

School on Medical Physics for Radiation Therapy: Dosimetry, Treatment Planning and Delivery for Advanced Applications



11 - 22 September 2023
An ICTP Meeting
Trieste, Italy

Further information:
<http://indico.ictp.it/event/10205/>
smr3871@ictp.it

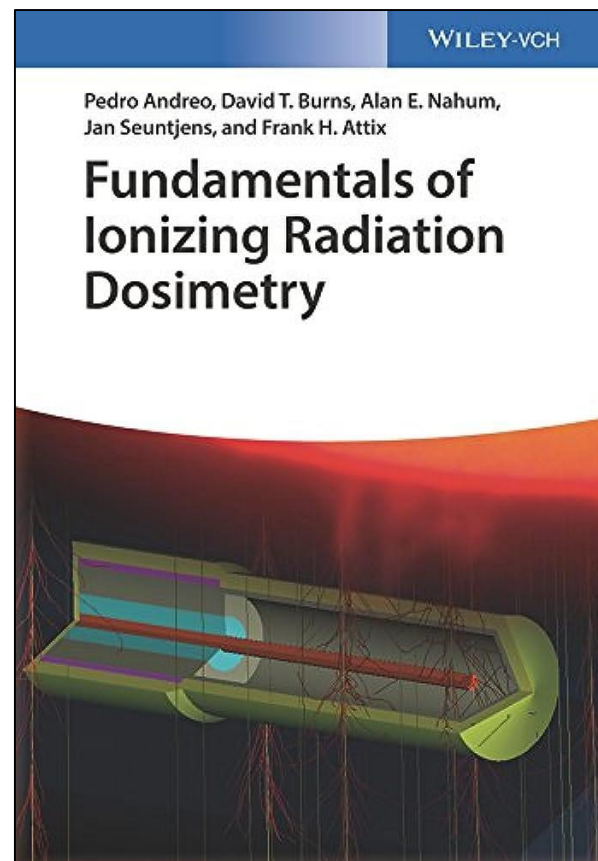
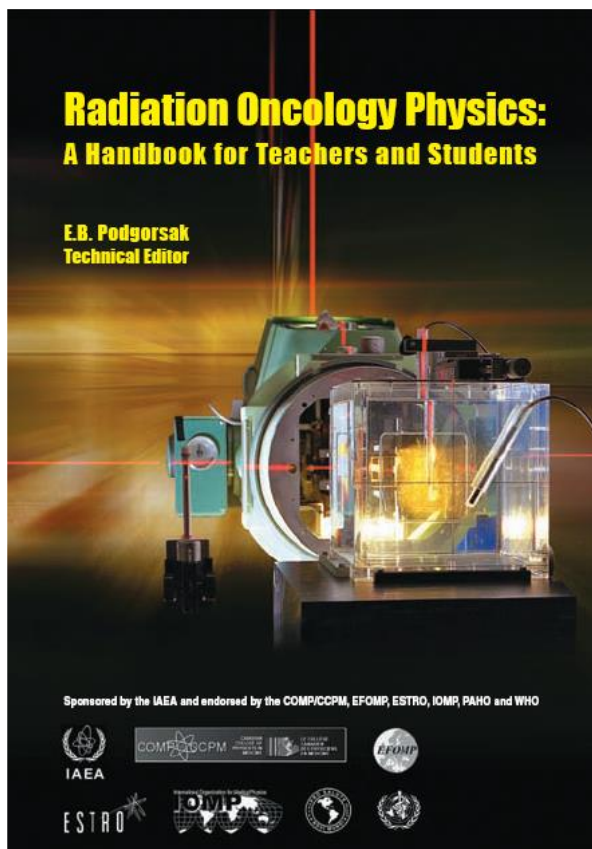
Dosimetry: Fundamentals 1 & 2

R. Padovani, ICTP
padovani@ictp.it

Content:

1. Introduction: Definition of "radiation dose"
2. General methods of dose measurement
3. Principles of dosimetry with ionization chambers:
 - Dose in air
 - Stopping Power
 - Conversion into dose in water, Bragg Gray Conditions
 - Spencer-Attix Formulation
4. General detector properties

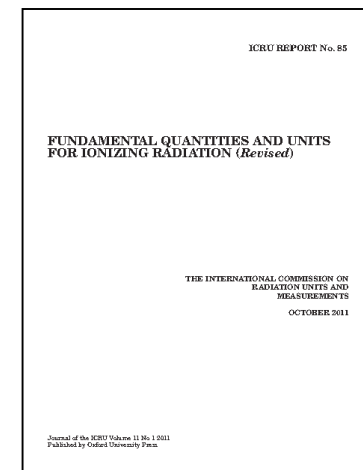
Lesson based on



and on lectures of E.B. Podgorsak and G. Hartmann

1. Introduction: physical meaning of "dose of radiation"

- "Dose" is a generic word to denote the dose of radiation and should be used only if your communication partner really knows its meaning.
- A dose of radiation is correctly expressed by the term and physical quantity of absorbed dose, D .
- The most fundamental definition of the **absorbed dose D** is given in Report ICRU 85a



1. Introduction: physical meaning of "dose of radiation"

According to ICRU Report 85a, the absorbed dose D is defined by:

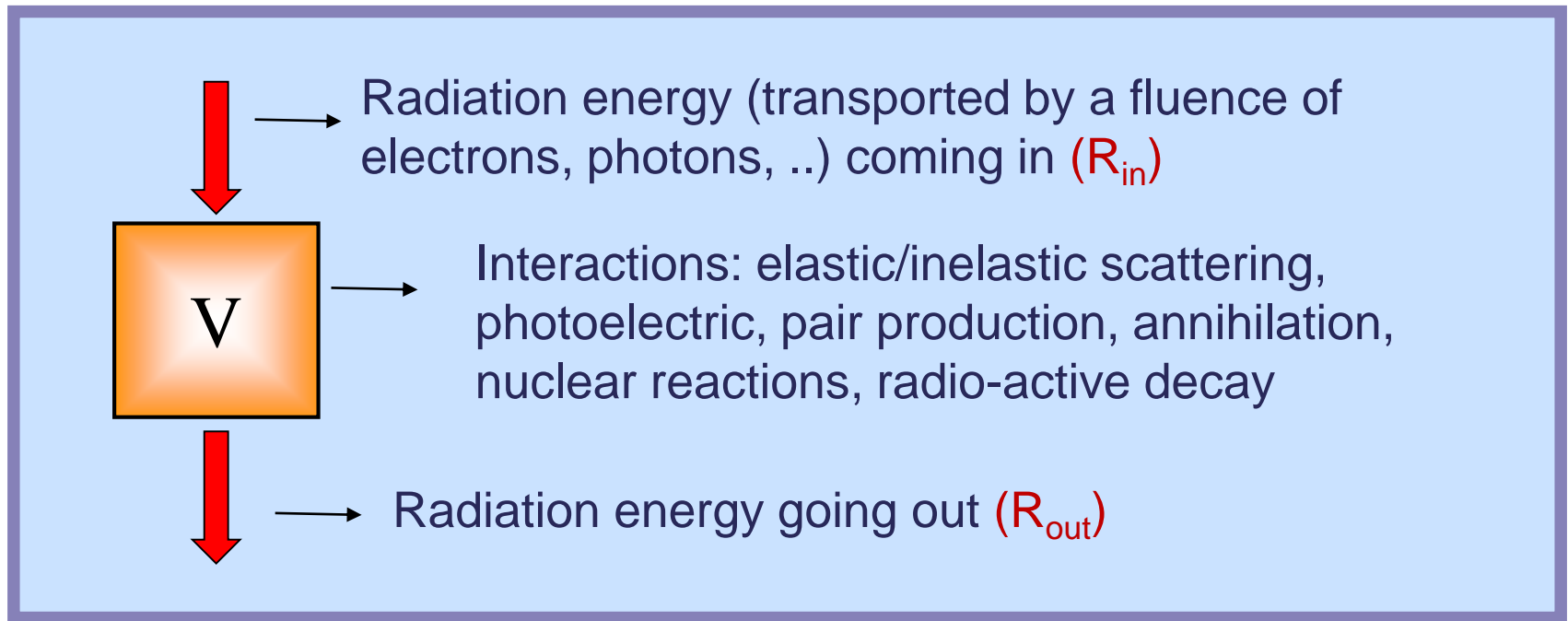
$$D = \frac{d\bar{\varepsilon}}{dm}$$

where $d\bar{\varepsilon}$ is the mean energy imparted to matter of mass dm , where dm is a small element of mass

The unit of absorbed dose is Joule per Kilogram (J/kg), the special name for this unit is Gray (Gy)

1. Introduction: 4 characteristics of absorbed dose = mean energy imparted / dm

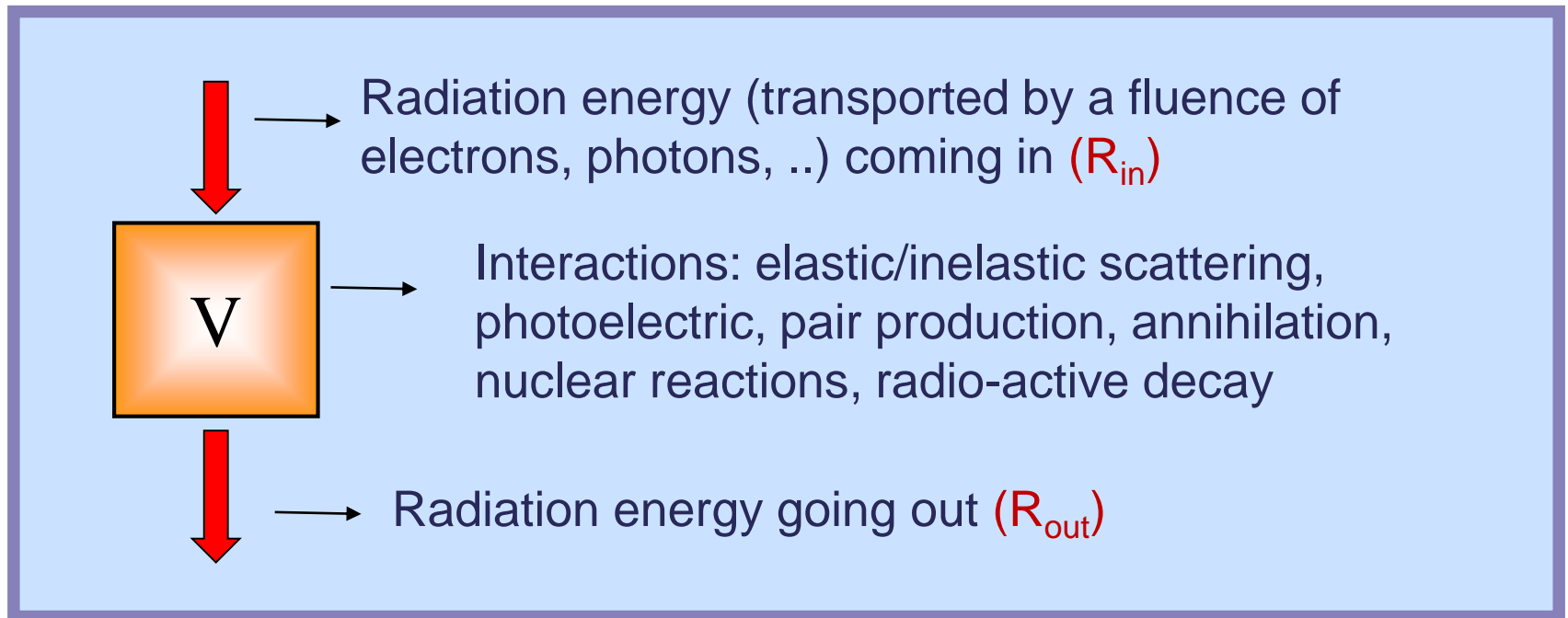
1. The term "energy imparted" can be considered to be the radiation energy absorbed in a volume:



$$\text{Absorbed (imparted) radiation energy} = R_{in} - R_{out}$$

1. Introduction: 4 characteristics of absorbed dose = mean energy imparted / dm

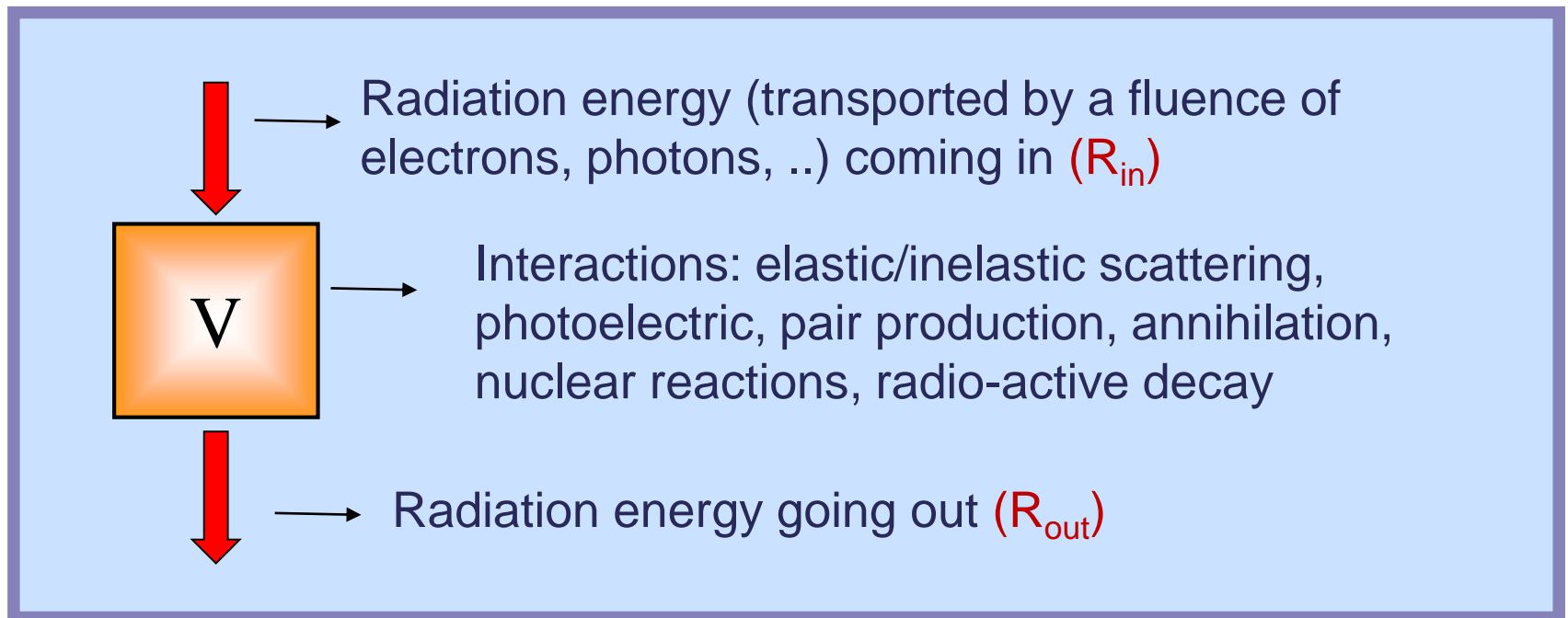
2. The term "**absorbed dose**" refers to an exactly defined volume and only to that volume V:



$$\text{Absorbed (imparted) radiation energy} = R_{in} - R_{out}$$

1. Introduction: 4 characteristics of absorbed dose = mean energy imparted/dm

3. The term "**absorbed dose**" refers to the material within the volume :
For example: air: D_{air} , water: D_{water}



$$\text{Absorbed (imparted) radiation energy} = R_{\text{in}} - R_{\text{out}}$$

1. Introduction: 4 characteristics of absorbed dose = mean energy imparted / dm

4. "absorbed dose" is a quantity that refers to a mathematical point \vec{r} in space:

$$D = D(\vec{r})$$

and

- D is steady in space and time
- D can be differentiated in space and time

Two contradictions from the definition of absorbed dose

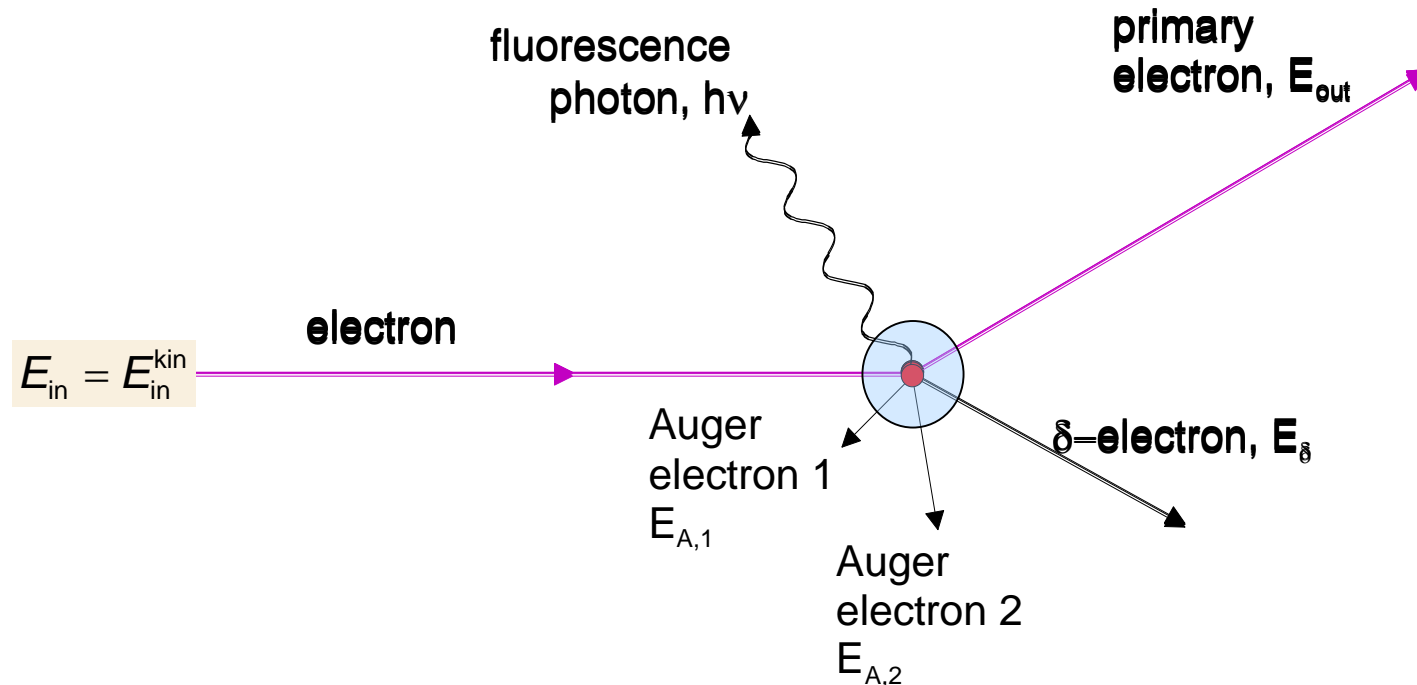
1. Absorbed dose refers to a **volume** and at the same time it is a quantity that refers to a **point** in space.
2. Absorbed dose comes from interactions at a microscopic level which are of **random character** (like any interaction at atomic and nuclear levels)
At the same time absorbed dose D is **a non-random quantity** that is steady in space and time

How can these contradictions be explained?

It is necessary a closer look on the atomic interactions and the associated energy deposition (de)

Example of a “Microscopic” interaction & single energy deposition **de**

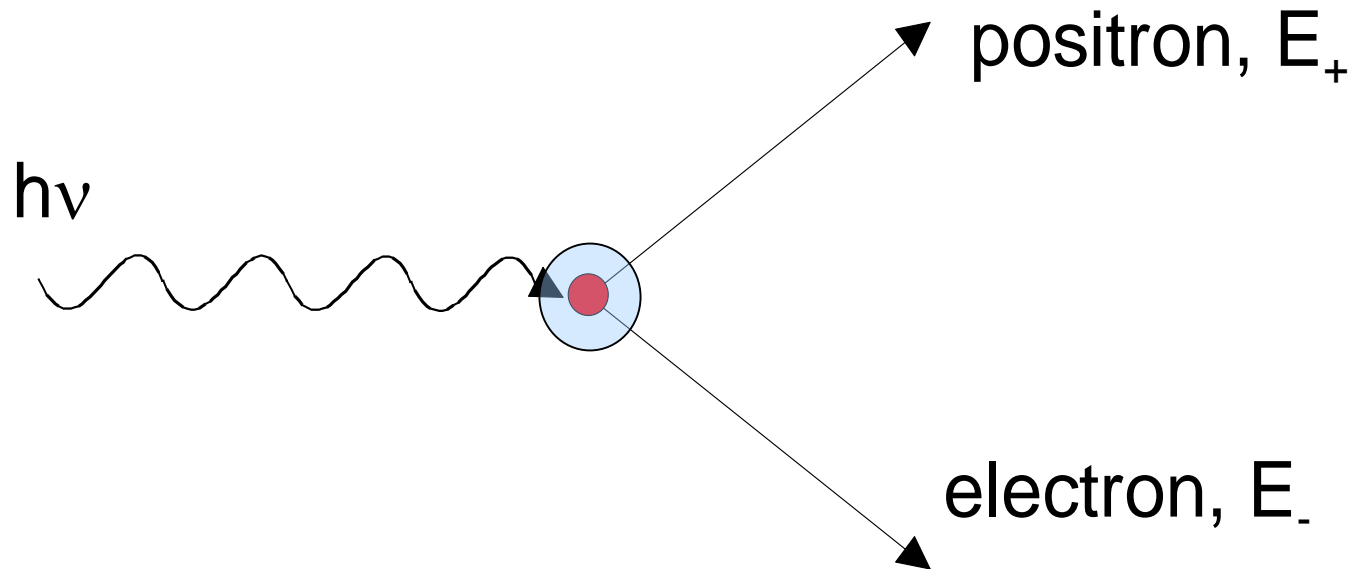
Energy deposition **de** by an electron knock-on interaction:



$$de = E_{in} - (E_{out} + E_{\delta} + h\nu + E_{A,1} + E_{A,2})$$

Example of a “Microscopic” interaction & single energy deposition de

Energy deposition de by pair production:

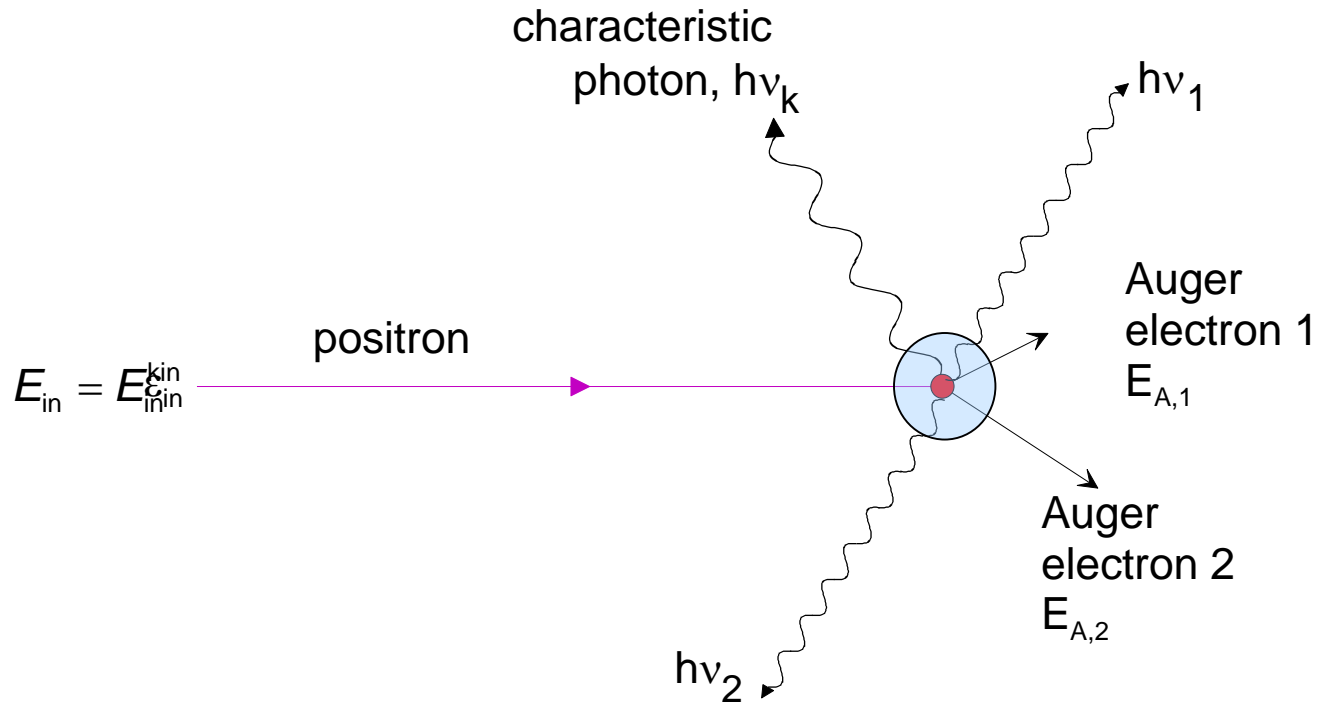


$$de = h\nu - \left(E_{\text{electron}}^{\text{kin}} + E_{\text{positron}}^{\text{kin}} + 2m_0c^2 \right)$$

Note: The rest energy of the positron and electron is escaping and therefore must be subtracted from the initial energy $h\nu$!

Example of a “Microscopic” interaction & single energy deposition **de**

Energy deposition **de** by positron annihilation:



$$de = E_{in} - (h\nu_1 + h\nu_2 + h\nu_k + E_{A,1} + E_{A,2}) + 2m_0c^2$$

Note: The rest energies of the positron and electron have to be added!

“Microscopic” interaction & single energy deposition **de**

The common aspects to the energy deposition:

- Almost any energy deposition is produced by **electrons**
- Primary as well as secondary electrons are depositing energy via interaction process called **energy loss**
- **Energy loss** depends on the:
 - **energy** of the electron
 - **material** through which the electron is moving

The process of energy loss is described by the **stopping power** S_{mat} of the material mat, defined as the **energy lost per unit path length**

$$S_{mat} = \frac{dE}{dl}$$

Definition of **stopping power** (ICRU Report 85a)

Normally we use the **mass stopping power** as the quotient of **S** with the density **ρ** of the material

4.4 Mass Stopping Power

The *mass stopping power*, S/ρ , of a material, for charged particles of a given type and energy, is the quotient of dE by ρdl , where dE is the mean energy lost by the charged particles in traversing a distance dl in the material of density ρ , thus

$$\frac{S}{\rho} = \frac{1}{\rho} \frac{dE}{dl}.$$

Unit: $\text{J m}^2 \text{kg}^{-1}$

Mass Stopping Power

Mass stopping power is the contribution of three components:

$$\frac{S}{\rho} = \frac{1}{\rho} \left(\frac{dE}{dl} \right)_{\text{el}} + \frac{1}{\rho} \left(\frac{dE}{dl} \right)_{\text{rad}} + \frac{1}{\rho} \left(\frac{dE}{dl} \right)_{\text{nuc}}$$

$\frac{1}{\rho} \left(\frac{dE}{dl} \right)_{\text{el}} = \frac{1}{\rho} S_{\text{el}}$ is the *mass electronic (or collision⁴) stopping power* due to interactions with atomic electrons resulting in ionization or excitation,

$\frac{1}{\rho} \left(\frac{dE}{dl} \right)_{\text{rad}} = \frac{1}{\rho} S_{\text{rad}}$ is the *mass radiative stopping power* due to emission of bremsstrahlung in the electric fields of atomic nuclei or atomic electrons, and

$\frac{1}{\rho} \left(\frac{dE}{dl} \right)_{\text{nuc}} = \frac{1}{\rho} S_{\text{nuc}}$ is the *mass nuclear stopping power⁵* due to elastic Coulomb interactions in which recoil energy is imparted to atoms.

Stopping Power and Mass Stopping Power

Why **stopping power**, i.e. the energy loss of electrons, is an important concept in dosimetry?

1. The **electronic energy loss dE_{el}** is at the same time the **energy absorbed**
2. There is a **fundamental relationship** between **absorbed dose** from charged particles and **mass electronic stopping power** (particle fluence concept is necessary for this relationship)

Characterization of a Radiation Field

- Definition of particle number N :
The particle number, N , is the number of particles that are emitted, transferred, or received

A **detailed description** of a radiation field, however, requires more information on the particle number N such as:

- of particle type: j
- at a point of interest: \vec{r}
- at energy: E
- at time: t
- with movement in direction $\vec{\Omega}$

$$N = N_j(\vec{r}, E, t, \vec{\Omega})$$

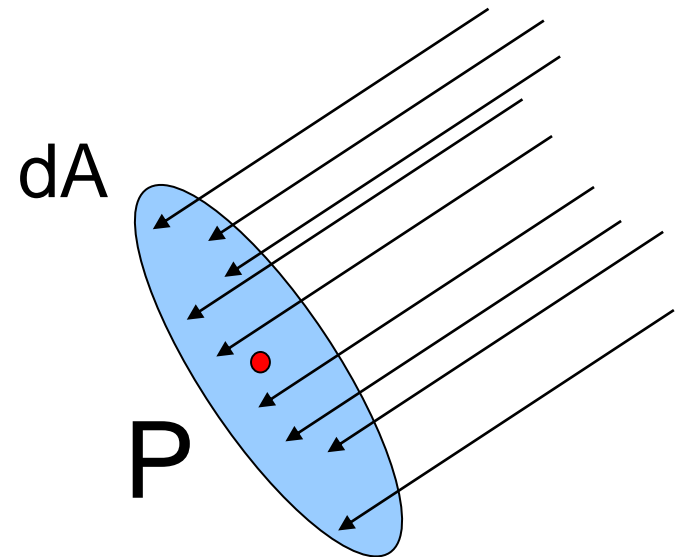
How to determine the number of particles at a certain point in space?

Consider a point P in space within a field of radiation.

Then use the following simple method:

In case of a **parallel radiation beam**, construct a small area dA around the point P in such a way, that its plane is **perpendicular** to the direction of the beam.

Determine the number of particles that intercept this area dA .



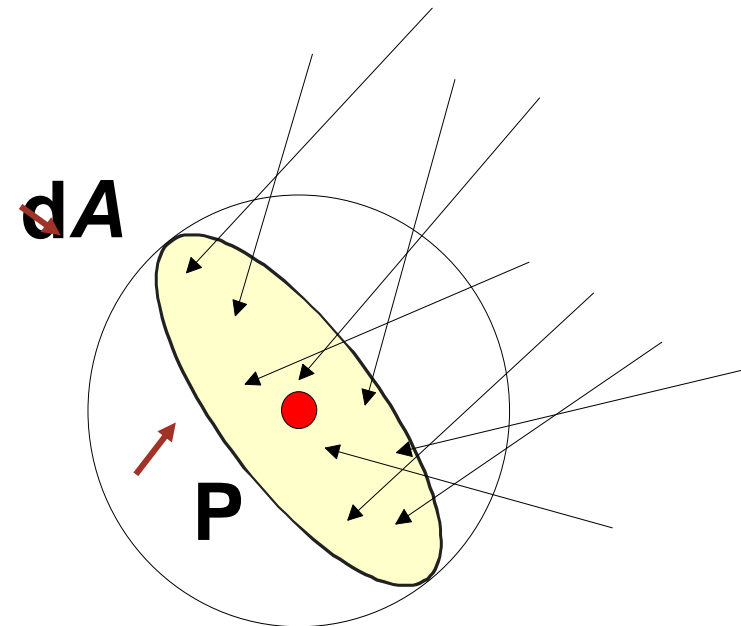
In the general case of **nonparallel particle directions** it is evident that a fixed plane cannot be traversed by all particles perpendicularly.

Then, the plane dA is allowed to move freely around P , so as to intercept each incident ray perpendicularly.

Practically this means:

- Generate a **sphere** by rotating dA around P

Count the number of particles **entering** the sphere



Particle fluence

The number of particles per area dA is called the

particle fluence Φ

Definition:

The fluence Φ is the quotient dN by dA , where dN is the number of particles incident on a sphere of cross-sectional area dA :

$$\Phi = \frac{dN}{dA} \quad \text{The unit of fluence is } m^{-2}.$$

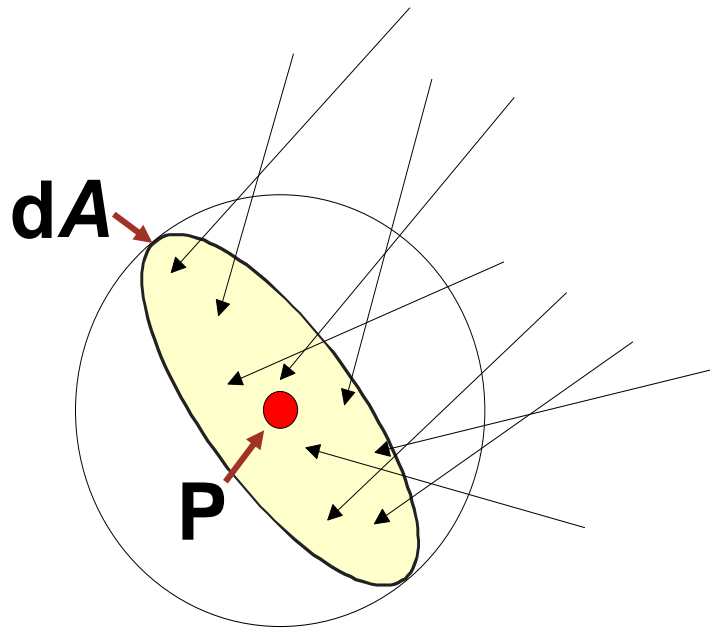
Also important is the **fluence differential in energy**, denoted as Φ_E

$$\Phi_E = \frac{d\Phi}{dE}$$

Note: The term **fluence** is sometimes also used for **particle fluence**.

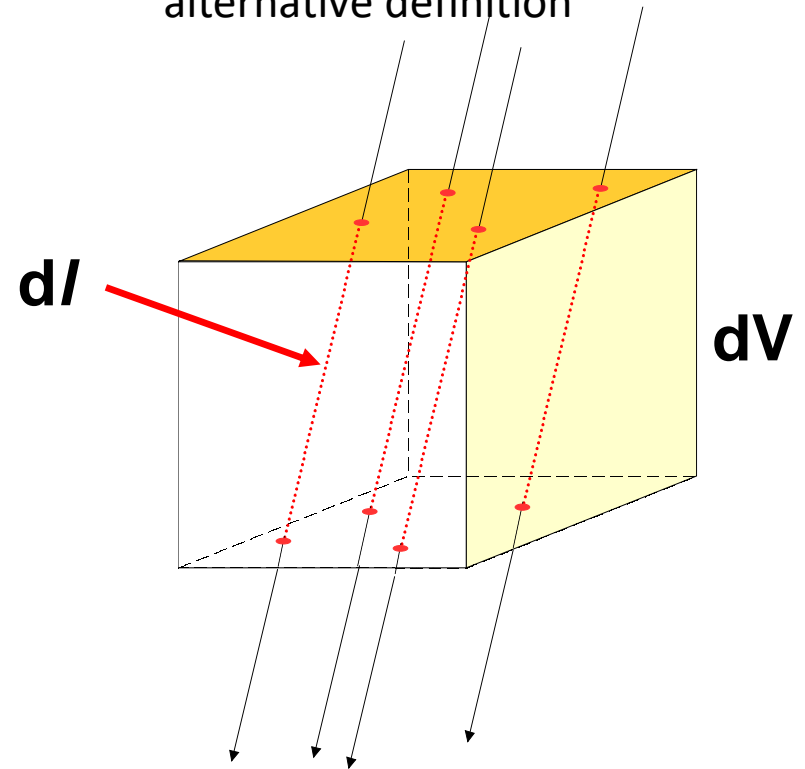
There is an important alternative definition for fluence:

conventional definition



$$\Phi(\vec{r}) = \frac{dN}{dA}$$

alternative definition



$$\Phi(\vec{r}) = \frac{dN}{dA} = \frac{dNdl}{dV} = \frac{dL}{dV}$$

with dL the sum of the track lengths

Absorbed dose and Mass Stopping Power

Now an important relationship between **absorbed dose from charged particles** and the **mass electronic stopping power**.

Take the mass electronic stopping power and multiply with the primary fluence differential in energy:

$$\frac{S_{el}}{\rho} \Phi_E = \frac{1}{\rho} \left(\frac{dE}{dl} \right)_{el} \frac{d\Phi}{dE}$$

since $dl = \Phi dV$

$$\frac{1}{\rho} \left(\frac{dE}{dl} \right)_{el} \frac{d\Phi}{dE} = \frac{1}{\rho} \left(\frac{dE}{dV} \right)_{el} \frac{1}{\Phi} \frac{d\Phi}{dE} = \frac{d \left(\frac{dE}{dm} \right)_{el}}{dE}$$

integrated over all dE:

$$\int \Phi_E \frac{S_{el}}{\rho} dE = \left(\frac{dE}{dm} \right)_{el}$$

→ The integral over the product of fluence spectrum and mass electronic stopping power yields a dosimetry quantity!

$$(absorbed\ dose)_{el} = \left(\frac{dE}{dm}\right)_{el} = \int \Phi_E(E) \frac{S_{el}}{\rho} dE$$

*primary fluence spectrum $\Phi_E(E)$
of the electrons
in the volume of interest*

*mass stopping power in the
material within the
volume of interest*

This formula is a fundamental relationship between absorbed dose in a material and the primary fluence spectrum of the electrons moving in that material.

Remember this relation and that $\Phi_E(E)$ refers to the primary fluence spectrum

ICRU 85 has defined a dosimetical quantity called **Cema**

CEMA = Converted Energy per Mass

The *cema*, C , for ionizing charged particles, is the quotient of dE_{el} by dm , where dE_{el} is the mean energy lost in electronic interactions in a mass dm of a material by the charged particles, except secondary electrons, incident on dm , thus

$$C = \frac{dE_{\text{el}}}{dm}.$$

Unit: J kg^{-1}

The special name of the unit of cema is gray (Gy).

$$cema = \left(\frac{dE}{dm} \right)_{\text{el}} = \int \Phi_{\text{E}}(E) \frac{S_{\text{el}}}{\rho} dE$$

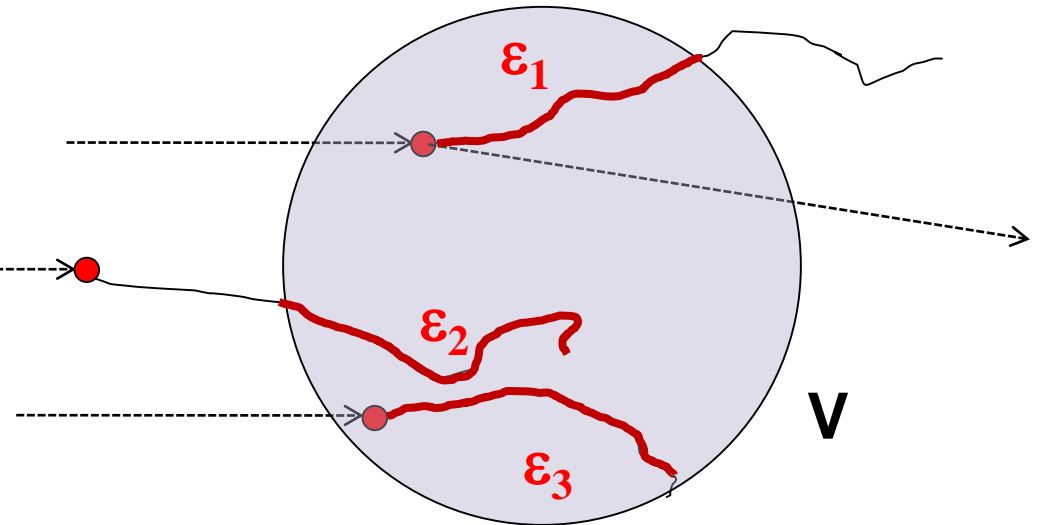
Interactions: "energy deposit" and "energy imparted"

An **energy deposit** ε_i is the sum of all single energy depositions along the charged particle track within the volume V due to the various interactions.

$$\varepsilon_i = \sum de_j$$

In the figure the energy deposit along 3 charged particle tracks in the volume V .

In the example the charged particles are coming from the interaction of photons (red bullet) in matter (inside or outside the volume V)



The total energy imparted, ε , to matter in a given volume is the sum of all **energy deposits** ε_i in that volume.

energy imparted $\longrightarrow \varepsilon = \sum \varepsilon_i \longleftarrow$ energy deposit

Radiation measurement

Application to dosimetry:

A radiation detector responds to radiation with a signal **M** which is proportional to the energy imparted ε in the detector volume.

$$M \propto \varepsilon = \sum_i \sum_j de_j$$

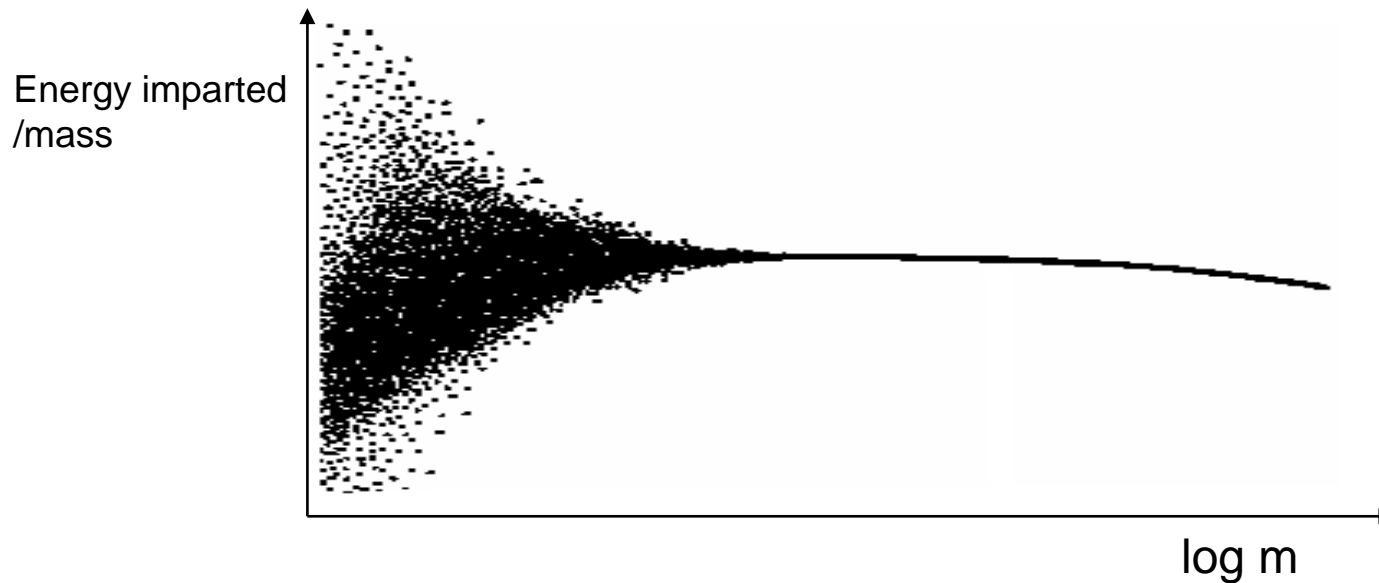
Random distribution of energy deposition:

- The values of single energy depositions de are randomly distributed
- The sum (= energy imparted) is **also** of random character, but with lower variance!

This means that repeated measurements of M will never give the same value!

As a consequence of the random character of the interactions, we can observe:

In the figure the **energy imparted ε to mass m ratio** of a detector as a function of a **mass m** (in logarithmic scaling)



The distribution of (**ε/m**) will be larger and larger with decreasing m because of:

$$\varepsilon = \sum_i \varepsilon_i$$

1. Introduction

Exact physical meaning of "dose of radiation"

That is the reason why the absorbed dose D is not defined by:

$$~~D = \frac{d\varepsilon}{dm}~~$$

but by the mean $d\bar{\varepsilon}$

$$D = \frac{d\bar{\varepsilon}}{dm}$$

where $d\bar{\varepsilon}$ is the mean energy imparted
 dm is a small element of mass

With the additional conditions:

- dm is large enough to include atoms for interactions,
- small enough that $d\bar{\varepsilon}/dm$ does not depend on the size of dm

Summary 1: Energy absorption and absorbed dose

- absorbed dose D :
(not randomly distributed)

$$D = \frac{d\bar{\varepsilon}}{dm}$$

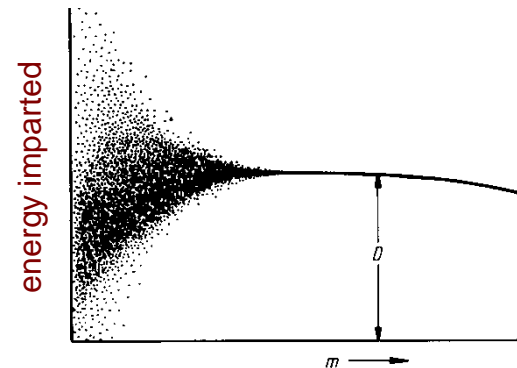
- energy imparted ε :
(randomly distributed)

$$\varepsilon = \sum \varepsilon_i$$

- energy deposition de
from a single interaction:
(randomly distributed)

$$de = E_{\text{in}} - E_{\text{out}} + Q$$

- random character
of energy absorption



Summary 2: Energy absorption and absorbed dose

- Relation between
absorbed dose D
and the
primary spectral fluence of electrons

$$(absorbed\ dose)_{el} = Cema = \int \Phi_E(E) \frac{S_{el}}{\rho} dE$$

Content:

1. Introduction: Definition of "radiation dose"
- 2. General methods of dose measurement**
3. Principles of dosimetry with ionization chambers:
 - Dose in air
 - Stopping Power
 - Conversion into dose in water, Bragg Gray Conditions
 - Spencer-Attix Formulation
4. General detector properties

2. Fundamentals for the measurement of absorbed dose

Absorbed dose is measured with a radiation detector called **dosimeter**.

In radiotherapy almost exclusively **absorbed dose in water** is determined.

The four most common radiation dosimeters used are:

- **Ionization chambers**
- **Radiographic and radiochromic films**
- **Solid state detectors**
 - **TLDs**
 - **Si-Diodes**
 - **Diamond detector**

Characteristics: Ionization chambers

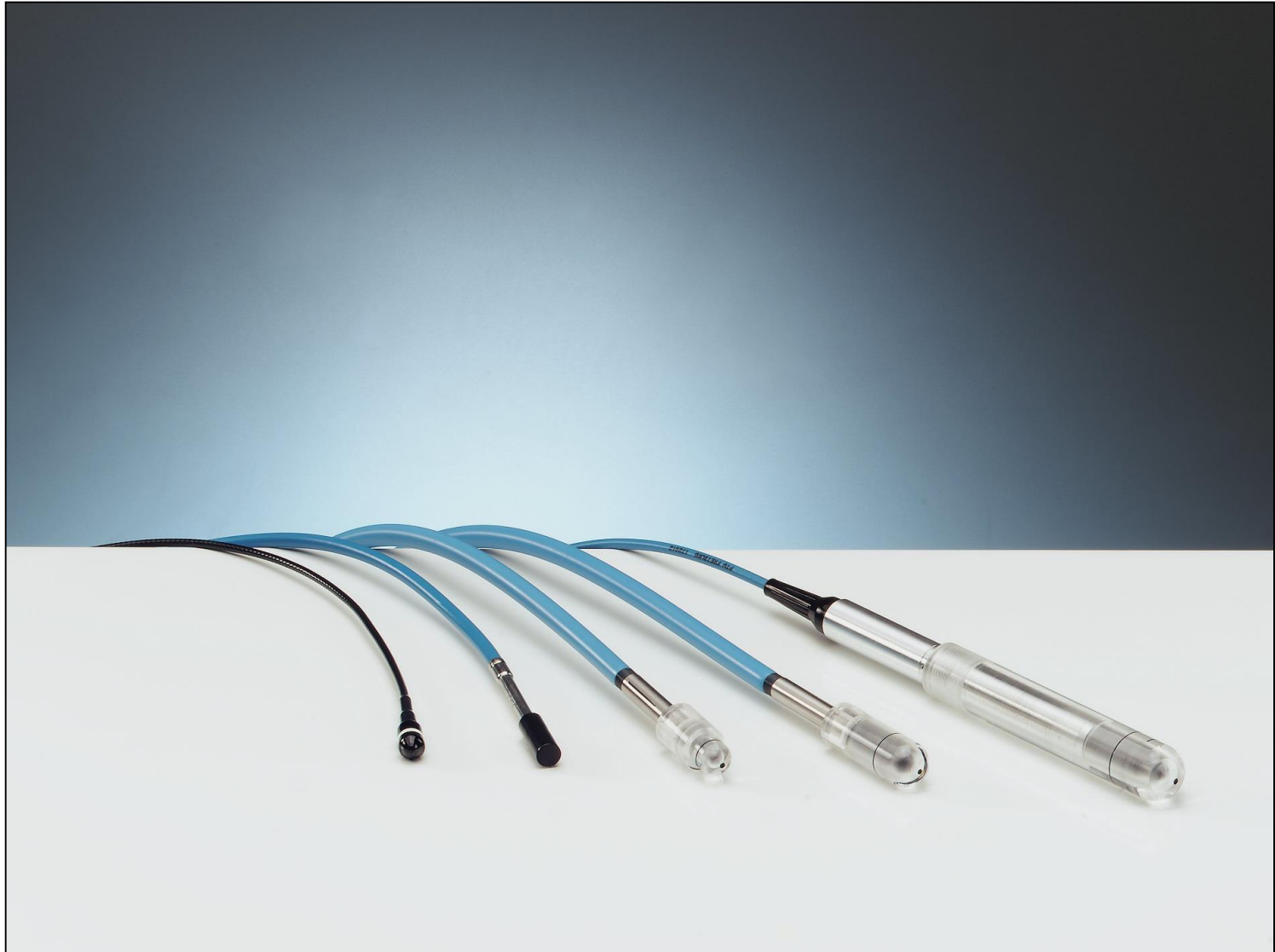
Advantage

- Accurate and precise
- Recommended for beam calibration
- Necessary corrections well understood
- Instant readout

(small) Disadvantage

- Connecting cables required
- High voltage supply required
- Many corrections required

Ionization chambers



Characteristics: Radiographic film

Advantage

- 2-D spatial resolution
- Very thin: does not perturb the beam

Disadvantage

- Darkroom and processing facilities required
- Processing difficult to control
- Variation between films & batches
- Needs proper calibration against ionization chambers
- Energy dependence problems
- Cannot be used for beam calibration

Characteristics: Radiochromic film

Advantage

- 2-D spatial resolution
- Very thin: does not perturb the beam
- No energy dependence

Disadvantage

- ~~Darkroom and processing facilities required~~
- ~~Processing difficult to control~~
- Variation between films & batches
- Needs proper calibration against ionization chambers
- Needs an appropriate scanner

Characteristics: Thermoluminescence Dosimeter (TLD)

Advantage

- Small in size: point dose measurements possible
- Many TLDs can be exposed in a single exposure
- Available in various forms
- Some are reasonably tissue equivalent
- Not expensive

Disadvantage

- Signal erased during readout
- Easy to lose reading
- No instant readout
- Accurate results require care
- Readout and calibration time consuming
- Not recommended for beam calibration

Characteristics: Solid state detectors

Advantage

- Small size
- High sensitivity
- Instant readout
- No external bias voltage
- Simple instrumentation
- Good to measure relative distributions!**

Disadvantage

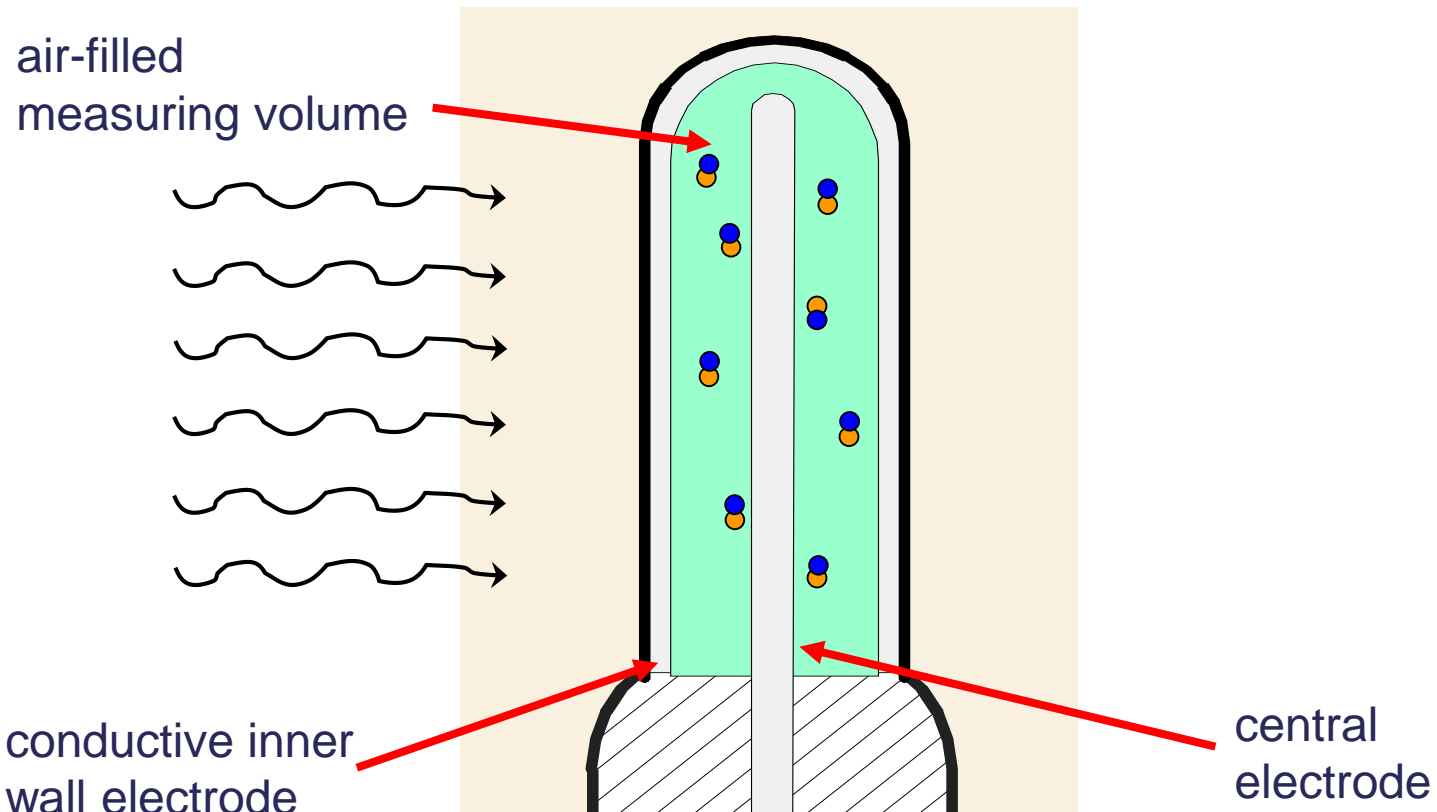
- Requires connecting cables
- Variability of response with temperature
- Sensitivity may change with accumulated dose
- Response is dependent on radiation quality and dose rate
- Therefore: questionable for beam calibration

Content:

1. Introduction: Definition of "radiation dose"
2. General methods of dose measurement
- 3. Principles of dosimetry with ionization chambers:**
 - Dose in air
 - Stopping Power
 - Conversion into dose in water, Bragg Gray Conditions
 - Spencer-Attix Formulation
4. General detector properties

Principles of dosimetry with **ionization chambers**

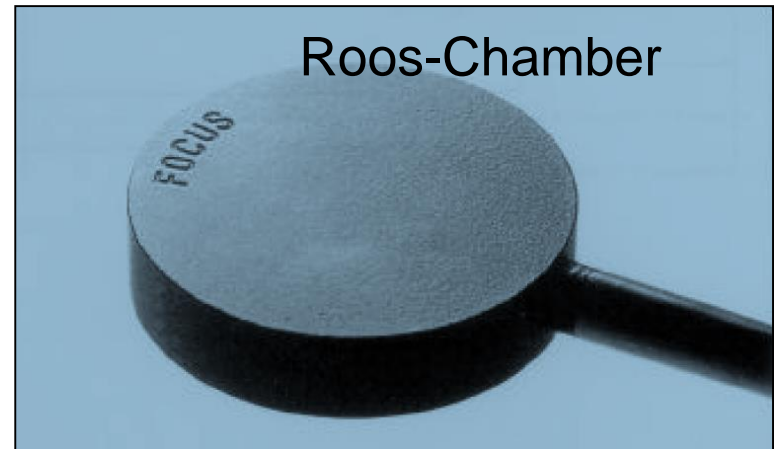
Measurement of absorbed dose is based on the production of charged ions in the air of the chamber volume and their collection at electrodes leading to a current during radiation.



Principles of dosimetry with **ionization chambers**

Thereby the **current is proportional to the dose rate**, and the **time integral over the current (= charge) is proportional to the dose**.

The creation and measurement of ionization in a gas is the basis for dosimetry with ionization chambers.



Because of the key role that ionization chambers play in radiotherapy dosimetry, it is vital that medical physicists have a good knowledge of the characteristics of ionization chambers.

Principles of dosimetry with **ionization chambers**

The relation between measured charge Q as well as air mass m_{air} with absorbed dose in air D_{air} is given by

$$D_{\text{air}} = \frac{\overline{d\varepsilon}}{dm} = \frac{Q}{e} \frac{\overline{W_{\text{air}}}}{m_{\text{air}}}$$

Q/e : the number of ions of a sign collected

$\overline{W_{\text{air}}}$: the mean energy required to produce an ion pair in air

$\overline{W_{\text{air}}}/e$: is the mean energy required to produce an ion pair in air per unit charge e .

Usually written $D_{\text{air}} = \frac{Q}{m_{\text{air}}} \left(\frac{\overline{W_{\text{air}}}}{e} \right)$

Principles of dosimetry with ionization chambers

It is generally assumed that for $\overline{W}_{\text{air}}/e$ a constant value can be used, valid for the complete photon and electron energy range used in radiotherapy dosimetry.

$\overline{W}_{\text{air}}/e$ depends on relative humidity of air:

- For air at relative humidity of 50%: $(\overline{W}_{\text{air}}/e) = 33.77 \text{ J/C}$
- For dry air: $(\overline{W}_{\text{air}}/e) = 33.97 \text{ J/C}$

Principles of dosimetry with ionization chambers

Thus the **absorbed dose in air** in the ionization chamber can be easily obtained by

$$D_{\text{air}} = \frac{Q}{m_{\text{air}}} \left(\frac{\overline{W}_{\text{air}}}{e} \right)$$

Now we have the next problem which is **fundamental for any detector**:

How one can determine the absorbed dose in water from the absorbed dose in the detector D_{air} ?

because: $D_{\text{water}} \neq D_{\text{detector}}$

We need a method for the conversion from D_{air} to D_{w} !!

Principles of dosimetry with **ionization chambers**

For this conversion and for most cases of dosimetry in clinically applied radiation fields such as:

- high energy photons ($E > 1 \text{ MeV}$)
- high energy electrons

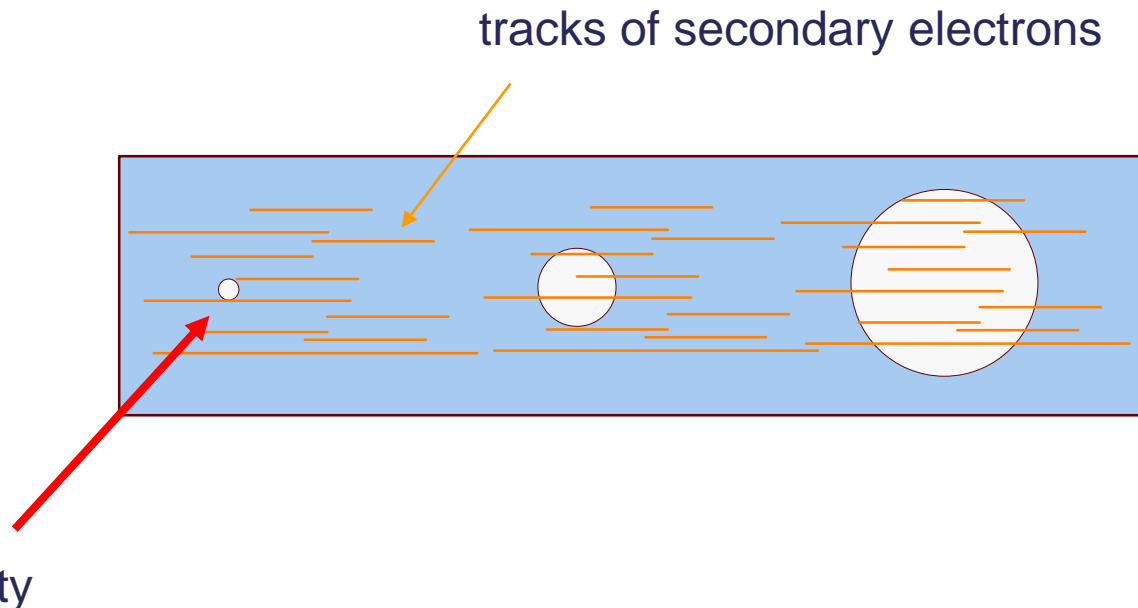
the so-called **Bragg-Gray Cavity Theory** can be applied.

This cavity theory can be applied if the so-called two Bragg-Gray conditions are met

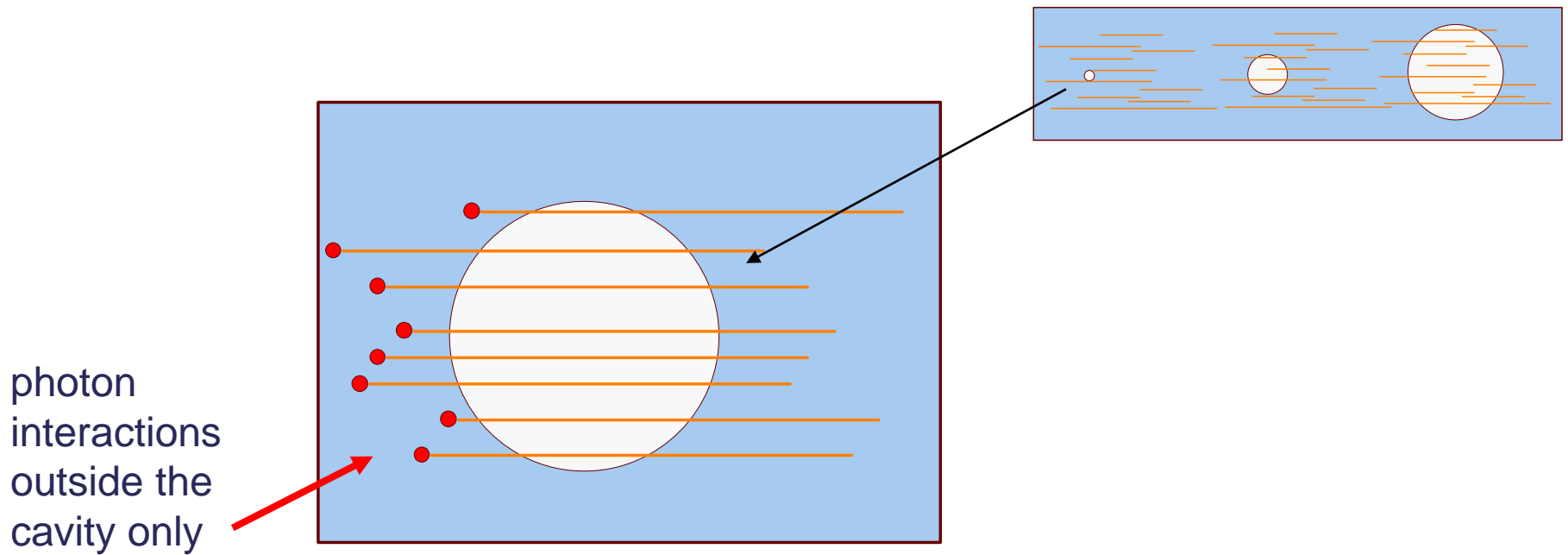
Bragg-Gray cavity theory

Condition (1):

The cavity must be small when compared with the **range of charged particles**, so that its presence does not perturb the **fluence** of charged particles in the medium.



Bragg-Gray cavity theory



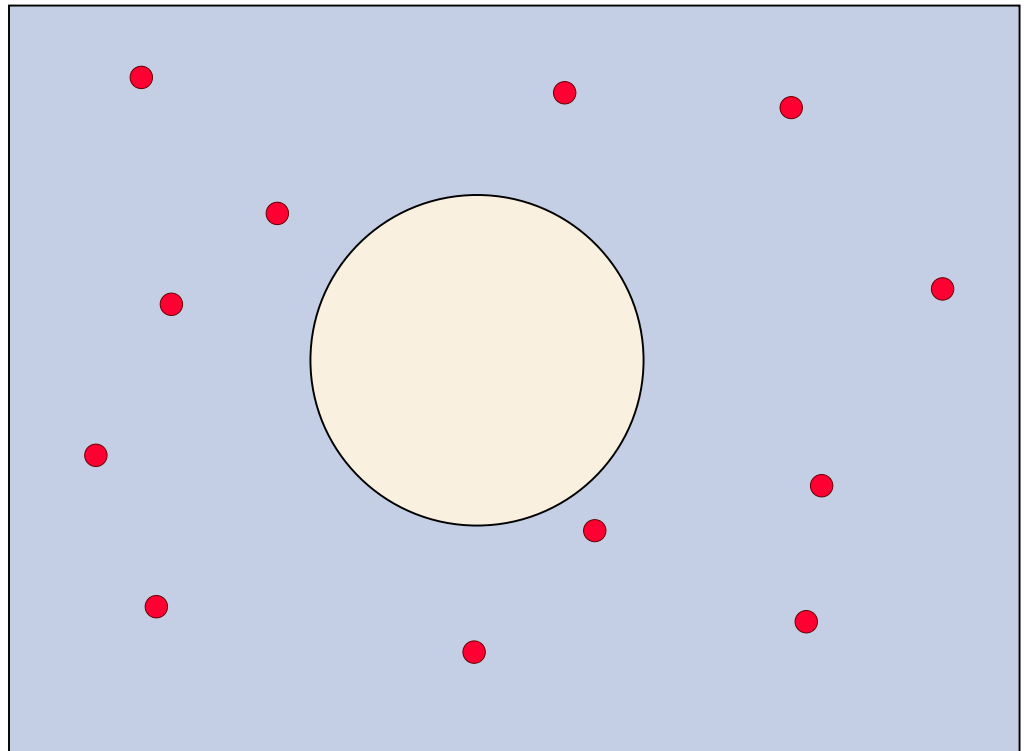
Condition (2) for photons:

The energy absorbed in the cavity has its origin solely by charged particles crossing the cavity.

Bragg-Gray cavity theory

we start to analyze the dose absorbed in the detector and assume, that the detector is an air-filled ionization chamber in water:

The interactions within a radiation field of photons then are photon interactions outside the cavity.



- photon interaction

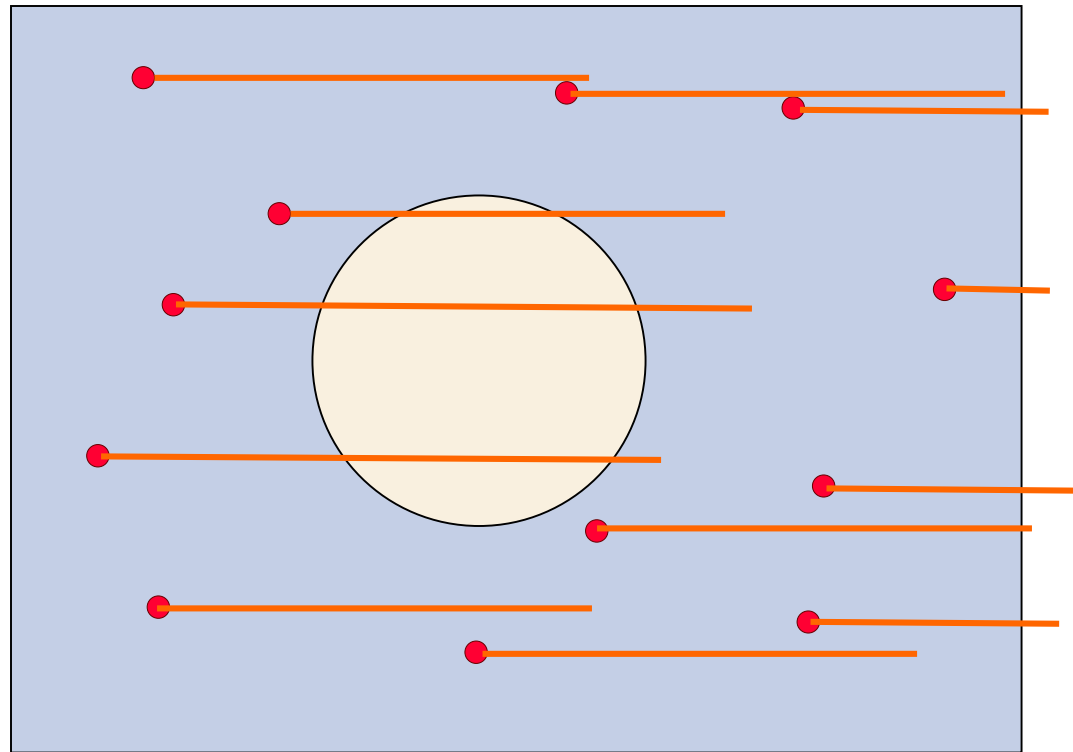
Bragg-Gray cavity theory

Note:

We assume that the number of interactions in the air cavity itself is negligible (BG condition 2)

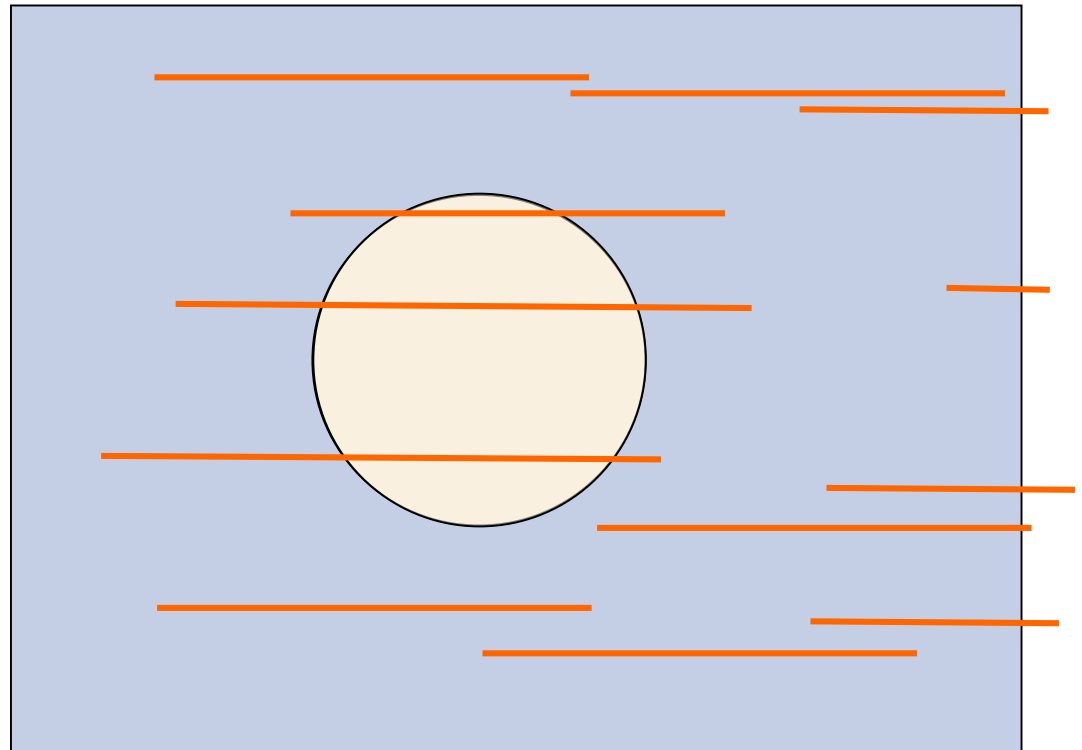
The primary interactions of the photon radiation mainly consist of those producing secondary electrons

— electron track



Bragg-Gray cavity theory

We know: Interactions of the secondary electrons in any medium are characterized by the **stopping power**.



Bragg-Gray cavity theory

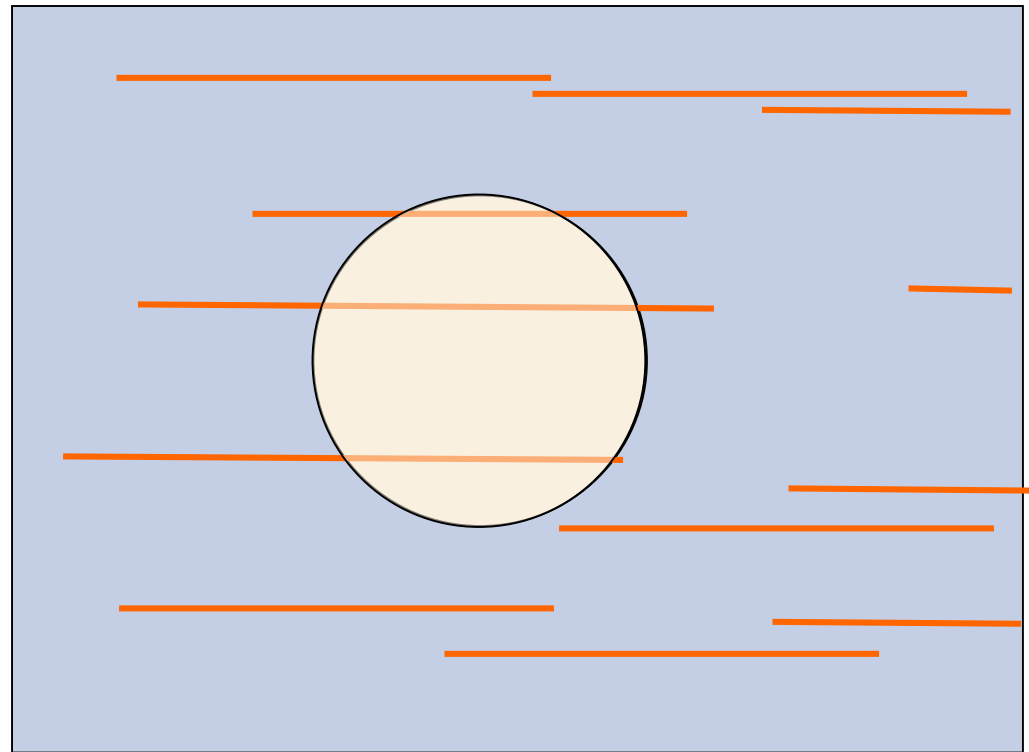
Consequently, the types of energy depositions

within the air cavity

are exclusively those of electrons characterized by stopping power.

and the Absorbed dose D in the air cavity can be calculated as

$$D_{air} = \int \Phi_E \cdot \left(\frac{S_{el}}{\rho} \right)_{air} \cdot dE$$



Bragg-Gray cavity theory

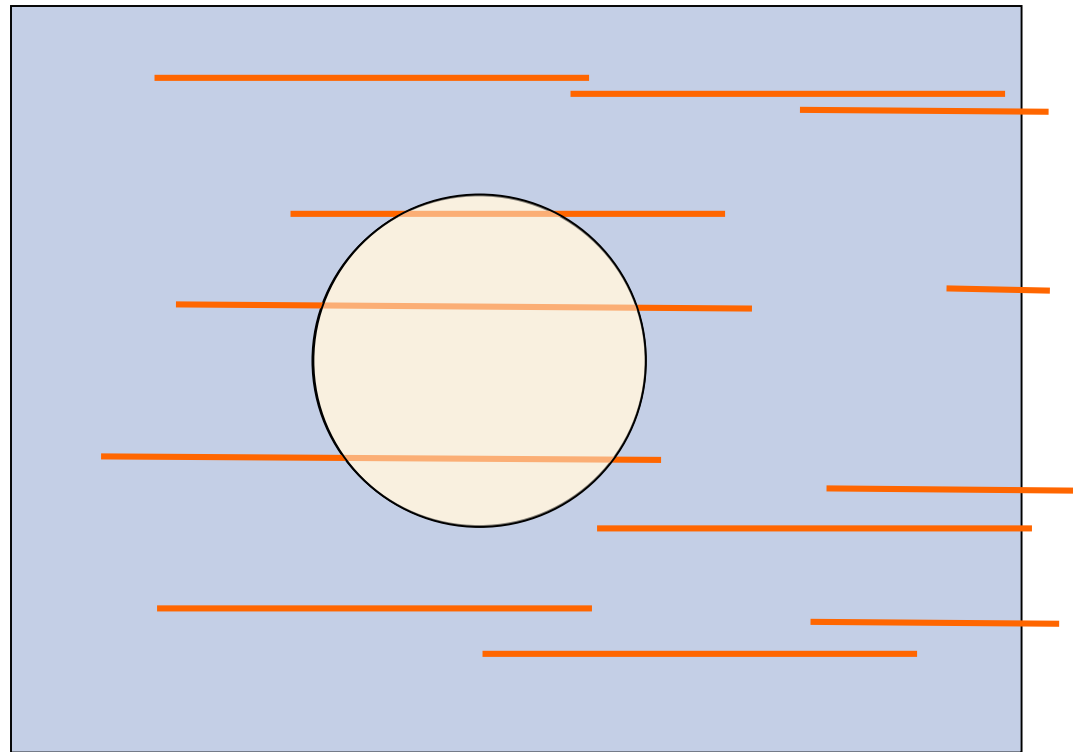
Let us further assume, that exactly the **same fluence** of the secondary electrons exists, independent from whether the cavity is filled with **air** or **water**.

We would have in air:

$$D_{air} = \int \Phi_E \cdot \left(\frac{S_{el}}{\rho} \right)_{air} \cdot dE$$

and we would have in water:

$$D_{water} = \int \Phi_E \cdot \left(\frac{S_{el}}{\rho} \right)_{water} \cdot dE$$



Bragg-Gray cavity theory

Now:

$$\frac{D_{water}}{D_{air}} = \frac{\int \Phi_E(E) \left(\frac{S_{el}}{\rho}\right)_{water} dE}{\int \Phi_E(E) \left(\frac{S_{el}}{\rho}\right)_{air} dE}$$

We call this ratio the **stopping power ratio water to air**, $s_{w,a}$

But $D_{air} = \frac{Q}{m_{air}} \left(\frac{W}{e}\right)$

and D_{water} becomes $D_{water} = D_{air} s_{w,a} = \frac{Q}{m_{air}} \left(\frac{W_{air}}{e}\right) s_{w,a}$

However, the formula:

$$D_{water} = \int \Phi_E \cdot \left(\frac{S_{el}}{\rho}\right)_{water} \cdot dE$$

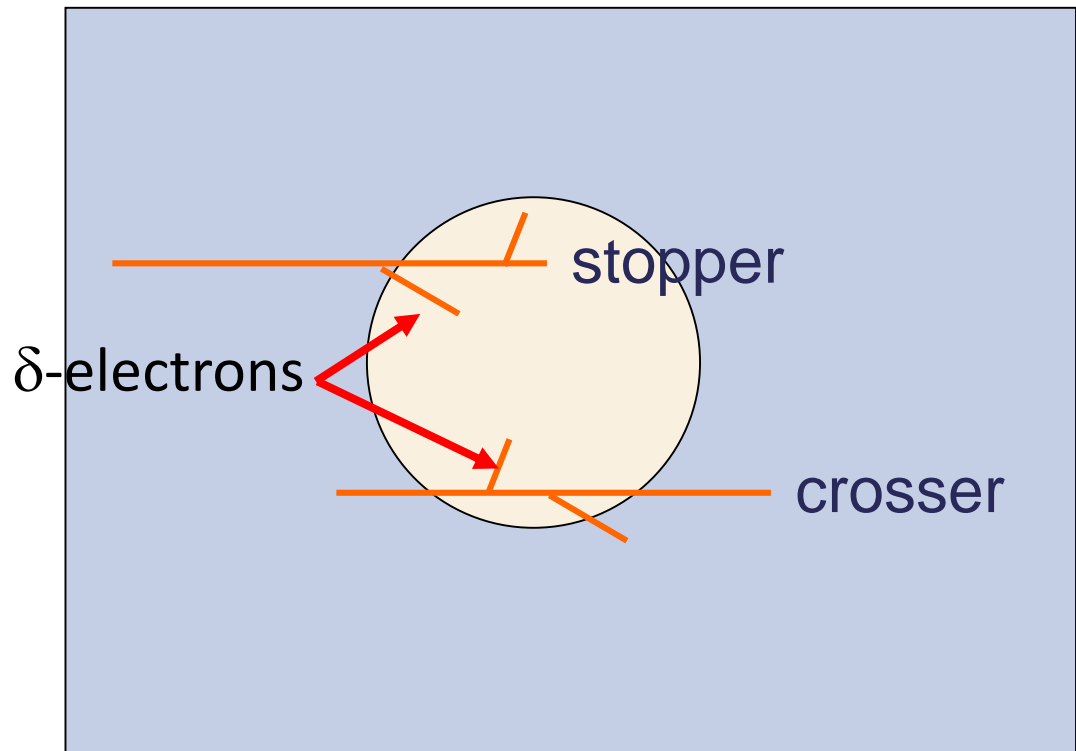
is not completely correct!

To improve the Bragg-Gray cavity theory

Not considered by the B-G:

- the **stoppers**
- and, the secondary **δ -electrons** created by primary electrons in hard collisions

Remember: $\Phi_E(E)$ refers to the primary electrons only. $D_{water} = \int \Phi_E \cdot \left(\frac{S_{el}}{\rho} \right)_{water} \cdot dE$



Do they create a problem ??

Yes, they do!

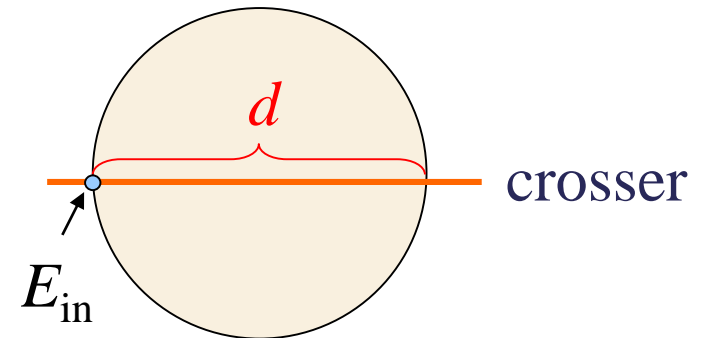
5.2 The crossers

Let us exactly analyze the process of energy absorption of a crosser:

We assume that the energy E_{in} of the electron entering the cavity is almost not changed when moving along its track length d within the cavity (small cavity and low density)

Then the energy deposit ε is:

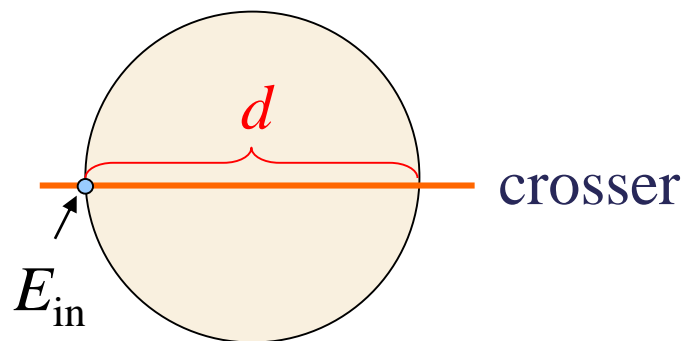
$$\varepsilon = S_{el}(E_{in}) \times d$$



5.2 The stoppers

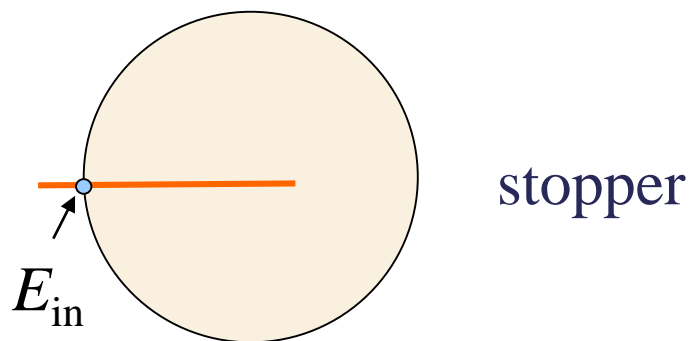
We compare this situation:

$$\varepsilon = S_{el}(E_{in}) \times d$$



With the energy absorption of a **stopper**:

$$\varepsilon = E_{in}$$



The energy deposition of the stoppers has nothing to do with stopping power !!

Therefore, the calculation of absorbed dose using the stopping power according to the formula:

$$D_{air} = \int \Phi_E \cdot \left(\frac{S_{el}}{\rho} \right)_{air} \cdot dE$$

only works for crossers!

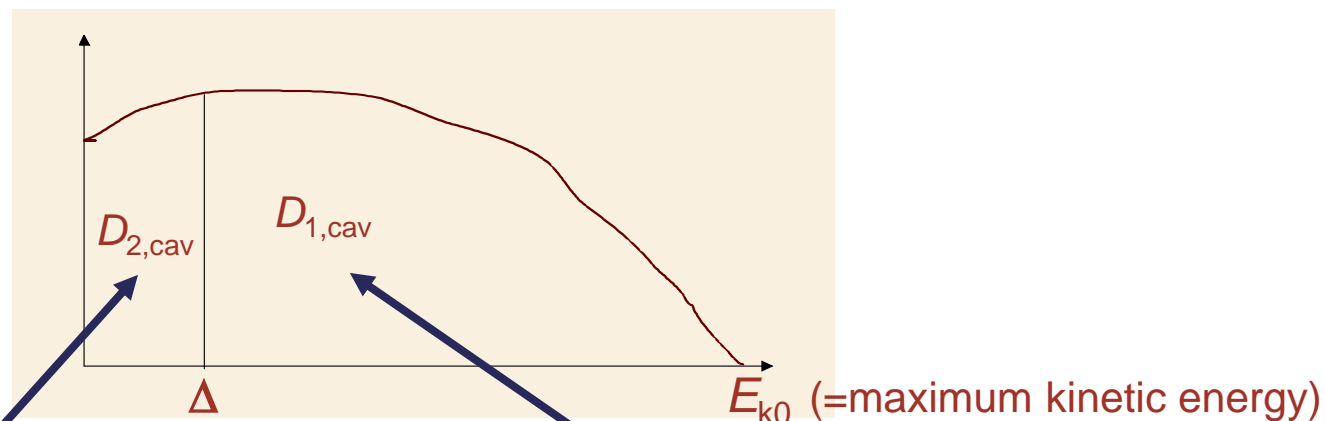
As a consequence, the calculation of the stopping power ratio

$$\frac{D_{water}}{D_{air}} = \frac{\int \Phi_E(E) \left(\frac{S_{el}}{\rho} \right)_{water} dE}{\int \Phi_E(E) \left(\frac{S_{el}}{\rho} \right)_{air} dE}$$

also works only for crossers and hence needs some corrections to take into account the stoppers as well as the secondary δ -electrons !

The Spencer-Attix cavity theory

The total **primary and secondary electron fluence** (crossers + δ electrons + stoppers) is divided into two components based on a user-defined **energy threshold Δ** .

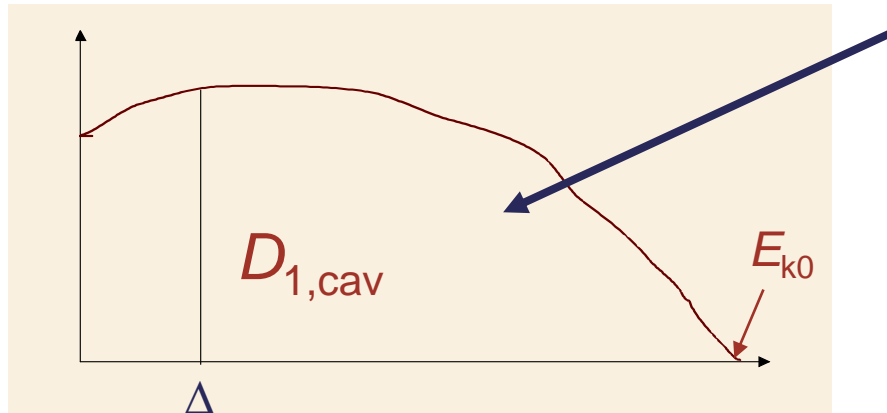


Electrons with kinetic energies $E_k < \Delta$ are considered "slow" electrons (stoppers).

They deposit all their energy locally.

Electrons with energies larger than or equal to Δ are considered "fast" electrons. They all deposit their energy like **crossers**.

The Spencer-Attix cavity theory



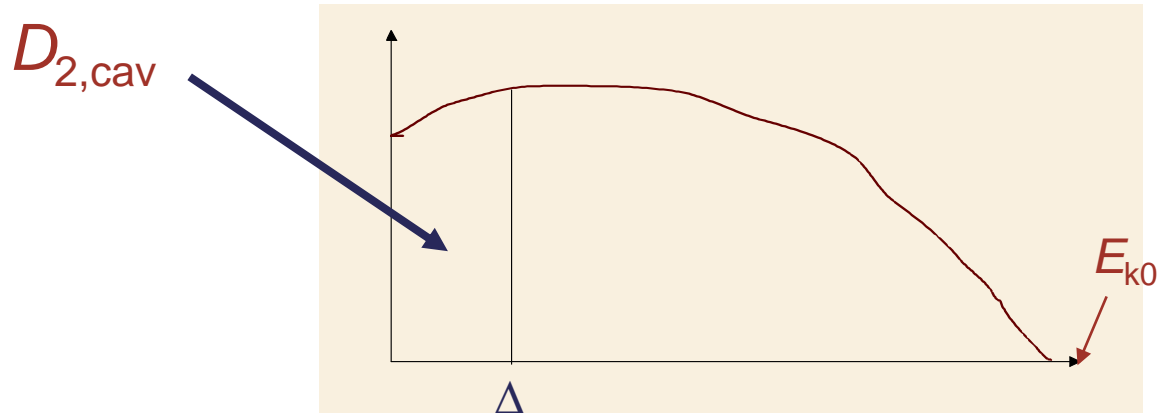
All electrons (including δ electrons) with energies $E_k \geq \Delta$ are treated as crossers.

$$D_{1,cav} = \int_{\Delta}^{E_{k0}} \Phi_{E_k}^{\delta}(E_k) \cdot \frac{L_{\Delta,cav}(E_k)}{\rho} dE_k$$

where $\Phi_{E_k}^{\delta}(E_k)$ is now the fluence spectrum of **all electrons, including the δ electrons with $E_k \geq \Delta$**

and $L_{\delta,cav}(E_k)$ is the **restricted mass electronic stopping power** that doesn't include the energy deposited by δ electrons with energy $\geq \Delta$

The Spencer-Attix cavity theory



For the energy imparted by the stoppers (or track end term) it is used the approximation of A. Nahum as:

$$TE = \Phi_{E_k}^{\delta}(\Delta) \cdot \frac{S(\Delta)}{\rho} \cdot \Delta$$

5.2 The Spencer-Attix cavity theory

The **Spencer & Attix stopping power ratio** $S_{w,a}^{SA}$ becomes

$$\frac{D_{water}}{D_{air}} = S_{w,a}^{SA}$$
$$S_{w,air}^{SA} = \frac{\int_{\Delta}^{E_{max}} \Phi_E^{w,\delta}(E) \cdot \frac{L_{\Delta,w}(E)}{\rho} dE + \Phi_E^{w,\delta}(\Delta) \cdot \frac{S_w(\Delta)}{\rho} \cdot \Delta}{\int_{\Delta}^{E_{max}} \Phi_E^{w,\delta}(E) \cdot \frac{L_{\Delta,air}(E)}{\rho} dE + \Phi_E^{w,\delta}(\Delta) \cdot \frac{S_{air}(\Delta)}{\rho} \cdot \Delta}$$

What has been changed from B-G theory:

- 1) The fluence spectrum now includes all electrons, the primary electrons as well as the secondary δ -electrons
- 2) The second term which takes into account the energy deposition of stoppers

$$D_{water} = D_{air} S_{w,a}^{SA}$$

The Spencer-Attix cavity theory

Another step.

Remember the **Bragg-Gray-Condition (1)**:

The cavity must be small when compared with the **range of charged particles**, so that its presence does not perturb the **fluence** of charged particles in the medium.

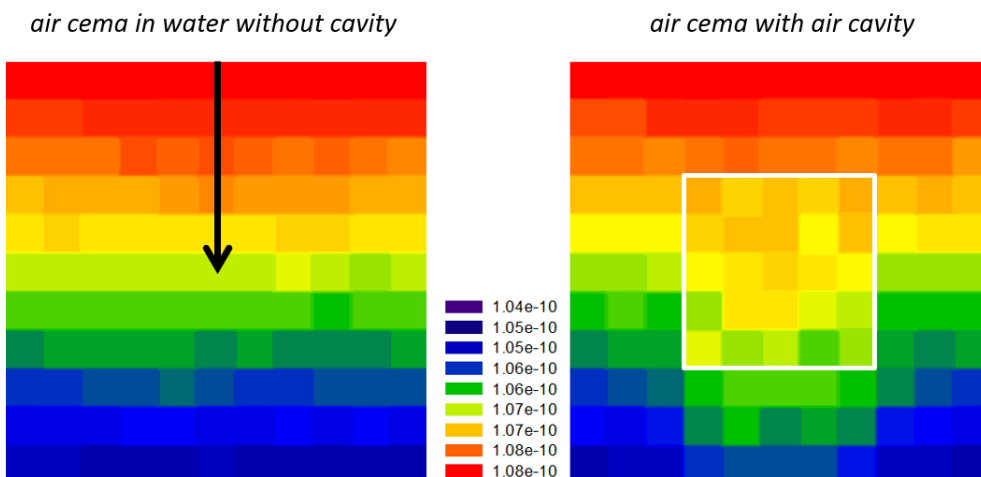
Let us consider a real cavity with air (2.5 mm length) in water.

The figure shows a MC simulation with and without the air cavity.

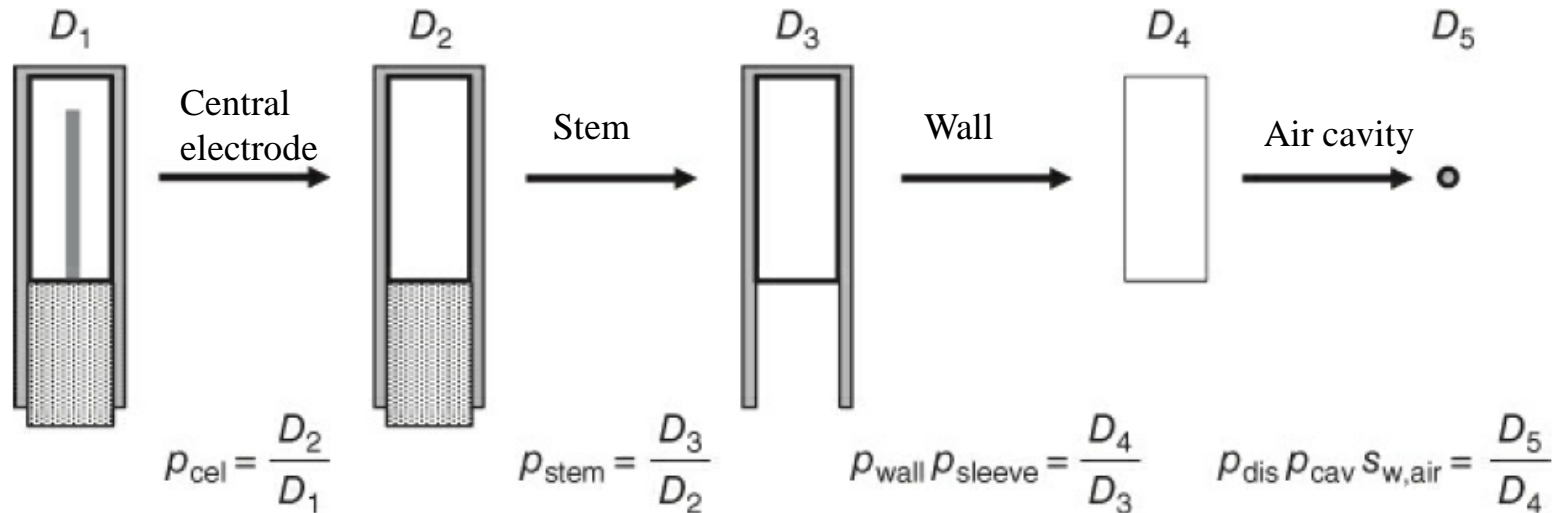
It is recognized a perturbation of the fluence
(BG condition not meet !)

It is necessary to estimate
a **perturbation factor p**

6 MV photon field, 5 cm depth



Perturbation factors calculated with MC simulations



- MC simulations for the determination of ionization chamber perturbation correction factors
- The various perturbation factors are defined by absorbed dose ratios from one step to another in the ionization chambers' cavity ($D_1 \rightarrow D_4$) and the dose to a small volume of water (D_5).

p_{cel} : central electrode; p_{stem} : chamber stem

Summary: Determination of Absorbed dose in water

The absorbed dose in water is obtained from the measured charge in an ionization chamber by:

$$D_w = D_{air} f = D_{air} s_{w,air}^{SA} p$$

where:

$s_{w,air}^{SA}$ is now the water to air ratio of the mean mass **Spencer-Attix stopping power**

p is for all perturbation correction factors required to take into account deviations from BG-conditions

f is the dose conversion factor

Two other concepts

The first, really important to understand the fundamentals in dosimetry, is **KERMA**

The **kerma**, K , is the quotient of dE_{tr} by dm , where dE_{tr} is the sum of the initial kinetic energies of all the charged particles liberated by uncharged particles in a mass dm of material, thus

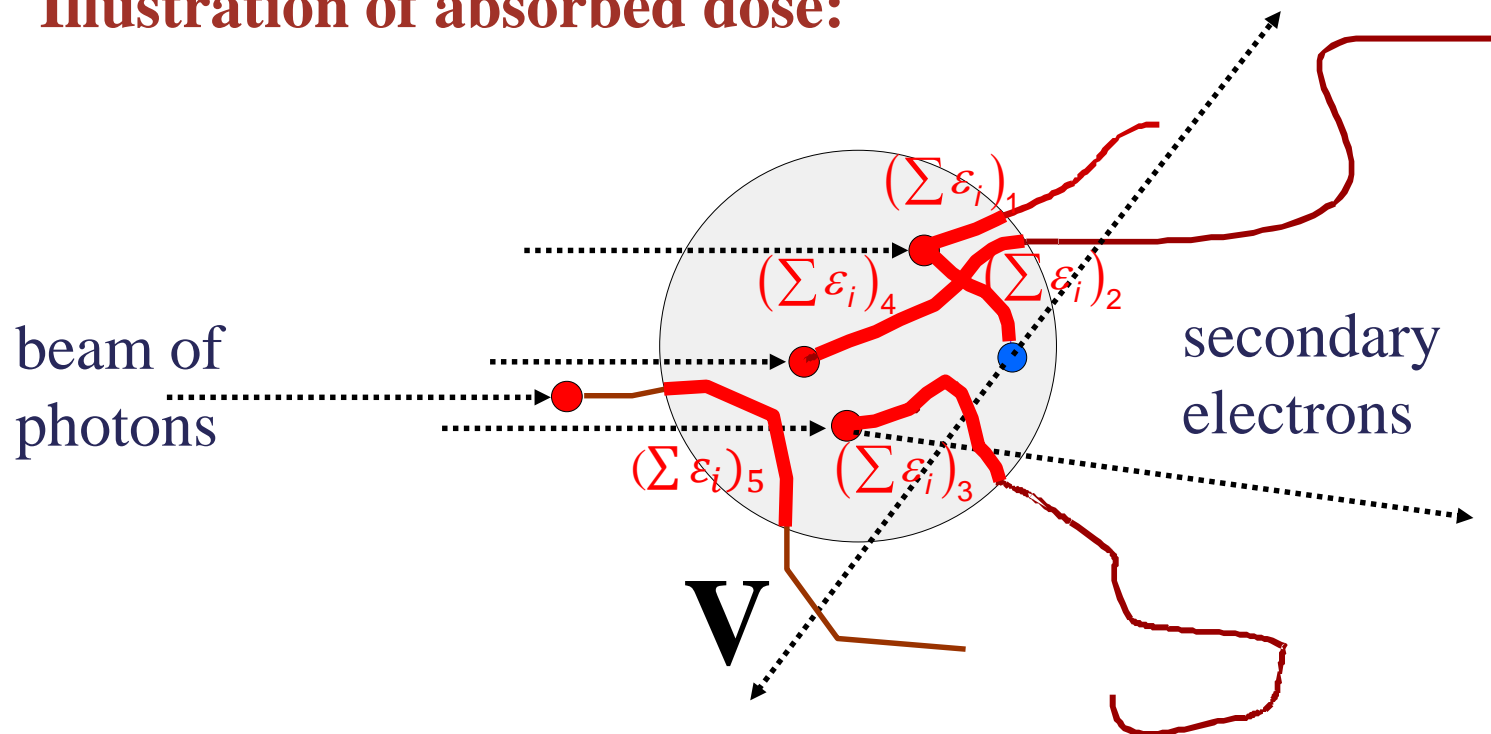
$$K = \frac{dE_{\text{tr}}}{dm} .$$

Unit: J kg^{-1}

The special name for the unit of kerma is gray (Gy).

Difference between absorbed dose and Kerma

Illustration of absorbed dose:

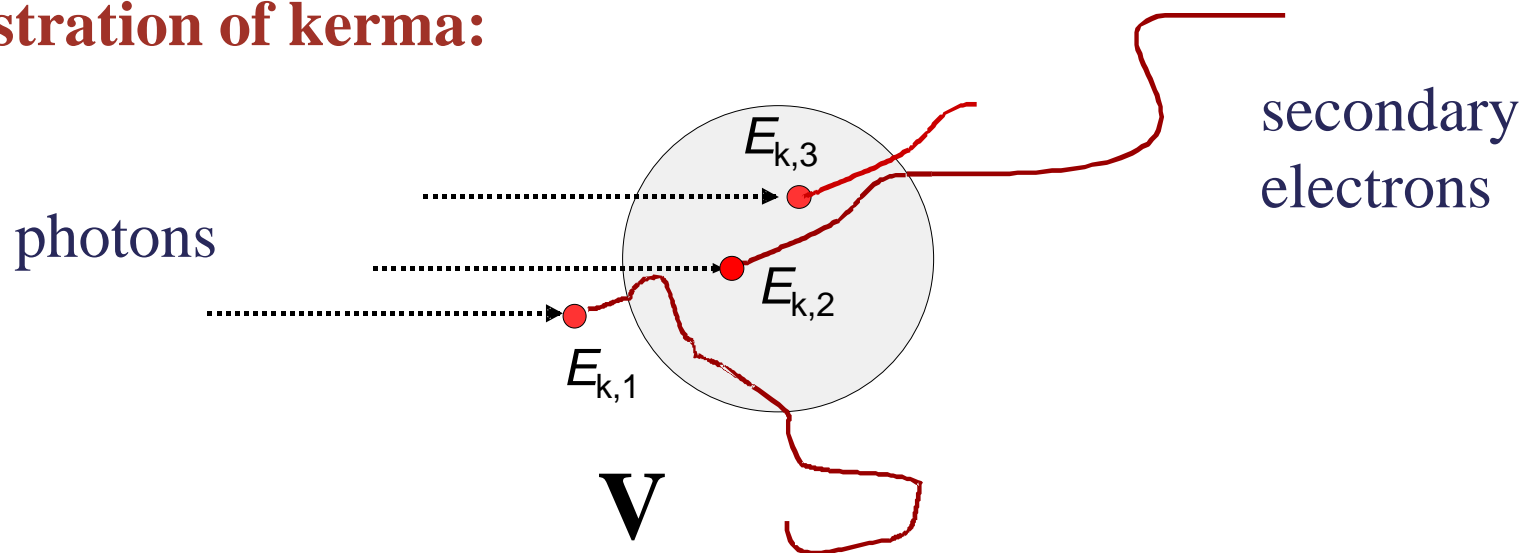


$(\sum \varepsilon_i)$ is the sum of energy losts by collisions along the track of the secondary particles **within the volume V** .

$$\text{energy absorbed in the volume} = (\sum \varepsilon_i)_1 + (\sum \varepsilon_i)_2 + (\sum \varepsilon_i)_3 + (\sum \varepsilon_i)_4 + (\sum \varepsilon_i)_5$$

Kerma

Illustration of kerma:



The collision energy transferred **within the volume** is:

$$E_{\text{tr}} = E_{k,2} + E_{k,3}$$

where E_k is the initial kinetic energy of the secondary electrons.

Note: $E_{k,1}$ is transferred **outside the volume** and is therefore not taken into account in the definition of kerma!

Photon energy transfer quantities

Kerma, as well as the following dosimetical quantities can be **calculated**, if the energy fluence of photons is known:

Terma

(Total Energy Release per unit Mass)

$$\int \Phi_E \cdot \left(\frac{E\mu}{\rho} \right) \cdot dE \quad \left[\frac{\text{J}}{\text{kg}} \right]$$

Kerma

(Kinetic Energy Released to Matter)

$$\int \Phi_E \cdot \left(\frac{E\mu_{tr}}{\rho} \right) \cdot dE \quad \left[\frac{\text{J}}{\text{kg}} \right]$$

Collision Kerma

$$\int \Phi_E \cdot \left(\frac{E\mu_{en}}{\rho} \right) \cdot dE \quad \left[\frac{\text{J}}{\text{kg}} \right]$$

} for photons

A important difference between absorbed dose and KERMA

The absorbed dose D is a quantity which is accessible mainly by a **measurement**

KERMA is a dosimetical quantity which cannot be measured but **calculated only**, from the knowledge of photon fluence differential in energy

$$\int \Phi_E \cdot \left(\frac{E \mu_{tr}}{\rho} \right) \cdot dE \quad \left[\frac{\text{J}}{\text{kg}} \right]$$

Content:

1. Introduction: Definition of "radiation dose"
2. General methods of dose measurement
3. Principles of dosimetry with ionization chambers:
 - Dose in air
 - Stopping Power
 - Conversion into dose in water, Bragg Gray Conditions
 - Spencer-Attix Formulation
4. **General detector properties**

The second concept: Detector response

The second term is the response of a detector.

It applies to any detector. Response R is defined as

$$R = \frac{M}{D_w}$$

that can be written

$$R = \frac{M}{\bar{D}_{det}} \frac{\bar{D}_{det}}{D_w}$$

where \bar{D}_{det} is the **mean** dose absorbed in the entire sensitive volume of the detector

D_w is the absorbed dose in water at the point of measurement

$$R = \frac{M}{\bar{D}_{det}} \frac{\bar{D}_{det}}{D_w}$$

There are two separate physical processes involved in the response R of a detector:

$\frac{M}{\bar{D}_{det}}$ it describes the process of how the absorbed dose in the detector is converted into a measurable signal, called **intrinsic response R_{int}** .

$\frac{\bar{D}_{det}}{D_w}$ it describes the difference of energy absorption at the point of measurement and the sensitive volume of the detector.
The reciprocal value called **dose conversion factor f** $f = \frac{D_w}{\bar{D}_{det}}$

Then $R = \frac{R_{int}}{f}$ and $D_w = \frac{M}{R} = M \cdot f / R_{int}$

The issue of relative measurements

In the case of **relative measurements**: $D_{rel} = \frac{D}{D_{ref}}$

Because $D = Mf/R_{int}$, we can write

$$D_{rel} = \frac{D}{D_{ref}} = \frac{M}{M_{ref}} \frac{f}{f_{ref}} \frac{R_{int,ref}}{R_{int}}$$

Question: In relative dosimetry is it correct to use only the signal ratio M/M_{ref} ??

For most detectors the intrinsic response R_{int} does not depend on the measuring conditions. $R_{int}=1$

But f changes with measuring conditions when different from the reference condition.

We must consider the dose conversion factor f in detail.

Remember the definition of Cema:

(CEMA = Converted Energy per Mass)

The *cema*, C , for ionizing charged particles, is the quotient of dE_{el} by dm , where dE_{el} is the mean energy lost in electronic interactions in a mass dm of a material by the charged particles, except secondary electrons, incident on dm , thus

$$C = \frac{dE_{\text{el}}}{dm}.$$

Unit: J kg^{-1}

The special name of the unit of cema is gray (Gy).

$$cema = \left(\frac{dE}{dm} \right)_{\text{el}} = \int \Phi_{\text{E}}(E) \frac{S_{\text{el}}}{\rho} dE$$

For the quantity **restricted cema** $C_{\Delta,med}$ (stopping power S is substitute by the restricted stopping power L_{Δ})

$$C_{\Delta,med} = \int_{\Delta}^{E_{max}} \Phi_{E,med} \left(\frac{L_{\Delta}}{\rho} \right)_{med} dE + TE_{med},$$

Bouchard (2012) demonstrates the **restricted cema** can be a good approximation of the absorbed dose (when there is Partial Charged Particle Equilibrium PCPE and when binding energies end nuclear interactions are negligible → for photons $E > 0.5$ MeV and low Z material).

Then, the dose conversion factor $f = D_w / D_{det}$ can be approximated by

$$f = S_{w,det}^{SA} \frac{cema_w}{\overline{cema}_{det}}$$

where

$cema_{det}$ is the detector cema at the point of measurement in water (unperturbated fluence)

\overline{cema}_{det} is the mean detector cema in the sensitive volume of the detector (perturbated fluence by the presence of the detector)

With the ratio $\frac{cema_w}{\overline{cema}_{det}}$ called **global fluence correction factor**, p_{glf}

This means that for any detector, for any measuring condition (particularly for non-reference condition measurements) and without the need that the Bragg-Gray conditions are met:

$$D_w = D_{det} f = D_{det} S_{w,det}^{SA} p$$

with the perturbation factor $p = cema_{det} / \overline{cema}_{det}$

Hartmann (2021), with the following limitations:

- formula applies to photons
- photon energy > 0.5 MeV

demonstrates deviations from SA formulation <0.1%

It means *cema* is a good approximation of absorbed dose

TABLE A2 Ratio between $(f_{cema})_{Q,Q_0}$ and $(f)_{Q,Q_0}$ for photon beams with a spectral distribution

Beam type	Mean energy (MeV)	$\frac{(f_{cema})_{Q,Q_0}}{(f)_{Q,Q_0}}$ in a sphere of 1-mm radius filled with		
		Air	Diamond	Silicon
20 MV	4.41	1.0002	1.0009	0.9991
6 MV	1.90	1.0002	0.9998	0.9992
¹⁹² Ir source	0.36	0.9989	0.9985	1.0021

Note: The reference quality Q₀ refers to ⁶⁰Co.

Recent evidences for measurements in non-reference condition

- Roers (2023) studying with MC simulations 2 i.c. and their components: *“Cema formalism provides the possibility to determine energy dependent (spectral) fluence-based correction factors accounting for the detector-induced charged particle fluence disturbance.”*
- He has evidenced:
 - the influence is considerably increasing with decreasing depth; the depth-depending detector response can differ from unity from 1.4% to 2.8% depending on the chamber design.
 - a compensation of the displacement effect can not fully be achieved by the shift of the effective point of measurement $0.5 \cdot r$
- *“Therefore, it is necessary to further investigate the influence of different detector geometries and components on the spectral electron and positron fluence distribution.”*

Summary

- Definition of "radiation dose"
- General methods of dose measurement
- Principles of dosimetry with ionization chambers: dose in air, stopping power, conversion into dose in water with cavity theories: Bragg Gray conditions, BG and Spencer-Attix formulation, detector response
- Role of cema for measurements in reference and, in particular, in non-reference condition