Primary standards for healthcare: Metrology in support of accurate patient dosimetry

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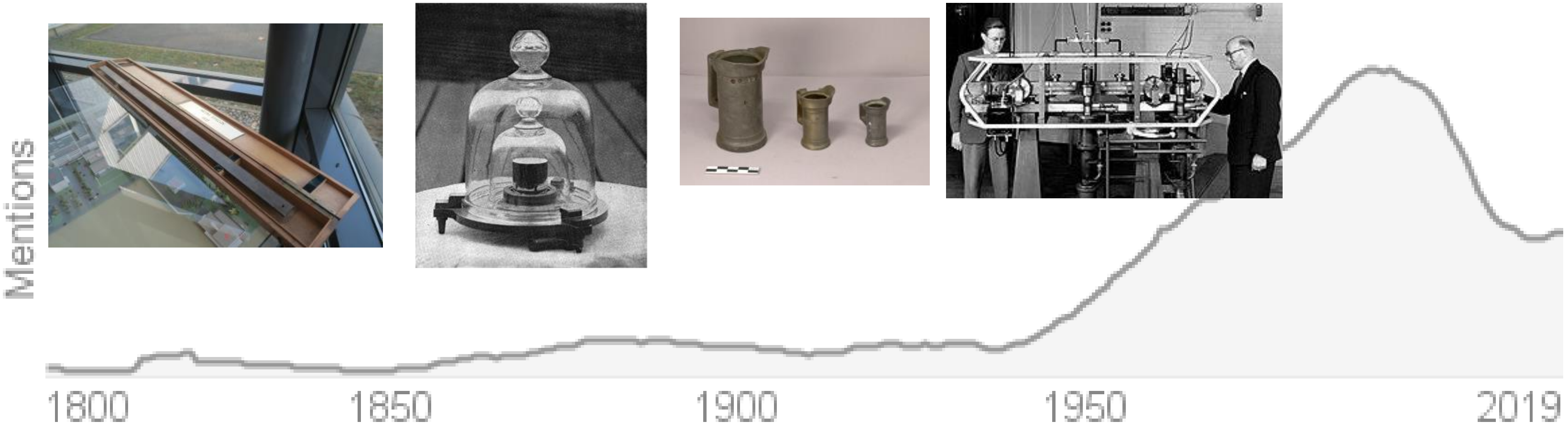
Metrology: what is about ?

Not the same as Meteorology

Meaning: Greek's « Metron » - « Logos » (The study of measurements)

An official definition: « Metrology is the science of measurement; it encompasses both experimental and theoretical determinations at all levels of uncertainty and in all fields of science and technology » (International Bureau of Weights and Measures, BIPM)

Roots in the French Revolution's political motivation to standardise units in France starting with a length standard : creation of the decimal-based metric system in 1795



Metrology: missions

The definition of units of measurement

The realization of the units of measurement in practice : primary standards

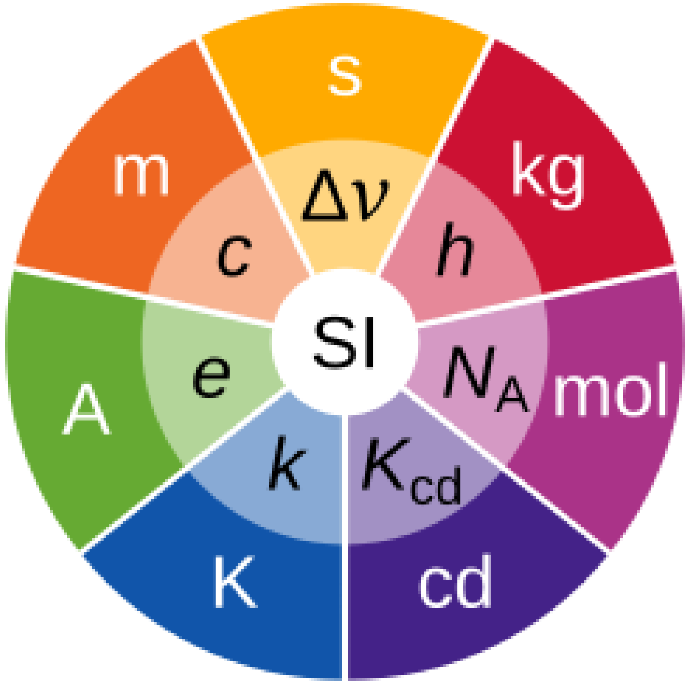
Traceability—linking on-field measurements to the primary standards

And in all fields of daily life, we find the notion of metrology

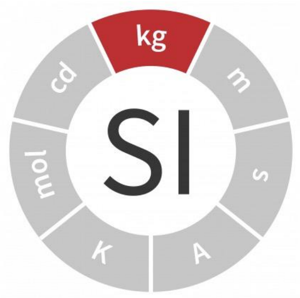
Metrology: missions

The definition of units of measurement

The seven SI's base units



And the derived units



Kilogram derived units

Quantity	Unit	Expressed in terms of SI based units
force	newton (N)	$m.kg.s^{-2}$
pressure	pascal (Pa)	$m^{-1}.kg.s^{-2}$
electric potential difference	volt (V)	$m^{2}.kg.s^{-3}.A^{-1}$
energy	joule (J)	$m^{2}.kg.s^{-2}$
power, radiant flux	watt (W)	$m^{2}.kg.s^{-3}$

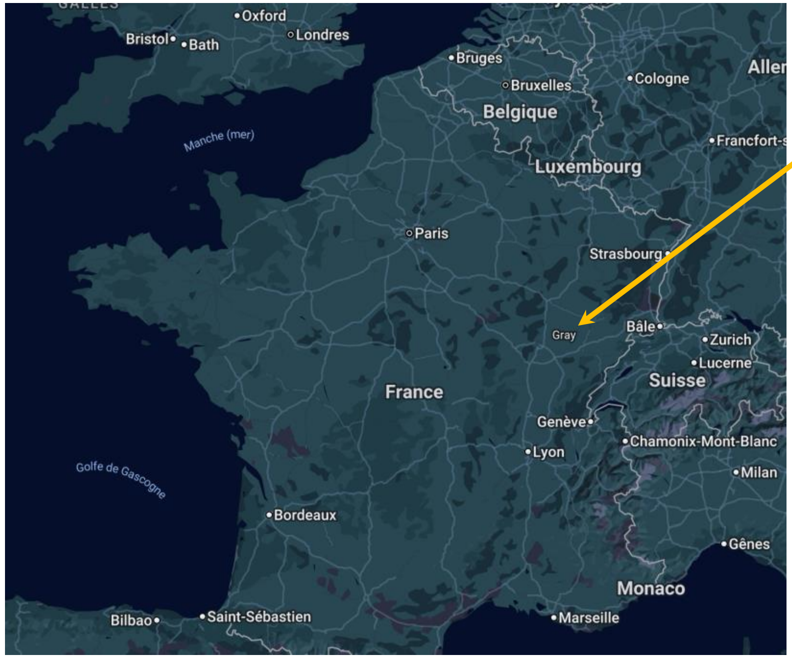
Second derived units

Quantity	Unit	Expressed in terms of SI based units
frequency	hertz (Hz)	s^{-1}
activity refered to a radionucleide	becquerel (Bq)	s^{-1}
dose equivalent	sievert (Sv)	$m^{2}.s^{-2}$
absorbed dose	gray (Gy)	$m^{2}.s^{-2}$

Metrology: missions

The definition of units of measurement

Gray

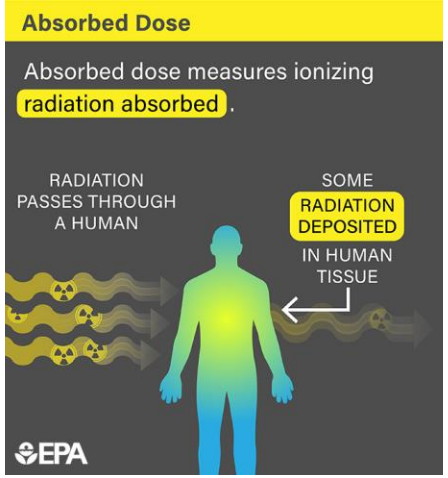


Ville de GRAY

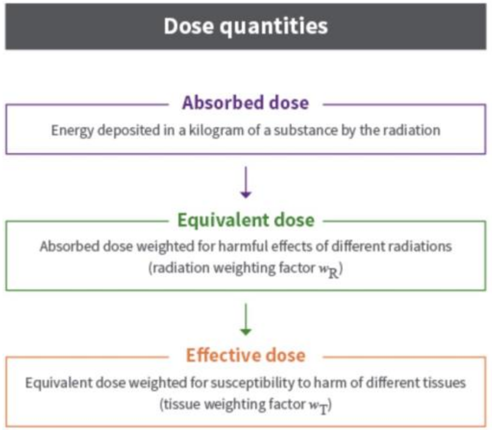
Gray – 70100

Cités de caractère BOURGOGNE FRANCHE-COMTÉ

The Gray (Gy): the unit of ionizing radiation dose in the SI; defined as the absorption of 1 Joule of radiation energy per kilogram of matter



Unit system	SI
Unit of	absorbed dose of ionizing radiation
Symbol	Gy
Named after	Louis Harold Gray
Conversions	
1 Gy *in ...*	*... is equal to ...*
SI base units	$m^2 \cdot s^{-2}$
CGS units (non-SI)	100 rad



Metrology: missions

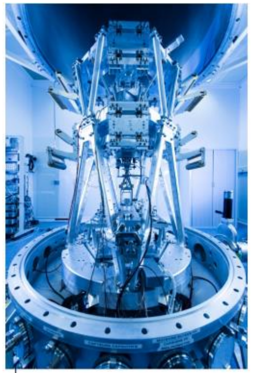
The realization of the units of measurement in practice : primary standards

The measurement of a quantity Q is :

- A numerical value {Q}
- A unit [Q]
- A measurement uncertainty

The primary standards

- The above elements must be delivered with **the best possible accuracy achievable for the quantity**
- Are used for ongoing calibrations of other instruments, they must offer:
  - **Durability**: their stability over time must be sufficient and adapted to the need
  - **Uniformity**: sampling should not alter its accuracy
  - **Accessibility**: calibrations must be easy to make and at the moment when the need is expressed

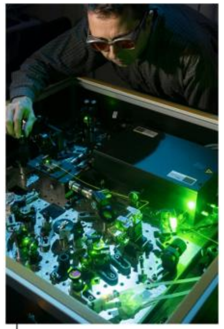


The LNE's Kibble balance, used to produce the value of the Planck constant, h

The kilogram
Fixed numerical value of the Planck constant $h = 6.626\,070\,15 \times 10^{-34}$ J·s ($kg \cdot m^2 \cdot s^{-1}$)
Uncertainty 10^{-8}

Atomic clock

The second
Duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom
Uncertainty 10^{-16}



The LNE's femtosecond laser, used for practical realization of the meter

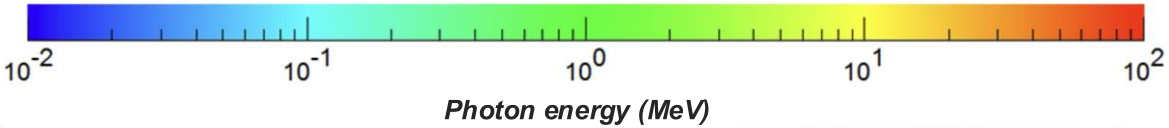
The meter
Length of the path travelled by light in vacuum during a time interval of 1/299,792,458 of a second
Uncertainty 10^{-9}

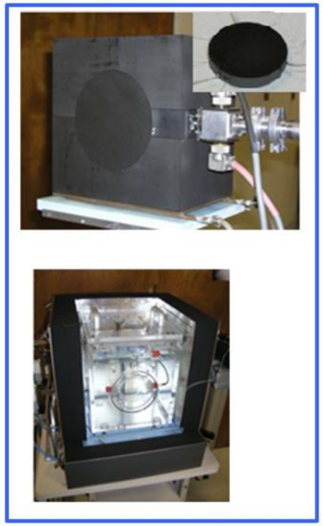
Metrology: missions

The realization of the units of measurement in practice : primary standards

<u>The Gray</u>

Variety of radiation types and interacting media: an unique primary standard is not feasible





Free-air ionization chambers

Cavity ionization chambers

Calorimeters

Dose quantity to determine in given conditions:

- radiation field
- medium

in one point in the medium

Choice of an instrument sensitive to radiation

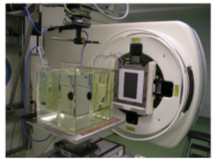
Problem to solve : getting the value of the quantity from the instrument output

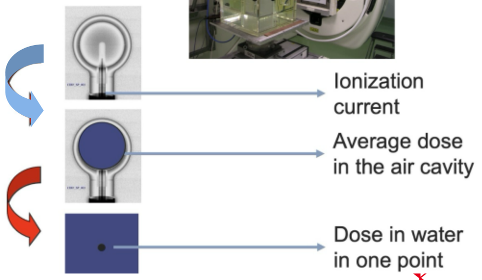
Instrument output

Dose quantity averaged over the sensitive volume

Dose quantity in the media of interest
in one point and in the absence of the instrument

Measuring the reference quantity for radiotherapy D_W



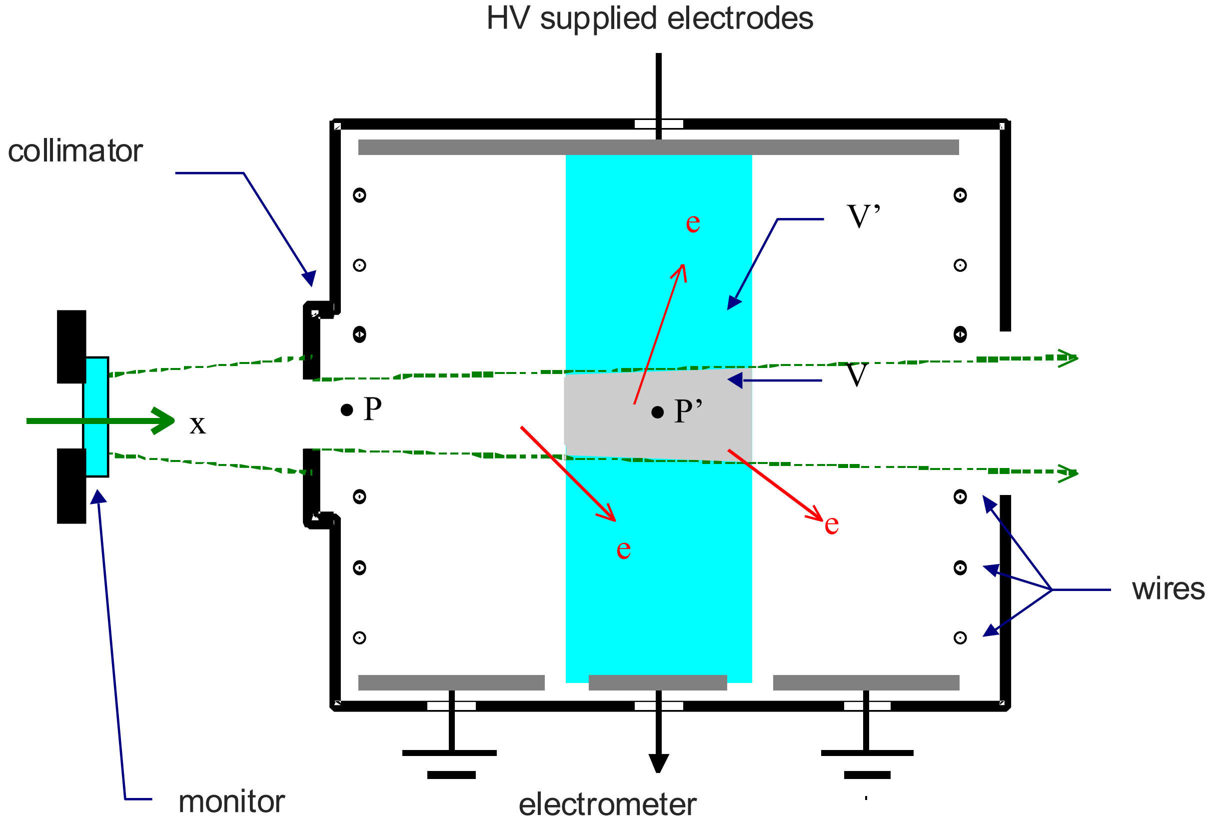


Metrology: missions

The realization of the units of measurement in practice : primary standards

The Gray : X-Ray imagery, low-energy radiotherapy - TRS beams; radiation protection - ISO beams

Free-air ionization chamber

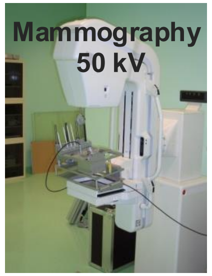


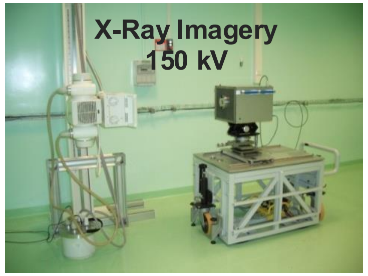
$$K_{air} = X \frac{W_{air}}{e} \frac{1}{1-g} = \frac{Q}{m} \frac{W_{air}}{e} \frac{1}{1-g} \prod_i k_i \pm 0{,}4\%$$

Corrections k_i : - photon attenuation in air between P and P'
- photon scattering
- charges recombination
- T, P, H
- electron loss before collection

Sensitive air volume V
Electron equilibrium at P'

Chamber ID	WK07	MD03	WK06
KV range	10-60	40-150	60-300
Electron equilibrium PP' (cm)	7,2	20,4	31,8
Sensitive volume (cm^3)	0,402	3,781	4,783



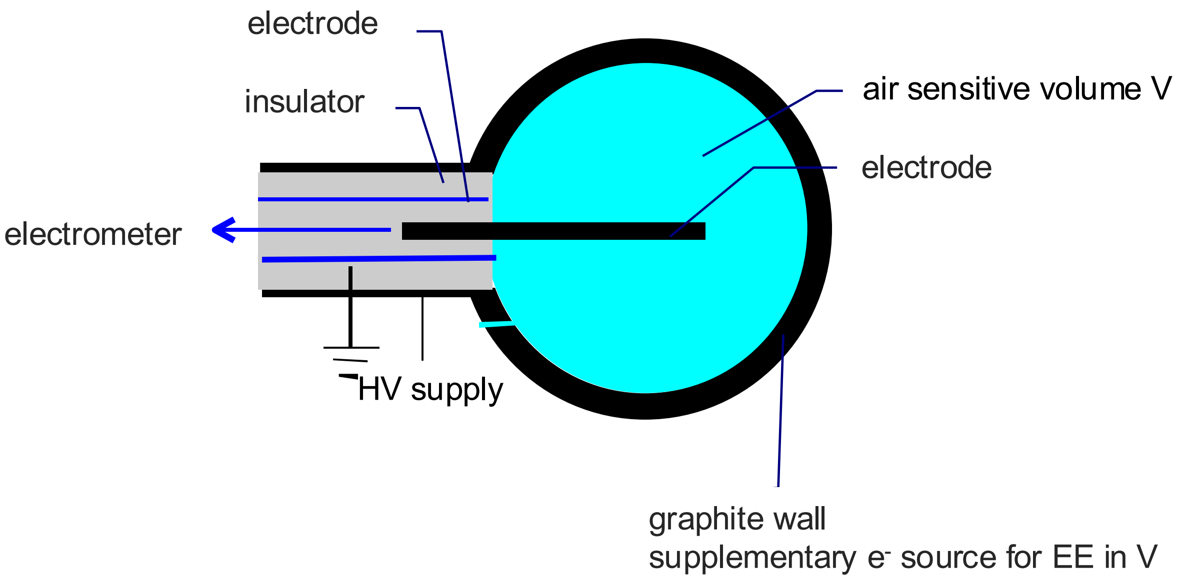


Metrology: missions

The realization of the units of measurement in practice : primary standards

The Gray : Radiation protection ^{137}Cs, ^{60}Co - ISO beams

Cavity ionization chamber



$$K_{air} = \frac{Q}{m}\frac{W_g}{e}\frac{k_w}{\beta_w(1-g_{air})}s_{w,g}\left(\frac{\mu_{en}}{\rho}\right)_{g,w}\prod_i k_i \pm 0{,}38\%$$

Corrections k_i : - T, P, H
- charges recombination
- HV polarity +/-

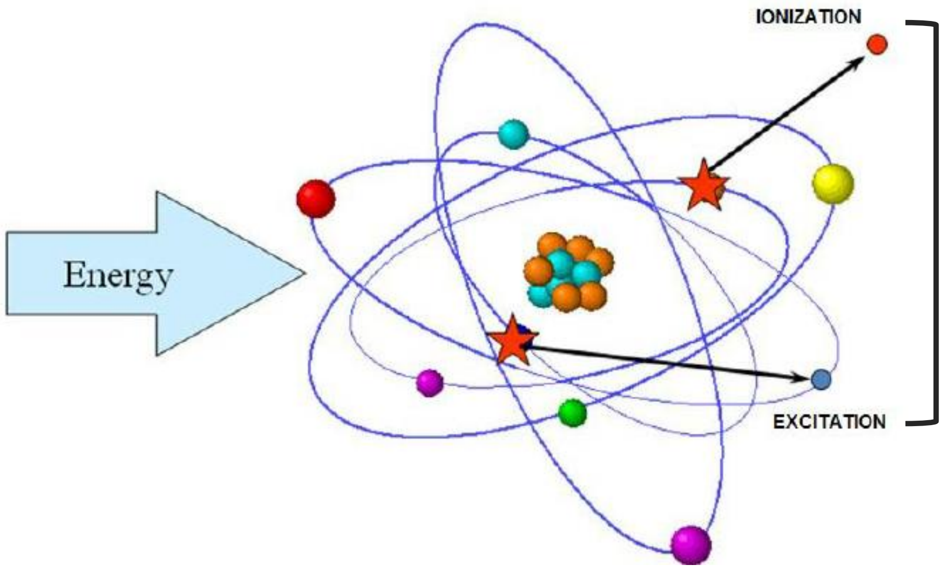
Metrology: missions

The realization of the units of measurement in practice : primary standards

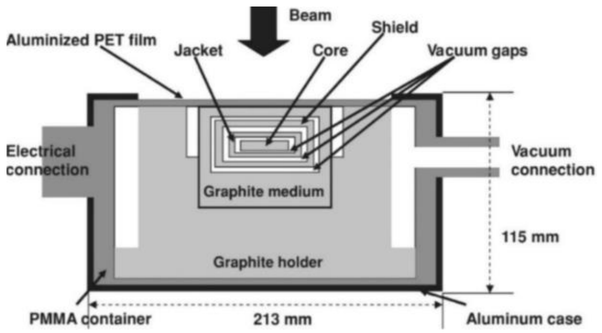
<u>The Gray : Radiotherapy – TRS 398 beams</u>

Calorimeters

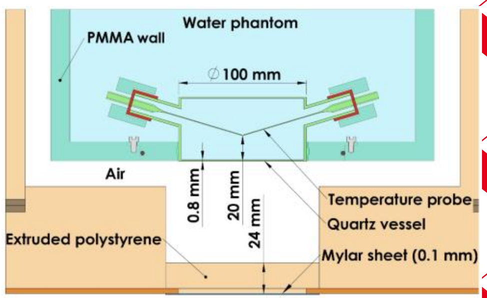
Ionization chambers
absorbed energy limitation



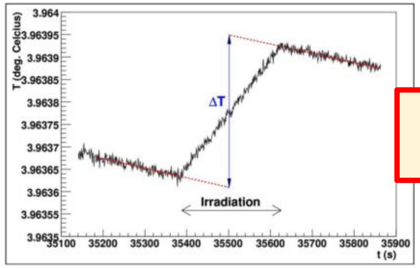
Heat



Graphite



Water



$$\Delta T \, c_p \frac{1}{r_{cal}} \prod_i k_i = \frac{Q}{m} \frac{1}{r_{cal}} = D \pm (0{,}4 - 0{,}6\%)$$

Corrections k_i : vacuum gaps
materials ≄ graphite

Corrections k_i : heat diffusion
ρ=f(T)
materials ≄ water

Benefit: solid
sensitivity 1,4 mK/Gy

Drawback: requires $D_g \rightarrow D_W$
Monte-Carlo – uncertainty ++

Benefit: straight to D_W

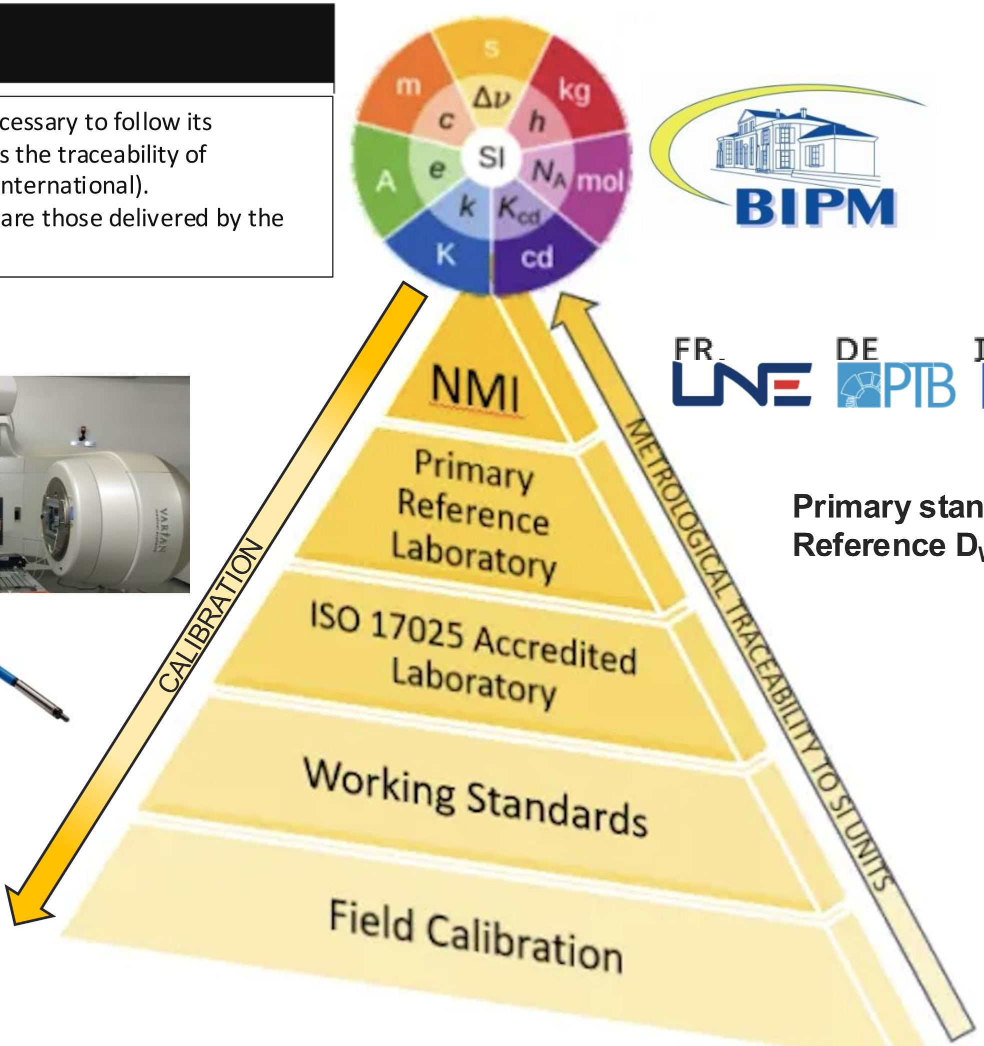
Drawback: liquid (convection)
sensitivity 0,2 mK/Gy
radiolysis – energy loss

Metrology: missions

Traceability—linking on-field measurements to the primary standards

Key points

1. To have the guarantee to carry out a good measurement, it is necessary to follow its instrumentation and its drifts by regular calibrations. This ensures the traceability of measurements made with the highest level standards (national, international).
2. The references with the best uncertainties on the National scale are those delivered by the National metrology network.



BIPM

FR LNE · DE PTB · IT ENEA · GB NPL · US NIST

Primary standard measurement
Reference $D_W(ref)$

IC calibration
$N_{Dw} = D_W(ref) / L$

Calibrated IC measurement
Treatment beam $D_W(clinics) = L \times N_{Dw}$

Metrology: missions

That was for the routine

Metrology is also sustained R&D in the perpetual battle against uncertainties

Metrology: missions

Metrology is also sustained R&D in the perpetual battle against uncertainties

- **Improve the existing primary standards**
  - **Dose in X-Ray imagery: Improve accuracy in measuring dose to patients and staff**
  - **French regulation : accuracy in dose measurement for QC must be ± 5%**

Reference value

$$K_{air} = X \frac{W_{air}}{e} \frac{1}{1-g} = \frac{Q}{m} \frac{W_{air}}{e} \frac{1}{1-g} \prod_i k_i \pm 0,4\%$$

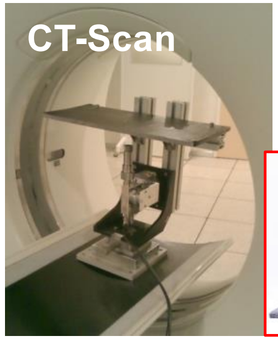
Require knowledge of photon spectra

Calibration laboratory

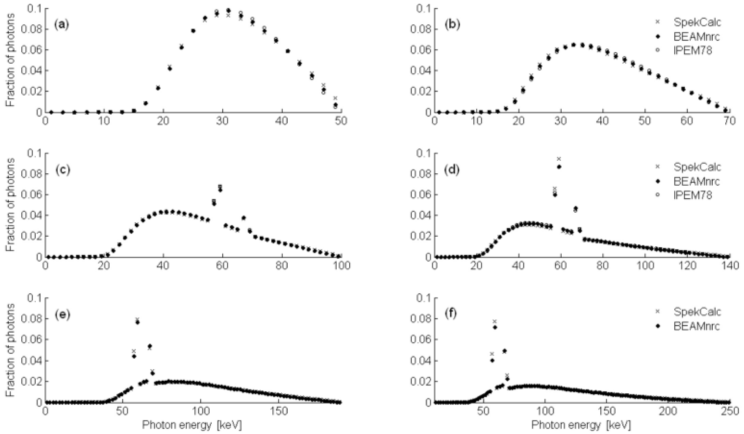
$N_{kair} \pm 1,3\%$ (k=2)

Δ(u) ↙

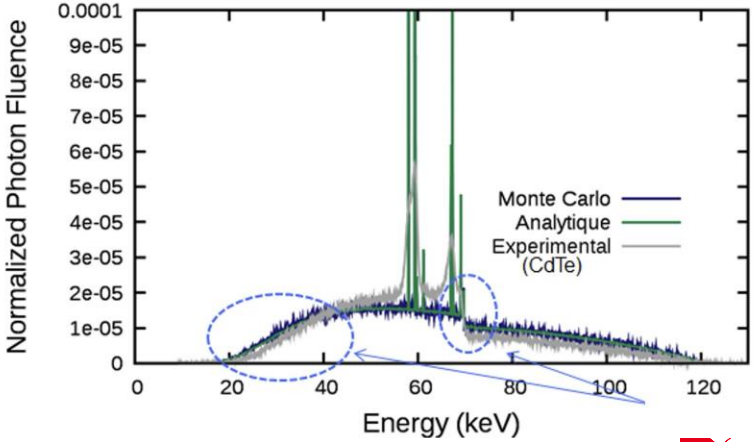
Clinics



Best accuracy when based on the photon spectra actually emitted by the tube



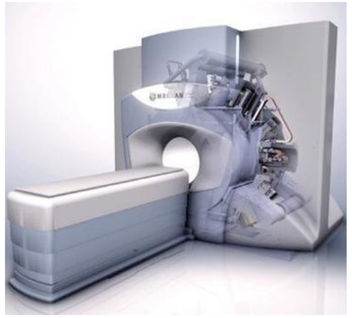
- Codes are mostly theory
- Limited accuracy of models (geometry, materials)
- Does not account for X-Ray tube aging (anode ++) and consequent change in photon spectrum



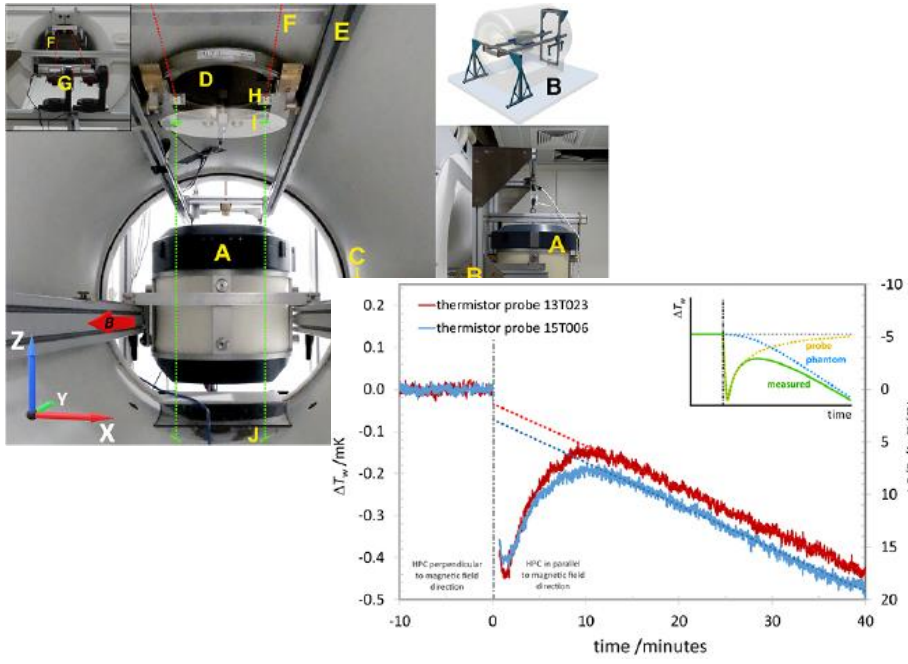
Metrology: missions

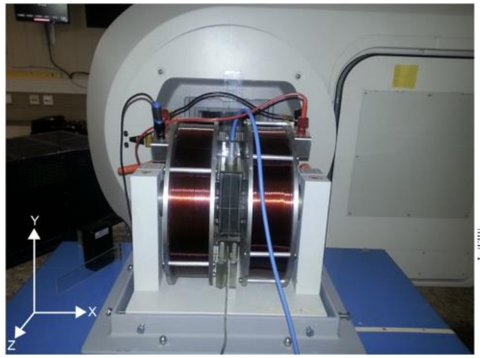
Metrology is also sustained R&D in the perpetual battle against uncertainties

- **New primary standards following the innovations to increase quality of treatments**
  - **MR-guided radiotherapy: New standards design to account for for the influence of B**

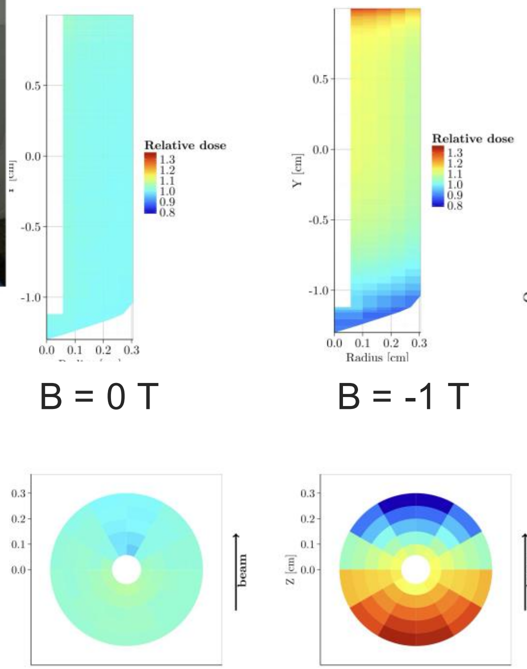


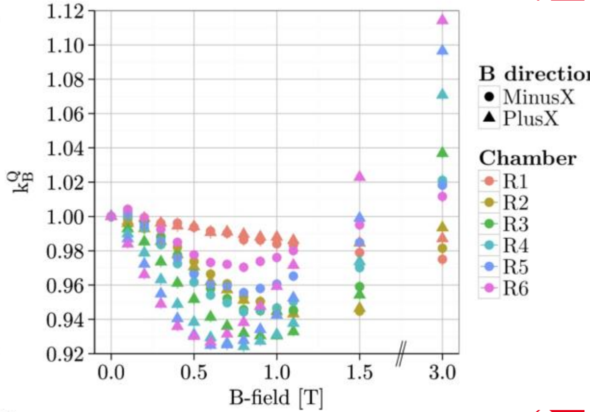
Commissioning of dedicated water calorimeter





(a)





Correction to the response of Farmer-type IC

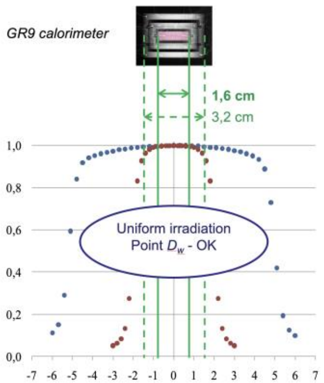
Metrology: missions

Metrology is also sustained R&D in the perpetual battle against uncertainties

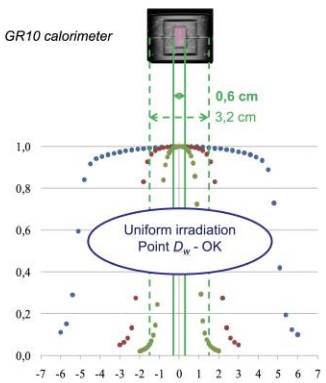
- **New primary standards following the innovations to increase quality of treatments**
  - **Small-fields radiotherapy (IMRT, VMAT, SRT, SRS, …) : Overcome limits of existing standards**

Implementation of a new methodology for primary standards

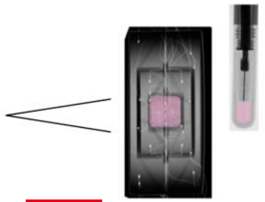
4 x 4 cm^2 field



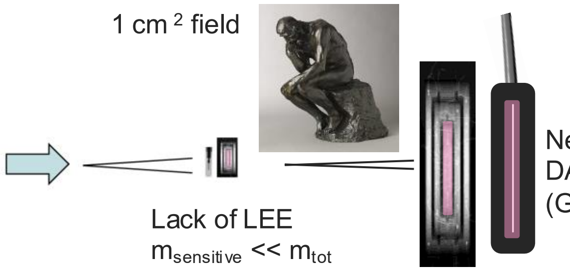
2 x 2 cm^2 field



2 x 2 cm^2 field



1 cm ^{2} field

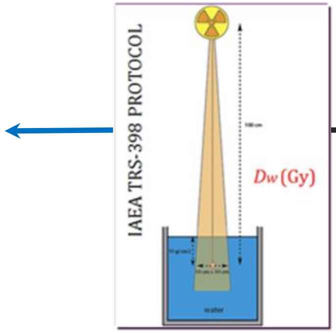


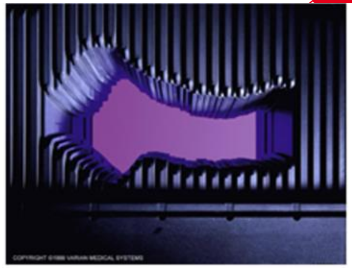
Lack of LEE

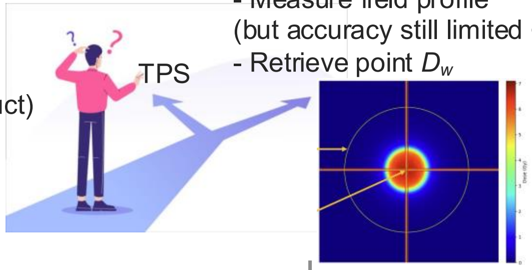
$m_{sensitive} << m_{tot}$

New reference quantity
DAP (Dose Area Proiduct)
(Gy . cm^2)

Irradiation under non-reference conditions is now the norm
(especially use of smaller fields)







- Measure field profile
(but accuracy still limited ~2%)
- Retrieve point D_w

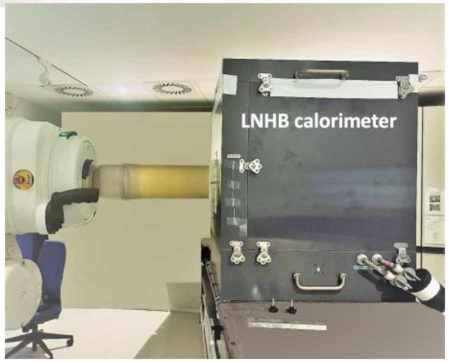
Metrology: missions

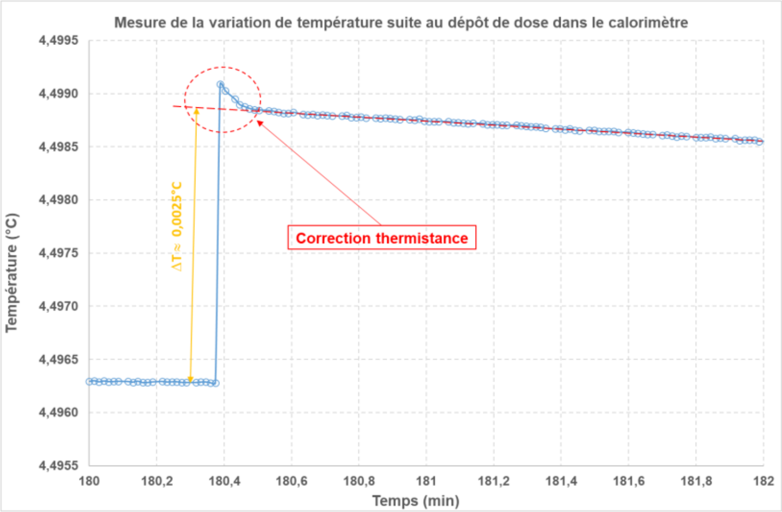
Metrology is also sustained R&D in the perpetual battle against uncertainties

- **New primary standards following the innovations to increase quality of treatments**
  - **Flash radiotherapy: New standards and QC instruments design to account for the influence of ΔD/Δt**

First water calorimetry measurement performed in a Flash beam

Flashknife
Institut Goustave Roussy
9 MeV electrons
100 Gy/s





Future measurements for a new prototype (2027)

FRATHEA
Institut Curie, CEA, THALES
VHEE 200 MeV electrons
10 Gy/100 msec

Final thoughts

The SI allows all countries to synchronize to the same universal standards to ensure consistent measurements worldwide.

Metrology must be perceived by the communities dealing with measurements as the provider of the calibration to the most reliable and accurate standards to help assure the safe use of products.
And so as a guarantee since without calibration, we risk relying on measurements and measurement tools that could be incorrect - a risk that can very quickly escalate to hazardous, even deadly situations.

But metrology can be slow in providing appropriate standards in due time in fields with very (too) rapid technological evolution (sometimes driven primarly by bussiness considerations):

- **measuring at the metrology precision level is always a technically complex problem which takes time to solve**
- **sometimes stronger commitment than usual is needed from the final user (e.g., allow access to a specific equipment as the only way to establish the appopriate primary standard**

Without precision the standardization is impossible and the metrology has exclusive responsibility in providing the tools
But so should be for the commercialization and use of any measurement product without proper calibration and this this also involves user awareness

Thank you for your attention

and for your daily efforts for an improved patients healthcare

Have a nice and enriching conference

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