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Quantum-based Metrology - *The role of quantum technologies in precision methods and standards*

Isabel Godinho | IPQ | 2024-09-12

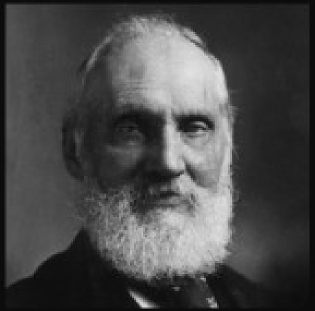
Summary

- National Metrology
- Metrology - *Basic Concepts*
- The *new* SI & The role of quantum technologies in precision methods and standards
- Metrology Research & Development Activities in Quantum Metrology
- Conclusions

Metrology ?

Metrology - science of measurement and its applications

Why measure?



> If you can not measure it, you can not improve it.
>
> ~ Lord Kelvin









Metrology - science of measurement and its applications

Why measure?

Measuring instruments

↓

Metrological regulation

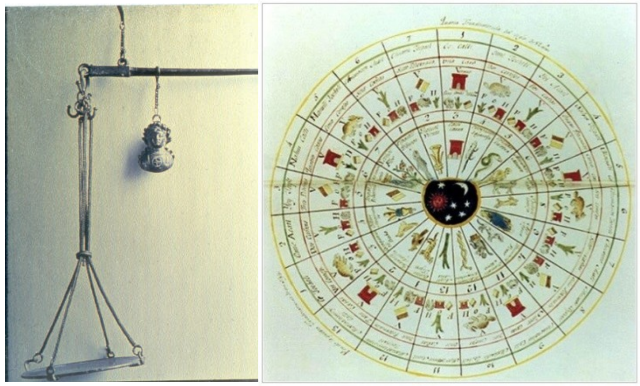
↓

Internationally agreed technical requirements

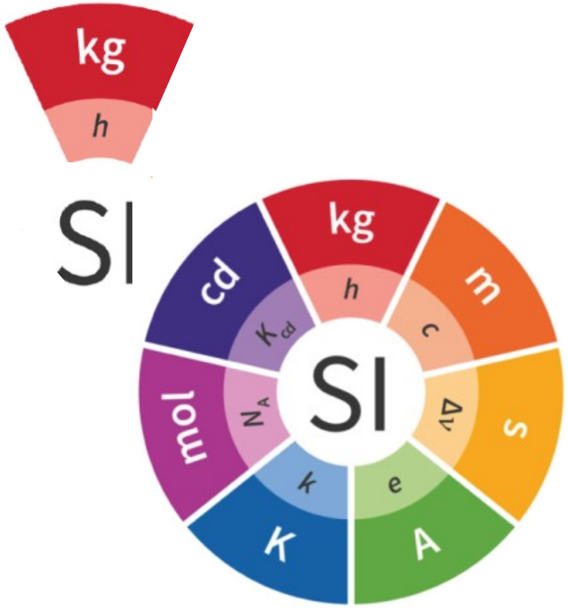
- Eliminate technical barriers in trade
- Ensure fair trade exchanges
- Taking care of the environment, health,...
- Ensure reliable measurements



Metrology - science of measurement and its applications



h = 6,626 070 15 × 10^{-34} J · s



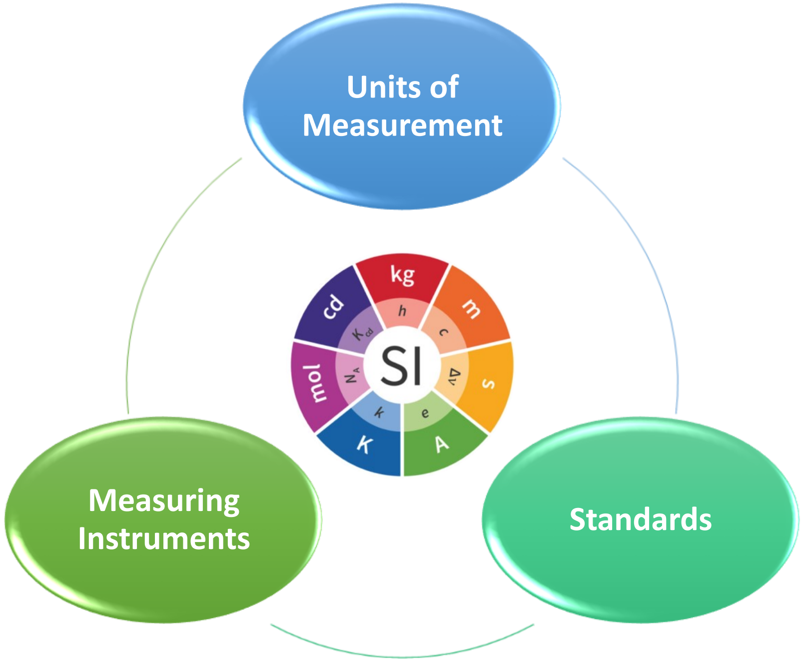
Since ancient times mankind was aware that there are certain quantities that are measurable, i.e., that can be compared

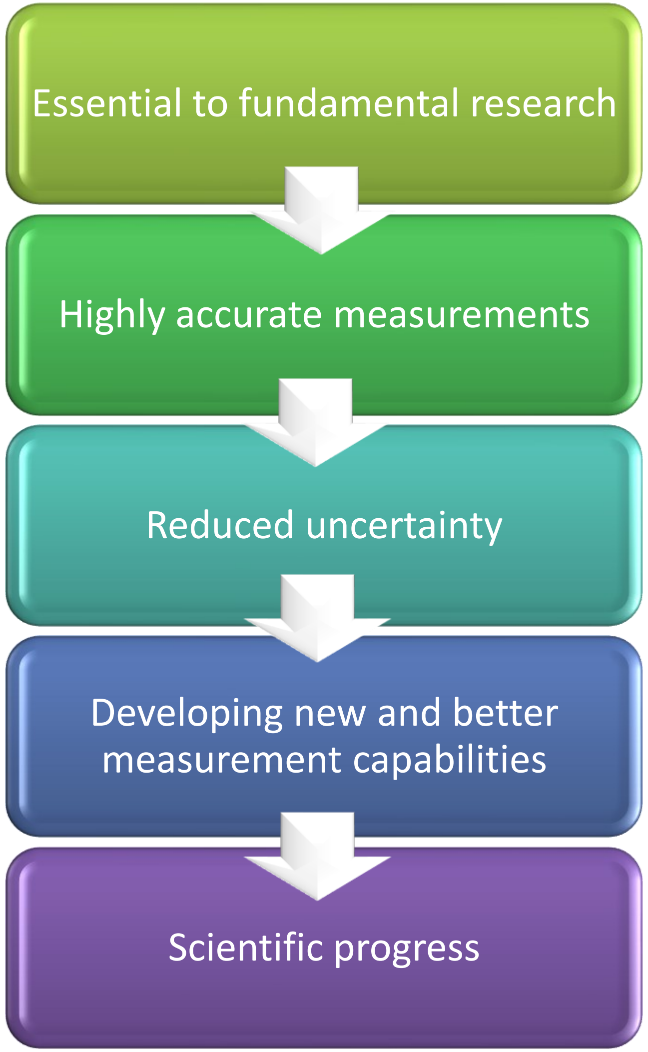
Measurements have been based on artefacts over thousands of years, most prominently, the international prototype of the kilogram, the IPK

In 2018, the General Conference on Weights and Measures, CGPM, abolished all artefacts in a revolutionary decision defining the International System of Units, the SI, by fixing the numerical values of 7 defining constants

Metrology - science of measurement and its applications

Metrology Mission: To assure the **accuracy** and the **traceability** of the measurements in Portugal, realizing the **Constitutional purpose of sovereign national measuring standards** and realizing the **metrological control** of measuring instruments satisfying the Portuguese industrial and society needs.





National Metrology

- Laboratory - 52 technical domains
- Metrology Department staff - 40 people
- 2 200 m^2 Laboratory Area
- 10 000 m^2 Covered Area

IPQ´s responsibilities as the **National Metrology Institution** develops activities in the fields of:

- **Scientific Metrology -** *assures the realization and implementation of the SI units and **national standards***
- **Applied Metrology -** *assures the **national traceability chain** of measurement reference & industrial standards of accredited laboratories*
- **Legal Metrology -** *is the national authority to assure and manage the legal metrological control system of the measuring instruments of current measurements-final users: Pattern Approval, Verification of Speed meters and Breath analysers and Qualification and Coordination of Metrological Verification Entities*

National Metrology Subsystem

IPQ
National de Metrology Institution

Scientific Metrology

NML

IPQ – LNM

DI (IST – LMRI)

DI (IH – LQPM)

DI (UHM – LNEC)

Applied Metrology

IPQ – NML

Accredited Calibration Laboratories NP EN ISO/IEC 17025 and ISO 17034

Legal Metrology

IPQ

DR - Autonomous Regions (Madeira + Açores)

SMM & SCM (Public Metrology Services)

OVM (Metrological Verification Bodies)

R&I (Installers & Repairs)

Meter Convention

Convention du Mètre (1875)
Comité Internacional des Poids et Mesures
Accord de Règlement Mutuel (CIPM - MRA) (1999)

CIPM MRA

- **National Standards**
- **Interlaboratory Comparisons**
- **Quality Management System**
- **150 CMC** (Calibration and Measurement Capabilities)

Portugal signed the **Meter Convention** on 20th May 1875, in the first group of 17 signatory countries

1875 – Convention du Mètre

1984 - OIML

1987 – EURAMET

1990 – WELMEC

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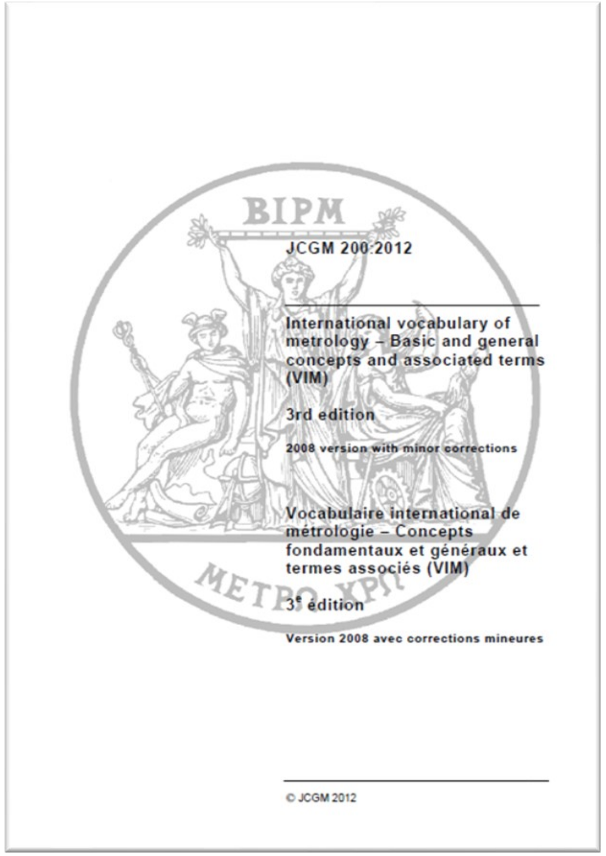
Metrology – Basic Concepts

JCGM Publications: Guides in Metrology

www.bipm.org/en/committees/jc/jcgm/publications

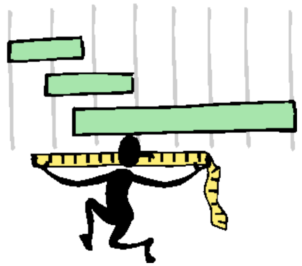
VIM: International Vocabulary of Metrology



GUM: Guide to the Expression of Uncertainty in Measurement

SI Brochure: The International System of Units (SI)

International vocabulary of metrology – Basic and general concepts and associated terms (VIM)



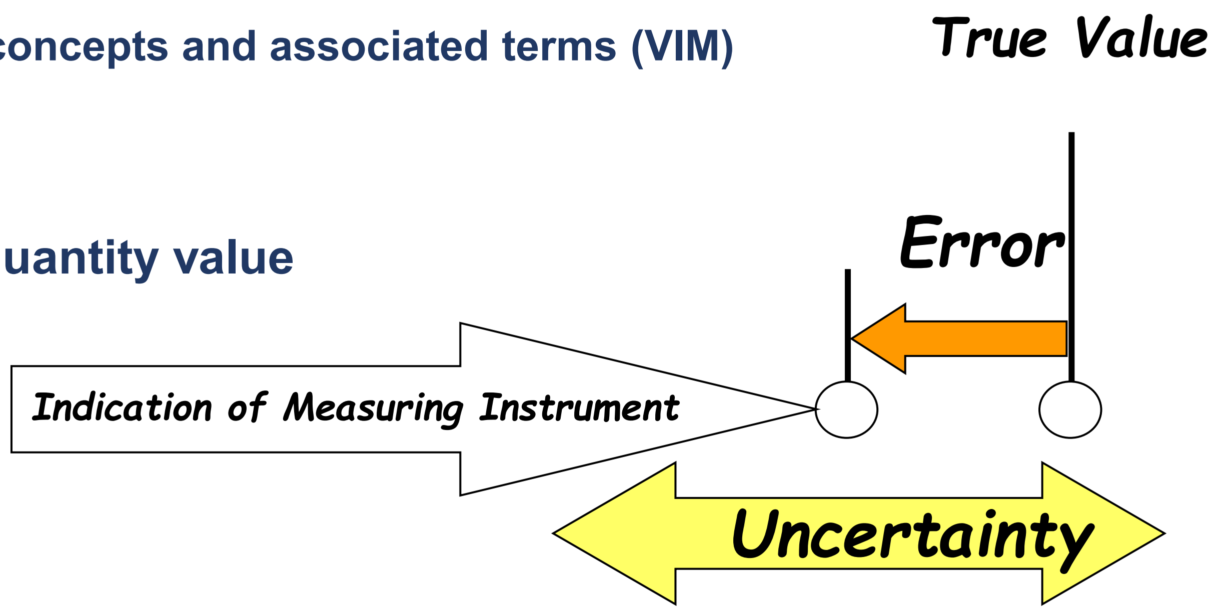
2.1 – **measurement**: process of experimentally obtaining one or more **quantity values** that can reasonably be attributed to a **quantity**

- Measurement does not apply to **nominal properties**.
- Measurement implies comparison of quantities or counting of entities.
- Measurement presupposes a description of the quantity commensurate with the intended use of a **measurement result**, a **measurement procedure**, and a calibrated **measuring system** operating according to the specified measurement procedure, including the measurement conditions.

2.13 - **measurement accuracy:** closeness of agreement between a **measured quantity value** and a **true quantity value** of a **Measurand**

- A measurement is said to be more accurate when it offers a smaller measurement error.

International vocabulary of metrology – Basic and general concepts and associated terms (VIM)



2.16 - **measurement error**

measured quantity value minus a **reference quantity value**

2.17 - **systematic measurement error**

component of **measurement error** that in replicate **measurements** remains constant or varies in a predictable manner

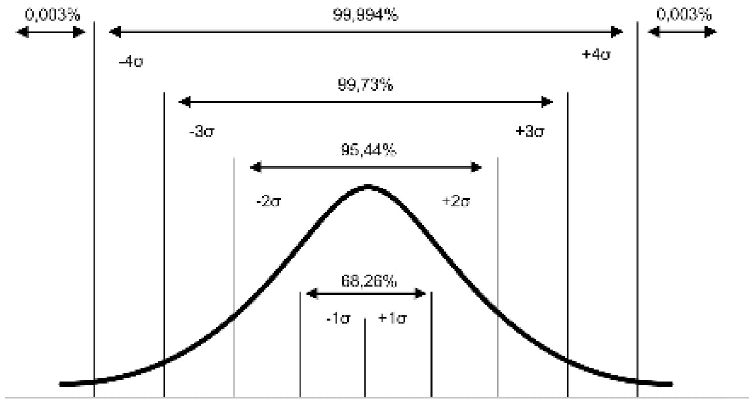
2.19 - **random measurement error**

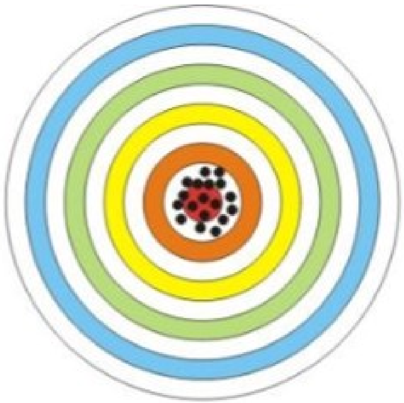
component of **measurement error** that in replicate **measurements** varies in an unpredictable manner

International vocabulary of metrology – Basic and general concepts and associated terms (VIM)

2.26 - **measurement uncertainty**

non-negative parameter characterizing the dispersion of the **quantity values** being attributed to a **measurand**, based on the information used





2.9 - **measurement result**

set of **quantity values** being attributed to a **measurand** together with any other available relevant Information

$$Y = y \pm U$$

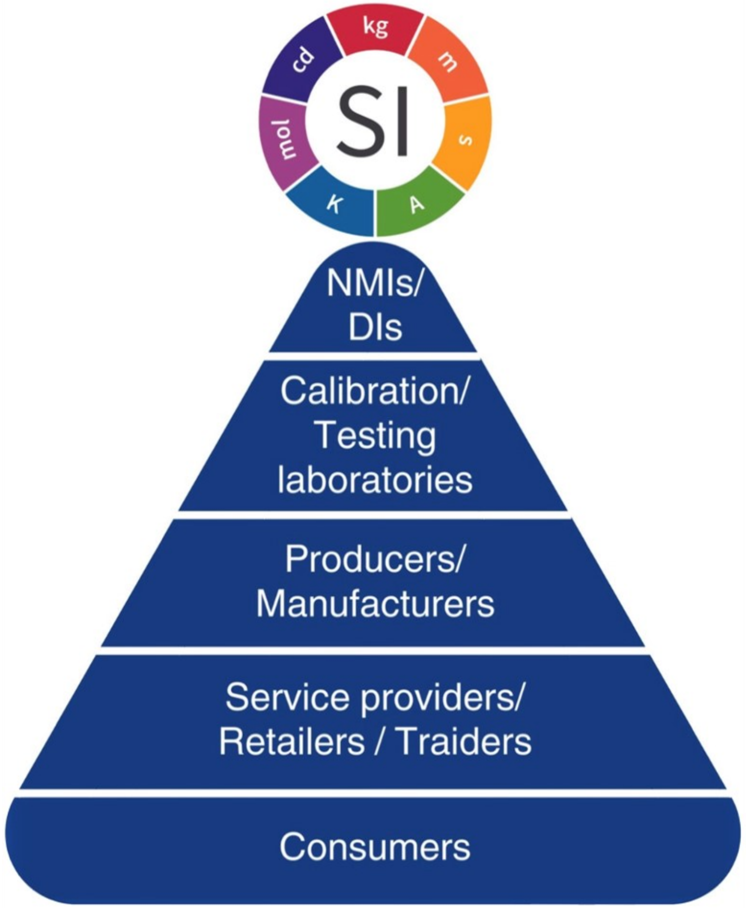
$$m_S = (100{,}021 \pm 0{,}035)\ \text{g}$$

International vocabulary of metrology – Basic and general concepts and associated terms (VIM)

2.16 – **metrological traceability**

property of a **measurement result** whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the **measurement uncertainty** measured quantity value minus a reference quantity value

Metrological traceability requires an established calibration hierarchy.



Traceability chain of reference standards in Portugal

International vocabulary of metrology – Basic and general concepts and associated terms (VIM)

2.16 – **metrological traceability**

The *new* SI

International System of Units

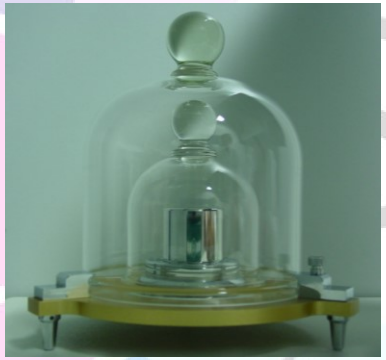
The new International System of Units (SI) **officially approved on November 2018** following 26th General Conference of Weights and Measures (CGPM), the highest body of the Meter Convention of which Portugal is a founding signatory (1875) and **adopted in 20th May 2019**.

- ***New Paradigm Change*** - new definitions use "***explicit constant***" formulation *(instead of "explicit unit")*, which **allows separate the definition from the realisation of the units,** based on the physics equations;

- ***New SI is called as Quantum SI*** → units are defined considering microscopic properties and considering the quantum nature of phenomena

  → *the previous definition of* kg *– based on an artefact consisting of many atoms* →

  *is now replaced by the definition using Planck constant **h***



- ***Objective***

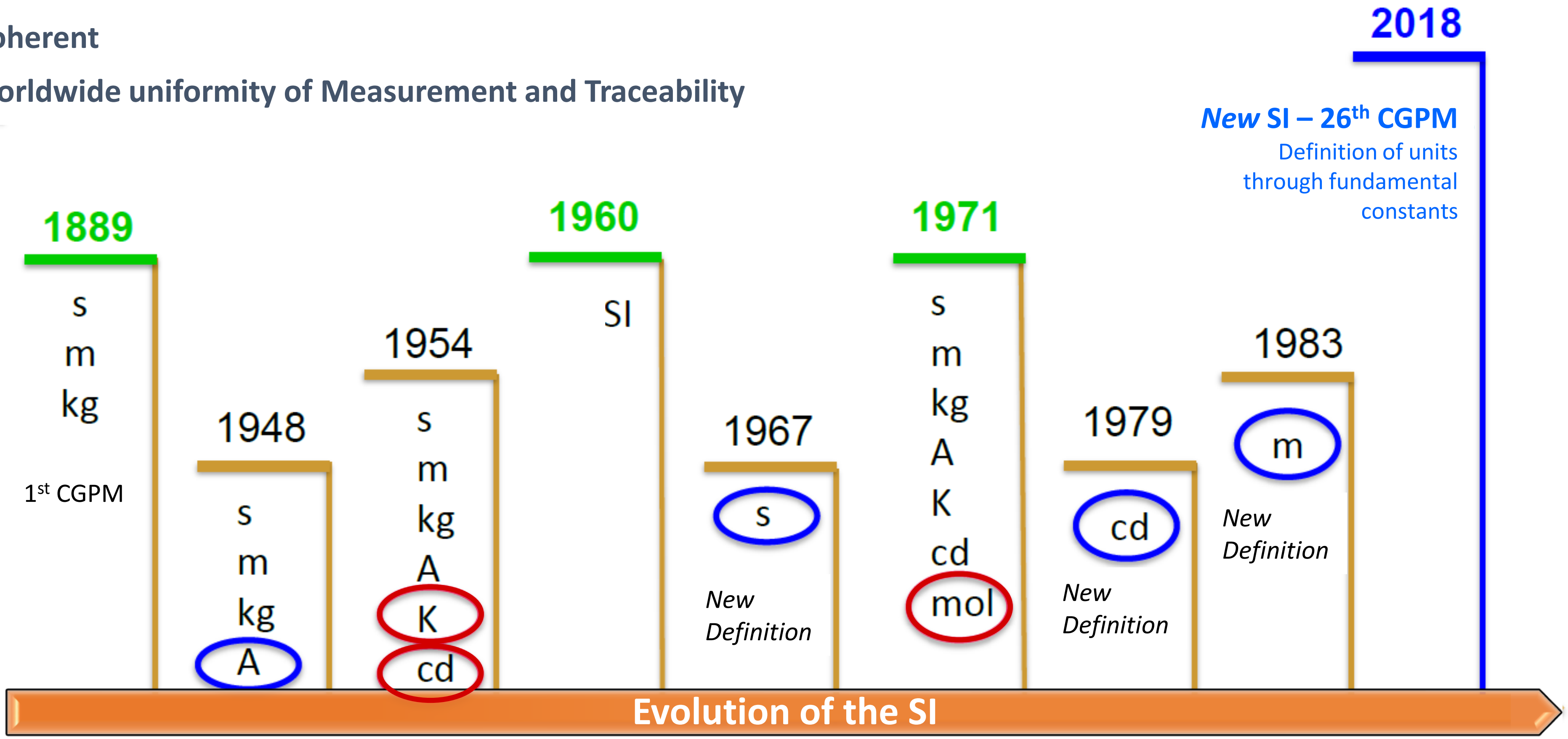
  More accurate and rigorous Measurement System

- ***And to Support***

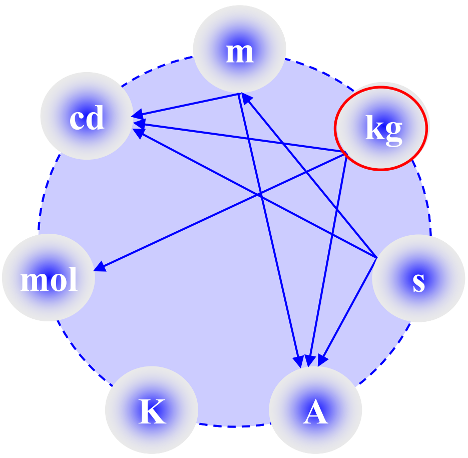
  Science, Research and Technological Developments

International System of Units (SI) - system of units, used around the world as the preferred *basic language for science, technology, industry and trade* since it was established in **1960** by a resolution at the 11th meeting of the General Conference on Weights and Measures (CGPM) of BIPM

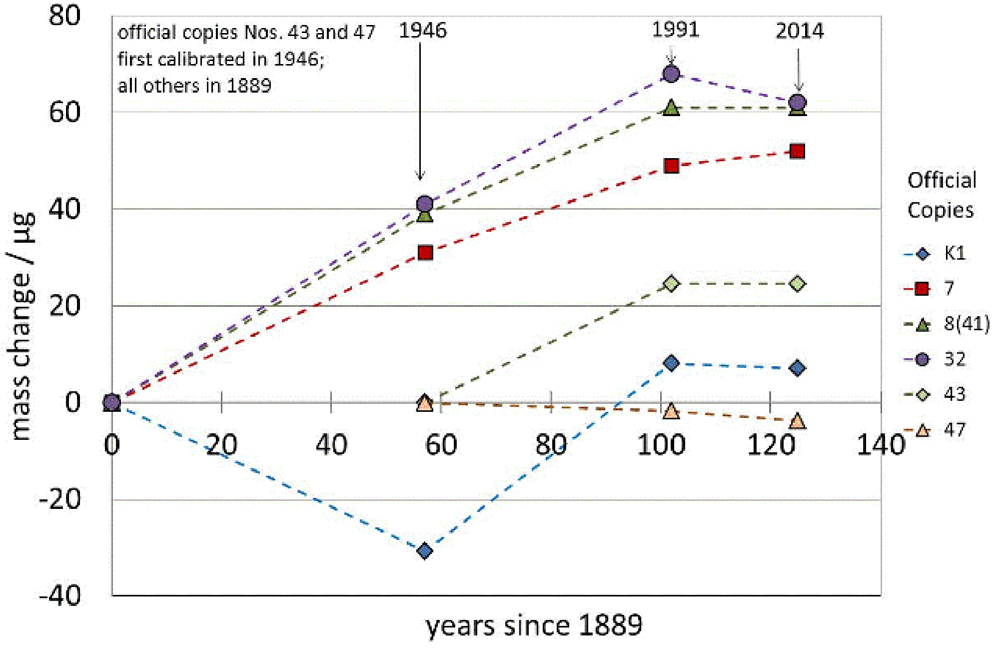
- **It has been periodically updated - to keep up with the science developments and answer the need for more accurate measurements and in the new technical domains;**
- **Unique and Coherent**
- **Ensures the worldwide uniformity of Measurement and Traceability**



– But ... the seven base units of the SI, the kg was still defined (based) in terms of the mass of an artifact → international prototype of the kilogram **IPK**, kept in the BIPM - which is not stable ....



IPK - international prototype of the kilogram (platinum-iridium alloy)

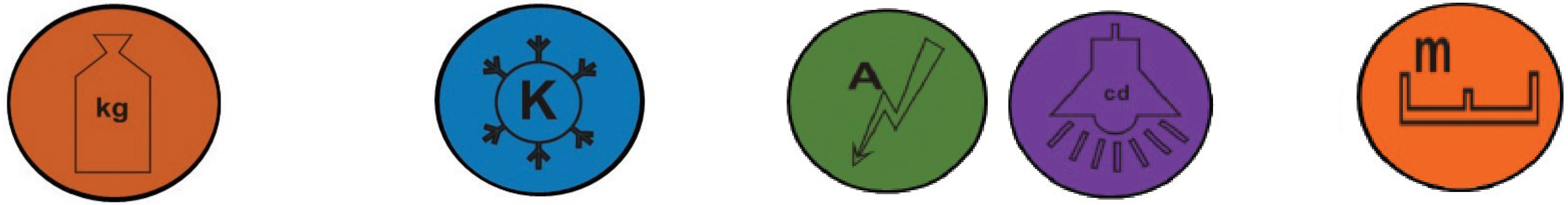


Drift observed in the six copies of the international kilogram prototype (comparisons in **1889**, **1946**, **1991** e **2014**) **≈ 50 µg**

Until November 2018:

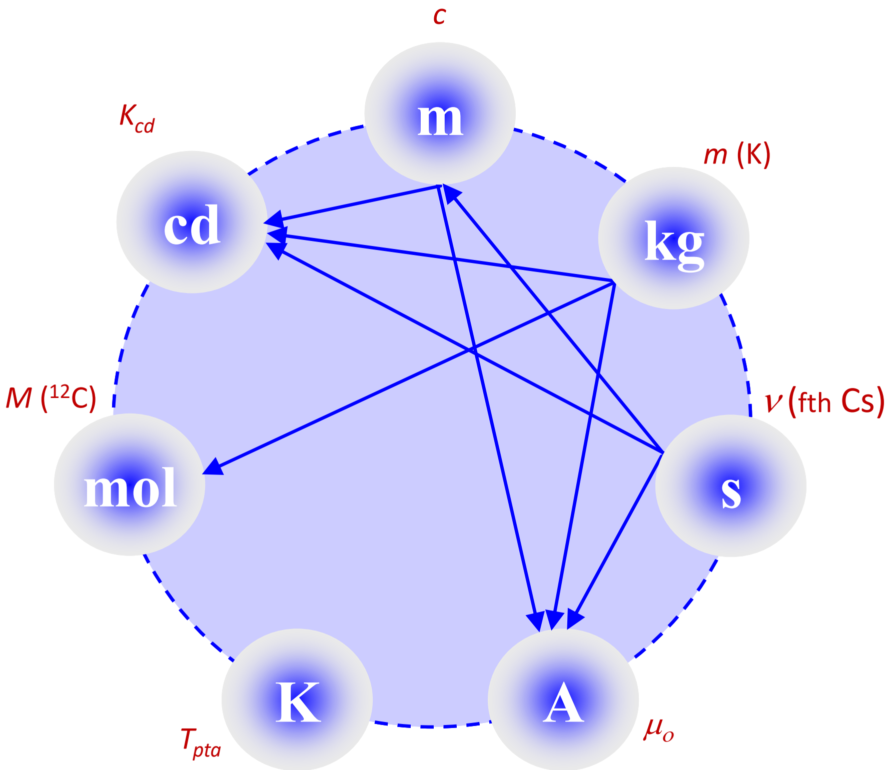
Definition of the unit of measure

Material measures	Material parameters	Ideal experimental *prescriptions*	Fundamental constants
e.g. International prototype of **kilogram**	e.g. Triple point of water – to define the **kelvin**	e.g. Ideal situation to define **ampere** and **candela**	e.g. Speed of light in vacuum, *c*, to define the **metre**



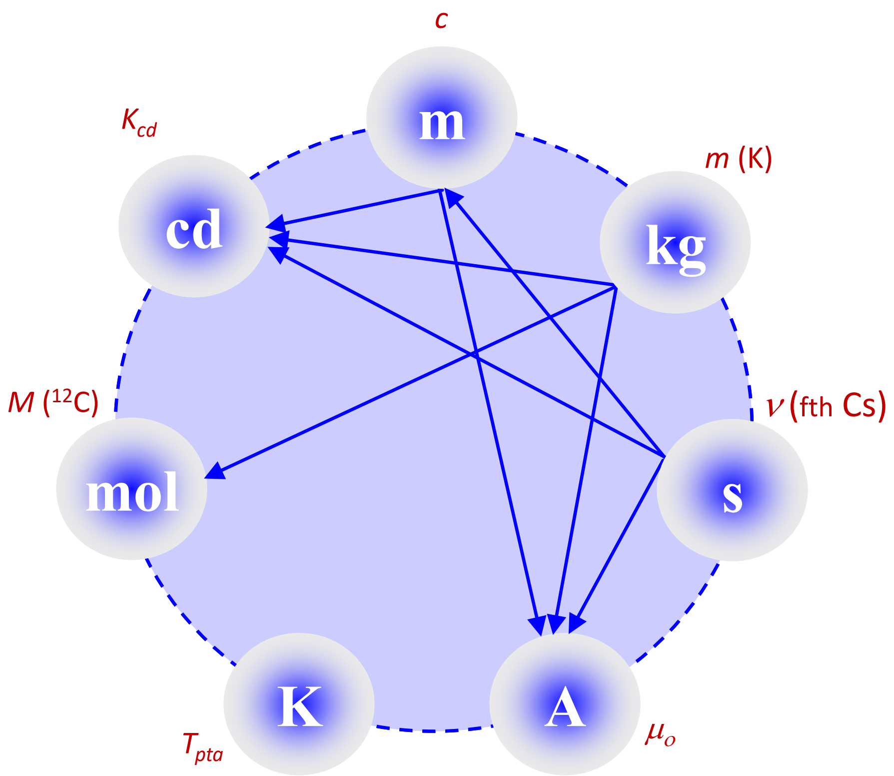
Situation in 2018 – *before 26th General Conference on Weights and Measures*

- 3 definitions based on fundamental constants (*or conventional values*)
  - metre (c)
  - ampere (μ_0)
  - candela (K_{cd})
- 3 definitions based on the properties of materials
  - second (^{133}Cs)
  - kelvin (H_2O)
  - mole (^{12}C)
- 1 definition based on an artifact
  - kilogram (IPK)



Uncertainty Values in 2018 - *before 26th General Conference on Weights and Measures*

– metre: speed of light in vacuum	10^{-11}
⇒ numerical value of the speed of light *c*	
* mechanical quantities	
– kilogram: prototype of iridium platinum	10^{-9}
* mechanical quantities	
– second: atomic cesium clock	1 ns
– ampere: implementation of Laplace's law	
⇒ magnetic permeability in vacuum μ_0	10^{-7}
* electrical quantities	
⇒ quantum standards K_J e R_K	10^{-8}
– kelvin: triple point of *pure* water	1 μK
* thermal quantities	
– mole: number of atoms in 0,012 kg of ^{12}C	10^{-8}
* physicochemical, chemistry, biochemistry, biology	
– candela: spectra for human vision	10^{-4}
* photometric and radiometric quantities	



Since May 20, 2019 - The International System of Units, the SI, is the system of units in which: the 7 constants are chosen in such a way that any unit of the SI can be written either through a defining constant itself or through products or quotients of defining constants

The numerical values of the seven defining constants have no uncertainty!

kilogram	kg	• the Planck constant h is $6{,}626\ 070\ 15 \times 10^{-34}$ J s
metre	m	• the speed of light in vacuum c is 299 792 458 m/s
second	s	• the unperturbed ground state hyperfine transition frequency of the cesium 133 atom $\Delta\nu_{Cs}$ is 9 192 631 770 Hz
ampere	A	• the elementary charge e is $1{,}602\ 176\ 634 \times 10^{-19}$ C,
kelvin	K	• the Boltzmann constant k is $1{,}380\ 649 \times 10^{-23}$ J/K,
candela	cd	• the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, is 683 lm/W
mole	mol	• the Avogadro constant N_A is $6{,}022\ 140\ 76 \times 10^{23}$ mol^{-1}

Practical Realization of Base Units

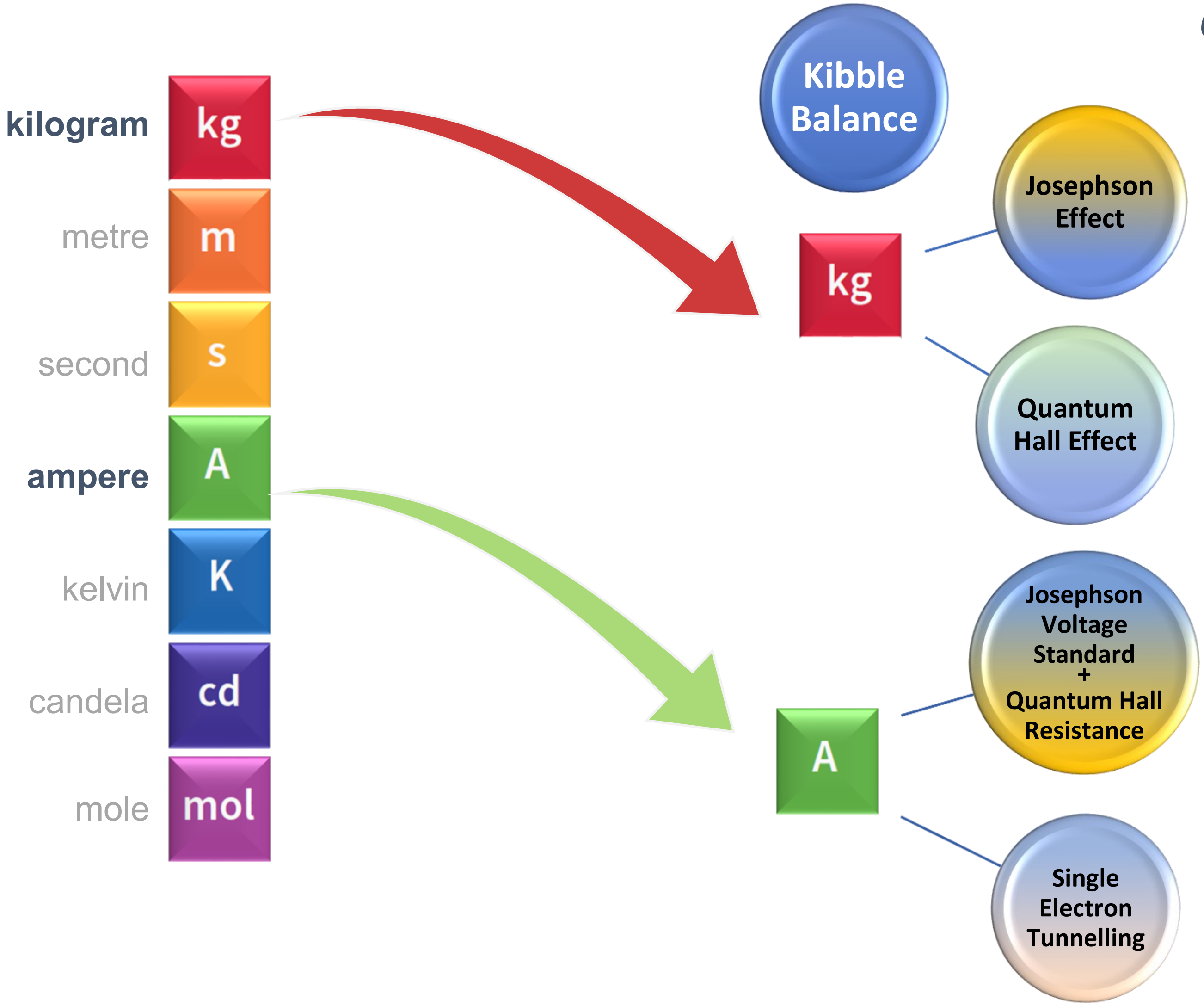
kilogram kg
metre m
second s
ampere A
kelvin K
candela cd
mole mol

- In the new formulation of the SI, the definitions allow the use of new methods for the practical realization of units - *instead of each definition specifying a particular condition or physical state, which established a fundamental limit for the accuracy of the realization* $\rightarrow$ **it is now possible choose any equation of physics that links the respective fundamental constants to the quantity to be measured!**

- **Different Realizations** - the new definitions are not limited to a single technique $\rightarrow$ *future developments may allow different ways of realizing units with better accuracy* - in principle, **there is no limit to the accuracy with which a unit can be implemented!**

Practical Realization of Base Units

Quantum Standards



Practical Realization of Base Units - kilogram

Previous definition

The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram (IPK). It follows that the mass of the international prototype of the kilogram is always 1 kilogram exactly, $m(\mathcal{K})$ = 1 kg.

(3rd CGPM, 1901)

26th CGPM - 2018

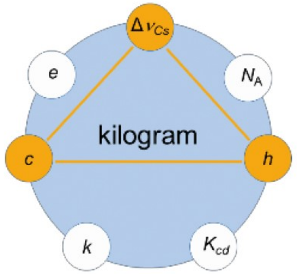
The kilogram, symbol **kg**, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be 6,626 070 15 × 10^{-34} when expressed in the unit J s, which is equal to kg m^2 s^{-1}, where the metre and the second are defined in terms of c and $\Delta\nu_{Cs}$.

$$h = 6{,}626\ 070\ 15 \times 10^{-34}\ \text{kg m}^2\ \text{s}^{-1}$$

$$1\ \text{kg} = \left(\frac{h}{6{,}626\ 070\ 15 \times 10^{-34}}\right) \text{m}^{-2}\,\text{s} = \frac{(299\ 792\ 458)^2}{(6{,}626\ 070\ 15 \times 10^{-34})\ (9\ 192\ 631\ 770)} \frac{h\,\Delta\nu_{Cs}}{c^2} \approx 1{,}475\ 5214 \times 10^{40}\ \frac{h\,\Delta\nu_{Cs}}{c^2}$$

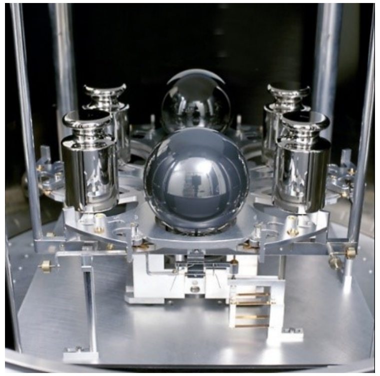
The number chosen for the numerical value of the Planck constant in this definition is such that at the time of its adoption, the kilogram was equal to the mass of the international prototype, **$m(\mathcal{K})$ = 1 kg**, with a relative standard uncertainty of **1 × 10^{-8}** (*which was the best standard uncertainty of the combined best uncertainties of the Planck constant)*

Practical Realization of Base Units - kilogram

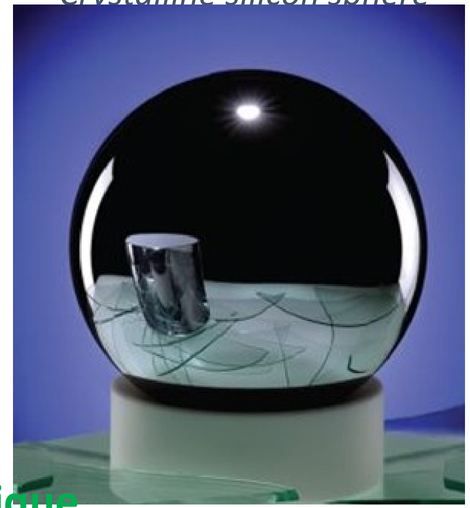


The primary realization of the kilogram can be performed using any physics equation that relates mass, Planck's constant, the speed of light in a vacuum and the frequency transition of the ^{133}Cs atom

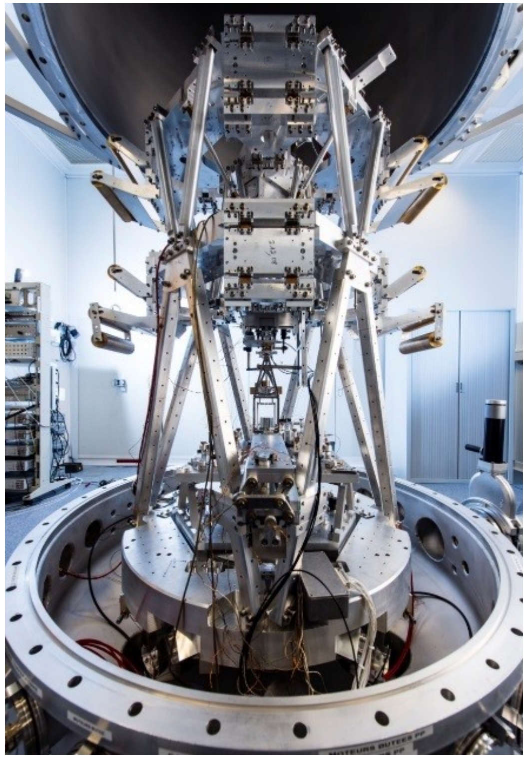
In the past few decades, significant efforts have been made to link the unit of mass to a fundamental constant of physics with high accuracy:



Crystalline silicon sphere

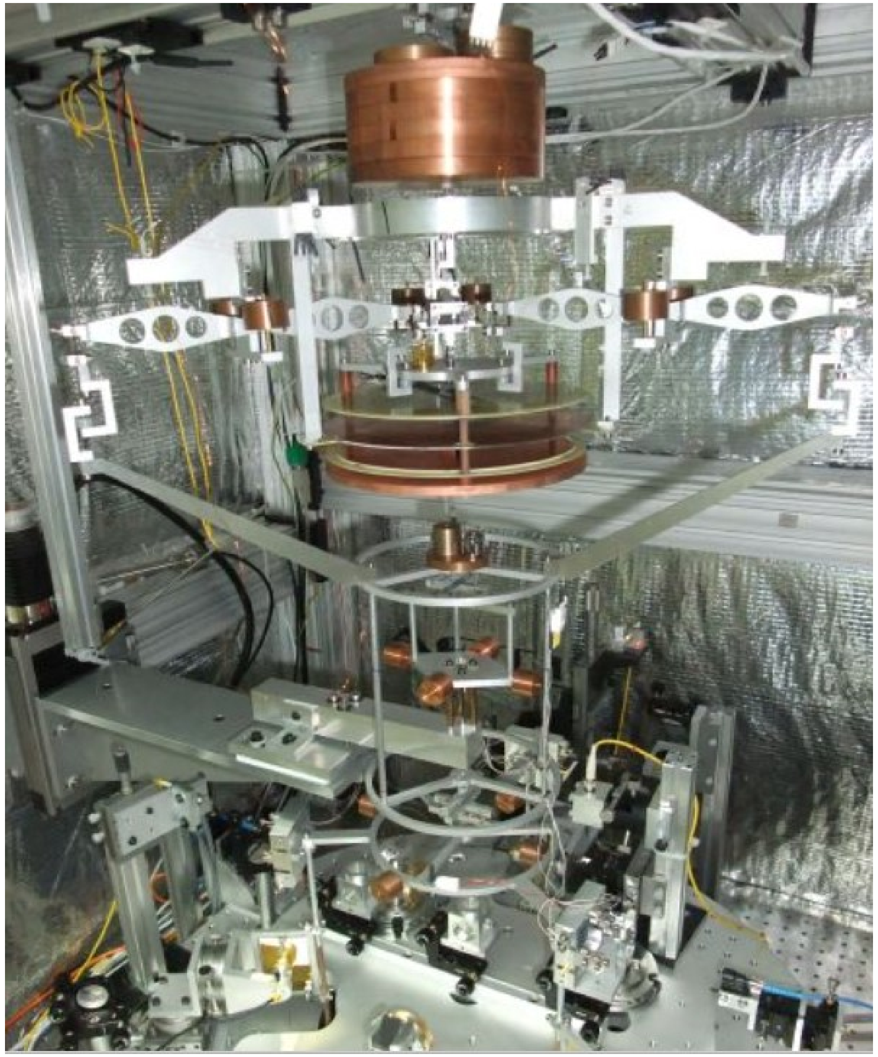


x-ray crystal density technique
(to *determine Avogadro constant N_A*)



Kibble balance
(*to measured Planck constant h*)

Practical Realization of Base Units - kilogram



Electrical Power ⇔ Mechanical Power

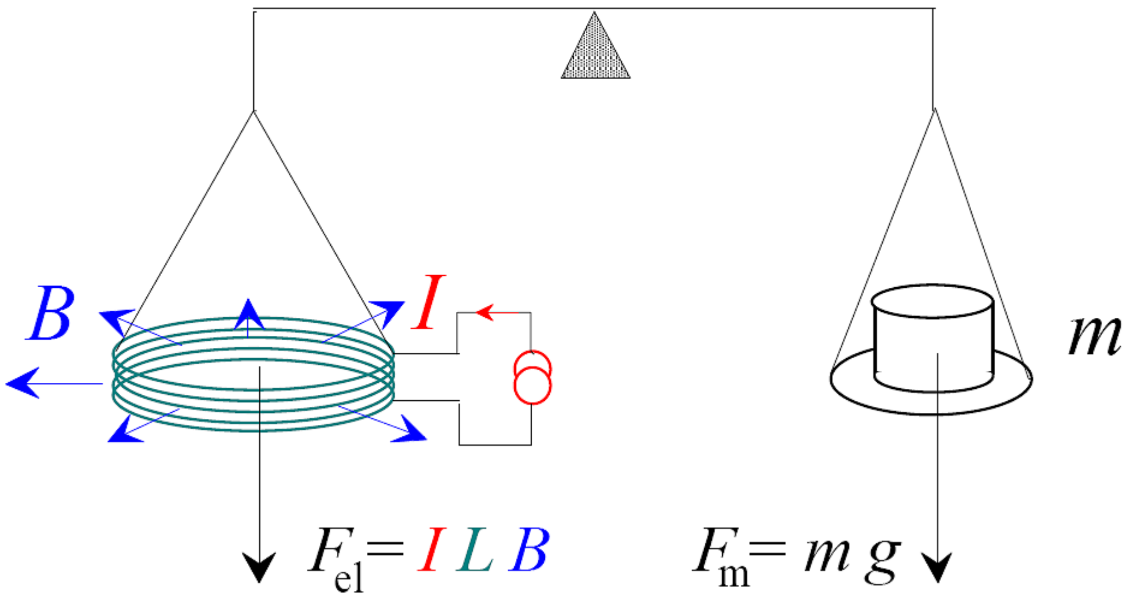
Two Phases

- Static phase: weighing of the artefact
  (that we want to determine the respective mass)
- Dynamic phase: determination of a movement

BIPM relative standard uncertainty for realizing the *new kilogram definition* using Kibble balance ≈ **5×10^{-8}**

Practical Realization of Base Units - kilogram

Static phase: **weighing of the artefact**



- horizontal and circular coil
- horizontal and radial magnetic field

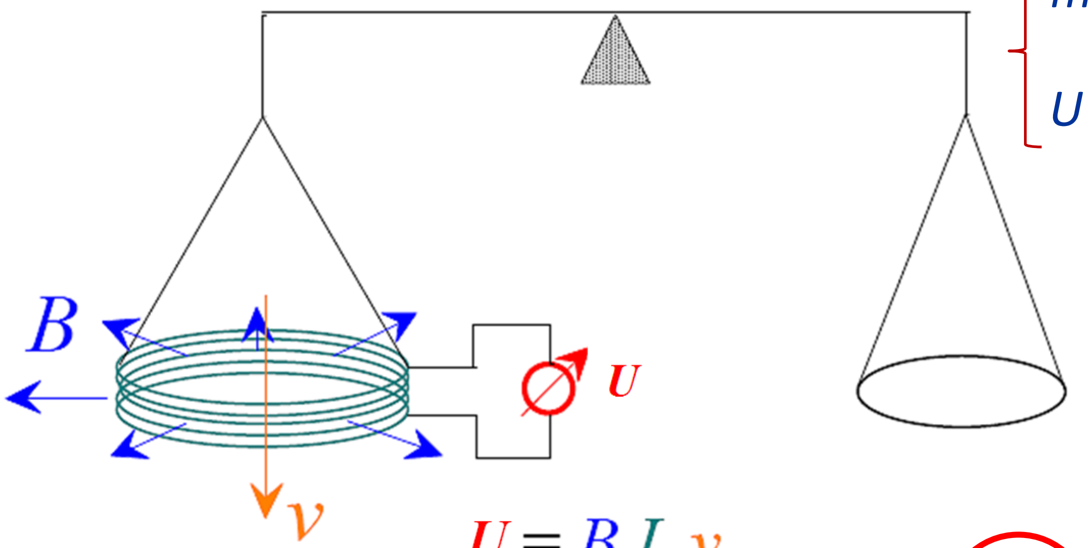
In a perfect alignment of the system
→ Balance between

- Laplace force *(a coil of length **L** in which flows a current **I** when the coil is immersed in a magnetic field **B**)*
- Gravitational force *(weight **m** · **g** of a standard mass **m** subject to a gravitational acceleration **g**)*

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

Practical Realization of Base Units - kilogram

Dynamic phase: **determination of a movement**



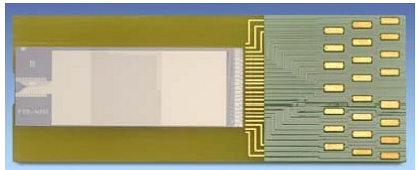
$U = B\,L\,v$

$$\left\{\begin{array}{l} m\,g = I\,L\,B \\ U = v\,L\,B \end{array}\right.$$

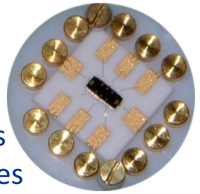
Equality of Mechanical and Electrical Power

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

Josephson junctions' array
SINIS (supercondutor - isolador - metal normal - isolador – supercondutor)



$U = hf / 2e$ → Josephson Effect
$R = h / e^2$ → Quantum Hall Effet



- GaAs / AlGaAs Heterostructures
- Graphene samples (Nobel Prize Physics 2010)

$$m = \frac{U^2}{R} \cdot \frac{1}{gv} = \frac{n^2 f^2}{i} \cdot \frac{h}{4} \cdot \frac{1}{gv}$$

the coil is moved at a vertical velocity v in the same magnetic field B

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

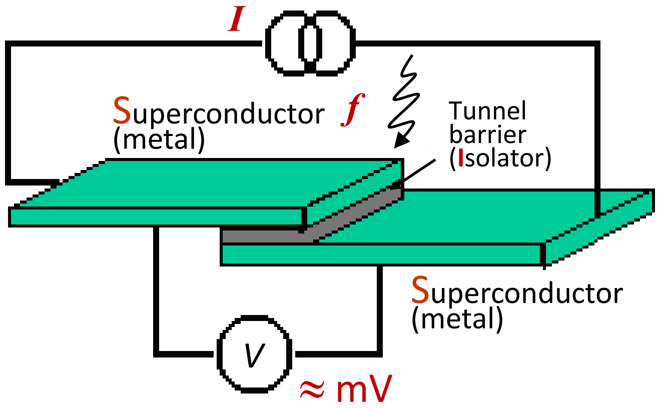
The *new* SI – Josephson Effect

Josephson Effect – observed in 1962 by Brian Josephson (Nobel Prize in Physics in 1973) - allows to base the representation of the volt in terms of fundamental constants

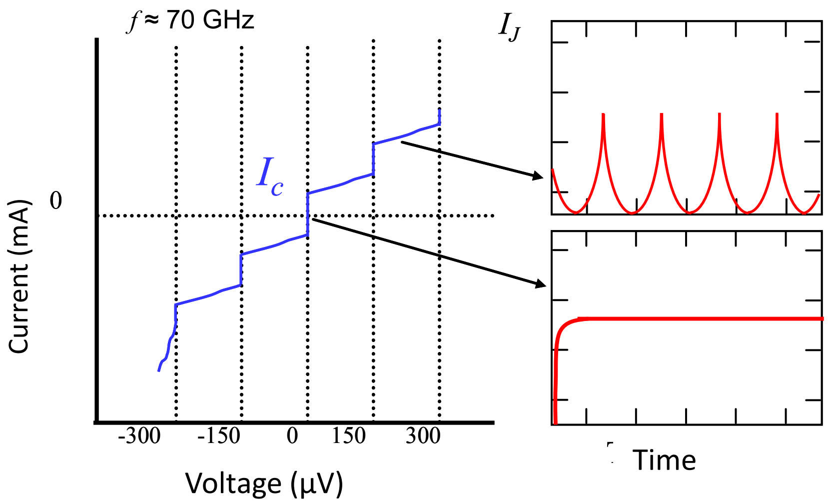
- Superconducting electrodes are separated by a tiny gap or insulating layer (≈ nm) → **Josephson junction**
- Cooled below their transition temperature (~ 4,2 K)
- Exposed to microwave radiation with a frequency f and a bias I applied
- Superconducting state ⇒ formation of pairs of electrons – **Cooper pairs**

⇒ responsible for the existence of a superconducting current

SIS - Nb /Al_2O_3 /Nb



$$I = I_c \; sen\left[\left(\frac{4\pi e}{h}\right)\int V\,dt\right]$$



- changing the polarization current ⇒ I_J synchronizes with f
- "*quantized*" voltage develops across the junction α f

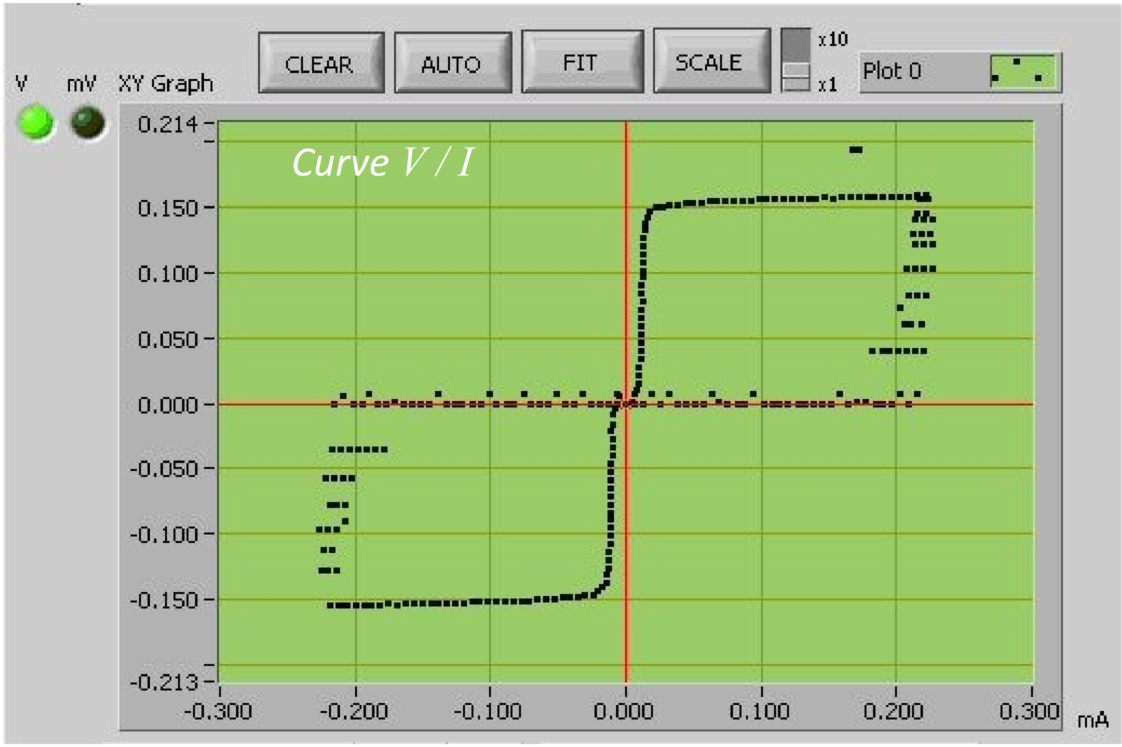
- $I < I_c$ ⇒ zero voltage in the junction terminals

  Continuous Josephson Effect

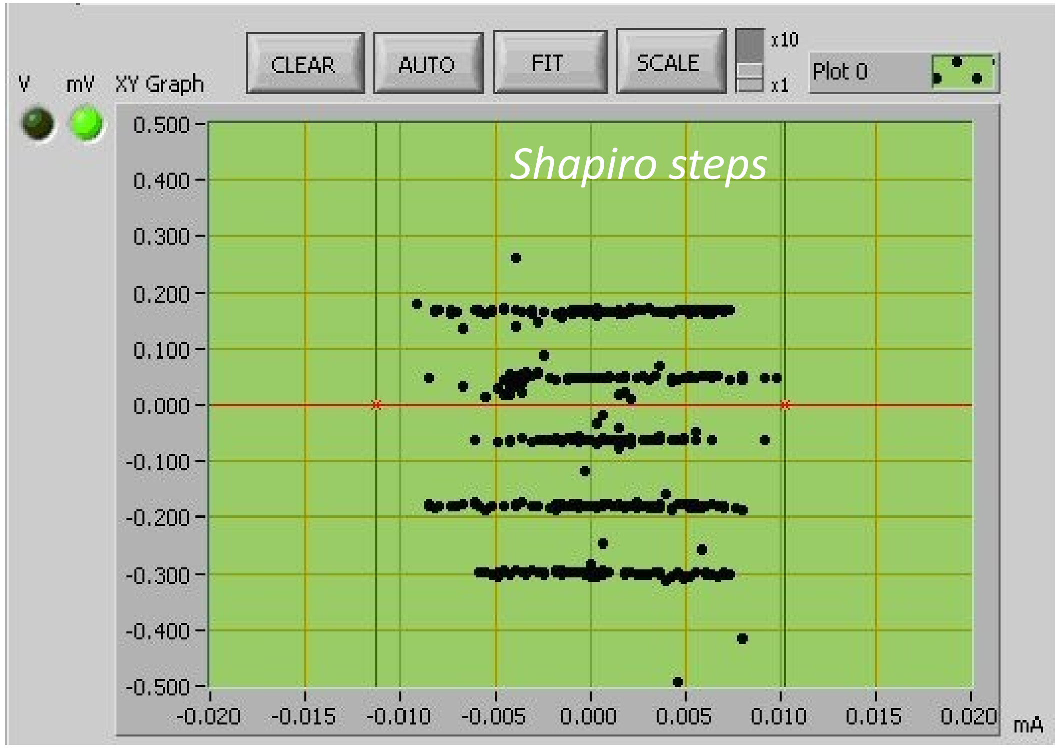
- $I > I_c$ ⇒ voltage V in the junction terminals and a current oscillation of electron pairs I_J at frequency f

  Alternate Josephson Effect

The *new* SI – Josephson Effect



Quantized voltage - voltage steps for multiple integers of V - proportional to the frequency of the radiation



$$V_J(n) = \frac{n\,f\,h}{2e} = \frac{n\,f}{K_{J-90}}$$

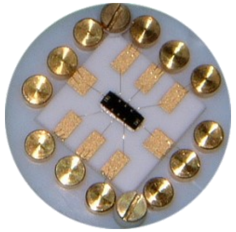
$$K_{J-90} = \frac{2e}{h} = (483\ 597{,}9 \pm 0{,}2\ )\ \mathrm{GHz/V}$$

Josephson constant - 1990 18th CGPM

f = 75 GHz - difference between two adjacent voltage steps ≈ 155 μV

Typical uncertainty ≈ 10^{-10}

Quantum Hall Effect – discovered 1980 by Klaus von Klitzing (Nobel Prize in Physics in 1985) - allows to base the representation of the ohm in terms of fundamental constants



- ⇨ 2 DEG existing in the interface semiconductor-semiconductor or in the semiconductor-isolator

  Si – MOSFET or Heterostructures GaAs / Ga Al As

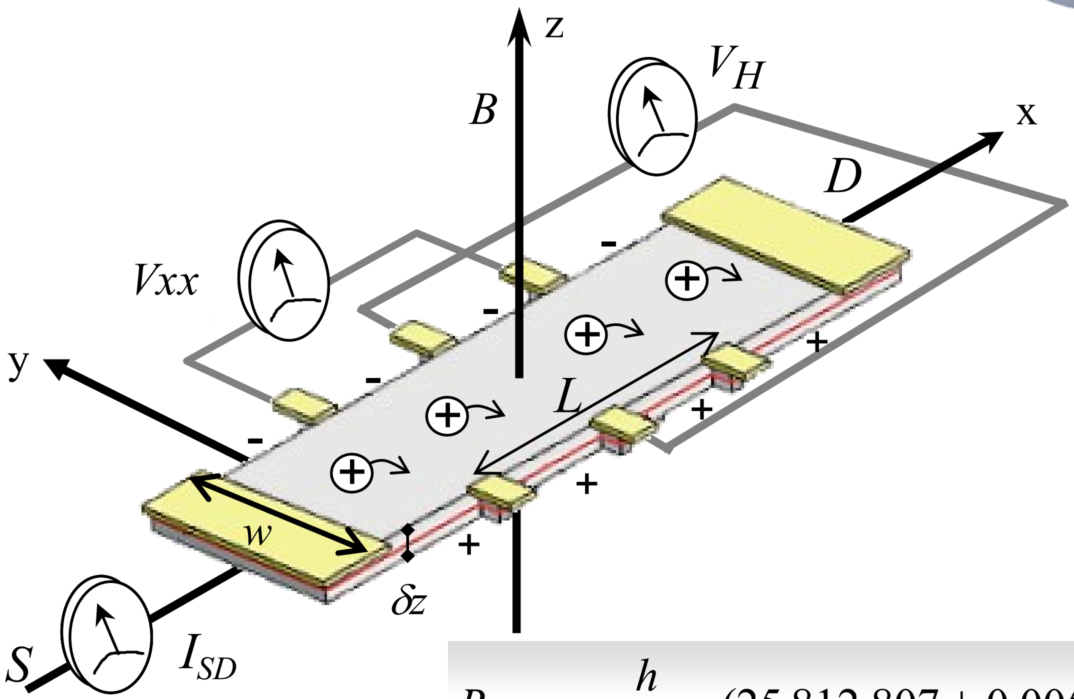
- ⇨ Low temperatures (≈ 1 K)
- ⇨ High magnetic field (≈ 10 tesla)
- ⇨ DC Current ≈ µA

Electrical Resistance

$$R_{xx} = \frac{V_{xx}}{I}$$

Hall resistance

$$R_H(i) = \frac{V_H}{I} = \frac{R_{K-90}}{i} = \frac{h}{ie^2}$$



$$R_{K-90} = \frac{h}{e^2} = (25\,812{,}807 \pm 0{,}005\ )\ \Omega$$

von Klitzing Constant

The *new* SI – Quantum Hall Effect

Hall resistance

$$R_H\,(i) = \frac{V_H}{I} = \frac{R_{K-90}}{i} = \frac{h}{ie^2}$$

$$R_H\,(i=1) = R_{K-90} = (25\,812{,}807 \pm 0{,}005)\,\Omega$$

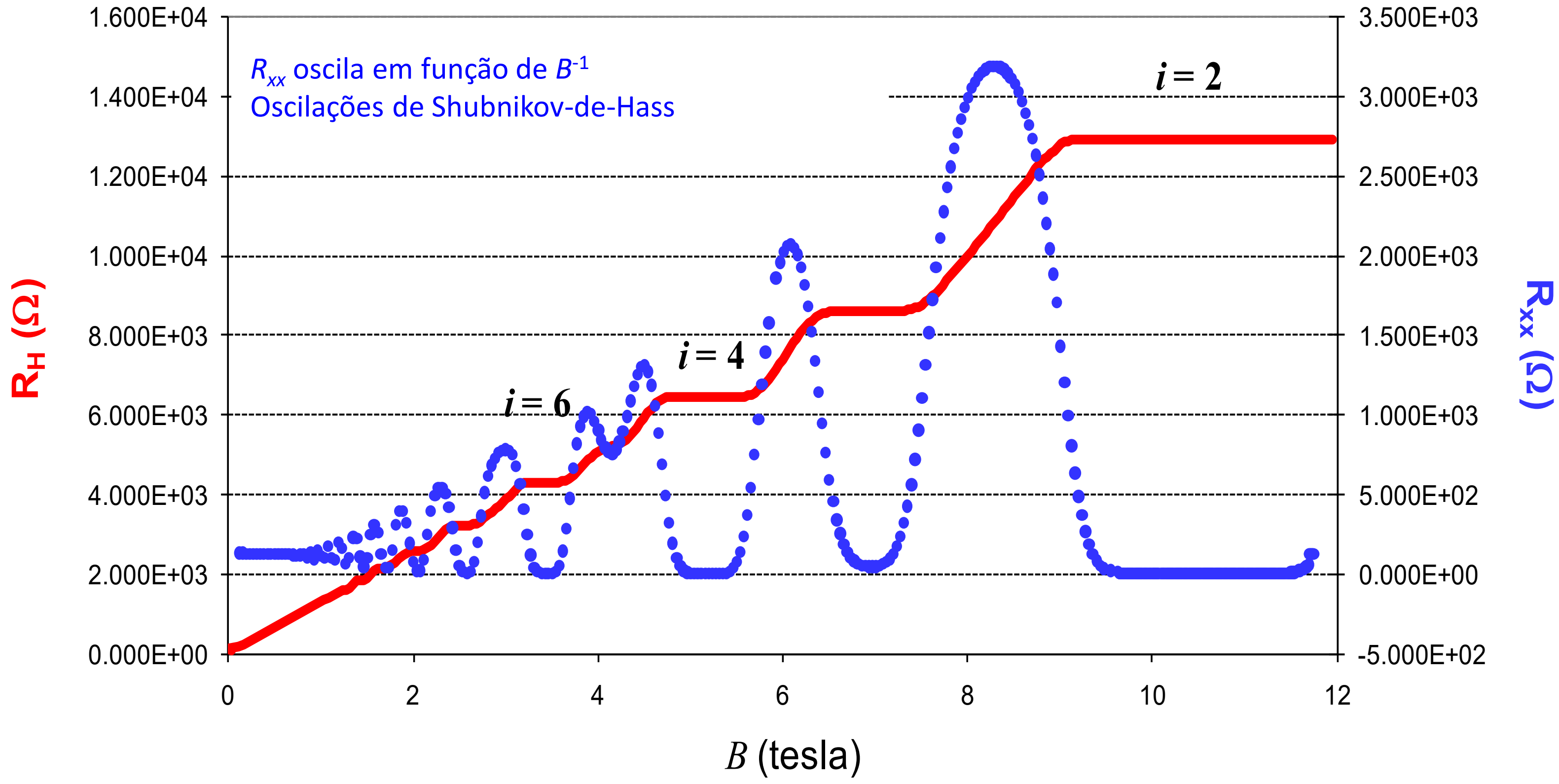
$$R_H\,(2) = 12\,906{,}404\,\Omega$$

$$R_H\,(3) = 8\,604{,}269\,\Omega$$

$$R_H\,(4) = 6\,453{,}202\,\Omega$$

$$R_H\,(6) = 4\,302{,}134\,\Omega$$

Typical uncertainty $\approx 10^{-9}$



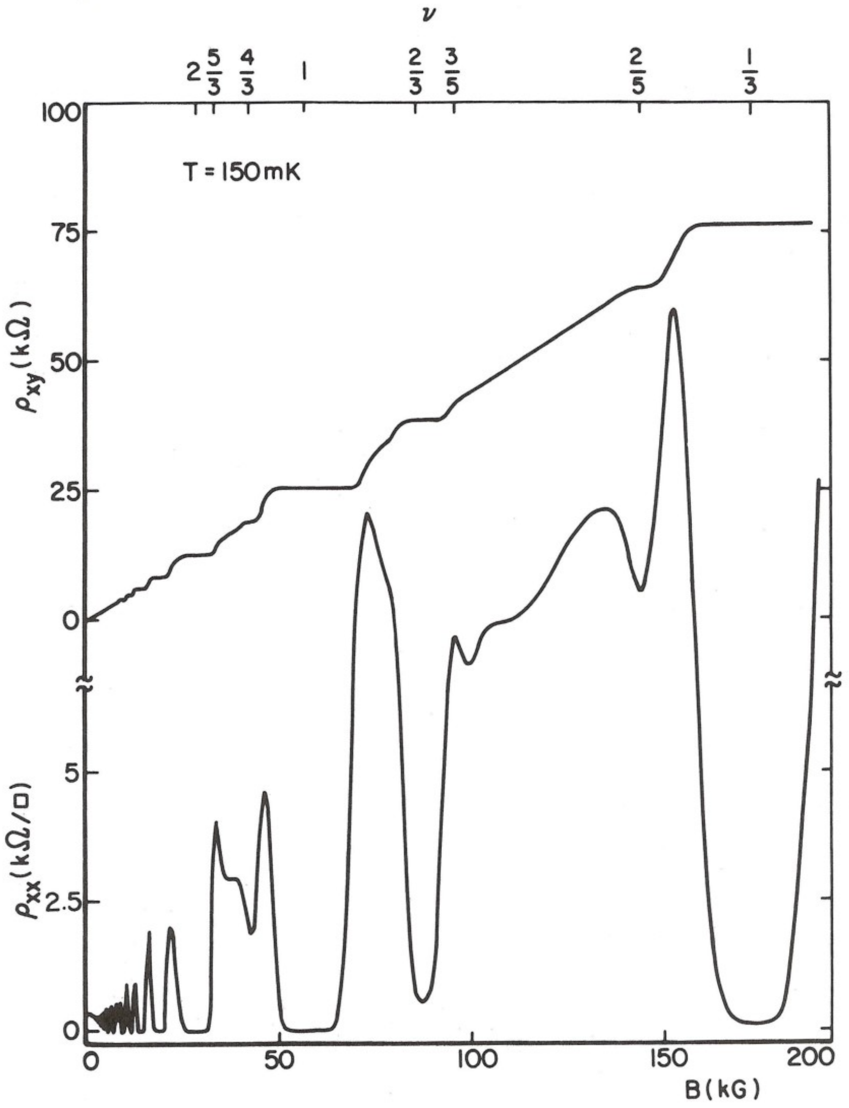
Ratio of R_H in 2 followed steps :

$$\frac{R_H\,(N)}{R_H\,(N-1)} = \frac{N-1}{N}$$

The *new* SI – Fractional Quantum Hall Effect

In 1982, Tsui, Stormer e Laughlin

- ⇨ using $GaAs/Al_xGa_{1-x}As$ heterostructures
- ⇨ with high mobility values
- ⇨ T ≈ 0,1 K and B ≈ 20 T
- ⇨ observed new step of Hall resistance = 3 x R_K (i = 1/3)



T = 0,15 K e *B* > 5 T : R_{xy} corresponding to a Landau fill levels for *i* = 1/3, 2/5, 3/5, 2/3, 4/3 e 5/3

Limitations :

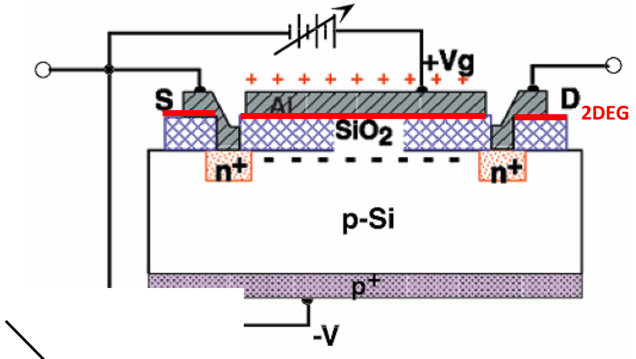
The accuracy of R_H in the fractional steps is still very low for metrological applications

(for *i* = 1/3 the accuracy is ≈ some parts 10^{-5}, with *B* = 20 T e *T* = 150 mK

The *new* SI – Quantum Hall Samples

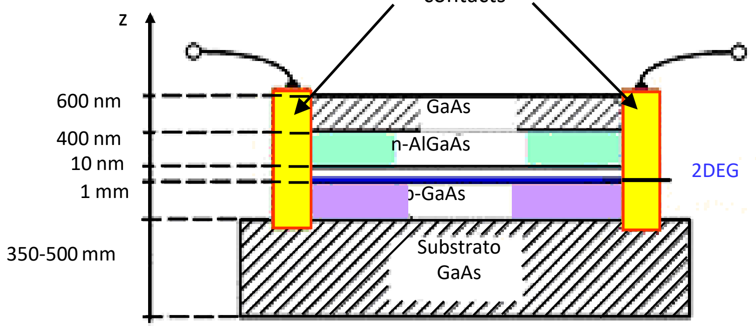
- Si – MOSFET

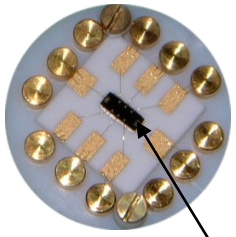
Substrate Si, doped type *p* (impurities - holes), allows the isolation of voltage V_g.
The contact area de (source S and drain D) is strongly doped type n+ (electrons), promoting the formation of ohmic contact to 2DEG.



- GaAs / AlGaAs Heterostructures

2 DEG is located in the inversion layer formed at the interface between two semiconductors - AlGaAs as an insulator



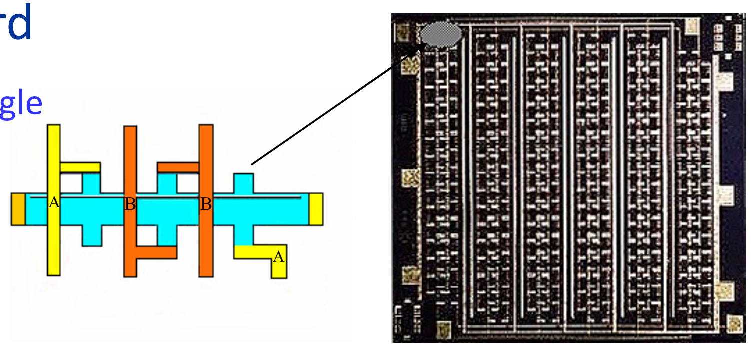


(3 x 1,1) mm

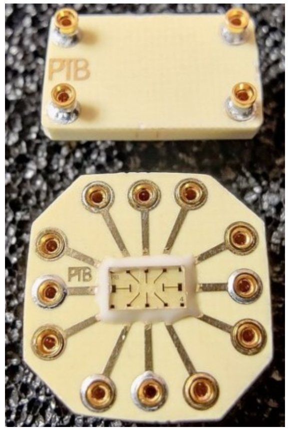
- QHARS – Quantum Hall Array Resistance Standard

series or in parallel – increasing the range of ohmic values by a single Hall sample

- ✓ between 100 Ω e 10 MΩ
- ✓ allowing to use higher current values



PTB flip-chip encapsulation of a graphene-based electric quantum resistance standard



- Graphene samples (Nobel Prize Physics 2010)

Two-dimensional carbon crystals - By means of flip-chip technology, the graphene-based quantum resistance standards (from PTB) can be sealed to maintain constant properties even in changing environments and over long periods of time.

The *new* SI – Practical Realisation of ampere

Previous definition

The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.

(9th CGPM, 1948)

26th CGPM - 2018

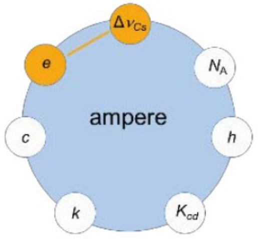
The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge ***e*** to be $1{,}602\ 176\ 634 \times 10^{-19}$ when expressed in the unit C, which is equal to **A s**, where the second is defined in terms of $\Delta\nu_{Cs}$.

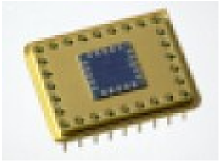
$$e = 1{,}602\ 176\ 634 \times 10^{-19}\ \text{A s}$$

$$1\ \text{A} = \left(\frac{e}{1{,}602\ 176\ 634 \times 10^{-19}}\right) \text{s}^{-1} = \frac{1}{(9\ 192\ 631\ 770)\ (1{,}602\ 176\ 634 \times 10^{-19})} \Delta\nu_{Cs}\, e$$

$$\approx 6{,}789\ 687 \times 10^{8}\ \Delta\nu_{Cs}\, e$$

The *new* SI – Practical Realisation of ampere





Single-electron transport (SET)

SET devices

- allows the most direct unit realization of ampere using the physical definition of current and to count individual electrons with a tiny device

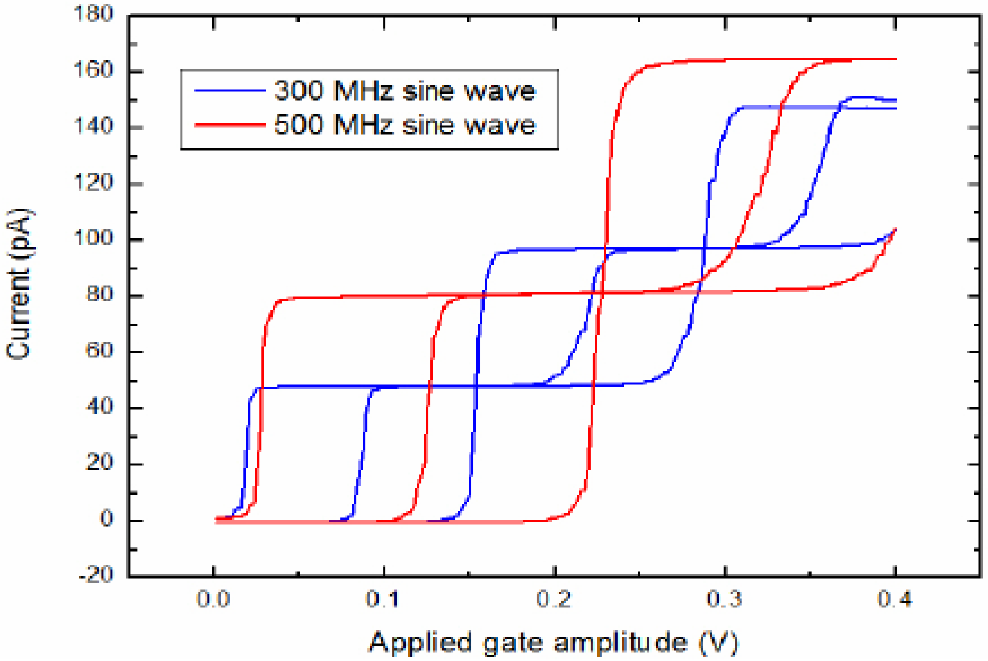
SET allows to control the charge transfer and "producing" quantified current

$$I_{SET} = n \cdot Q_X \cdot f \equiv n \cdot e \cdot f$$

$f \rightarrow$ frequency

n = 1 or 2 (1 electron / Copper pair)

$Q_X \rightarrow$ estimate of the elementary charge e

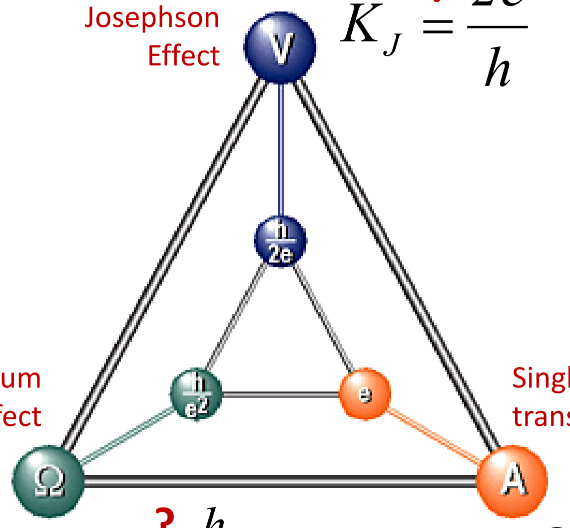


Typical Results: $\Rightarrow f\text{max} \sim 1$ GHz $\Rightarrow I_{max} \sim 160$ pA

Metrology needs $I \sim 1$ µA

Limitations $\rightarrow$ low current values and high uncertainty ($\approx$ **± 10^{-7}**)

The combination of three electrical quantum effects JE - QHE – SET is called "**Quantum Metrological Triangle**“ - provides the accuracy of three quantum standards in the electrical domain



Josephson Effect: $V_{JVS} = n \cdot f_J / K_J$

Quantum Hall Effect: $R_{QHR} = R_K / i$

Single Electron Tunnelling: $I_{SET} = Q_S f_S$

$$K_J = \frac{2e}{h} \qquad R_K = \frac{h}{e^2} \qquad Q_S = e$$

Ohm's law V = R I

$$\frac{n_J f_J}{K_J} = \frac{R_K}{i} Q_S f_S \longrightarrow n_J i \frac{f_J}{f_S} = K_J R_K Q_S \longrightarrow \underbrace{\frac{1}{2} n_J i \frac{f_J}{f_S}}_{=1} = 1$$

integer numbers and frequencies – quantities that can be quantified experimentally with very high accuracy

Experimental realization of QMT - Evaluates the consistency of the constants K_J - R_K - Q_X

$$1 = 1 + \Delta_{exp} \pm u_{exp}$$

Δ_{exp} → the deviation from equality

u_{exp} → associated standard uncertainty

The new SI - *Nobel Prizes in Physics*

1918 – Max Planck (Theory of Energy Quanta – 1900)

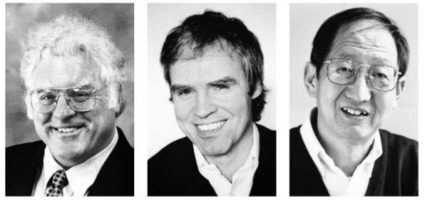
In 1900 Max Planck introduced the theory of "quanta" - radiation consists of quanta with specific energies determined by *a new fundamental constant* now called Planck's constant.

1972 - John Barden, Leon Cooper, John Schrieffer (**BCS Theory** – 1957)

1973 – Brian Josephson (**Josephson Effect** – 1962)

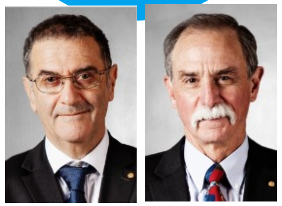
1985 – Klaus von Klitzing (**Quantum Hall Effect** – 1980)

1988 – D. Tsui, H. Stormer, R. Laughlin (**Fractional Quantum Hall Effect** – 1982)



2010 – Andre Geim, Konstantin Novoselov (**Graphen**)

2012 – D. Wineland, S. Haroche (Measur / Manipul **Individual Quantum Systems**)



In 2018 - 26th General Conference on Weights and Measures set the exact value of **h = 6,626 070 15 × 10 $^{-34}$ J · s**

kg

h

SI

1st step towards the:

- quantum computer
- **optical clocks** (redefinition of second in 2030?)

The new SI - *Nobel Prizes in Physics*

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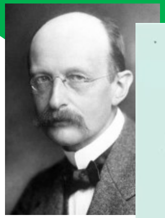
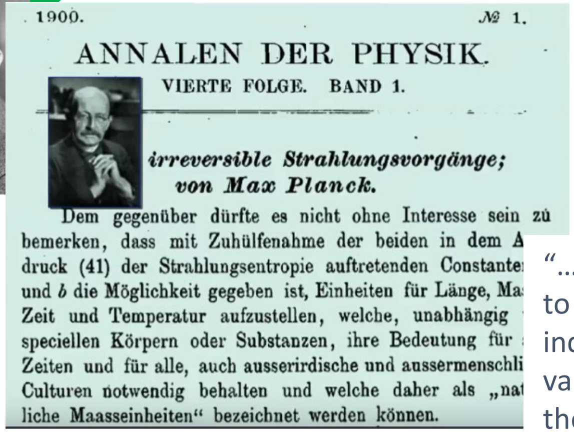




1900. № 1.

ANNALEN DER PHYSIK.

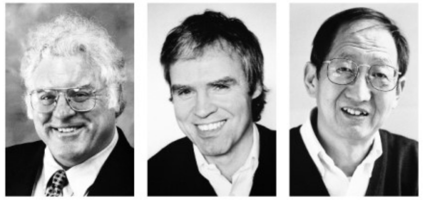
VIERTE FOLGE. BAND 1.

irreversible Strahlungsvorgänge;
von Max Planck.

Dem gegenüber dürfte es nicht ohne Interesse sein zu bemerken, dass mit Zuhülfenahme der beiden in dem A druck (41) der Strahlungsentropie auftretenden Constante und *b* die Möglichkeit gegeben ist, Einheiten für Länge, Ma Zeit und Temperatur aufzustellen, welche, unabhängig speciellen Körpern oder Substanzen, ihre Bedeutung für Zeiten und für alle, auch ausserirdische und aussermenschli Culturen notwendig behalten und welche daher als „nat liche Maasseinheiten" bezeichnet werden können.

1973 – Brian Josephson (**Josephson Effect** – 1962)

1988 – D. Tsui, H. Stormer, R. Laughlin (**Fractional Quantum Hall Effect** – 1982)



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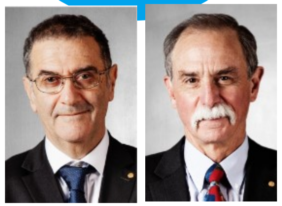
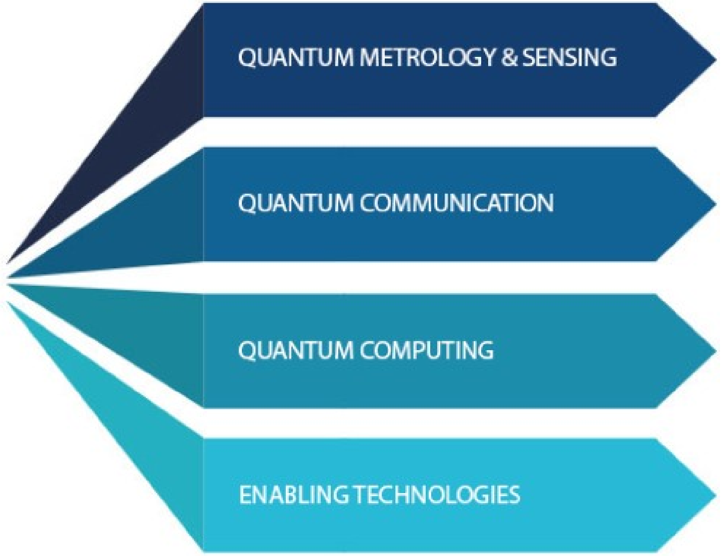


1st step towards the:

- quantum computer
- **optical clocks**
  (redefinition of second in 2030?)

"… with the help of the two constants ***a*** e ***b***, it is possible to establish units of length, mass, time and temperature, independent of bodies or special substances which remain valid for all times and for everyone and which can therefore be called "natural units of measurement".

Metrology Research & Development Activities in Quantum Metrology



R&D Activities in Quantum Metrology

- The Strategic Research Agenda for Metrology in Europe identified a requirement for further metrology in this area and several programmes and initiatives are underway:

- ➢ Quantum-Flagship

QUANTUM FLAGSHIP

- ➢ European Metrology Network (EMN) for Quantum technologies

European Metrology Network for Quantum Technologies

EURAMET

- ➢ Metrology R&I Programmes

EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

EUROPEAN PARTNERSHIP Co-funded by the European Union METROLOGY PARTNERSHIP EURAMET

- Quantum-Flagship

QUANTUM FLAGSHIP

The Quantum Flagship: One of the most ambitious long-term research and innovation initiatives of the European Commission

The Flagship works closely with **Standardisation** and **Metrology Institutes** (EURAMET) and the European committees for standardisation (e.g. CEN-CENELEC and ETSI-European Telecommunications Standards Institute) to drive standardisation of quantum technologies.

The Quantum Flagship is a large-scale initiative funded at the 1 b€ level on a 10-year timescale:

- ✓ **Coherent** set of Research and Innovation Projects selected through a peer-review process;
- ✓ **Calls for Projects** - issued based on the Flagship's Strategic Research Agenda, ensuring that all actors are aligned in the pursue of the Flagship's goals;
- ✓ **Goal** - to consolidate and expand European scientific leadership and excellence in this research area, to kick-start a competitive European industry in Quantum Technologies and to make Europe a dynamic and attractive region for innovative research, business and investments in this field;
- ✓ **> 5000** Researchers residing in all EU and associated countries involved;
- ✓ **140** Research and Innovation Actions proposals submitted in response of the first Quantum Flagship call

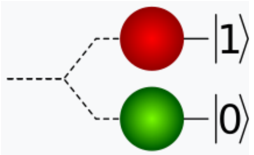
R&D Activities in Quantum Metrology

- Quantum-Flagship

The Quantum Flagship: One of the most ambitious long-term research and innovation initiatives of the European Commission

- **Quantum Communications:** It has some of the most mature quantum technologies in quantum key distribution (QKD) and quantum random number generators (QRNG) as well as facing some of the most demanding challenges for quantum technologies, such as developing a pan-European quantum communication network, even a global network (Quantum Key Distribution; Quantum Repeaters; Quantum Teleportation)

- **Quantum Computing:** Quantum computation is among the most far-reaching and challenging goals of quantum technologies exploits quantum mechanical phenomena (qubit (quantum bits) - Basic unit of information in quantum computing - **that can be zero and one at the same time** and instantaneous correlations across the device)



- **Quantum Sensing & Metrology:** In quantum-optical metrology and quantum imaging, quantum effects of light, and in particular quantum entanglement, are exploited to improve the sensitivity in phase measurements or the spatial resolution of optical systems and a **new generation of quantum enhanced optical clock** is now emerging showing significantly **improved accuracy with respect to the present atomic clocks**.

- **Quantum Simulations:** Quantum simulators based on the laws of quantum physics will allow us to overcome the shortcomings of supercomputers and to simulate materials or chemical compounds, as well as to solve equations in other areas, like high-energy physics.

R&D Activities in Quantum Metrology

➢ Quantum-Flagship

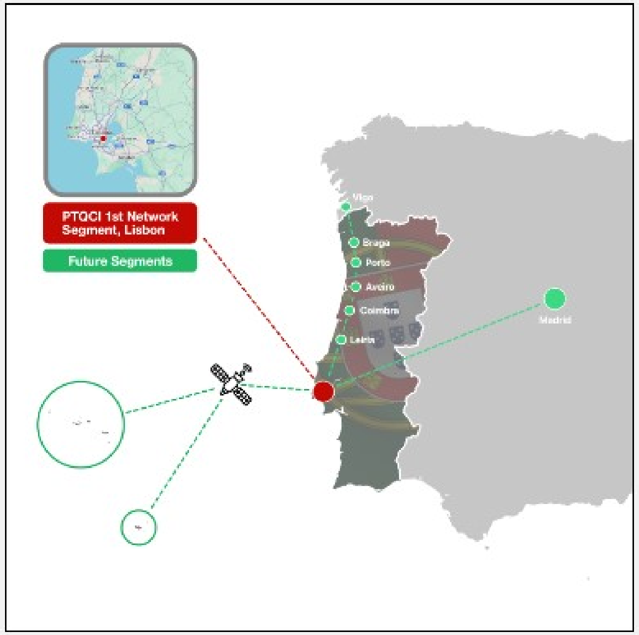
QUANTUM FLAGSHIP

The Quantum Flagship: One of the most ambitious long-term research and innovation initiatives of the European Commission

PTQCI

National Project PTQCI - Portuguese Quantum Communication Infrastructure (www.ptqci.pt)

- First quantum network in Portugal – first terrestrial segment of the European Quantum Communication Infrastructure (EuroQCI)
- Represents the first step towards the integration in the European infrastructure
- Objective: deploying **secure communication infrastructures** and technology provision and shall allow the deployment of highly **secure, scalable, and resilient networks based on Quantum Key Distribution (QKD)** between different public authorities in Lisbon, as well as a testbed network involving academic and private stakeholders.
- Consortium: 12 participants



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- [Quantum-Flagship](#)

QUANTUM FLAGSHIP

The Quantum Flagship: One of the most ambitious long-term research and innovation initiatives of the European Commission

National Project PTQCI - Portuguese Quantum Communication Infrastructure

(www.ptqci.pt)

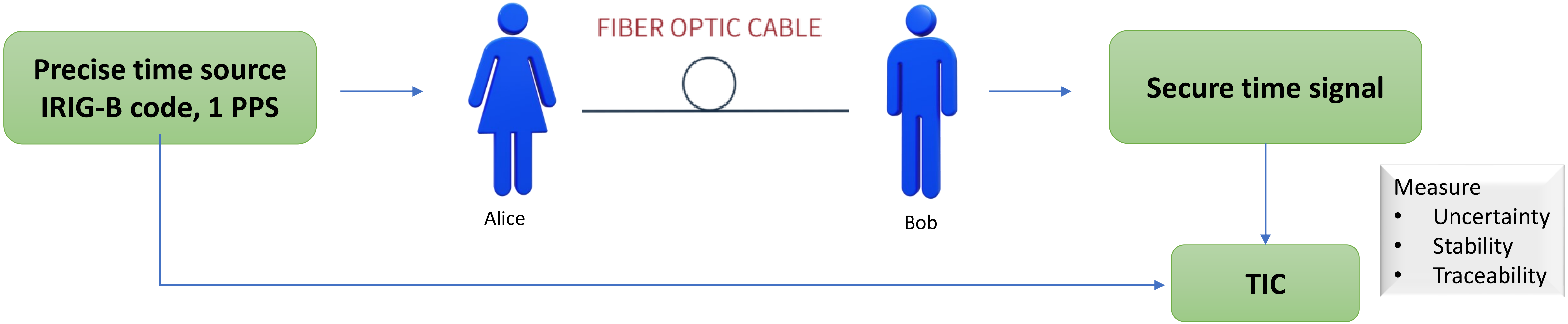
PTQCI

IPQ

NMI Activity - Secure time transfer

- To provide a platform for the testing and development of a system that provides secure time transfer.

  The QKD solution provides reliable timing that is resistant to spoofing attacks, one of the most significant disadvantages of GNSS systems.
- Ensure a reliable and traceable time transfer to all entities that require timestamps - financial transactions and stock exchange markets - taking advantage of the existing optical fiber infrastructure of the consortium.



R&D Activities in Quantum Metrology

- European Metrology Network (EMN) for Quantum technologies (since July 2019)

European Metrology Network for Quantum Technologies

www.euramet.org

establish globally accepted measurement services for quantum technologies and devices - **Provides active coordination of European measurement science research** to maintain competitiveness in the field of quantum technologies by promoting and facilitating **knowledge sharing, collaboration** and **the uptake of measurement science in the development of quantum technology**

Strategic Research Agenda – it is expected future developments, considering needs from stakeholders in science and technology, industry, economy and society, regarding electrical quantum-based metrology

- Quantum Electronics
- Quantum Clocks and Atomic Sensors
- Quantum Photonics

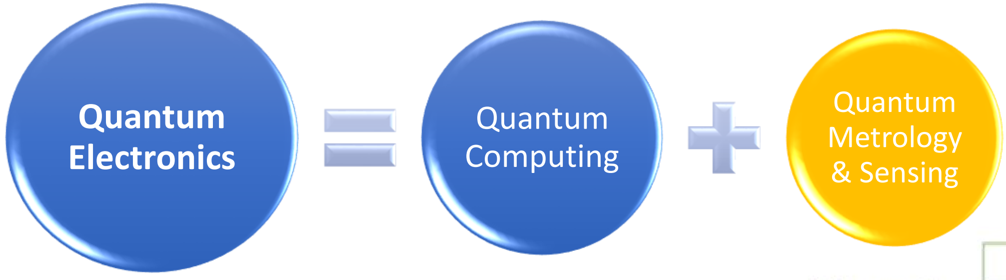
Promote the inclusion of metrology (Measurement Science) in the development of quantum technologies – accuracy, traceability and comparability of measurements – globally accepted measurement services for quantum technologies and devices.

Develop new measurement capabilities and dedicated services to meet the requirements of industry and R&D institutions.

Contribute to the development of Standards, Regulation and Certification for quantum technologies.

Support the needs of industry in conjunction with the technological objectives of the EC - Quantum Flagship and national quantum technology programmes.

R&D Activities in Quantum Metrology

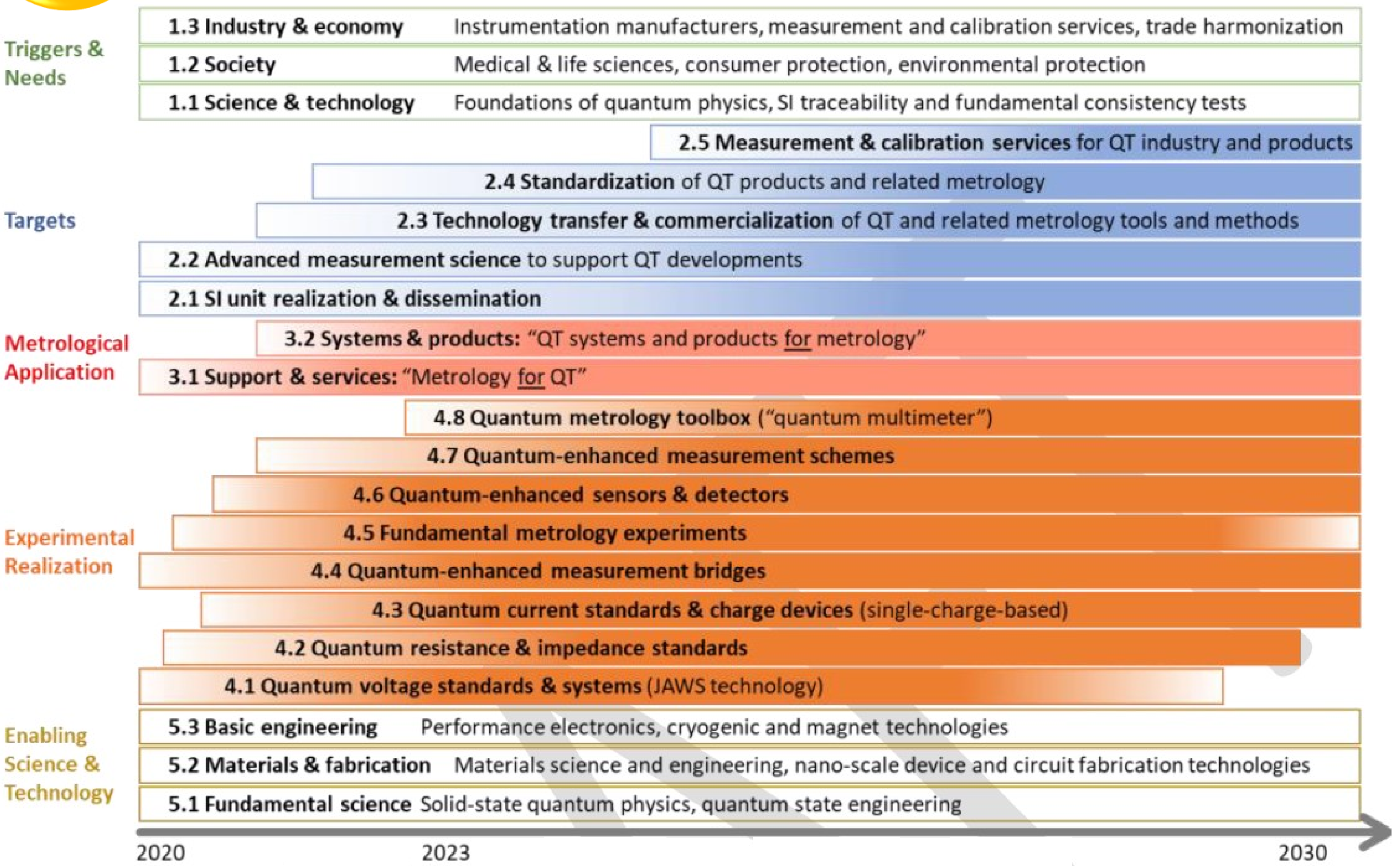


European Metrology Network for Quantum Technologies

EURAMET

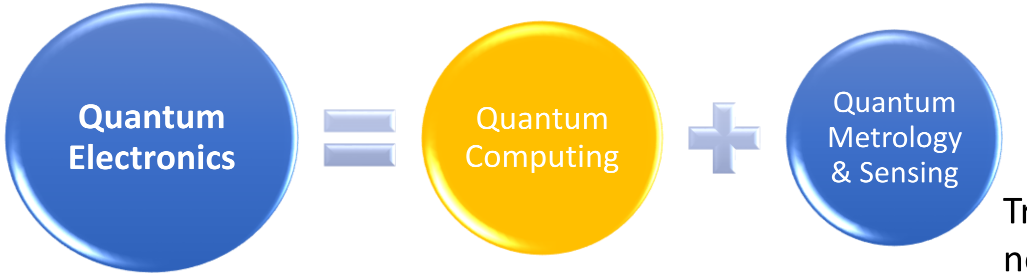
Roadmap "Quantum Metrology and Sensing"

- ✓ Ultra-sensitive quantum electromagnetic sensors and quantum-based high-precision/high-accuracy electrical measurements
- ✓ Metrology will contribute to quantum measurement science, **SI traceability** and efficient "best practice" measurement system, for **Test + Validation + Standardization**



R&D Activities in Quantum Metrology

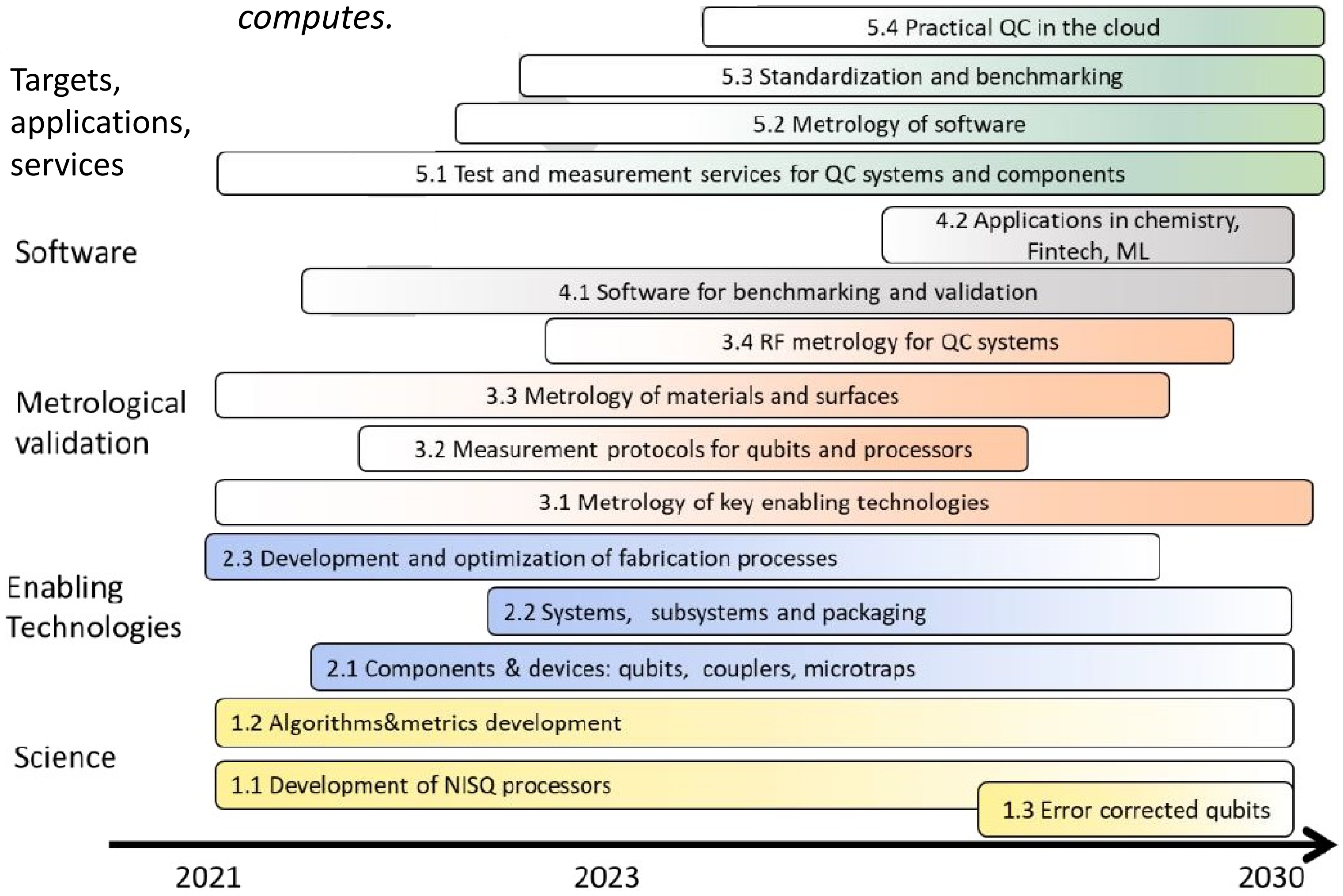
European Metrology Network for Quantum Technologies



Quantum computers - based on **'qubits'**

- state-of-the-art systems with ≈ **10 s of qubits have been demonstrated**
- Noisy Intermedia Scale Quantum (NISQ) processors with ≈ 100 s of qubits will become available in the next few years.

Quantum computers hardness non-classical resources of quantum systems to solve important problems that are intractable on classical computes.



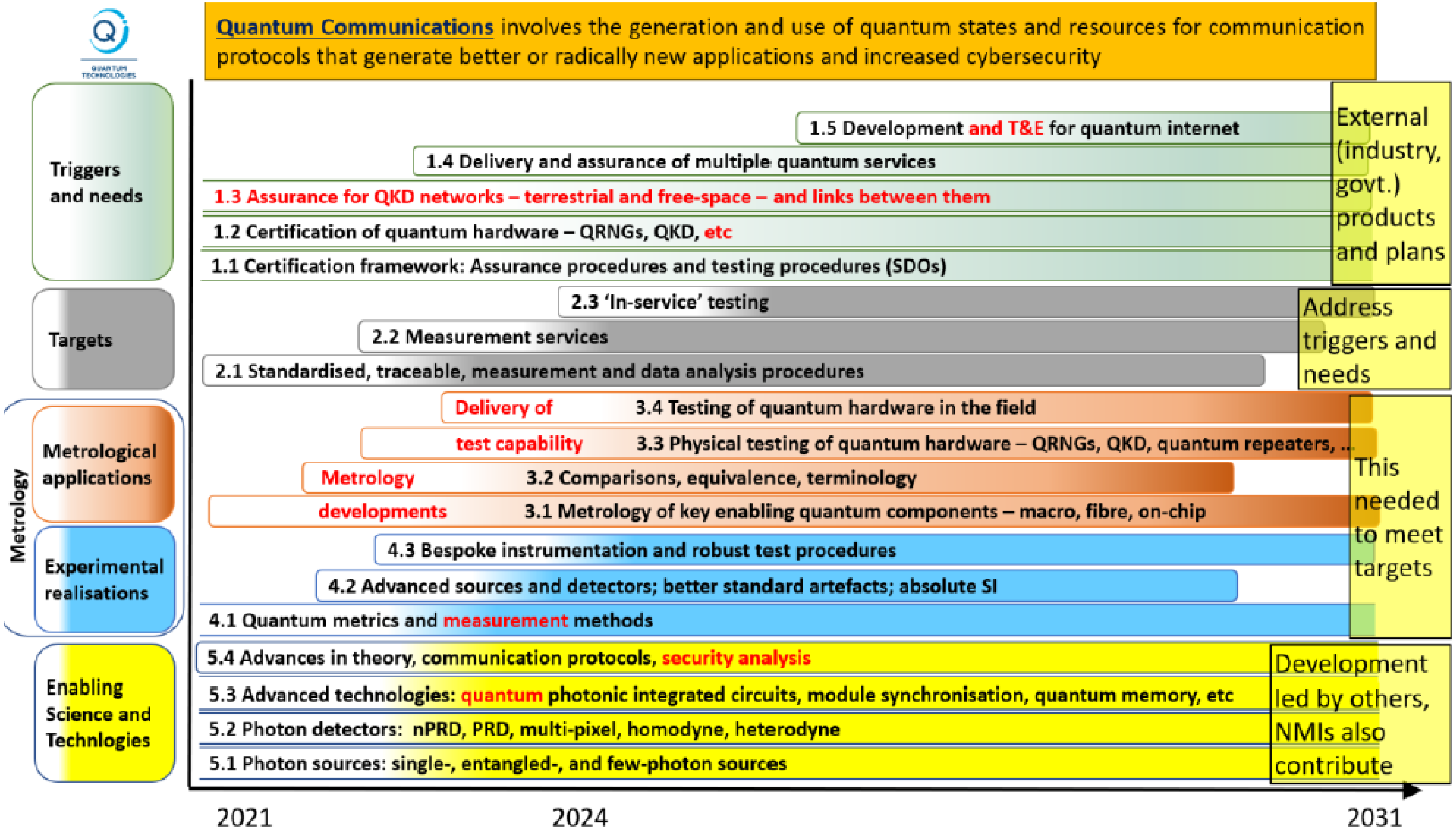
R&D Activities in Quantum Metrology

European Metrology Network for Quantum Technologies

Quantum Photonics = Quantum Communications + Quantum Metrology & Sensing

Quantum communications - exploitation of quantum resources for the purpose of:

- ✓ securing the communication of information
- ✓ transmitting quantum information
- ✓ transmitting information at a higher capacity than possible with purely classical systems

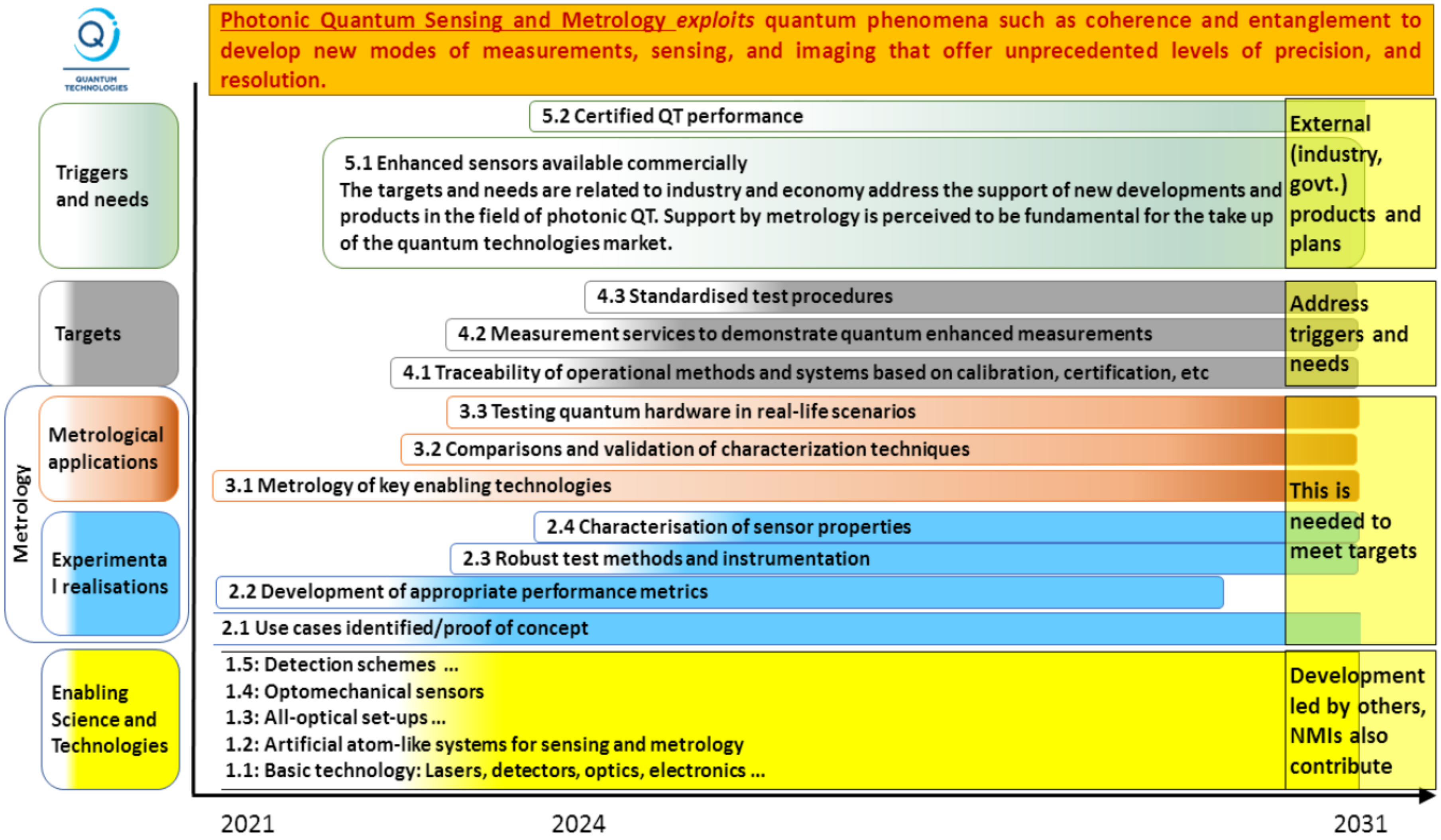


R&D Activities in Quantum Metrology

European Metrology Network for Quantum Technologies

Quantum metrology & sensing

- ✓ Quantum metrology and sensing will particularly benefit quantum photonic thermometry, light-based calibration, electric field measurements, pressure sensing, gravitometry, magnetometry, and accelerometry and include the prospects of offering new medical imaging and diagnostic tools.



R&D Activities in Quantum Metrology

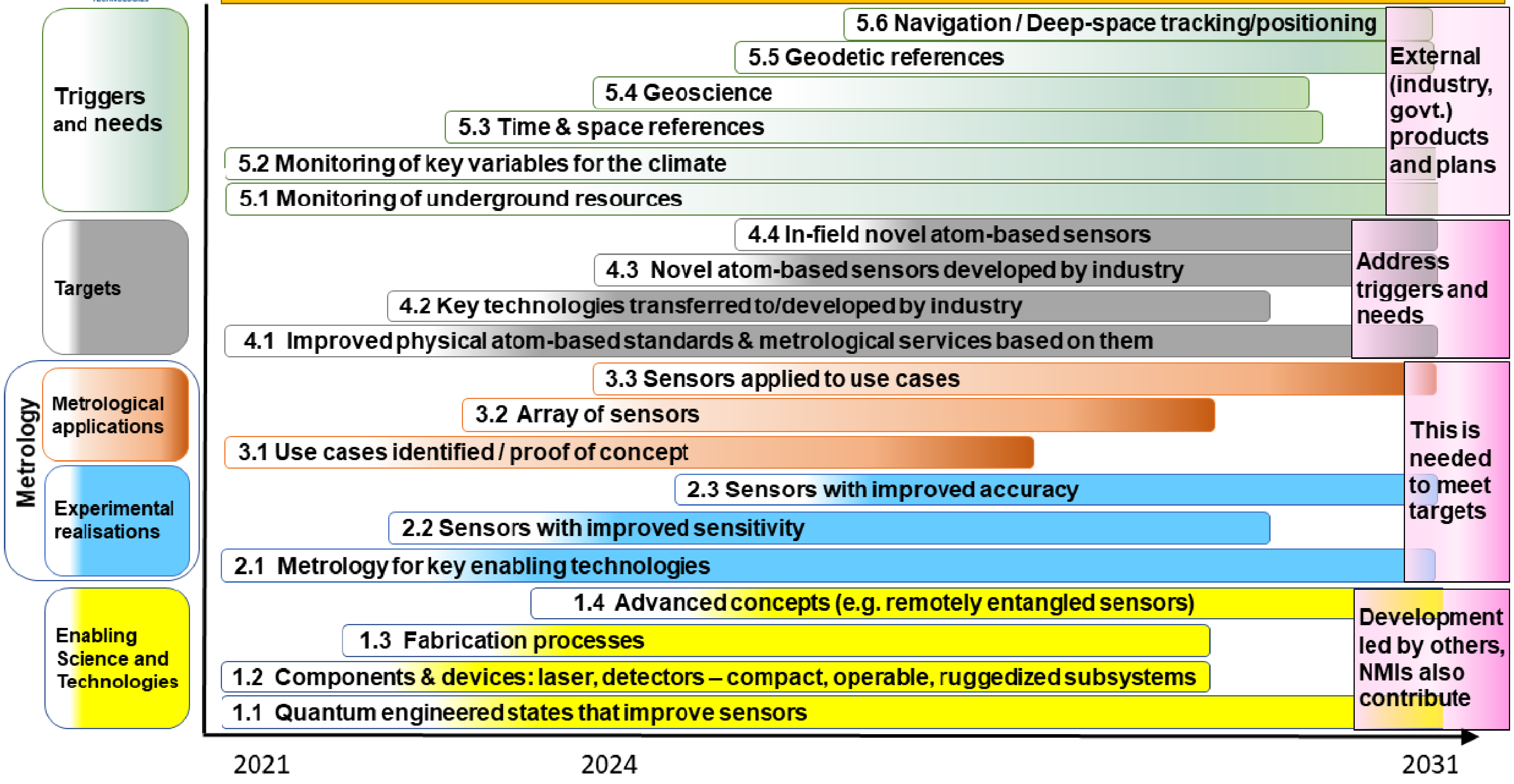
European Metrology Network for Quantum Technologies

Quantum Clocks and Atomic Sensors

Quantum clocks and atomic sensors - exploitation of quantum resources for the purpose of:

- ✓ provide accuracy and long-term stability for quantities such as time, length, rf-fields, temperature, magnetic fields, gravity and rotation
- ✓ key assets for addressing grand challenges and societal needs in several areas, such as monitoring climate variables, monitoring underground resources, time, space and geodetic references, geoscience, navigation and space science

Clocks & Atomic Sensors use quantum manipulation of atoms to derive time & space references, to enable navigation and the monitoring of key variables for climate, geoscience, and underground resources



R&D Activities in Quantum Metrology

EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States
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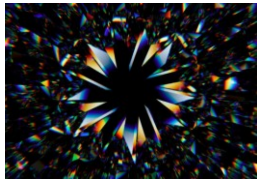
METROLOGY PARTNERSHIP EURAMET




EURAMET's European Metrology Research Programmes are fostering international collaboration, driving research excellence, and addressing society's grand challenges in areas such as **Quantum Technologies** towards an **Improved Measurement Infrastructure for New Technologies**

The EC and National Governments invested in collaborative research projects, involving research groups in all Member States (38): European NMIs, Academia, Industry, Regulators and Stakeholders

The Portuguese Participation in the activities of the R&D programme contributes to:

- the development of scientific and applied metrology related services between NMIs, DIs, Academia, Industry and Stakeholders to implement new fields and new methods
- a better support of traceability and CMCs
- an effective knowledge transfer between partners and it was for us an important Capacity Building tool
- **Important return of national commitment (7 M€ for 2021-2027)**

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Memristive devices as Quantum Standard for Nanometrology - MEMQud

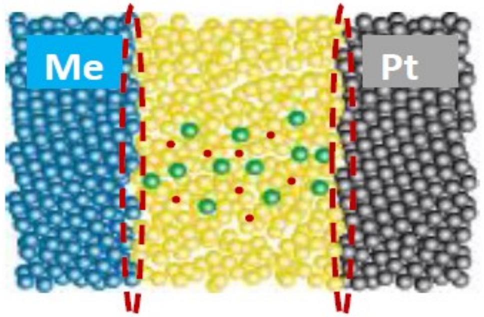
EMPIR – FUN | 15 participants | 2021-2024 | 1,5 M€

Objective: *Developing a room temperate, self-calibrating standard for electrical resistance*

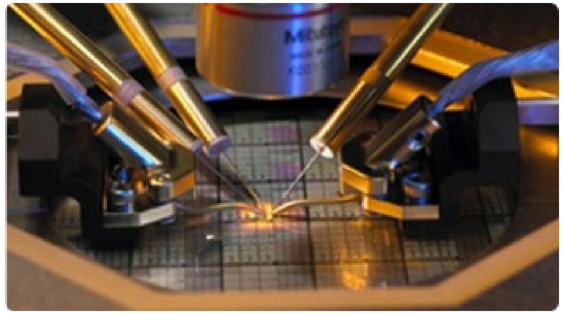
investigate and exploit quantum conductance effects in memristive devices for the realisation of quantum-based standards of resistance that operate reliably, in air and at room temperature with scalability down to nanometre precision

Nanoscale structures of metal/insulator/metal

Working electrode materials:
Ag, Cu, Ni, Fe, Nb, Au, AgCu, AgNi



Counter electrode materials:
Pt, Ru, Ir, Au, TiN, ITO



Switching film
SiO_2, Ta_2O_5, NbO_2, Graphene, MoS_2, ZnO, Ag, nanowires

When operated under specific conditions - memristive devices to produce quantized conductance states - corresponding to multiple values of the fundamental conductance value

$$G_0 = \frac{2e^2}{h}$$

A new approach for **realizing the electrical unit of resistance**, **Ω**, at room temperature and without the need for a magnetic field, as occurs with the primary Quantum Hall Effect system, in which the accuracy of measurements is lower, but has great advantage of having a very simplified application, with great **industrial impact,** and with immediate traceability to the SI → a direct traceability chain based on **Planck's constants *h*** and **elementary charge *e*.**

Vision: "Zero" traceability chain

On-chip integration

MEMRISTIVE devices on-chip (CMOS) integrated in instrumentation allowing auto-adjustment and auto-calibration processes

Quantum Standard

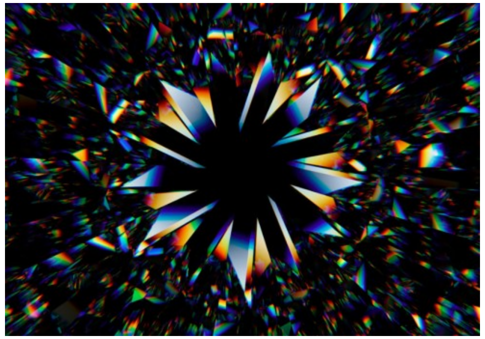
MEMRISTIVE devices

MEMRISTIVE devices

EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Quantum sensors for metrology based on single-atom-like device technology - QADeT

EMPIR – IND | 12 participants | 2021-2024



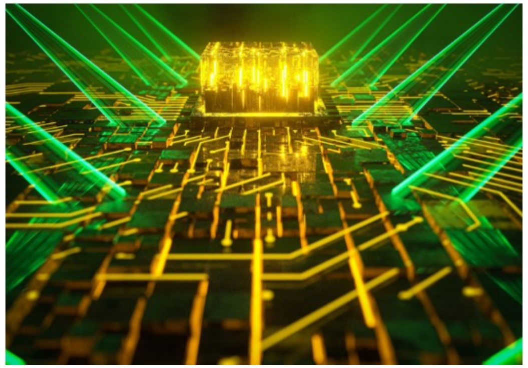
Objective: *Development of Quantum sensors for metrology based on single-atom-like device technology*

- ✓ Contribute to the growth and consolidation of the QT market by offering new types of QSs based on diamond and other materials, which can lead to several long term societal and economic benefits, in the fields of:
  - disease diagnosis and treatment: **via medical imaging**
  - environment: through **optimised battery consumption**
  - optimised wireless communications
  - QSs will be at the heart of the *Quantum internet of Things*
- ✓ Develop the necessary **traceability chains** for such single-atom-based sensors.
- ✓ **Facilitate the take up of the knowledge**, technology and measurement infrastructure developed in the project by the measurement supply chain, standards developing organisations (ISO, CEN) and end users (quantum sensing, computing, and communications).

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Microwave metrology for superconducting quantum circuits

EMPIR – FUN | 9 participants | 2021-2024 |



Objective: *Accelerating the development of quantum computers through improved microwave metrology at cryogenic temperatures*

'**microwave toolbox**' in Europe, providing enhanced measurements and standards for the emerging quantum industry and sectors such as telecommunications, cryogenic systems for QT, and medical imaging – Measurement of microwave signals in circuits in cryogenic environments (mK) using a combination of superconducting, semiconducting, integrated and conventional photonics, and plasmonic techniques.

– *Impact on industrial and other user communities:*

The project will support the development of the quantum technologies and quantum computing industries by establishing fundamentally novel microwave metrological and scientific tools for the measurement of microwave signals in circuits in-situ in cryogenic environments down to the millikelvin range.

Telecommunications, **microwave components**, **space and military communications systems**, cryogenic systems for QT, and **medical imaging** are examples of industries that need of improved signal measurement capabilities and will benefit from the successful development of quantum microwave signal measurement standards include test and measurement

Conclusions

Next Quantum Revolution is here - Quantum Technology will continue to shape our lives!

The use of primary methods and national standards directly or indirectly ensures the traceability of measuring instruments with traceability to the SI, ensuring the comparability of data and results.

Greater Interdisciplinary Cooperation between Manufacturers, R&D Institutions, Regulators, National Authorities and the Metrological Community, contributing to making metrological traceability of results effective and technically and scientifically supporting new challenges of Quantum!

Thank you for you attention!

Isabel Godinho | IPQ | 2024-09-12