The Abdus Salam International Centre for Theoretical Physics
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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, 27 March - 7 April 2017

Dosimetry: Fundamentals

G. Hartmann
German Cancer Research Center (DKFZ) & EFOMP
g.hartmann@dkfz.de

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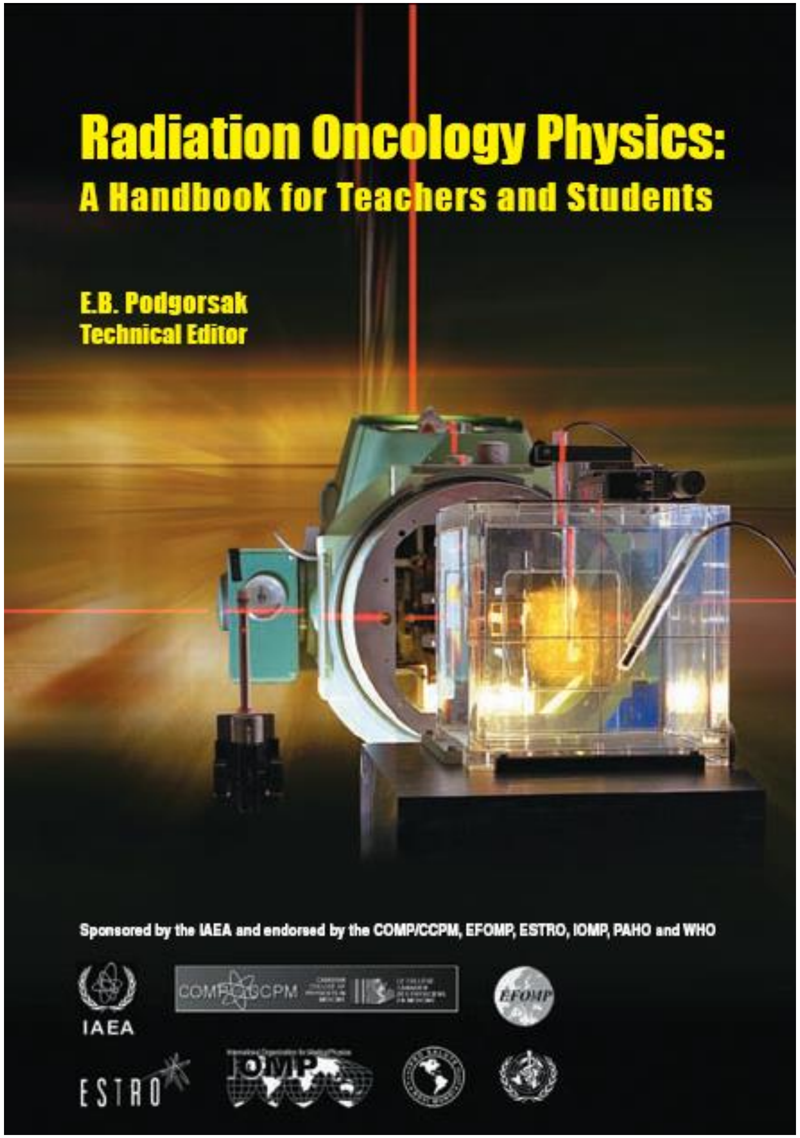
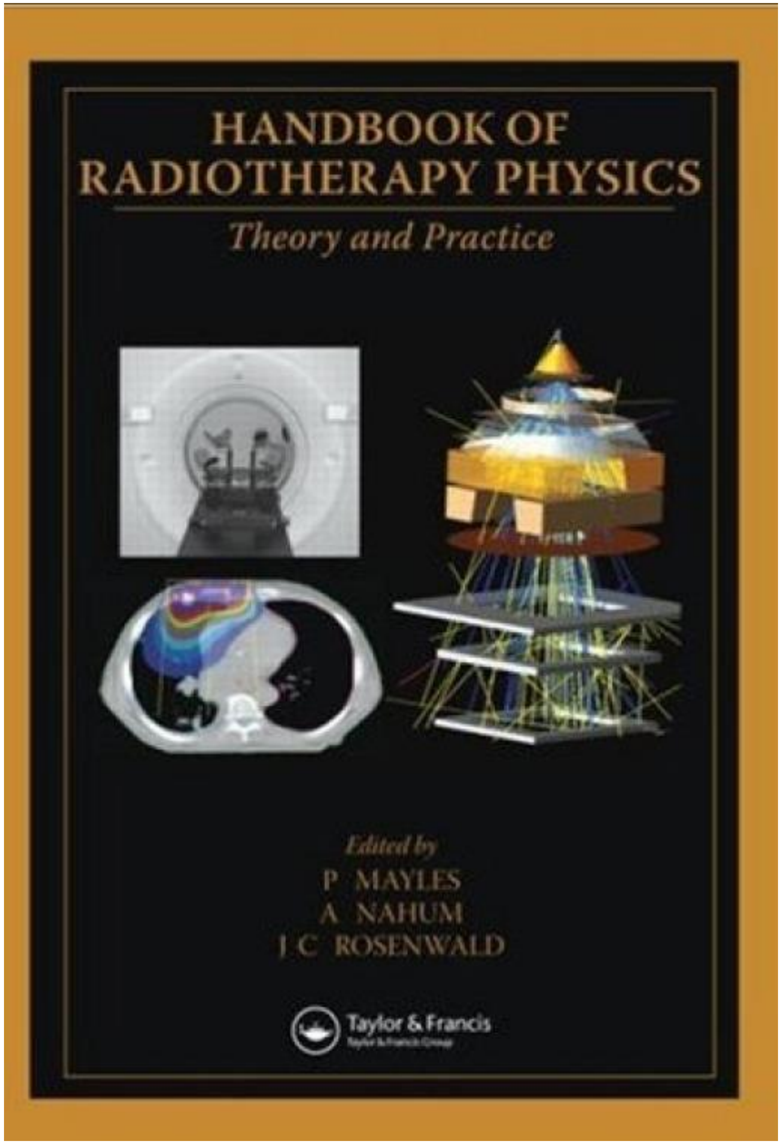
(1) Introduction: Definition of "radiation dose"

(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

This lesson is partly based on:





1. Introduction

Exact physical meaning of "dose of radiation"

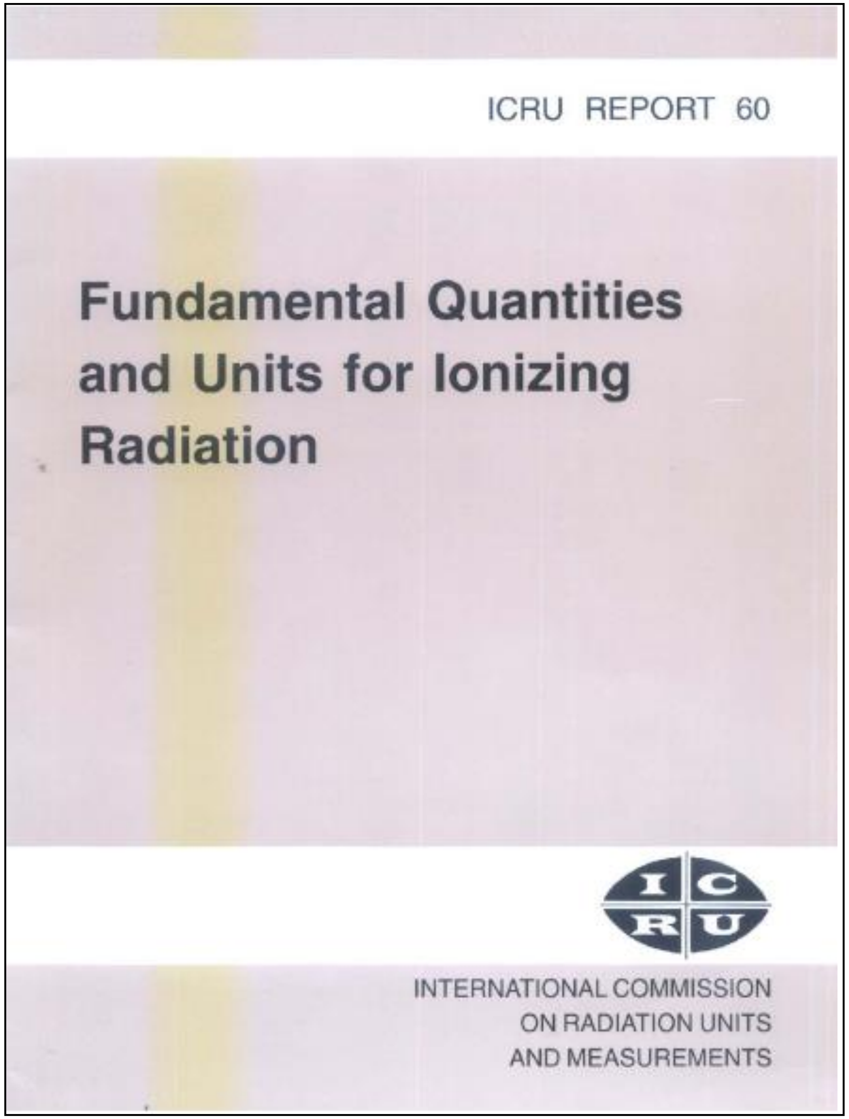
"Dose" is a sloppy expression to denote the dose of radiation and should be used only if your communication partner really knows its meaning.

A dose of radiation is correctly expressed by the term and, at the same time, the physical quantity of **absorbed dose,** *D*.

The most fundamental definition of the absorbed dose *D* is given in Report ICRU 85a

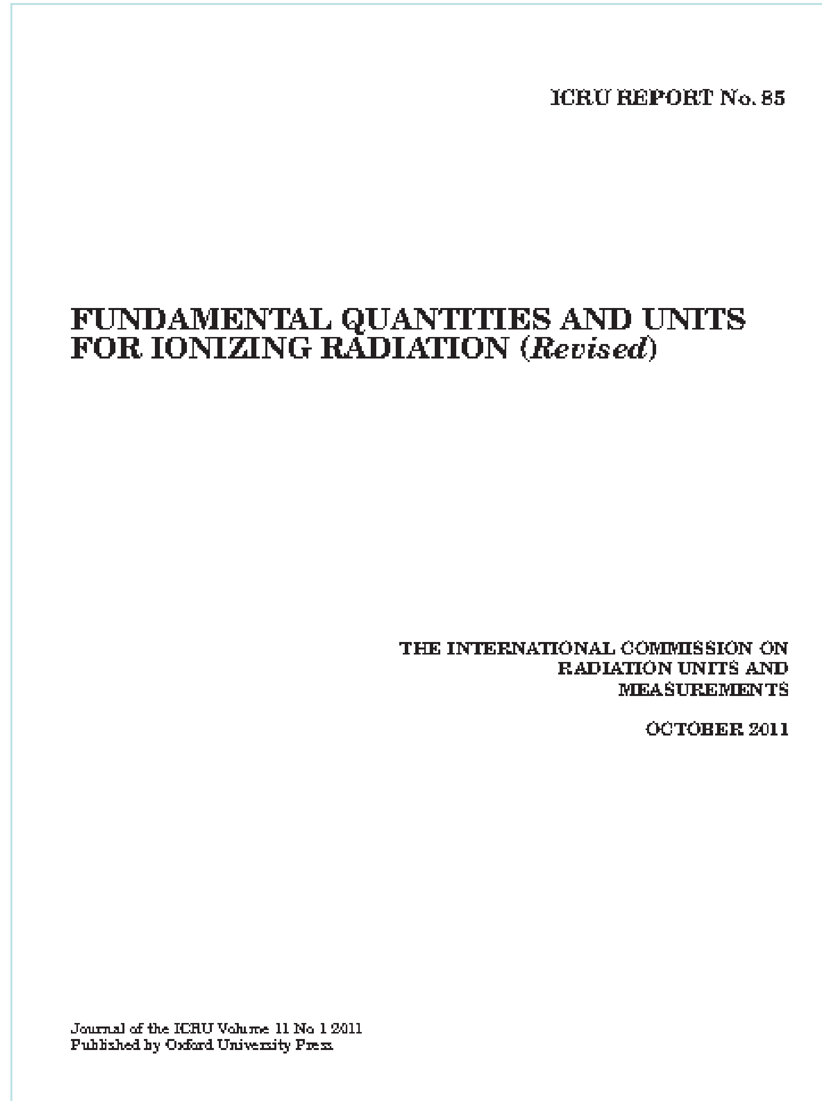
1. Introduction

Exact physical meaning of "dose of radiation"


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:

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

where $d\bar{\varepsilon}$ is the mean energy imparted to matter of mass

dm is a small element of mass

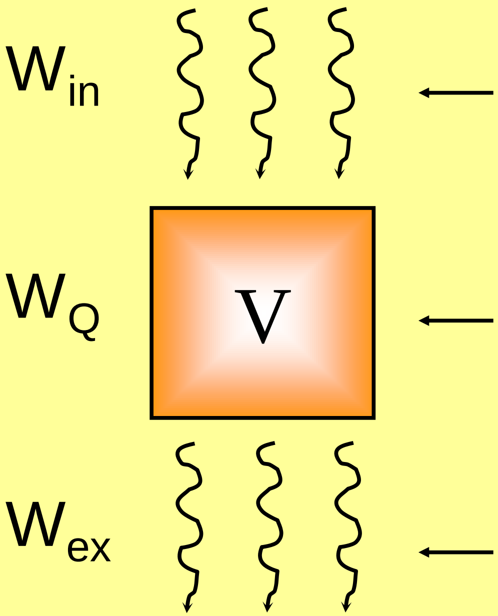
- The unit of absorbed dose is Joule per Kilogram (J/kg), the special name for this unit is Gray (Gy).

1. Introduction

Exact physical meaning of "dose of radiation"

- 4 characteristics of absorbed dose:

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



Energy coming in (electrons, photons)

Interactions + elementary particle processes (pairproduction, annihilation, nuclear reactions, radioaktive decay)

Energy going out

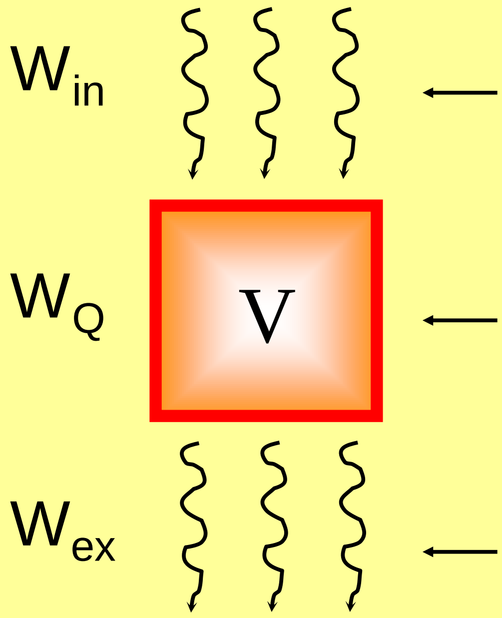
$$\text{Energy absorbed} = W_{in} - W_{ex} + W_Q$$

1. Introduction

Exact physical meaning of "dose of radiation"

- Four characteristics of absorbed dose :

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



Energy coming in (electrons, photons)

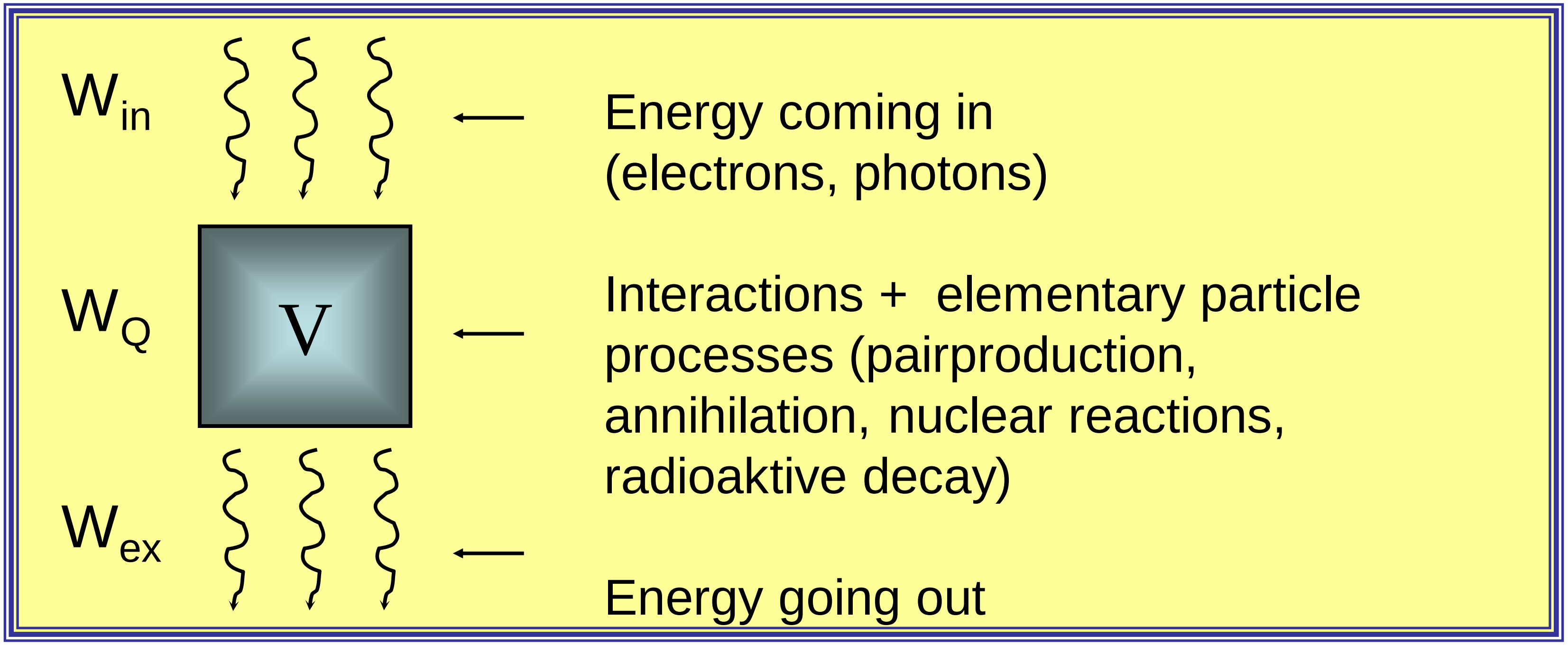
Interactions + elementary particle processes (pairproduction, annihilation, nuclear reactions, radioaktive decay)

Energy going out

1. Introduction

Exact physical meaning of "dose of radiation"

- Four characteristics of absorbed dose :
  - (3) The term "**absorbed dose**" refers to the material of the volume :



= air: D_{air}

= water: D_{water}

1. Introduction

Exact physical meaning of "dose of radiation"

- Four characteristics of absorbed dose:

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

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

This is associated with:

(a) D is steadily in space and time

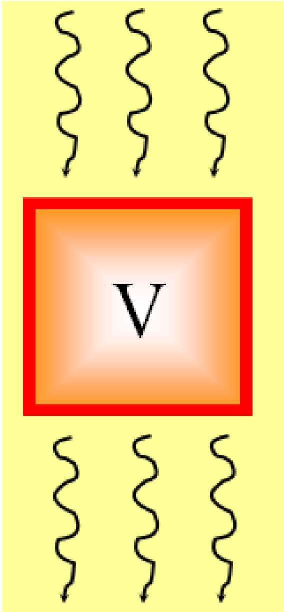
(b) D can be differentiated in space and time

This last statement on absorbed dose:

"absorbed dose is a macroscopic quantity that refers to a mathematical **point in space,** $\vec{r}$ "

seems to be a contradiction to:

“The term absorbed dose refers to an exactly defined **volume**”



We need a closer look into:

What is happening in an irradiated volume?

In particular, facing our initial definition:

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

This question:

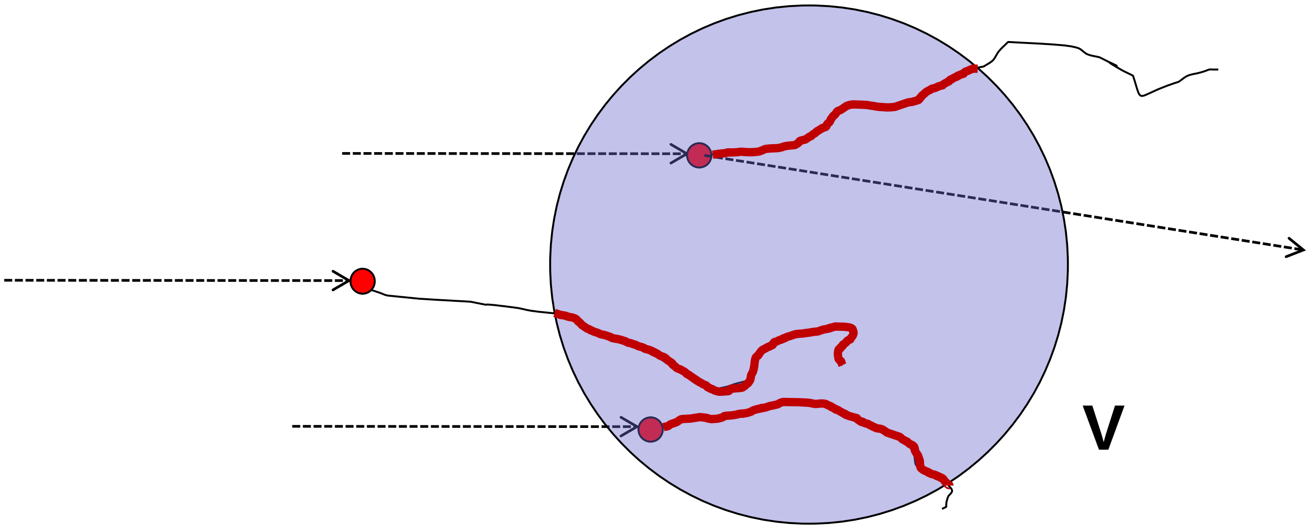
What is happening in a volume

Is synonym to the question, what energy imparted really means !!!

1. Introduction
"Absorbed dose" and "energy imparted"

Definition:

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



1. Introduction

"Absorbed dose" and "energy imparted"

The energy imparted **ε** is the sum of all elemental **energy deposits** by those basic interaction processes which have occurred **in the volume** during a time interval considered:

$$\varepsilon = \sum_i \varepsilon_i$$

energy imparted (ε) energy deposits (ε_i)

1. Introduction

"Absorbed dose" and "energy imparted"

Now we need a definition of an **energy deposit** (symbol: ε_i).

The **energy deposit** is the elemental absorption of radiation energy as

$$\varepsilon_i = \varepsilon_{in} - \varepsilon_{out} + Q$$

Unit: J

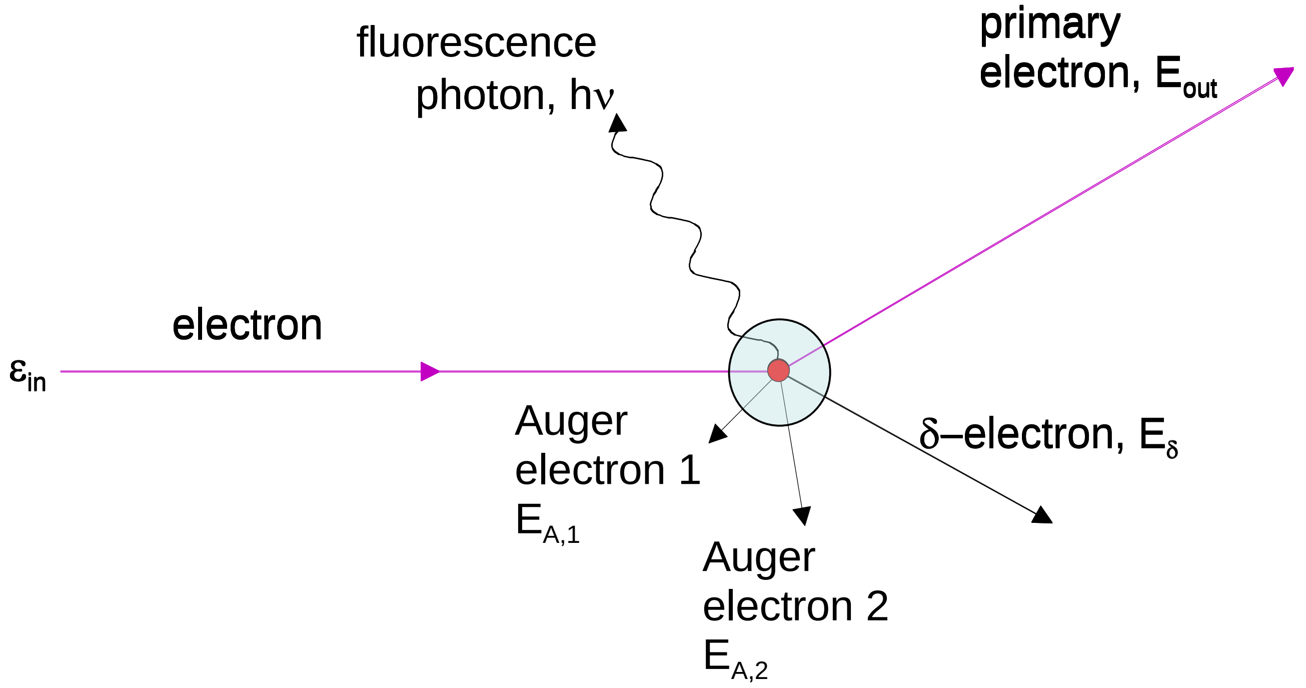
in a single interaction process.

- Three examples will be given for that:
  - electron knock-on interaction
  - pair production
  - positron annihilation

1. Introduction

"Absorbed dose" and "energy imparted"

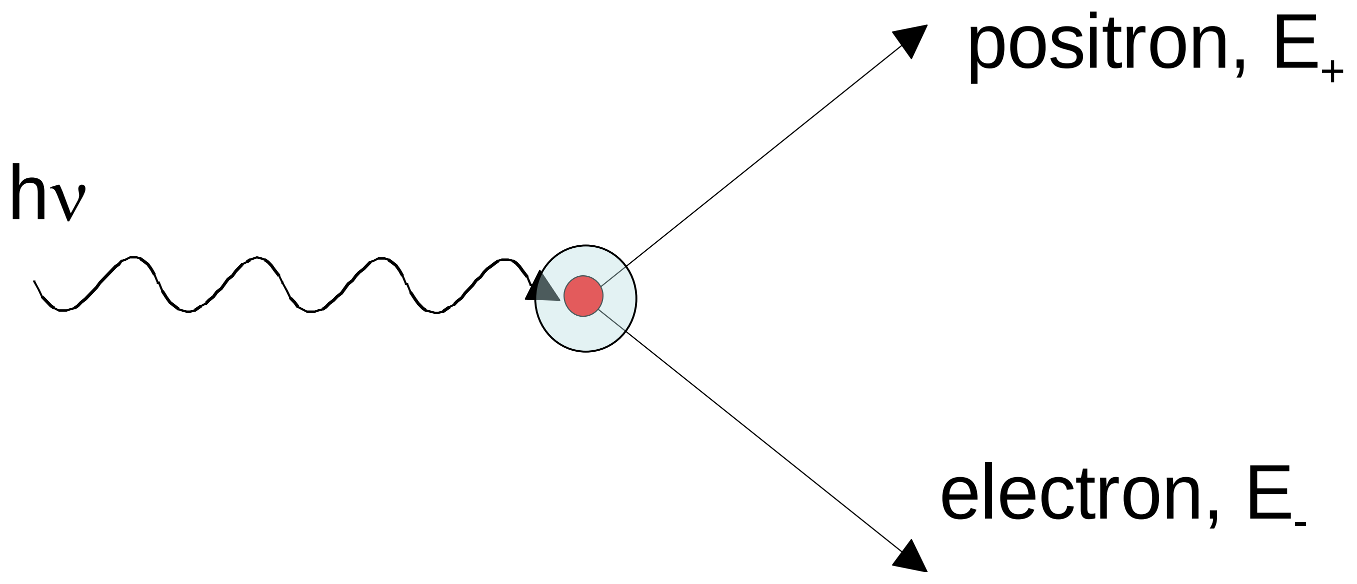
Energy deposit ε_i by electron knock-on interaction:



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

1. Introduction
"Absorbed dose" and "energy imparted"

Energy deposit ε_i by pair production:



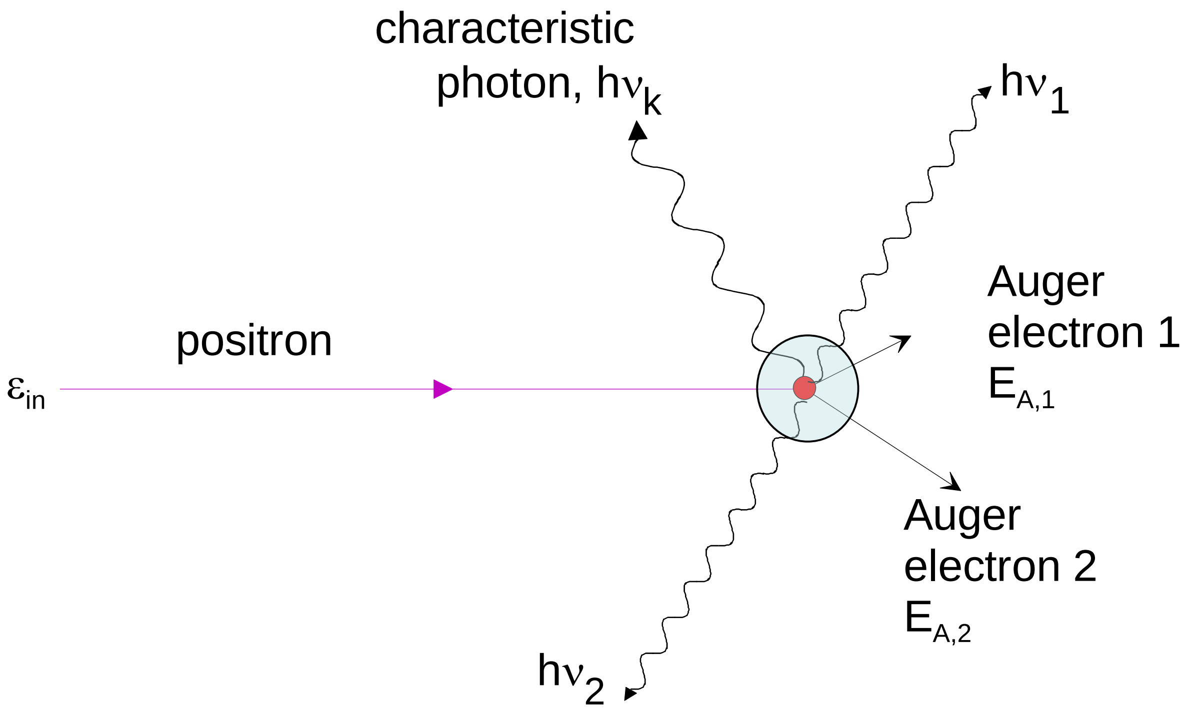
Note: **The rest energy of the positron and electron is also escaping!**

$$\varepsilon_i = h\nu - (E_+ + E_-) - 2m_0c^2$$

1. Introduction
"Absorbed dose" and "energy imparted"

Energy deposit ε_i by positron annihilation:

Note: The rest energies have to be added !



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

1. Introduction
Energy imparted and energy deposit

- The energy deposit ε_i is the energy deposited in a single interaction *i*

$$\varepsilon_i = \varepsilon_{in} - \varepsilon_{out} + Q$$ Unit: J

where

ε_{in} = the energy of the incident ionizing particle (excluding rest energy)

ε_{out} = the sum of energies of all ionizing particles leaving the interaction (excluding rest energy),

Q = is the change in the rest energies of the nucleus and of all particles involved in the interaction.

1. Introduction
Energy imparted and energy deposit

Application to dosimetry:

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

$$M \propto \varepsilon = \sum_i \varepsilon_i$$

Intrinsic detector response: $$R_{int} = \frac{M}{\varepsilon}$$

1. Introduction

Stochastic of energy deposit events

By nature, a single energy deposit ε_i is a stochastic quantity.

$$\varepsilon = \sum_i \varepsilon_i$$

It follows:
energy imparted is **also** a stochastic quantity:

energy imparted (ε)

energy deposits (ε_i)

That means with respect to repeated measurements of energy imparted:

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

As a consequence we can observe the following:

Shown below is the value of (**ε/**m**)** as a function of the size of the mass m (in logarithmic scaling)

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

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:

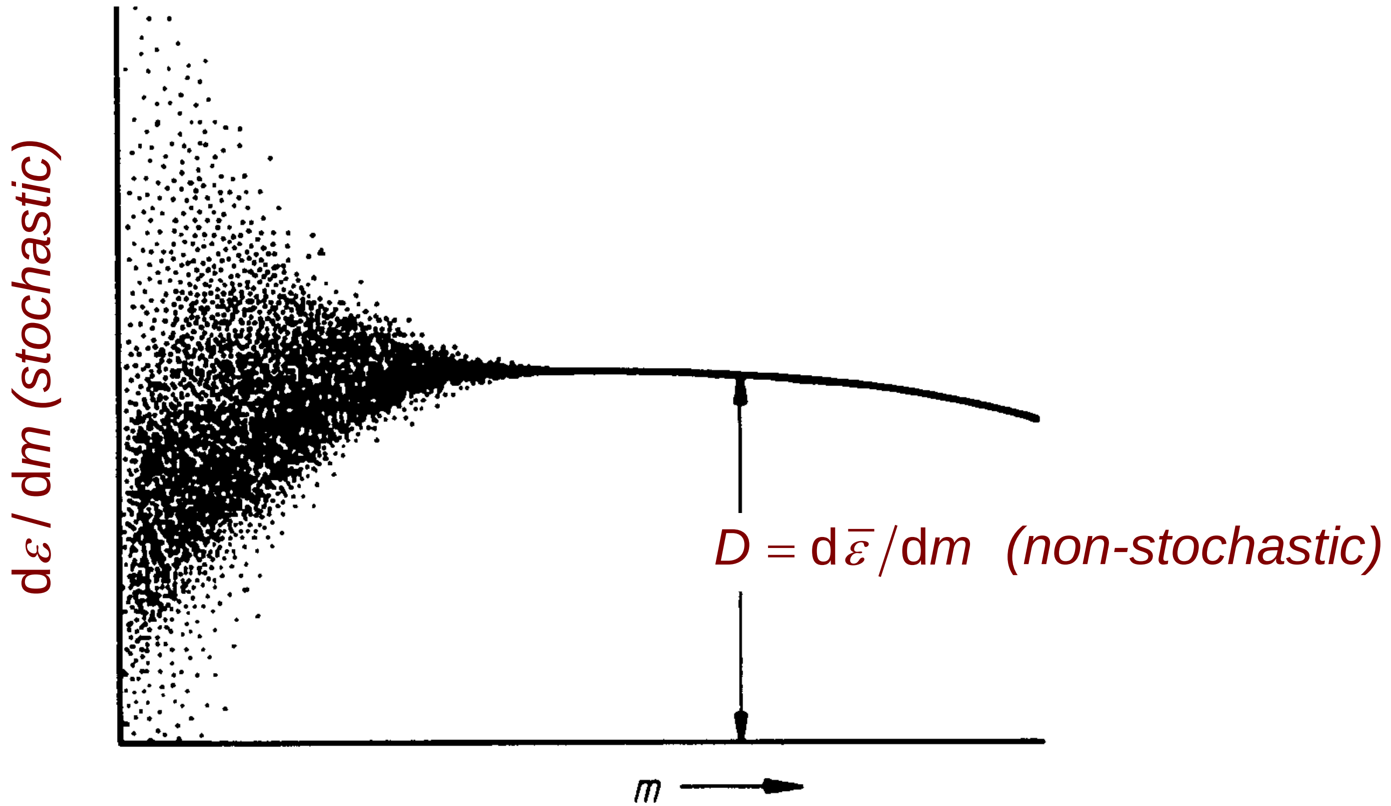
$$D = \frac{d\bar{\varepsilon}}{dm}$$

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

dm is a small element of mass

The difference between energy imparted and absorbed dose

- The energy imparted ε is a **stochastic quantity**
- The absorbed dose *D* is a **non-stochastic quantity**



1. Introduction

What is meant by "radiation dose"

- Often, the definition of absorbed dose is expressed in a simplified manner as:

$$D = \frac{\mathrm{d}E}{\mathrm{d}m}$$

- But remember:
  The correct definition of absorbed dose *D* as being a non-stochastic quantity is:

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

Now we should have a more precise idea of what is meant with the expression: a dose of radiation.

However, there are also further dose quantities which are frequently used.

One important example is the **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

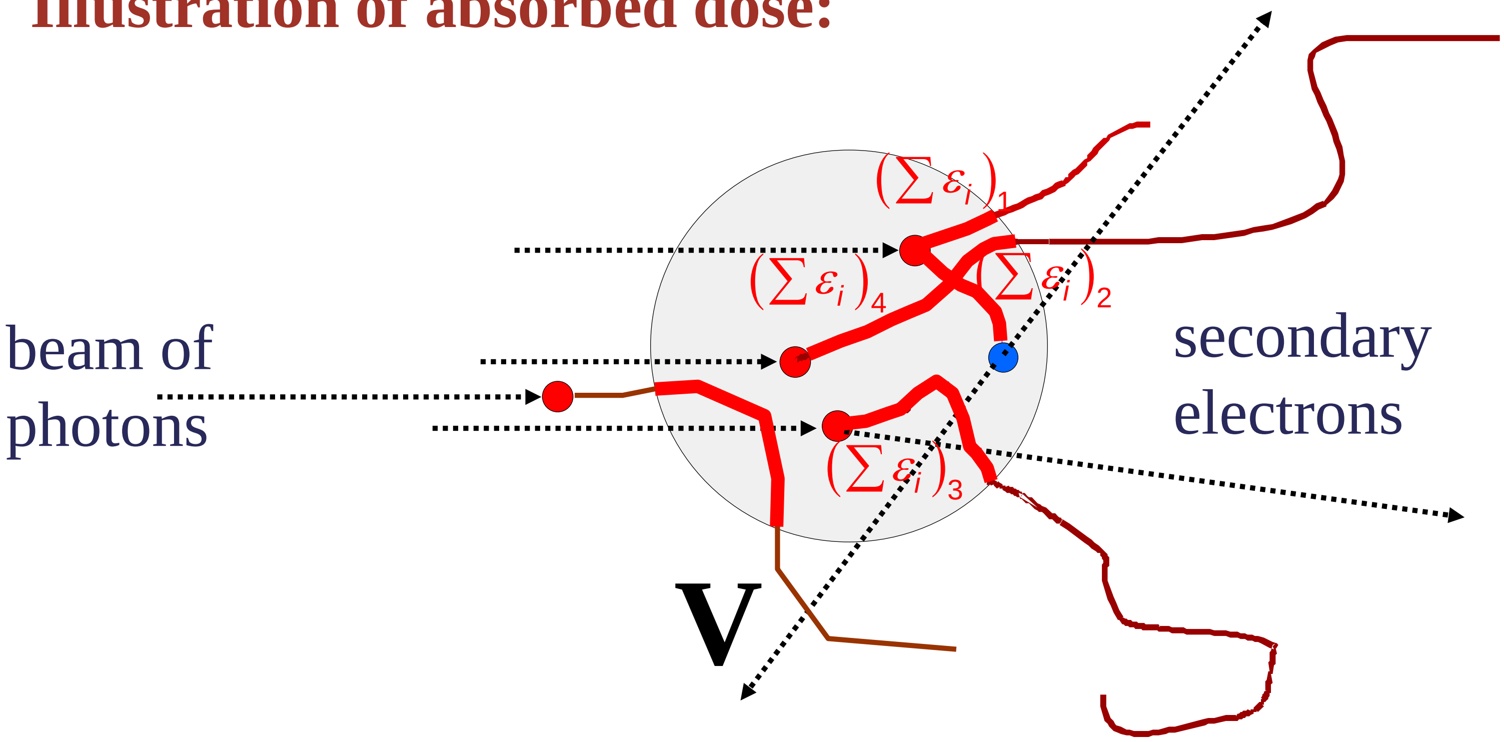
$$K = \frac{dE_{tr}}{dm}.$$

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

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

Absorbed dose

Illustration of absorbed dose:

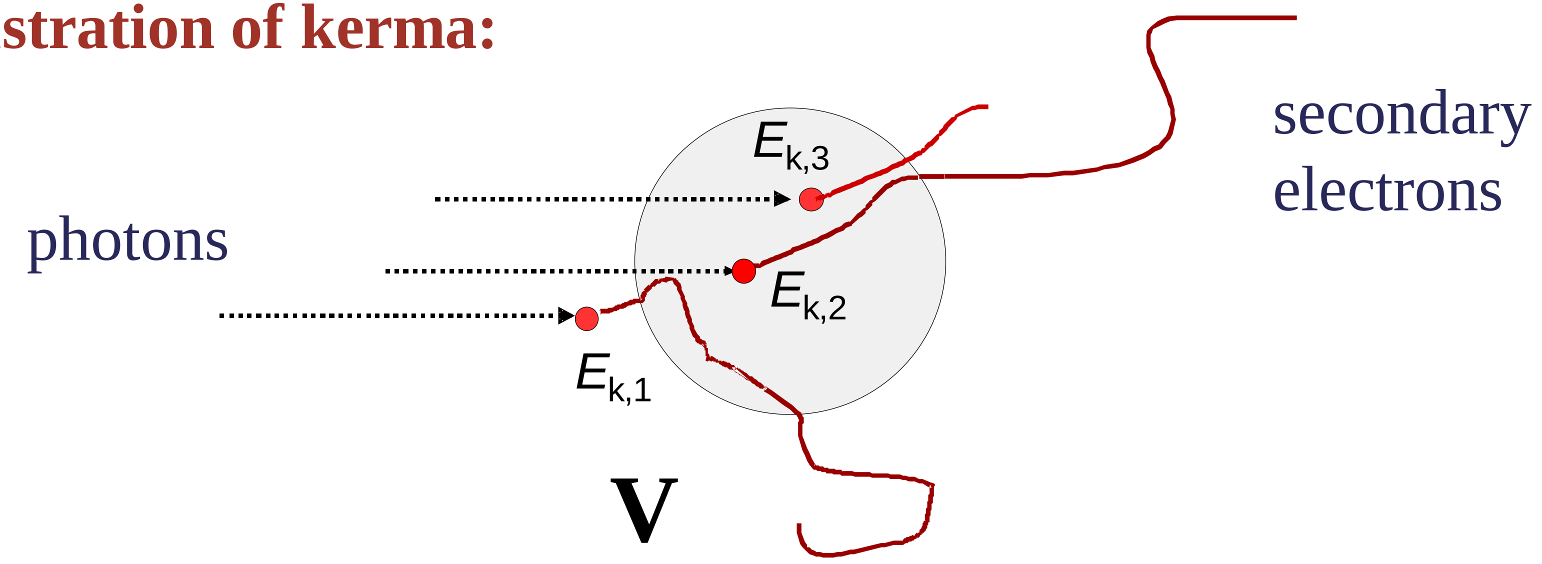


$(\sum \varepsilon_i)$ is the sum of energy losts by collisions along the track of the secondary particles **within the volume V**.

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

Kerma

Illustration of kerma:



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

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

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:

Terma	$\int \Phi_E \cdot \left(\frac{E\mu}{\rho}\right) \cdot dE \quad \left[\frac{J}{kg}\right]$	for photons
Kerma	$\int \Phi_E \cdot \left(\frac{E\mu_{tr}}{\rho}\right) \cdot dE \quad \left[\frac{J}{kg}\right]$	for photons
Collision Kerma	$\int \Phi_E \cdot \left(\frac{E\mu_{en}}{\rho}\right) \cdot dE \quad \left[\frac{J}{kg}\right]$	for photons
Cema	$\int \varphi_E^{el} \cdot \left(\frac{S}{\rho}\right) dE$	for electrons

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 only calculated !

(based on the knowledge of photon fluence differential in energy)

Absorbed dose from charged particle:

This requires the introduction of the concept of stopping power

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

Stopping Power and Mass Stopping Power

The mass stopping power can be expressed as a sum of independent components by

$$\frac{S}{\rho} = \frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{el}} + \frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{rad}} + \frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{nuc}}, \qquad (4.4.1)$$

$\frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{el}} = \frac{1}{\rho}S_{\mathrm{el}}$ 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 **stopping power, i.e.** the energy lost of electrons is such an important concept in dosimetry?

Answer 1: The energy lost is at the same time the energy absorbed

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

Absorbed dose of charged particles is approximately equal to CEMA.
Exact definition of CEMA:
(CEMA = C onverted E nergy per Ma ss)

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

$$C = \frac{dE_{el}}{dm}. \quad = \int \Phi_E(E) \frac{S_{el}}{\rho} dE$$

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

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

Summary: Energy absorption and absorbed dose

absorbed dose

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

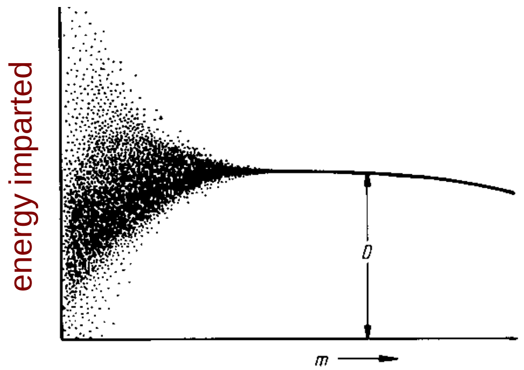
energy imparted

$$\varepsilon = \sum_i \varepsilon_i$$

energy deposit

$$\varepsilon_i = \varepsilon_{in} - \varepsilon_{out} + Q$$

stochastic character of energy absorption



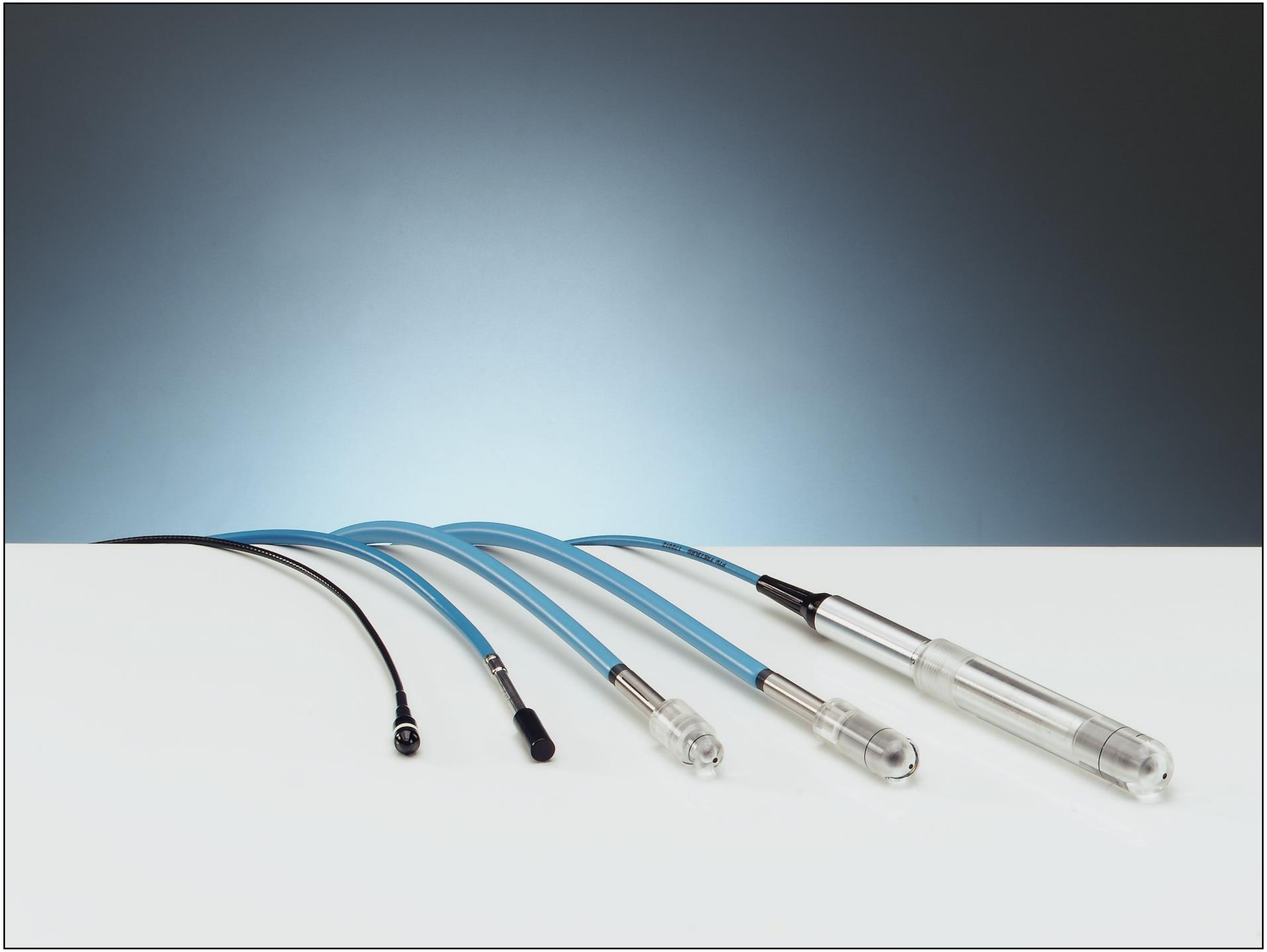
2. General methods of dose measurement

- Absorbed dose is measured with a (radiation) **dosimeter**

- The four most commonly used radiation dosimeters are:
    - **Ionization chambers**
    - **Radiographic films**
    - **TLDs**
    - **Diodes**

2. General methods of dose measurement:

Ionization chambers



2. General methods of dose measurement: Ionization chambers

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

2. General methods of dose measurement:
Film

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

2. General methods of dose measurement:

Radiochromic film

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

2. General methods of dose measurement: Thermo-Luminescence-Dosimeter (TLD)

Advantage	Disadvantage
❑ 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	❑ 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

2. General methods of dose measurement: Diode

Advantage	Disadvantage
❑ Small size ❑ High sensitivity ❑ Instant readout ❑ No external bias voltage ❑ Simple instrumentation ❑ Good to measure relative distributions!	❑ Requires connecting cables ❑ Variability of calibration with temperature ❑ Change in sensitivity with accumulated dose ❑ Special care needed to ensure constancy of response ❑ Should not be used for beam calibration

3. Some principles of dosimetry with ionization chambers

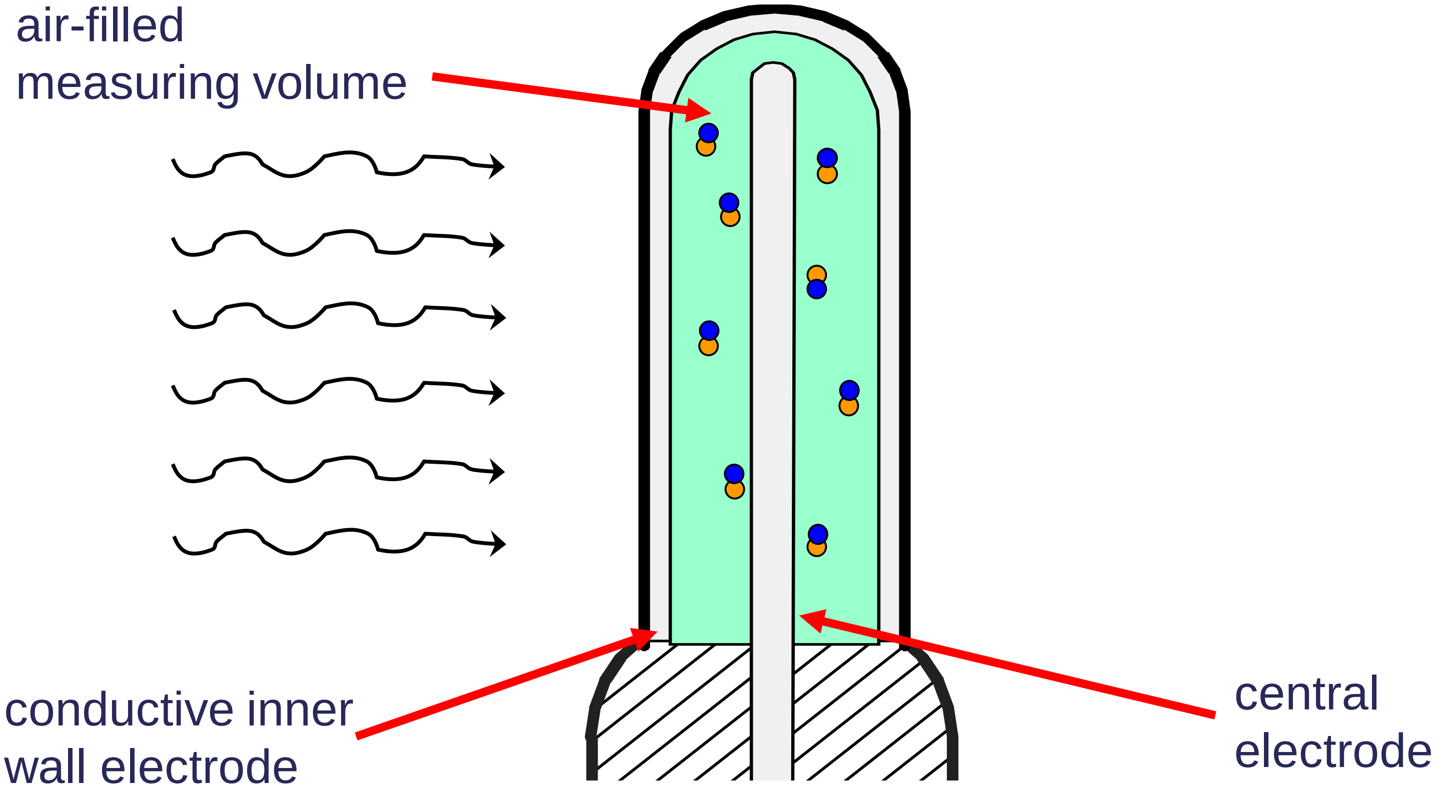
Ionization

- Measurement of absorbed dose requires the measurement of the mean energy imparted in small volume by various interaction processes.
- Such interaction processes normally result in the creation of ion pairs.

3. Some principles of dosimetry with ionization chambers

Ionization

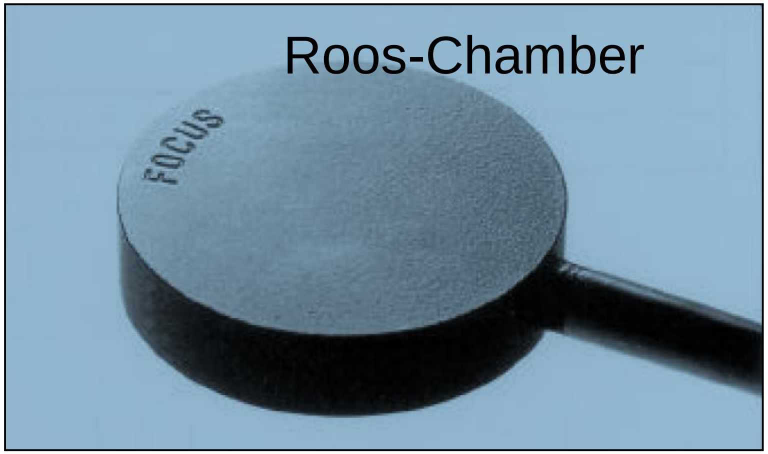
- Example: Creation of charge carriers in an ionization chamber



3. Some principles of dosimetry with ionization chambers

Ionization

- 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 practizing physicists have a thorough knowledge of the characteristics of ionization chambers.**

3. Some principles of dosimetry with ionization chambers

Ionization chambers

The Ionization chamber is the most practical and most widely used type of dosimeter for accurate measurement of machine output in radiotherapy.

It may be used as an absolute or relative dosimeter.

Its sensitive volume is usually filled with ambient air and:

- The dose related measured quantity is charge *Q*,
- The dose rate related measured quantity is current *I*,

produced by radiation in the chamber sensitive volume.

3. Some principles of dosimetry with ionization chambers

Absorbed dose in air

- Measured charge Q and sensitive air mass m_{air} are related to absorbed dose in air D_{air} by:

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

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

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

3. Some principles of dosimetry with ionization chambers

Values of $(\overline{W}_{air}/e)$

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

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

  - For air at relative humidity of 50%:

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

  - For dry air:

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

3. Some principles of dosimetry with ionization chambers

Absorbed dose in water

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

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

Next the measured absorbed dose in air of the ionization chamber D_{air} must be converted into absorbed dose in water D_w.

The factor $f = D_w / D_{air}$ is often referred to as

the dose conversion factor

The dose conversion factor depends on several conditions such as:

- type and energy of radiation
- type and volume of the ionization chamber

For the theoretical derivation of the dose conversion factor in clinically applied radiation fields such as:

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

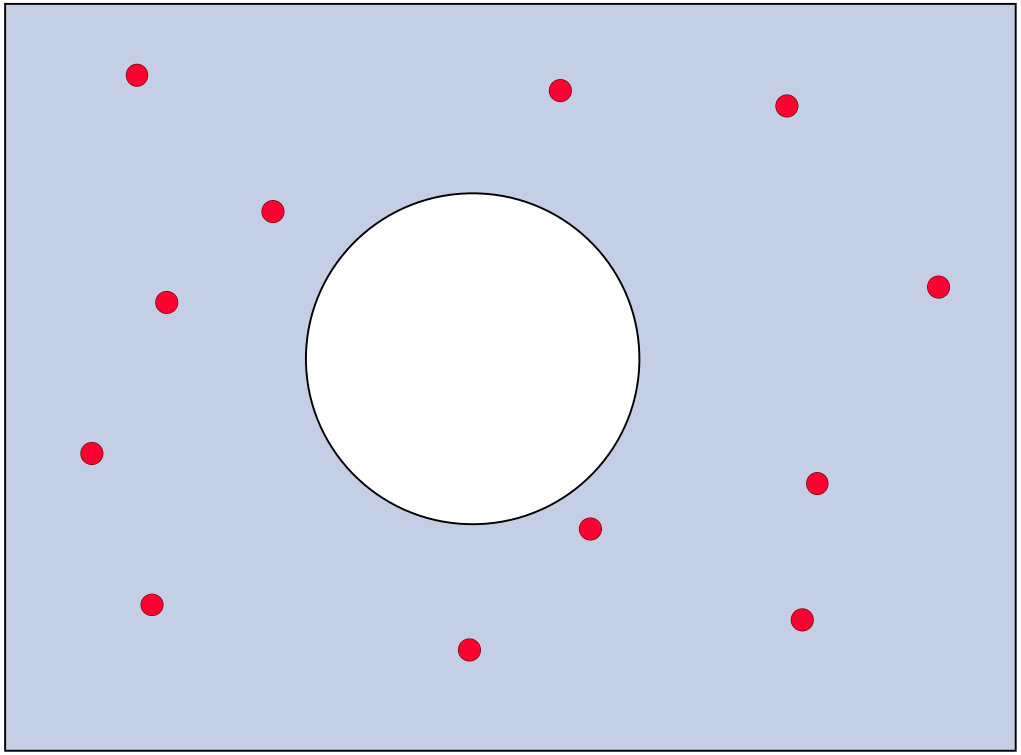
the so-called **Bragg-Gray Cavity Theory** can be applied.

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 primary inter-actions within a radiation field of photons then are photon interactions.

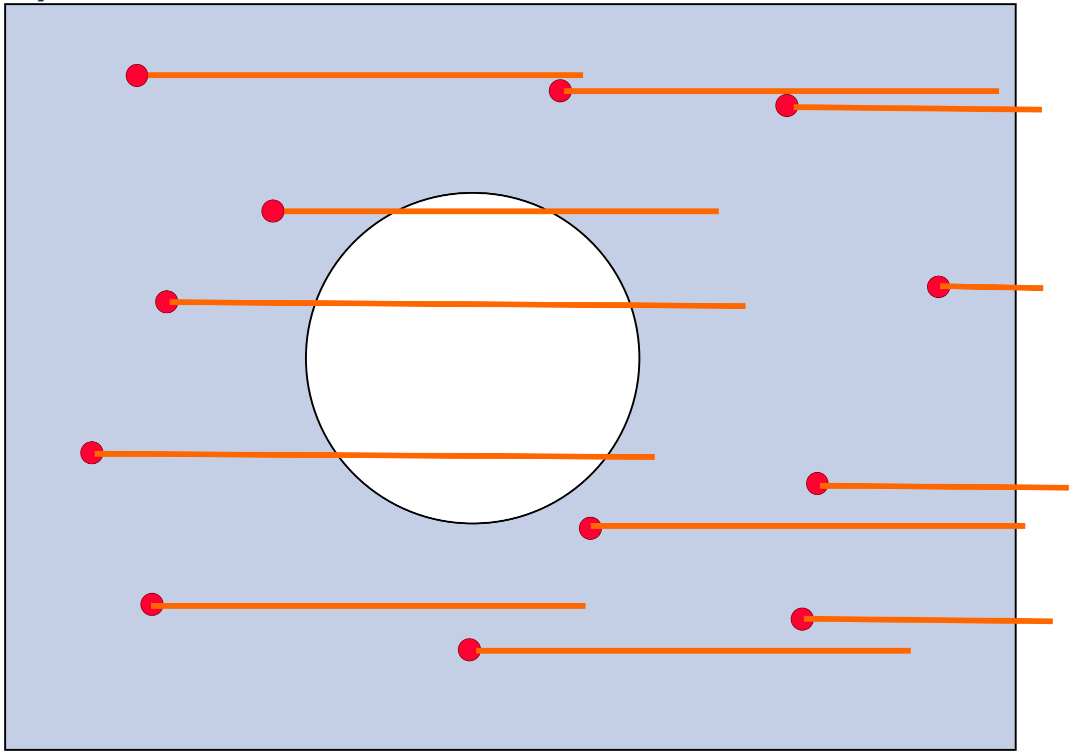


● photon interaction

Note:

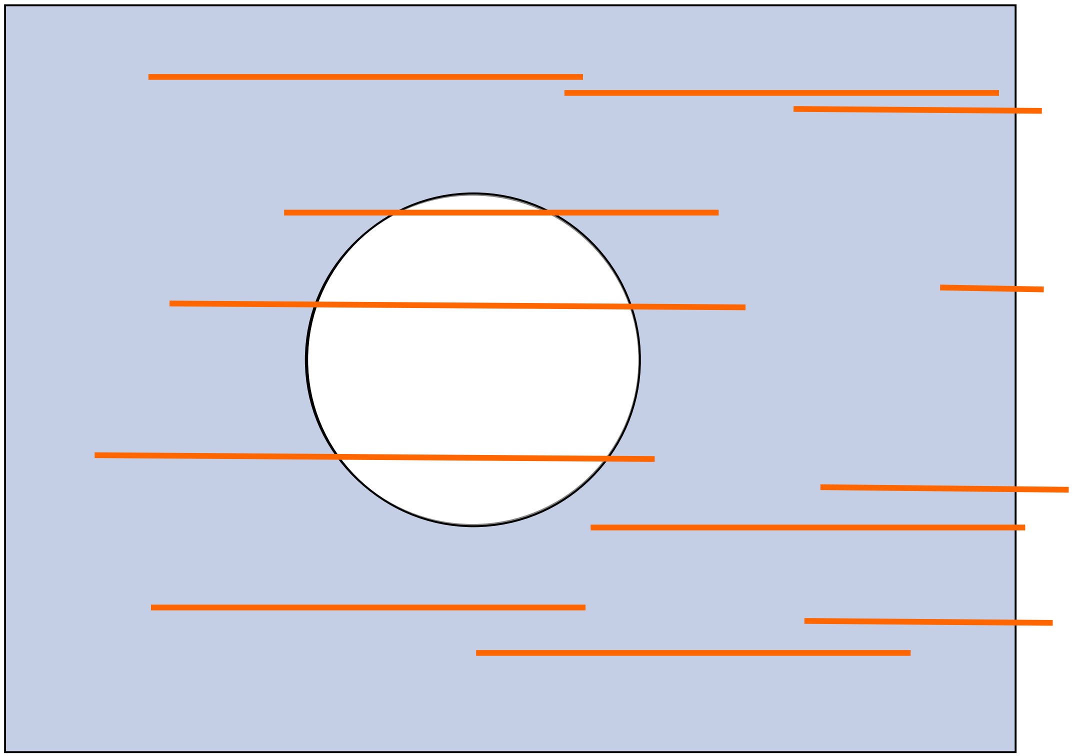
We assume that the number of interactions in the air cavity itself is negligible (due to the ratio of density between air and water)

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



electron track

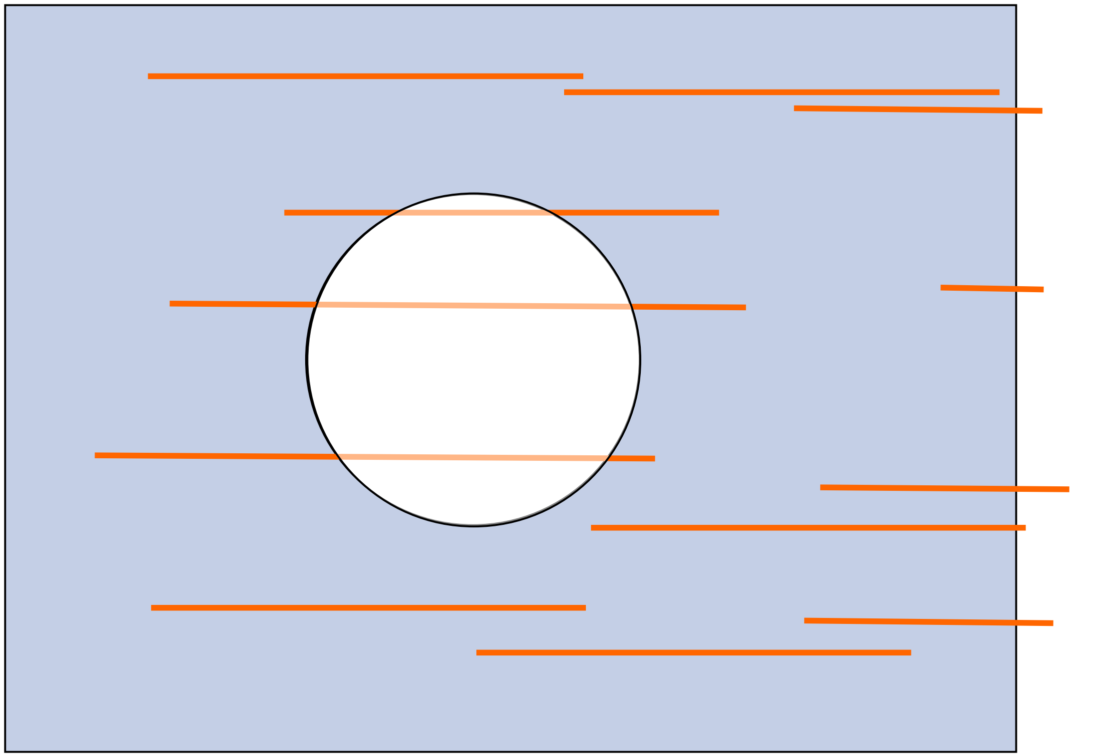
We know: Interactions of the secondary electrons in any medium are characterized by the **stopping power**.



Consequently, the types of interactions
within the air cavity
are exclusively those of electrons characterized by stopping power.

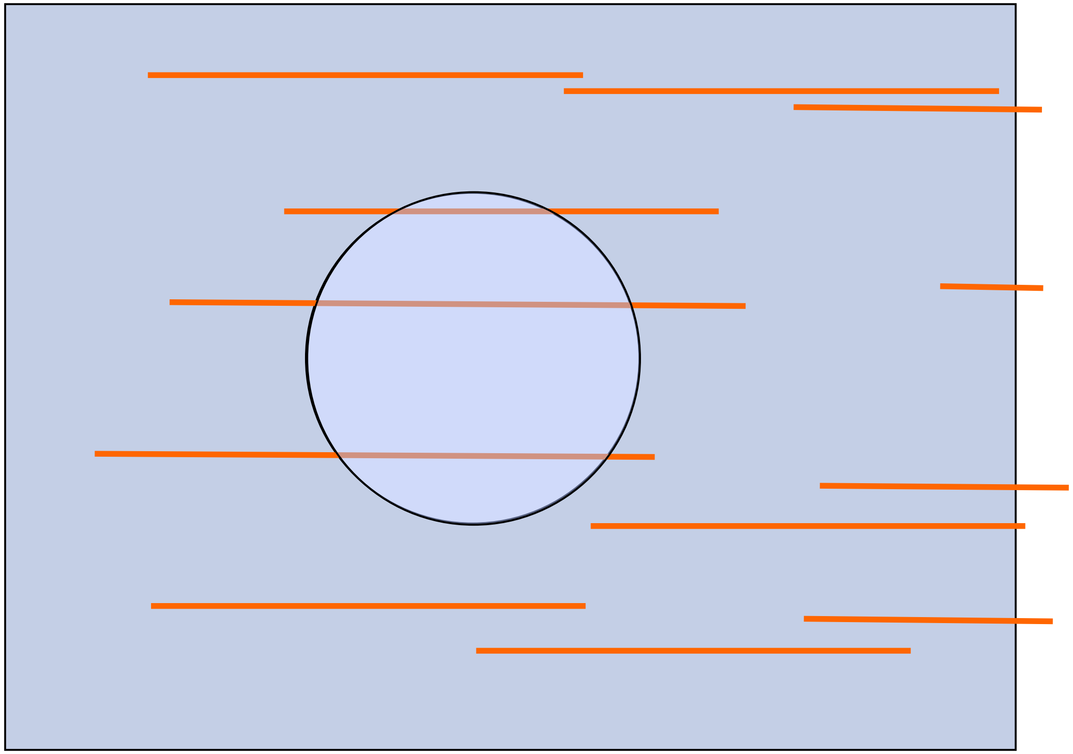
Absorbed dose D in the air can be calculated D as:

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



In water we would have:

$$D_w = \int \Phi_E \cdot \left(\frac{S_{el}}{\rho} \right)_w dE$$



It follows:

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

Introducing a mean mass stopping power as

$$\left(\frac{\overline{S}_{el}}{\rho} \right) = \int \Phi_E \cdot \left(\frac{S_{el}}{\rho} \right) dE \Big/ \Phi$$

one obtains:

$$\boxed{f = \frac{D_w}{D_{air}} = \left(\frac{\overline{S}_{el}}{\rho} \right)_w \Big/ \left(\frac{\overline{S}_{el}}{\rho} \right)_{air}}$$

Summary of the derivation of the equation (Bragg-Gray):

$$f = \frac{D_w}{D_{air}} = \left(\frac{\overline{S}_{el}}{\rho}\right)_w \bigg/ \left(\frac{\overline{S}_{el}}{\rho}\right)_{air}$$

This conversion formula is valid under the two conditions:

1) The cavity must be **small** when compared with the range of charged particles incident on it, so that its presence **does not perturb the fluence** of the electrons in the medium;

2) The absorbed dose in the cavity is deposited **solely by the electrons** crossing it (i.e. photon interactions in the cavity are assumed to be negligible and thus can be ignored).

Conversion of absorbed dose

- These considerations are the essence of the Bragg-Gray theory, and the two conditions are hence called the

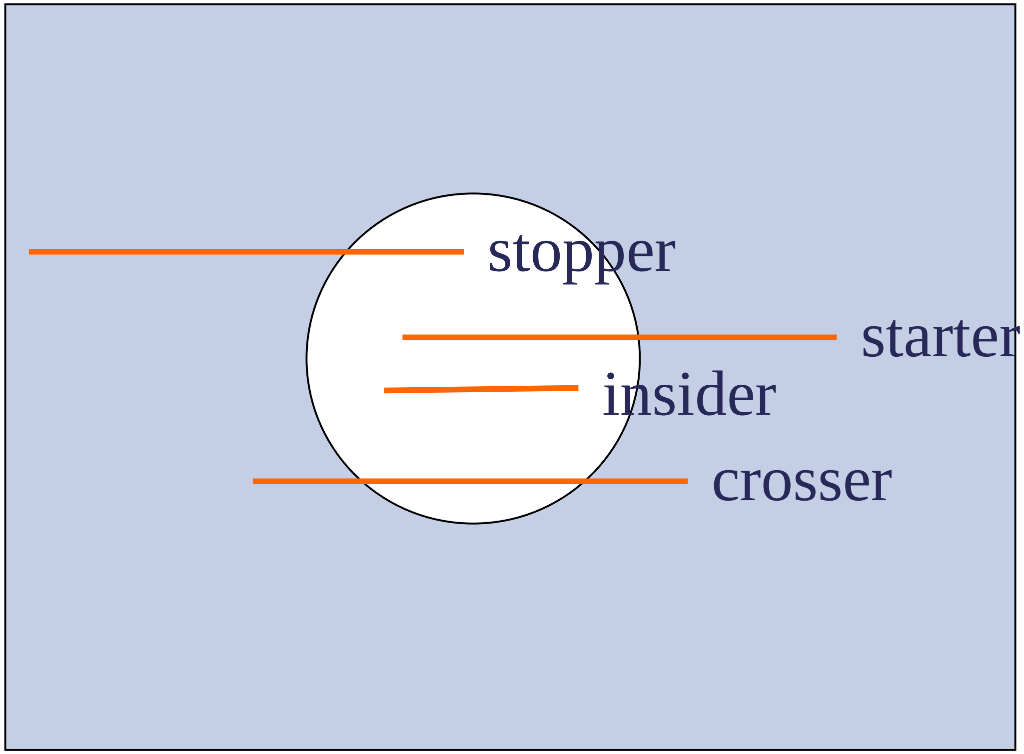
  two Bragg-Gray conditions.

- Thus Bragg-Gray theory provides the most important mean to determine water absorbed dose from a detector measurement which is not made of water:
- If the two Bragg-Gray conditions are fulfilled, the absorbed dose in water can be obtained by the absorbed dose measured in the detector using

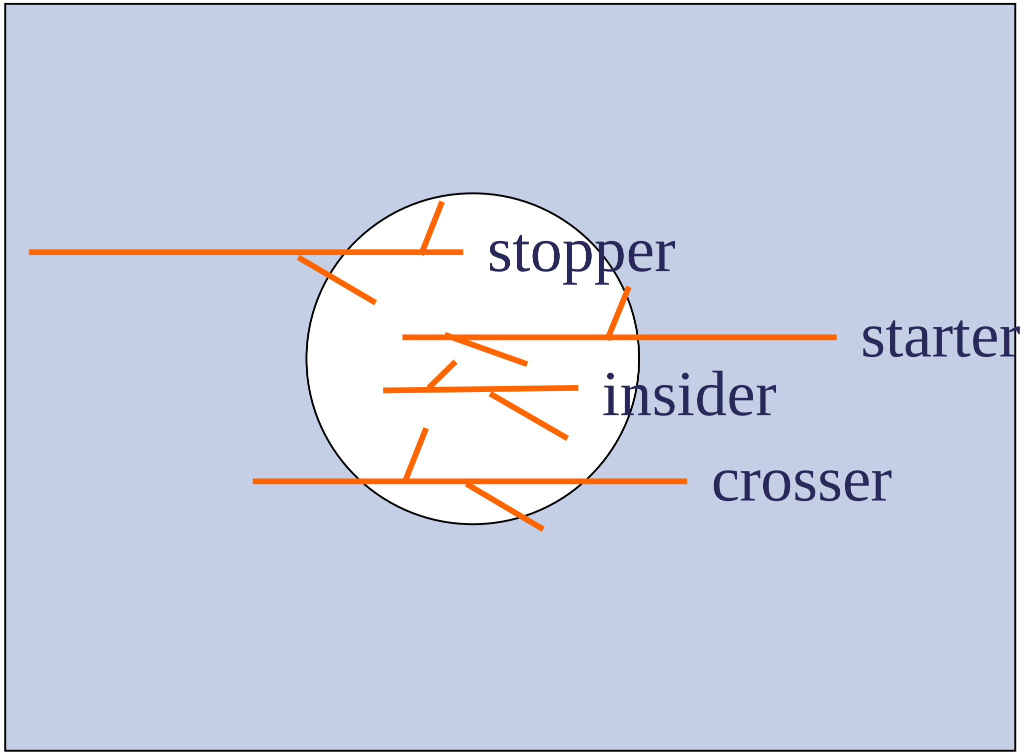
$$D_{water} = \frac{Q}{m_{air}} \cdot \left(\frac{\overline{W}_{air}}{e} \right) \cdot \frac{\left(\overline{S}_{el}/\rho\right)_{water}}{\left(\overline{S}_{el}/\rho\right)_{air}}$$

How well are the two Bragg-Gray conditions really fulfilled??

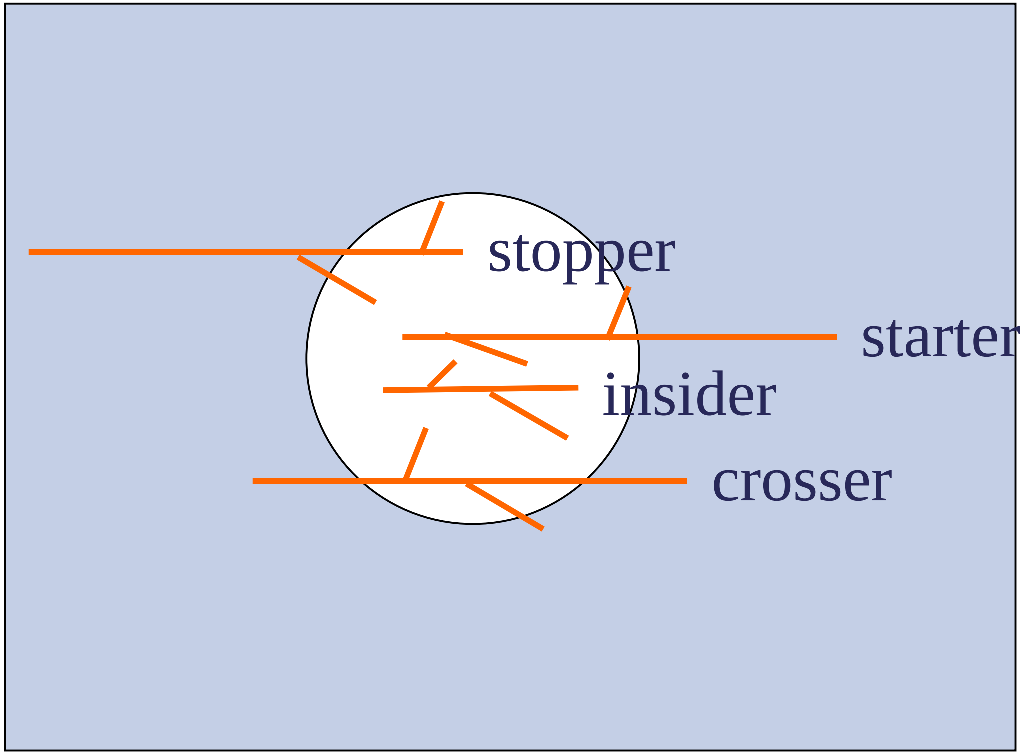
To discuss this question, we need a closer look on the cavity and all **possible electron tracks** in the following:



In addition, the electron tracks must also include the production of so-called δ electrons:

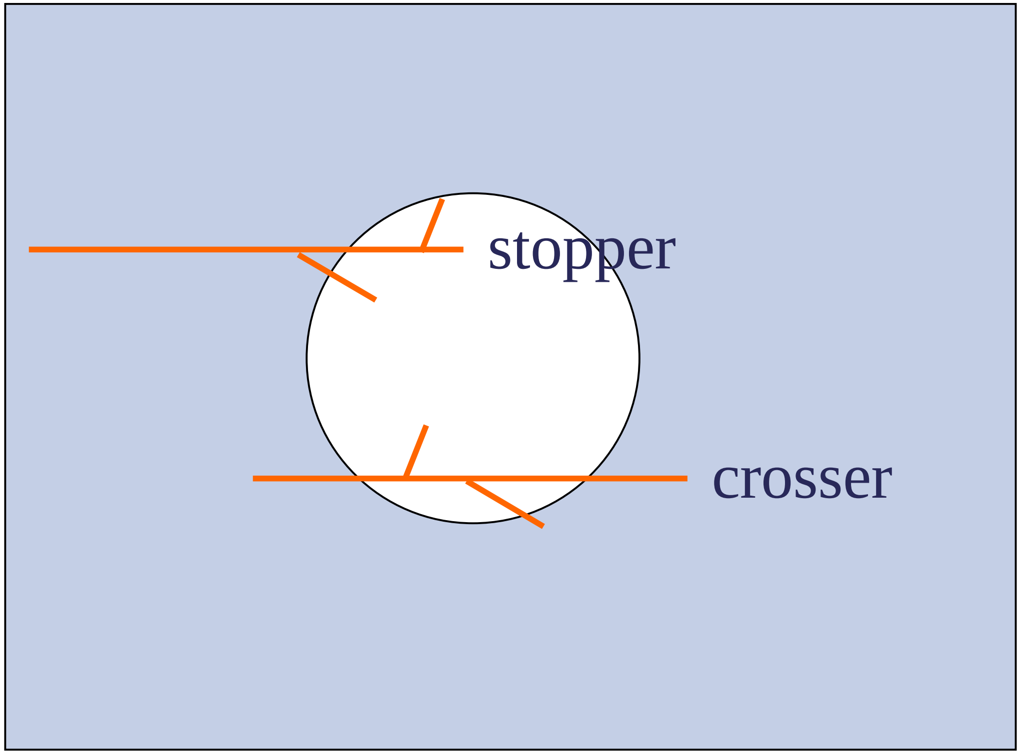


- In a very good approximation we can neglect photon interactions within the cavity.
- Thus we will neglect the starters and insiders!



In a very good approximation, also the fluence of the pure crossers and stoppers is not changed (a density change does not change the fluence!).

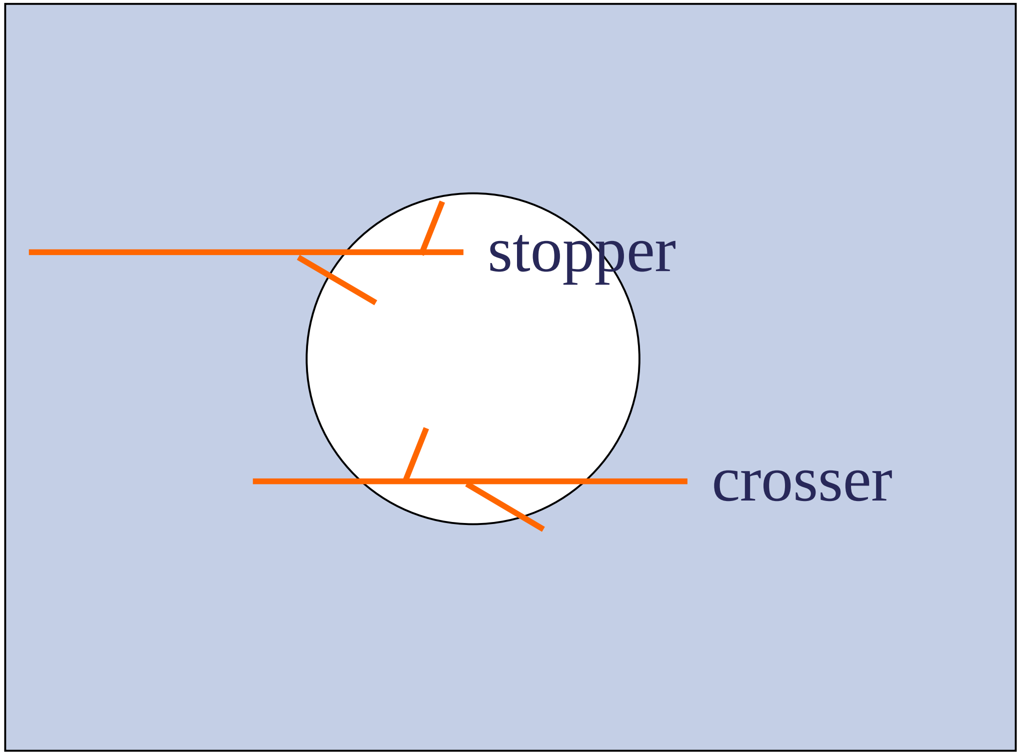
However, the fluence of the δ electrons is slightly changed close to the border of the cavity (the number of δ electrons entering and leaving the cavity is unbalanced).



It follows:

Thus the Bragg-Gray condition, that the fluence of **all electrons** must not be disturbed, cannot be exactly fulfilled.

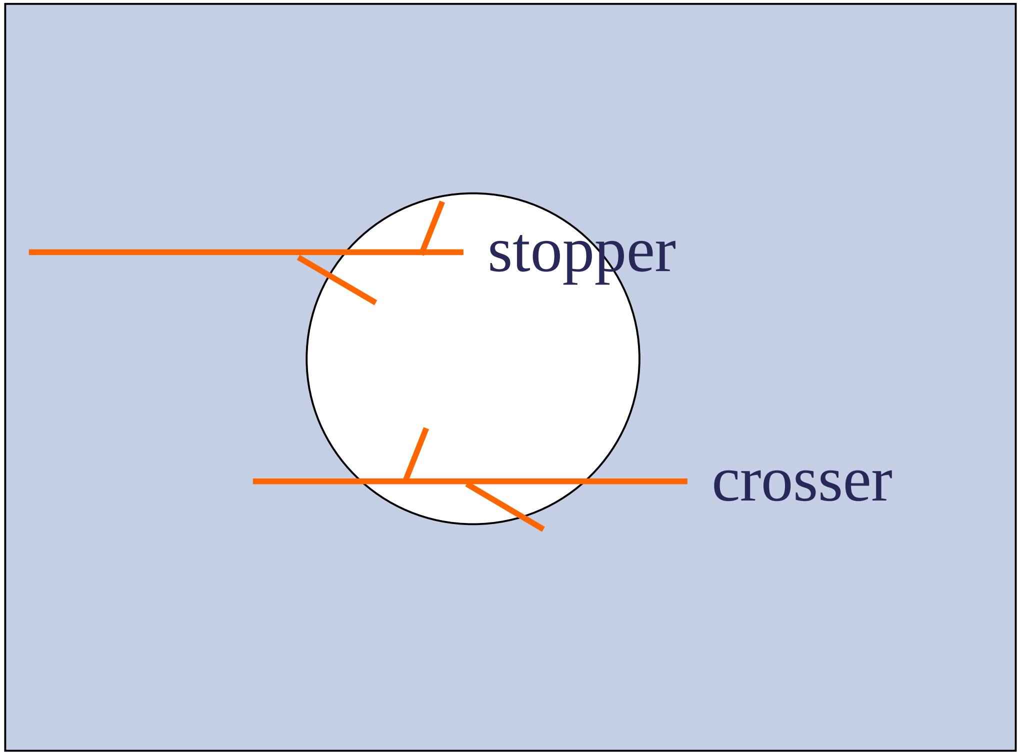
Hence this must be taken into account by a so-called **perturbation factor** when converting dose in air to dose in water.



$$D_{water} = \frac{Q}{m_{air}} \cdot \left(\frac{\overline{W}_{air}}{e} \right) \cdot \frac{\left(\overline{S}_{el} / \rho \right)_{water}}{\left(\overline{S}_{el} / \rho \right)_{air}}$$

$$D_{water} = \frac{Q}{m_{air}} \cdot \left(\frac{\overline{W}_{air}}{e} \right) \cdot \frac{\left(\overline{S}_{el} / \rho \right)_{water}}{\left(\overline{S}_{el} / \rho \right)_{air}} \cdot p$$

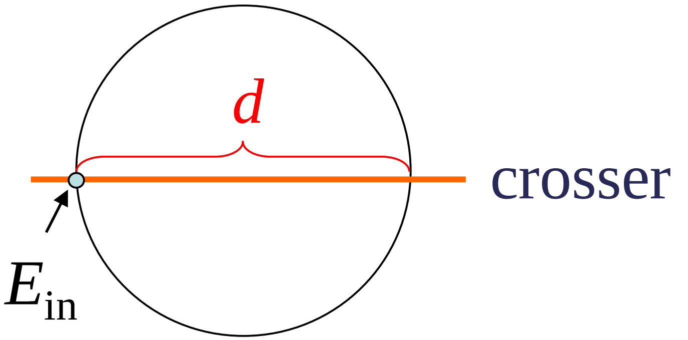
- What about the stoppers ???? Do they create a problem???
- The answer is: Yes, they do!



- 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.

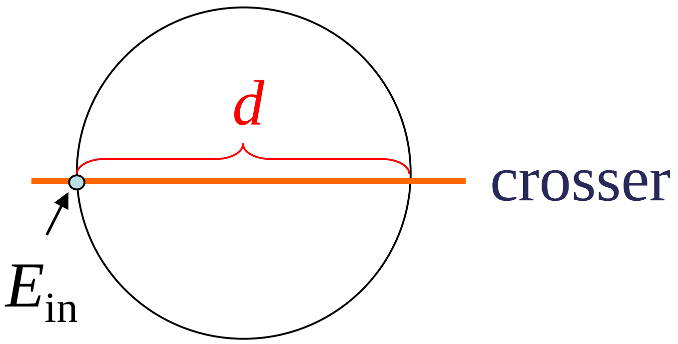
- Then the energy imparted ε is:

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



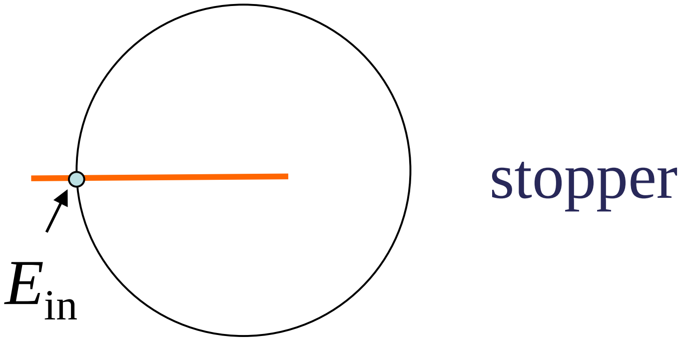
We compare this sitution:

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



With the energy absorption of a stopper:

$$\varepsilon = E_{in}$$



- 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 ratio of the mean mass collision stopping power also works only for crossers

$$s_{water,air} = \left(\frac{\overline{S}_{el}}{\rho}\right)_{water} \Bigg/ \left(\frac{\overline{S}_{el}}{\rho}\right)_{air}$$

and hence needs some corrections for the stoppers!

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!

$$\left(\bar{S}/\rho\right)_{w,a}^{SA} = \frac{\int_{\Delta}^{E_{max}} \Phi_E^{w,\delta}(E) \cdot \frac{L_{\Delta,w}(E)}{\rho} dE + \Phi_E^{w,\delta}(\Delta) \cdot \frac{S_w(\Delta)}{\rho} \cdot \Delta}{\int_{\Delta}^{E_{max}} \Phi_E^{w,\delta}(E) \cdot \frac{L_{\Delta,air}(E)}{\rho} dE + \Phi_E^{w,\delta}(\Delta) \cdot \frac{S_{air}(\Delta)}{\rho} \cdot \Delta}$$

Summary: Determination of Absorbed dose in water

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

$$D_{water} = \frac{Q}{m_{air}} \cdot \left(\frac{\overline{W}_{air}}{e} \right) \cdot s_{w,a}^{SA} \cdot p$$

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.

4. Some very recent ideas on the **dose conversion factor**

Purpose:

1) To extend the theoretical base also to any other detector type (not only chambers)
2) To extend the theoretical base to non-reference conditions (for example to relative dosimetry)

A very general approach to dosimetry is the following:

- We apply a dose detector that has a certain size and which is not consisting of water
- We have a certain detector reading M after a radiation dose
- We want to know the dose (in water) D_w at the **point** of measurement if there is no detector

The relation between these two quantities is taken into account in the definition of **detector response R**:

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

The response can be split up into two factors:

$$R = \frac{M}{D_w} = \frac{D_{det}}{D_w} \cdot \frac{M}{D_{det}}$$

$$R = \frac{M}{D_w} = 1/f \cdot R_{int}$$

← **Intrinsic detector response**

Thus the dose in water is obtained by:

$$D_w = M \cdot f \cdot (1/R_{int})$$

That means:

For any detector and for any condition the dose is determined from the detector reading M and the knowledge of:

- The **dose conversion factor f** which is typically obtained from Monte Carlo calculation

- The **intrinsic response** of the detector which must be obtained from a measurement for most of detectors (exception: ionization chambers !!!!!!)

Just to remind you:

The famous k_Q factor which we know well from beam calibration according TRS 398 is nothing else than:

$$k_Q = \frac{f_Q}{f_{Q_0}}$$

So the knowledge of the dose conversion factor **f** plays an important role in dosimetry!!

Since the **dose conversion factor f** nowadays almost always is calculated by Monte Carlo, it pays to spend a closer look into the associated calculation principles.

1. MC energy depositions (and thus the dose) may arise directly from photons or from electrons (+ positrons)

$$D = D_{phot} + D_{el} = \sum \varepsilon_i^{phot} + \sum \varepsilon_i^{el}$$

However, the ratio D_{phot}/D is very small.

detector medium	air	water	aluminum
D_{phot}/D	0.02%	0.02%	0.06%

It follows: $$D = \sum \varepsilon_i^{el}$$

2. The sum of electron based energy contributions can be expressed using the fluence distribution of the electrons

$$\sum \varepsilon_i^{el} = \sum_i \varphi_{i,vol}^{S_{med}} \cdot \left(\frac{L_i^{\Delta}}{\rho} \right)_{med}$$

electron fluence in bin i obtained in the scoring volume vol and using the restriced stopping power of the medium in the scoring volume to calculate the fluence

This expression will be written in the next slides as

$$D = \varphi_{vol}^{S_{med}} \times L_{med}$$

The **dose conversion factor f** then is

$$f = \frac{D_w}{D_{det}} = \frac{\varphi_p^{S_w} \times L_w}{\varphi_{det}^{S_{med}} \times L_{det}}$$

This expression tells us:

Once the involved electron fluence distributions are known, the dose conversion factor f can be easily calculated.

We can go one step further:

The **dose conversion factor f** can be factorized according:

$$f = \frac{\varphi_{p}^{S_w} \times L_w}{\varphi_{det}^{S_{med}} \times L_{det}} =$$

$$\frac{\varphi_{cav}^{S_{med}} \times L_{det}}{\varphi_{det}^{S_{med}} \times L_{det}} \cdot \frac{\varphi_{cav}^{S_w} \times L_{det}}{\varphi_{cav}^{S_{med}} \times L_{det}} \cdot \frac{\varphi_{cav}^{S_w} \times L_w}{\varphi_{cav}^{S_w} \times L_{det}} \cdot \frac{\varphi_{p}^{S_w} \times L_w}{\varphi_{cav}^{S_w} \times L_w} =$$

$$f_1 = \frac{\varphi_{cav}^{S_{med}} \times L_{det}}{\varphi_{det}^{S_{med}} \times L_{det}}$$

Volume perturbation factor

$$f_2 = \frac{\varphi_{cav}^{S_{w}} \times L_{det}}{\varphi_{cav}^{S_{med}} \times L_{det}}$$

Stopping power ratio

$$f_3 = \frac{\varphi_{cav}^{S_{w}} \times L_{w}}{\varphi_{cav}^{S_{w}} \times L_{det}}$$

Cavity & medium perturbation factor

$$f_4 = \frac{\varphi_{p}^{S_{w}} \times L_{w}}{\varphi_{cav}^{S_{w}} \times L_{w}}$$

Extra cavitary perturbation factor

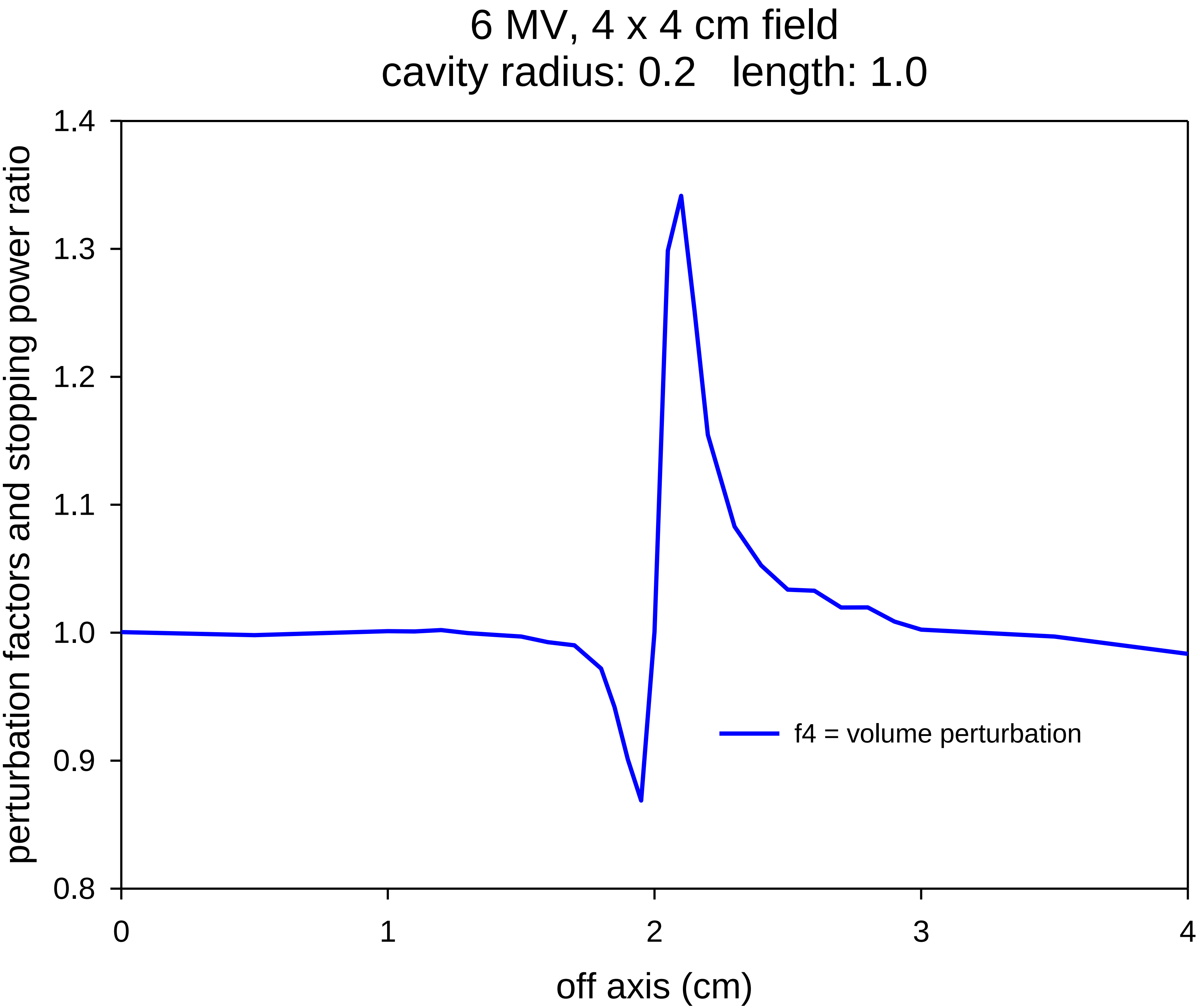
Summary of this new approach

The absorbed dose in water is obtained from the detector reading by:

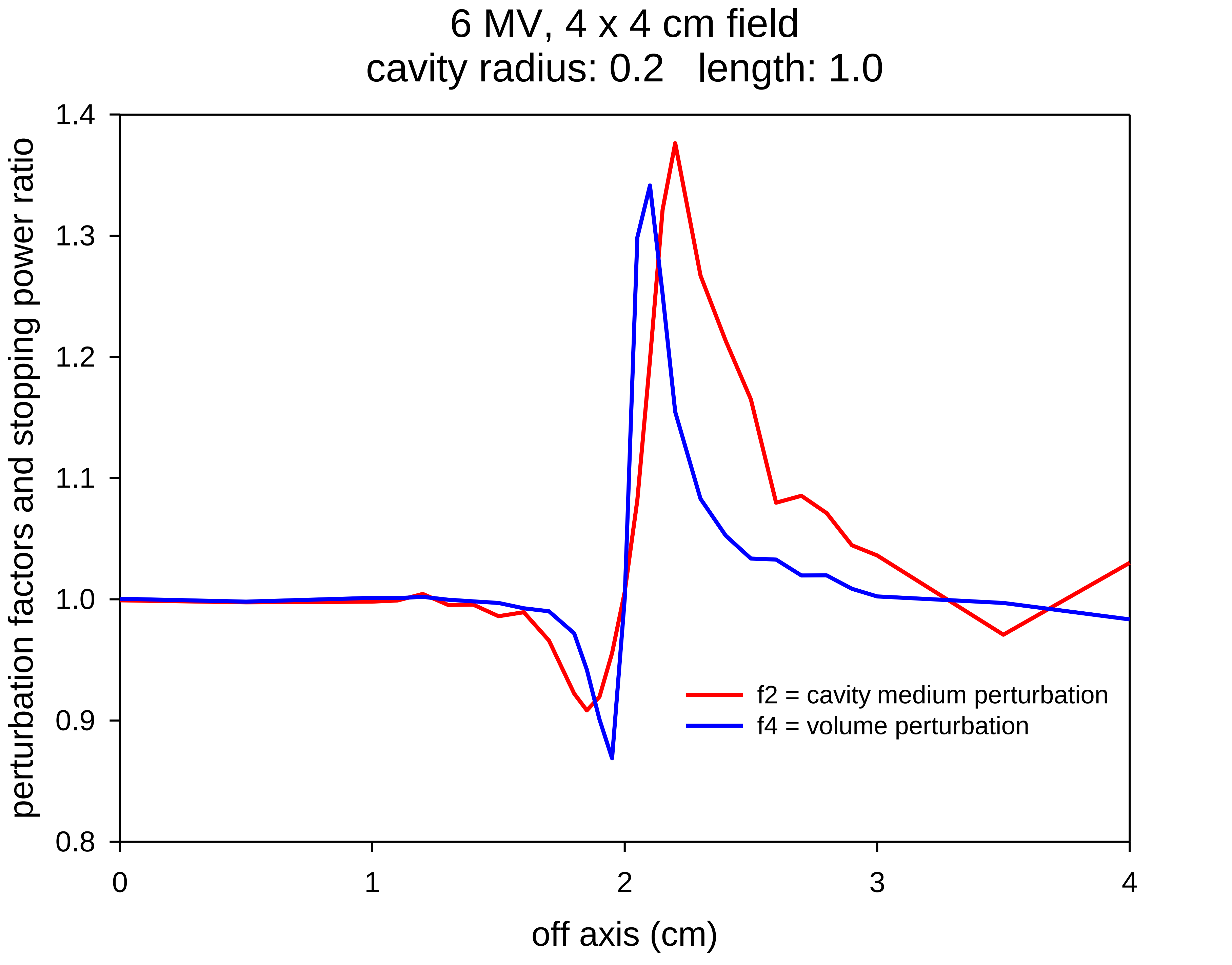
$$D_w = M \cdot (f_1 \cdot f_2 \cdot f_3 \cdot f_4) \cdot (1/R_{int})$$

Advantage:

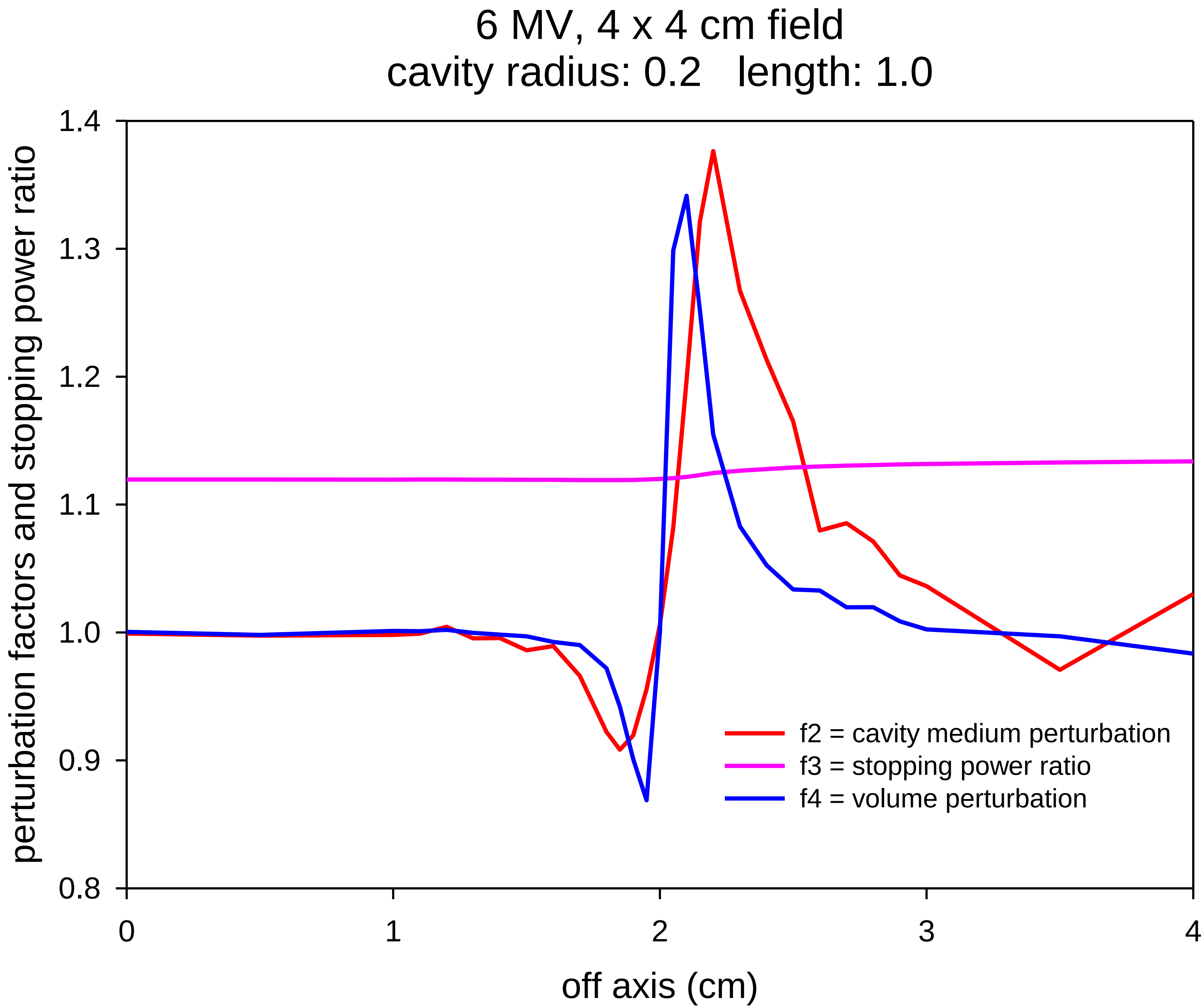
- Applicable to any dose detector
- Applicable also in non-reference conditions
- Focosses on the different influences on a dose measurement from the dose conversion factor f and from the intrinsic response R_{int}
- Offers clear (fluence based) expressions for perturbation factors such as volume perturbation, cavity & medium perturbation or extra cavitary perturbation.

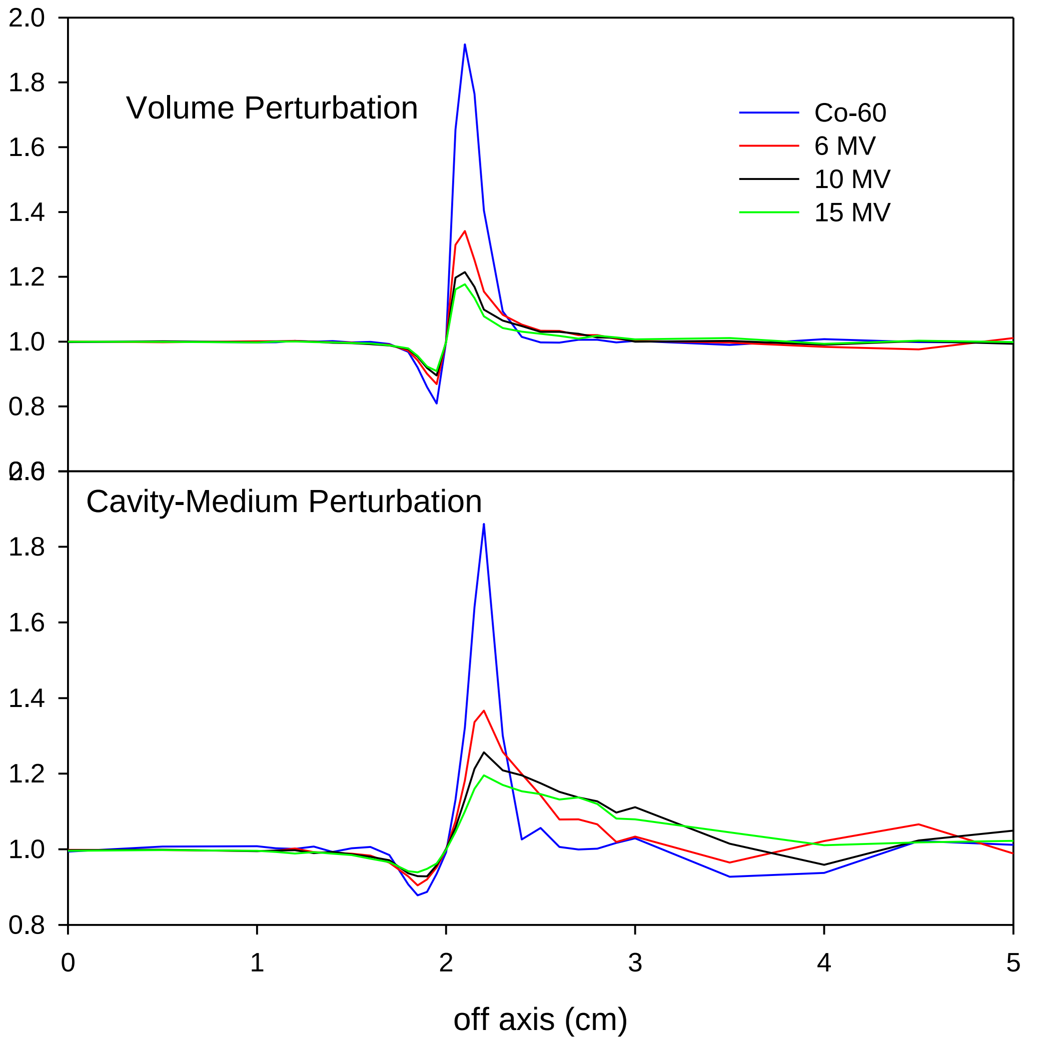


6 MV, 4 x 4 cm field
cavity radius: 0.2 length: 1.0
perturbation factors and stopping power ratio
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0
1
2
3
4
off axis (cm)
f4 = volume perturbation

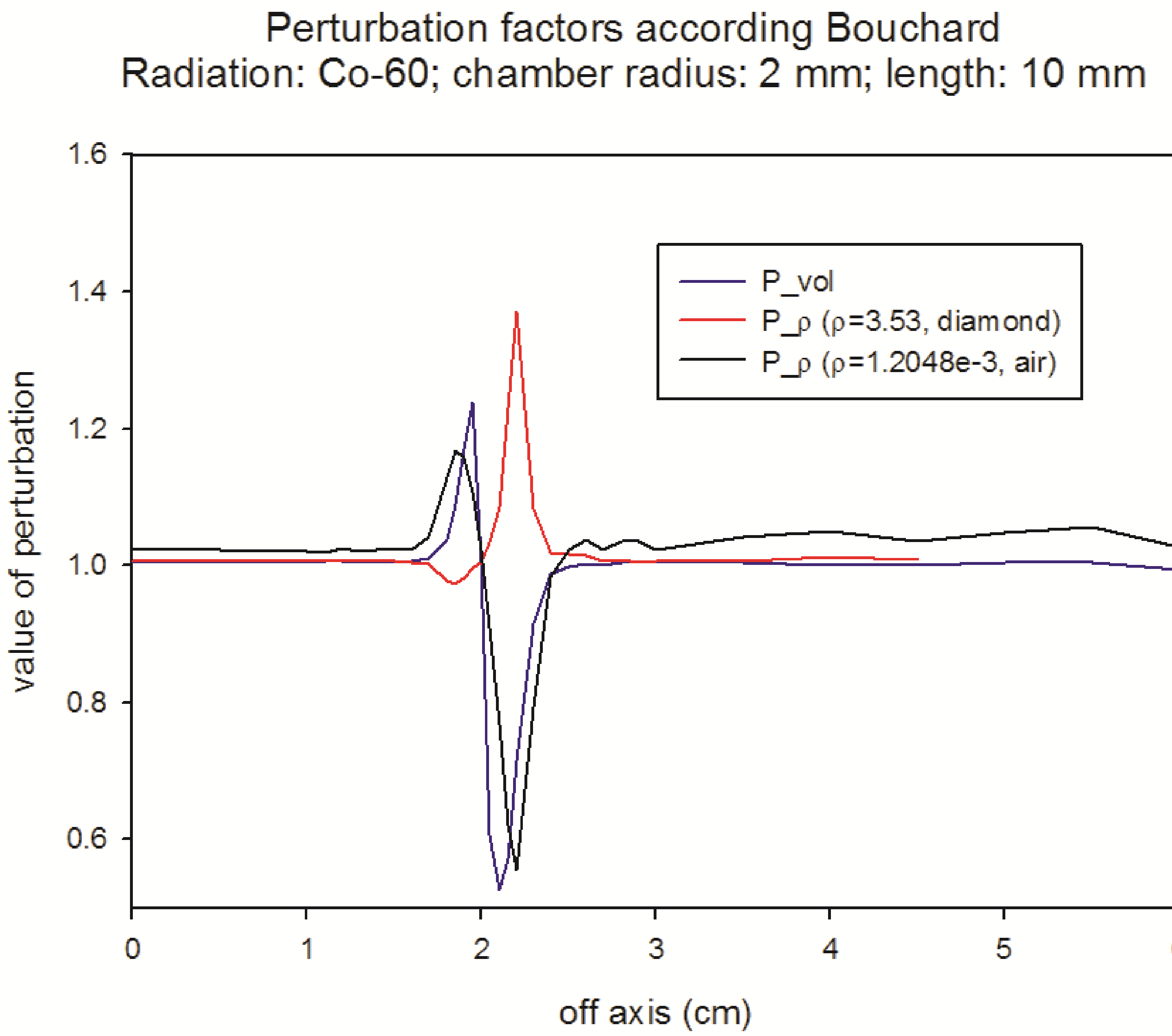


6 MV, 4 x 4 cm field
cavity radius: 0.2 length: 1.0
perturbation factors and stopping power ratio
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0
1
2
3
4
off axis (cm)
f2 = cavity medium perturbation
f4 = volume perturbation


6 MV, 4 x 4 cm field
cavity radius: 0.2 length: 1.0
perturbation factors and stopping power ratio
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0
1
2
3
4
off axis (cm)
f2 = cavity medium perturbation
f3 = stopping power ratio
f4 = volume perturbation



Volume Perturbation
Co-60
6 MV
10 MV
15 MV
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
Cavity-Medium Perturbation
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0
1
2
3
4
5
off axis (cm)



Perturbation factors according Bouchard
Radiation: Co-60; chamber radius: 2 mm; length: 10 mm
1.6
1.4
1.2
1.0
0.8
0.6
value of perturbation
0
1
2
3
4
5
6
off axis (cm)
P_vol
P_ρ (ρ=3.53, diamond)
P_ρ (ρ=1.2048e-3, air)