Accuracy, Calibration, Type Testing and Traceability

General

[Chapter 6 & 7 of RP 160]

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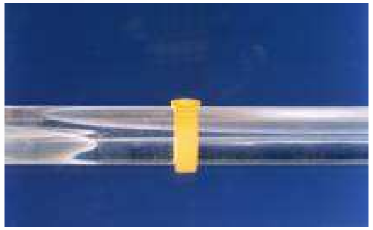
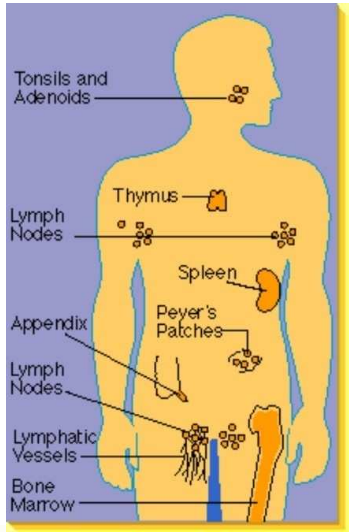
PTB

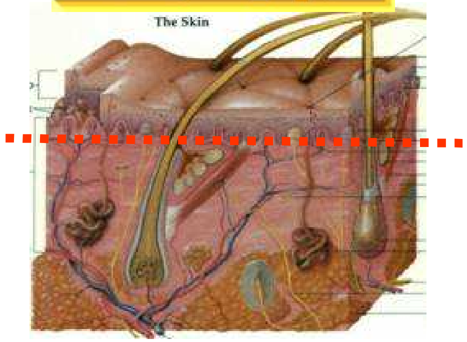
Content

- Introduction
  - Aim of Measurement & type of requirements
- Recommendations on overall uncertainty
- Terms
- Accuracy/Uncertainty of dose assessment
- Type test ⇔ Calibration ⇔ Verification
- Requirements from IEC 62387:2012
- Special considerations
  - Charged particle equilibrium
  - High energy photons
  - Pulsed radiation
  - Personal ⇔ Area dosemeters
  - Algorithms
- Summary

Introduction: Aim of Measurement







Definition of operational quantities

Measurement result ≈ Operational quantity ≳ Body dose quantity (E, H_T)

Calibration and Type Testing

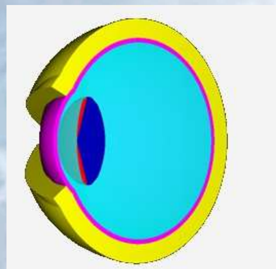
Introduction: Type of requirements

- **Technical requirements on ~~area~~/individual dosemeter**
  - limit
    - maximum of $|\text{measured value} - \text{quantity value}|$
    - maximum overall uncertainty
    - maximum deviation from linearity
  - for
    - rated ranges for measuring quantity
    - rated ranges for influence quantities

- **Requirements on dosemeter position**
  - correct wearing position of whole body dosemeter, e.g., under/over lead apron
  - correct wearing position of finger ring
  - correct wearing position of eye dosemeter

- **Requirements on assessment of annual dose**
  - overall uncertainty of annual dose
  - data security

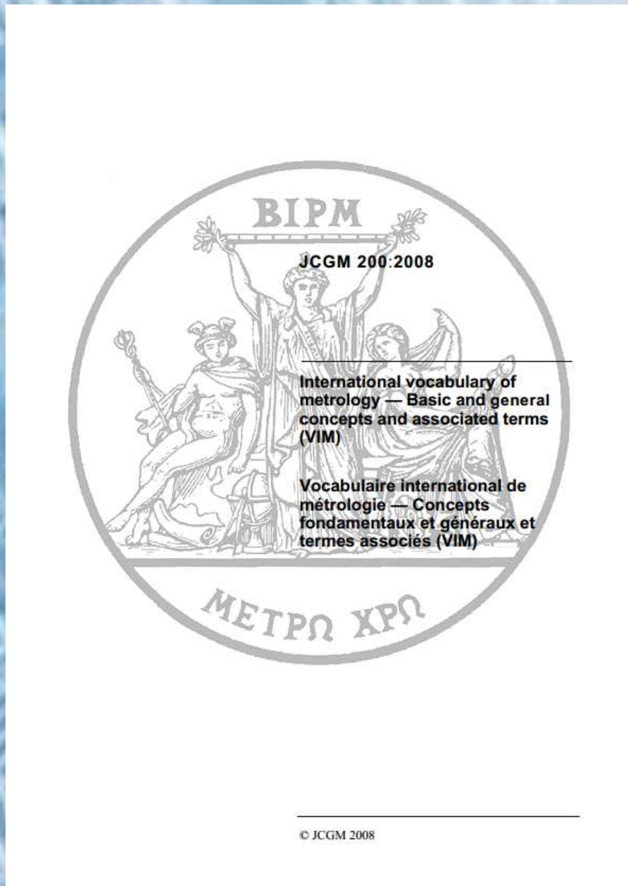
Recommendations on overall uncertainty



- **Quantity $H_p(10)$ for Photon radiation**
  std. uncertainty $\boldsymbol{u} \leq$ **30 %** for $H_p(10) \geq 1$ mSv
- **Quantity $H_p(10)$ for Neuton radiation**
  std. uncertainty $\boldsymbol{u} \leq$ **50 %** for $H_p(10) \geq 1$ mSv
- **Quantity $H_p(3)$ for Photon/Beta radiation**
  std. uncertainty $\boldsymbol{u} \leq$ **30 %** for $H_p(3) \geq 15$ mSv → 1 mSv ?
- **Quantity $H_p(0.07)$ for Photon/Beta radiation**
  std. uncertainty $\boldsymbol{u} \leq$ **30 %** for $H_p(0.07) \geq 50$ mSv

- **Annual dose at or near the limits**
  - annual dose = mean value of ≥ 12 measurements
  - std. uncertainty $\boldsymbol{u} \leq$ **20 %**
  - 95 % confidence interval: **(1/1.5) ≈ 0.67 to 1.5**
  - figure of **1.5** given by ICRP

Terms [General from VIM]


BIPM

JCGM 200:2008

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

Vocabulaire international de métrologie — Concepts fondamentaux et généraux et termes associés (VIM)

ΜΕΤΡΩ ΧΡΩ

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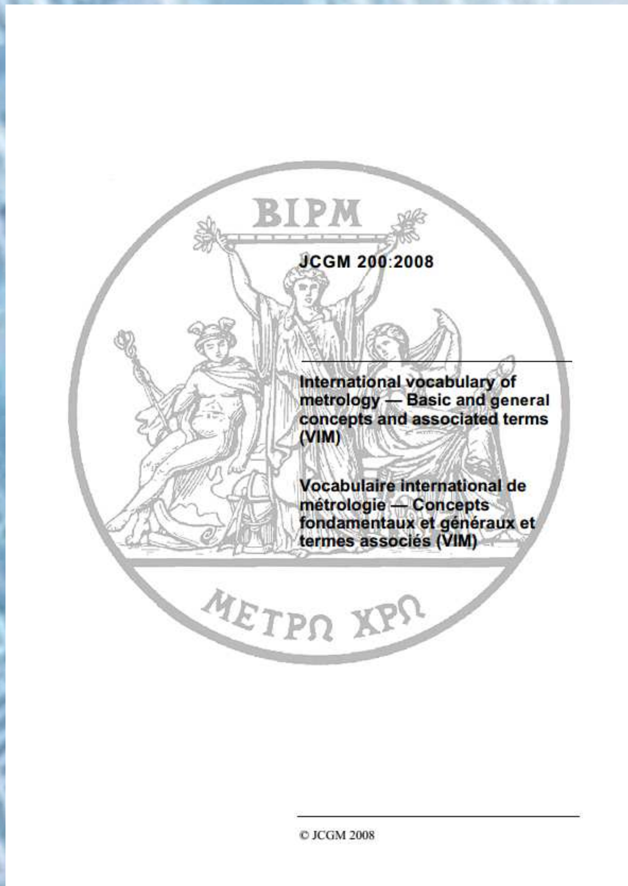
- **Quantity [VIM 1.1]**
  property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference

  NOTE 2 A reference can be a measurement unit, a …
- **Quantity value [VIM 1.19]**
  number and reference together expressing magnitude of a **quantity**

  EXAMPLE 1 Length of a given rod: 5.34 m or 534 cm
- **Measurement result [VIM 2.9]**
  set of **quantity values** being attributed to a **measurand** together with any other available relevant information

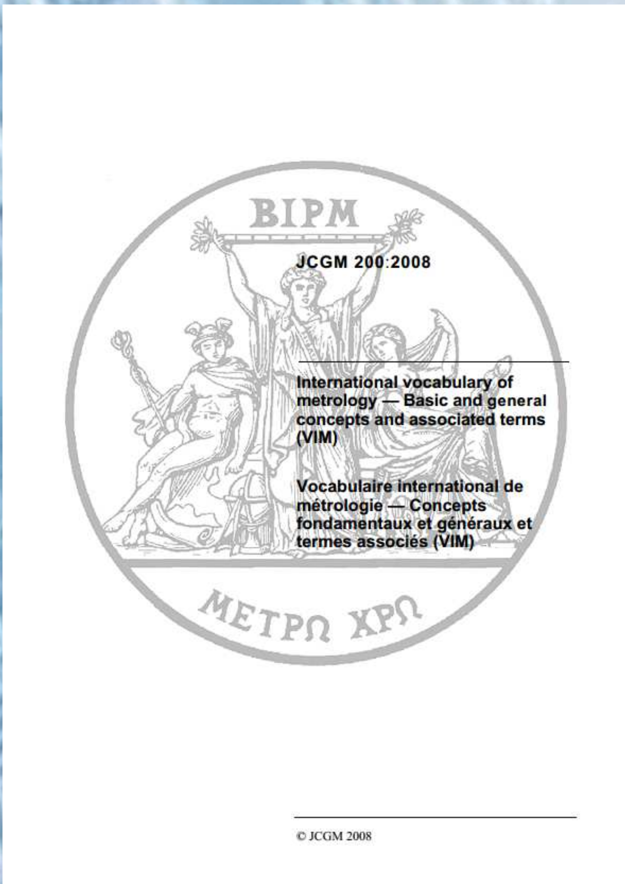
  NOTE 2 A measurement result is generally expressed as a single measured quantity value <u>**and**</u> a measurement uncertainty

Terms [Accuracy etc.]



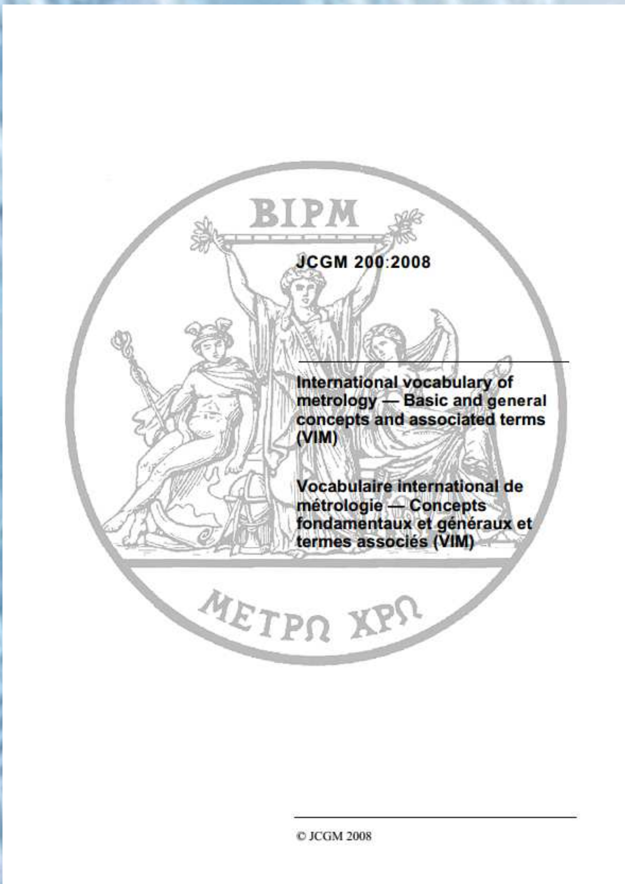
- **Accuracy [VIM 2.13]**
  - **Classical (Error) approach:**
    Δ = measured quantity value - true quantity value
  - **Uncertainty approach:**
    no numerical value, a **measurement** is said to be more accurate when it offers a smaller **measurement error**
- **Trueness [VIM 2.14]**
  closeness of agreement between the average of an infinite number of replicate **measured quantity values** and a **reference quantity value**
- **Bias [VIM 2.18]**
  estimate of a **systematic measurement error**
- **Precision [VIM 2.15]**
  closeness of agreement between **indications** or **measured quantity values** obtained by replicate **measurements** on the same or similar objects under specified conditions
- **Error [VIM 2.16]**
  Δ = measured quantity value - reference quantity value

Terms [Indication]



- **Indication [VIM 4.2]**
  quantity value provided by a measuring instrument or a measuring system
- **Influence quantity [VIM 2.52]**
  quantity that, in a direct **measurement**, does not affect the quantity that is actually measured, but affects the relation between the **indication** and the **measurement result**
- **Background (blank) indication [VIM 4.2]**
  indication obtained from a phenomenon, body, or substance similar to the one under investigation, but for which a **quantity** of interest is supposed not to be present, or is not contributing to the indication
- **Natural (radiation) background**
  radiation not produced by the artificial radiation field

Terms [Traceability]

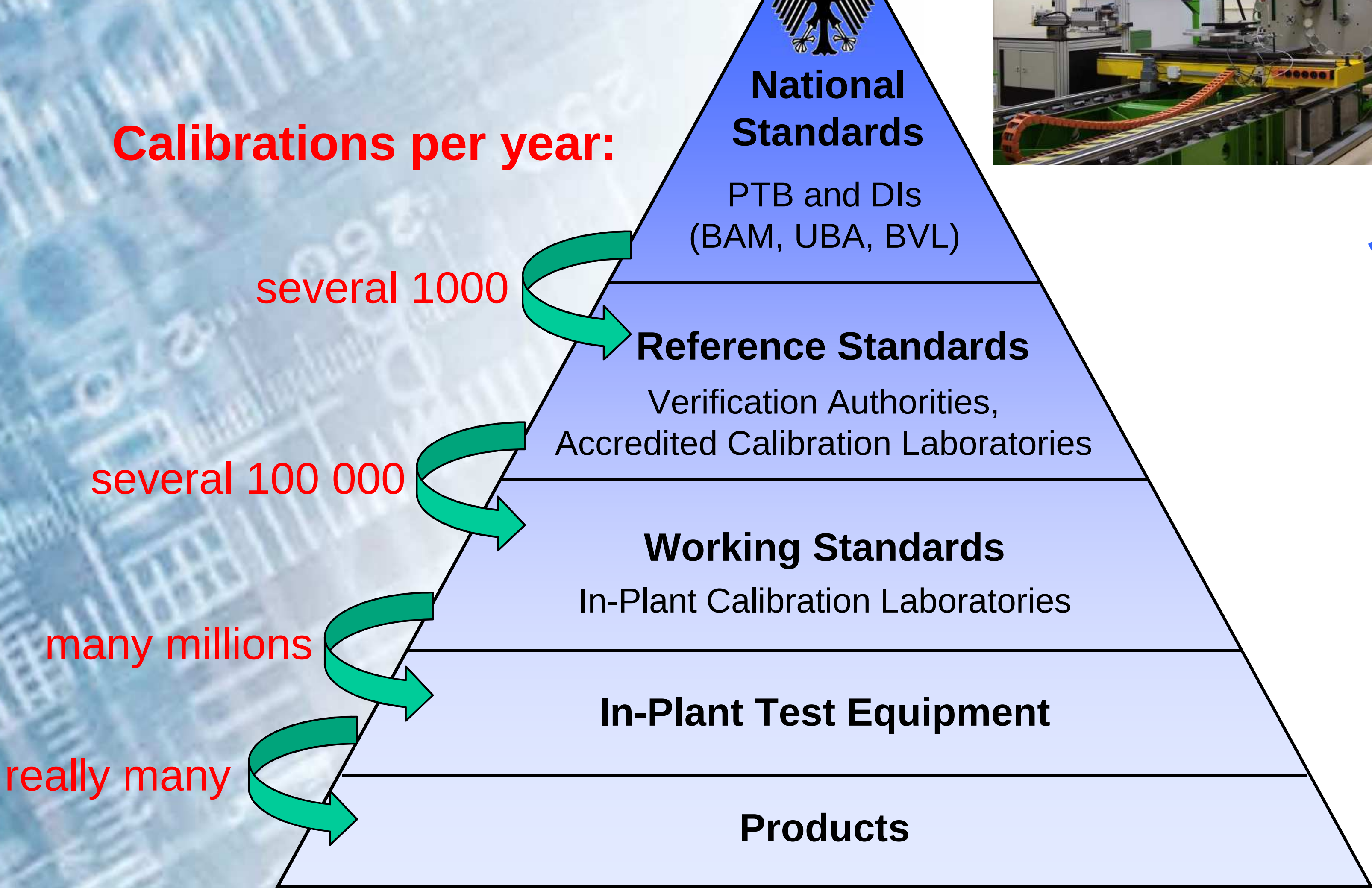


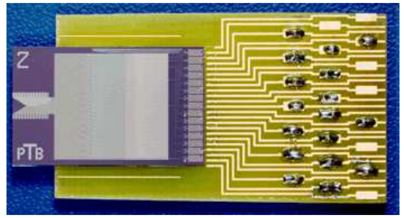
- **metrological traceability [VIM 2.41]**
  property of a **measurement result** whereby the result can be related to a reference through a documented unbroken chain of **calibrations,** each contributing to the **measurement uncertainty**
- **Metrological traceability chain [VIM 2.42]**
  sequence of **measurement standards** and **calibrations** that is used to relate a **measurement result** to a reference

  NOTE 1 A metrological traceability chain is defined through a **calibration hierarchy.**
- **calibration hierarchy [VIM 2.40]**
  sequence of **calibrations** from a reference to the final **measuring system,** where the outcome of each calibration depends on the outcome of the previous calibration

  NOTE 1 Measurement uncertainty necessarily increases along the sequence of calibrations**.**

Calibration hierarchy, National





Calibration hierarchy, International

1875: The Meter Convention

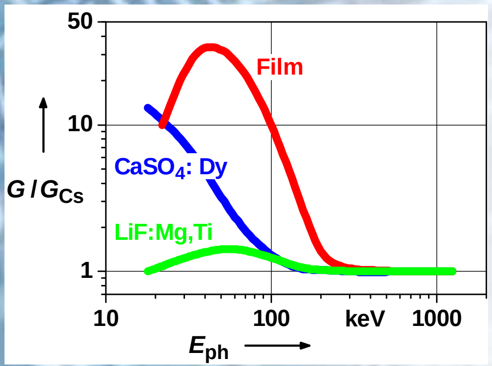
→ Long-standing international cooperation!

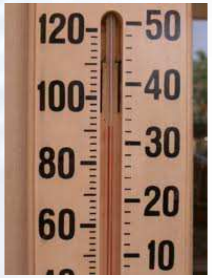
1999: Mutual Recognition Arrangement (MRA)

→ Measured once, accepted everywhere

- The MRA requires "key comparisons" every 10 years for each "Calibration and Measurement Capabilities" (CMC) entry,
  e.g., $H_p(10)$; X-ray (50 kV to 420 kV); 3 % (k = 2); PTB Germany
- One coordinating authority per country – PTB in Germany
- Several designated institutes (DI) per country possible – BAM, UBA, BVL

Accuracy/Uncertainty of dose assessment





- **Assessment := Measurement + Corrections**
  corrections depend on knowledge
- **General model function of dosemeter (one detector)**

$$M_{\text{dos}} = N \times k_{\text{lin}} \times \prod_{f=1}^{q} k_f \times \left(G_{\text{det}} - \sum_{s=1}^{p} G_s \right)$$

- G_{det} : Signal/indication of the detector/dosemeter
- G_s : Correction summands (influence quant. of type S)
- k_f : Correction factors (influence quantity of type F)
- k_{lin} : Correction factor for non-linearity (no infl. quant.)
- N : Calibration factor
- **Simplified to**

$$M_{\text{dos}} = N \times k_{\text{lin}} \times k_{E,\varphi} \times \left(G_{\text{det}} - G_{\text{zero}} \right)$$

Two levels of correction

$$D_{\mathrm{dos}} = N \times k_{\mathrm{lin}} \times k_{E,\varphi} \times (G_{\mathrm{det}} - G_{\mathrm{zero}})$$

$$M_{\mathrm{corr}} = N \times k_{\mathrm{lin}} \times k_{E,\varphi} \times (D_{\mathrm{dos}} - D_{\mathrm{zero}})$$

- **Correction internal to the dosemeter, examples**
  (G_{det} is the Signal of the detector)
  - indicate measuring quantity
  - non-linearity (dead time)
  - photon energy (by using appropriate filter)
  - background (blank) indication
- **External correction, examples**
  (same symbol doesn't mean same value)
  - calibration factor (close to unity)
  - non-linearity (other than dead time)
  - radiation energy and angle (workplace specific)
  - radiation background depending on location
- **Clear distinction between both possible?**
  - easy: direct reading dosemeter
    ➔ D_{dos} is reading of instrument
  - difficult: self developed dosemeter of IMS
    ➔ D_{dos} is dose value before applying workplace specific corrections

Type test ⇔ Calibration ⇔ Verification

- **Model function for external correction**

$$M_{\mathrm{corr}} = N \times k_{\mathrm{lin}} \times k_{E,\varphi} \times (D_{\mathrm{dos}} - D_{\mathrm{zero}})$$

- M_{corr}: Measured value of the dosemeter
- D_{dos}: Indication of dosemeter
- D_{zero}: Indication due to radiation background or EMC, shock

$$M_{\mathrm{corr}} = H_{\mathrm{irr}}$$

$$H_{\mathrm{irr}}(1-\alpha) \leq N_{\mathrm{Cs}} \times D_{\mathrm{dos}} \leq H_{\mathrm{irr}}(1+\beta)$$

- **Type test:** Determination and limitation of
  k_{lin}, $k_{E,\varphi}$ and D_{zero}
  for rated ranges of dose(rate) and influence quantities
  for the (unchanged) **type** of dosemeter
- **Influence quantities:** independent of each other,
  if not: combine them (e.g. energy and angle)
- **Characterization of dosemeter type**
  - identical design and production (Hardware + Software)
  - manufacturer has responsibility

(Reference) Calibration ⇔ Verification

- **Model function for external correction**

$$M_{\mathrm{corr}} = N \times k_{\mathrm{lin}} \times k_{E,\varphi} \times (D_{\mathrm{dos}} - D_{\mathrm{zero}})$$

- **Reference calibration**
  - Determ. of N for **each** dosem. for **fixed** rad. quality,
    e.g., $N_{\mathrm{Cs}} = 1.13$ or $N_{\text{N-100}} = 5.2$
  - one value for **each** dosemeter
- **Verification**
  - Limitation of N for **each** dosemeter,
    e.g., $0.8 \le N \le 1.2$
  - decision yes/no for **each** dosemeter
- **Calibration**
  - scope of calibration task can vary
  - between type test and reference calibration
  - might be several values for **each (type of)** dosemeter

Uncertainty of dose assessment

- **Model function for external correction**

$$M_{\text{corr}} = N \times k_{\text{lin}} \times k_{E,\varphi} \times (D_{\text{dos}} - D_{\text{zero}})$$

see also **IEC TR 62461:2015-01**
Radiation protection instrumentation – Determination of uncertainty in measurement

M_{corr} = 5.0 mSv ± 1.7 mSv
(k = 2)
(within rated ranges)

- **No information/consideration of workplace conditions**
  - take value of indication D_{dos} (= 5 mSv)
  - assume D_{zero} = 0 mSv and $k_{E,\varphi}$ = k_{lin} = N = 1.0
    ➔ $M_{\text{corr}} = D_{\text{dos}}$
- **Perform uncertainty calculation**
  - take values of standard uncertainties of D_{dos} ; D_{zero} ; $k_{E,\varphi}$; k_{lin} and N from type test results for entire rated range
  - Details of calculation: see tomorrow

Uncertainty of dose assessment

$$M_{\mathrm{corr}} = N \times k_{\mathrm{lin}} \times k_{E,\varphi} \times (D_{\mathrm{dos}} - D_{\mathrm{zero}})$$

- **Model function for external correction**

  see also **IEC TR 62461:2015-01**
  Radiation protection instrumentation – Determination of uncertainty in measurement

M_{corr} = 5.2 mSv ± 0.8 mSv
(k = 2)
(X-rays, $k_{E,\varphi}$ = 1.08
k_{lin} = 0.97)

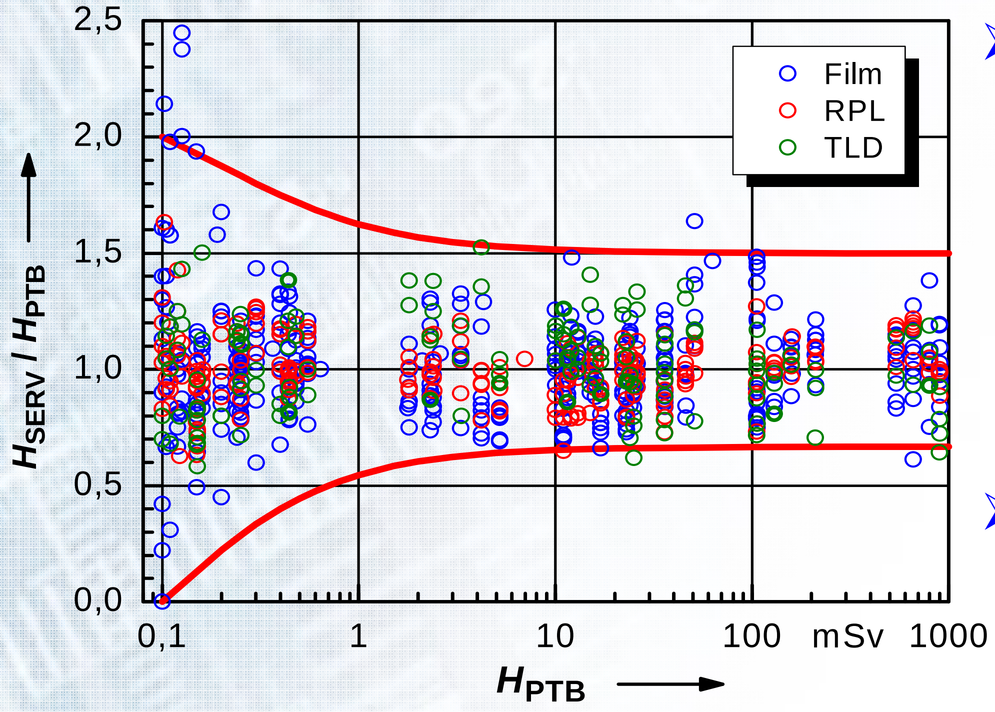
- **Use (Consider) information of workplace conditions**
  - take value of indication D_{dos} (= 5 mSv)
  - take values of D_{zero} = 0 mSv; $k_{E,\varphi}$ = 1.08; k_{lin} =0.97 and N = 1.0 for workplace conditions and this measurement
    ➔ $M_{\mathrm{corr}} = 1.048 \times D_{\mathrm{dos}}$

- **Perform uncertainty calculation**
  - take values of standard uncertainties of D_{dos} ; D_{zero} ; $k_{E,\varphi}$; k_{lin} and N from type test results for workplace conditions and this measurement

  - Details of calculation: see tomorrow

Performance testing

➤ **Routine test on limited number of dosemeters**
- usually 10 to 40 dosemeters
- Example: 10 dosemeters irradiated once a year of any type of dosemeter in use by an IMS



Example: German surprise test for whole body dosemeters

➤ **Requirements**
- 90 % within limits of trumpet curves
- see for details:
  ISO 14146:2000, *Radiation protection — Criteria and performance limits for the periodic evaluation of processors of personal dosemeters (IMS) for X and gamma radiation*

➤ **Organization**
- blind test
- surprise test
- announced test

Two type testing standards IEC/EN 62387

IEC 62387

Edition 1.0 2012-12

INTERNATIONAL STANDARD

Radiation protection instrumentation – Passive integrating dosimetry systems for personal and environmental monitoring of photon and beta radiation

IEC 61066:2006 has been withdrawn

EUROPEAN STANDARD **EN 62387-1**

NORME EUROPÉENNE

EUROPÄISCHE NORM February 2012

ICS 13.280

English version

Radiation protection instrumentation - Passive integrating dosimetry systems for environmental and personal monitoring - Part 1: General characteristics and performance requirements
(IEC 62387-1:2007, modified)

Requirements from IEC 62387, Scope

Table 1 – Mandatory and maximum energy ranges covered by this standard

Measuring quantity	Mandatory energy range for photon radiation	Maximum energy range for testing photon radiation	Mandatory energy range for beta-particle radiation[a]	Maximum energy range for testing beta-particle radiation[a]
$H_p(10)$, $H^*(10)$	80 keV to 1,25 MeV	12 keV to 10 MeV	–	–
$H_p(3)$	30 keV to 250 keV	8 keV to 10 MeV	0,8 MeV almost equivalent to an E_{max} of 2,27 MeV	0,7 MeV[b] to 1,2 MeV almost equivalent to E_{max} from 2,27 MeV to 3,54 MeV
$H_p(0,07)$, $H'(0,07)$	30 keV to 250 keV	8 keV to 10 MeV	0,8 MeV almost equivalent to an E_{max} of 2,27 MeV	0,06 MeV[c] to 1,2 MeV almost equivalent to E_{max} from 0,225 MeV to 3,54 MeV

a The following beta radiation source are suggested for the different mean energies: For 0,06 MeV: ^{147}Pm; for 0,8 MeV: ^{90}Sr/^{90}Y; for 1,2 Mev: ^{106}Ru/^{106}Rh.

b For beta-particle radiation, an energy of 0,7 MeV is required to reach the radiation sensitive layers of the eye lens in a depth of about 3 mm (approximately 3 mm of ICRU tissue).

c For beta-particle radiation, an energy of 0,07 MeV is required to penetrate the dead layer of skin of 0,07 mm (approximately 0,07 mm of ICRU tissue).

Requirements from IEC 62387, $H_p(10)$

Table 8 – Performance requirements for $H_p(10)$ dosemeters

Line	Characteristic under test	Main characteristics or mandatory measuring range or mandatory range of influence quantity	Performance requirement for the rated range	Clause/ Sub-clause
1	Capability of the dosimetry system	Measuring range; influence quantities; t_{max}; model function	To be documented by the manufacturer for the type test	7
2	Requirements to the design of the dosimetry system	Dose indication; information on reader, dosemeter and evaluation algorithm	To be documented by the manufacturer for the type test and checked during type test	8
3	Effects of radiation not intended to be measured	Response to thermal neutrons, ^{252}Cf and ^{252}Cf (D_2O-moderated)	Response to be stated by the manufacturer	8.7
4	Instruction manual	Information for correct use; information about the performance of the system	To be documented by the manufacturer for the type test and checked during type test	9
5	Software, data and interfaces	Authenticity of the software; correctness and integrity of data	To be documented by the manufacturer for the type test and checked during type test	10
6	Coefficient of variation, v	$H < 0{,}1$ mSv $0{,}1$ mSv $\leq H < 1{,}1$ mSv $H \geq 1{,}1$ mSv	15 % $(16 - H/0{,}1$ mSv$)$ % 5 %	11.2

Requirements from IEC 62387, $H_p(10)$

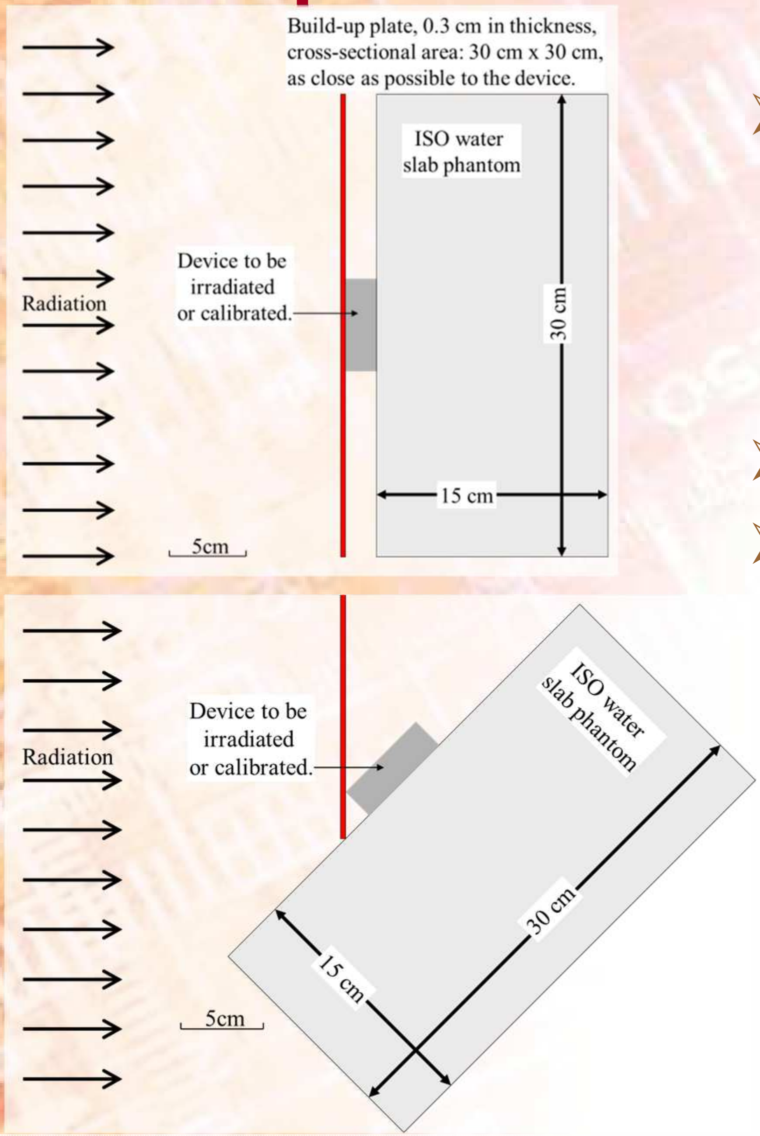
7	Relative response due to non-linearity	0,1 mSv $\leq H \leq$ 1 Sv	–9 % to +11 %	11.3
8	Overload, after-effects, and reusability	10 times the upper limit of the measuring range: $10 \cdot H_{up}$, however at maximum 10 Sv. Reused dosemeters shall fulfil the requirements	Perception to be off-scale on the high end side of the measuring range, after-effects may not cause fault measurements and $v(H_{low})$ shall be according to line 6	11.4
9	Relative response due to mean photon radiation energy and angle of incidence	80 keV to 1,25 MeV and 0° to ± 60° from reference direction	For 12 keV $\leq E_{ph} <$ 33 keV: r_{min} = 0,67 to r_{max} = 2,00 and for 33 keV $\leq E_{ph} <$ 65 keV: r_{min} = 0,69 to r_{max} = 1,82 and for $E_{ph} \geq$ 65 keV: r_{min} = 0,71 to r_{max} = 1,67	11.5.1
10	Relative response due to mean beta radiation energy	0,8 MeV	Indicated value maximal 10 % of $H_p(0{,}07)$ dose equivalent	11.5.2
11	As in lines 9 and 10 but new reference direction opposite to that one used	See lines 9 and 10, if no statement by the manufacturer	See lines 9 and 10, if no statement by the manufacturer	8.4 f)
12	Radiation incidence from the side of the dosemeter	Radiation incidence from 60° to 120°	Indication less than 1,5 times of indication due to irradiation free in air from the front	11.8
13	Response to mixed irradiations	Irradiation with different radiation qualities	Response within ranges of radiation qualities under test	12

Requirements from IEC 62387, $H_p(10)$

14	Total effect due to environmental performance requirements	Temperature, light, time; for details, see Table 13	See Table 13	13
15	Deviation due to electromagnetic performance requirements	See Table 14	See Table 14	14
16	Deviation due to mechanical performance requirements	Drop; for details, see Table 15	$\pm$ 0,7$\cdot H_{low}$ at a dose of H = 7 H_{low}	15

NOTE The non-symmetrical borders of relative responses r are derived from symmetrical borders of correction factors (1/r), for example: ± 40 % for 1/r $\in$ [0,6 .. 1,4] ➔ r $\in$ [1/1,4 .. 1/0,6] = [0,71 .. 1,67]

Special considerations: charged particle equilib.



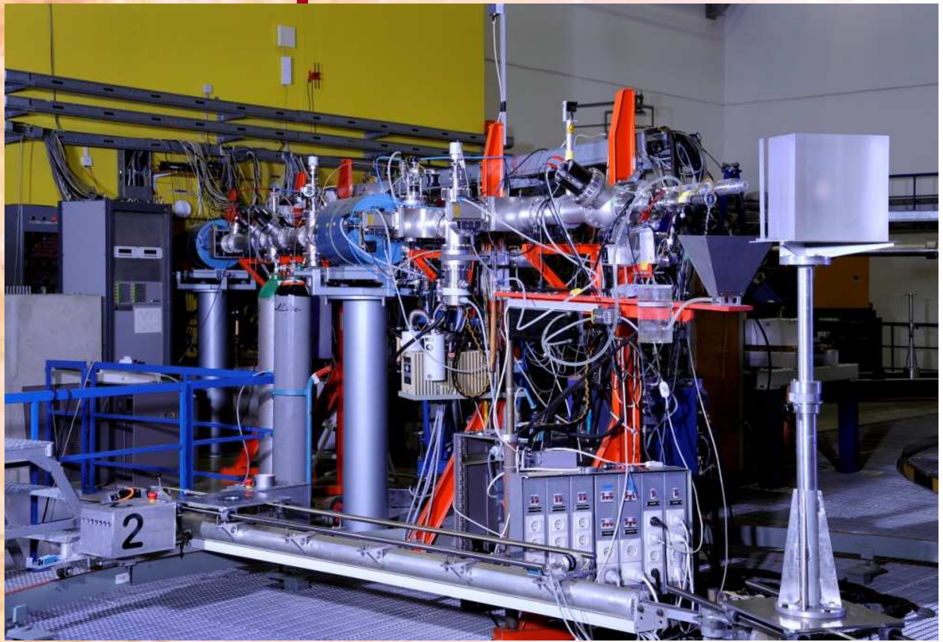
SECONDARY CHARGED PARTICLE EQUILIBRIUM IN ^{137}Cs AND ^{60}Co REFERENCE RADIATION FIELDS

R. Behrens, M. Kowatari and O. Hupe, RPD (2009), **136**, 168–175

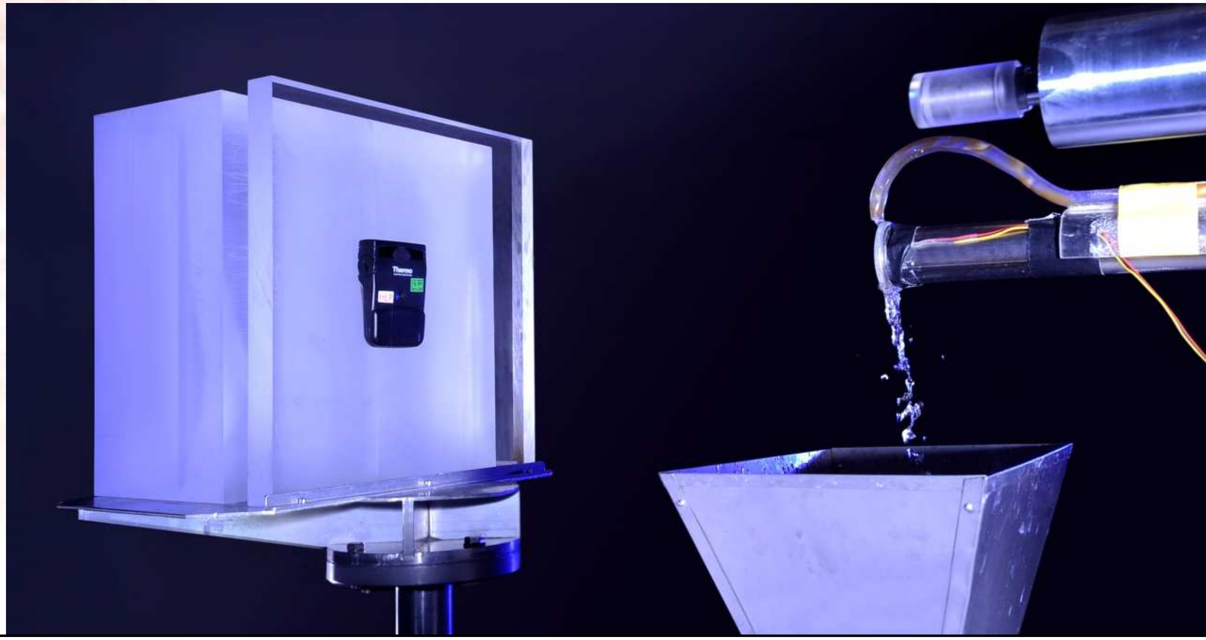
- **Is charged particle equilibrium (CPE) required?**
  - operational quantities are defined with **and** without CPE
  - conversion coefficients are **only** given for CPE
- **Type tests and calibrations always under CPE**
- **Required PMMA build-up layer**
  - see ISO 4037-3:1999
  - position: very close to dosemeter (fingering)

Reference field	Mean energy	PMMA build-up layer
S-Cs	662 keV	2 mm → 3 mm
S-Co	1250 keV	4 mm → 3 mm
R-C	4.36 MeV	25 mm
R-F	6.61 MeV	25 mm

Special considerations: High energy photons



- **Reference fields use nuclear reactions**
  - see ISO 4037-3:1999
  - R-F: $^{19}F(p,\alpha\gamma)^{16}O$, $\bar{E}$ = 6.61 MeV
  - R-C: $^{12}C(p,p'\gamma)^{126}C$, $\bar{E}$ = 4.36 MeV
- **Maximum dose rate for $H_p(10)$**
  - 3 mSv/h at 1 m distance from source



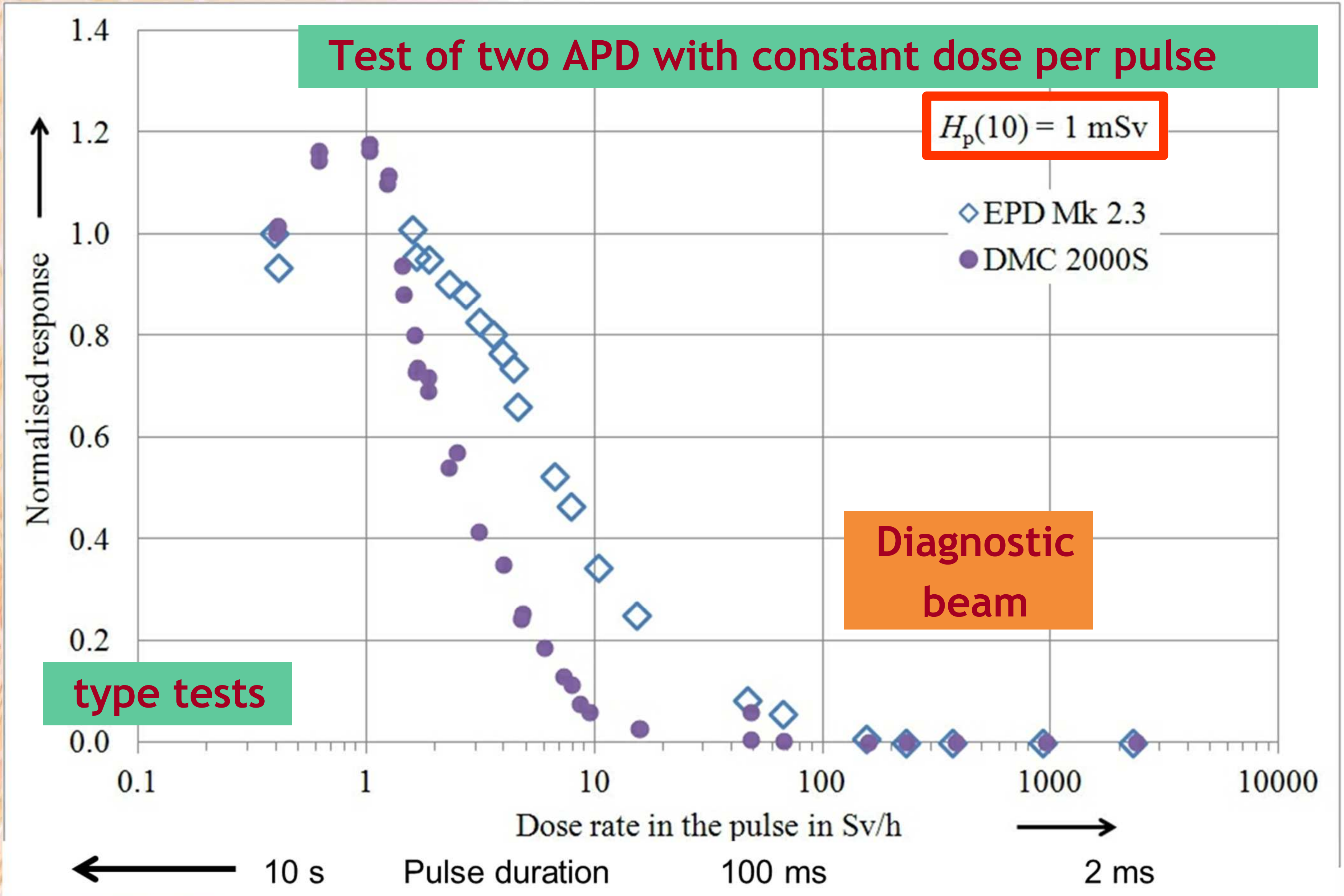
Special considerations: pulsed radiation

Nearly all radiation in medical diagnostics and at accelerators is pulsed!

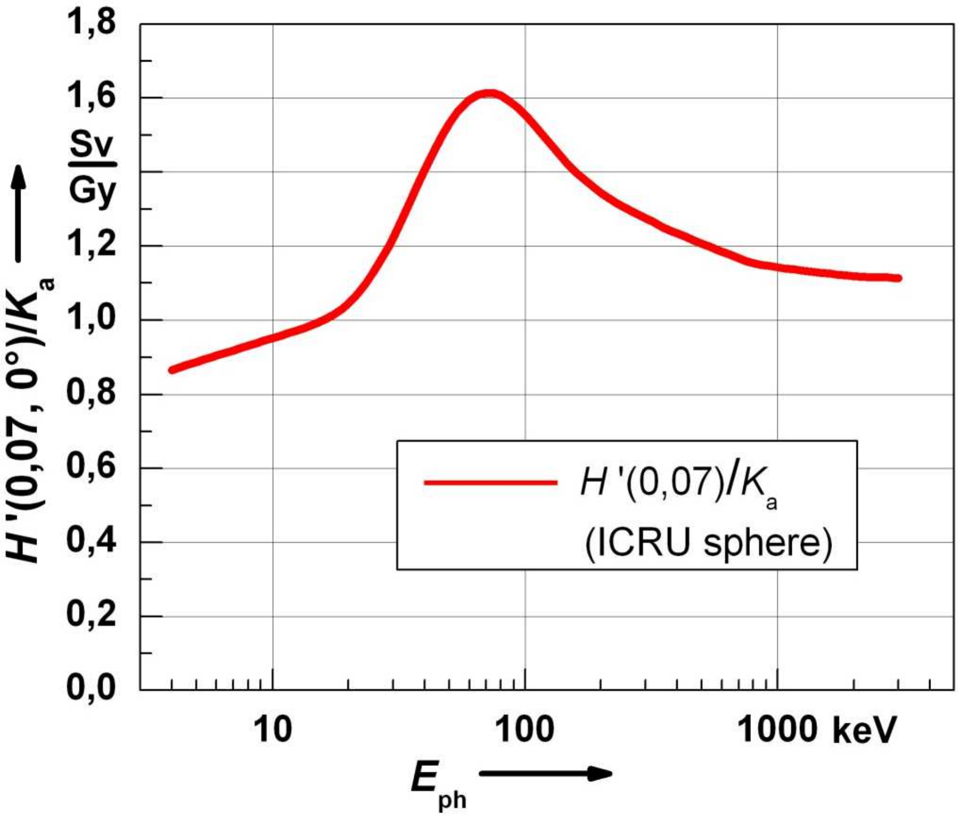
Most direct reading rad. prot. dose-meters use pulse counting techniques

- dead time → maximum dose rate
- short pulses
  → high dose rate in the pulse
- IEC standards
  → no test for pulsed radiation
- **NEW: IEC TS 62743:2012 Ed.1,** *Radiation protection instrumentation - Electronic counting dosemeters for pulsed fields of ionizing radiation*
- **NEW: ISO/FDIS TS 18090-1, Ed.1,** *Characteristics of reference pulsed radiation - Part 1: Photon radiation*

Special considerations: pulsed radiation



Special considerations: personal ⇔ area dosem.



- **Personal dosemeter:**
  phantom is part of measurement
  - field at dosemeter enhanced by backscatter factor (up to 1.6)
  - dosemeter should measure backscattered radiation together with direct radiation
  - indication angle depend
- **Area dosemeter:**
  never use a phantom for measurement
  - "phantom backscatter" included in quantity and design of dosemeter (e.g. by filtration)
  - indication angle independent
- **Conclusion:**
  a personal dosemeter cannot be used to measure area dose

Special considerations: Algorithms

- **Model function for external correction**

$$\boxed{M_{\text{corr}} = N \times k_{\text{lin}} \times k_{E,\varphi} \times (D_{\text{dos}} - D_{\text{zero}})}$$

- **Indication of dosemeter:** D_{dos}
- **Type test:** Determination and limitation of

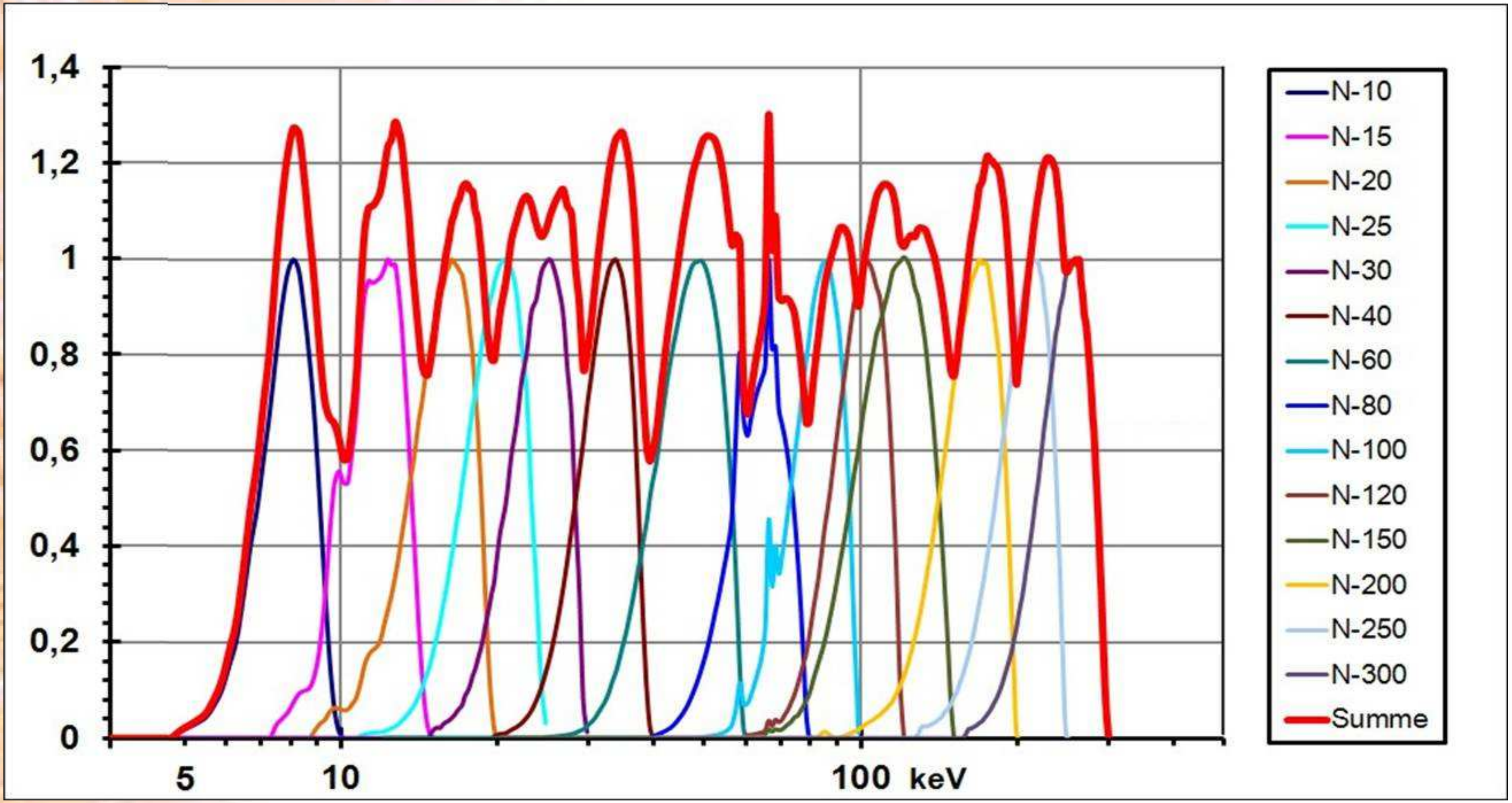
  k_{lin}, $k_{E,\varphi}$ (and other factors) plus

  D_{zero} (and other summands)

  for rated ranges of dose(rate) and influence quantities for the (unchanged) type of dosemeter
- **Influence quantities:** independent of each other
- **Are there any requirements on D_{dos}?**
  - Must be additive (linear) with respect to mixed radiations (with different radiation qualities)
  - Reason: Tests for E, φ performed with narrow spectra and results deemed representative for all spectra

Special considerations: Algorithms

- **Radiation qualities used for type tests**
  - photons: Narrow spectrum series of ISO 4037
  - within given limits any spectrum can be generated (the same applies to the angular distribution)



Special considerations: Algorithms

- Model function for external correction

$$\boxed{M_{\text{corr}} = N \times k_{\text{lin}} \times k_{E,\varphi} \times (D_{\text{dos}} - D_{\text{zero}})}$$

- Are there any requirements on D_{dos}?
  - Must be additive (linear) with respect to mixed radiations (with different radiation qualities)

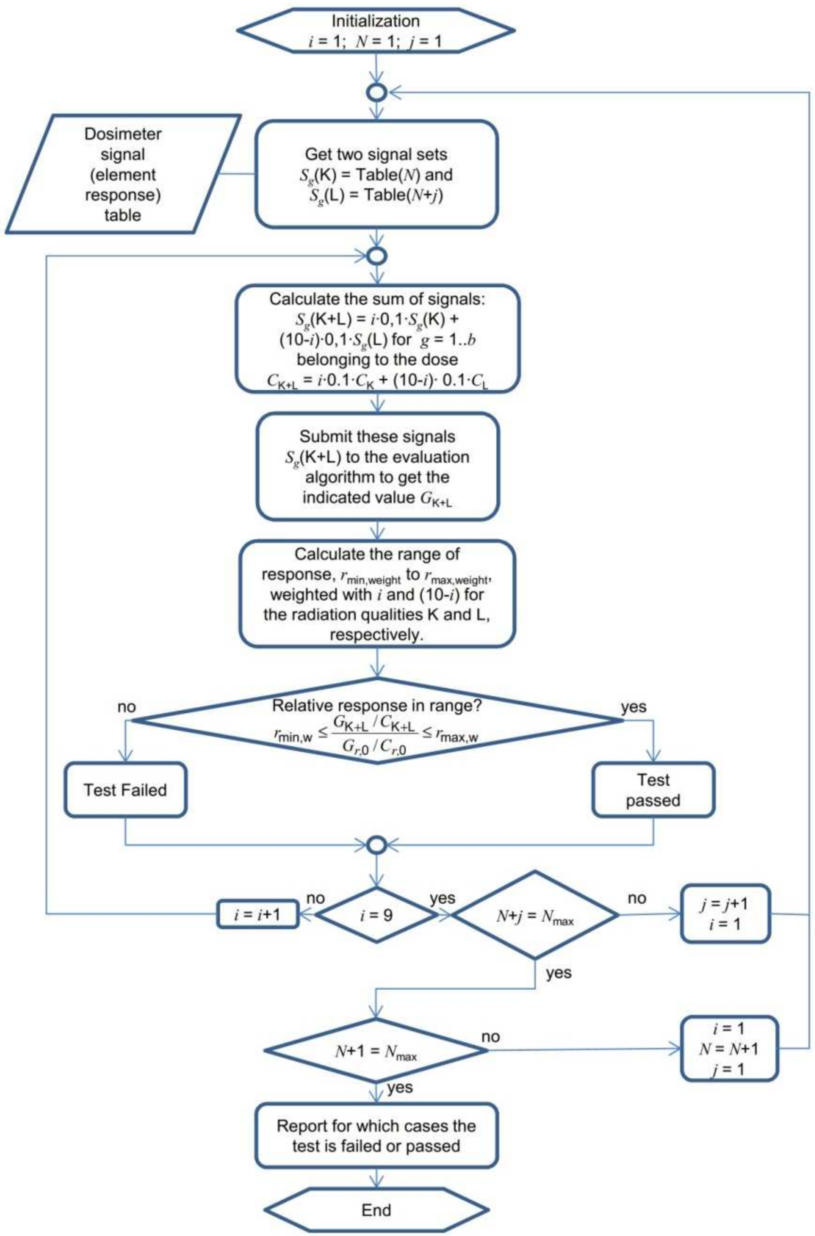
$$\boxed{\textbf{Requirement:}\ M_{\text{corr}}(D_{\text{dos},1+2}) = M_{\text{corr},1}(D_{\text{dos},1}) + M_{\text{corr},2}(D_{\text{dos},2})}$$

- Internal model function shall be linear →

$$\boxed{\textbf{Requirement:}\ D_{\text{dos},1+2} = D_{\text{dos},1} + D_{\text{dos},2}}$$

- Only one signal: $D_{\text{dos}} = \alpha \cdot S_1$
  - trivial, fulfilled
- Linear combination of several signals:
  $G_{\text{dos}} = \alpha \cdot S_1 + \beta \cdot S_2 + \gamma \cdot S_3 + \delta \cdot S_4 + \ldots$
  - also trivial, fulfilled

Special considerations: Algorithms



- **Requirement**

$$\boxed{D_{\mathrm{dos},1+2} = D_{\mathrm{dos},1} + D_{\mathrm{dos},2}}$$

- **Nonlinear internal model function (Branching algorithm of several signals):**
  - $D_{\mathrm{dos}} = F(S_1, S_2, S_3, S_4, \ldots)$
  - **no simple solution**, in principle not allowed
  - **But:** if M_{corr} within type test limits ➔ ok
  - test method see EN 62387-1:2012
  - test uses simulation of mixed radiation based on the measured signals for the used narrow spectrum series
  - requires the knowledge of the internal model function

You should now know

- The dosemeter indication should be derived from a linear algorithm
- Type test is the in depth investigation of a type of dosemeter
- Type tests are based on a linear model function of the dosemeter
- Reference calibration is necessary for any dosemeter
- Overall uncertainty can be calculated from the results of a type test
- Consideration of workplace conditions reduces uncertainty
- In pulsed radiation fields nearly all counting dosemeter fail
- Charged particle equilibrium is necessary for reference fields used for type tests

Thank you for your attention

Questions ??