ICTP SCHOOL ON MEDICAL PHYSICS FOR RADIATION THERAPY: DOSIMETRY AND TREATMENT PLANNING FOR BASIC AND ADVANCED APPLICATIONS

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Dosimetry: Electron Beams

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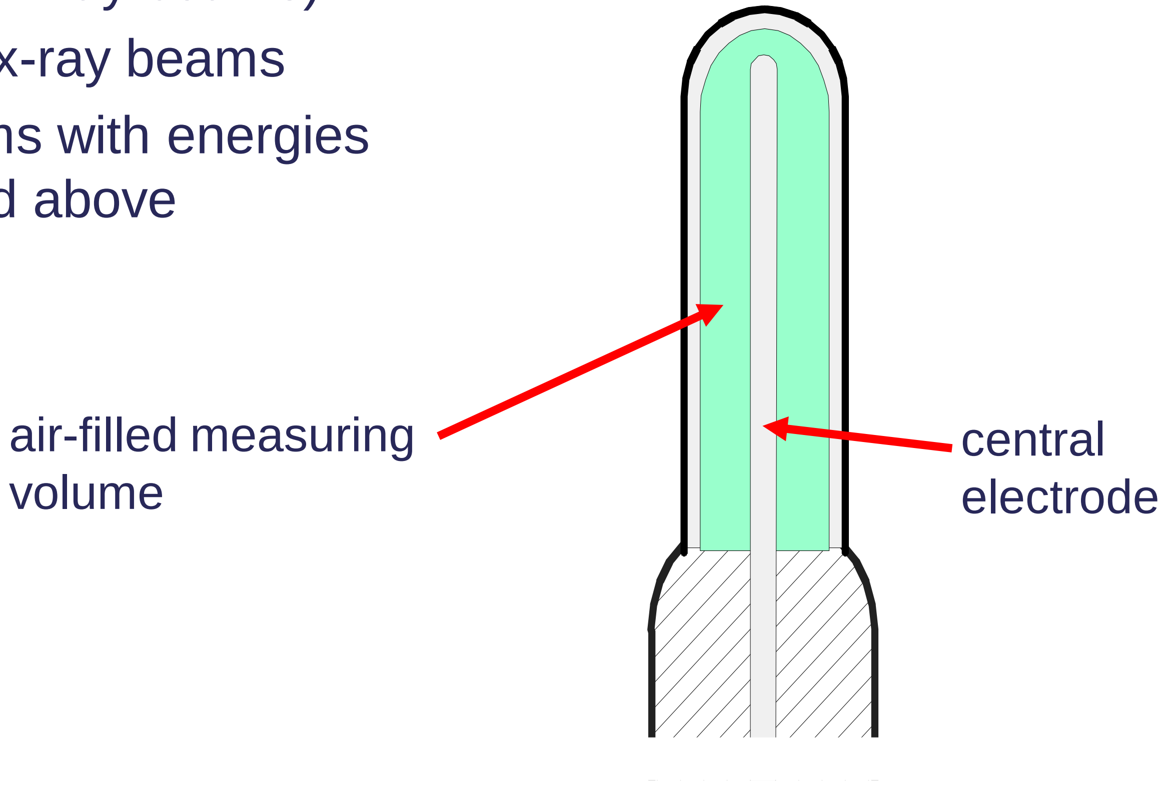
Content:

1. Dosimetry equipment
2. Calibration procedure
3. Correction factors
4. The radiation quality correction factor k_Q :
   Determination & Calculation
5. Depth of measurement:
   at reference depth & at depth of maximum dose
6. Cross calibration

1. Dosimetry Equipment
Ionization chambers

Types of chambers used:

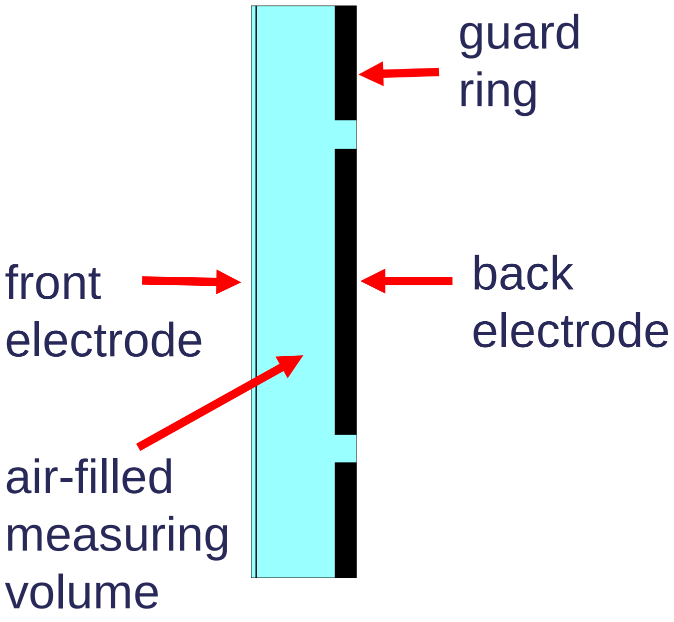
- Cylindrical (also called thimble) chambers are used in calibration of:
  - (Orthovoltage x-ray beams)
  - Megavoltage x-ray beams
  - Electron beams with energies of 10 MeV and above



1. Dosimetry Equipment
Ionization chambers

Types of chambers used:

- Parallel-plate (also called end window or plane-parallel) chambers are used :
  - for the calibration of superficial x-ray beams
  - for the calibration of electron beams with energies below 10 MeV
  - for dose measurements in photon beams in the buildup region and surface dose



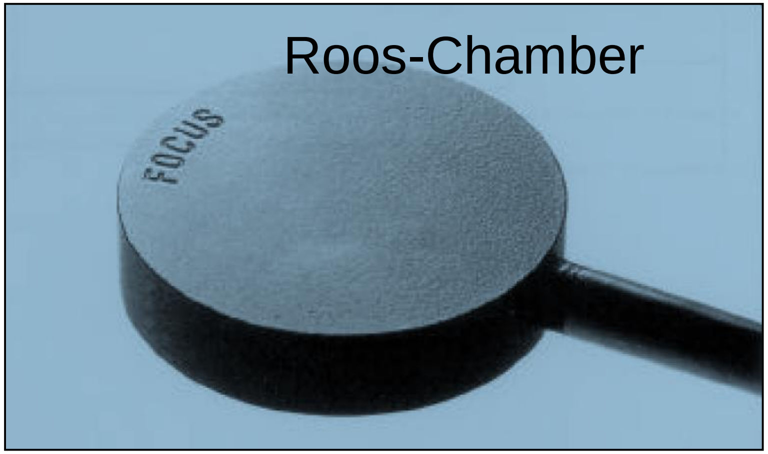
1. Dosimetry Equipment
Ionization chambers

Cylindrical Chambers

Farmer-Chamber

Plane Parallel Chambers

Roos-Chamber



1. Dosimetry Equipment

1. Dosimetry Equipment

Electrometer, ioniation camber and radioactive check source

1. Dosimetry Equipment
Electrometer plus connectors

From the PTW Catalogue:

"Ionizing Radiation Detectors"

"The following overview of connecting systems facilitates the identification of a variety of adequate connectors"

1. Dosimetry Equipment

Phantoms

Water Phantoms

Solid Phantoms

1. Dosimetry Equipment
Phantoms

Pease note:

- **Water** is always recommended in the IAEA Codes of Practice as the phantom material for the **calibration** of megavoltage photon and electron beams.
- The phantom should extend to at least 5 cm beyond all four sides of the largest field size employed at the depth of measurement.
- There should also be a margin of at least 5 g/cm^2 beyond the maximum depth of measurement except for medium energy X rays in which case it should extend to at least 10 g/cm^2.

1. Dosimetry Equipment
Phantoms for measurements

Solid (plastic) phantom:

Please note:

In spite of their increasing popularity, the **use of plastic phantoms is strongly discouraged for reference measurements**.

In general such measurements are responsible for the largest discrepancies in the determination of absorbed dose for most beam types.

1. Dosimetry Equipment

Phantoms for measurements

Solid (plastic) phantom:

Several disadvantages because a plastic phantom requires:

- **scaling of depth:** $z_w = z_{pl} \; c_{pl}$

  where c_{pl} is a depth scaling factor

- **scaling of dosimeter reading $M_{Q,pl}$:** $M_Q = M_{Q,pl} \; h_{pl}$

  h_{pl} is a fluence scaling factor

1. Dosimetry Equipment
Phantoms for measurements

Values from TRS 398 for c_{pl} and h_{pl}

Plastic phantom	c_{pl}	h_{pl}	ρ_{pl} (g cm^{-3})
Solid water (WT1)	0.949	1.011	1.020
Solid water (RMI-457)	0.949	1.008 [a]	1.030
Plastic water	0.982	0.998 [b]	1.013
Virtual water	0.946	- [c]	1.030
PMMA	0.941	1.009	1.190
Clear polystyrene	0.922	1.026	1.060
White polystyrene [d]	0.922	1.019	1.060
A-150	0.948	- [c]	1.127

[a] Average of the values given in Ref. [95] below 10 MeV.

[b] Average of the values given in Ref. [64] below 10 MeV.

[c] Data not available.

[d] Also referred to as high-impact polystyrene.

Note:
The **high uncertainty** associated with h_{pl} is the main reason for avoiding the use of plastic phantoms.

2. Calibration procedure

General formula

$$\boxed{D_{w,Q} = M_Q \; N_{D,w,Q_o} \; k_{Q,Q_o}}$$

M_{Q_O} is the **chamber reading in beam of quality *Q*** and corrected for influence quantities to the reference conditions used in the standards laboratory.

N_{D,w,Q_O} is the **water dose calibration coefficient** provided by the standards laboratory for reference beam quality Q_o.

k_{Q,Q_o} is a **factor correcting for the differences between the reference beam quality Q_o and the actual user quality *Q*.**

2. Calibration procedure

Positioning of the ionization chamber in water

Positioning can be defined as the adjustment of the **reference point** of a chamber with respect to the **measuring depth**.

Positioning of the reference point of a **cylindrical chamber** according to the International Code of Practice of the IAEA, TRS 398:

	Purpose	
	Beam calibration	**Depth dose measurement**
Co-60	at measuring depth	0.6 *r* deeper than measuring depth
HE photons	at measuring depth	0.6 *r* deeper than measuring depth
HE electrons	0.5 *r* deeper than measuring depth	0.5 *r* deeper than measuring depth

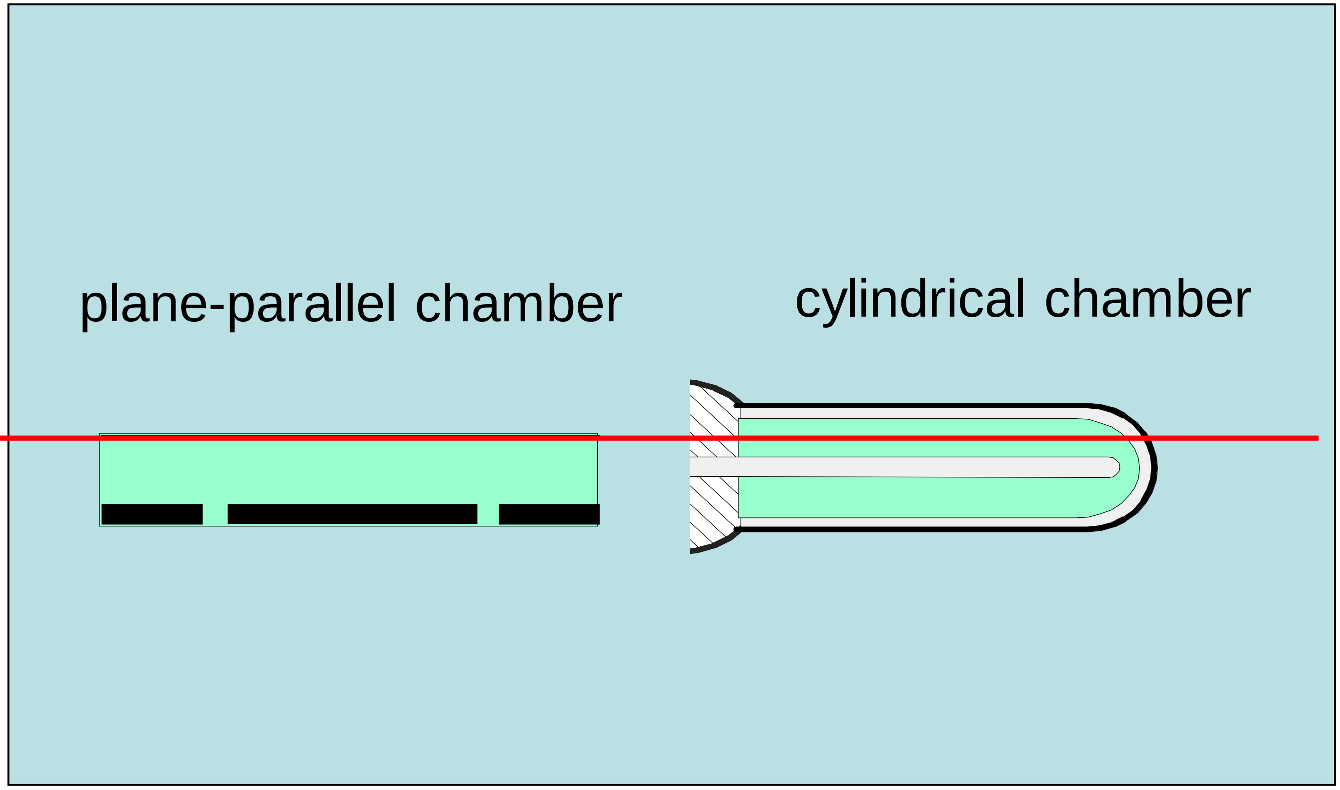
2. Calibration procedure
Positioning of the ionization chamber in water

Positioning of the reference point of a **plane parallel chamber** according to the International Code of Practice of the IAEA, TRS 398:

	Purpose	
	Beam calibration	**Depth dose measurement**
Co-60	always at measuring depth	
HE photons	always at measuring depth	
HE electrons	always at measuring depth	

Positioning for **high energy electrons**

depth of measurement



3. Correction factors

- If the chamber is used under conditions that differ from the reference conditions, then the measured charge must be corrected for the influence quantities by so-called influence correction factors k.

- The three most import correction factors are:
  - $k_{T,P}$ for air density
  - k_{pol} for polarity effects
  - k_{sat} for missing saturation effects

4. The **beam quality correction factor**

- Frequently, the **reference** quality Q_o used for the calibration of ionization chambers is the cobalt-60 gamma radiation and the symbol k_Q is then normally used to designate the beam quality correction factor:

$$k_{Q,Qo} = k_{Q,Co\text{-}60} = k_Q$$

Determination of radiation quality correction factor k_Q

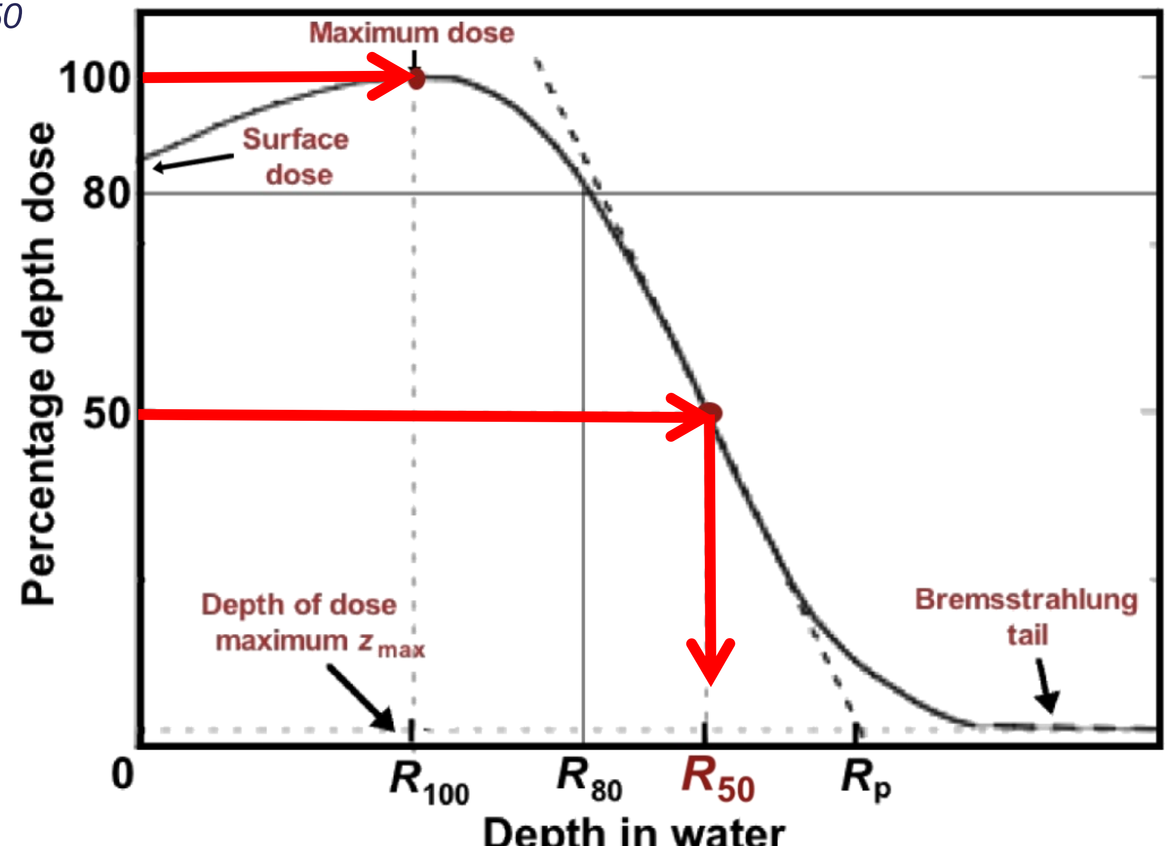
TABLE 18. CALCULATED VALUES FOR k_Q FOR ELECTRON BEAMS, FOR VARIOUS CHAMBER TYPES CALIBRATED IN ^{60}Co GAMMA RADIATION, AS A FUNCTION OF BEAM QUALITY R_{50}
(the data are derived using values for stopping-power ratios and perturbation factors, as given in Appendix II)

Ionization chamber type[a]	Beam quality index																
	1.0	1.4	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	7.0	8.0	10.0	13.0	16.0	20.0
Plane-parallel chambers																	
Attix RMI 449	0.953	0.943	0.932	0.925	0.919	0.913	0.908	0.904	0.900	0.896	0.893	0.886	0.881	0.871	0.859	0.849	0.837
Capintec PS-033	—	—	0.921	0.920	0.919	0.918	0.917	0.916	0.915	0.913	0.912	0.908	0.905	0.898	0.887	0.877	0.866
Exradin P11	0.958	0.948	0.937	0.930	0.923	0.918	0.913	0.908	0.904	0.901	0.897	0.891	0.885	0.875	0.863	0.853	0.841
Holt (Memorial)	0.971	0.961	0.950	0.942	0.936	0.931	0.926	0.921	0.917	0.913	0.910	0.903	0.897	0.887	0.875	0.865	0.853
NACP / Calcam	0.952	0.942	0.931	0.924	0.918	0.912	0.908	0.903	0.899	0.895	0.892	0.886	0.880	0.870	0.858	0.848	0.836
Markus	—	—	0.925	0.920	0.916	0.913	0.910	0.907	0.904	0.901	0.899	0.894	0.889	0.881	0.870	0.860	0.849
Roos	0.965	0.955	0.944	0.937	0.931	0.925	0.920	0.916	0.912	0.908	0.904	0.898	0.892	0.882	0.870	0.860	0.848
Cylindrical chambers																	
Capintec PR06C (Farmer)	—	—	—	—	—	—	0.916	0.914	0.912	0.911	0.909	0.906	0.904	0.899	0.891	0.884	0.874
Exradin A2 (Spokas)	—	—	—	—	—	—	0.914	0.913	0.913	0.913	0.912	0.911	0.910	0.908	0.903	0.897	0.888
Exradin T2 (Spokas)	—	—	—	—	—	—	0.882	0.881	0.881	0.881	0.880	0.879	0.878	0.876	0.871	0.865	0.857
Exradin A12	—	—	—	—	—	—	0.921	0.919	0.918	0.916	0.914	0.911	0.909	0.903	0.896	0.888	0.878

Determination of the quality index for HE electrons

Definition of the quality parameter *Q* for HE photons

- The quality parameter used for megavoltage electron beam specification is commonly based upon the **half-value depth** in water, R_{50}



The unit of **R_{50}** is gcm^{-2}

Determination of the quality index for HE electrons

Definition of the quality parameter Q for HE electrons according TRS 398:

- R_{50} is measured with
  - a constant SSD of 100 cm
  - a field size at the phantom surface of

    at least 10 cm x 10 cm for $R_{50} \leq 7$ g cm^{-2} ($E_0 < 16$ MeV)

    at least 20 cm x 20 cm for $R_{50} > 7$ g cm^{-2} ($E0 \leq 16$ MeV).

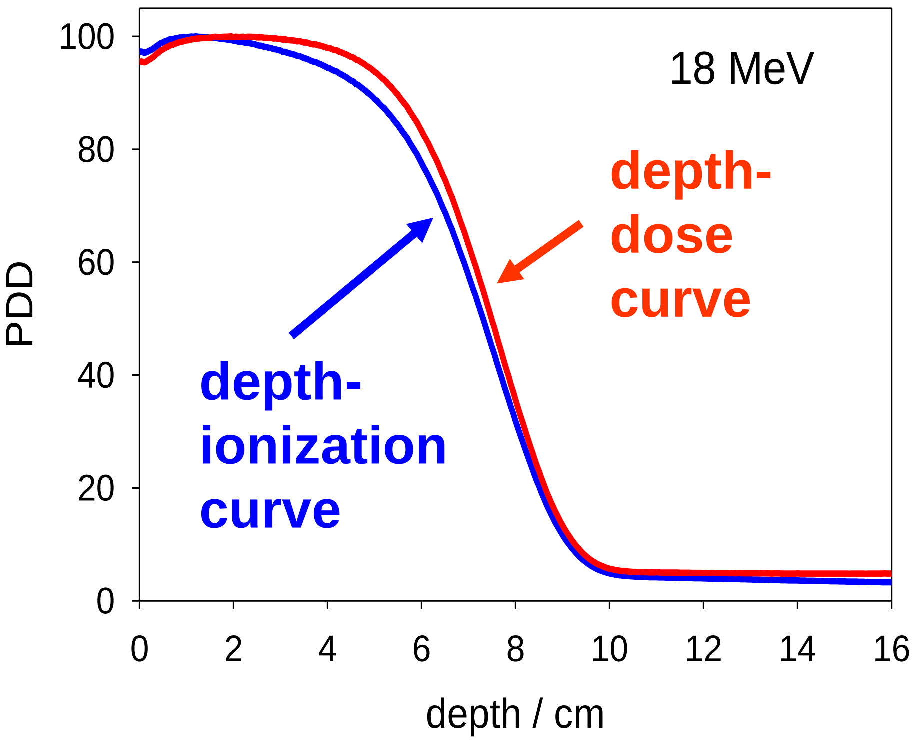
Determination of the quality index for HE electrons

Measurement of R_{50}:

- **Problem:**
  The measurement with an ionization chamber yields an **ionization-depth** curve (dose in air), not a dose-depth curve (dose in water).

- $$D_W(P) = D_{air} \cdot \bar{s}_{w,air} \cdot p$$

  $\bar{s}_{w,air}$ however, is dependent on energy, and hence on the depth



Determination of the quality index for HE electrons

Solution of this problem:

- The half-value of the depth-dose distribution in water R_{50} can be obtained directly from measured depth ionization curves using:

$$\boldsymbol{R_{50} = 1.029\, R_{50,ion} - 0.06 \quad \mathrm{g\ cm^{-2}} \quad (R_{50,ion} \leq 10\ \mathrm{g\ cm^{-2}})}$$

$$\boldsymbol{R_{50} = 1.059\, R_{50,ion} - 0.37 \quad \mathrm{g\ cm^{-2}} \quad (R_{50,ion} > 10\ \mathrm{g\ cm^{-2}})}$$

- As an alternative to the use of an ionization chamber, other detectors (for example diode, diamond, etc.) may be used to determine R_{50}.

- In this case the user must verify that the detector is suitable for depth-dose measurements by test comparisons with an ionization chamber at a set of representative beam qualities.

Calculation of k_Q

The values k_Q tabulated in TRS 398 have been obtained by **calculation**.

$$k_Q = \frac{\left(\dfrac{W}{e}\right)^{Q} \cdot s_{w,air}^{Q} \cdot p_Q}{\left(\dfrac{W}{e}\right)^{Q_0} \cdot s_{w,air}^{Q_0} \cdot p_{Q_0}}$$

5. Reference depth for HE electrons

A further reference condition for HE elctrons:

- The values of k_Q are valid only if the calibration measurement is performed at **the reference depth z_{ref}**

- **z_{ref} is energy dependent**, and obtained by:

$$z_{ref} = 0.6\ R_{50} - 0.1 \quad \text{g cm}^{-2} \quad (R_{50} \text{ in g cm}^{-2})$$

- This depth is close to the depth of the absorbed-dose maximum z_{max} at beam qualities $R_{50} < 4$ g cm^{-2} (E_0 <10 MeV), but at higher beam qualities is deeper than z_{max}.

Absorbed dose at z_{max} for HE electrons

Frequently, the basic output for an electron beam is wanted to be obtained at z_{max}.

- This again requires the determination of a depth dose curve.

- **A depth dose curve** has to be converted from a measured **depth ionization curve**.

- The conversion is performed by multiplying the depth ionization curve with the depth dependent water to air stopping power ratio adjusted to the beam quality of the electron beam.

Absorbed dose at z_{max} for HE electrons

This is the depth dependent water to air stopping power ratio adjusted to the beam quality of the electron beam:

$$s_{w,a}^{\Delta}(z) = \frac{a + bx + cx^2 + dy}{1 + ex + fx^2 + gx^3 + hy}$$

- with $x = \ln(R_{50}/\mathrm{cm})$, and $y = z / R_{50}$

a = 1,0752 b = -0,50867 c = 0,08867 d = -0,08402

e = -0,42806 f = 0,06463 g = 0,003085 h = -0,1246

6. Cross calibration in electron beams

Concept

- What is a cross-calibration of an ionization chamber?
  - Cross-calibration refers to the calibration of a **user chamber** by direct comparison in a suitable user beam against a **reference chamber** that has previously been calibrated.
  - A particular example is the cross-calibration of a **plane-parallel chamber** for use in electron beams against a **reference cylindrical chamber** calibrated in ^{60}Co gamma radiation.
  - Despite the additional step, such a cross-calibration generally results in a determination of absorbed dose to water using the plane-parallel chamber **that is more reliable** than that achieved by the use of a plane-parallel chamber calibrated directly in ^{60}Co
  - The main reason is: problems associated with the p_{wall} correction for plane-parallel chambers in ^{60}Co, entering into the determination of k_Q, are avoided.

Uncertainty of Calibration for High Energy Electrons (from the International Code of Practice TRS 398)

Physical quantity or procedure	Relative standard uncertainty (%)	
User chamber type:	**cylindrical**	**plane-parallel**
Beam quality range:	$R_{50} \geq 4$ g cm^{-2}	$R_{50} \geq 1$ g cm^{-2}
Step 1: Standards laboratory		
$N_{D,w}$ calibration of secondary standard at PSDL	0.5	0.5
Long-term stability of secondary standard	0.1	0.1
$N_{D,w}$ calibration of user dosimeter at SSDL	0.4	0.4
Combined uncertainty of Step 1 [b]	*0.6*	*0.6*
Step 2: User electron beam		
Long-term stability of user dosimeter	0.3	0.4
Establishment of reference conditions	0.4	0.6
Dosimeter reading M_Q relative to beam monitor	0.6	0.6
Correction for influence quantities k_i	0.4	0.5
Beam quality correction k_Q (calculated values)	1.2	1.7
Combined uncertainty of Step 2	*1.5*	*2.0*
Combined standard uncertainty of $D_{w,Q}$ (Steps 1+2)	**1.6**	**2.1**

6. Cross calibration in electron beams

Cross-calibration procedure

- The highest-energy electron beam available should be used; E_o > 16 MeV is recommended.
  Note: This is now the calibration quality!
- The reference chamber and the chamber to be calibrated are compared by alternately positioning each at the reference depth z_{ref} in water
- The calibration factor $N^{x}_{D,w,Q_{cross}}$ in terms of absorbed dose to water for the chamber under calibration, at the cross-calibration quality Q_{cross}, is then given by:

$$N^{x}_{D,w,Q_{cross}} = \frac{M^{ref}_{Q_{cross}}}{M^{x}_{Q_{cross}}} N^{ref}_{D,w,Q_o} k^{ref}_{Q_{cross},Q_o}$$

6. Cross calibration in electron beams

Cross-calibration procedure

Such equations require some exercise for reading.

$$\boxed{N_{D,w,Q_{cross}}^{x} = \frac{M_{Q_{cross}}^{ref}}{M_{Q_{cross}}^{x}} N_{D,w,Q_o}^{ref} \, k_{Q_{cross},Q_o}^{ref}}$$

However, when applied to an example, they can be "translated"

Example:

chamber to be cross calibrated: plane-parallel Roos chamber

cross calibrated against: cylindrical Farmer chamber

cross calibration performed at an electron energy of 18 MeV

$$\boxed{N_{D,w,18\,\mathrm{MeV}}^{\mathrm{Roos}} = \frac{M_{18\,\mathrm{MeV}}^{\mathrm{Farmer}}}{M_{18\,\mathrm{MeV}}^{\mathrm{Roos}}} N_{D,w}^{\mathrm{Farmer}} \, k_{18\,\mathrm{MeV}}^{\mathrm{Farmer}}}$$

6. Cross calibration in electron beams

Cross-calibration procedure

- Subsequent use of a cross-calibrated chamber
  - The cross-calibrated chamber with calibration factor $N^{X}_{D,w,Q_{cross}}$ may be used subsequently for the determination of absorbed dose in a user beam of quality *Q* using the basic equation:

$$\boxed{D_{w,Q} = M^{X}_{Q} \cdot N^{X}_{D,w,Q_{cross}} \cdot k^{X}_{Q,Q_{cross}}}$$

  - The values for $k^{X}_{Q,Q_{cross}}$ are derived using the procedure:

$$\boxed{k^{X}_{Q,Q_{cross}} = \frac{k^{X}_{Q,Q_{\mathrm{int}}}}{k^{X}_{Q_{cross},Q_{\mathrm{int}}}}}$$

where $k^{X}_{Q,Q_{\mathrm{int}}}$ and $k^{X}_{Q_{cross},Q_{\mathrm{int}}}$ are given in TRS 398, Table 19.

Summary: Beam Calibration of Electron Beams TRS 398

1) Cylindrical chambers are used in the calibration of electron beams at energies of 10 MeV and above; Parallel-plate chambers are used below 10 MeV
2) The “mother” of any calibration equation is:

$$D_{w,Q} = M_Q \; N_{D,w,Q_o} \; k_{Q,Q_o}$$

3) The most important correction factors to be applied to the measured charge are:
   - $k_{T,P}$ for air density
   - k_{pol} for polarity effects
   - k_{sat} for missing saturation effects

Summary: Beam Calibration of Electron Beams TRS 398

4) Quality correction factors are tabulated in TRS 398. k_Q can be calculated as:

$$k_Q = \frac{\left(\frac{W}{e}\right)^{Q} \cdot s^{Q}_{w,air} \cdot p_Q}{\left(\frac{W}{e}\right)^{Q_0} \cdot s^{Q_0}_{w,air} \cdot p_{Q_0}}$$

5) Measurement have to be performed at energy dependent reference depths:

$z_{ref} = 0.6\, R_{50} - 0.1$ g cm^{-2} (R_{50} in g cm^{-2})

6) Cross calibration is used for plane-parallel chambers in electron dosimetry to reduce the uncertainty of the resultant absorbed dose to water