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International Organization for Medical Physics

School on Medical Physics for Radiation Therapy:

Dosimetry and Treatment Planning for Basic and Advanced Applications

Miramare, Trieste, Italy, 25 March - 5 April 2019

Dosimetry: Fundamentals

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Content:

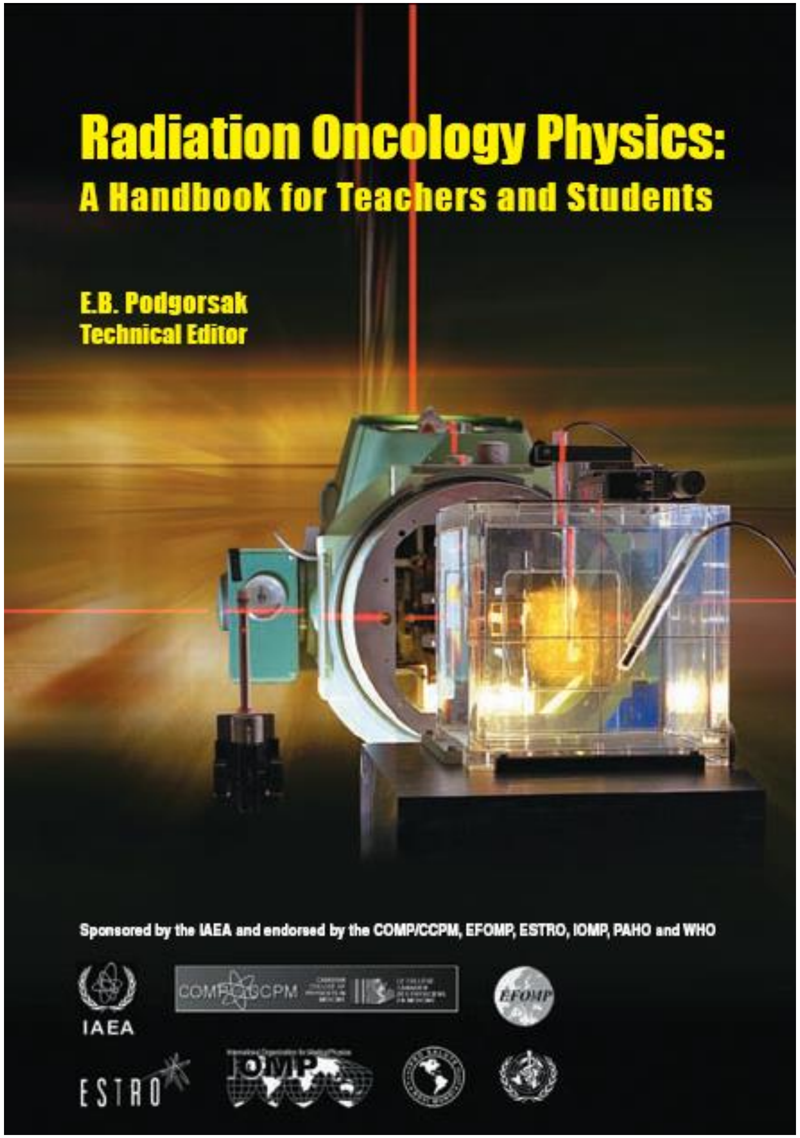
(1) Introduction:
"radiation dose“, what is it?

(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) More general properties of dosimetry detectors

This lesson is partly based on:



Radiation Oncology Physics:

A Handbook for Teachers and Students

E.B. Podgorsak
Technical Editor

Sponsored by the IAEA and endorsed by the COMP/CCPM, EFOMP, ESTRO, IOMP, PAHO and WHO

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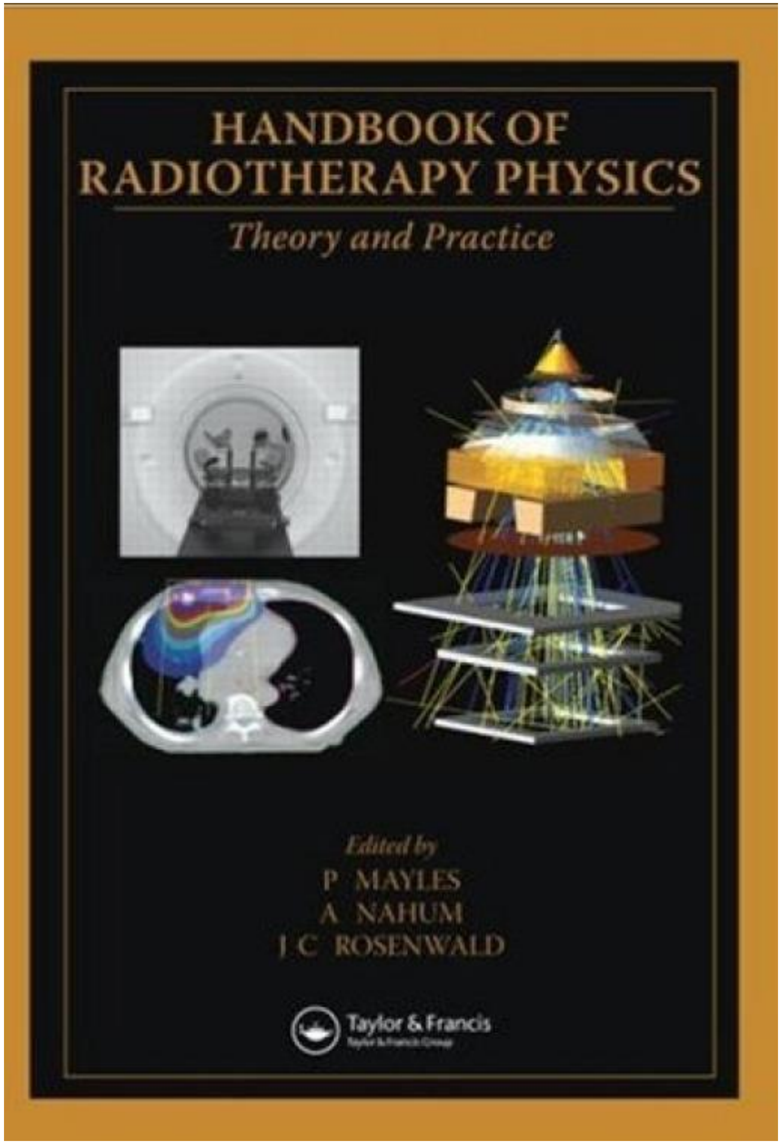


HANDBOOK OF
RADIOTHERAPY PHYSICS
Theory and Practice

Edited by
P MAYLES
A NAHUM
J C ROSENWALD

Taylor & Francis

1. Introduction

Exact physical meaning of "dose of radiation"

"Dose" is a somewhat sloppy expression to denote the dose of radiation.

This term should be used **only** if your colleague really knows its meaning.

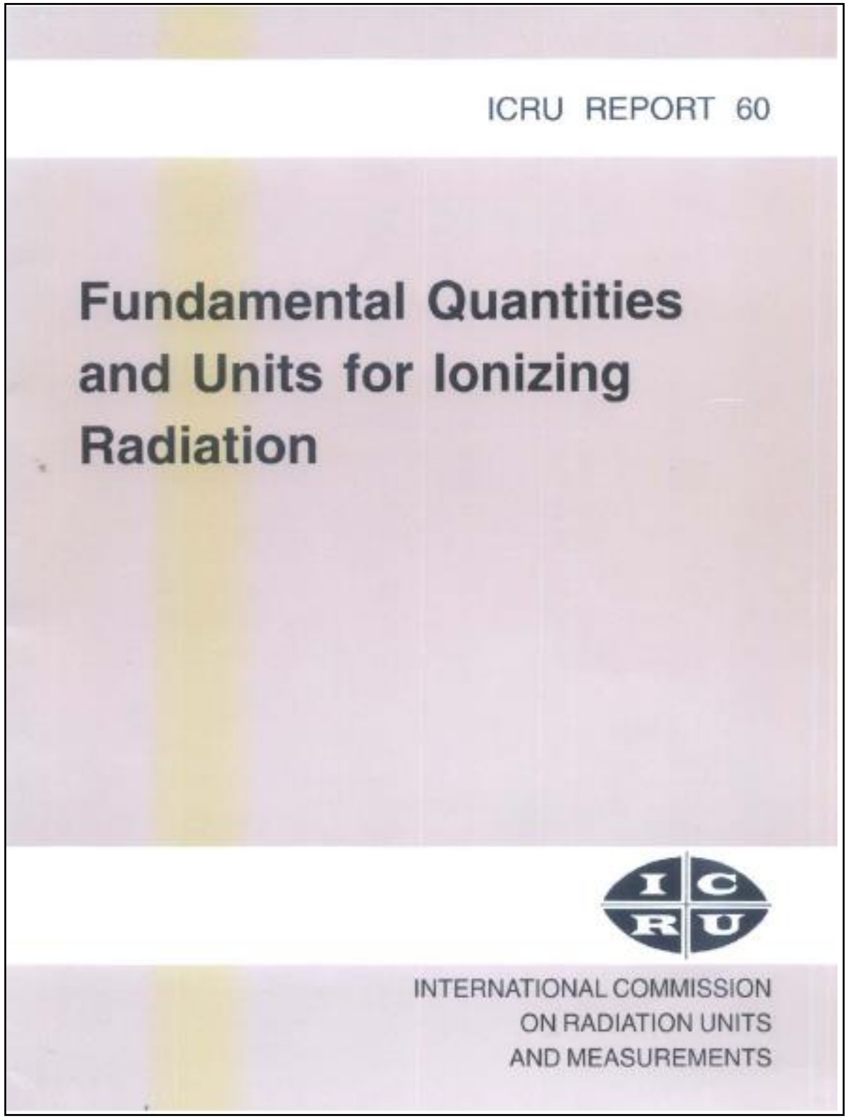
A dose of radiation is correctly expressed by the term

absorbed dose, *D*

which is, at the same time, a physical quantity.

The most fundamental definition of the absorbed dose *D*
(as well as of any other radiological term)
is given in ICRU Report 85a

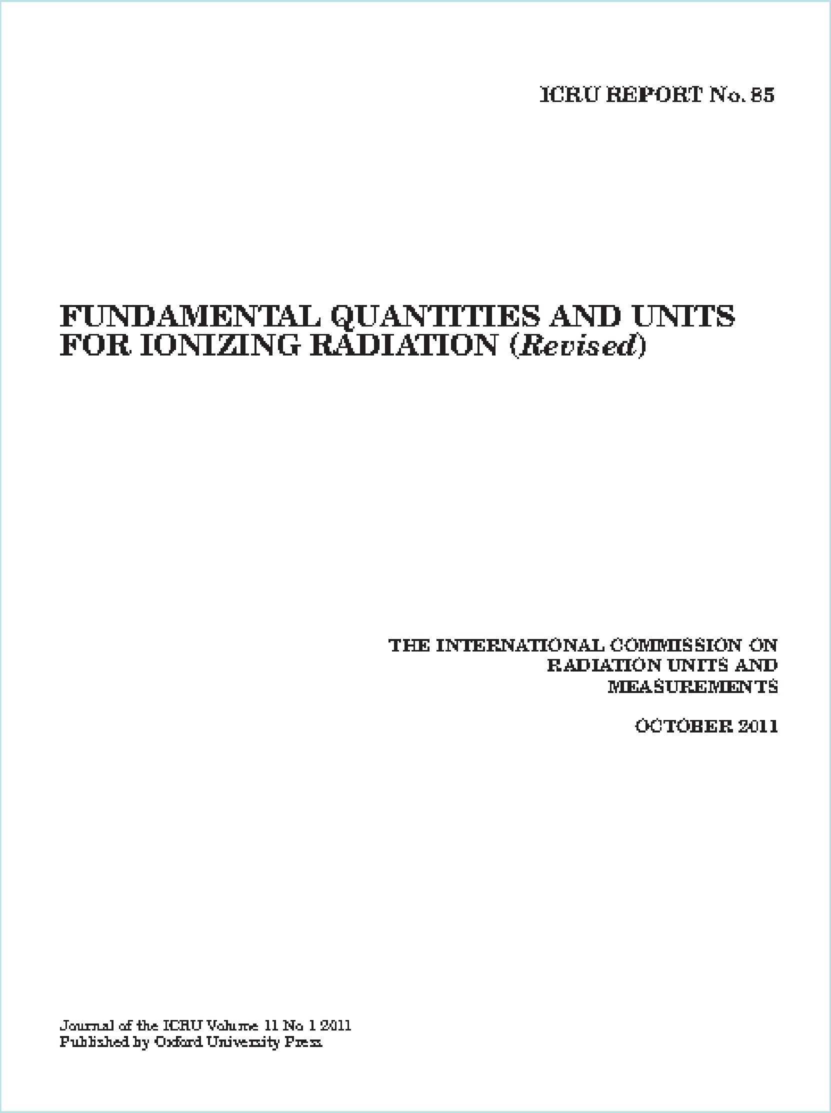
ICRU Report 60   and 85a



ICRU REPORT 60

Fundamental Quantities and Units for Ionizing Radiation

INTERNATIONAL COMMISSION
ON RADIATION UNITS
AND MEASUREMENTS



ICRU REPORT No. 85

FUNDAMENTAL QUANTITIES AND UNITS FOR IONIZING RADIATION (*Revised*)

THE INTERNATIONAL COMMISSION ON
RADIATION UNITS AND
MEASUREMENTS

OCTOBER 2011

Journal of the ICRU Volume 11 No 1 2011
Published by Oxford University Press

1. Introduction

Exact physical meaning of "dose of radiation"

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

$$\boxed{D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m}}$$

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

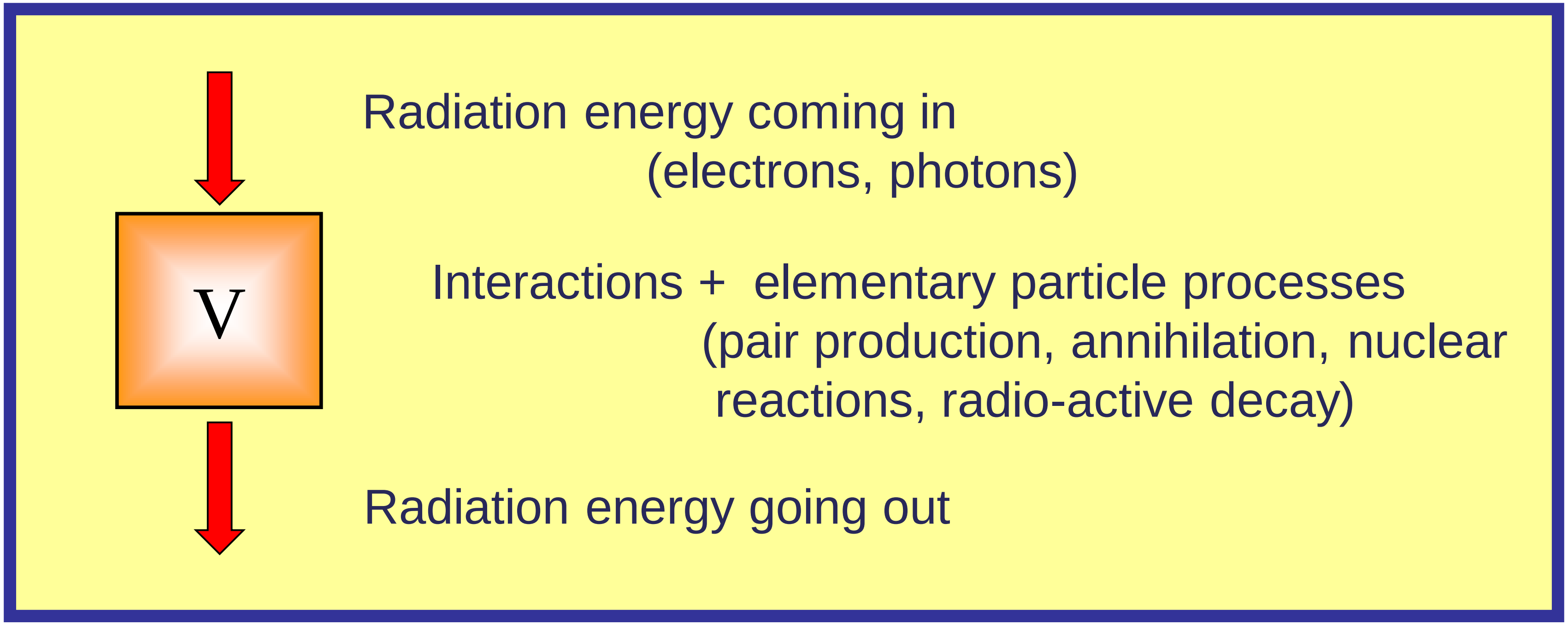
The unit of absorbed dose is Joule per Kilogram (J/kg), the special name for this unit is Gray (Gy).

We will discuss this in more detail:

There are

Four 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**:



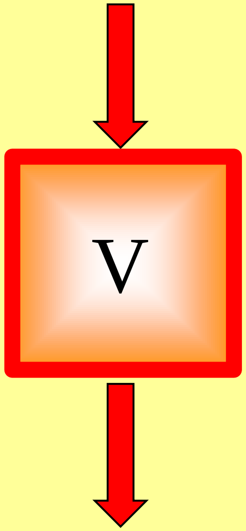
Radiation energy coming in
(electrons, photons)

Interactions + elementary particle processes
(pair production, annihilation, nuclear reactions, radio-active decay)

Radiation energy going out

absorbed radiation energy =
radiation energy coming in minus radiation energy going out

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

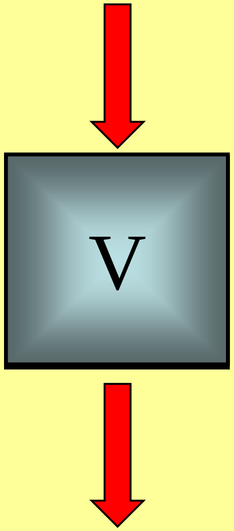


Radiation energy coming in
(electrons, photons)

Interactions + elementary particle processes
(pair production, annihilation, nuclear reactions, radio-active decay)

Radiation energy going out

(3) The term "**absorbed dose**" refers to the **material** within the volume :



Radiation energy coming in
(electrons, photons)

Interactions + elementary particle processes
(pair production, annihilation, nuclear reactions, radio-active decay)

Radiation energy going out

Example: 🟧 = air: D_{air} ⬛ = water: D_{water}

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

$$\boxed{D = D\left(\vec{r}\right)}$$

and:

D is steady in space and time

D can be differentiated in space and time

There are two conceptual difficulties with this definition:

1) Absorbed dose refers to a **volume** and at the same it is a quantity that refers to a **mathematical point** in space.

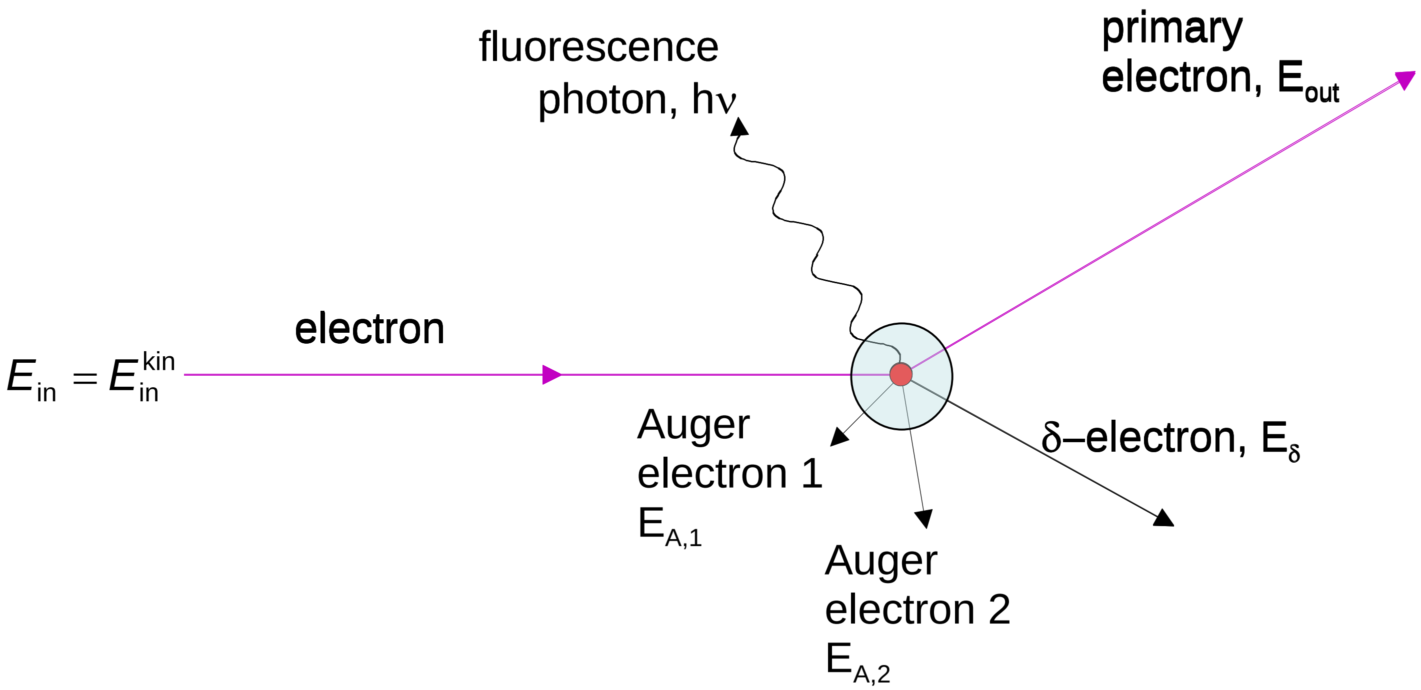
2) Absorbed dose comes from interactions at a microscopic level which are of **random character**, like any interaction on an atomic level.
At the same time dose it is **a non-random quantity** that is steady in space and time.

How can these contradictions be matched??

⇨ Needs a closer look on atomic interactions and associated energy deposition (de)

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

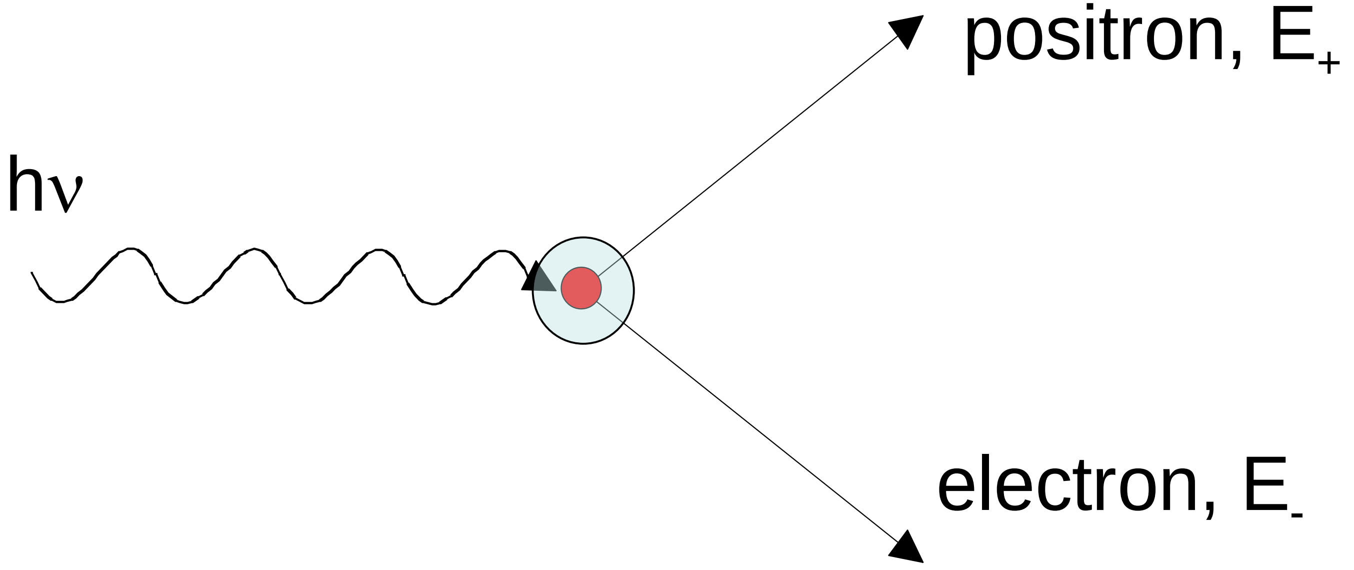
Energy deposition **de** by an electron knock-on interaction:



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

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

Energy deposition **de** by pair production:

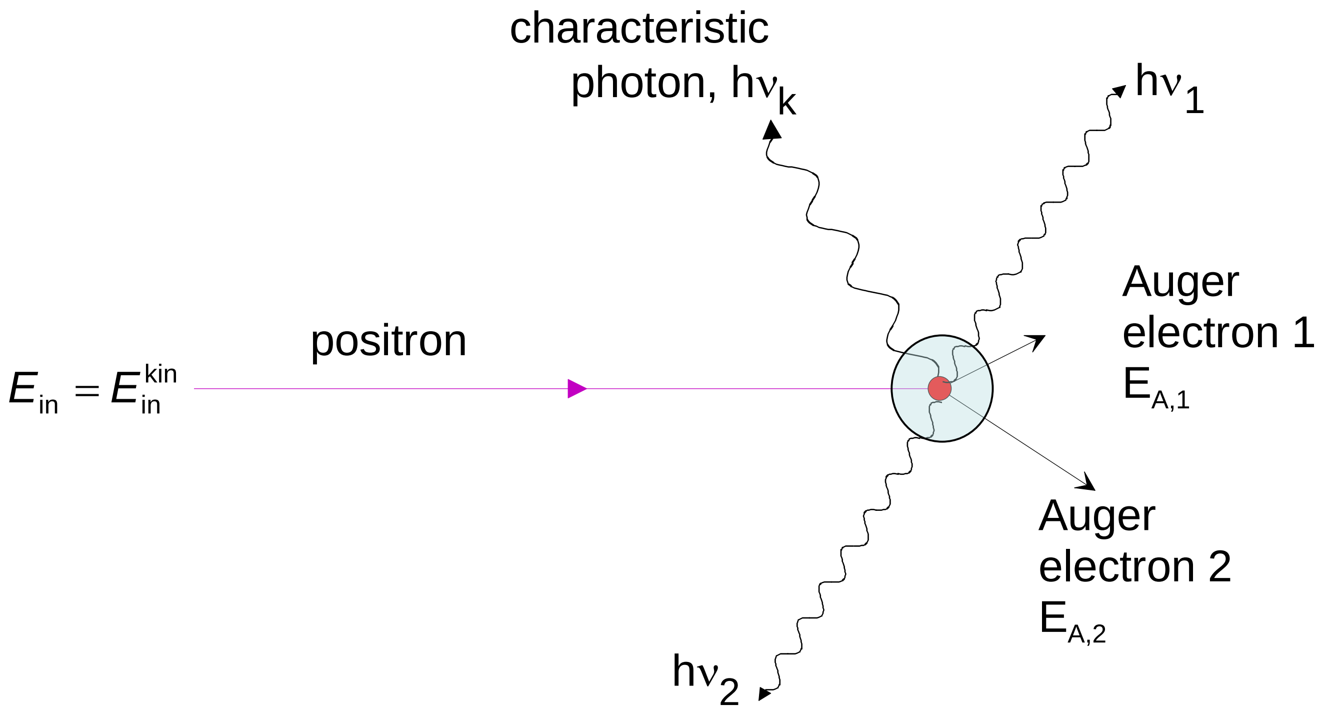


$$\boxed{de = h\nu - \left(E^{\mathrm{kin}}_{\mathrm{electron}} + E^{\mathrm{kin}}_{\mathrm{positron}} + 2m_0c^2\right)}$$

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

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

Energy deposition **de** by positron annihilation:



$$\boxed{de = E_{\text{in}} - \left(h\nu_1 + h\nu_2 + h\nu_{\text{k}} + E_{\text{A},1} + E_{\text{A},2}\right) + 2m_0c^2}$$

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

"Microscopic" interaction & single energy deposition **de**

The nature, common to any energy deposition is the following:

Almost each energy deposition is produced by

electrons

(primary as well as secondary electrons) via the

interaction process called **energy loss**

⇨ needs a closer look on what the electrons are doing!!!!!

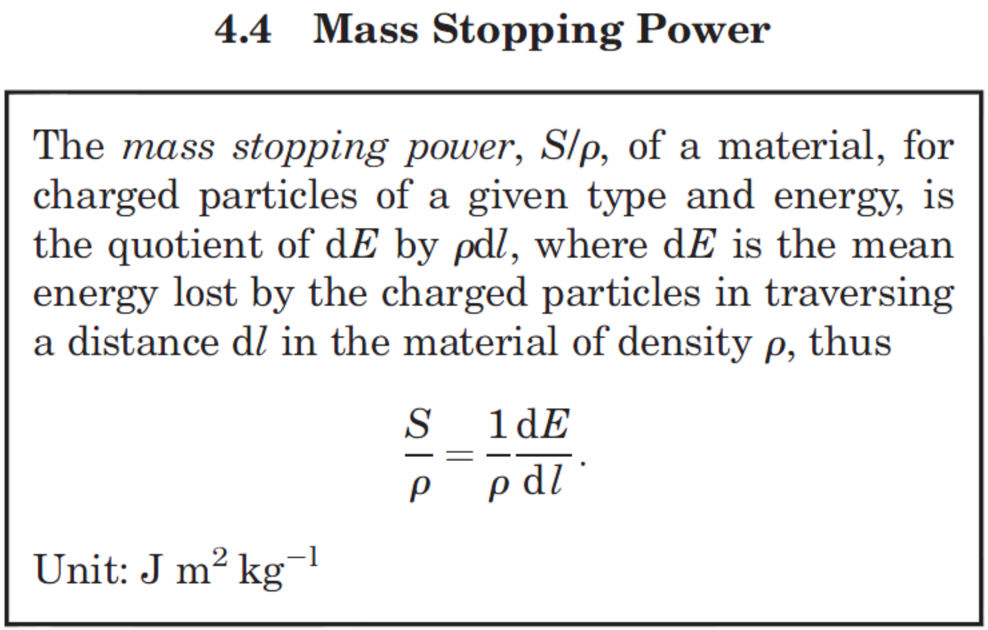
Energy loss depends on the:

- **energy** of the electron
- **material** through which the electron is moving

The process is formally described by the interaction process called stopping power S_{mat} of the material.

Definition of stopping power as in ICRU Report 85:

Note: Stopping power is normally formulated as the quotient with the density of the material and then called: **mass stopping power**:



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 $\mathrm{d}E$ by $\rho \mathrm{d}l$, where $\mathrm{d}E$ is the mean energy lost by the charged particles in traversing a distance $\mathrm{d}l$ in the material of density ρ, thus

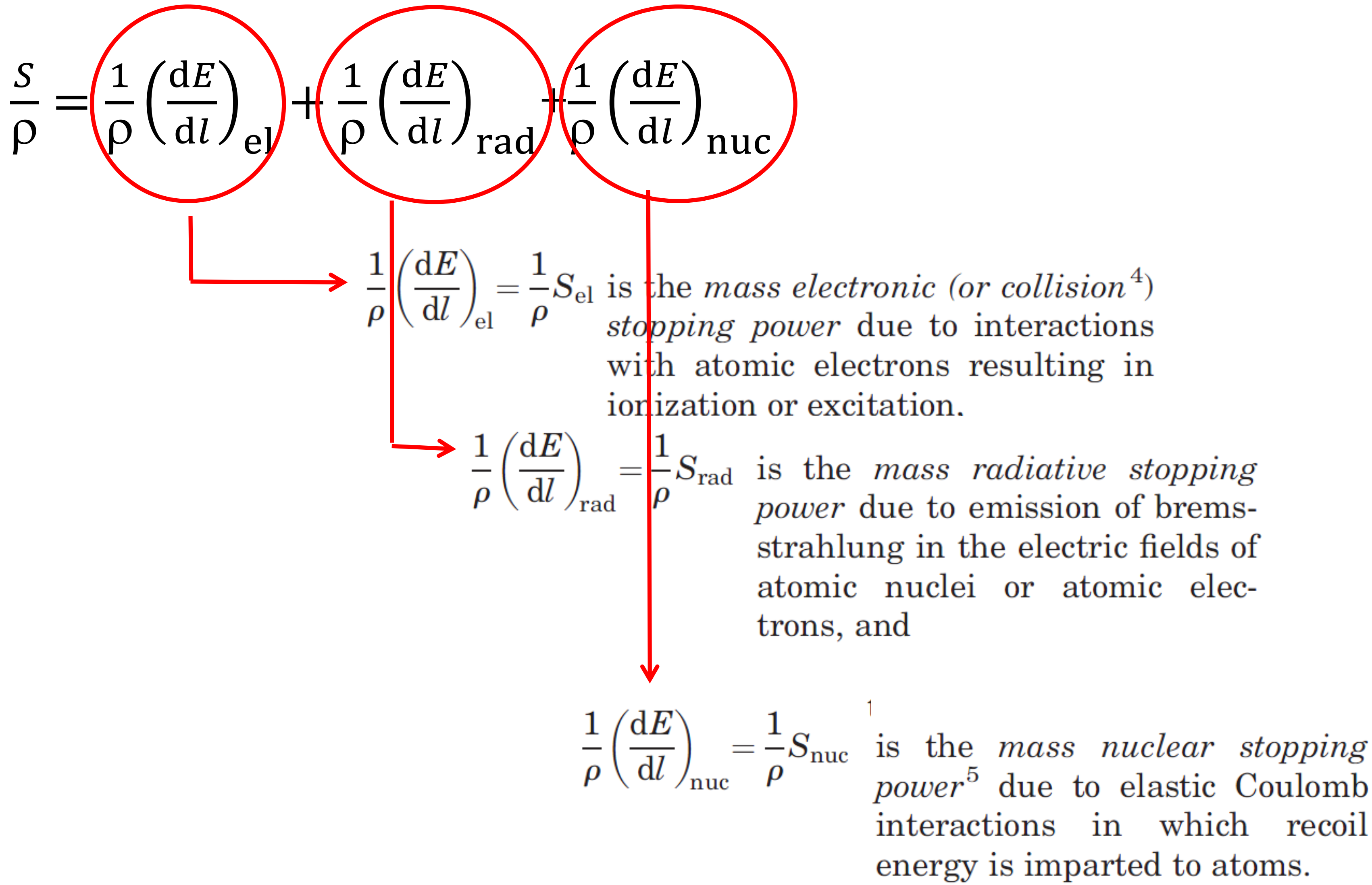
$$\frac{S}{\rho} = \frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}l}.$$

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

Keep in mind: Stopping power is the energy lost per unit path length

Stopping Power and Mass Stopping Power

Stopping power consists of three components:



$$\frac{S}{\rho} = \frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{el}} + \frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{rad}} + \frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{nuc}}$$

$\frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{el}} = \frac{1}{\rho}S_{\mathrm{el}}$ is the *mass electronic (or collision*[4]) *stopping power* due to interactions with atomic electrons resulting in ionization or excitation.

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

$\frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{nuc}} = \frac{1}{\rho}S_{\mathrm{nuc}}$ is the *mass nuclear stopping power*[5] due to elastic Coulomb interactions in which recoil energy is imparted to atoms.

Stopping Power and Mass Stopping Power

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

Answer 1: The **electronic energy loss dE_{el}** is at the same time the **energy absorbed**

Answer 2: There is a **fundamental relationship** between **mass electronic stopping power** and **absorbed dose** from charged particles

For this relation we need a good knowledge of the concept of particle fluence used for the characterization of a radiation field:

Characterization of a Radiation Field

We start with the definition of **particle number:**

The **particle number, *N*,** is the number of particles that are emitted, transferred, or received (Unit: 1)

A **detailed description** of a radiation field generally will require further 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 $\vec{\Omega}$

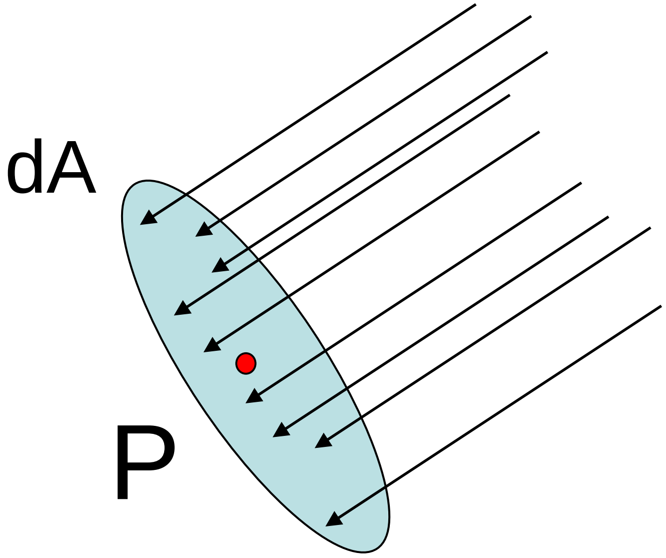
$$\boxed{N = N_j(\vec{r}, E, t, \vec{\Omega})}$$

How can the number of particles constituting a radiation field be determined 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 d*A*
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 d*A*.

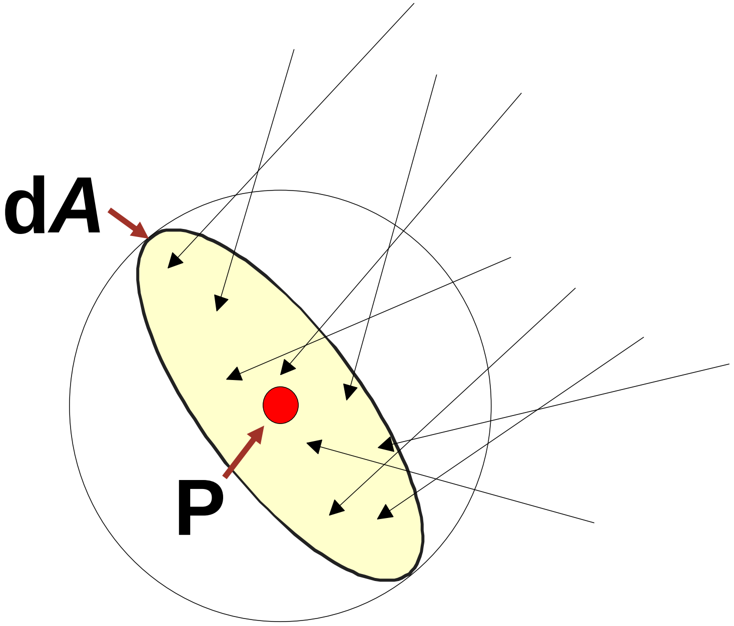
In the general case of many **nonparallel** particle directions it is evident that a fixed plane cannot be traversed by all particles **perpendicularly**.

⇨ A somewhat modified concept is needed!

The plane d*A* is allowed to move freely around P, so as to intercept each incident ray perpendicularly.

Practically this means:

- Generate a **sphere** by rotating d*A* around P
- Count the number of particles **entering** the sphere



Fluence

The number of particles per area dA is called the

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:

$$\Phi = \frac{\mathrm{d}N}{\mathrm{d}A}$$

The unit of fluence is m^{-2}.

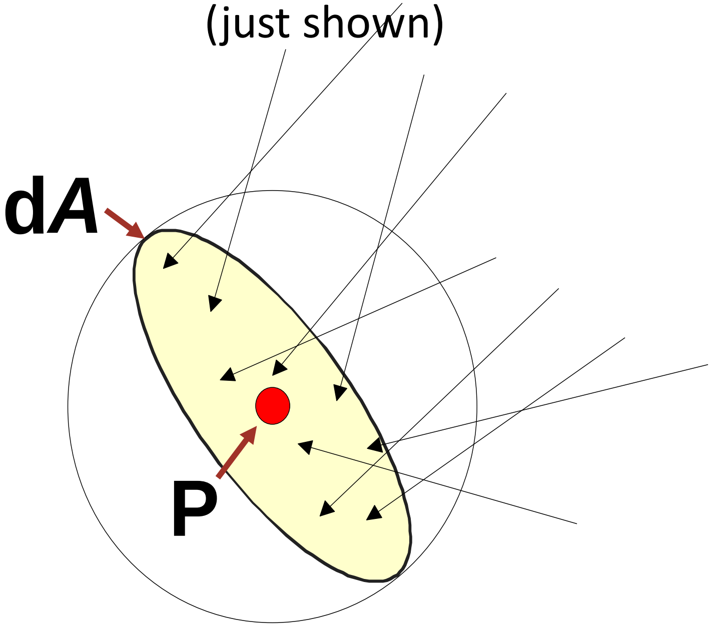
Note: The term **particle fluence** is sometimes also used for **fluence**.

Equally important is the fluence differential in energy , denoted as Φ_E

$$\Phi_E = \frac{\mathrm{d}\Phi}{\mathrm{d}E}$$

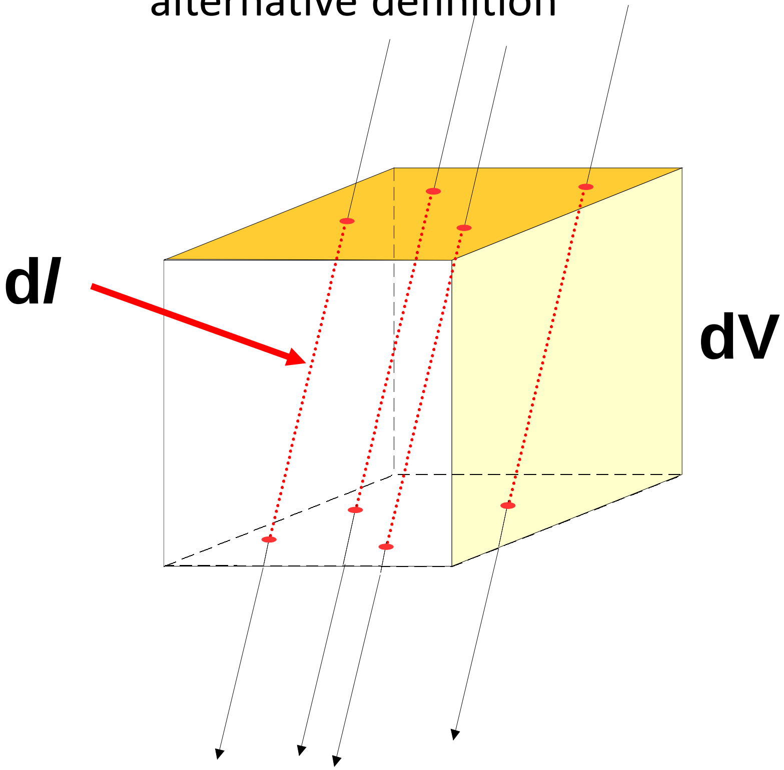
There is an important alternative definition for fluence:

conventional definition
(just shown)



$$\Phi(\bar{r}) = \frac{\mathrm{d}N}{\mathrm{d}A}$$

alternative definition



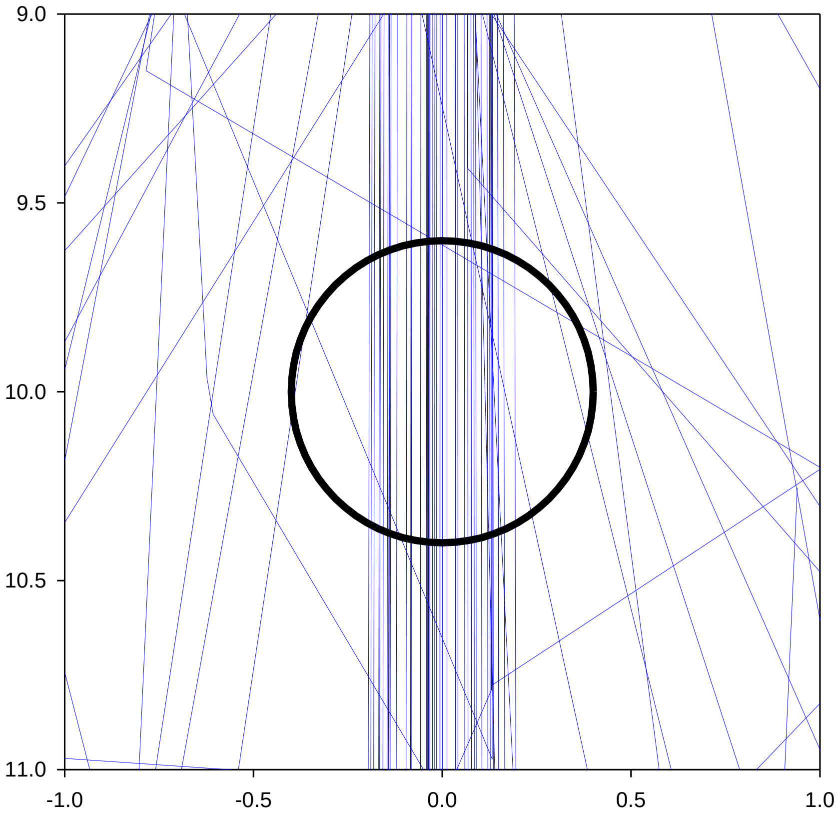
$$\Phi(\bar{r}) = \frac{\mathrm{d}l}{\mathrm{d}V}$$

For illustration

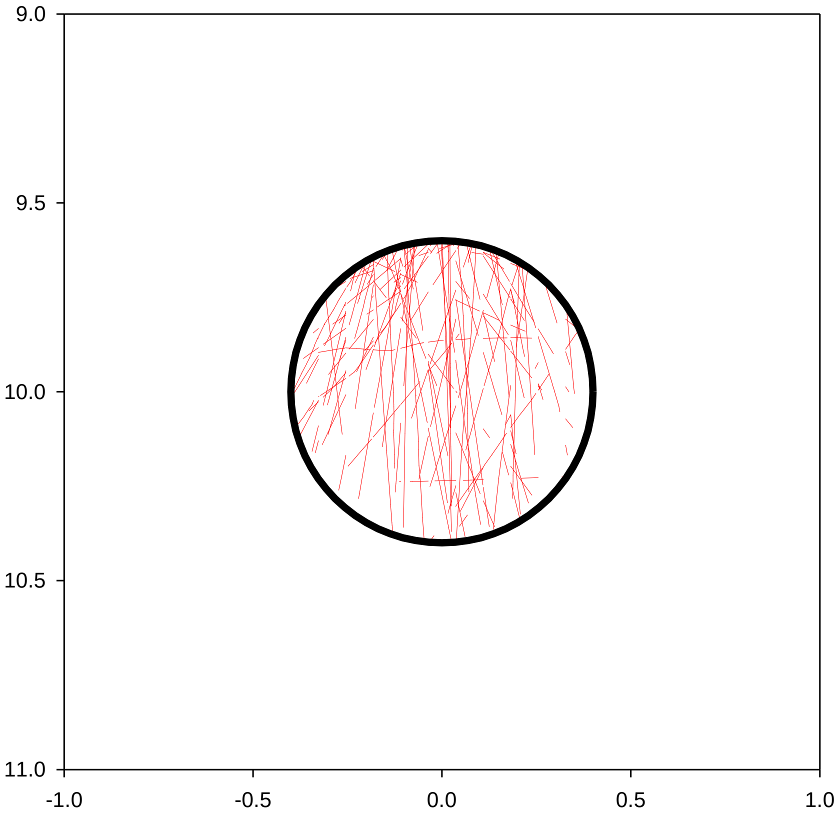
Two more realistic examples (MC calculated) for the particle tracks within a cylindrical air filled detector positioned at 10 cm depth in a water phantom.

4 mm x 4 mm of a 6 MV photon beam (= small field); cylinder diameter: 8 mm

photon tracks



produced secondary electron tracks



Stopping Power and Mass Stopping Power

Back to the **fundamental relationship** between **absorbed dose** from charged particles and **mass electronic stopping power.**

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

$$\Phi_E \cdot \frac{S_{\mathrm{el}}}{\rho} = \frac{\mathrm{d}\Phi}{\mathrm{d}E} \cdot \frac{1}{\rho} \left(\frac{\mathrm{d}E}{\mathrm{d}l} \right)_{\mathrm{el}}$$

since: $\mathrm{d}l = \frac{\mathrm{d}V}{\Phi}$

$$\Longrightarrow \quad \Phi_E \cdot \frac{S_{el}}{\rho} = \frac{\mathrm{d}\Phi}{\mathrm{d}E} \cdot \frac{1}{\rho} \left(\frac{\mathrm{d}E}{\mathrm{d}l} \right)_{\mathrm{el}} = \frac{\mathrm{d}\left(\frac{\mathrm{d}E}{\mathrm{d}m} \right)_{\mathrm{el}}}{\mathrm{d}E}$$

integrated over all dE:

$$\int \Phi_E \frac{S_{\mathrm{el}}}{\rho} \mathrm{d}E = \left(\frac{\mathrm{d}E}{\mathrm{d}m} \right)_{\mathrm{el}}$$

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

$$\boxed{(absorbed\ dose)_{\mathrm{el}} = \int \Phi_{\mathrm{E}}(\mathrm{E})\,\frac{\mathrm{S}_{\mathrm{el}}}{\rho}\,\mathrm{dE}}$$

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

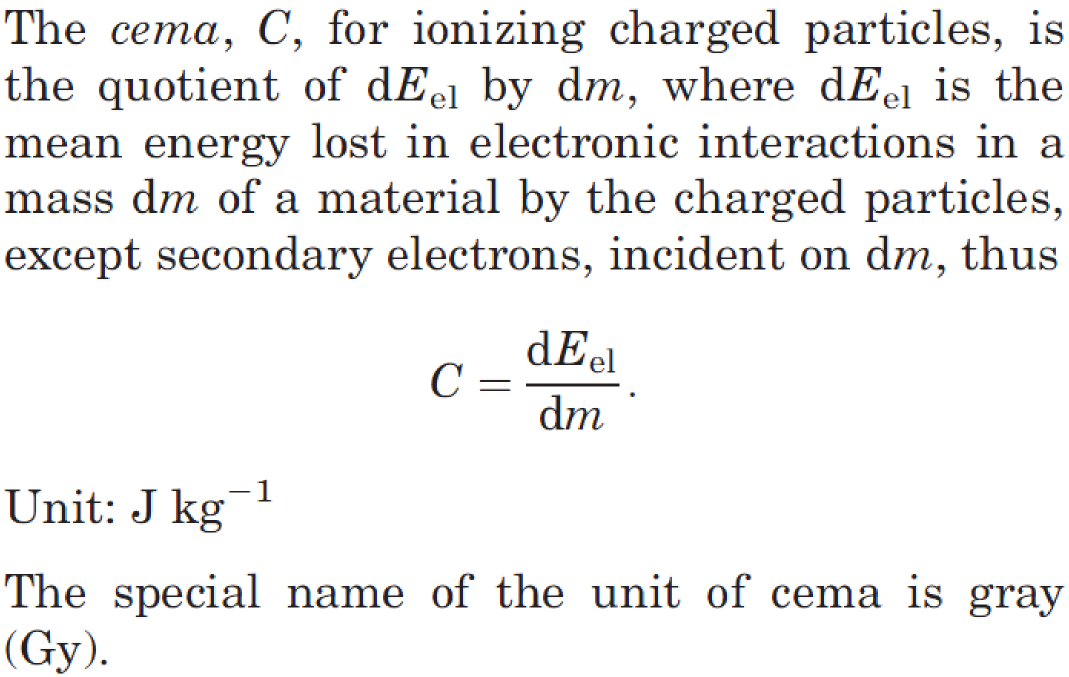
mass stopping power in
the material within the
volume of interest

This formula constitutes a very fundamental relation between absorbed dose in a material and the primary fluence spectrum of the electrons moving in that material.

Please remember this relation and the fact that $\boldsymbol{\Phi_E(E)}$ refers to the primary fluence spectrum !!!!!!!

ICRU 85 has defined a dosimetrical quantity called Cema:

(CEMA = Converted Energy per Mass)



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

$$C = \frac{\mathrm{d}E_{\mathrm{el}}}{\mathrm{d}m}.$$

Unit: $\mathrm{J\ kg^{-1}}$

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

Using our fundamental relationship:

$$\boxed{cema = \left(\frac{\mathrm{d}E}{\mathrm{d}m}\right)_{\mathrm{el}} = \int \Phi_{E}(E)\,\frac{S_{\mathrm{el}}}{\rho}\,\mathrm{d}E}$$

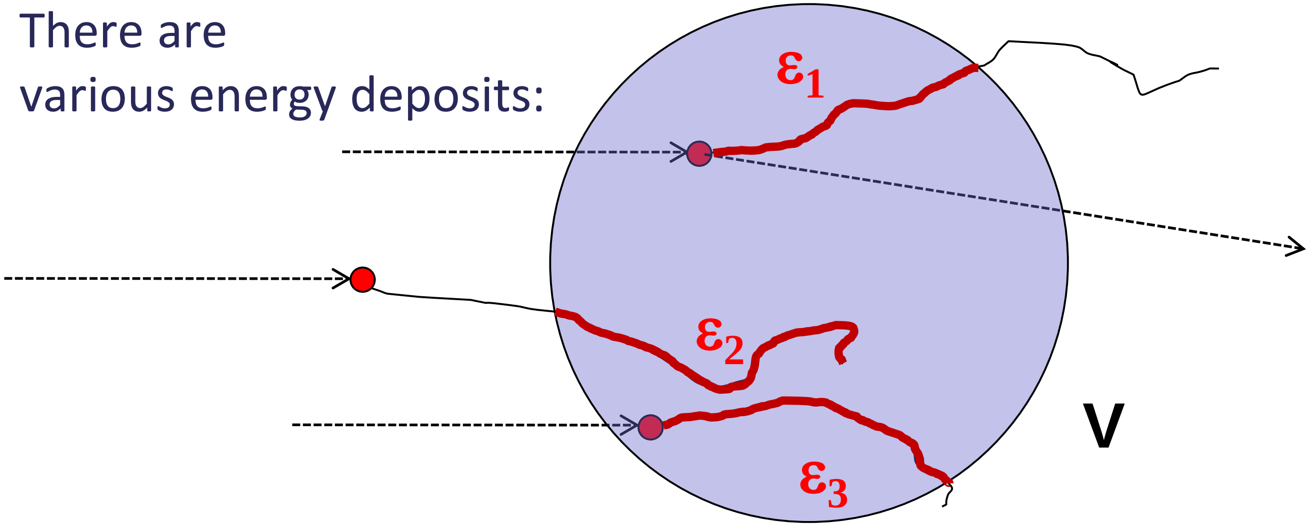
We will see later: Cema is an extremely useful quantity and concept!!!!

Back to interactions and "energy imparted“

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

$$\varepsilon_i = \sum de_j$$

There are various energy deposits:



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 → $\varepsilon = \sum \varepsilon_i$ ← energy deposit

Randomly distributed energy depositions and measurement

Application to dosimetry:

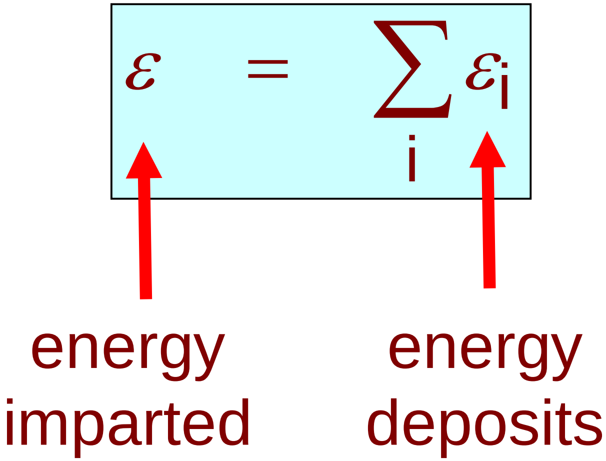
A radiation detector responds to radiation with a signal ***M*** which is proportional to the energy imparted ε in the detector volume.

$$M \quad \propto \quad \varepsilon = \sum_{i}\sum_{j} \mathrm{de}_{j}$$

Randomly distributed energy depositions and measurement

By nature, the values of single energy depositions de are randomly distributed.

It follows:
The sum (= energy imparted ε) must **also** be of random character.
(However with a lower variance!!!)



$$\varepsilon = \sum_i \varepsilon_i$$

energy imparted

energy deposits

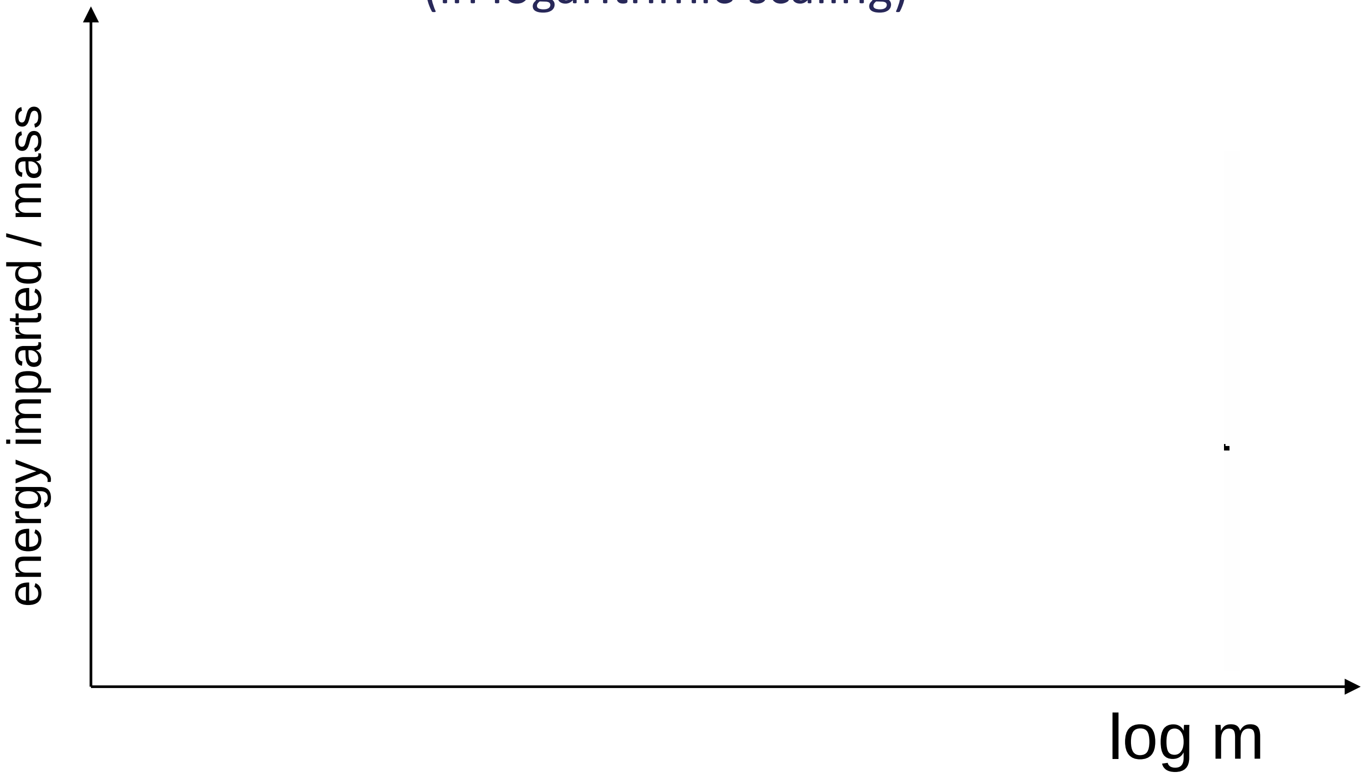
And because of: $M \propto \varepsilon = \sum_i \sum_j de_j$

If the determination of M is repeated,
it will never will yield exactly the same value.

As a consequence we can observe the following:

Shown below is the relation between the **quotient of energy imparted ε and the mass m** of a detector volume as a function of a **decreasing m**

(in logarithmic scaling)



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

$$\boxed{\varepsilon = \sum_i \varepsilon_i}$$

1. Introduction

Exact physical meaning of "dose of radiation"

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

$$\xcancel{\boxed{D = \frac{\mathrm{d}\varepsilon}{\mathrm{d}m}}}$$

but by
the mean:

$$\boxed{D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m}}$$

where $\mathrm{d}\bar{\varepsilon}$ is the **mean** energy imparted

$\mathrm{d}m$ is a small element of mass

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

First Summary: Energy absorption and absorbed dose

- **absorbed dose *D*:**
  (not randomly distributed)

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m}$$

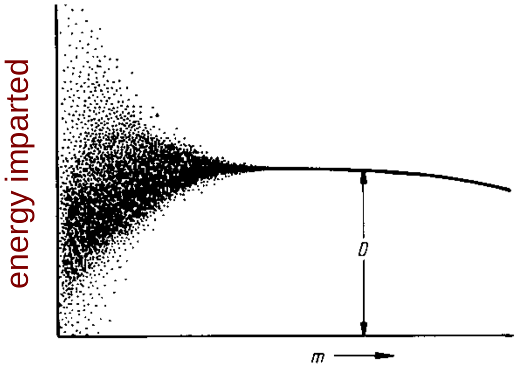
- **energy imparted ε :**
  (randomly distributed)

$$\varepsilon = \sum \varepsilon_{\mathrm{i}}$$

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

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

- **random character**
  of energy absorption



First Summary: Energy absorption and absorbed dose

- **Relation between**

  absorbed dose *D*

  and the

  primary spectral fluence of electrons

$$\boxed{(absorbed\ dose)_{\mathrm{el}} = Cema = \int \Phi_{\mathrm{E}}(\mathrm{E})\,\frac{\mathrm{S}_{\mathrm{el}}}{\rho}\,\mathrm{dE}}$$

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** must be determined.

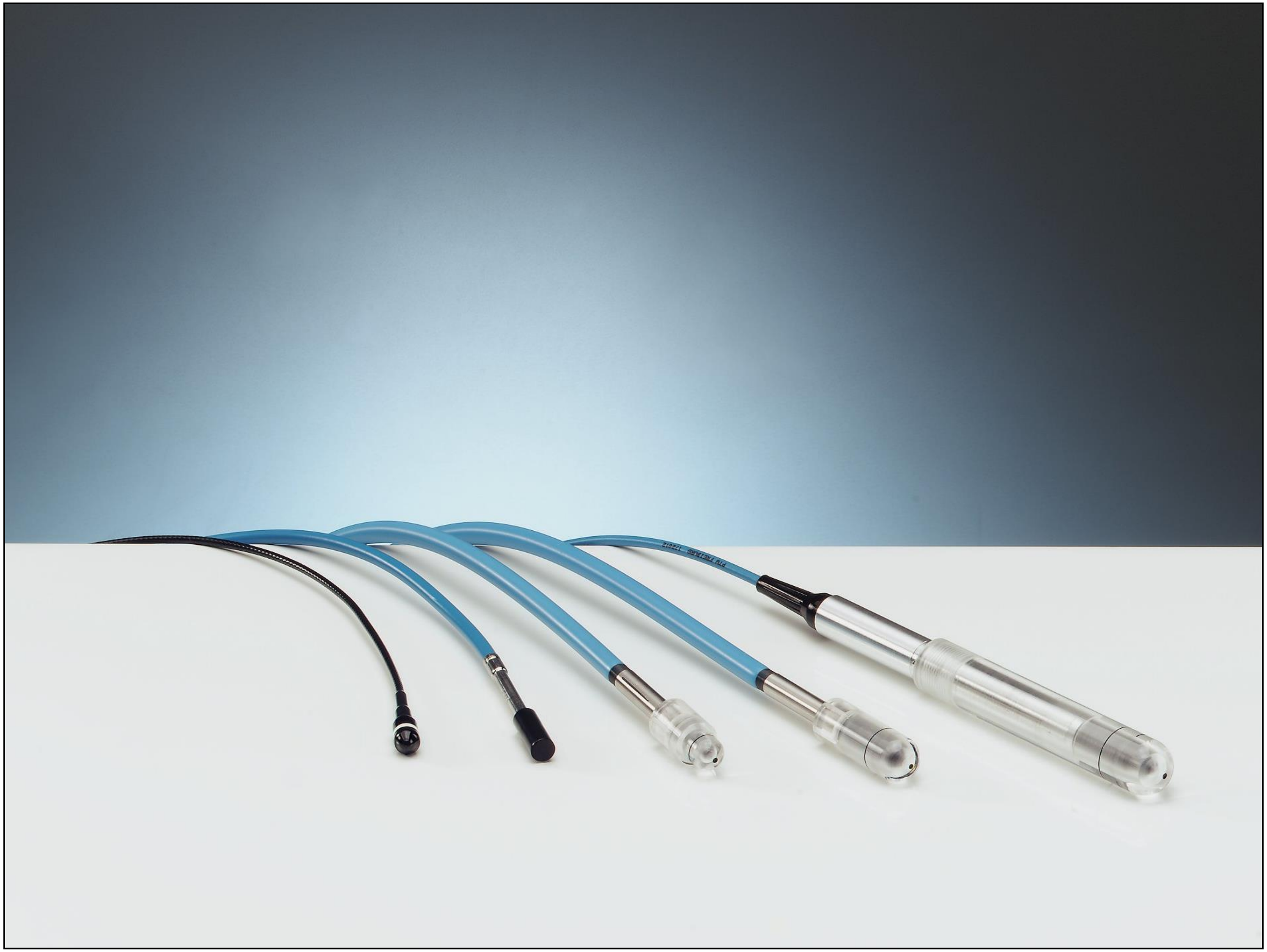
The most commonly used radiation dosimeters are:

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

Characteristics: Ionization chambers

Advantage	(small) Disadvantage
Accurate and precise	Connecting cables required
Recommended for beam calibration	High voltage supply required
Necessary corrections well understood	Many corrections required
Instant readout	

Ionization chambers



Characteristics: 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	Disadvantage
☐ 2-D spatial resolution	☐ ~~Darkroom and processing facilities required~~
☐ Very thin: does not perturb the beam	☐ ~~Processing difficult to control~~
	☐ Variation between films & batches
	☐ Needs proper calibration against ionization chambers
	☐ ~~Energy dependence problems~~
	☐ Needs an appropriate scanner!

Characteristics: Thermo-Luminescence-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

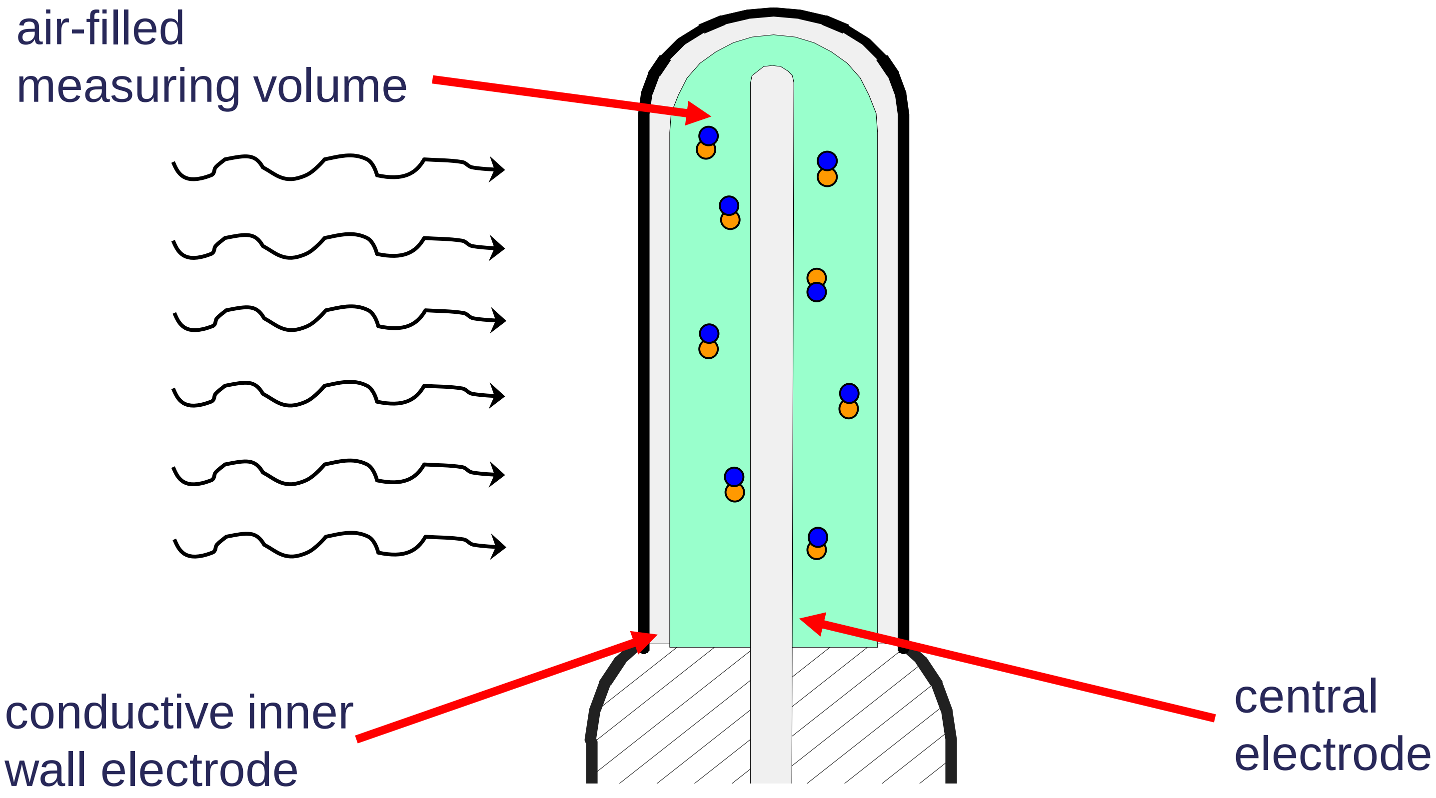
- Signal erased during readout
- Easy to lose reading
- No instant readout
- Accurate results require care
- Readout and calibration time consuming
- Not recommended for beam calibration

Characteristics: Solid state detectors

Advantage	Disadvantage
- Small size - High sensitivity - Instant readout - No external bias voltage - Simple instrumentation - **Good to measure relative distributions**!	- Requires connecting cables - Variability of response with temperature - Response may change with accumulated dose - Response is frequently dependent on radiation quality - Therefore: questionable for beam calibration

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.



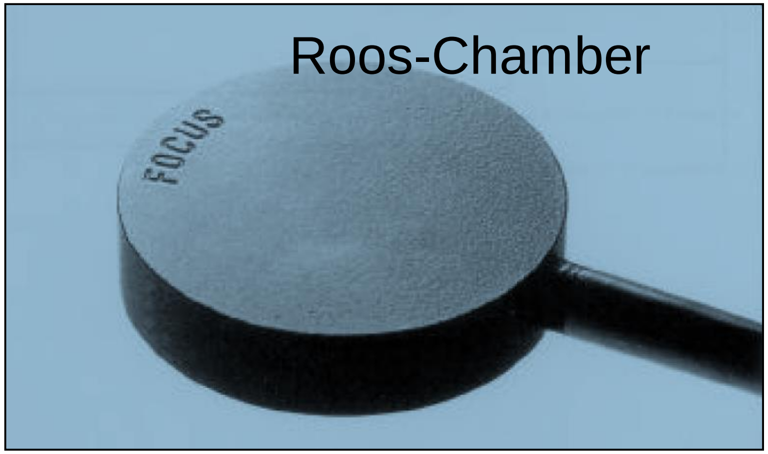
Principles of dosimetry with ionization chambers

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

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

cylindrical chamber

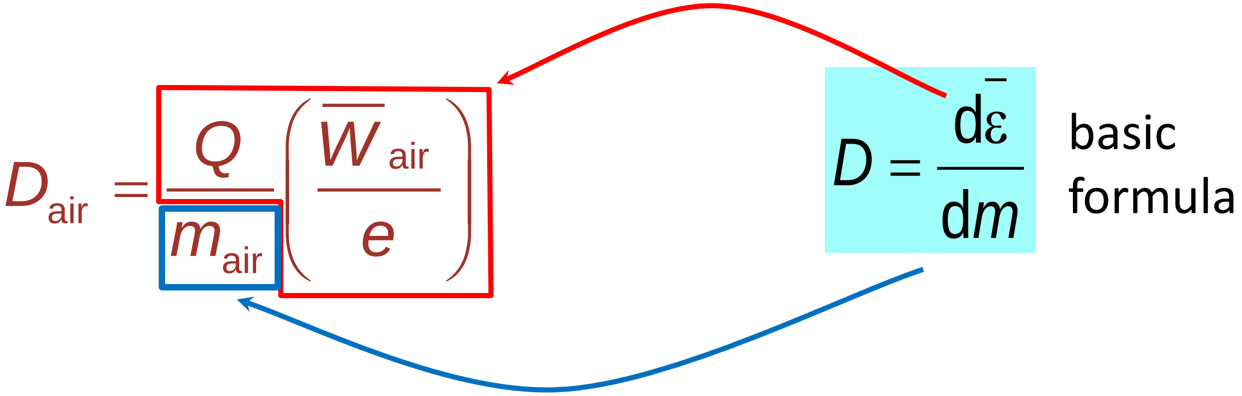
plane-parallel chamber



Because of the key role that ionization chambers play in radiotherapy dosimetry, it is vital that practizing physicists have a thorough 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:



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

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

basic formula

$\overline{W}_{air}/e$ is the mean energy required to produce an ion pair in air per unit charge *e*.

Principles of dosimetry with ionization chambers

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

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

- For air at relative humidity of 50%:

$$(\overline{W}_{\mathrm{air}}/e) = 33.77 \text{ J/C}$$

← Used in dose protocols

- For dry air:

$$(\overline{W}_{\mathrm{air}}/e) = 33.97 \text{ J/C}$$

Principles of dosimetry with **ionization chambers**

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

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

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, here from D_{air}???

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

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:

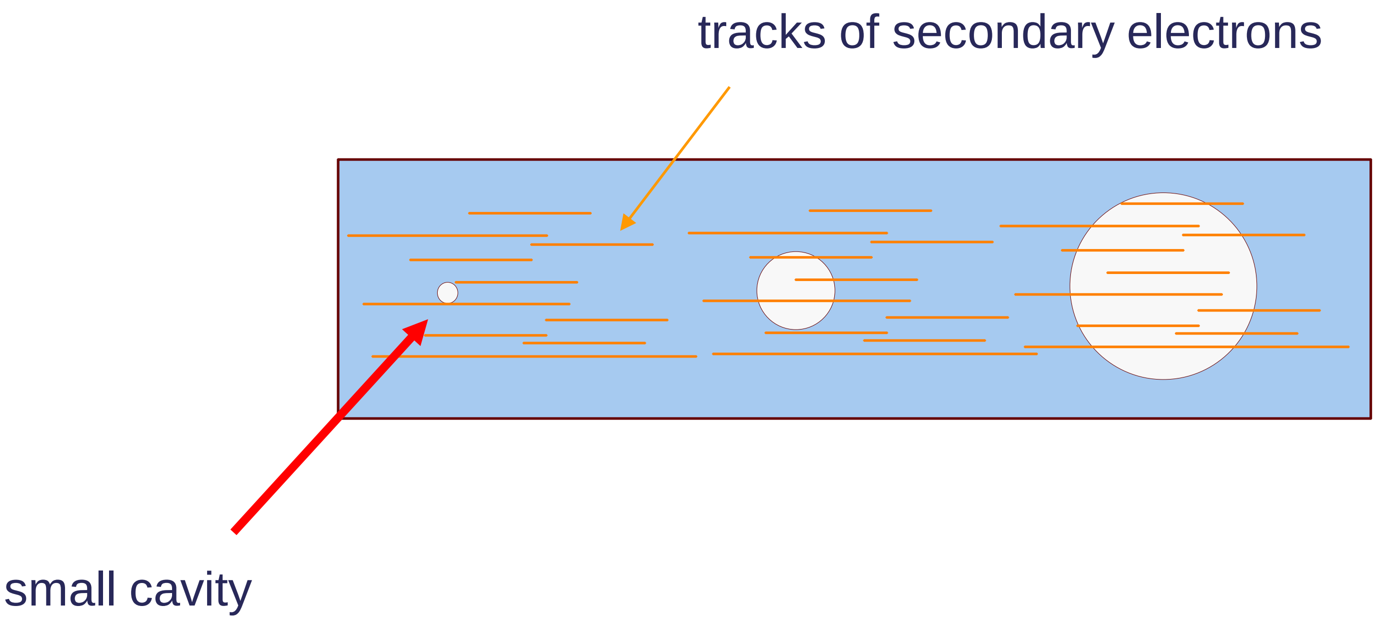
- high energy photons (E > 1 MeV)
- high energy electrons

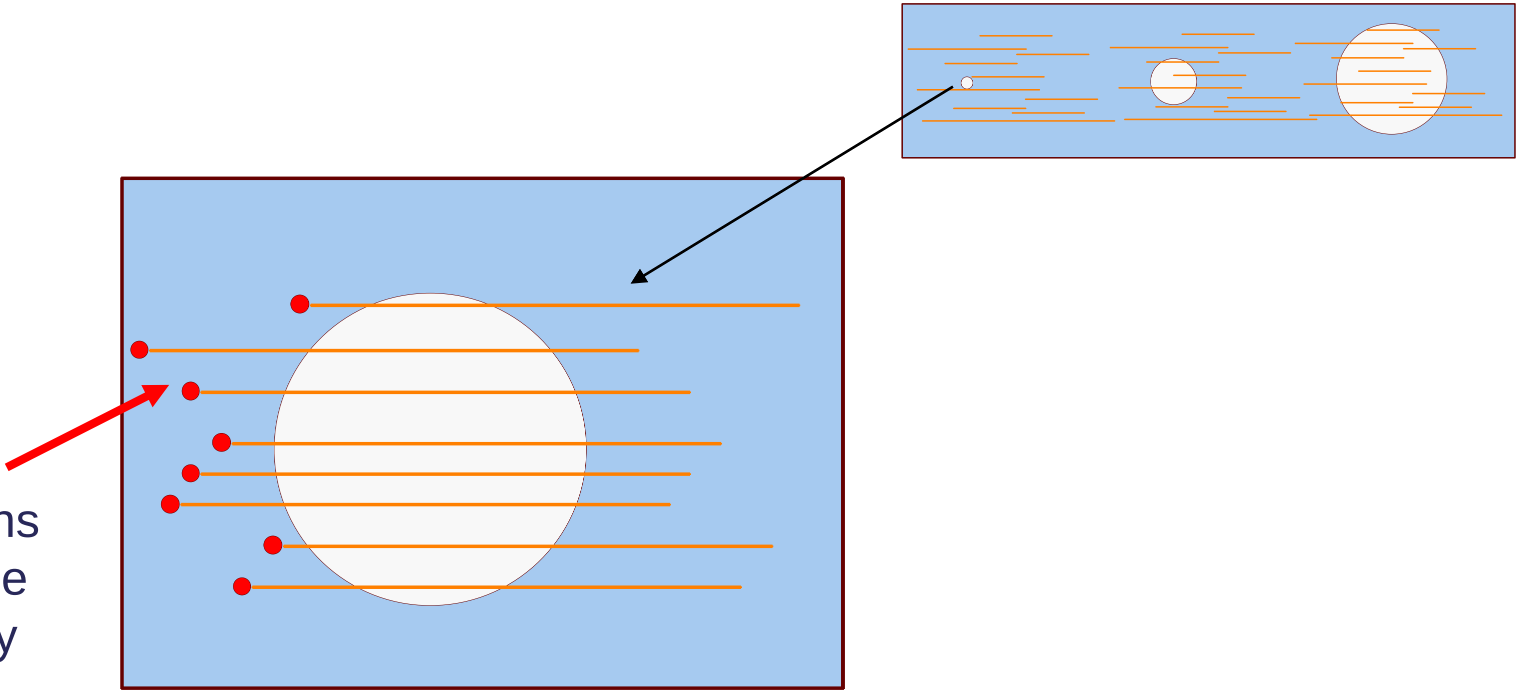
the so-called **Bragg-Gray Cavity Theory** can be applied.

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

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.





photon interactions outside the cavity only

Condition (2) for photons:

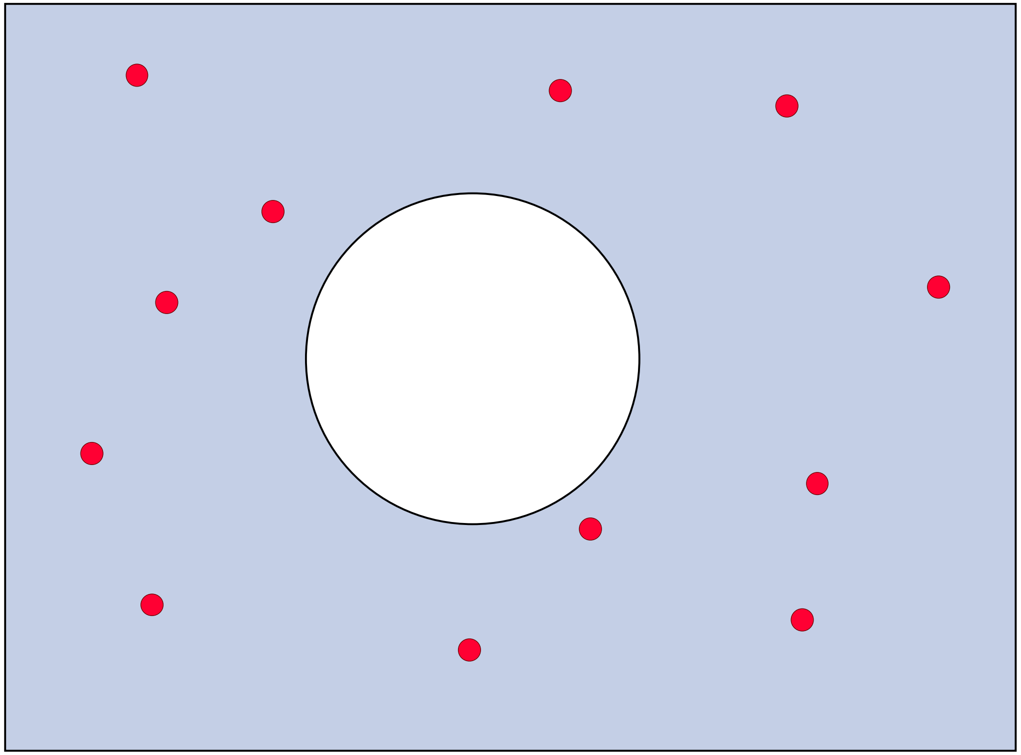
The energy absorbed in the cavity has its origin solely by charged particles crossing the cavity.

To enter the discussion of what is meant by:

Bragg-Gray 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 only outside the cavity.

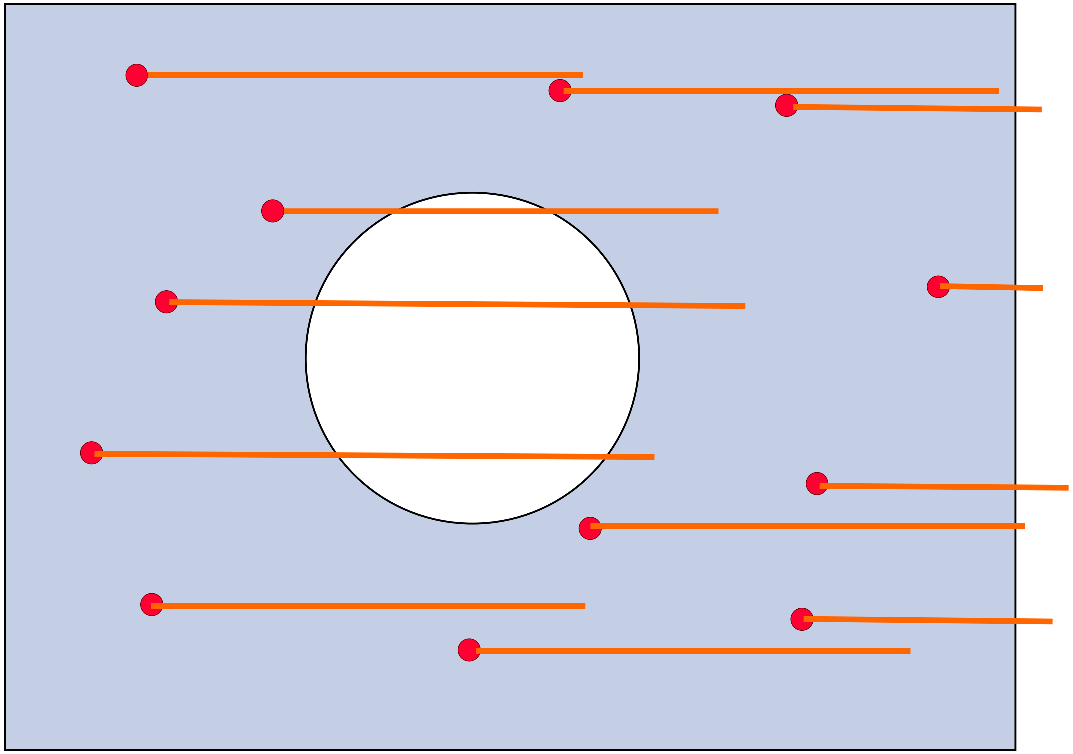


● photon interaction

Note:

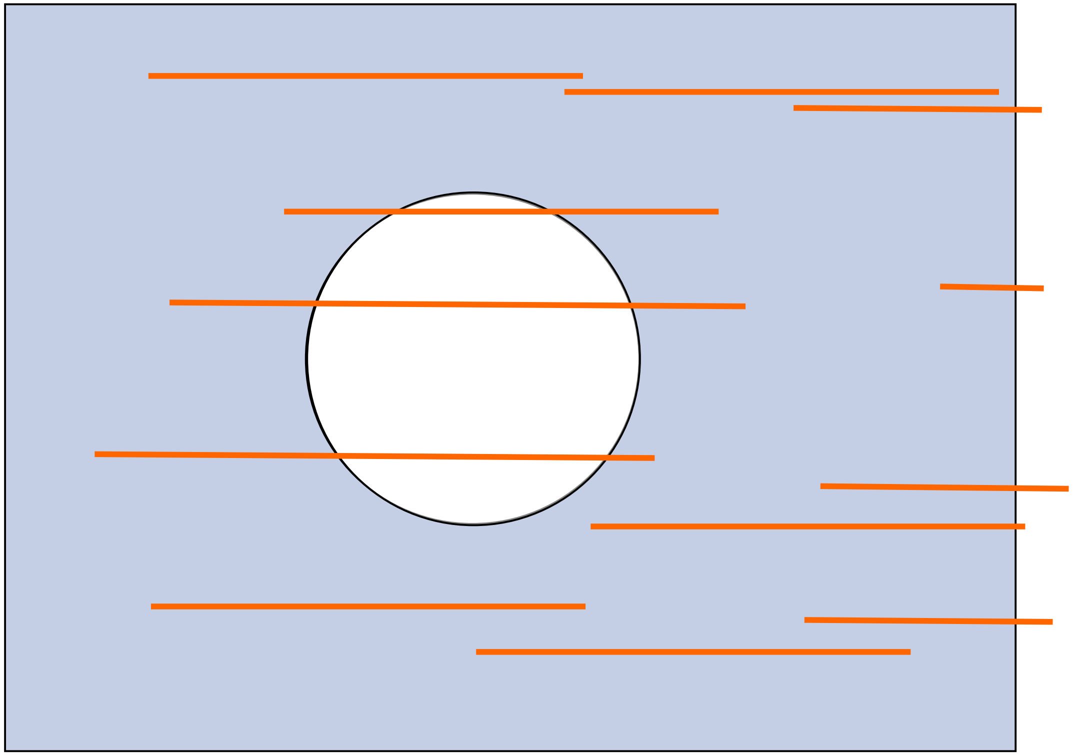
We assume that the number of photon interactions in the air cavity itself is negligible (BG condition 2)

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



electron track

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



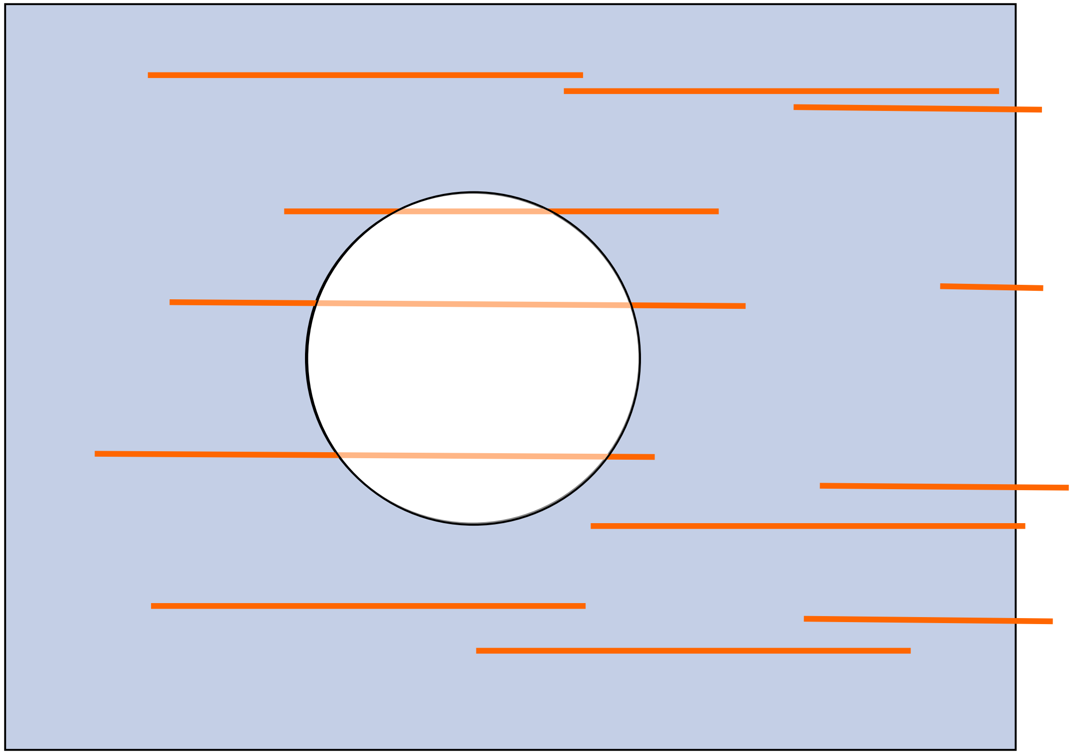
Consequently, the types of energy depositions

within the air cavity

are exclusively those of electrons loosing energy characterized by the stopping power of the material within the volume.

Absorbed dose D in the air can be calculated as:

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



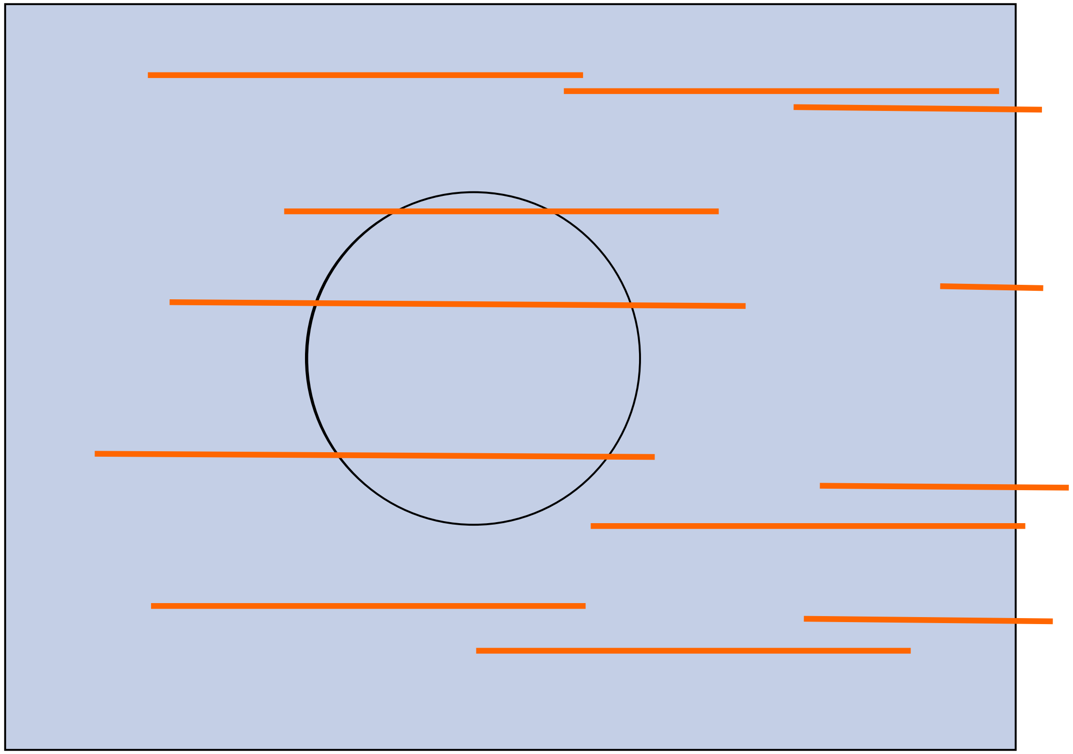
Let us further assume, that exactly the **same fluence** of the secondary electrons exists, independent from whether the cavity is filled with **air** or **water**.

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:

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



We will call this ratio:

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

the **stopping power ratio water to air** denoted as $s_{w,a}$.

Now we can convert $D_{air} = \frac{Q}{m_{\mathrm{air}}}\left(\frac{W}{e}\right)$ into D_{water}:

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

However, the formula:

$$\boxed{D_{water} = \int \Phi_{\mathrm{E}} \cdot \left(\frac{S_{el}}{\rho}\right)_{water} \cdot \mathrm{dE}}$$

is not completely correct!

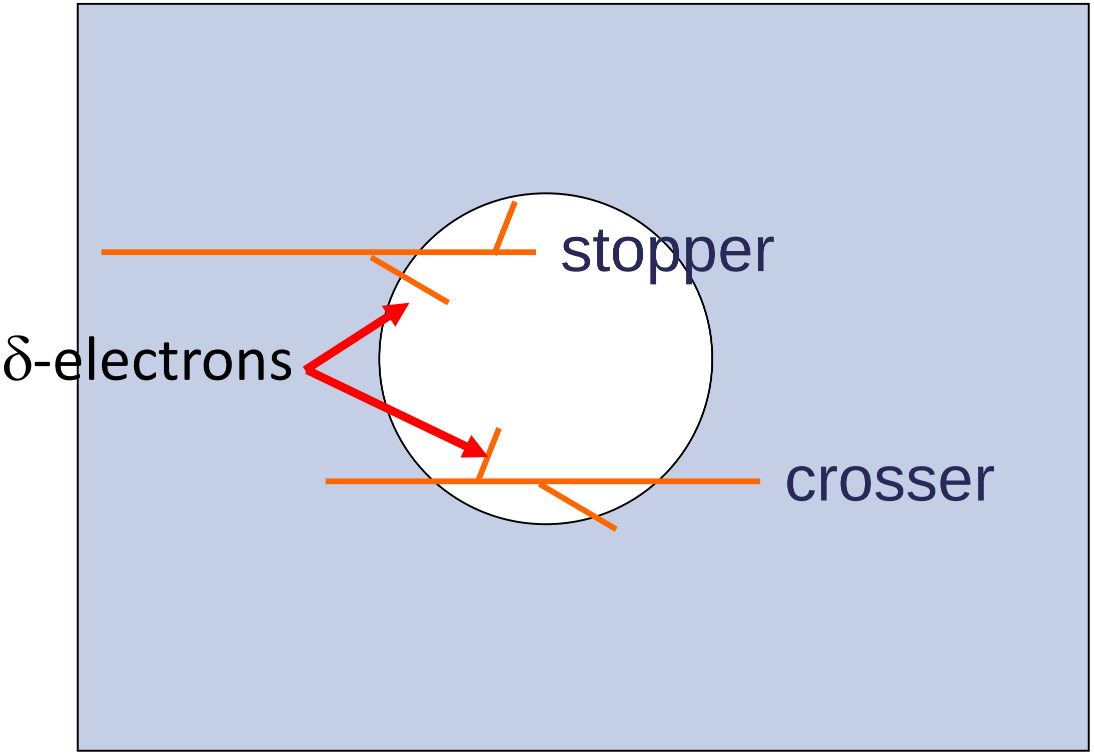
What about the stoppers ????

What about the secondary δ-electrons created by primary electrons???
Remember: $\Phi_E(E)$ refers to the primary electrons only.

Do they create a problem???

The answer is: Yes, they do!

A closer look:

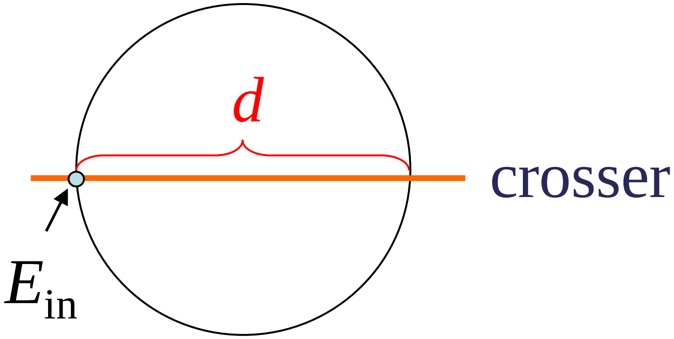


Let us consider the process of energy absorption of a crosser:

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.

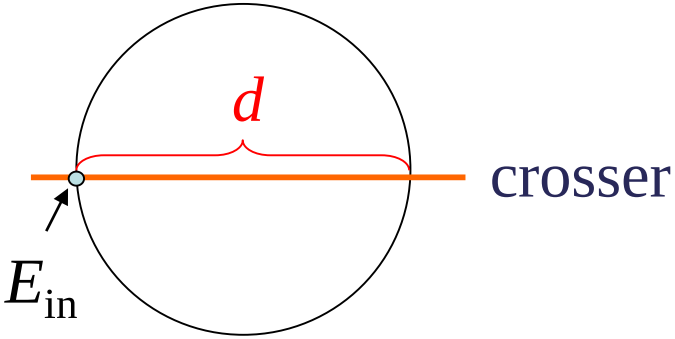
Then the energy deposit ε is:

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



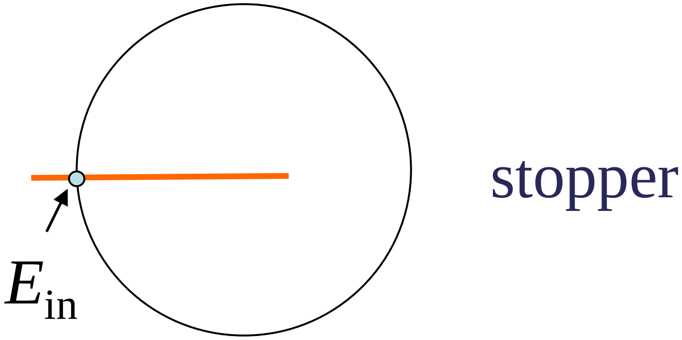
We compare this sitution:

$$\boxed{\varepsilon \quad = \quad S_{el}\left(E_{in}\right) \times d}$$



With the energy absorption of a stopper:

$$\boxed{\varepsilon \quad = \quad E_{in}}$$



This energy deposit has nothing to do with stopping power!!

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

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

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 !

Spencer-Attix stopping power ratio

Spencer & Attix have developed a method in the calculation of the water to air stopping power ratio which explicitly takes into account the problem of the stoppers and the secondary δ-electrons!

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

What has been changed:

1. Use of the fluence spectrum which now includes all electrons, the primary electrons as well as the secondary δ-electrons
2. Use of the so-called restricted stopping power L_Δ
3. A second term which takes into account the energy deposition of stoppers

The same corrections must also be made for the cema concept which now is called the **restricted cema**:

$$cema_{\Delta} = \int_{\Delta}^{E_{max}} \Phi_{\mathrm{E}}(\mathrm{E}) \frac{\mathrm{L}_{\Delta,\mathrm{el}}}{\rho} \mathrm{dE} + \Phi_{\mathrm{E}}(\Delta) \frac{\mathrm{S}_{\mathrm{el}}(\Delta)}{\rho}$$

Note:

Now the **restricted cema** is really almost equal to the absorbed dose from electrons due to electronic colissions.

Subsequently, restricted cema is always used.

Using the definition of the restricted cema, one can express the calculation of the Spencer-Attix stopping power ratio in a much more elegant way as:

$$s_{water,air}^{SA} = \frac{cema_{\Delta,water}}{cema_{\Delta,air}}$$

Where the fluence differential in energy used for the cema calculation is that at the point of measurement in water.

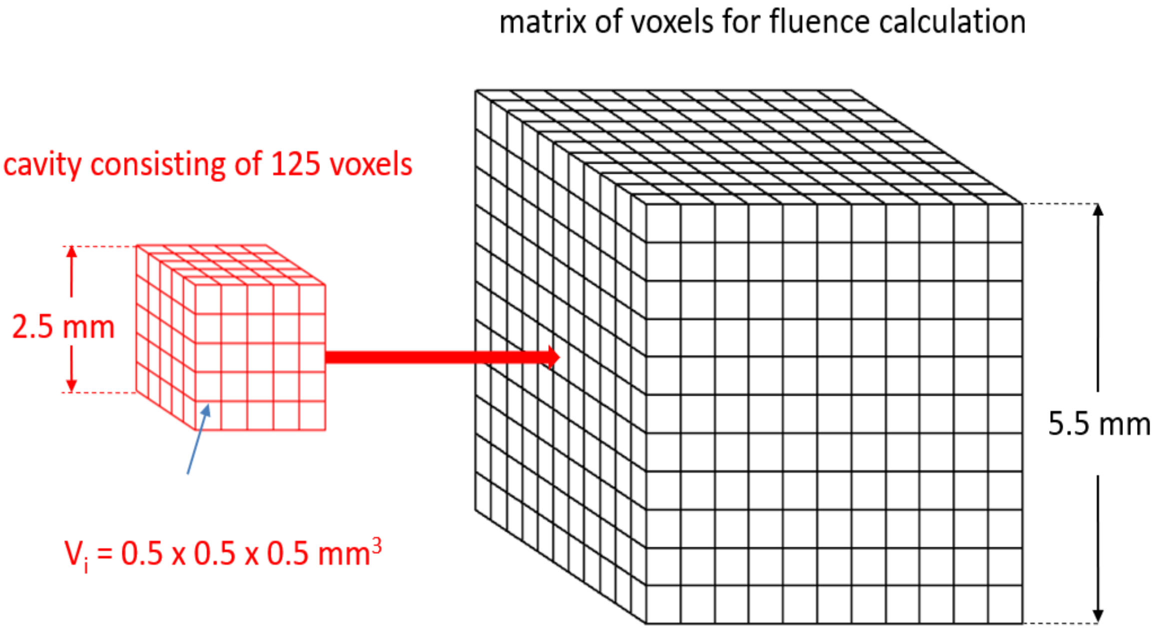
⇨

$$D_{water} = D_{air} s_{w,a}^{\mathrm{SA}}$$

However, still not completely correct!

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 embedded in water

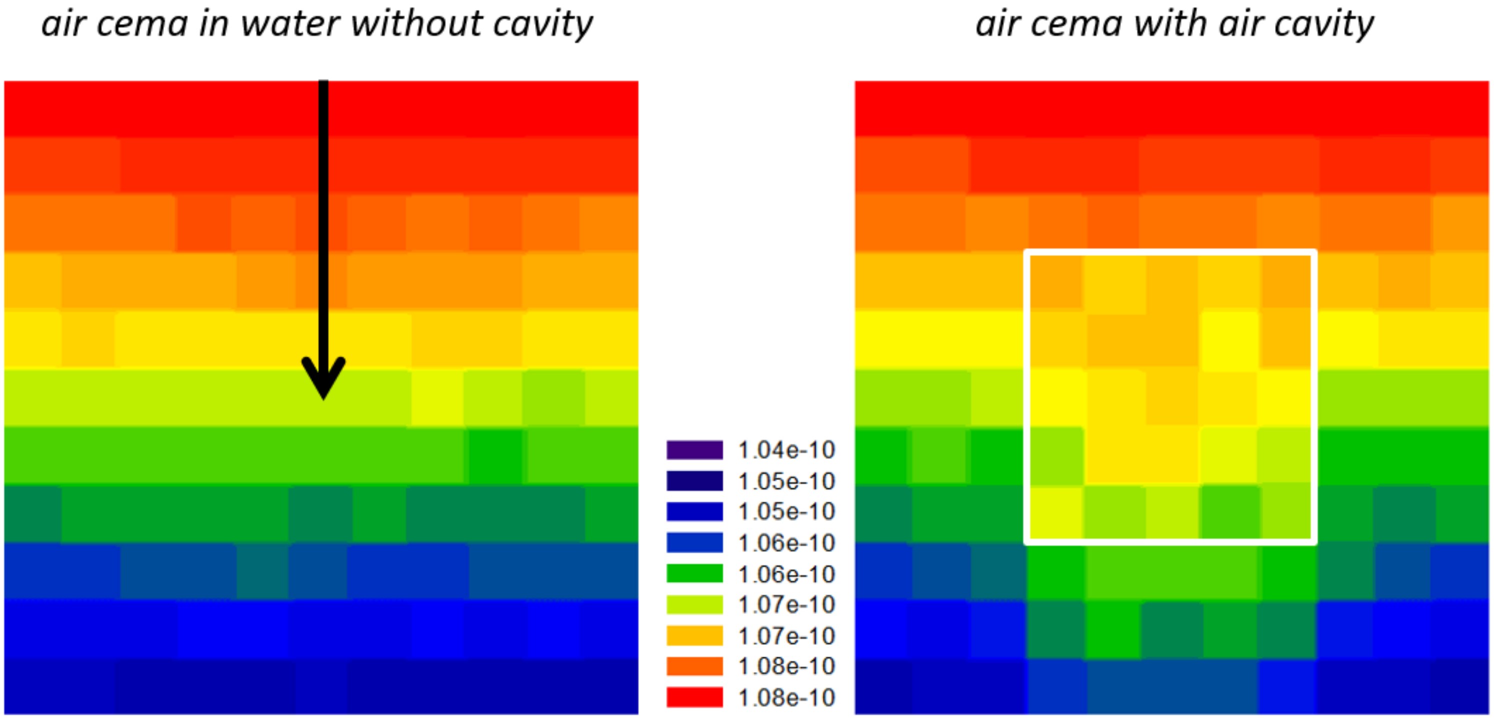


Use of air cema which is calculated as:

$$air\ cema_{\Delta} = \int_{\Delta}^{E_{max}} \Phi_{E}(E)\,\frac{L_{\Delta,\mathrm{air,el}}}{\rho}\,dE + \Phi_{E}(\Delta)\,\frac{s_{\mathrm{el,air}}(\Delta)}{\rho}$$

Air cema is a single condensed value to express an entire fluence spectrum!

6 MV photon field, 5 cm depth


air cema in water without cavity

air cema with air cavity

Fluence is indeed disturbed, BG condition 1 is not met!!!

To take this perturbation into account, we need an additional perturbation factor p

Second summary: Determination of Absorbed dose in water with an ionization chamber

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

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

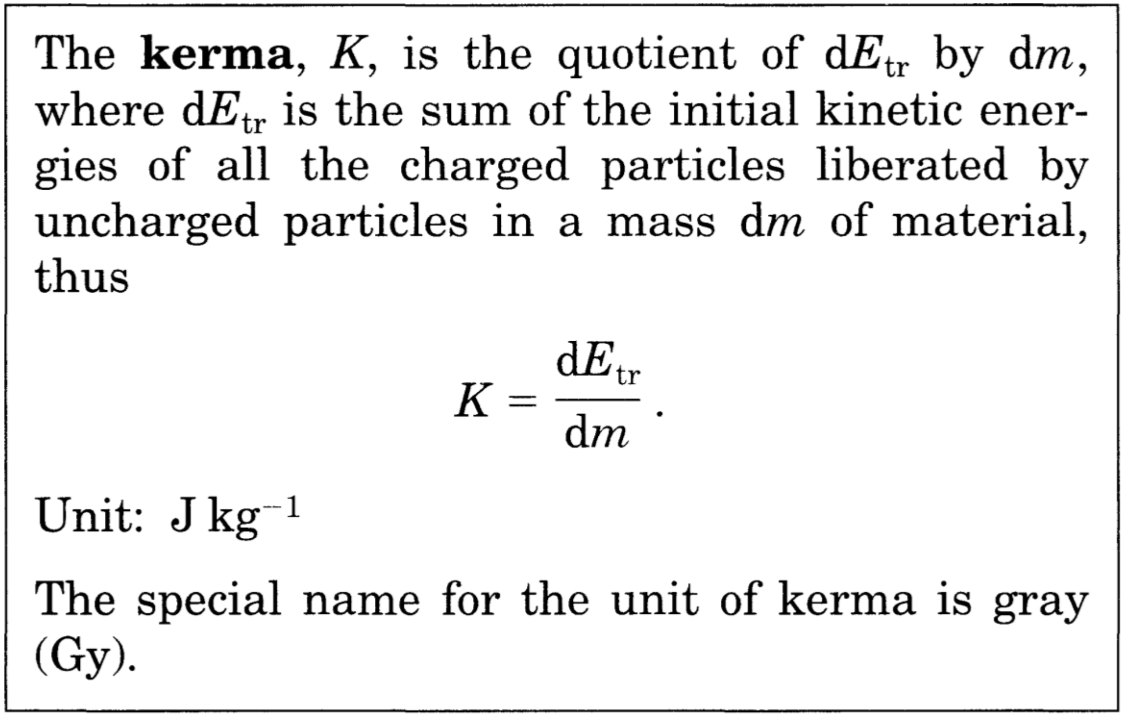
where:

$s_{w,air}^{SA}$	is now the **Spencer-Attix stopping power** water to air
p	is for all perturbation correction factors required to take into account deviations from the BG-conditions
$f = s_{w,air}^{SA}\, p$	is a factor called the dose conversion factor

There are two further terms which are really important to understand the fundamentals in dosimetry.

The first term is now addressed:

KERMA.



The **kerma**, K, is the quotient of $\mathrm{d}E_{\mathrm{tr}}$ by $\mathrm{d}m$, where $\mathrm{d}E_{\mathrm{tr}}$ is the sum of the initial kinetic energies of all the charged particles liberated by uncharged particles in a mass $\mathrm{d}m$ of material, thus

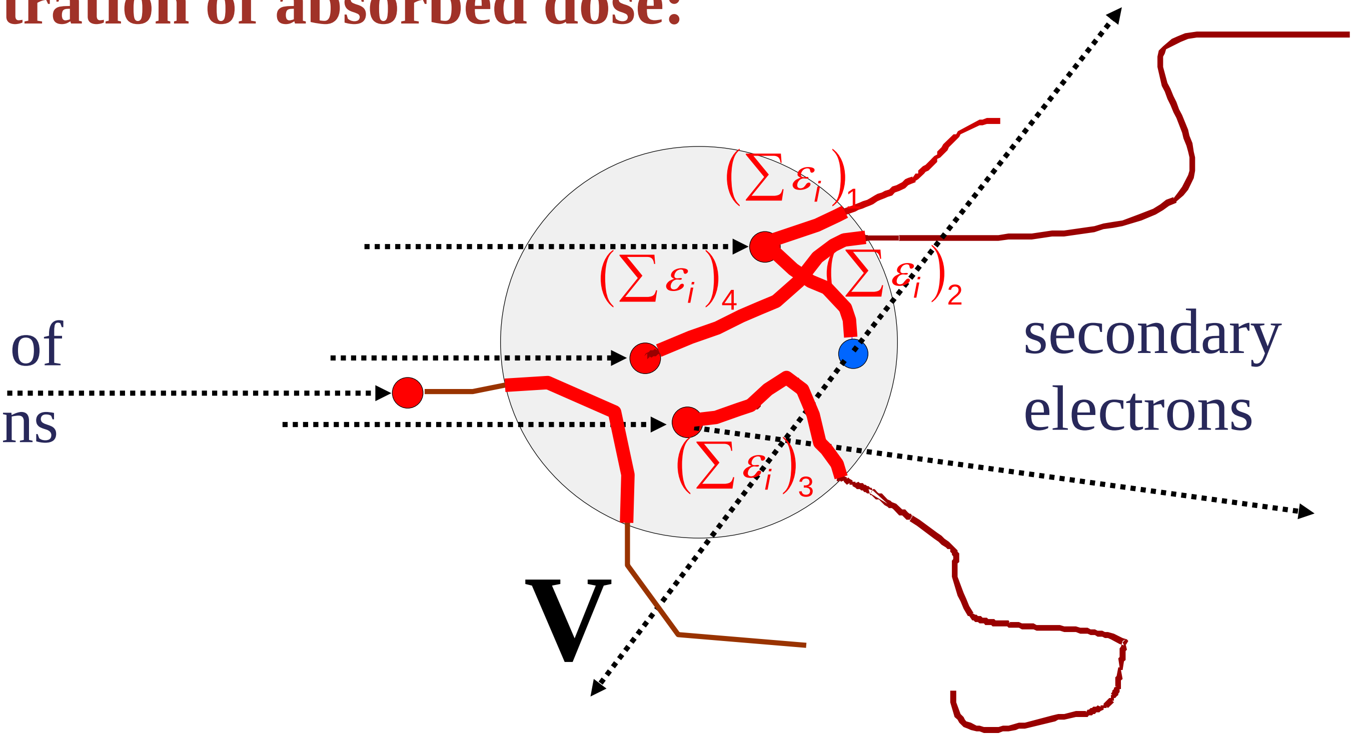
$$K = \frac{\mathrm{d}E_{\mathrm{tr}}}{\mathrm{d}m} .$$

Unit: $\mathrm{J\,kg^{-1}}$

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

Difference between absorbed dose and Kerma

Illustration of absorbed dose:



beam of photons

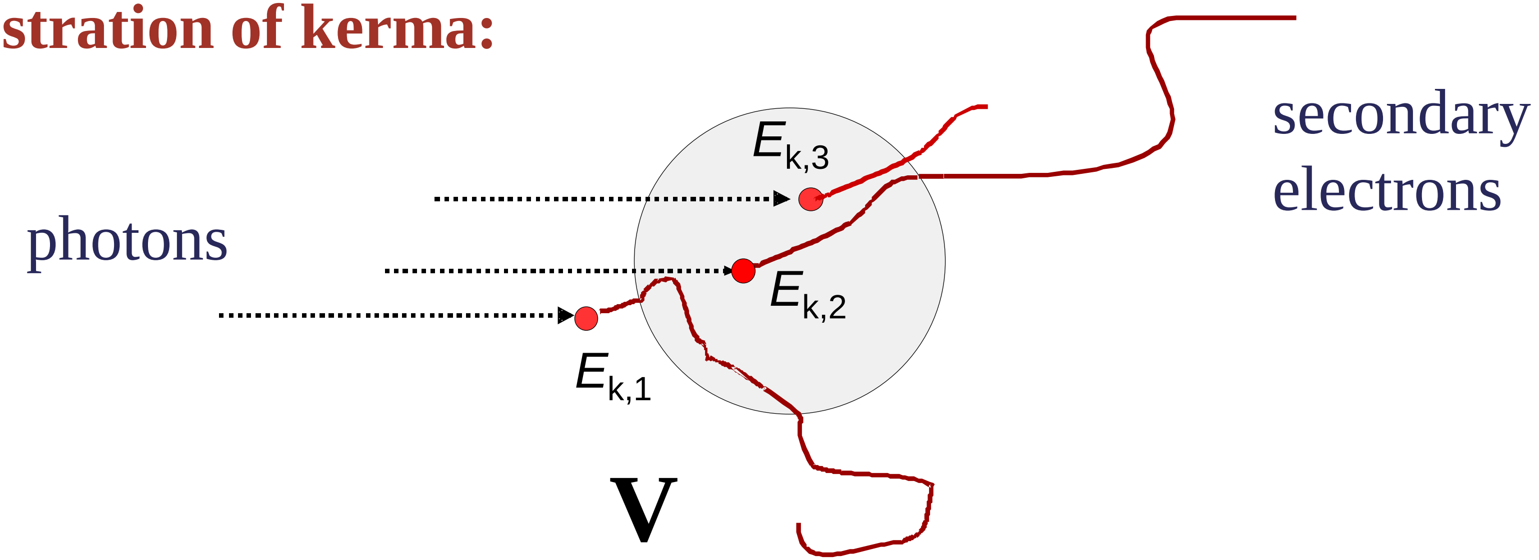
secondary electrons

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

energy absorbed in the volume = $\left(\sum \varepsilon_i\right)_1 + \left(\sum \varepsilon_i\right)_2 + \left(\sum \varepsilon_i\right)_3 + \left(\sum \varepsilon_i\right)_4$

Kerma

Illustration of kerma:



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

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

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!

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

$$\left.\begin{array}{ll}\text{Terma} & \boxed{\int \Phi_{\mathrm{E}} \cdot \left(\frac{E\mu}{\rho}\right) \cdot \mathrm{dE} \qquad \left[\frac{\mathrm{J}}{\mathrm{kg}}\right]} \\[2em] \text{Kerma} & \boxed{\int \Phi_{\mathrm{E}} \cdot \left(\frac{E\mu_{tr}}{\rho}\right) \cdot \mathrm{dE} \qquad \left[\frac{\mathrm{J}}{\mathrm{kg}}\right]} \\[2em] \text{Collision Kerma} & \boxed{\int \Phi_{\mathrm{E}} \cdot \left(\frac{E\mu_{en}}{\rho}\right) \cdot \mathrm{dE} \qquad \left[\frac{\mathrm{J}}{\mathrm{kg}}\right]} \end{array}\right\} \text{for photons}$$

A further difference between absorbed dose and KERMA

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

KERMA is a dosimetrical quantity which cannot be measured but calculated only (based on the knowledge of photon fluence differential in energy).

Therefore, the Kerma concept plays a fundamental role in dose calculations for treatment planning in which the photon fluence and its changes are frequently considered.

The second important term is that of the **response** of a detector.

This term applies to any detector.

Response *R* is defined as:

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

The response can be factorized into two components:

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

where $\overline{D}_{det}$ is the mean dose absorbed in the entire extended sensitive detector volume

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

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

This formula can be interpreted such that there are two separate physical processes involved in the response of a detector:

$\frac{M}{\bar{D}_{det}}$	is addressing the process of how an absorbed dose in the detector is converted into a measurable signal. It is called the intrinsic response R_{int}.
$\frac{\bar{D}_{det}}{D_w}$	is addressing the difference of energy absorption between that at the point of measurement and that in the sensitive volume of the detector. Its reciprocal value is the already known dose conversion factor denoted with the symbol f.

We can use these equations to express relative dose measurements by:

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

This equation can answer the question:
Is it allowed for relative dosimetry to use the signal ratio only?

For most of detectors the intrinsic response does not depend on the measuring conditions. Its ratio therefore is 1.0.

However, *f* does change with measuring conditions different from the reference condition.

Therefore, relative measurements cannot simply performed by using the signal ratio. Instead of, we must consider the dose conversion *f* in detail.

Using the cema concept one can express the dose conversion factor *f* as:

$$f = \frac{cema_{water}}{cema_{det}} \cdot \frac{cema_{det}}{\overline{cema}_{det}} = s_{w,det}^{SA} \cdot \frac{cema_{det}}{\overline{cema}_{det}}$$

where

$cema_{det}$	is the detector cema at the point of measurement in water
$\overline{cema}_{det}$	is the mean detector cema in the sensitive volume of the detector

This means for **any detector, for any measuring condition 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 $p = cema_{det} / \overline{cema}_{det}$

Conclusion for the conversion from *D*$_{\text{det}}$ to *D*$_{\text{w}}$ which is the key problem for any measurement of absorbed dose with an detector

1. The Spencer Attix stopping power ratio can and must be used for any detector
2. There is a formula for the perturbation factor available

There are only the following restrictions:

- This formula applies to photons (and probably to electrons?)
- Photon energy should be larger than 0.5 MeV
- Intrinsic response should not change with measuring conditions