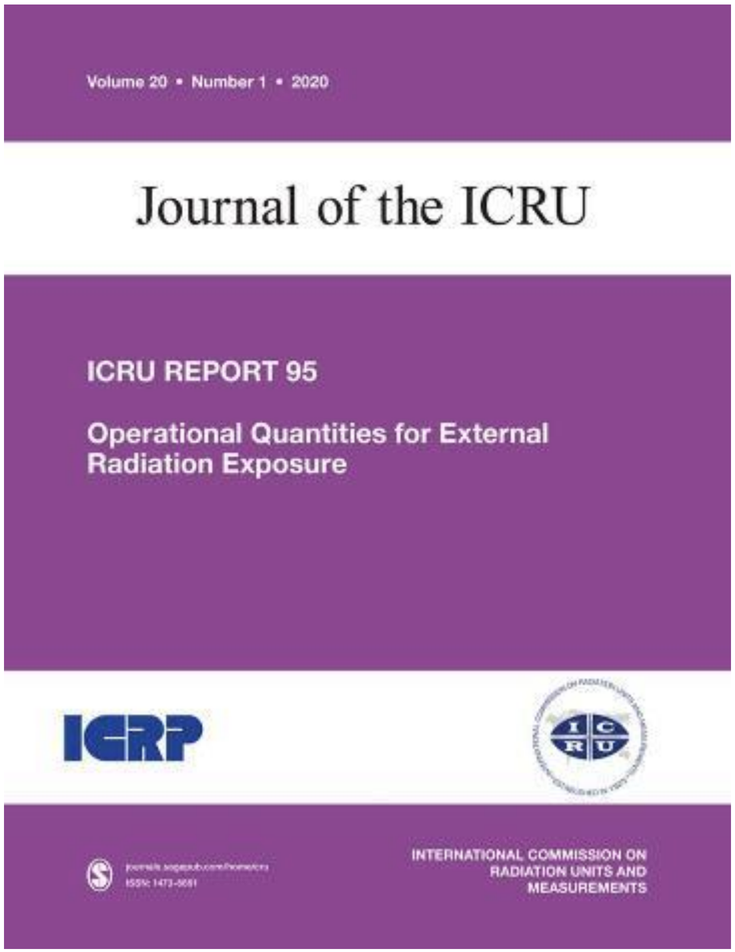
ICRU Report 95:
Operational Quantities for External Radiation Exposure
What Changes for Radiation Protection ?

Thomas Otto, ICRU and CERN

CCRI Webinar, 12. 10. 2021

ICRU Report 95 (2020)

Operational Quantities for External Radiation Exposure



- Previous quantities (ICRU 39 and 51)
- Operational Quantities for external exposure
- Conversion Coefficients
- Practical Consequences
- Appendices
  - Values of Conversion coefficients
  - Computer Codes

Contents

- Protection and Operational Quantities
- Present operational quantities (ICRU 39 /51 /57)
- Switch to new quantities (ICRU 95)
- Changes in conversion coefficients
- Consequences:
    - Dosimetry in real radiation fields
    - Calibration
    - Dosimeter response
- Summary

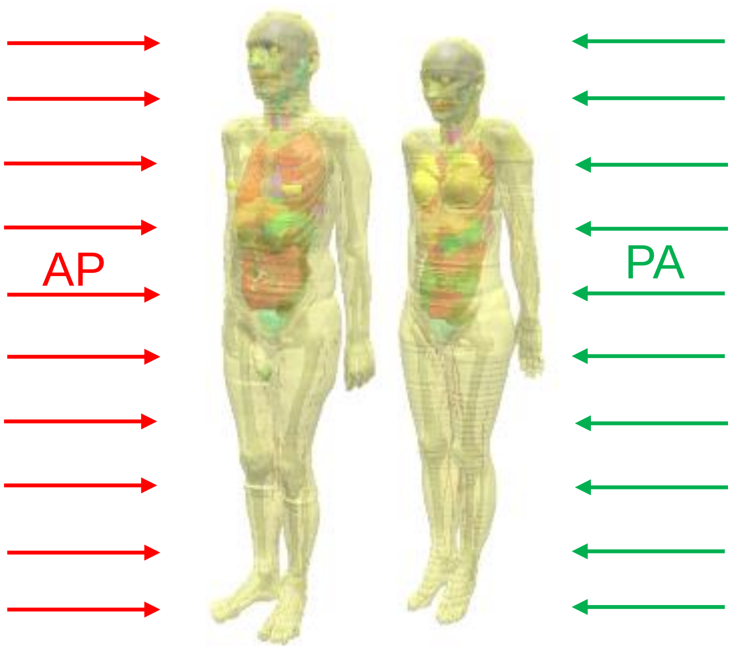
Protection Quantities

- ICRP defines Protection Quantities, to compare radiation detriment with limits and to enable optimization.
- Unifying concept to estimate radiation detriment from
  - External exposure
  - Internal exposure
- To organs (tissues) and whole body:
  - $D_{R,T} = \frac{1}{m_T} \int D_R \cdot dm$ Mean Organ Dose
  - $E = \sum_T w_T \sum_R w_R D_{R,T}$ Effective Dose

- Dose limits and constraints expressed in protection quantities

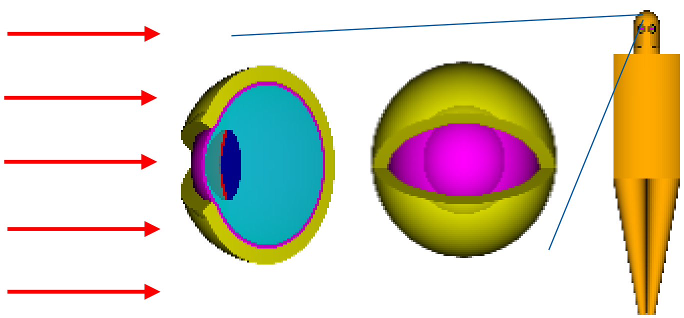
Calculation of Protection Quantities

- Whole Body: E

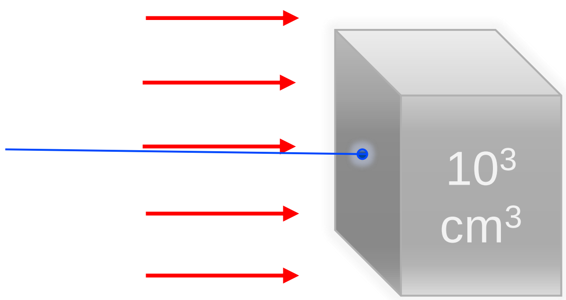


and other directions

- Eye lens: $H_{T\ lens}$



- Local skin: $H_{T\ skin}$



Phantoms: ICRP Report 110

Conversion Coefficients: ICRP Report 116

Need for Operational Quantities

- Protection quantities are defined as average over an extended volume: organ or body
- They cannot be measured
- Only quantities defined in a point are measurable by an instrument
- **ICRU 39: Define, in one point, a quantity as**

Dose equivalent = Absorbed dose * Quality factor

$$H(d) = D(d) * Q(L)$$

"Operational Quantity"

Calculation of conversion coefficients for present Operational Quantities

Area Monitoring

ICRU sphere

Personal Monitoring

slab and cylinder phantoms

(surrogates for trunk, head and extremities)

Phantoms are made from ICRU-4-component tissue surrogate (numerical)

Present Relation of Quantities

ICRP

Physical Quantities
Φ, K_a, D

Definition

Definition

ICRU

Protection Quantity
Effective dose E

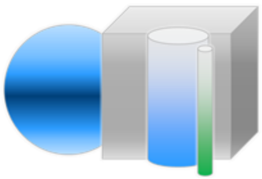
Calculation:
Anthropomorphic
Phantoms

$$E = \int dE_p \, \Phi_{E_p} h_E(E_p, \text{inc}^*)$$

* incident directions: AP, PA, LLAT, RLAT, ROT, ISO

$\neq$

Operational Quantities
Ambient dose equivalent $H^*(10)$
Personal dose equivalent $H_p(10)$



Calculation:
Geometric
Phantoms

$$H_p(d, \Omega) = \iint dE_p d\boldsymbol{\Omega} \, \Phi_{E_p} h_p \, (d, E_p, \boldsymbol{\Omega})$$

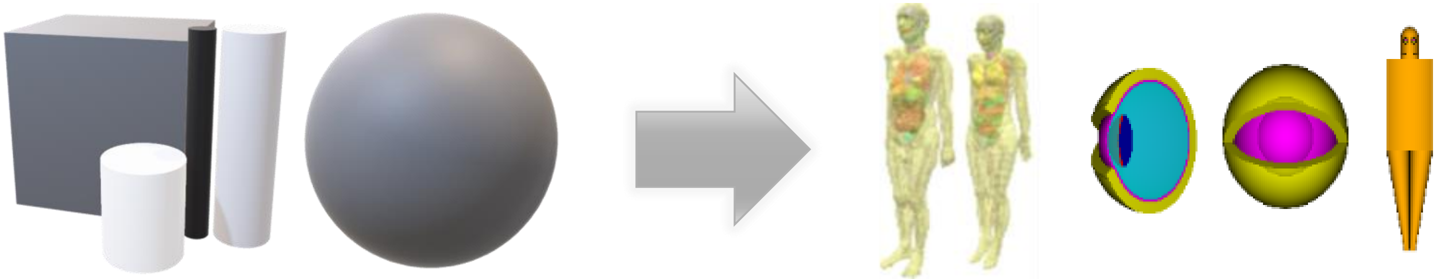
$$H^*(d, \Omega) = \iint dE_p d\boldsymbol{\Omega} \, \Phi_{E_p} h^* \, (d, E_p, \boldsymbol{\Omega})$$

For photons in kerma approximation

Measurement
Instrument response $R\,(E,\Omega)$

What changes for Operational Quantities?

- Use of anthropomorphic phantoms and w_T, w_R



- Better approximation of *E by definition*
- Also:
  - Definition of quantities to limit tissue effects (local dose to skin and to eye lens) as **absorbed dose**
  - More radiation types, e.g. positrons, protons, pions…
  - Much wider energy range
  - Quantities for photons with full electron transport

ICRU 95 Change of Paradigm

- Define the operational quantities as the product of field quantity (here fluence) and a conversion coefficient

$$H = h_{\varphi} \cdot \; \Phi_{E_{\mathrm{p}}}$$

- $\Phi_{E_{\mathrm{p}}}$ is the unperturbed external fluence spectrum
- Derive conversion coefficient $h(E_p)$ from the same phantoms as the protection quantities by:

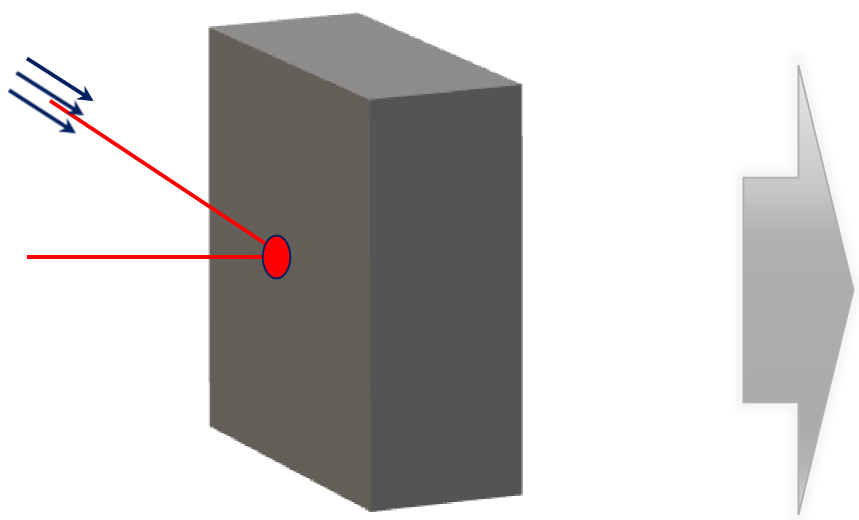
$$h(E_p) = E / \; \Phi_{E_{\mathrm{p}}} \text{ or } h(E_p) = D / \; \Phi_{E_{\mathrm{p}}}$$

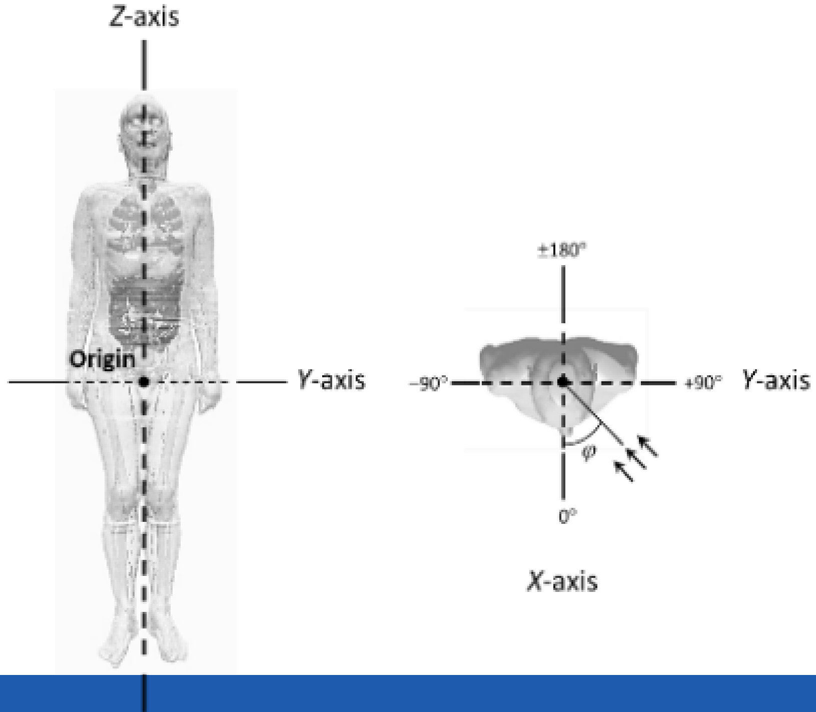
Kerma in air can be used alternatively to fluence

Whole-body dosimetry

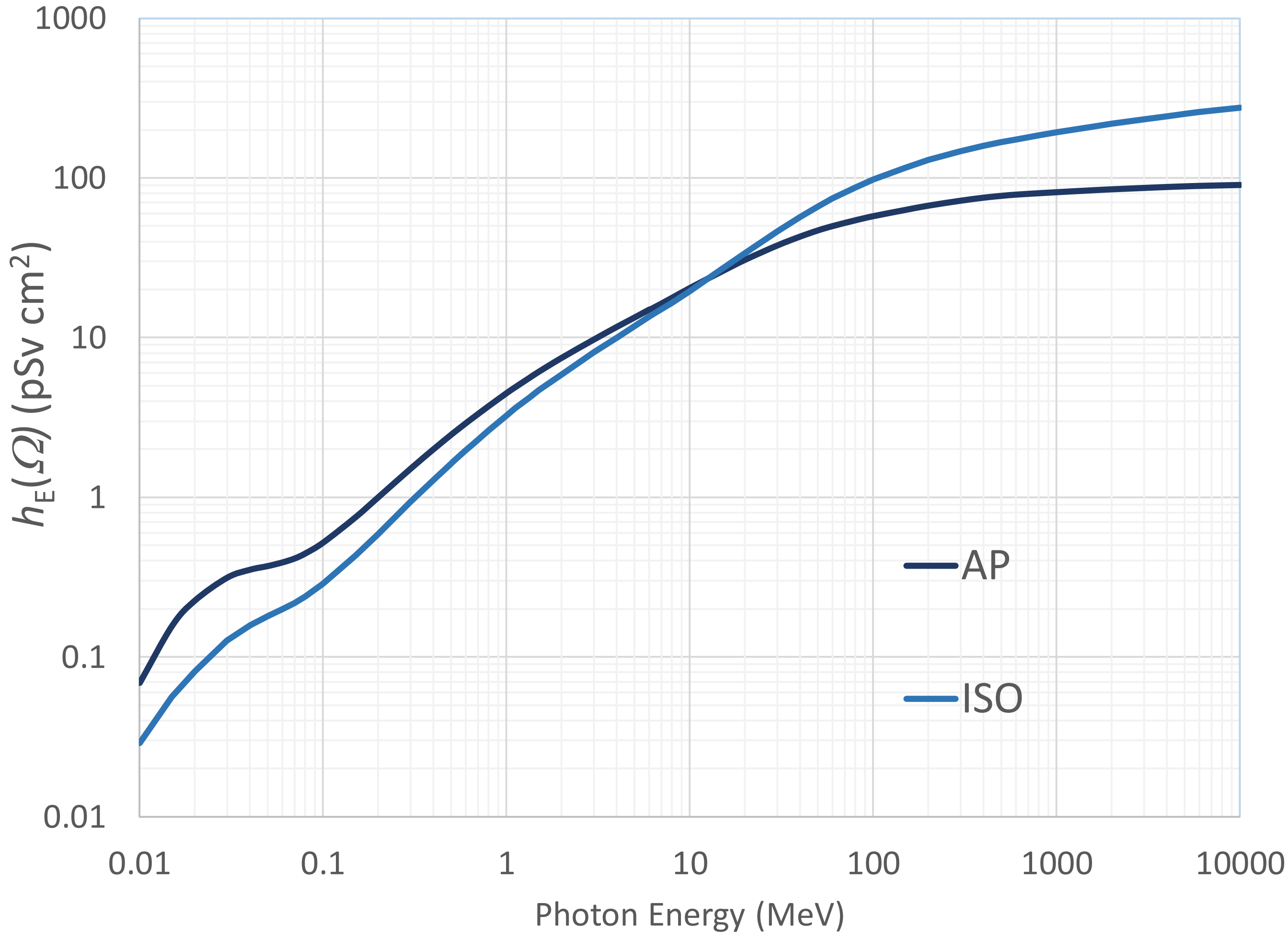
- **Personal Dose Equivalent $H_p(10)$**
- $H_p(10) = D(10) * Q(L)$
- 10 mm under the center of the ICRU-4-component tissue slab
- Expanded Radiation Field

- **Personal Dose H_p:**
- Calculated as weighted sum (w_R,w_T) of organ doses in anthropomorph phantom
- Plane-parallel radiation field from defined direction

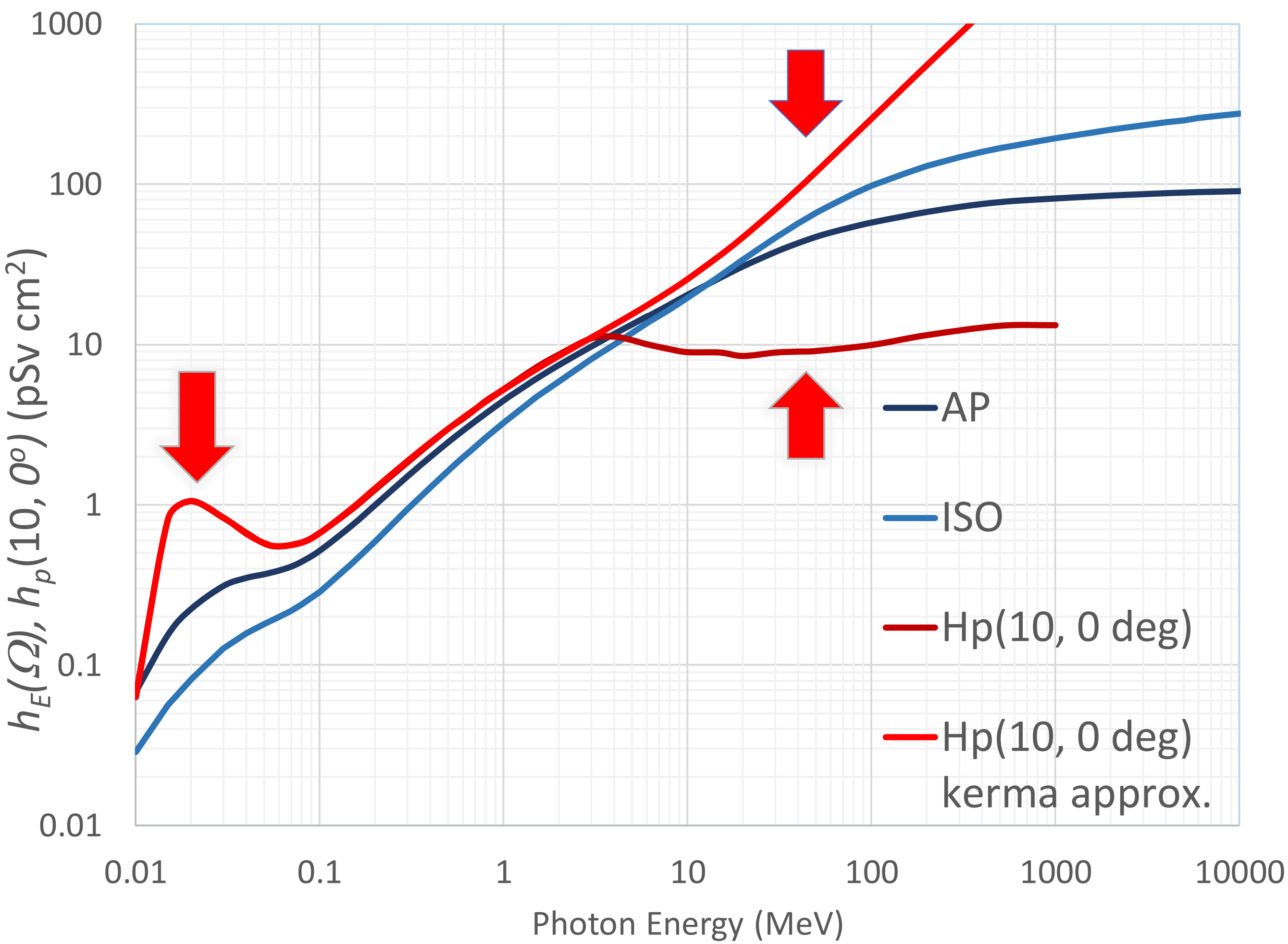




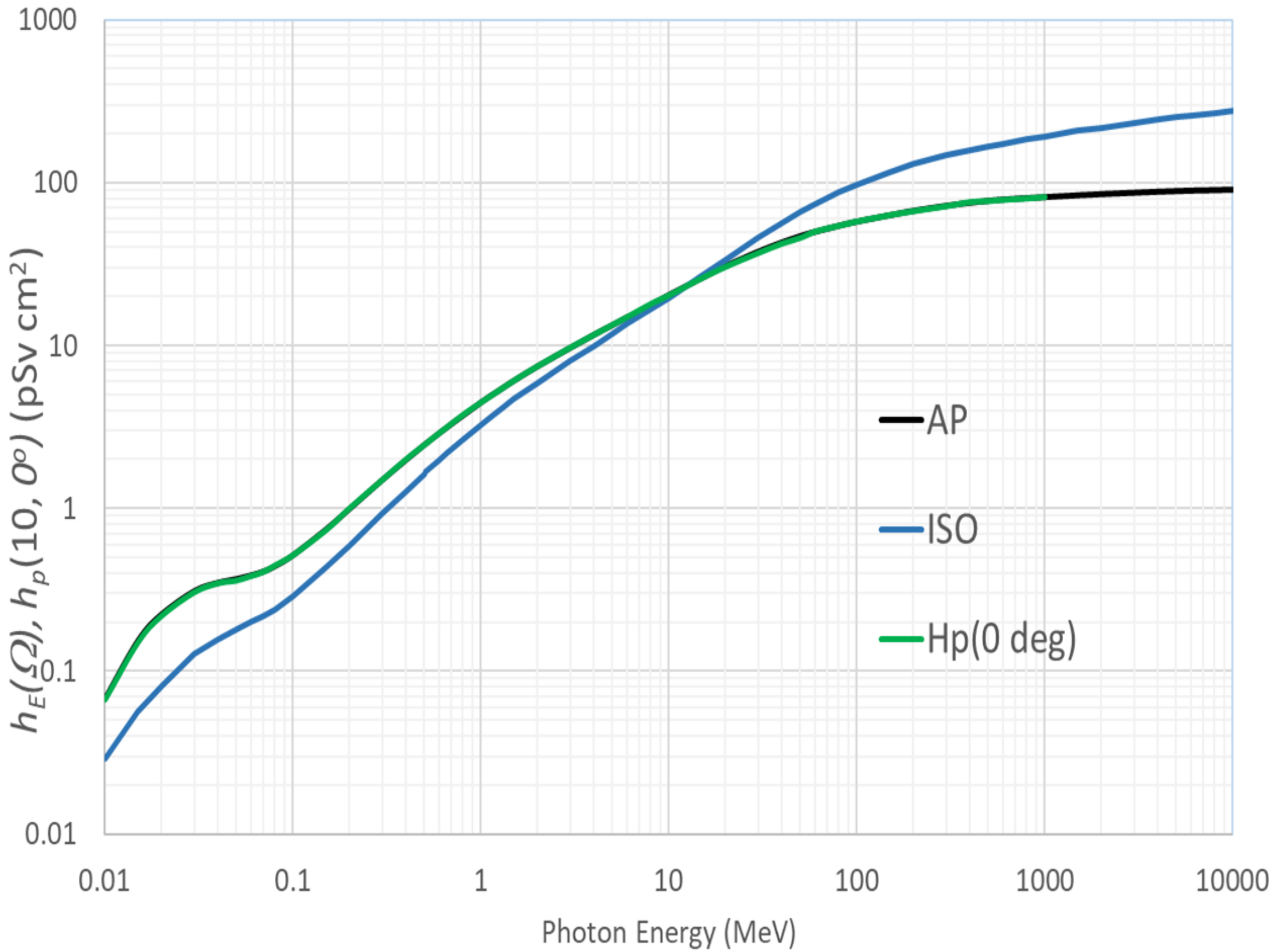
E for Photons



E, and $H_p(10)$ for Photons



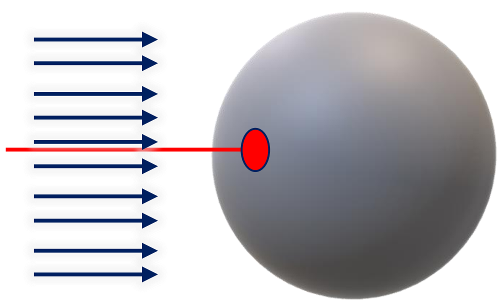
E and H_p (0º) for Photons



Area/ Ambient Dosimetry

Ambient Dose Equivalent *H(10)**

- $H^*(10) = D(10) * Q(L)$
- Absorbed dose in 10 mm depth in the ICRU sphere
- Expanded and aligned field (all radiation field components assembled under 0°)

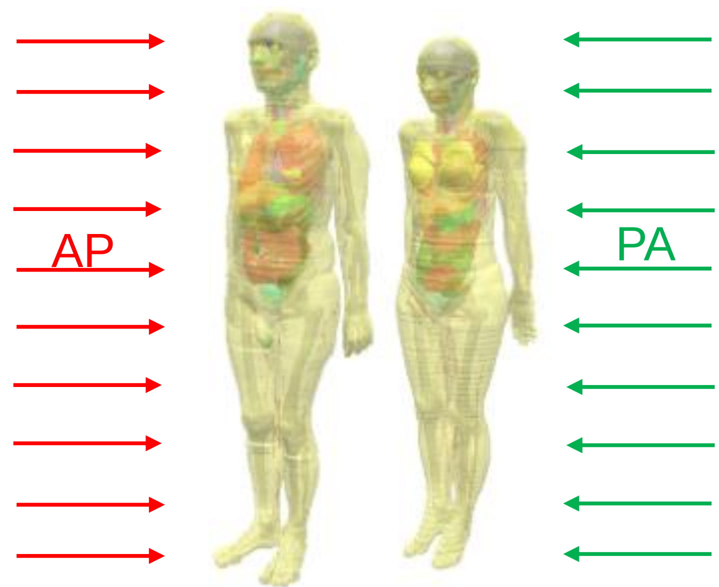


Ambient Dose *H**

Maximum of Effective Dose over the directional coefficients listed in ICRP Report 116

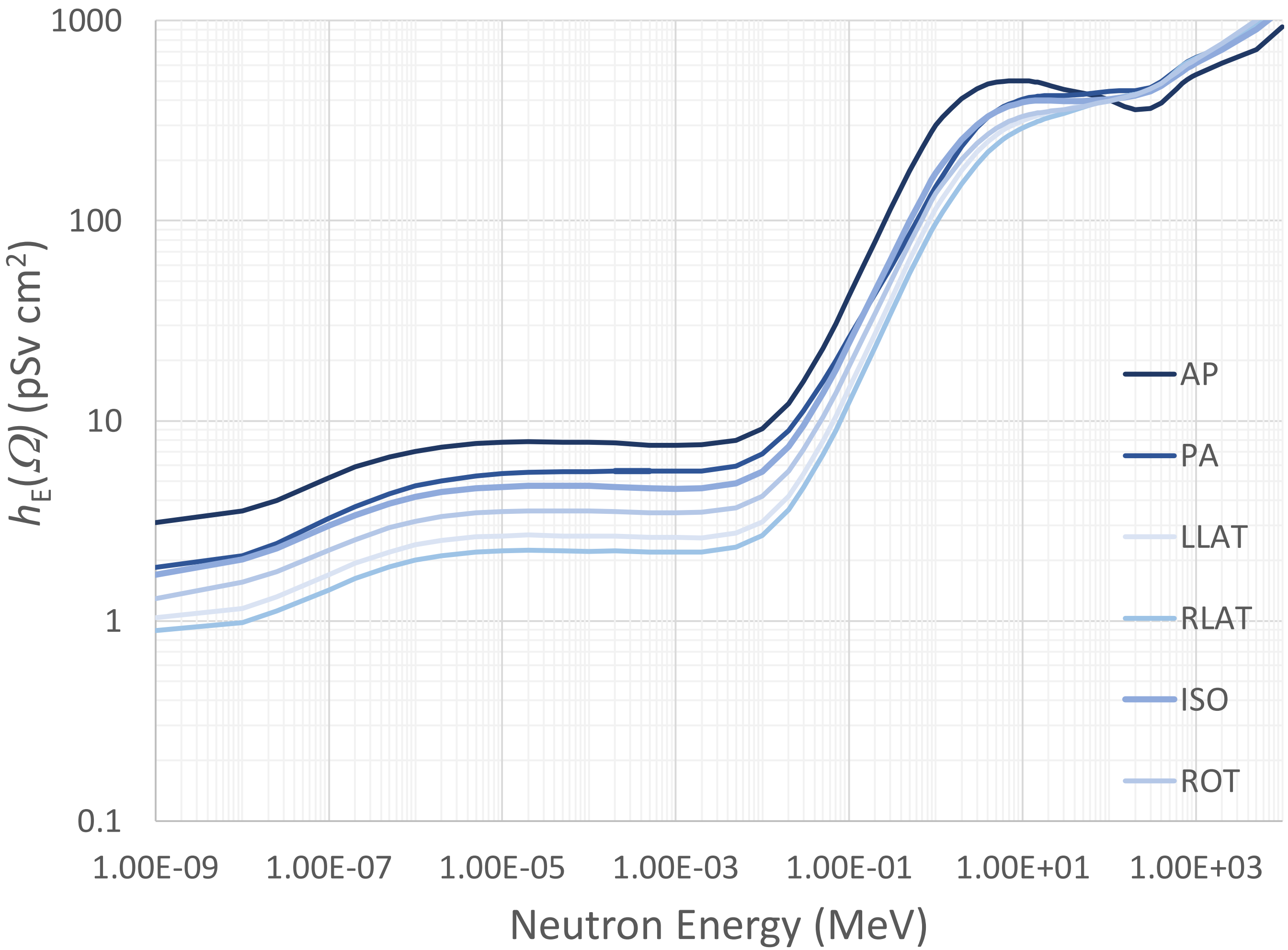
$$H^* = h_{E_{\max}} \cdot \Phi$$

$$h_{E_{\max}}(E_p) = E_{\max}(E_p) / \Phi(E_p)$$

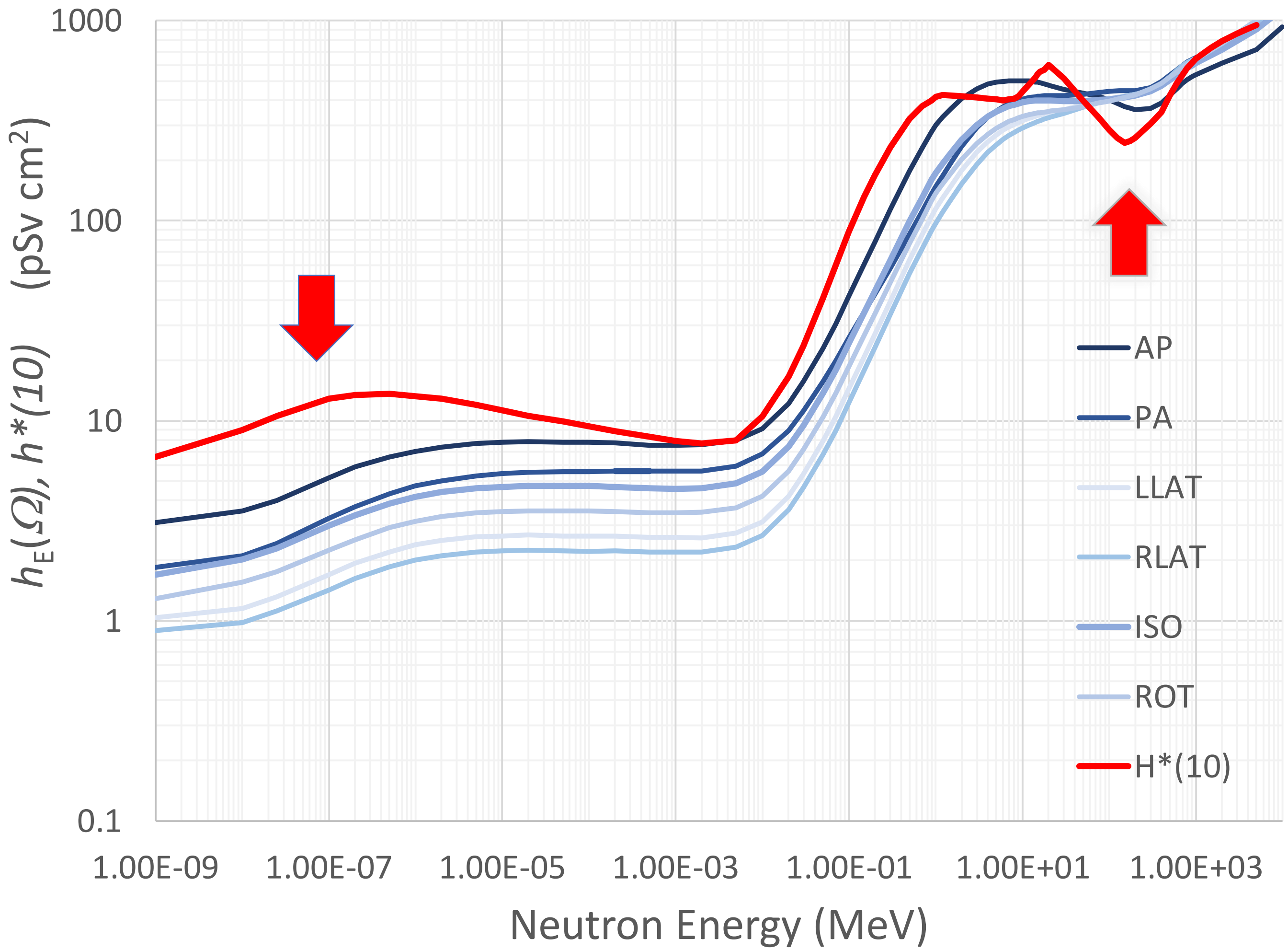


and 4 other directions

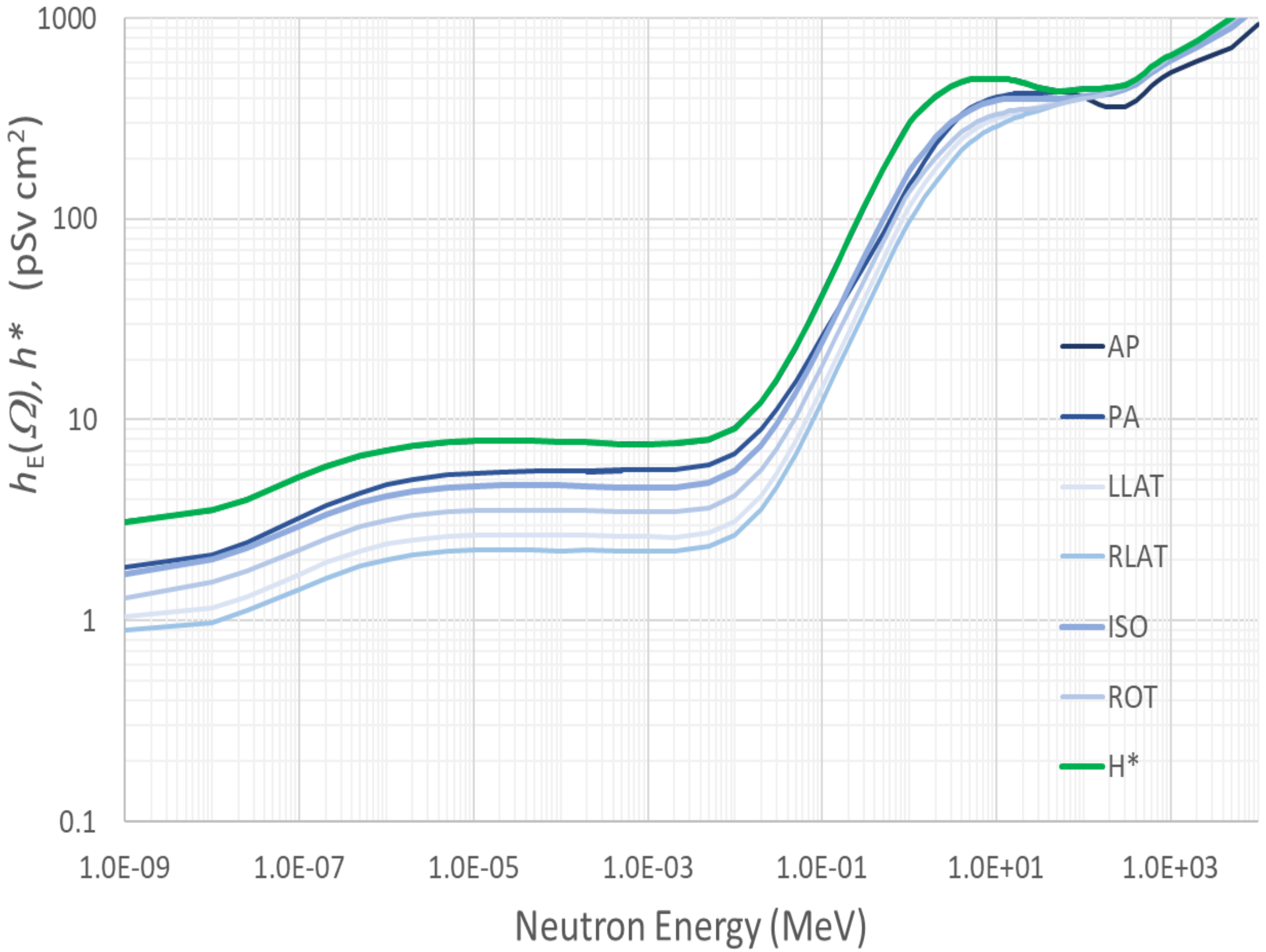
E for Neutrons



E and *H**(10) for Neutrons



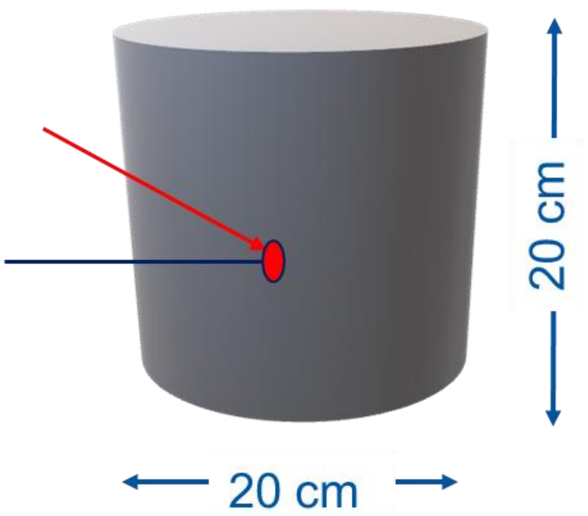
E and *H** for Neutrons

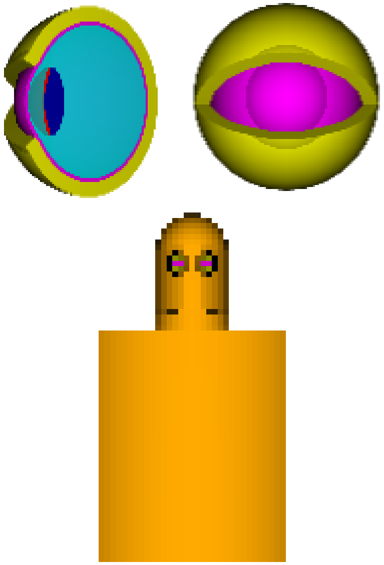


Eye Lens Dosimetry

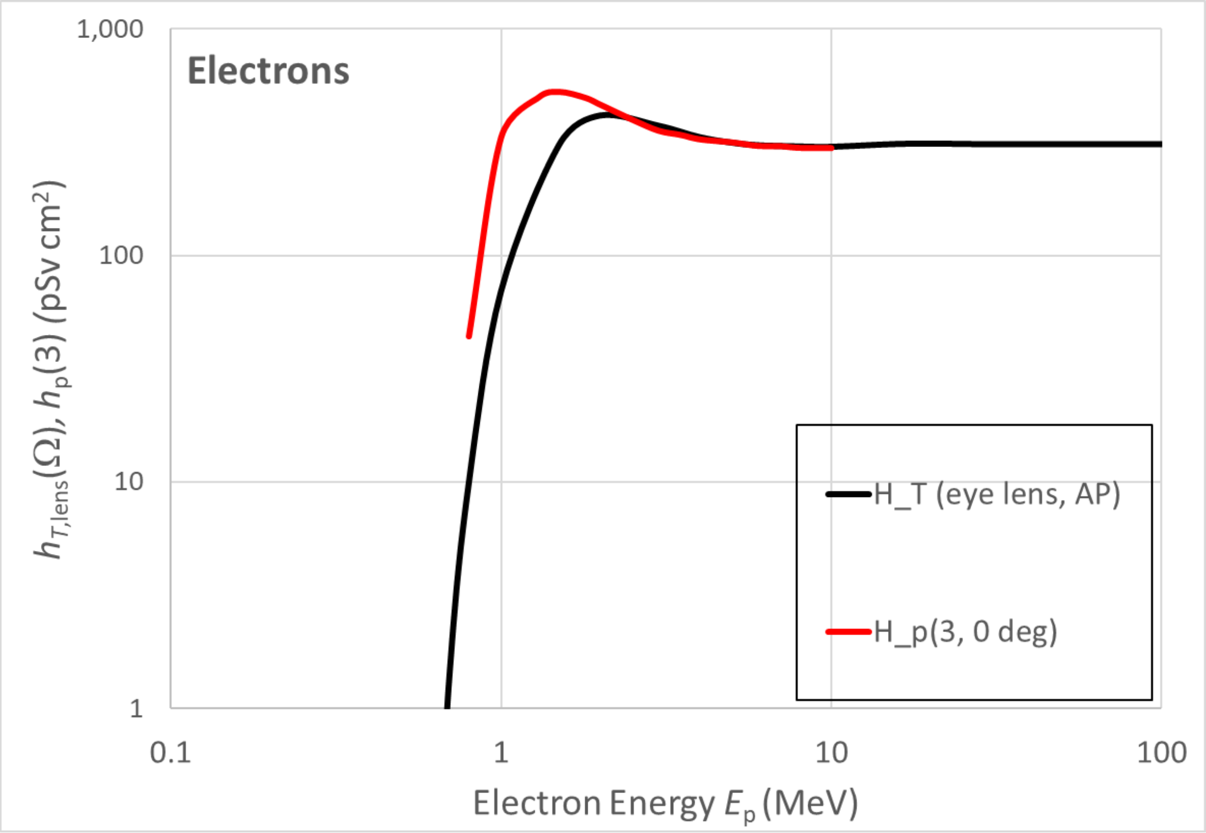
- **Personal dose equivalent H_p (3)**
- $H_p(3) = D(3) * Q(L)$
- In 20 cm square cylinder

- **Local absorbed dose to eye lens $D_{\text{eye lens}}$**
- Absorbed dose in the eye lens (Behrens–Dietze model)
- Change for neutrons ($Q \neq 1$) !

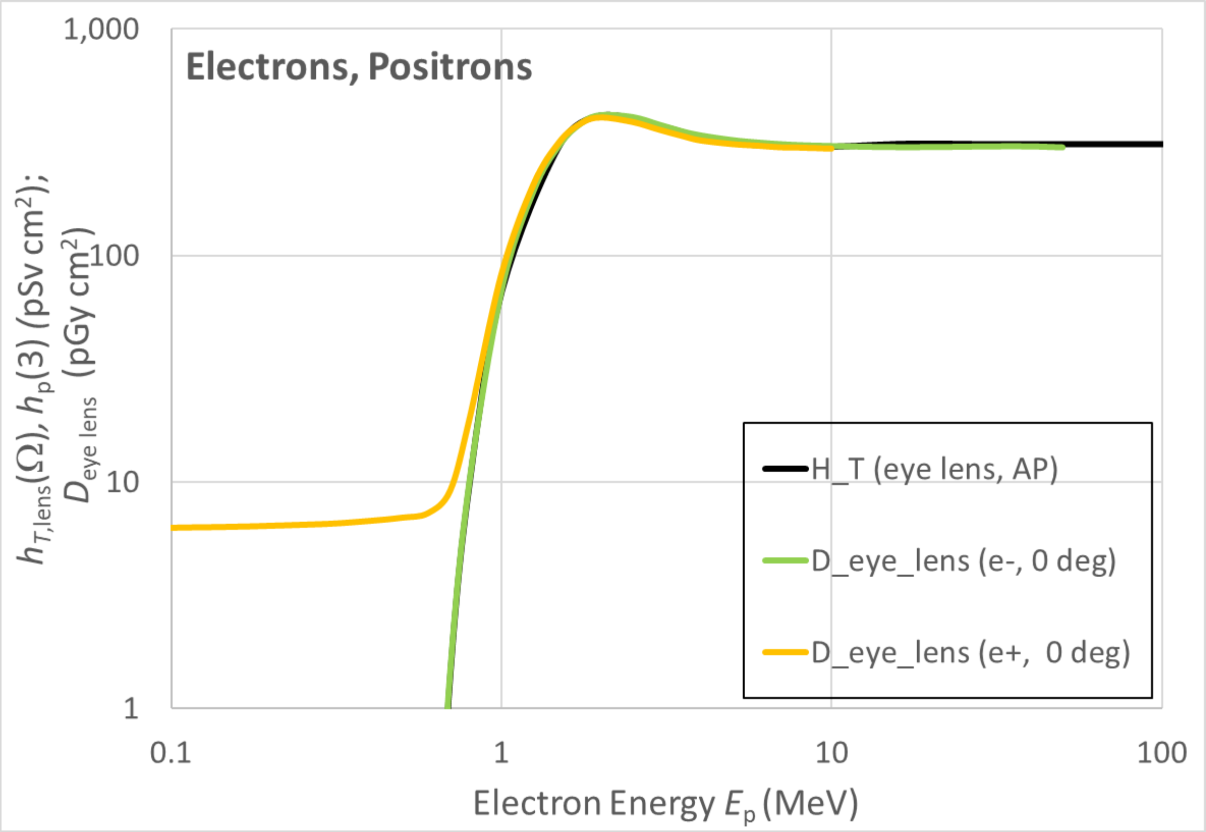




$H_{T,\text{ eye lens}}$ and H_p (3) for Electrons



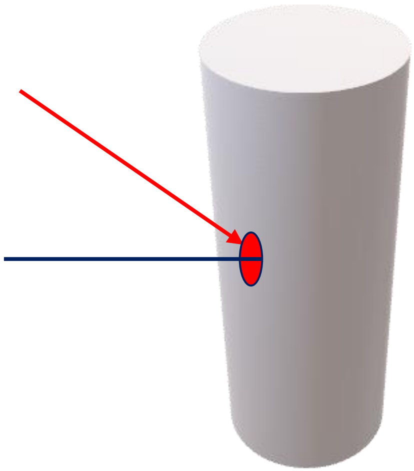
$H_{T,\text{ eye lens}}$ and $D_{\text{eye lens}}$ for Electrons

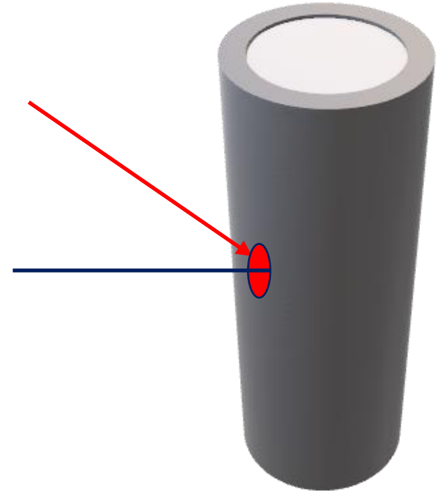


$D_{\text{eye lens}}$ has conversion coefficients for electrons and positrons

Extremity Dosimetry

- $H_p(0.07)$
- $D_{local\ skin}$





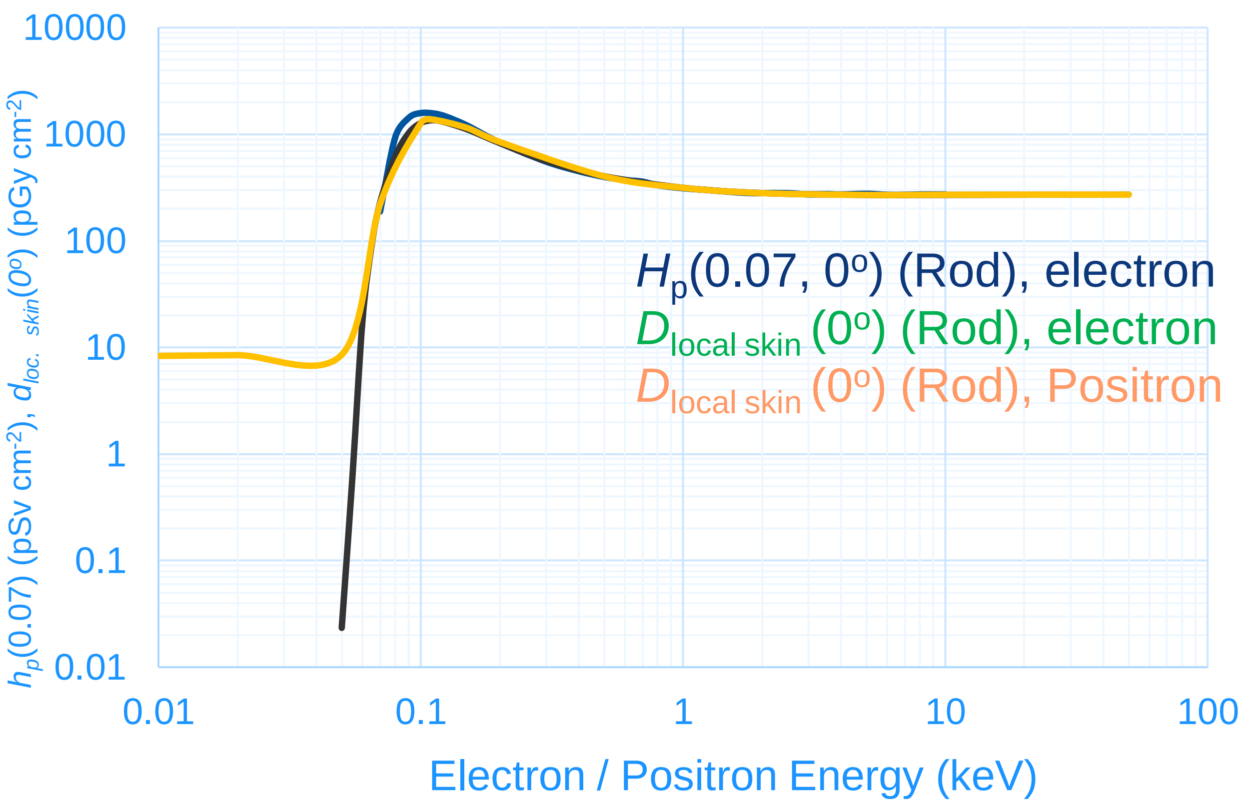
Absorbed dose between 0.05 and 0.1 mm in
- Finger: 1.9 cm * 30 cm
- Wrist: 7.3 cm * 30 cm

ICRU tissue $\rho = 1.11\ g/cm^3$ with 0.2 cm ICRP skin

Dose equivalent in 0.07 mm in
- Finger: 1.9 cm * 30 cm
- Wrist: 7.3 cm * 30 cm

ICRU tissue $\rho = 1.0\ g/cm^3$

$D_{\text{local skin}}$ and $H_p(0.07)$ for e⁻/ e⁺



- No changes with practical impact
- Conversion coefficients for Positrons

ICRU Report 95 Relation of Quantities

Physical Quantities
Φ, K_a, D

Definition

Definition

Protection Quantity
Effective dose E

Operational Quantities
Ambient dose H^*
Personal dose H_p

Calculation:
Anthropomorphic
Phantoms

Calculation:
Anthropomorphic
Phantoms

$$E = \int dE_p \, \Phi_{E_p} h_E(E_p, \mathrm{inc}^*)$$

$\triangleq$

$$H^* = \int dE_p \, \Phi_{E_p} \cdot h_{E_{max}}(E_p)$$

$$H_p = \iint d\Omega \, dE_p \, \Phi_{E_p} \cdot h_p(E_p, \boldsymbol{a})$$

* incident directions: AP, PA, LLAT, RLAT, ROT, ISO

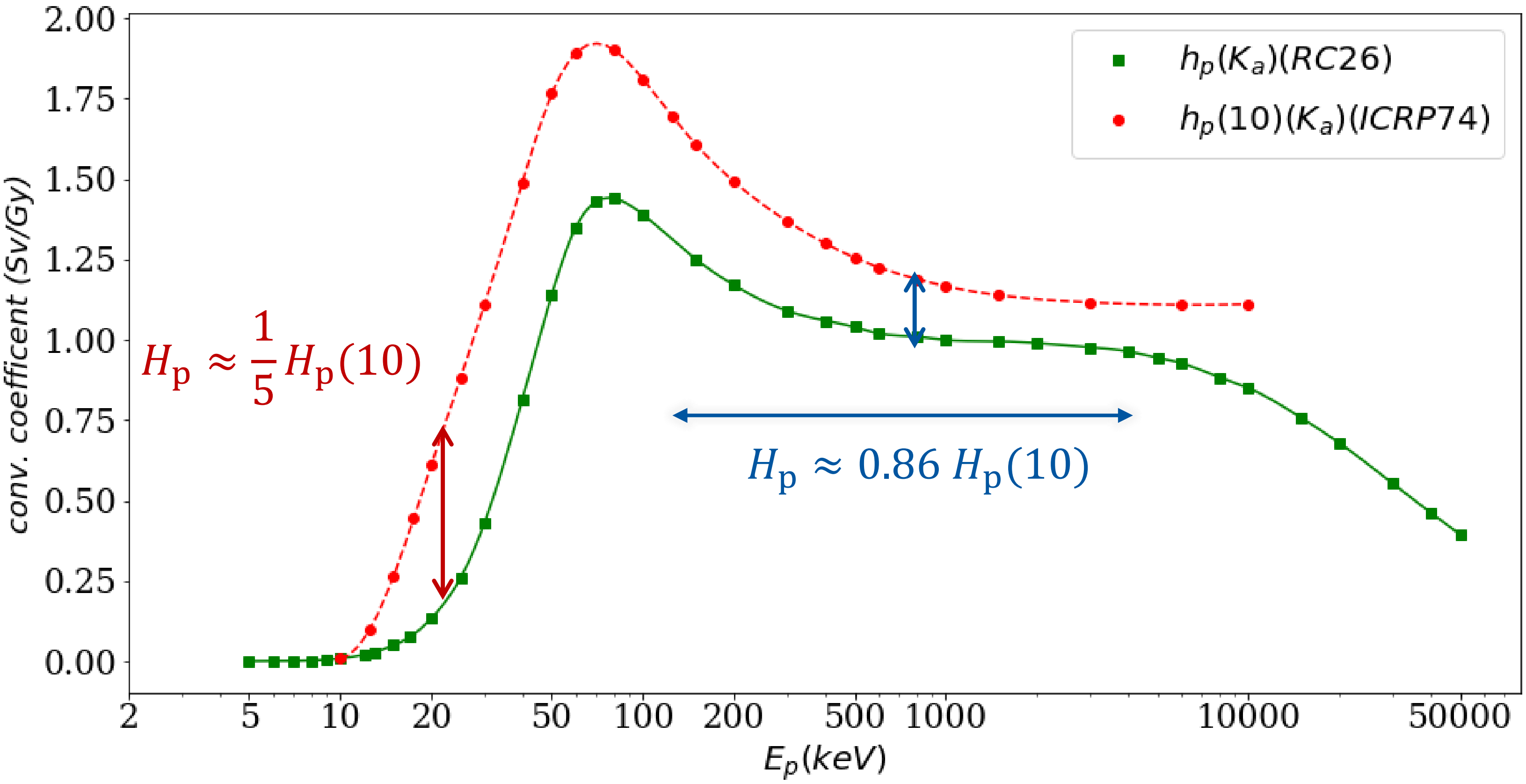
Measurement
Instrument response $R\,(E, \Omega)$

Consequences of the Change

- “Real” Radiation Fields
- Calibration of Dosimeters
- Response of Dosimeters

Personal dose – photons

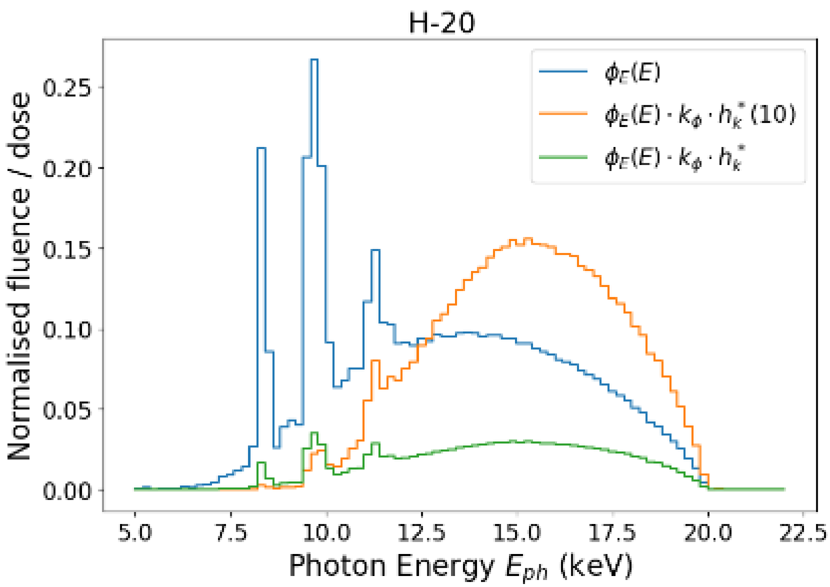
Conversion coefficients from **kerma K_a** to operational quantity

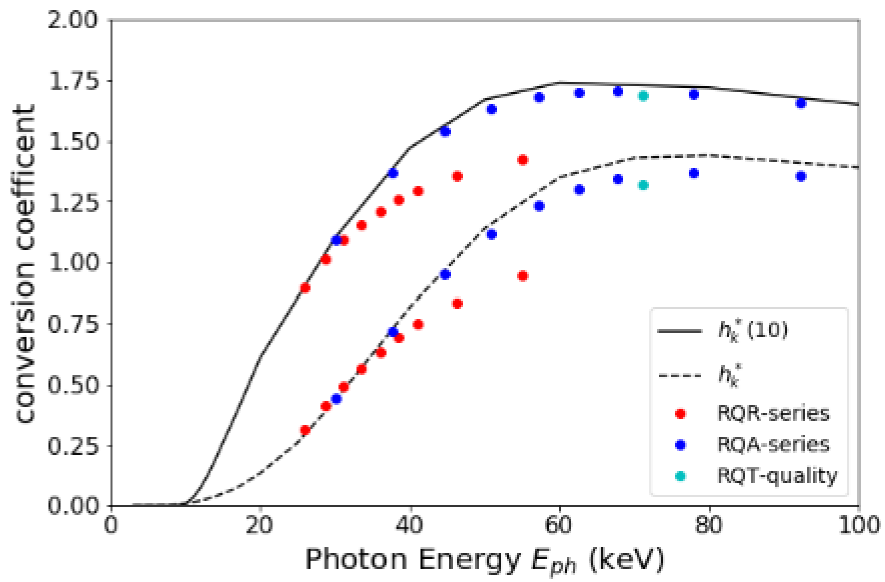


At energies typical for radioisotopes, $H_p = 0.86 * H_p(10)$

At low-energy x-ray (backscatter from patient) $H_p = 0.2 * H_p(10)$

Low-energy x-ray spectra





High-dose rate spectrum,
20 kV tube voltage
Fluence spectrum
*H**(10)-weigthed spectrum
*H**-weighted spectrum

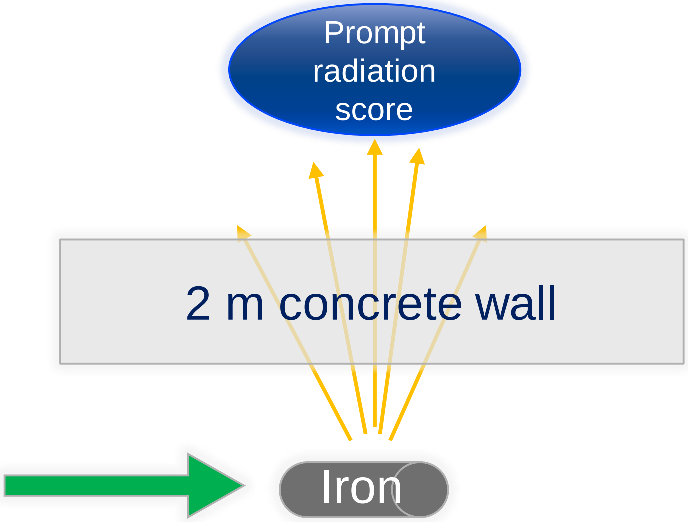
Diagnostic x-ray calibration spectra

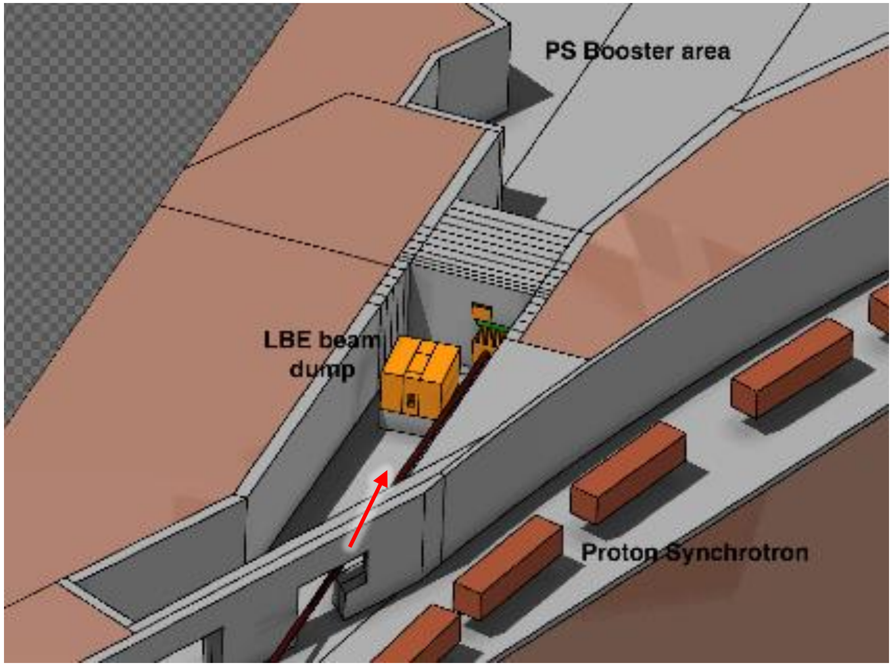
Upper curve: *H*(10)*
Lower curve: *H**
*H** ≈ 0.5 *H**(10) in broad spectra

Influence on dose of medical personnel during interventional radiology under study

T. Otto, JINST 14 P11011 (2019)
T. Otto, R. Behrens, J. Rad. Prot **139** (2020)

Radiation Fields at Particle Accelerators





Linac4 LBE dump

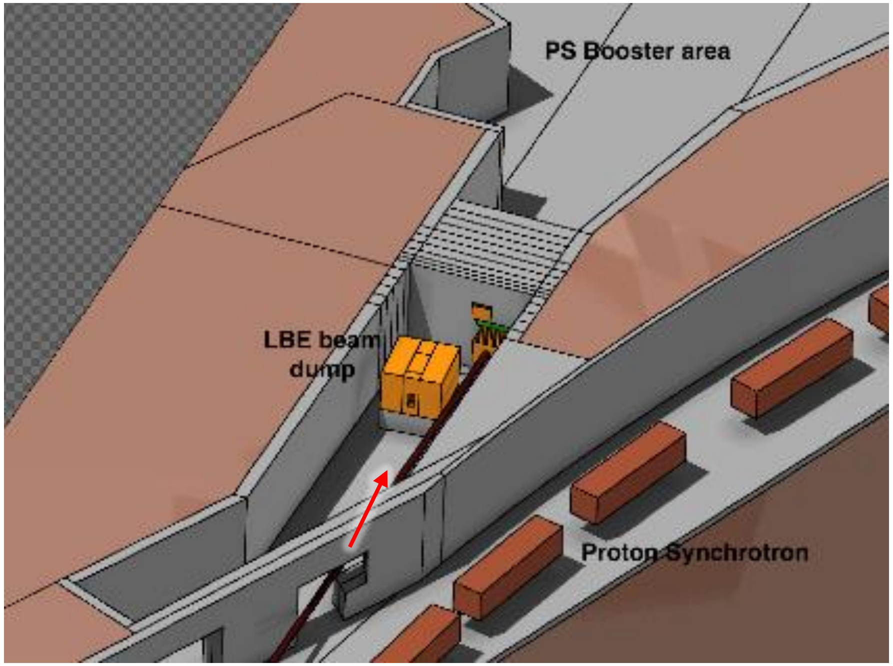
160 MeV protons

Generic Study:

0.1, 1 & 10 GeV proton

Th. Otto & M. Widorski, Int. Particle Accelerator Conference 2021, to be published

Radiation Fields at Particle Accelerators



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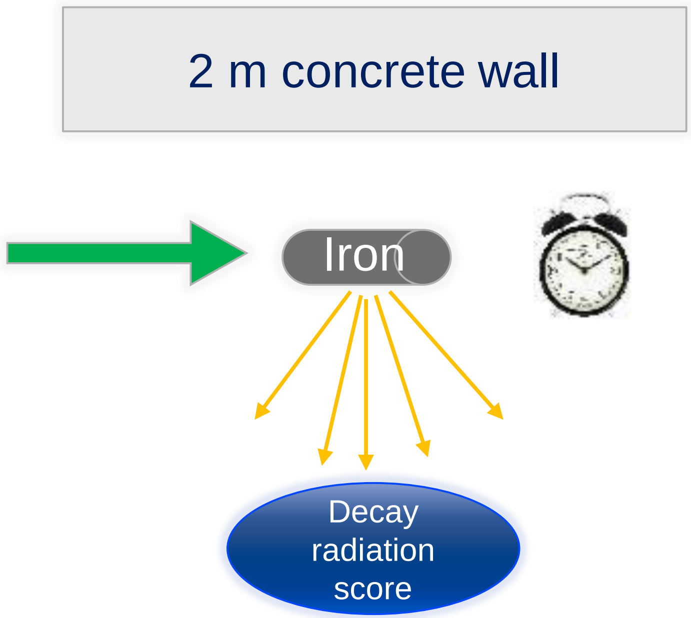

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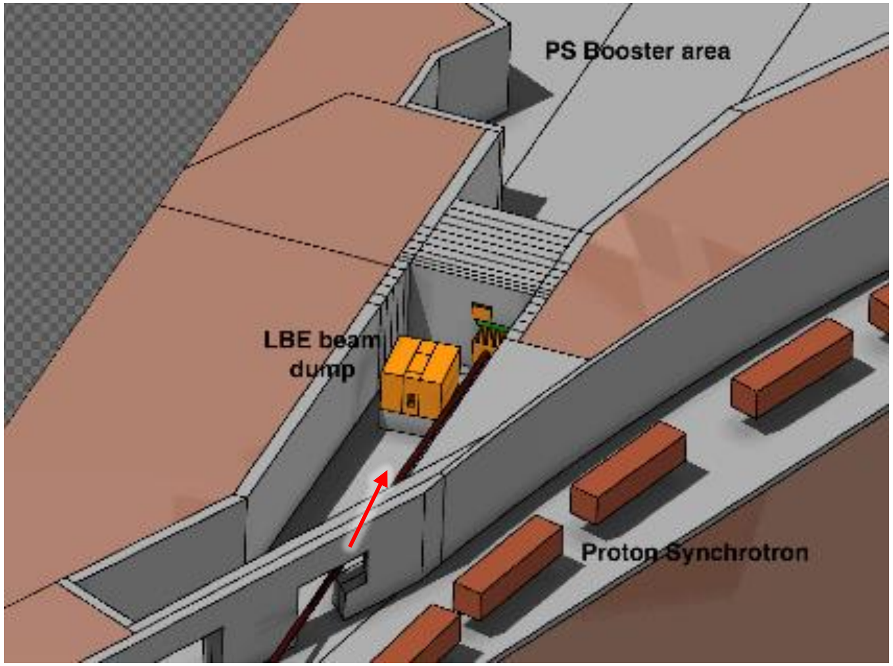
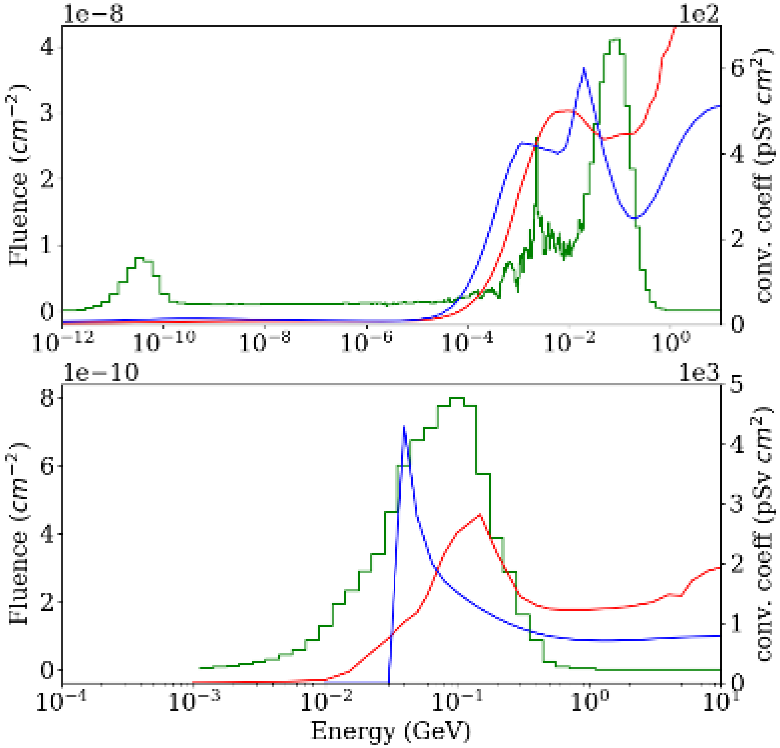


Linac4 LBE dump

160 MeV protons

Th. Otto & M. Widorski, Int. Particle Accelerator Conference 2021, to be published

Generic study: prompt radiation



Neutron and proton spectra (10 GeV proton beam)

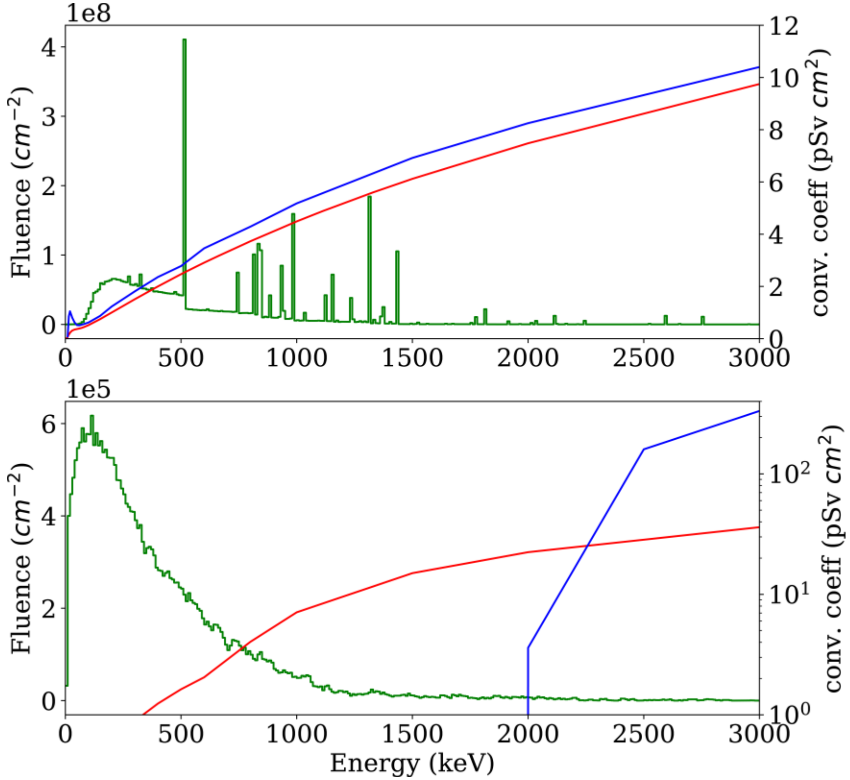
***H**(10) and *H** overlay**

Beam Energy	100 MeV	1 GeV	10 GeV
Neutron	1.00	1.17	1.19
Proton		1.07	1.15
Photon	1.10	1.10	1.18
$e^{+/-}$	0.18	0.22	0.33
Total	**0.99**	**1.16**	**1.18**

Ratio *H / *H**(10) (lateral)**

- Neutrons dominate
- For 100 MeV, no change
- From 1 GeV *H** > *H**(10) for *n*, *p* and γ.

Generic Study: activation



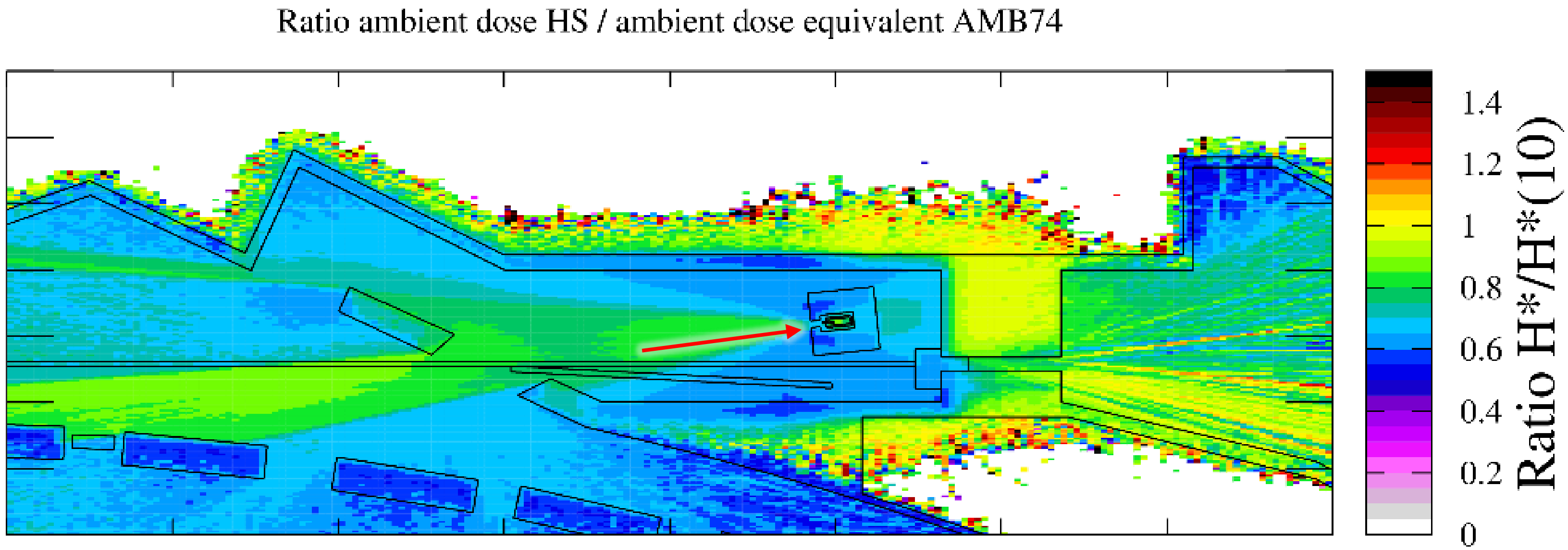
Decay Time	1 hour	1 week	1 year
Photon	0.87	0.86	0.86
Electron	2.9	2.0	2.2
Positron	0.9	1.0	1.0
Total	**0.87**	**0.87**	**0.86**

Activation with 3.5 GeV proton beam
Photon and electron spectra (1h decay)
H**(10) and *H** *overlay

Ratio *H** / *H**(10)

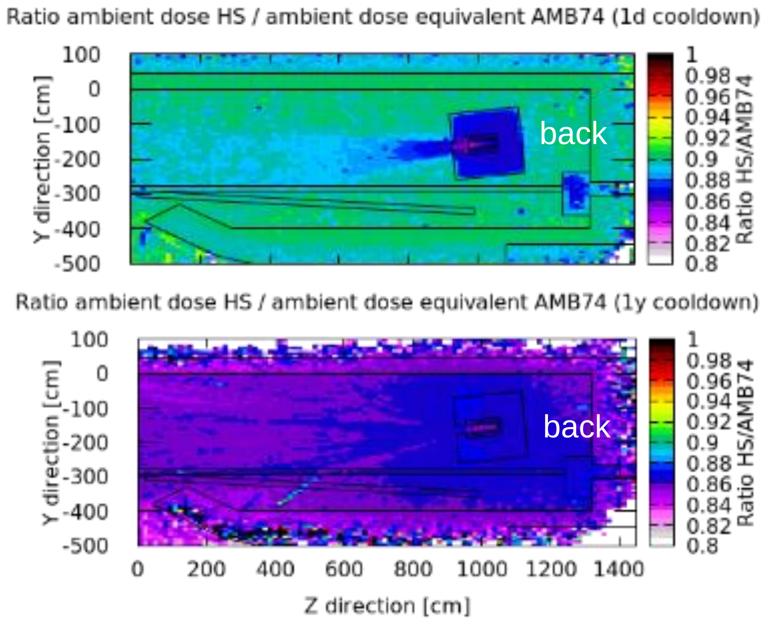
- Photons dominate
- *H** < *H**(10) by 15 %
- Typical for radionuclides

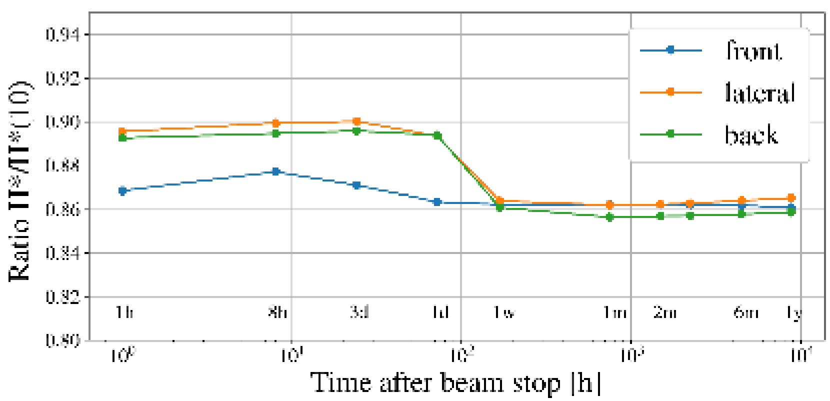
LBE dump: prompt radiation



- Behind the dump: high-energy particles, $H^* \geq H^*(10)$
- In Front: multiple scattered neutrons: $H^* < H^*(10)$

LBE dump: activation





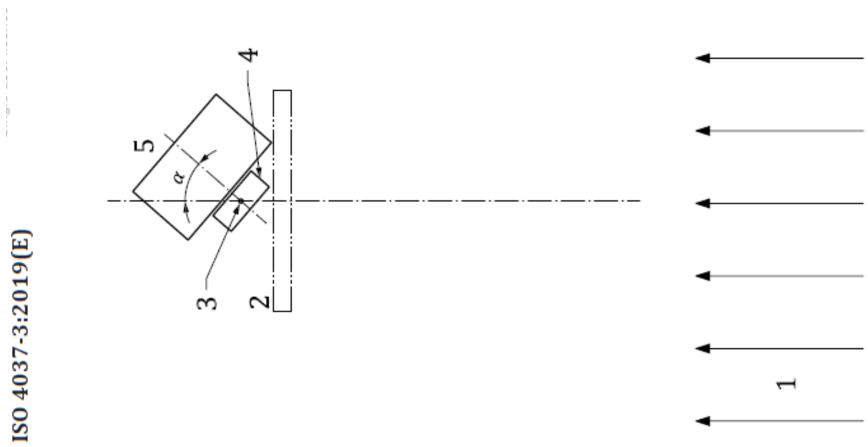
- *H* / H**(10) ratio depends initially on location
- For short decay time, high energy γ emitters – higher ratio
- In front of the dump, multiple scattering, lower energy, lower ratio
- After one month, only medium- and long-lived radioisotopes with the "typical" ratio 0.86

Calibration procedure does not change:

- Determine reference point in calibration field
- At this point, determine
  - K_a for Photons
  - Φ for neutrons
  - D for electrons
- Calculate operational quantity,
  for example $H^* = \Phi\, h^*(E)$
- Place dosimeter at reference point
  (on calibration phantom, where for personal dose)
- For photons, assure secondary electron equilibrium
  (SEE)
- Irradiate

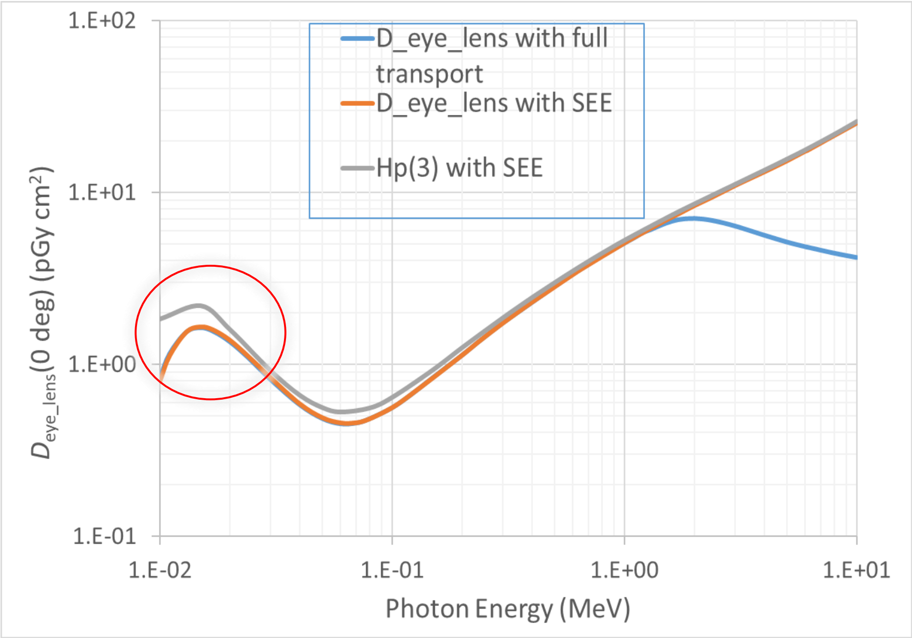
Photon Calibration: SEE (CPE)

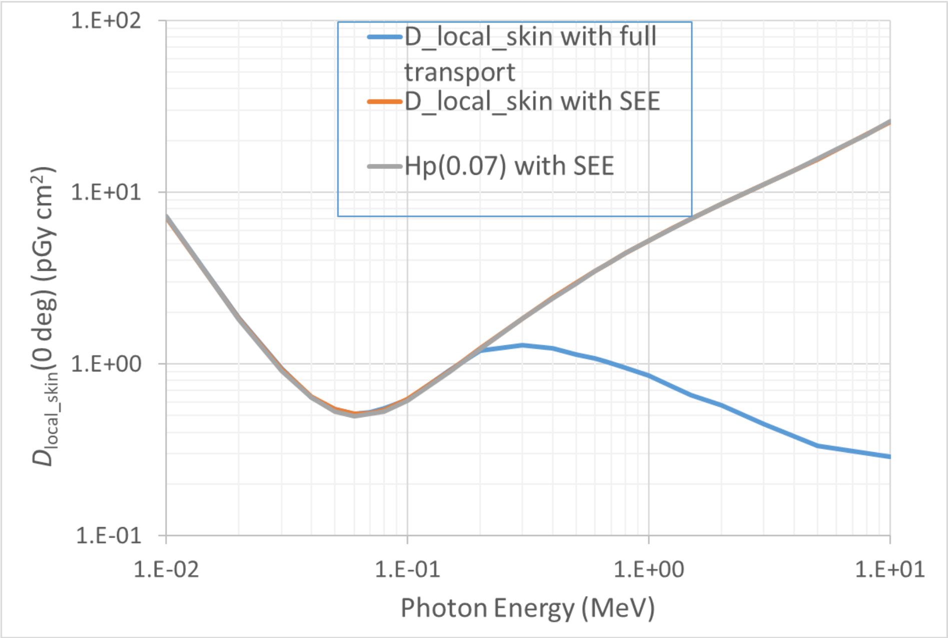
- Photons produce secondary electrons in source, collimator and air
- For reproducible conditions, assure SEE
  - Thick-walled dosimeters or low photon energies : o.k.
  - Thin dosimeters (e.g. personal) place build-up plate between source and dosimeter to create SEE



- ICRU 57 conversion coefficients for photons are calculated in kerma-approximation, i.e. assuming SEE
- ICRU 95: use conversion coefficients from Annex 5 with SEE

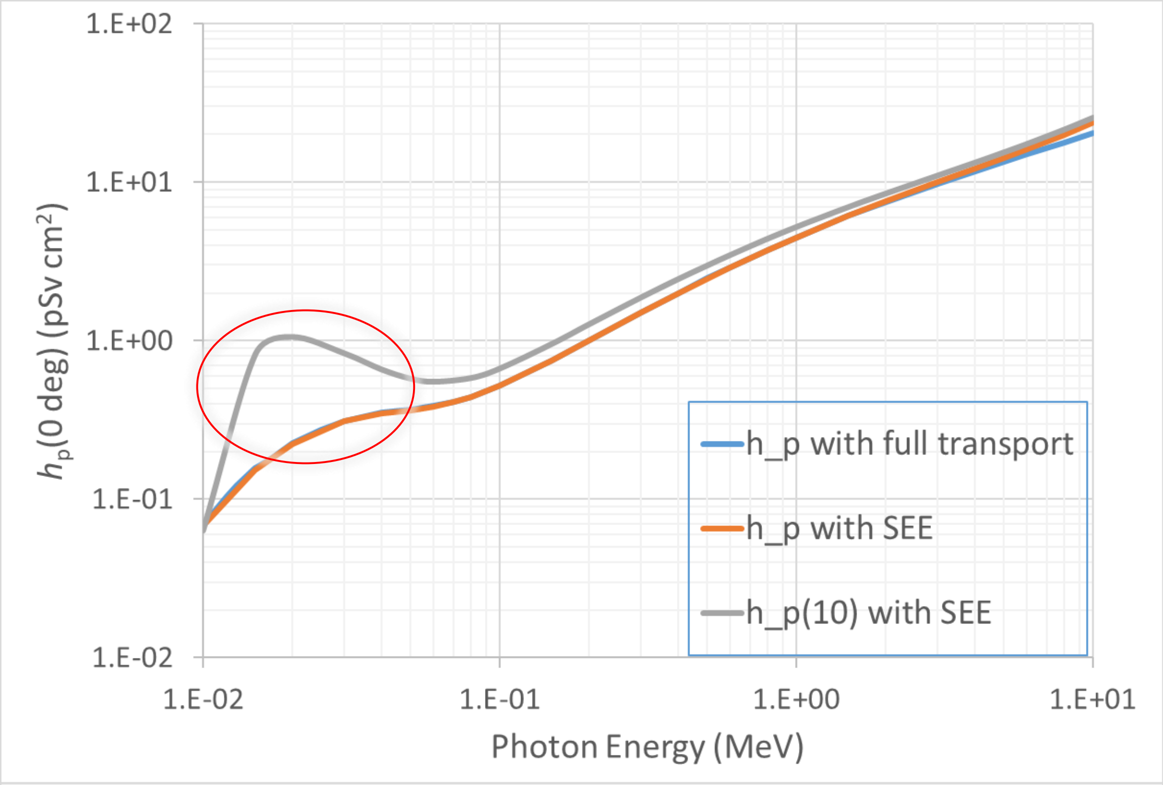
Calibration in $D_{\mathrm{eye\_lens}}$ and $D_{\mathrm{local\_skin}}$





- Existing dosimeters for $H_p(0.07)$ can be used unchanged
- Existing dosimeters for $H_p(3)$ – some attention needed at very low energy

Calibration in H_p



The energy-dependent response function of whole-body dosimeters must be modified

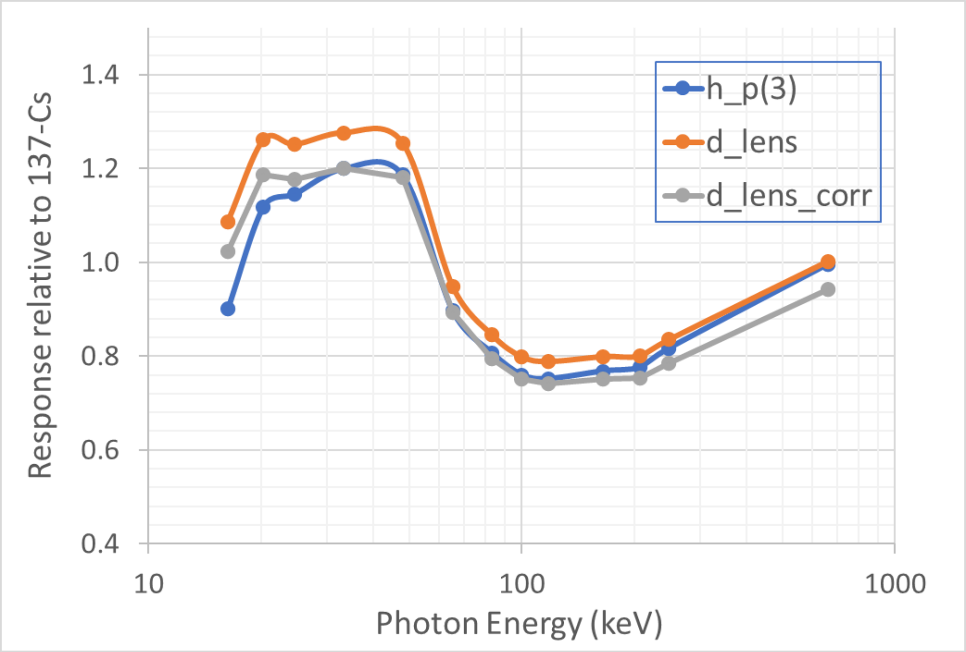
Response of dosimeters

- *Response:* $R = \frac{G}{C}$
  - Dose Indication *G* /Conventional true value *C*
- Change of quantity: $C_{old} \rightarrow C_{new}$
- Dose indication remains the same: $G \rightarrow G$

- Response of dosimeter in the new quantity:

$$R_{\mathrm{new}} = \frac{G}{C_{\mathrm{old}}} \frac{C_{\mathrm{old}}}{C_{\mathrm{new}}} = R_{old} \frac{C_{\mathrm{old}}}{C_{\mathrm{new}}} = R_{old} \frac{h_{\mathrm{old}}}{h_{\mathrm{new}}}$$

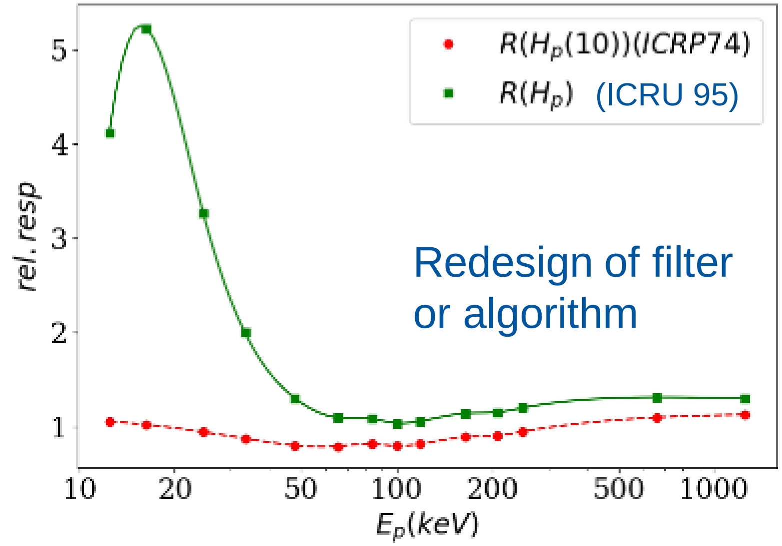
Response of Eye Lens Dosimeter

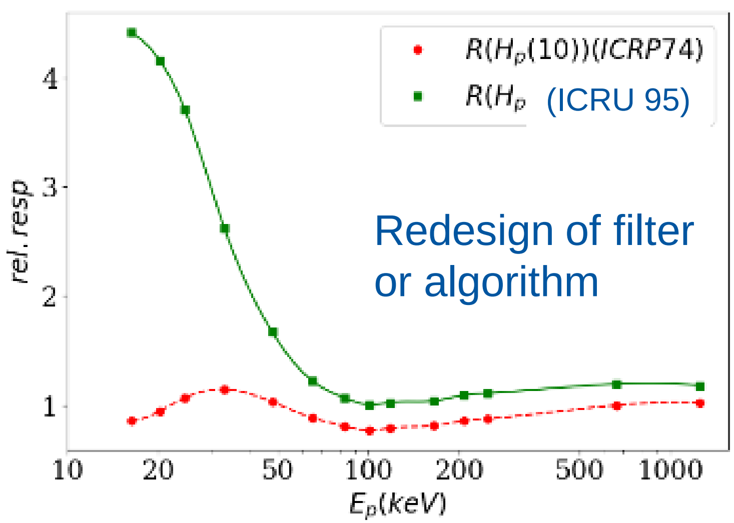


A small correction factor of 0.94 improves the energy-dependent response

Response of personal dosimeters

OSL
detectors



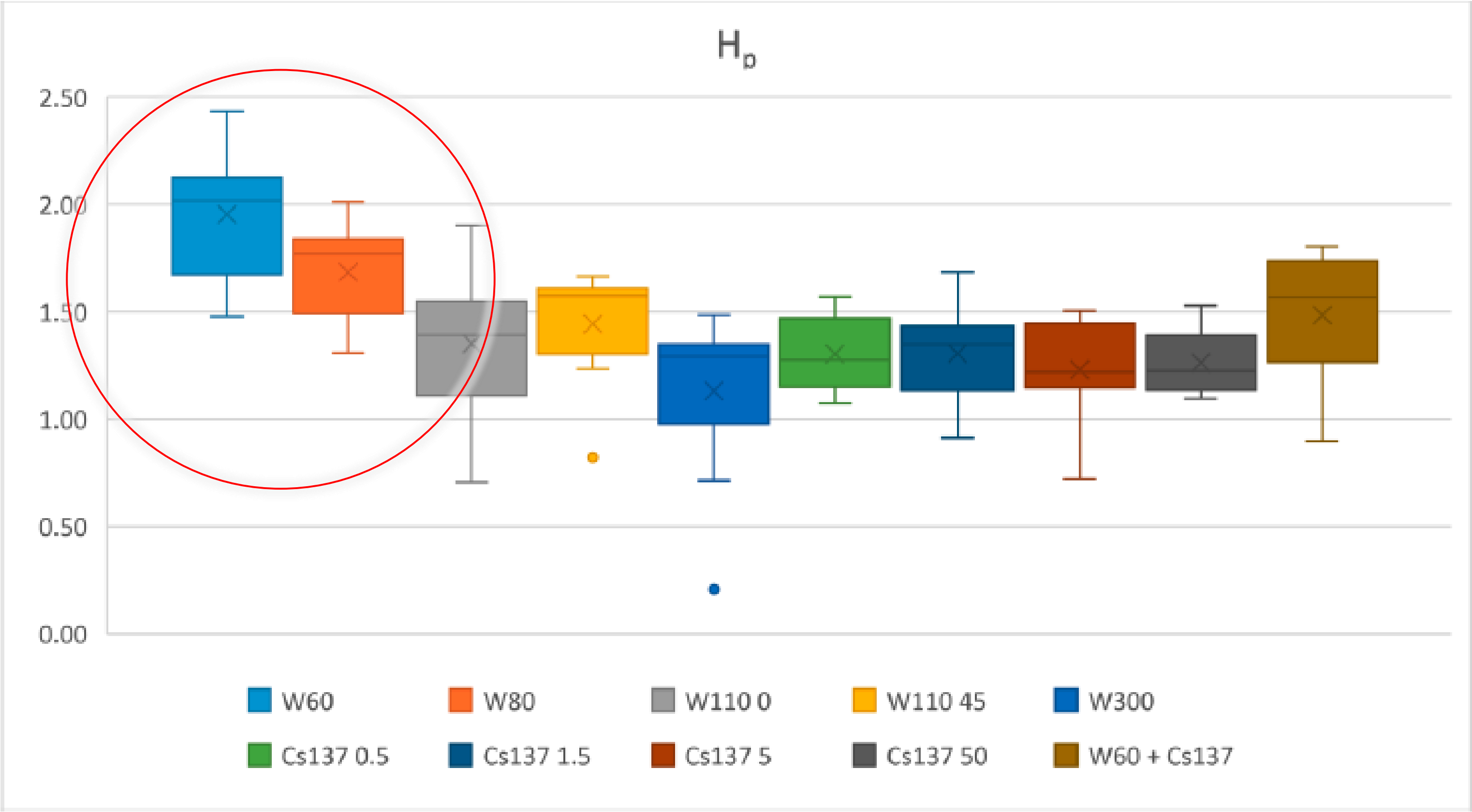


TL
detectors

T. Otto, *JINST* **14** P01010, 2019

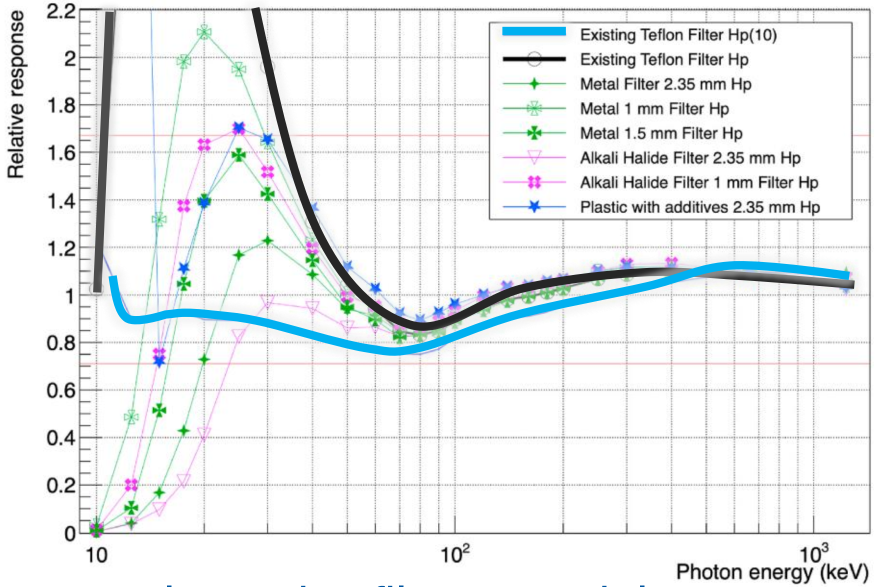
Response of Existing dosimeters

Intercomparison of Italian Dosimetry Services (2020)

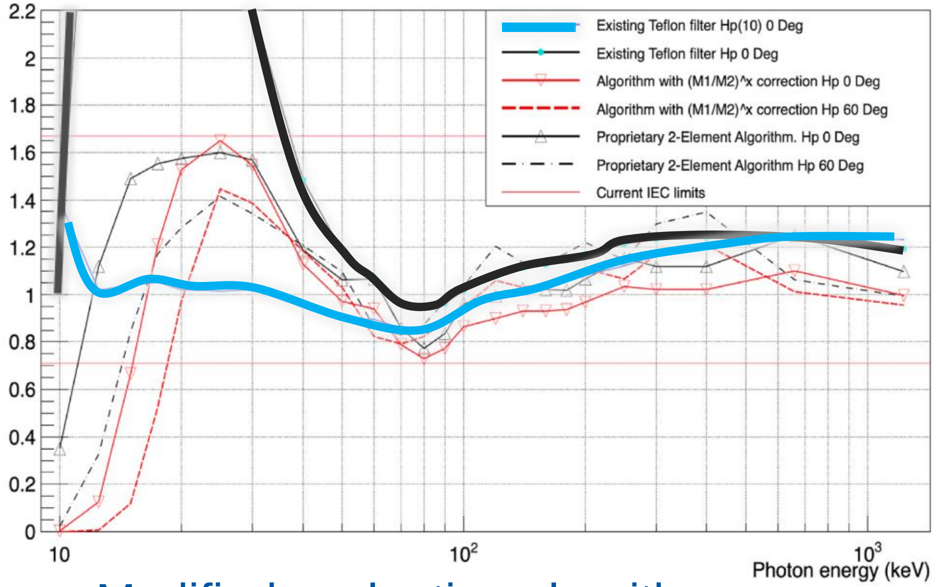


M. Caresana et al., *J. Radiol. Prot.*, 2021

Modification of an Existing Dosimeter



Alternative filter materials

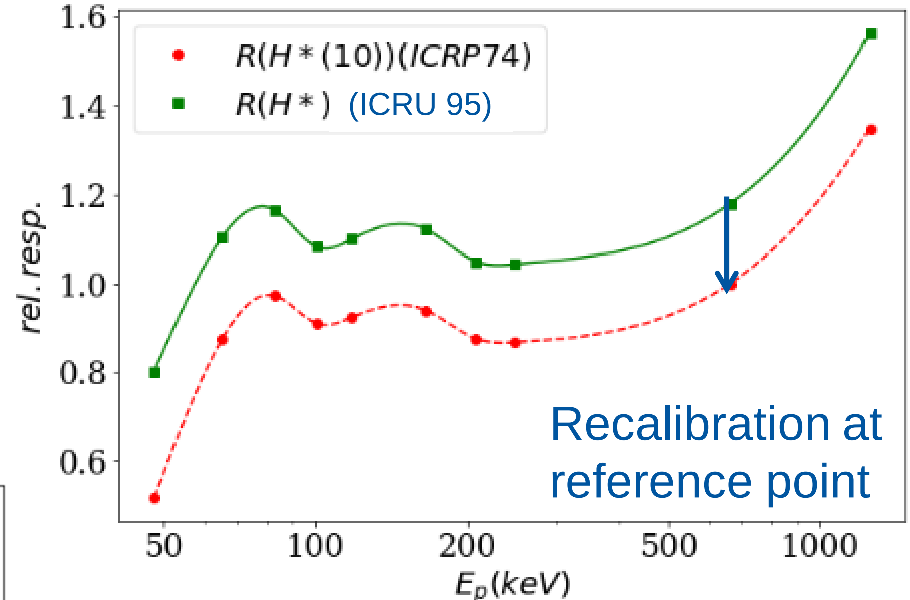


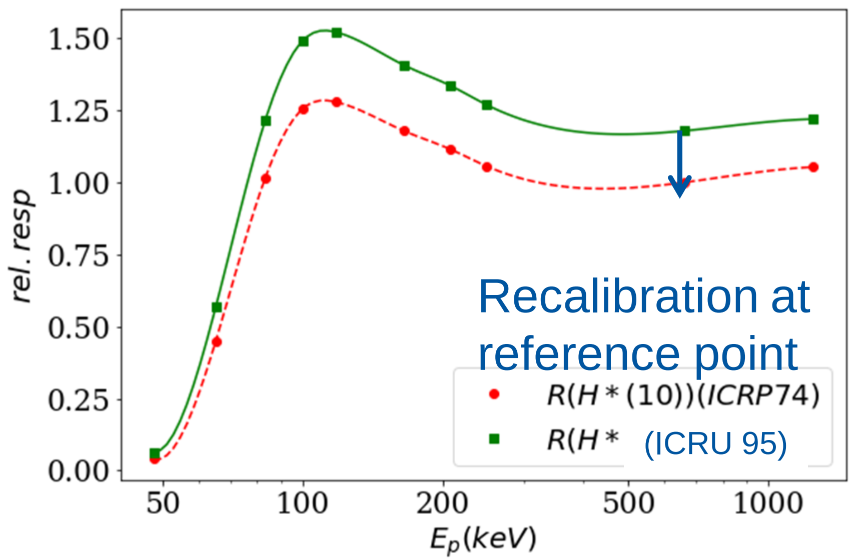
Modified evaluation algorithm

Hoedlmoser et al, Rad. Meas. 139 (2020)

Response of Survey instruments

Based on
G-M counter

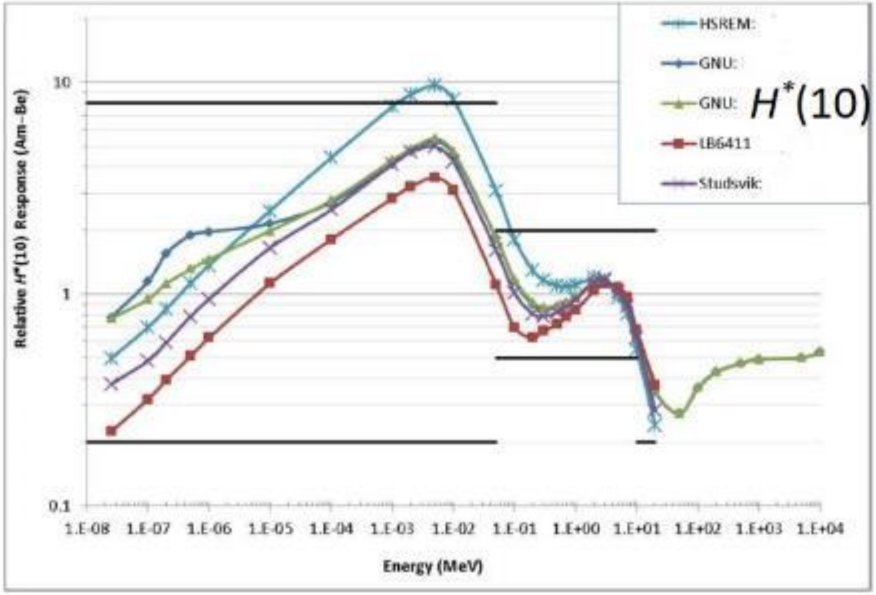




Based on
I-Chamber

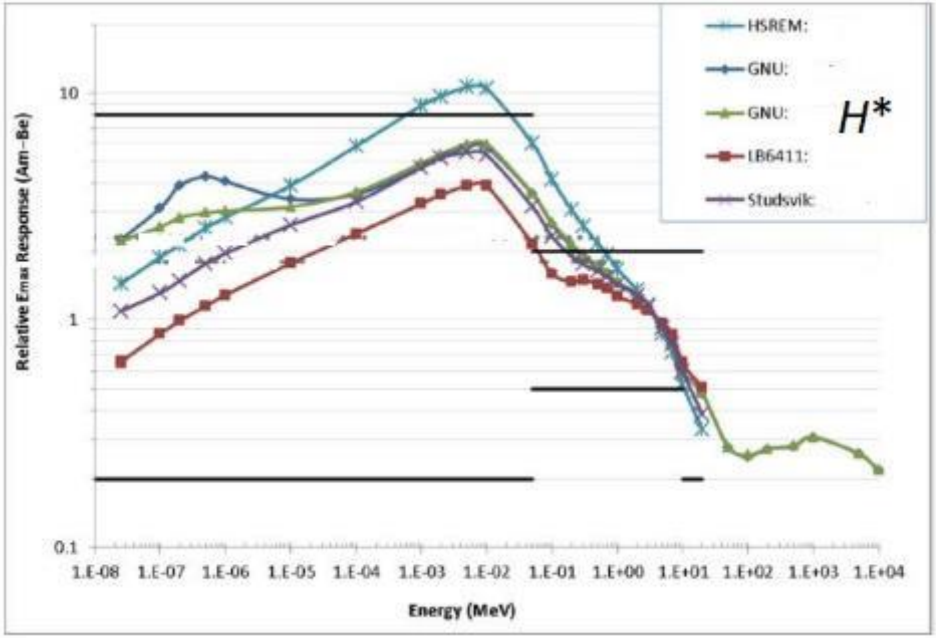
T. Otto, *JINST* **14** P01010, 2019

Response of Neutron Monitors (Rem-counters)



Black lines: IEC 61005 Ed. 3.0 b:2014 recommended response interval

Re-assessment of IEC acceptance regions required



As previously, standard Rem-counter response in mono-energetic fields within a large factor

No significant change for use at E_{kin} < 20 MeV

Field calibration may be necessary

J S Eakins *et al* 2018 *J. Radiol. Prot.* **38** 688

Summary Dosimeter Response

- Area dosimeters with cut-off *E* > 50 keV nearly unaffected
  - Recalibration of sensitivity
- Extremity dosimeters – no change needed
- Eye lens dosimeters – nearly unaffected
  - Recalibration
- Whole-body dosimeters: overresponse at low photon energies
  - Redesign of filter required (or algorithm for multi-detector types)
- Neutron Monitors continue to give “good estimate”
  - Recalibration, adaptation of acceptance limits by IEC

ICRU 95 – Conclusion

- Operational quantities are defined in a consistent manner to the protection quantities, using same phantoms and weighting factors
- System of quantities is easier to understand
- Numerical values and their trends with energy are coherent with protection quantities
- Changed dose values in real radiation fields: do not warrant change of RC practice.
  - Study required for fields in interventional radiology
- Calibration procedures unchanged, use new conversion coefficients, realize SEE for γ
- Adaptation of certain dosimeter types required:
  - Whole-body personal dosimeters for γ and β radiation at low energy

Thank you for your Attention