weighing using special artefacts derived from the 1 kg prototype
- each sphere price ~1 M€

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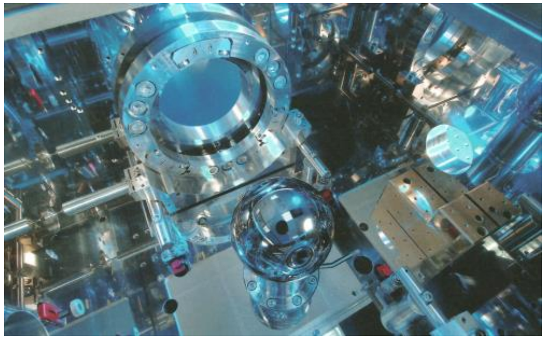
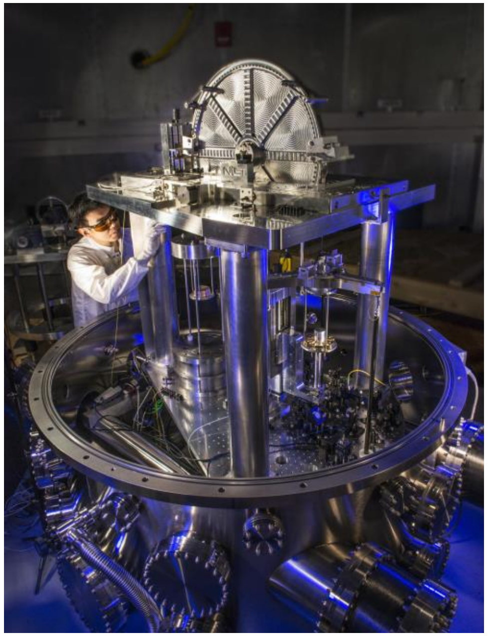
- two different methods for realization of the kilogram



  - **silicon sphere** (first experiments at PTB, Germany) – see the “new”mole realization



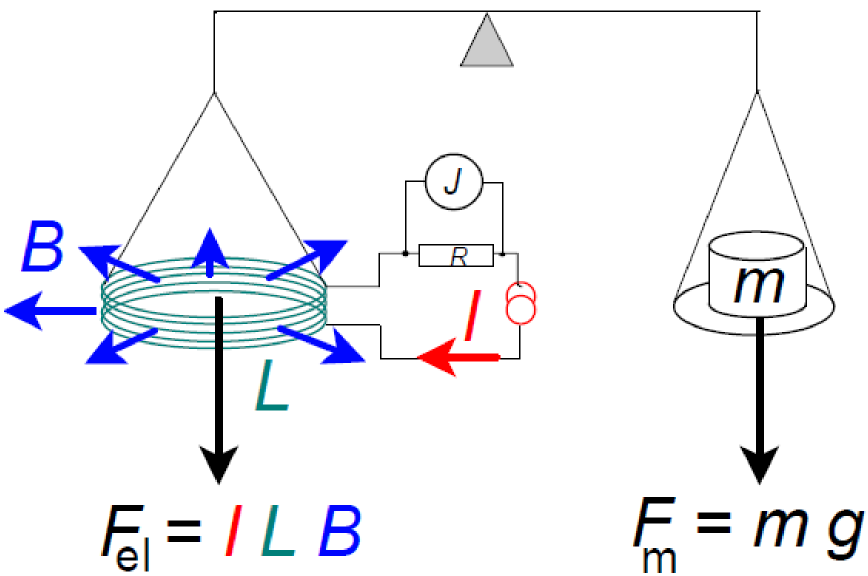
  - **watt balance** (first experiments at NPL, United Kingdom, and NIST, USA), experimental method of linking electric quantities to the kilogram, the meter and the second

  - both reached relative uncertainty of $\sim 2\times10^{-8}$

credit: PTB, NIST

- **watt balance** – Brian Kibble (1970s) had an idea of an improved current balance
  - 1st test: force which acts on a current-carrying conductor in a magnetic field is compared to the weight force of a mass standard
  - 2nd test: the same arrangement, the electric conductor is moved in the magnetic field and thus a voltage between its ends is generated
  - if the equations of these two tests are combined (magnetic induction eliminated), a relationship between current, voltage, mass, gravitational acceleration and speed is created – quantities which can be measured with much higher accuracy than the magnetic induction
  - first experiments NPL (UK), NIST (USA), later METAS (Switzerland) and other institutes joined the race; the same principle realized using different setups
  - extreme experimental effort to achieve consistent rel. unc. $\sim 2 \times 10^{-8}$
  - great legacy of B. Kibble (1938-2016) – **Kibble balance**

Phase 1: static experiment (weighing mode)



Ampere's Law

$$mg = -I\frac{d\Phi}{dz}$$

In a radial magnetic field, this can be simplified to

$$m\ g = I\ L\ B$$

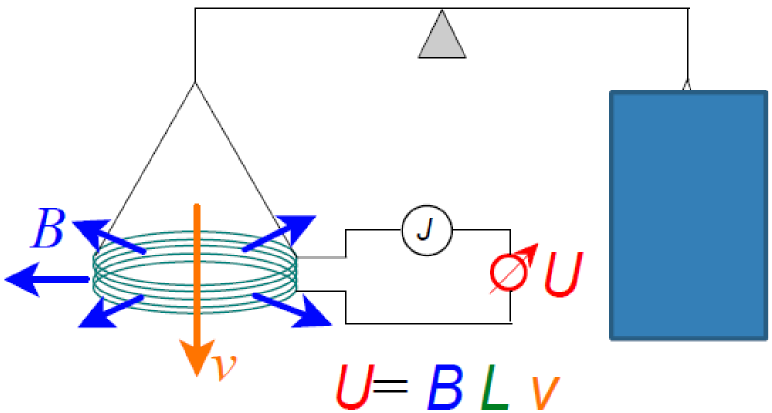
current

wire length

flux density

credit: BIPM

Phase 2: dynamic experiment (moving mode)



Faraday's Law

$$U = -\frac{d\Phi}{dt} = -v\frac{d\Phi}{dz}$$

In a radial magnetic field, this can be simplified to

$$U = B\,L\,v$$

ind. voltage, flux density, wire length, velocity

Coil is moved through the magnetic field and a voltage is induced.

$$m\,g = I\,B\,L$$

$$U = v\,B\,L$$

$$U\,I = m\,g\,v$$

both sides of the equation unit watt

credit: BIPM

- electrical quantum effects: $U \sim h/e$, $R \sim h/e^2$

$$\frac{f}{U} = \frac{2e}{n_1 h} \qquad R = \frac{h}{n_2 e^2}$$

n_1, n_2 = integer quantum numbers
f = frequency of the Josephson device

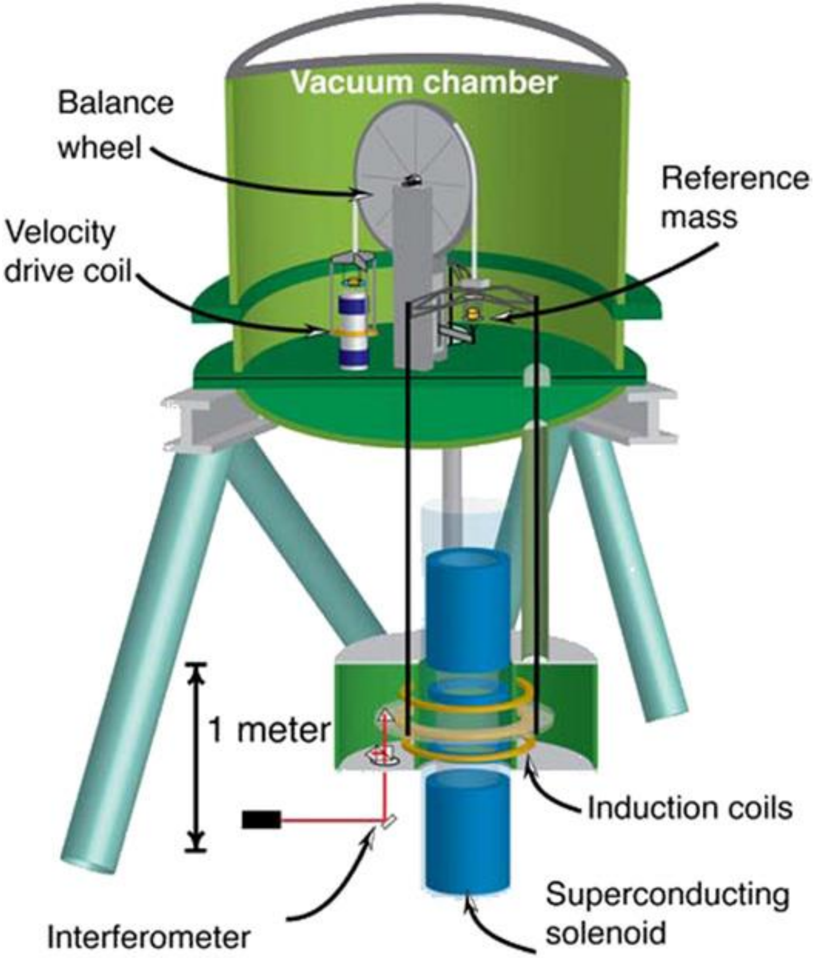
$$h = \frac{4mgf}{f_g f_m}$$

setting $n_1 = n_2 = 1$
f_g = microwave frequency of the voltage meas. in the gravitational mode
f_m = dtto in the moving coil mode

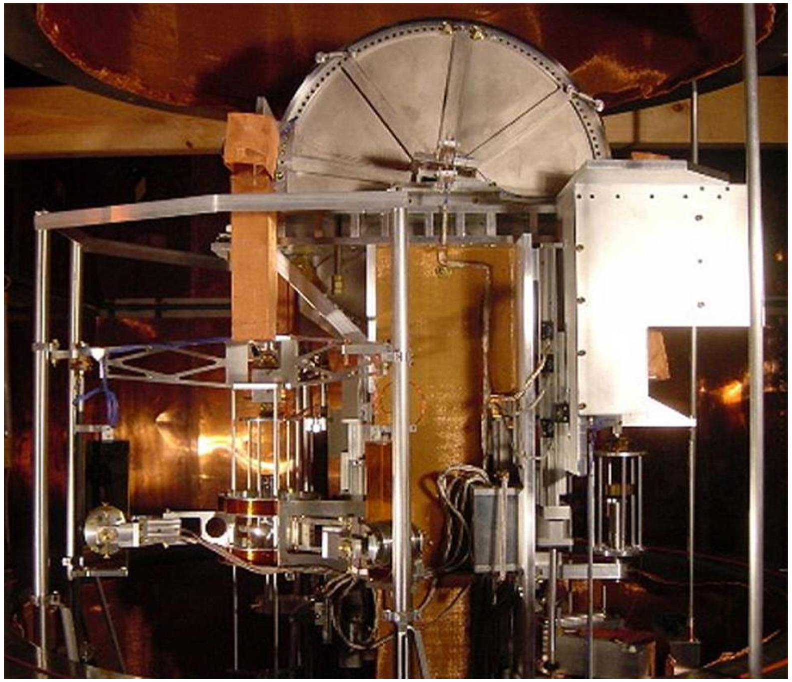
the watt balance enables the measurement of Planck's constant h

M. Gläser, M. Borys, Rep. Prog. Phys. **72** (2009) 126101

- different setups of the watt balance – NIST (USA)

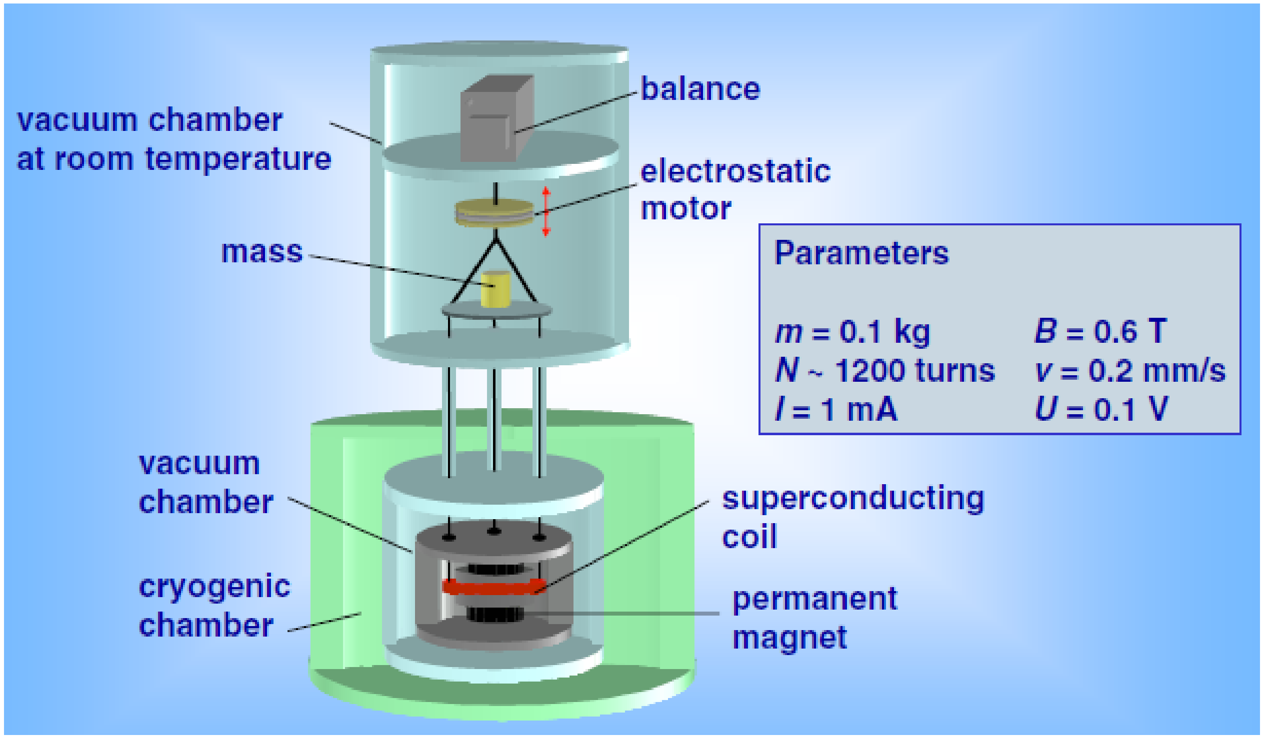


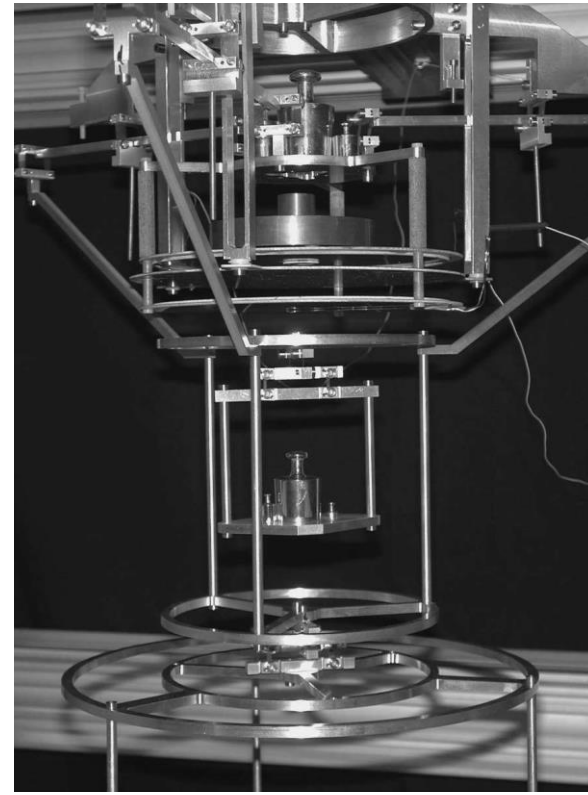
- superconducting magnet generates the magnetic field
- Michelson interferometer provides the velocity



https://www.nist.gov/publications/details-1998-watt-balance-experiment-determining-planck-constant

- different setups of the watt balance – BIPM (France)





- moving coil mode and gravitational mode combined into single mode
- mass of other weights – chain of comparison measurements
- comparison with the international 1 kg prototype provided as well

A. Picard, *et al.*, The BIPM Watt Balance, *IEEE Trans. Instrum. Meas.* **56** (2007) 538-542

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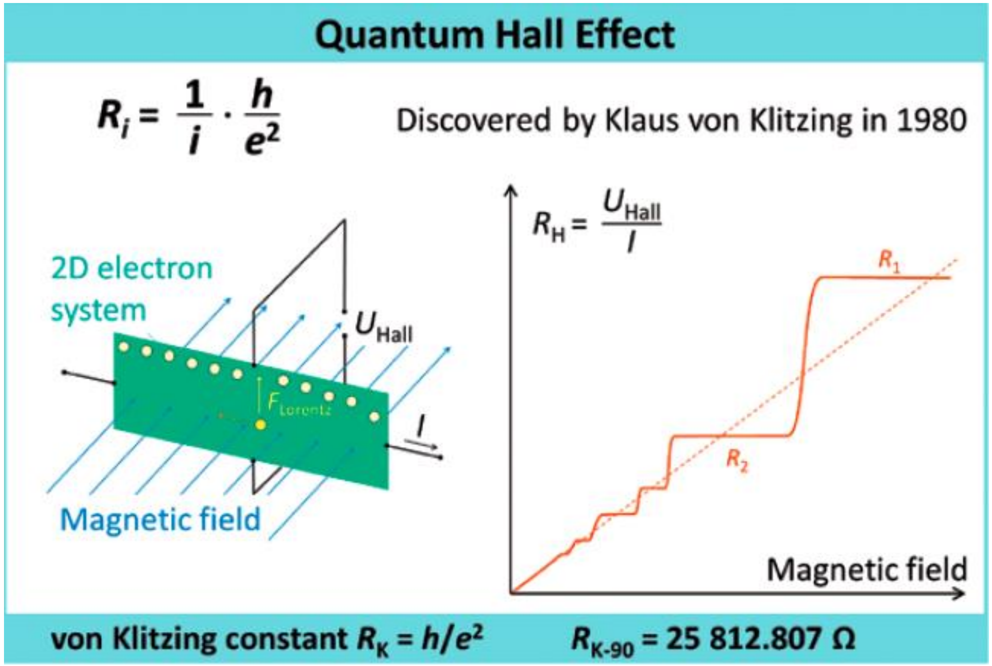
- the ampere realized by two procedures compatible with each other
  - Ohm's law $U = R\,I$, current I determined by measuring R using the quantum Hall effect and the U using the Josephson effect (better suited for generation of "high" currents pA – µA)
  - electronic circuit that measures the electric current by counting the electrons that pass the circuit in a certain time interval, traced to elementary charge e and the caesium frequency $\Delta\nu_{Cs}$ (better suited for "low" currents fA – pA)

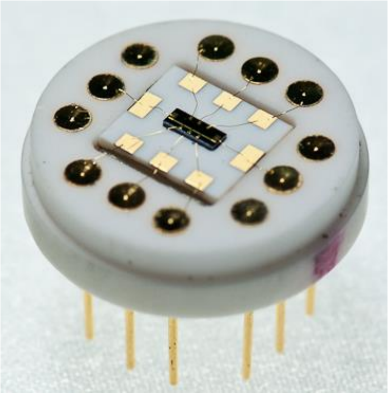
- the ampere realized using Ohm's law

quantum Hall effect



credit: PTB

T = 0.35 K (helium)
R_H = 25812.807 Ω (and its integer divisors)
B ~18 T (n=1)
B ~10 T (n=2) etc.

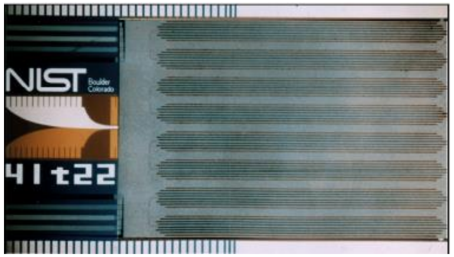


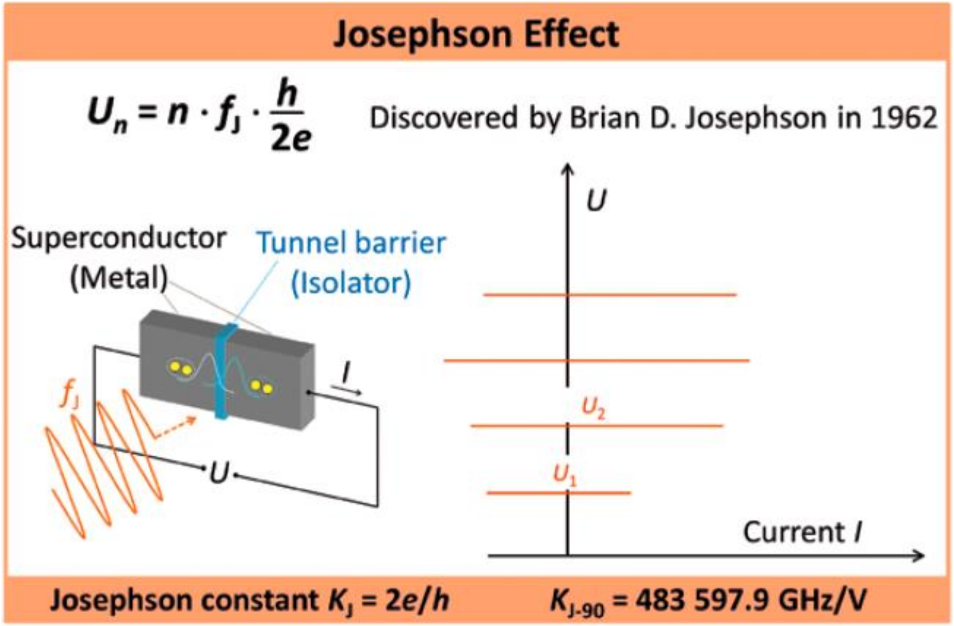
credit: CMI

- the ampere realized using Ohm's law

Josephson effect – weakly coupled superconductors, tunnel junction

T = 3.6 K (helium)





credit: PTB

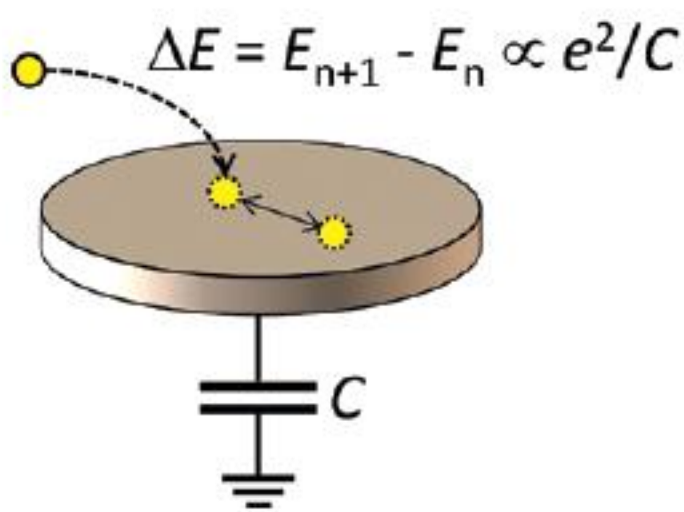
external magnetic field (alternating current) is applied to the structure, which creates precise voltage (U -> f conversion)

credit: CMI

- the reproducibility of the quantized voltage and resistance values was better than the accuracy with which the unit of the ampere could be realized -> $K_{J\text{-}90}$ = 483 597.9 GHz/V and $R_{K\text{-}90}$ = 25 812.807 Ω established in 1988
- since 1990s – ampere realized using QHE and JE was not treated as *realization* of the unit, but only as a *reproduction* (leaving SI)
- new SI – an elegant way out:

The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge e to be 1.602 176 634 × 10^{-19} when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{Cs}$.

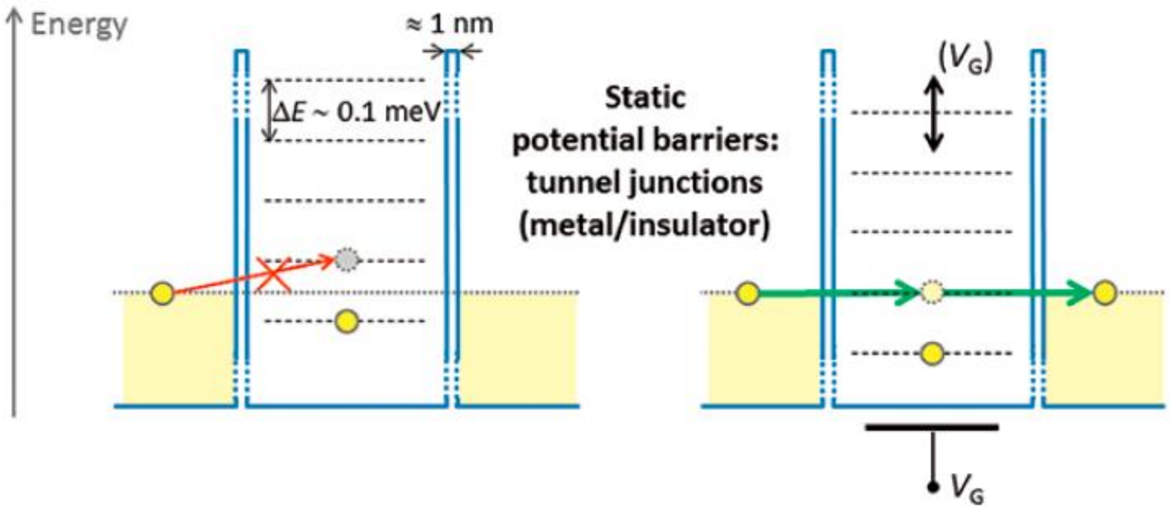
- second realization of **the ampere**: new definition based on flux of electric charge -> electronic circuit needed to transport single electrons in a controlled way, $I = n \cdot e \cdot f$
- *single-electron transport* developed since 1980s



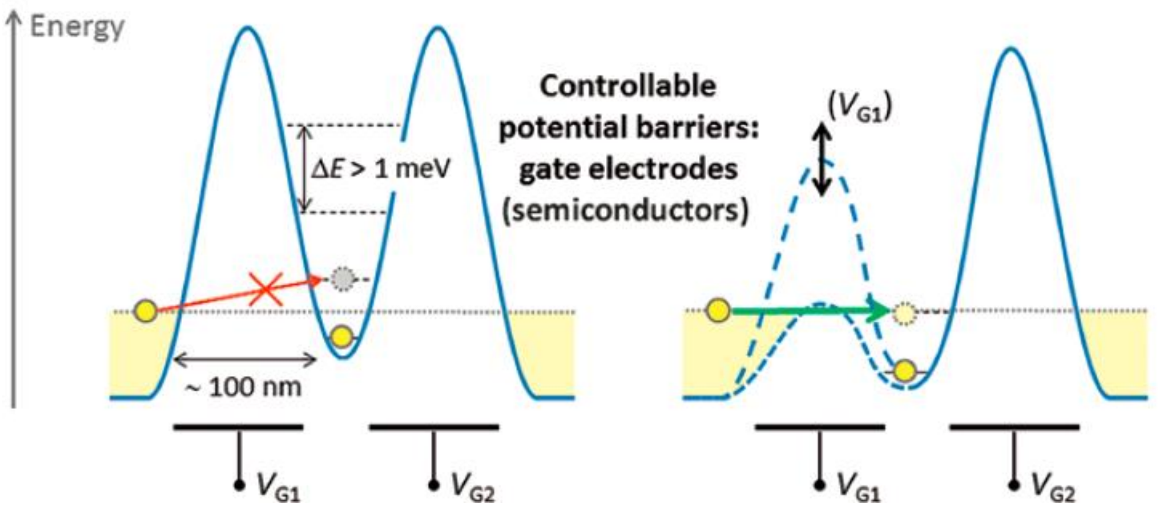
- adding electron to a conductor -> energy must be applied
- the smaller the “charge island”, the more energy needed
- low temperatures (0.1 K for 1 μm structure) -> Coulomb blockade, the added energy cannot be applied by means of thermal excitation

credit: PTB

electrons "trapped" (localized) by means of potential barriers using nanotechnology semiconductors; potential barriers can be generated perpendicularly to the current flow



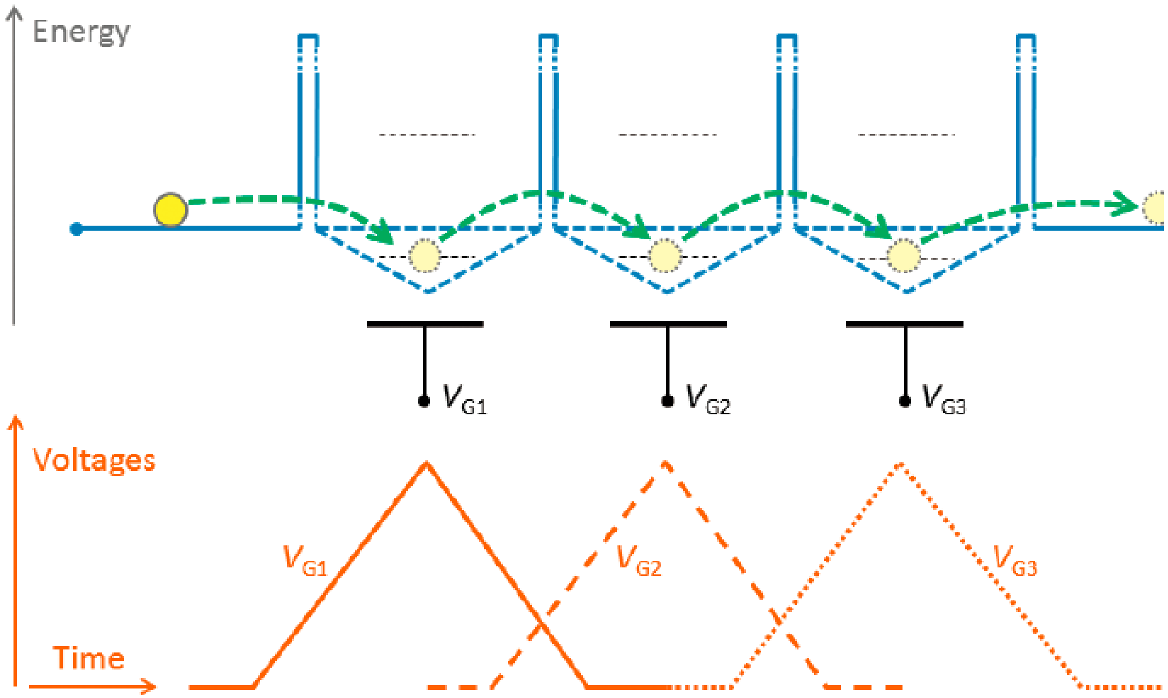
1). tunnel junctions (thin insulator layers in a conductor)

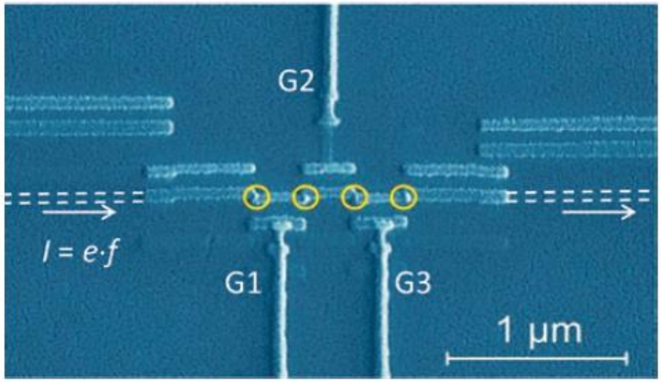


2). quantum dots, controllable potential barriers in semiconductors

credit: PTB

- single-electron pumps used to transport single electrons in a controlled manner





credit: PTB

currents typically < 100 pA

- all three voltages zero -> no electrons can flow
- stream of voltages sent across gate electrodes -> electrons travelling from island to island
- due to statistics – some tunneling occurs missed for f > 100 MHz -> more advanced SETs with controllable potential barriers exist

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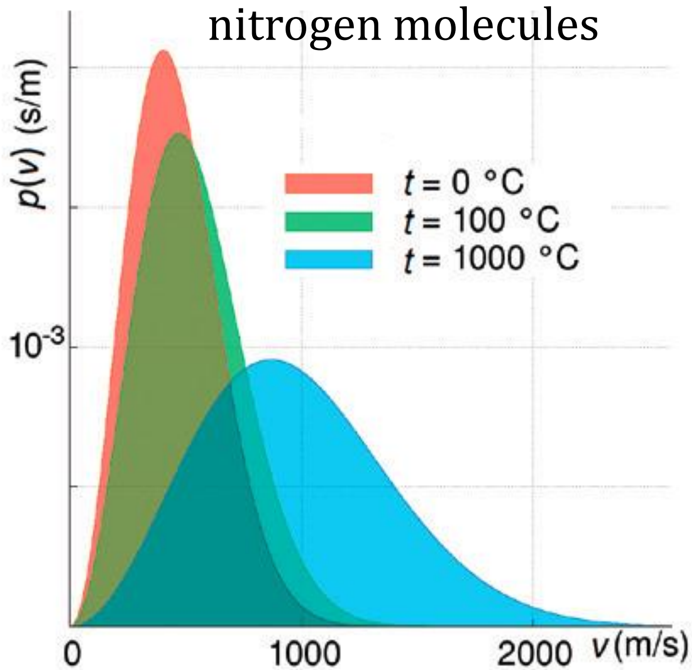
- Maxwell-Boltzmann velocity distribution



particle speeds probability distribution in idealized gases

quantity which is characteristic of the distribution is the mean microscopic thermal energy kT

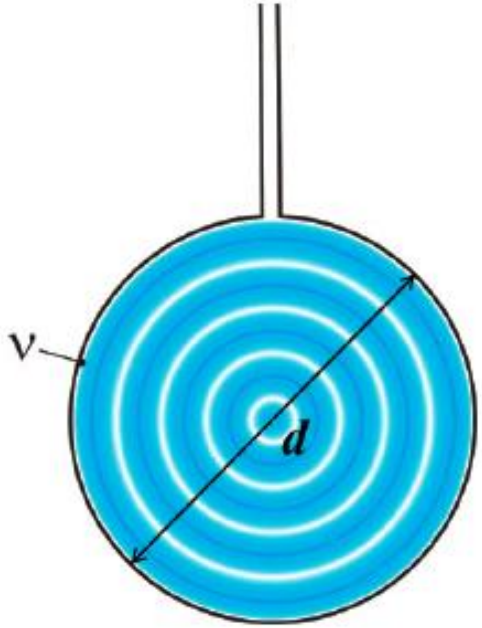
fixing k, **the kelvin** will be linked to the unit of energy, joule

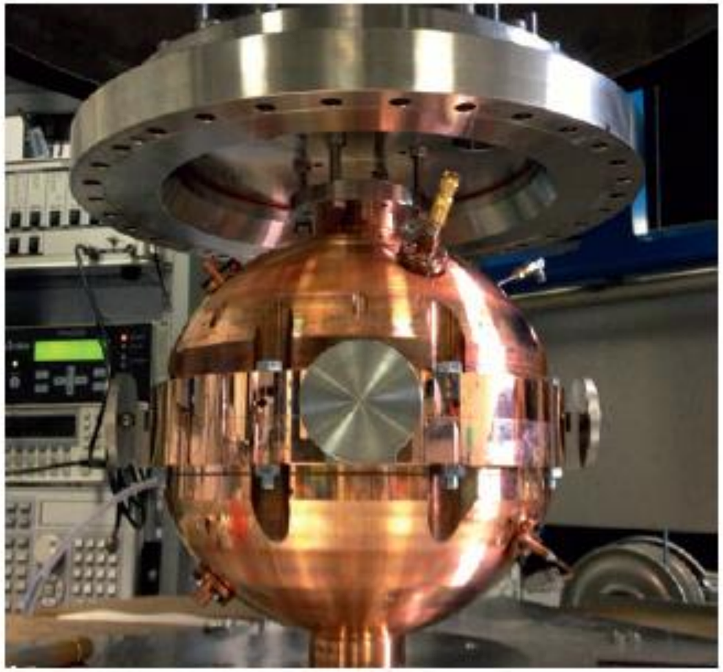
microscopic thermal energy kT not directly accessible -> macroscopic quantities correlated with the thermal energy must be measured

- several "primary" thermometer principles (do not require calibration), two of them explained here

Thermometer	Law of Physics	Relative Standard Uncertainty
Acoustic gas thermometer	$u_0 = \sqrt{\frac{\gamma_0 RT}{M}}$	$1 \cdot 10^{-6}$
Dielectric-constant gas thermometer	$p = kT\frac{(\varepsilon - \varepsilon_0)}{\alpha_0}$	$2 \cdot 10^{-6}$
Refractive index gas thermometer	$p = kT\frac{(n^2 - 1)\varepsilon_0}{\alpha_0}$	$10 \cdot 10^{-6}$
Johnson noise thermometer	$\langle U^2 \rangle = 4kTR_{el}\Delta\nu$	$2 \cdot 10^{-6}$
Doppler broadening thermometer	$\Delta\nu_D = \sqrt{\frac{2kT}{mc_0^2}}\nu_0$	$10 \cdot 10^{-6}$
Spectral radiation thermometer	$L_\lambda = \frac{2hc_0^2}{\lambda^5}\left[\exp\left(\frac{hc_0}{\lambda kT}\right) - 1\right]^{-1}$	$50 \cdot 10^{-6}$

- acoustic gas thermometer
  - the temperature-dependent speed of sound is measured in a gas; this speed of sound is proportional to $(k_BT)^{1/2}$
  - speed of sound of noble gases measured using a spherical resonator
  - problems: purity of the meas. gas, extrapolation to zero pressure, position of acoustic transducers and receivers





credit: PTB

M. Moldover, *et al.*, Acoustic gas thermometry, *Metrologia* **51** (2014) R1–R19

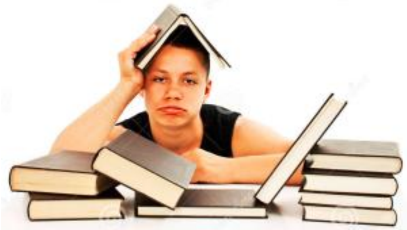
- dielectric constant gas thermometer
  - determining at a constant temperature the pressure-dependent density of helium with reference to its dielectric constant
  - polarizability of the helium calculated with rel. unc. $<10^{-6}$ in the last years; as the polarizability is low, the ε is measured from the relative change of capacitance of a capacitor filled with helium (p = 7 MPa) and evacuated
  - problems: deformation of the capacitor due to pressure

credit: PTB

C. Gaiser, *et* al., Dielectric-constant gas thermometry, *Metrologia* **52** (2015) 217–226

- Introduction - SI history
- The need for change of SI units
- Preparations for change
  - the mole
  - the kilogram
  - the ampere
  - the kelvin
- **Consequences for users**
- RF electrical quantities
  - CMI national standards
  - future “quantum realizations”

- main consequences
  - the last artefact (1 kilogram) will be replaced
  - triple point of water will become experimentally determined
  - mole will no longer link to mass (role of ^{12}C ends)
- consequence for "normal" users – **none**, the uncertainties far below commercial measurement systems
- consequence for students – rewritten textbooks



- consequences for high-precision measurements
  - K_J will change by ~0.1 ppm
  - R_K will change by ~0.02 ppm
  - μ_0 and ε_0 will become experimentally determined
- should be sufficient at least for the 21st century, unless...
  - much better atomic clocks will be developed
  - new quantum effects will be discovered
  - new physical theories discovered

- likely shifts in the values of the SI electrical units with respect to those based on the 1990 values

Quantity	Formula for SI Unit	Relative Change
voltage	$V = V_{90}\ [1 - (100 \times 10^{-9})]$	-100 ppb
resistance	$\Omega = \Omega_{90}\ [1 - (17 \times 10^{-9})]$	-17 ppb
current	$A = A_{90}\ [1 - (83 \times 10^{-9})]$	-83 ppb
charge	$C = C_{90}\ [1 - (83 \times 10^{-9})]$	-83 ppb
power	$W = W_{90}\ [1 - (183 \times 10^{-9})]$	-183 ppb
capacitance	$F = F_{90}\ [1 + (17 \times 10^{-9})]$	17 ppb
inductance	$H = H_{90}\ [1 - (17 \times 10^{-9})]$	-17 ppb

N. Zimmermann *et al.*, The Redefinition of the SI: Impact on Calibration Services at NIST, *NCSLI Measure J. Meas. Sci.*, vol. 10, no. 2, 2015

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- in the RF/microwave frequency range (~MHz to hundreds of GHz), various derived SI units are used
  - RF power ($W = m^2 \cdot kg \cdot s^{-3}$)
  - electric field strength ($V \cdot m^{-1} = m \cdot kg \cdot s^{-3} \cdot A^{-1}$)
  - impedance ($\Omega = m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$)
  - etc.

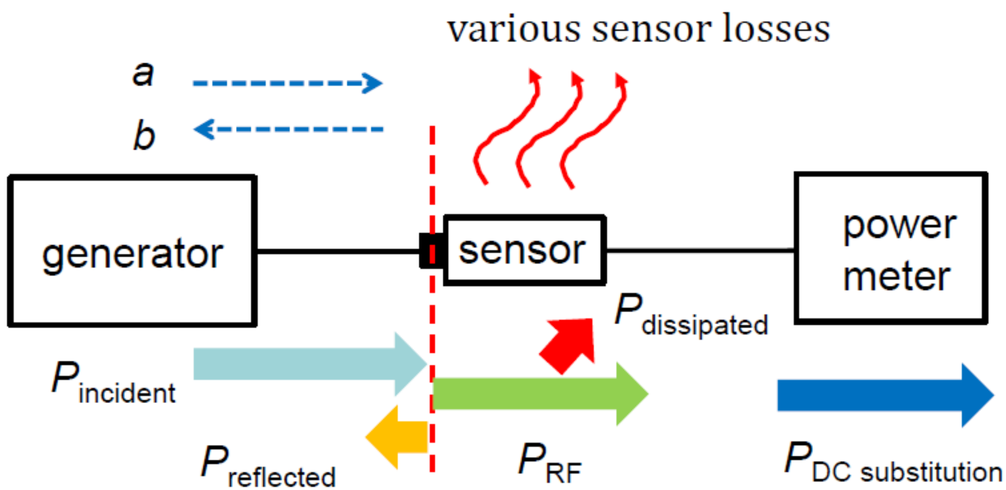
- CMI, Dept. of primary metrology of RF electrical quantities, maintains 3 national standards:
  - RF power standard DC to 50 GHz (secondary realization)
  - RF field strength standard 50 kHz to 18 GHz (primary realization)
  - reflection and transmission coefficient standard 100 kHz to 40(50) GHz (primary realization)

- measurement of RF power

microcalorimeter
100 kHz – 18 GHz
(TÜBITAK UME)

effective efficiency

$$P_{RF} = \frac{P_{DC}}{\eta_e}$$

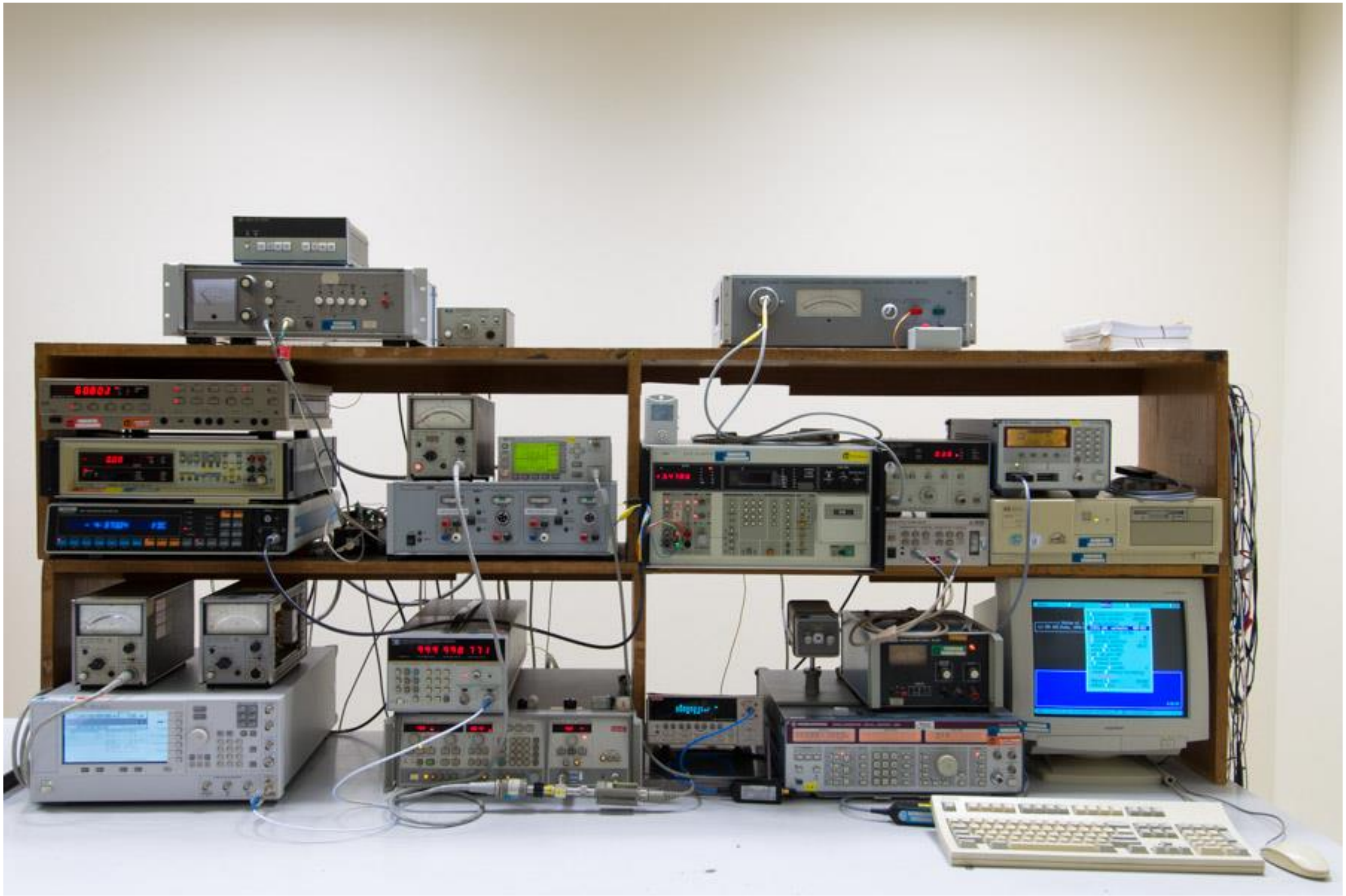


calibration factor

$$CF = \eta_e(1 - |\Gamma|^2)$$

- measurement of RF power

overview of the CMI's RF power standard, DC to 50 GHz

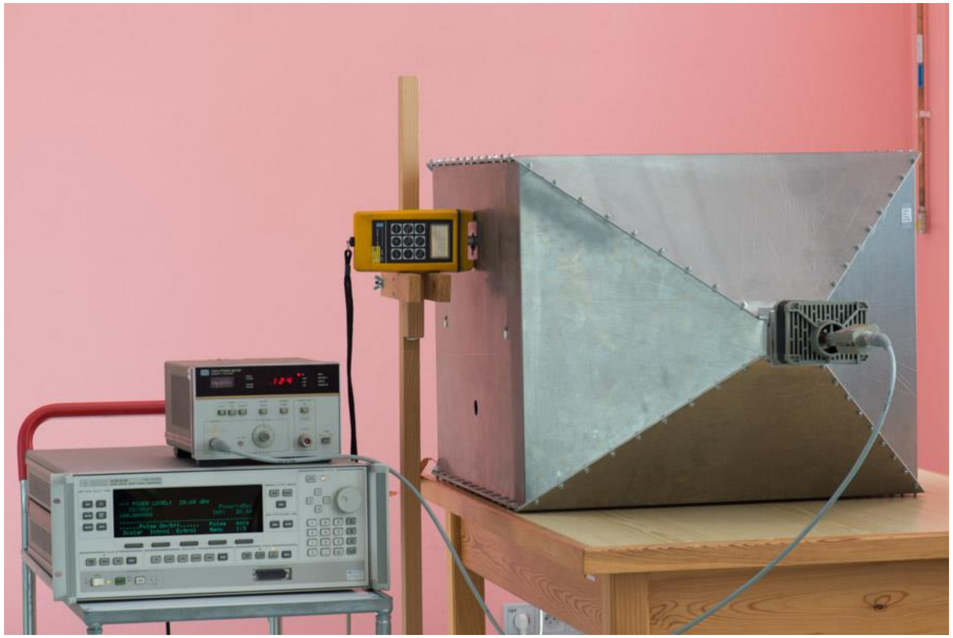


- measurement of RF power

power sensors for the range (0 to 40) GHz

CMI has no microcalorimeter, traceable to PTB (Germany) and NPL (UK)

- measurement of electromagnetic field strength
  - generating field: chamber or transmission line with calculable field distribution (intensity)
  - measurement of E: usually based on 3-axis diode sensor, best uncertainty ~(5-10) %, perturbs the measured field



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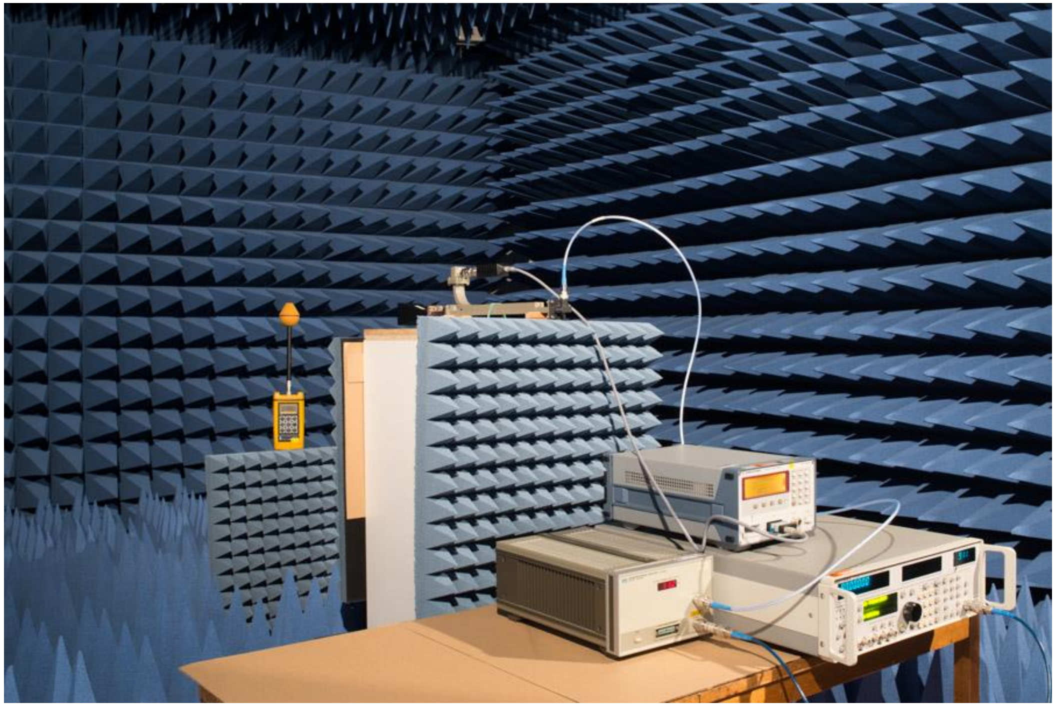
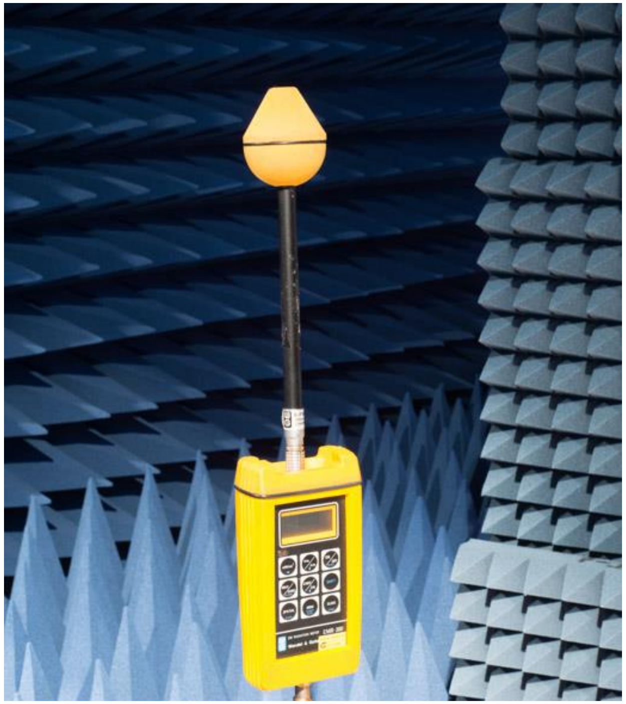
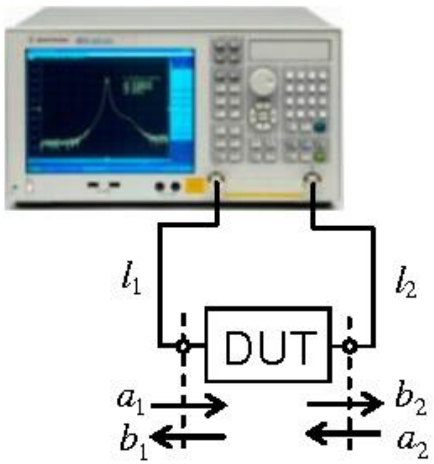
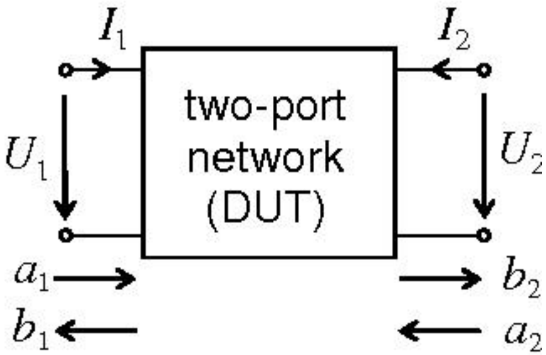


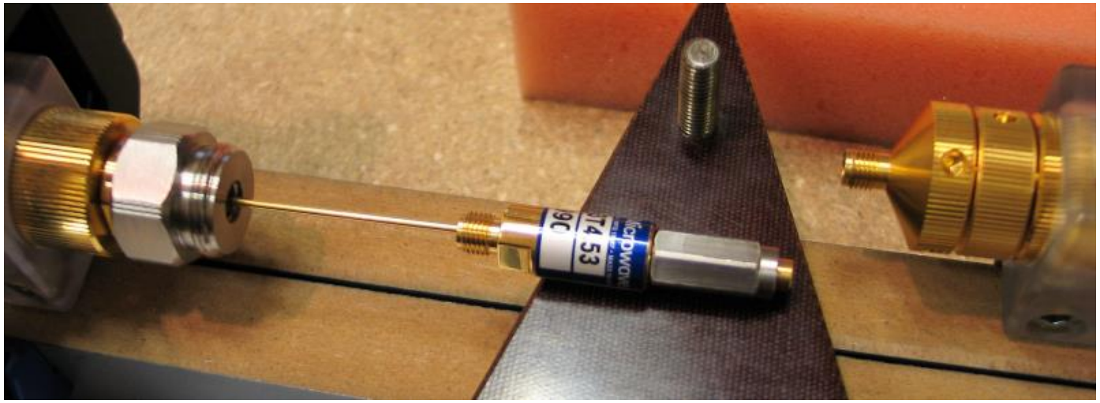


- measurement of transmission/reflection coefficient
  - precise air lines (coaxial or waveguide) and short-circuited section of transmission lines + convenient calibration method comprise the primary standard of impedance (reflection coefficient)
  - characteristic impedance of the air lines and the phase of the short-circuited transmission line calculated from their geometrical dimensions
  - measurements using a vector network analyzer (VNA); at high frequencies S-parameters are used





- measurement of transmission/reflection coefficient
  - many factors to be taken into account when calculating the characteristic impedance
    - surface roughness
    - conductivity
    - outer/inner diameter
    - bending of the line
    - reference plane



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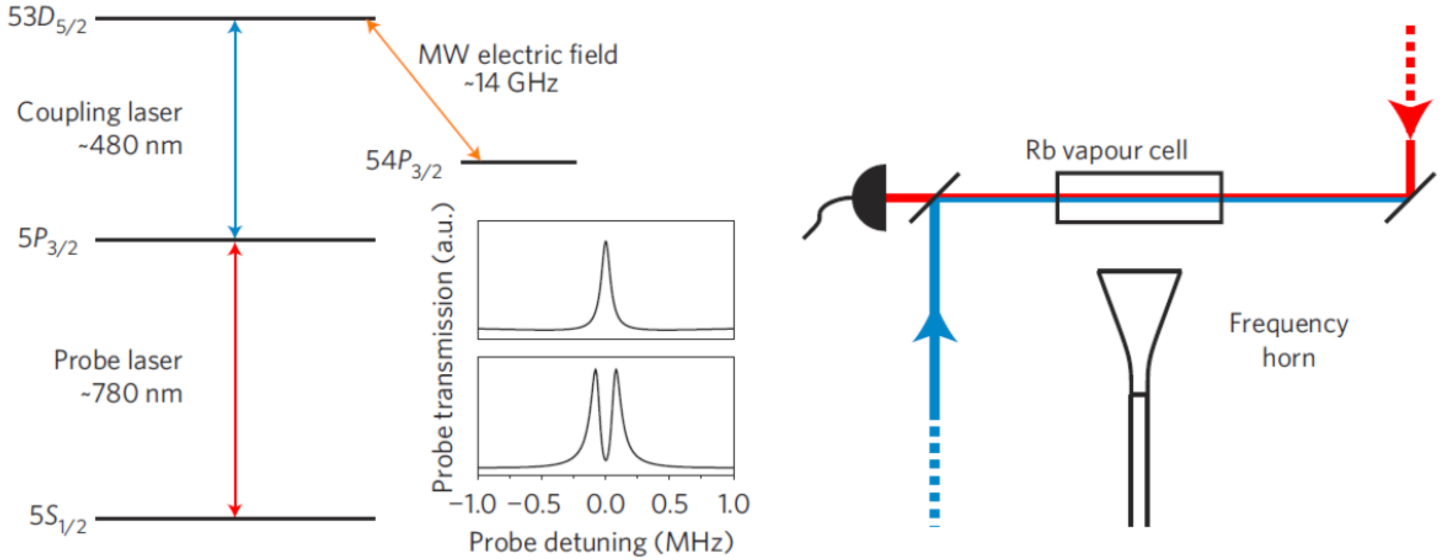
future “quantum realizations”

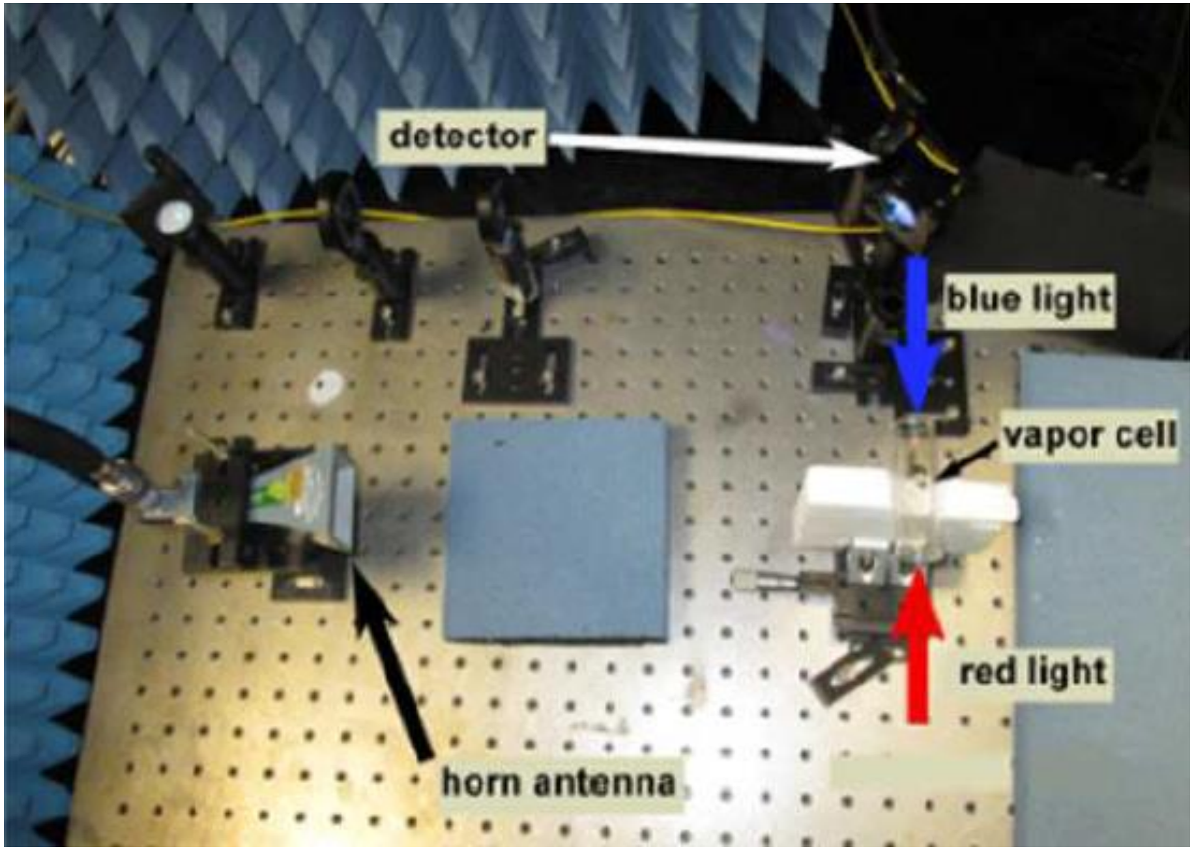
- redefinition of SI – intensive research of other primary realizations of RF power and E/H field strength
- usually based on interaction of optically excited atoms with electric/magnetic field, certain physical effects dependent on the E/H field intensity

- E-field: Rydberg atoms
  - optical excitation of gas vapor in a glass chamber
  - Rydberg gas – extremely excited state of matter, the valence electron is much farther from the nucleus than normally; such atoms are extremely sensitive to external E field
  - measurement of optically induced quantum interference (optically transparent material)



J. A. Sedlacek *et al.*, *Nature Physics*, **8** (2012) 819-824

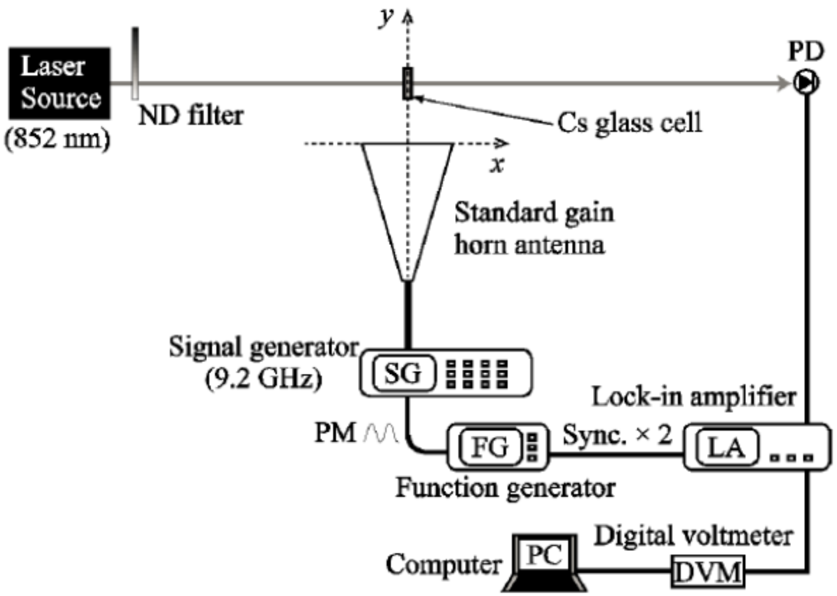
- E-field: Rydberg atoms

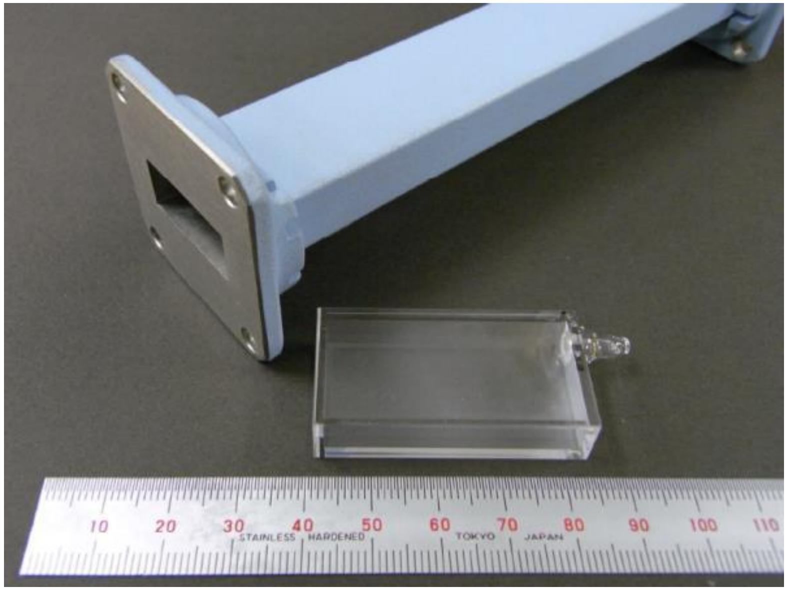


C. L. Holloway *et al.*, *IEEE Trans. Ant. Propag.* **62** (2014) 6169-6182

- currently available in NIST (USA), NIM (China), AIST (Japan)
- traceable to *h* (Planck constant)
- many technical problems (temperature, reflections inside the gas chamber)
- isotopes of ^{87}Rb, ^{133}Cs used
- very simple traceability chain in contrast to conventional diode E-field probes
- E-field ~(1 – 500) GHz, sensitivity 0.01 mV/m

- H-field: Rabi oscillations
  - atoms with two energetic levels in a magnetic field with the energy corresponding to the difference between the two energy levels → quantum state of the atom is periodically changed (Rabi oscillation with measurable frequency)
  - traceable to *h* (Planck constant), use of ^{133}Cs





M. Kinoshita and M. Ishii, *IEEE Trans. Instrum. Meas.* **66** (2017) 1592-1597

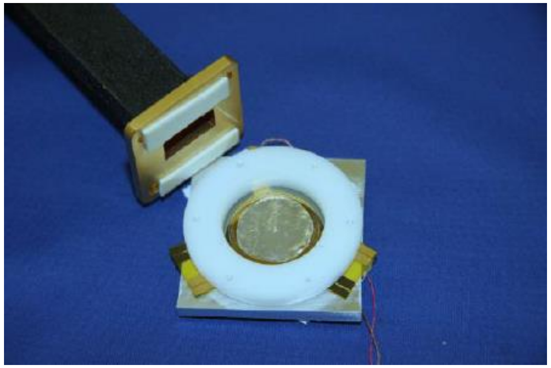
- RF power: radiation pressure
  - photons of light carry a momentum; laser beam reflected from a mirror causes force *F* due to the change of photons' momentum, which is proportional to the optical power *P*

$$F = (2P/c) r \cos\theta \qquad r = R + (1 - R)\alpha/2$$

(*R* is the mirror reflectivity, α is the absorbed portion of light, θ is the angle of incidence)

- in ideal case, the coefficient force/power is 6.67E-9 N/W
- works for both optical and microwave frequencies, traceable to mass (Planck constant *h*)

$$P = \frac{\langle \boldsymbol{E} \times \boldsymbol{H} \rangle}{c}$$



(12 – 18) GHz
power 23 W
force 150 nN

A. Artusio-Glimpse et al. *Proc. of CPEM 2018*, Paris, France (2018)

- RF power: radiation pressure
  - practical experiment – magnetron from a microwave oven (f = 2.45 GHz, power ~1 kW), use of kitchen scale
  - validated by measuring heat capacity of a glass of water

C. L. Holloway *et al.*, *Proc of EMC EUROPE Conference*, Amsterdam (2018)

Similar presentation already given here:

CTU FEE K13117 Departmental seminar (slides in English)
https://elmag.fel.cvut.cz/departmental-seminars-spring-2019/
CES 50th meeting of the Microwave group (slides and text in Czech)
http://web.cvut.cz/ces/mt/SI_jednotky_2019.pdf
http://web.cvut.cz/ces/mt/Hudlicka_Redefinice_SI_web.pdf

Thank you for attention