Fundamentals of Micro- and Nanodosimetry

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Acknowledgements

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To:	For material used on slides on:
B. Großwendt	Dosimetry and radiation protection concepts , nanodosimetry
O. Hupe, P. Ambrosi	Radiation protection quantities
P. Pihet, A. Rosenfeld	Microdosimetry, biological effectiveness
J. Rahm	Ionising radiation interaction

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Site Map

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(Macroscopic) Dosimetry:	Radiation Protection Dosimetry:
• Kerma • Absorbed dose • Fluence • Linear energy transfer / Stopping power	• Equivalent Dose • Ambient equivalent dose • Personal equivalent dose • Radiation quality factors
Microdosimetry: • Specific energy distributions • Lineal energy distributions	**Nanodosimetry:** • Ionisation cluster size distributions

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Outline

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- Refresher Course on Radiation Protection
- Refresher Course on Ionizing Radiation
- Macroscopic Dosimetry Concepts
- Microdosimetry
- Radiobiological Effectiveness
- Nanodosimetry

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Refresher Course on Radiation Protection Quantities

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The System of Quantities in Radiation Protection

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Physical Quantities
- fluence, Φ
- kerma, K
- absorbed dose, D

Protection (Body Dose) Quantities
- organ absorbed dose, D_T
- directional equivalent dose, H_T
- effective dose, E

Relate to biological effects induced by ionising radiation.

Operational Quantities
- ambient dose equivalent, $H^*(d)$
- directional dose equivalent, $H'(d, \Omega)$
- personal dose equivalent, $H_p(d)$

Measurable (in principle) at a point in the human body (or in a phantom)

Protection (Body Dose) Quantities

- **Organ absorbed dose**
- **Directional equivalent dose**
- **Effective dose**

Effective Dose

$$E = \sum_T w_T \sum_R w_R D_{T,R}$$

Tissue weighting factor

Radiation weighting factor related to external radiation or to radiation from radionuclides

Mean absorbed dose in the organ or tissue T from radiation of type R

The effective dose is seen to be related to the "risk" of a detriment (stochastic effects like cancer) from exposure by ionizing radiation.

The special name for the unit of effective dose, J kg^{-1}, is sievert (Sv).

Recommended Radiation Weighting Factors w_R

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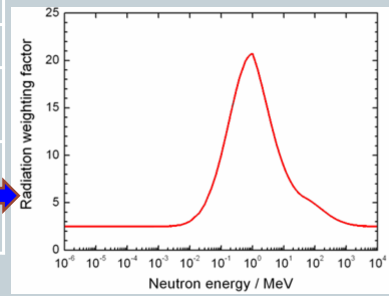
Radiation type	*Radiation weighting factor, w_R*
Photons	1
Electrons and muons	1
Protons, charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy

Recommendations of the International Commission on Radiological Protection ICRP Publication 103 (2007)



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Tissue-weighting Factors w_T

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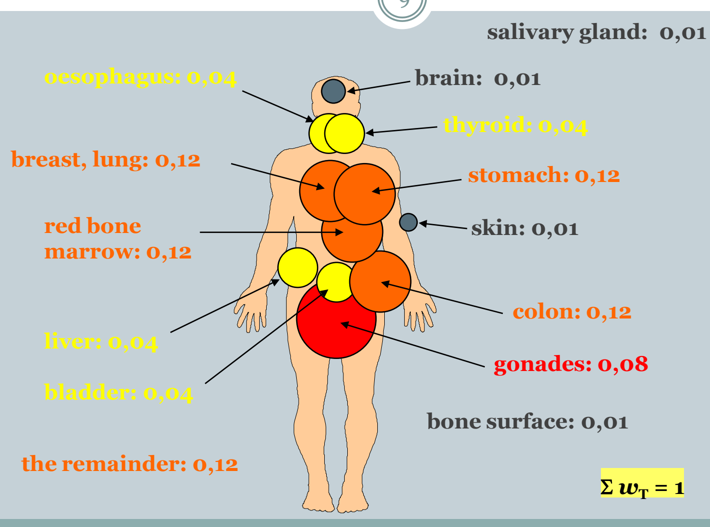

$\Sigma w_T = 1$

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Operational Quantities

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- Ambient Dose Equivalent
- Directional Dose Equivalent
- Personal Dose Equivalent

Ambient Dose Equivalent

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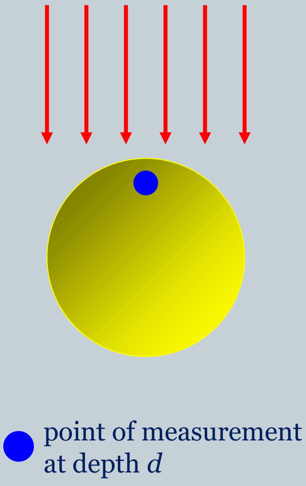
The ambient dose equivalent, $H^*(d)$, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded and aligned field, in the ICRU sphere at a depth, d, on the radius opposing the direction of the aligned field

The special name for the unit of ambient dose equivalent, J kg^{-1}, is sievert (Sv).



Directional Dose Equivalent

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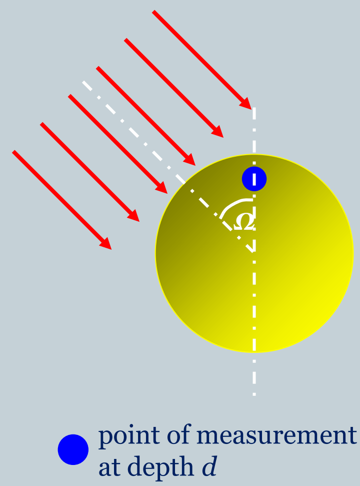
The directional dose equivalent, $H'(d, \Omega)$, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded field, in the ICRU sphere at a depth, d, on a radius in a specified direction, Ω.



The special name for the unit of directional dose equivalent, J kg^{-1}, is sievert (Sv).

Personal Dose Equivalent

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The personal dose equivalent, $H_p(d)$, is the dose equivalent in soft tissue, at an appropriate depth, d, below a specified point on the body.

The special name for the unit of personal dose equivalent, J kg^{-1}, is sievert (Sv).

Refresher Course on Ionising Radiation

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Ionising Radiation Interactions in Matter

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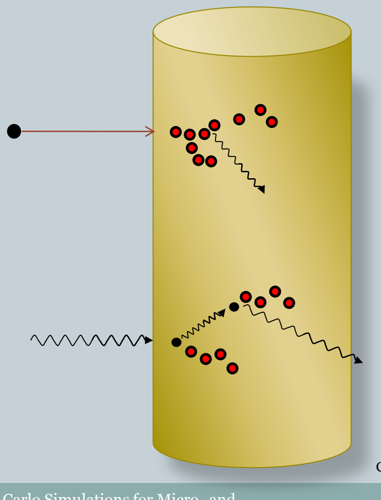
Electron β

Photon γ



electrically charged
directly ionising

electrically neutral
indirectly ionising

Courtesy of Johannes Rahm, TH Mittelhessen

100 keV Photons in a 30 cm Water Cube

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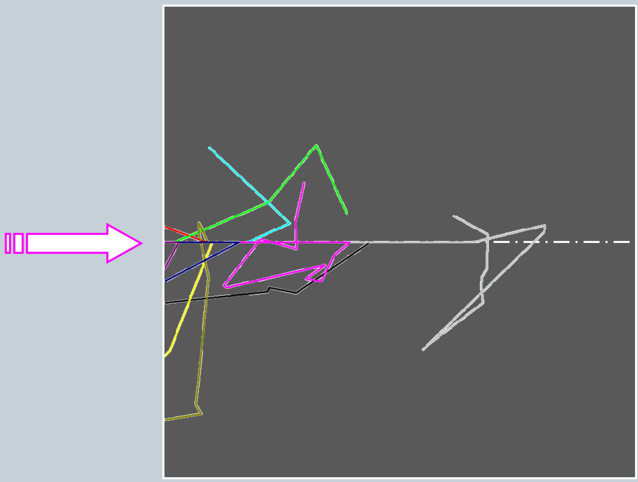

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Electron tracks due to 100 keV photons in a 30 cm water cube

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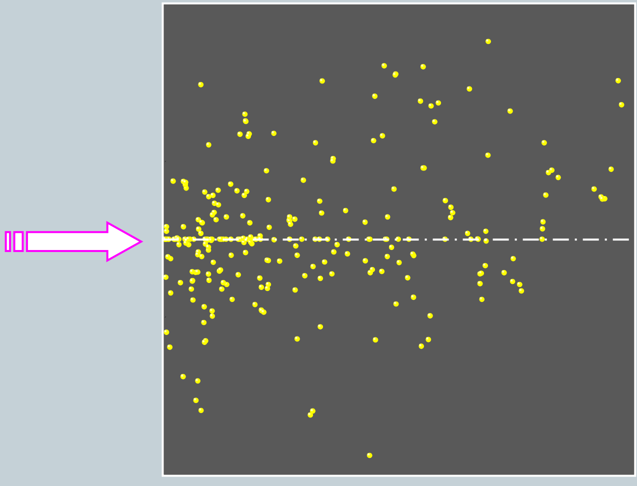

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Three sample tracks of 2.7 keV electrons in a 100 nm water phantom (only ionisations)

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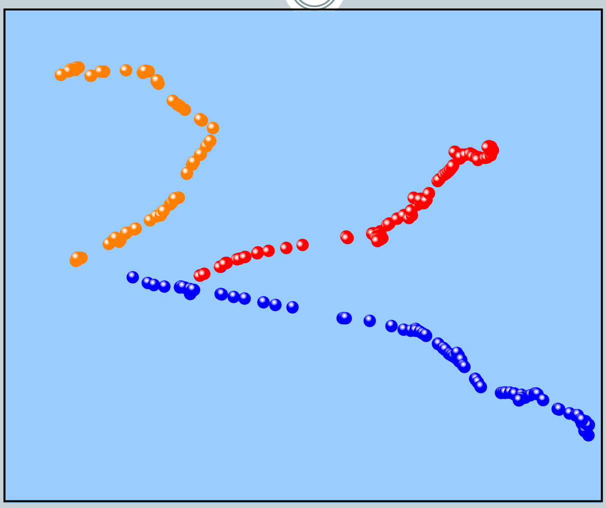

$v \approx 0.07\ c$

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One sample track of an electron in water (all interactions shown)

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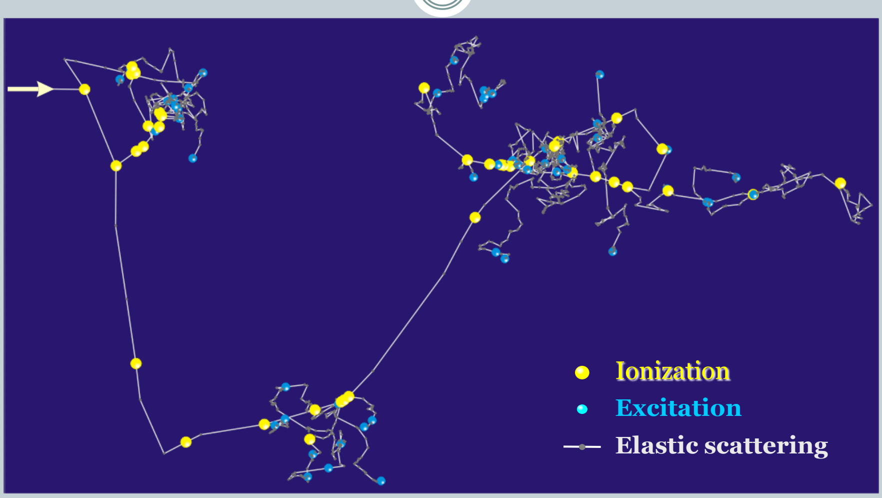

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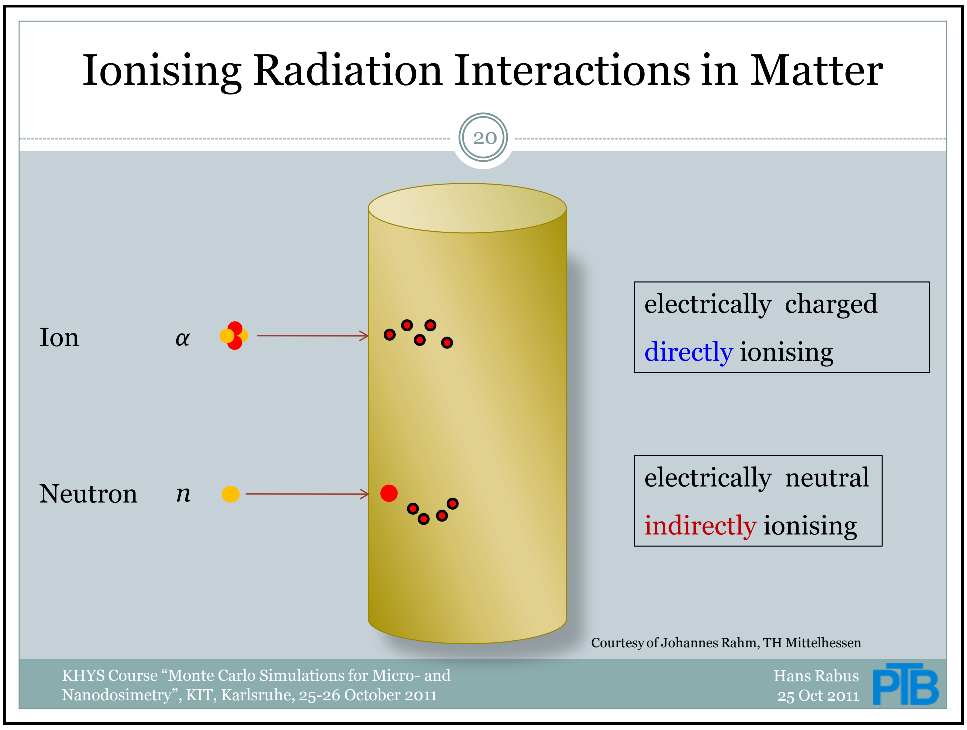
Ionising Radiation Interactions in Matter
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Ion α
Neutron n
electrically charged
directly ionising
electrically neutral
indirectly ionising
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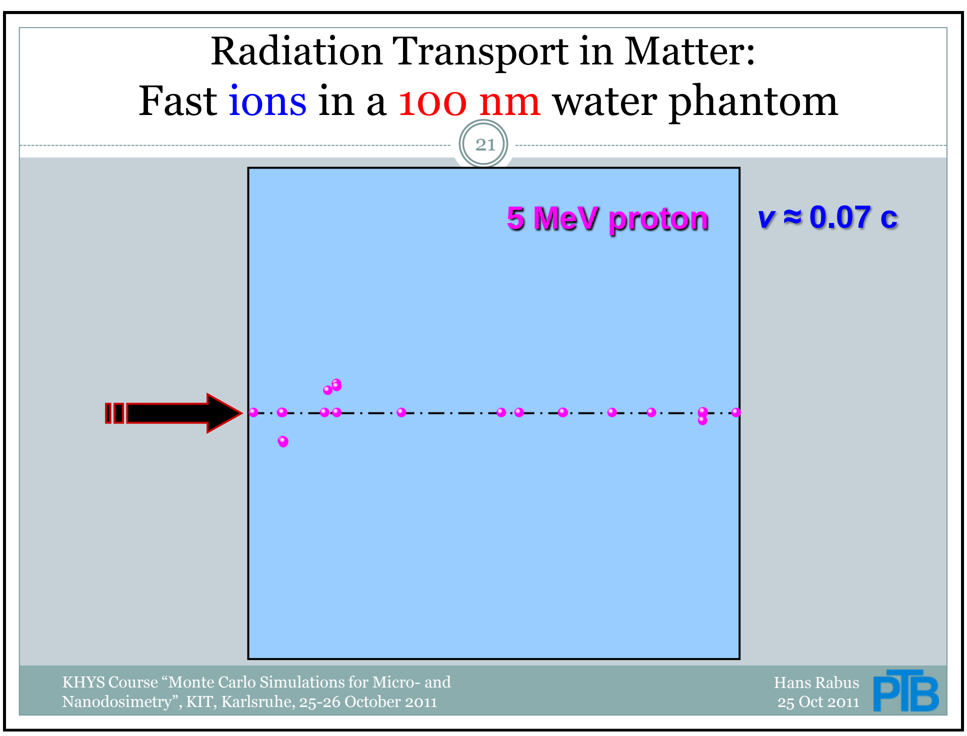
Radiation Transport in Matter:
Fast ions in a 100 nm water phantom
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5 MeV proton
v ≈ 0.07 c
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Radiation Transport in Matter: Fast ions in a 100 nm water phantom

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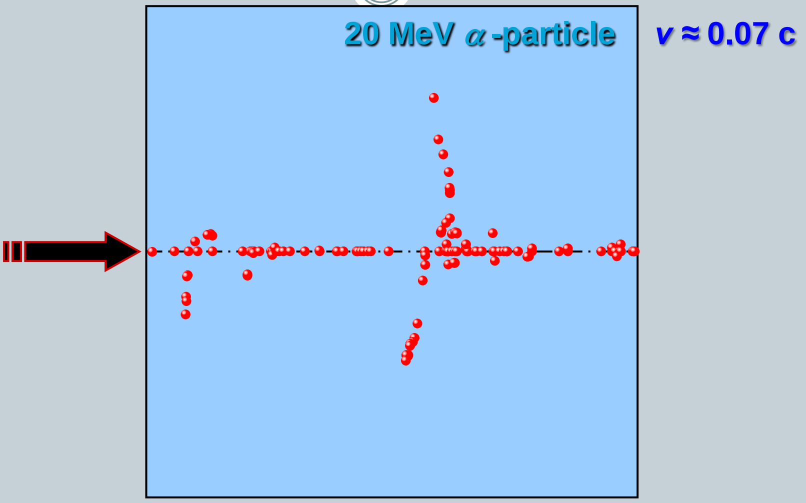

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Radiation Transport in Matter: Fast ions in a 100 nm water phantom

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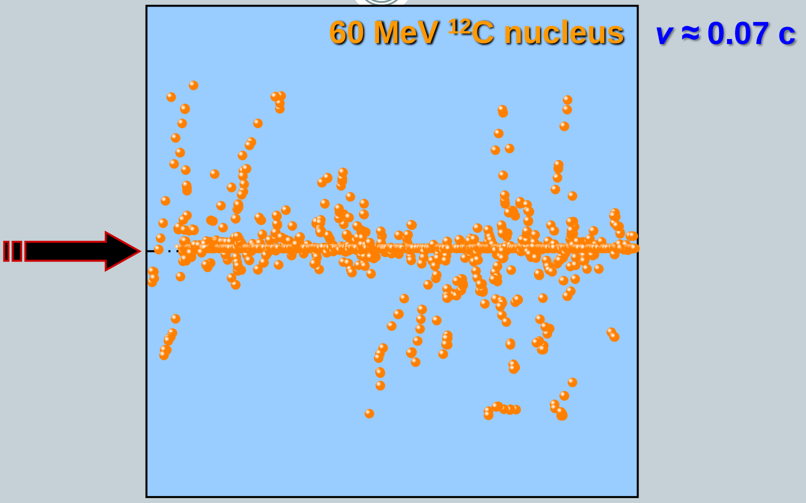

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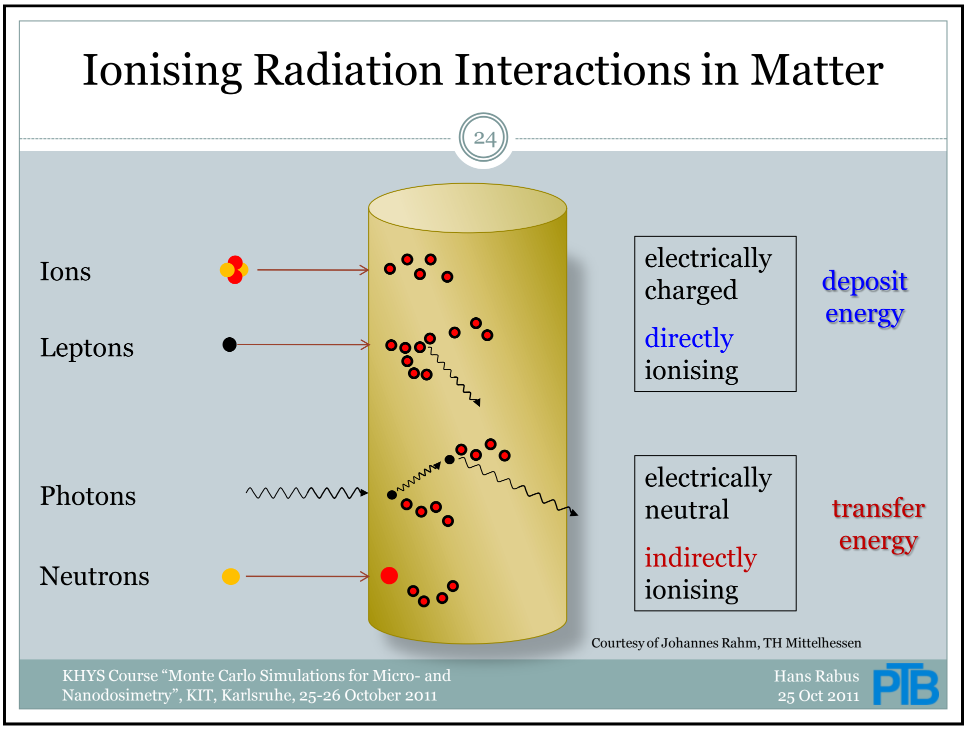
Ionising Radiation Interactions in Matter
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Ions
Leptons
Photons
Neutrons
electrically charged
directly ionising
deposit energy
electrically neutral
indirectly ionising
transfer energy
Courtesy of Johannes Rahm, TH Mittelhessen
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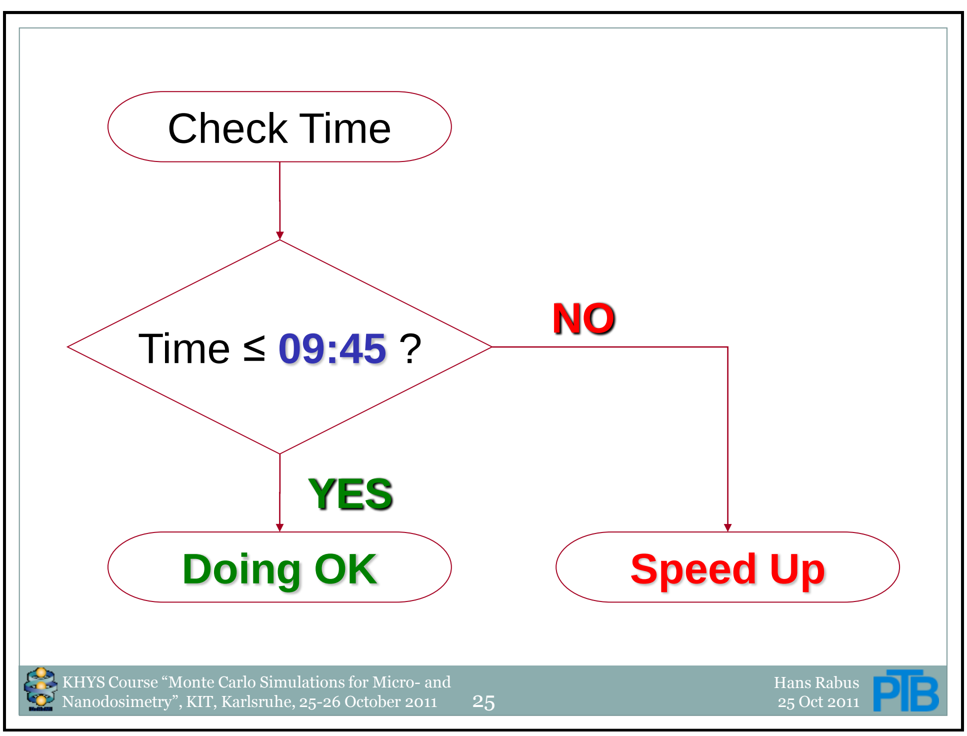
Check Time
Time ≤ 09:45 ?
NO
YES
Doing OK
Speed Up
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Macroscopic Dosimetry Concepts

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- Kinetic energy released in matter - KERMA
- Absorbed Dose (to a material)
- Particle and Energy Fluence
- Linear energy transfer – LET (Stopping Power)

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Kerma: Kinetic energy released per mass

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Formal definition (ICRU Report N. 85, 2011):

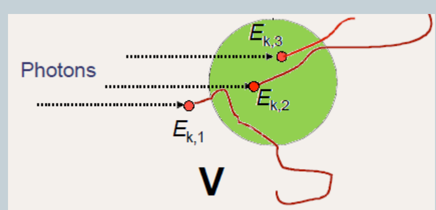
The *kerma*, K, for ionizing uncharged particles, is the quotient of $\mathrm{d}E_{\mathrm{tr}}$ by $\mathrm{d}m$, where $\mathrm{d}E_{\mathrm{tr}}$ is the mean sum of the initial kinetic energies of all the charged particles liberated in a mass $\mathrm{d}m$ of a material by the uncharged particles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

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

Unit: J kg^{-1}

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

Practical determination:



$$K = \frac{\sum_{i=2}^{3} E_{k,i}}{m} \qquad m = \rho V$$

Drawing from *Review of Radiation Oncology Physics: A Handbook for Teachers and Students* (IAEA)

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Absorbed dose to a material

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Formal definition (ICRU Report N. 85, 2011):

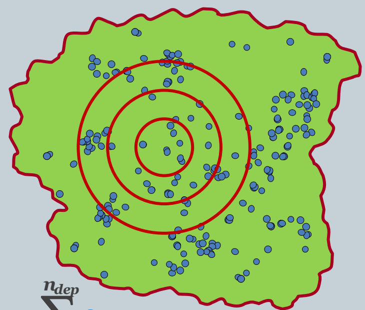
The *absorbed dose*, D, is the quotient of $d\bar{\varepsilon}$ by dm, where $d\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to matter of mass dm, thus

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

Unit: J kg^{-1}

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

Practical determination:



$$D = \frac{\sum_{i=1}^{n_{dep}} \varepsilon_i}{m}$$

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Kerma and absorbed dose

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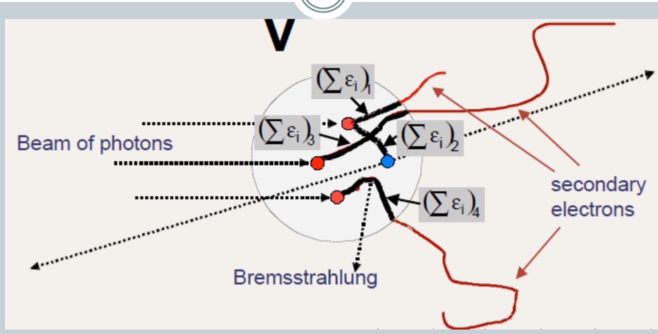

Because electrons travel in the medium and deposit energy along their tracks, this absorption of energy (= ▬) does not take place at the same location as the transfer of energy described by kerma (= ●).

Drawing from *Review of Radiation Oncology Physics: A Handbook for Teachers and Students* (IAEA)

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Absorbed dose in a volume of matter

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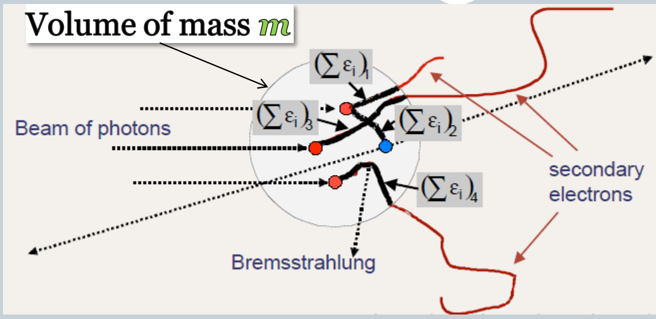

$(\sum \varepsilon_i)$ is the sum of energy lost in collisions along the track of the secondary particles within the volume.

Absorbed dose $$D = \frac{(\sum \varepsilon_i)_1 + (\sum \varepsilon_i)_2 + (\sum \varepsilon_i)_3 + (\sum \varepsilon_i)_4}{m}$$

Slide adapted from *Review of Radiation Oncology Physics: A Handbook for Teachers and Students* (IAEA)

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The Role of Electron Transport

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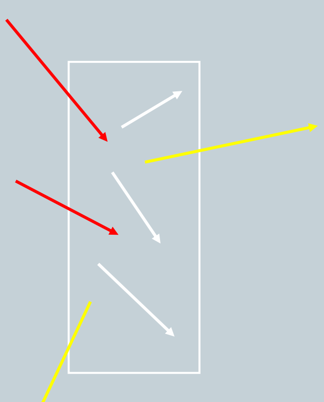
$$\dot{D} = \frac{i \times (W/e)}{m}$$



Secondary-electron equilibrium

The energy transported out of the volume by electrons set-in-motion inside must be compensated by the energy transported in by electrons set-in-motion outside.

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Kerma and absorbed dose

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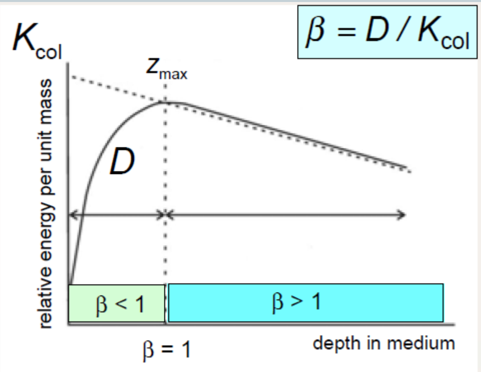
$$\beta = D / K_{col}$$



In the buildup region:
β < 1

In the region of a transient charged particle equilibrium:
β > 1

At the depth $z = z_{max}$, a true charged particle equilibrium exists.
β = 1

$$D = K_{col} = K(1 - \bar{g})$$

Drawing from *Review of Radiation Oncology Physics: A Handbook for Teachers and Students* (IAEA)

Macroscopic Dosimetry Concepts

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- **Kinetic energy released in matter – KERMA**
- **Absorbed Dose (to a material)**
- **Particle and Energy Fluence**
- **Linear energy transfer – LET (Stopping Power)**

Particle Fluence

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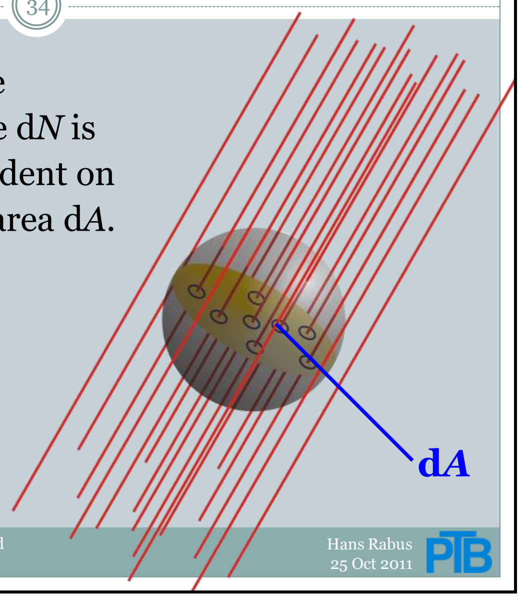
The particle fluence Φ is the quotient of dN by dA, where dN is the number of particles incident on a sphere of cross-sectional area dA.
Unit: m^{-2}

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



Energy Fluence

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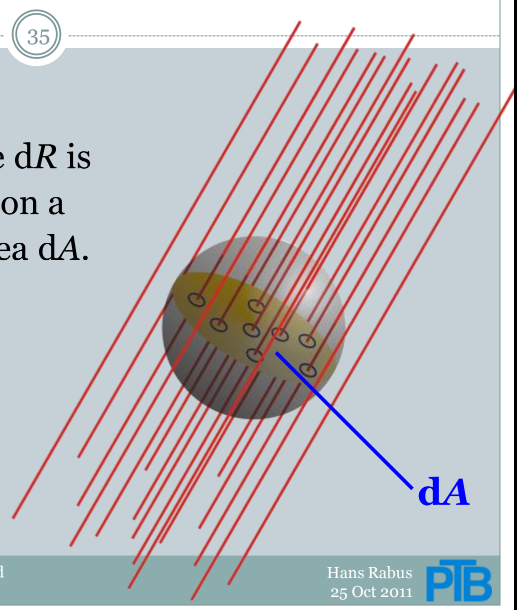
The energy fluence Ψ is the quotient of dR by dA, where dR is the radiant energy incident on a sphere of cross-sectional area dA.
Unit: J m^{-2}

$$\Psi = \frac{\mathrm{d}R}{\mathrm{d}A}$$



Particle vs. Energy Fluence

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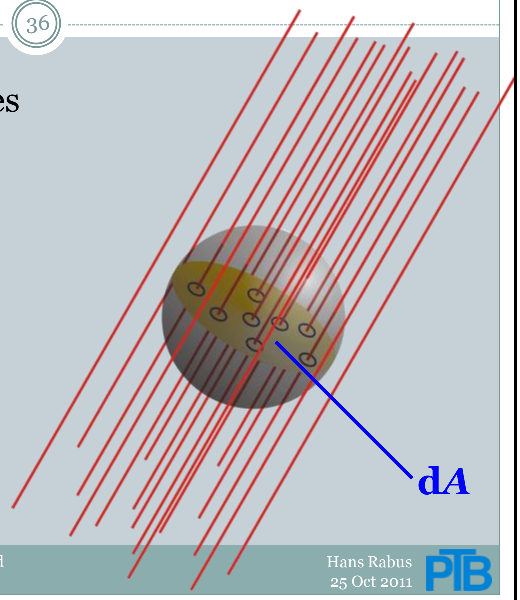
For mono-energetic particles of energy E: $\Psi = \Phi \cdot E$

For a spectrum of particle energies:

$\Psi_E(E) = \Phi_E(E) \cdot E$



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Spectral Particle and Energy Fluence

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$$\Phi_E = \frac{d^2 N}{dE\, dA}$$

… d^2N is the number of particles of energy E …

Unit: $J^{-1}m^{-2}$

$$\Psi_E = \frac{d^2 R}{dE\, dA}$$

… d^2R is the radiant energy of particles of energy E …

Unit: m^{-2}

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Interaction Probability and Cross Section

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The probability for a particular interaction of a particle with a target entity is the ratio of the number of successful interactions n_{hit} out of n trials.

$$P = \frac{n_{hit}}{n} = \frac{\sigma}{a} = \Phi \times \sigma$$

$$\sigma = \frac{P}{\Phi}$$

Interaction Cross Sections for Electrons in Water

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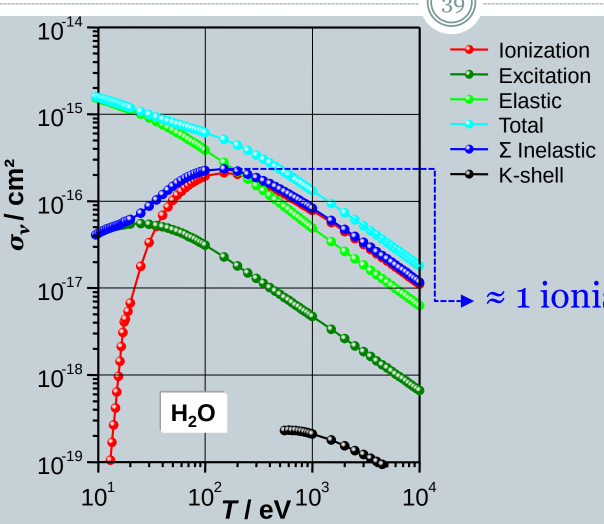

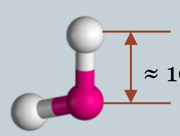

≈ 1 ionisation per nm

Macroscopic Dosimetry Concepts

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- **Kinetic energy released in matter - KERMA**
- **Absorbed Dose (to a material)**
- **Particle and Energy Fluence**
- **Linear energy transfer – LET** **(Stopping Power)**

Dose-effect curves

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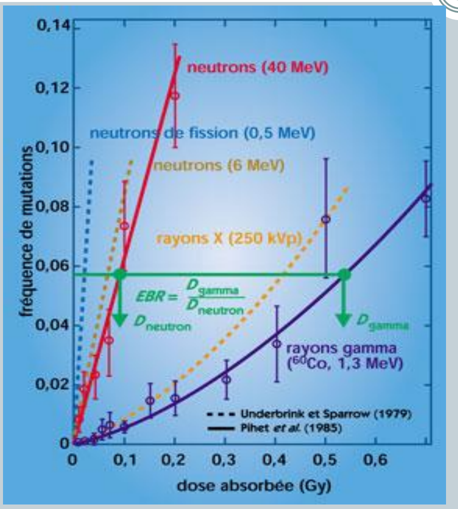

- No unique relation between absorbed dose and biological effect
- Different shape for
  - different particle type
  - same particle type at different energy.
- Biological effectiveness of different radiation qualities

Loosely and densely ionising radiation

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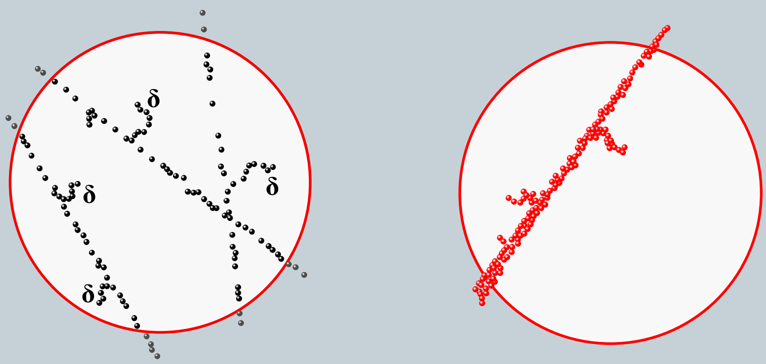
NB: The same absorbed dose is obtained in the sphere.



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Different particle tracks in tissue

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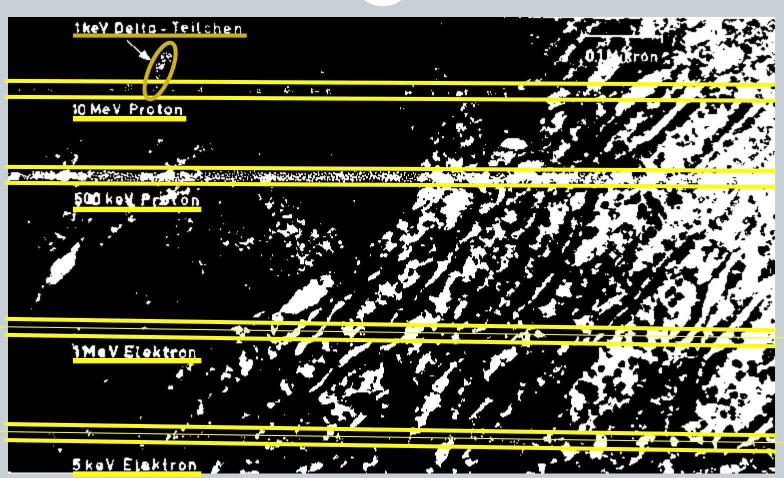

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Linear energy transfer (Stopping Power)

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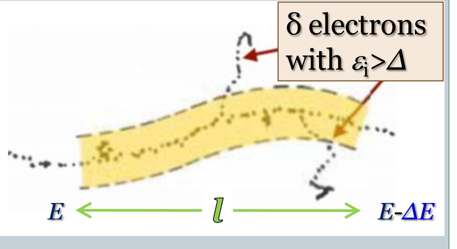
Formal definition (ICRU Report N. 85, 2011):

The *linear energy transfer* or *restricted linear electronic stopping power*, L_Δ, of a material, for charged particles of a given type and energy, is the quotient of dE_Δ by dl, where dE_Δ is the mean energy lost by the charged particles due to electronic interactions in traversing a distance dl, minus the mean sum of the kinetic energies in excess of Δ of all the electrons released by the charged particles, thus

$$L_\Delta = \frac{dE_\Delta}{dl}.$$

Unit: J m^{-1}

Practical determination:



$$L_\Delta = \frac{\sum_i^{\varepsilon_i < \Delta} \varepsilon_i}{l} \qquad S = L_\infty = \frac{\Delta E}{l}$$

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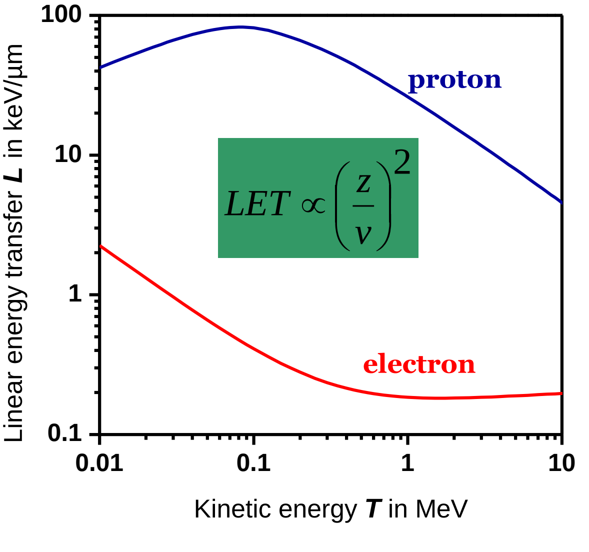
Linear Energy Transfer (Stopping Power) of Water



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Bragg peaks in linear energy transfer and range

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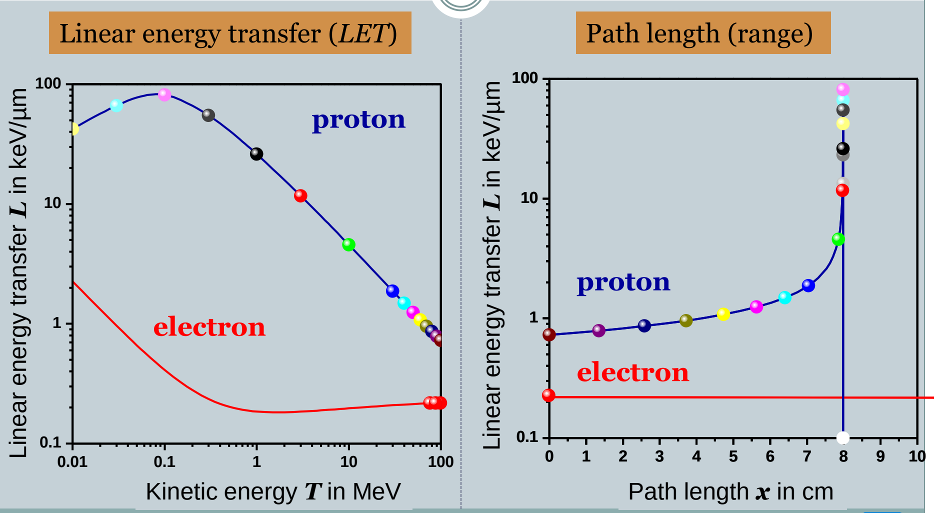

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Summary: Introduction and Motivation

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- At the microscopic level, ionising radiation interaction is a stochastic process.
- Conventional dosimetric quantities like absorbed dose are macroscopic averages.
- The same absorbed dose may lead to different biological effects.
- The reason for this is the radiation quality which is related to the microscopic particle track structure .
- The (macroscopic) concept of linear energy transfer (LET) is used to characterize radiation quality.

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Depth dose distributions for decreasing dose

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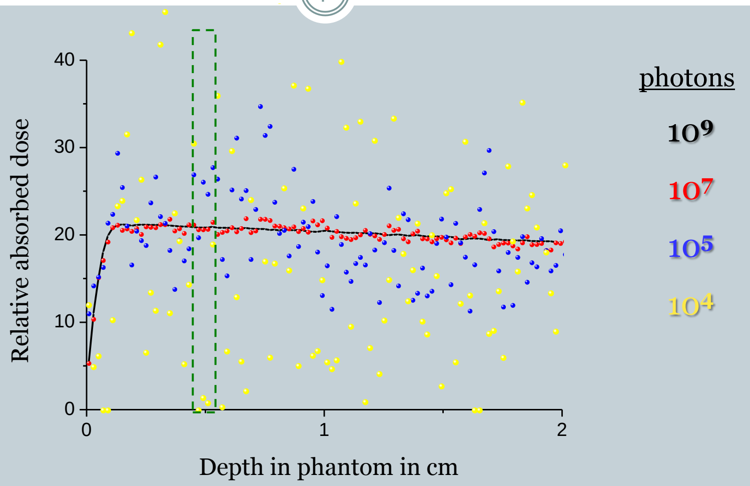

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Depth dose distributions for decreasing bin

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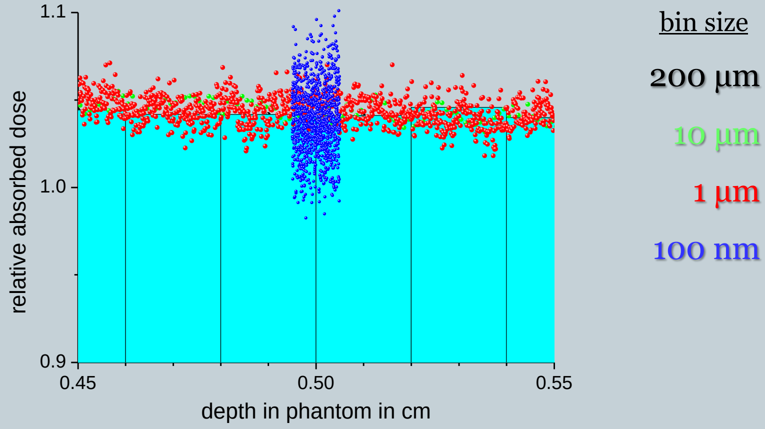

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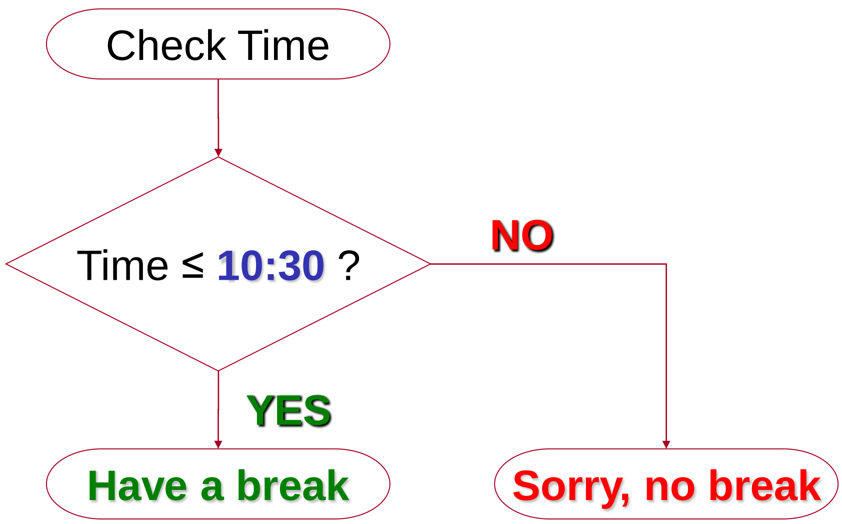

Microdosimetry

Definition of Microdosimetry

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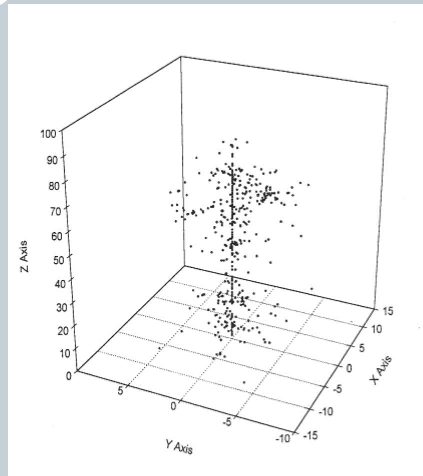
Microdosimetry:
The systematic study and quantification of the *spatial* and *temporal* distribution of absorbed energy in irradiated matter.
It deals with the *stochastics* of energy deposition.



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Definitions of Technical Terms (1)

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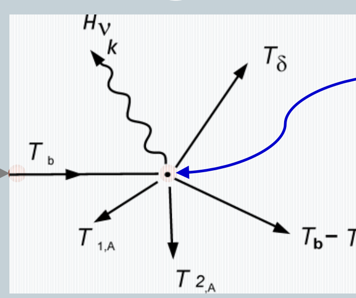
Incident ionising particle



Transfer point

Energy deposit $\varepsilon_i = T_{in} - \sum_k T_{out,k} + Q$

$[\varepsilon_i] = \mathrm{J}\ (or\ \mathrm{eV})$

Drawing from *Review of Radiation Oncology Physics: A Handbook for Teachers and Students* (IAEA)

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Definitions of Technical Terms (2)

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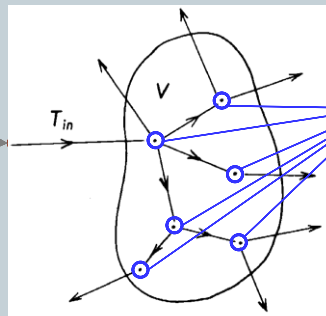
Event: production of statistically correlated transfer points

Incident ionising particle



Transfer points of the event

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Definitions of Technical Terms (3)

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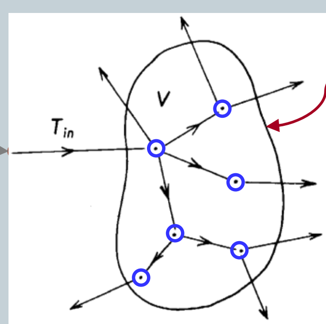
Incident ionising particle



Site: target volume

Energy imparted

$$\varepsilon = \sum \varepsilon_i$$

(by all events)

Specific energy $z = \frac{\varepsilon}{m}$

$[z] = \text{J/kg}\ (\equiv \text{Gy})$

Drawing from *Review of Radiation Oncology Physics: A Handbook for Teachers and Students* (IAEA)

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Specific energy and absorbed dose

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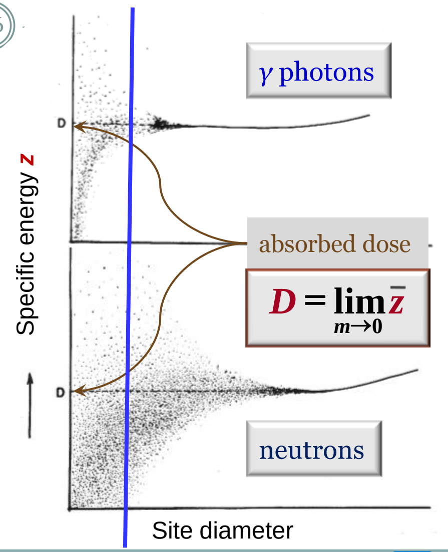
- The specific energy *z* is a stochastic quantity.
- Its variance increases with decreasing target size.
- Its mean value is related to (macroscopic) dose *D*
- Each radiation quality has its own signature.



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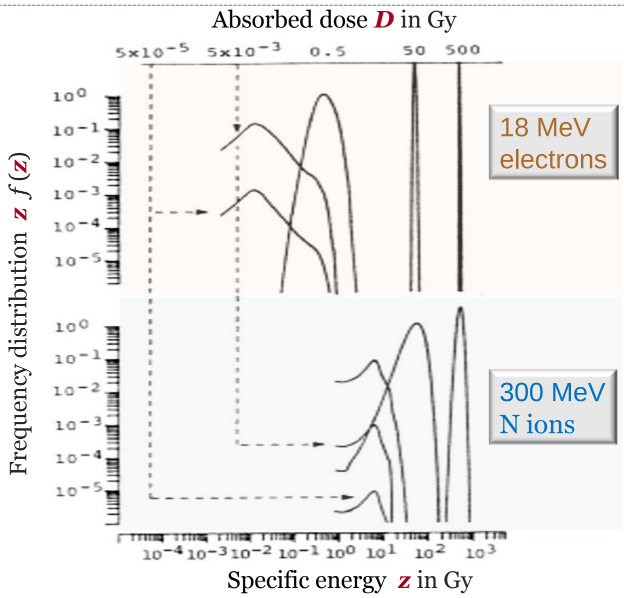
Specific energy distribution for fixed site diameter

- For large doses the distributions are Gaussian.
- For low doses the relative shape of the distributions is independent of dose.



Specific energy: Single and multi-event distribution

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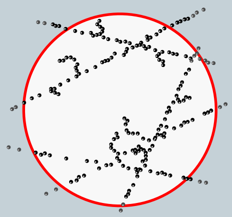
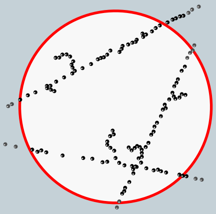
- Distribution of events in the site (target volume)



$\Rightarrow f(z;D)$

(multi-event distribution of z)

- Distribution of collisions for a specific event



$\Rightarrow f_1(z)$

(single-event distribution of z)

Definitions of Technical Terms (4)

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- $f(z;D)$ is the *frequency probability density* of z for absorbed dose D.
- $\bar{z} = \int_0^\infty z\, f(z;D)\,dz$ is the *mean specific energy*.
- $f_1(z)$ is the *single event probability density* of z.
- $\bar{z}_F = \int_0^\infty z f_1(z)\,dz$ is the *frequency-mean specific energy per event*.

$\bar{n} = \dfrac{\bar{z}}{\bar{z}_F}$ is the ***event frequency***

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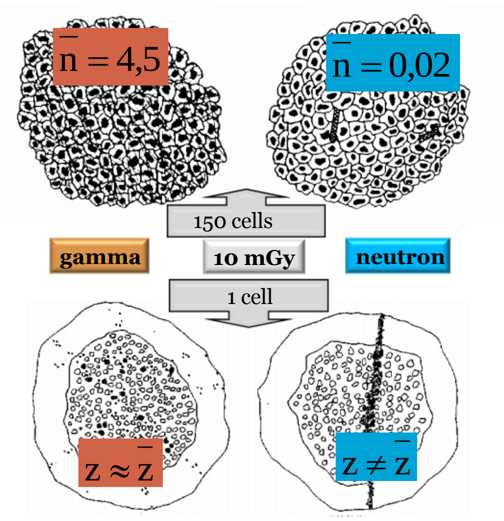
For a site of cell nucleus dimension

$$\bar{z} = \int_0^\infty z\, f(z;D)\, dz$$

$$\bar{z}_F = \int_0^\infty z f_1(z;D)\, dz$$

$$\bar{n} = \frac{\bar{z}}{\bar{z}_F}$$

$$D \approx \bar{z} = \bar{n} \times \bar{z}_F$$



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Definitions of Technical Terms (5)

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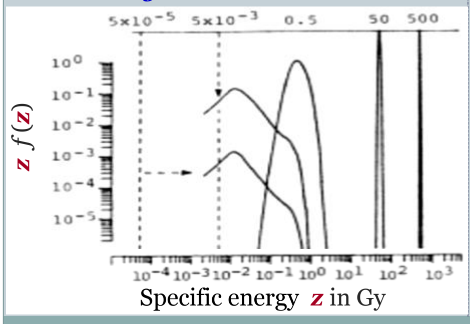
- $d(z) = \dfrac{z f(z;D)}{D}$

  is the *dose probability density* of z.



- $d_1(z) = \dfrac{z f_1(z)}{D}$

  is the *dose probability density* of z per *event*.

- $\bar{z}_D = \dfrac{1}{\bar{z}_F} \int_0^\infty z^2 f_1(z)\, dz$

  is the *dose-mean specific energy per event.*

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Reminder on the linear energy transfer

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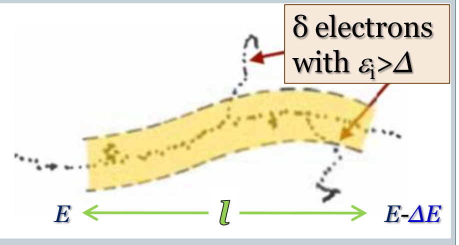
Formal definition (ICRU Report N. 85, 2011):

The *linear energy transfer* or *restricted linear electronic stopping power*, L_Δ, of a material, for charged particles of a given type and energy, is the quotient of dE_Δ by dl, where dE_Δ is the mean energy lost by the charged particles due to electronic interactions in traversing a distance dl, minus the mean sum of the kinetic energies in excess of Δ of all the electrons released by the charged particles, thus

$$L_\Delta = \frac{dE_\Delta}{dl}.$$

Unit: J m^{-1}

Practical determination:

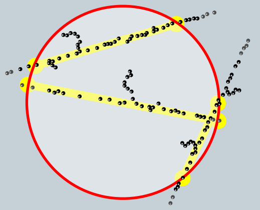


$$L_\Delta = \frac{\sum_i^{\varepsilon_i<\Delta} \varepsilon_i}{l} \qquad S = L_\infty = \frac{\Delta E}{l}$$

Energy imparted per chord length: Lineal energy

64

- Different events relate to different chord length



Chord: Section of primary particle trajectory in the site.

- Relate imparted energy and *mean chord length* $\bar{l}$
- Modeling the target (chord length distribution for isotropic or parallel trajectories)
- Convex volumes: $\bar{l} = \frac{4V}{S}$
- Sphere: $\bar{l} = \frac{2}{3}d$

Definitions of Technical Terms (6)

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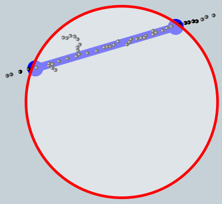

Energy imparted

$\varepsilon = \sum \varepsilon_i$

(by a *single* event)

mean chord length $\bar{l}$

Lineal energy $y = \frac{\varepsilon}{\bar{l}}$

$[y] = \text{keV}/\mu\text{m}$

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Definitions of Technical Terms (7)

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- $f(y)$ is the *frequency probability density* of y.
- $\bar{y}_F = \int_0^\infty y\, f(y) dy$ is the *frequency-mean* lineal energy.
- $d(y) = \frac{y f(y)}{\bar{y}_F}$ is the *dose probability density* of y.
- $\bar{y}_D = \int_0^\infty y\, d(y) dy$ is the *dose-mean* lineal energy.

$\bar{y}_F$ and $\bar{y}_D$ are ***deterministic*** quantities

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Specific energy *z* vs. lineal energy *y*

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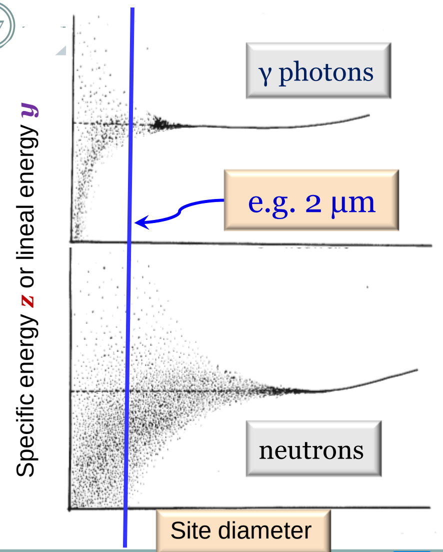
- The distributions of ***z*** **depend** on absorbed dose.
- The distributions of ***y*** are **independent** of absorbed dose (and dose rate).
- The distributions of ***z*** and ***y*** depend on
  - radiation quality
  - site diameter



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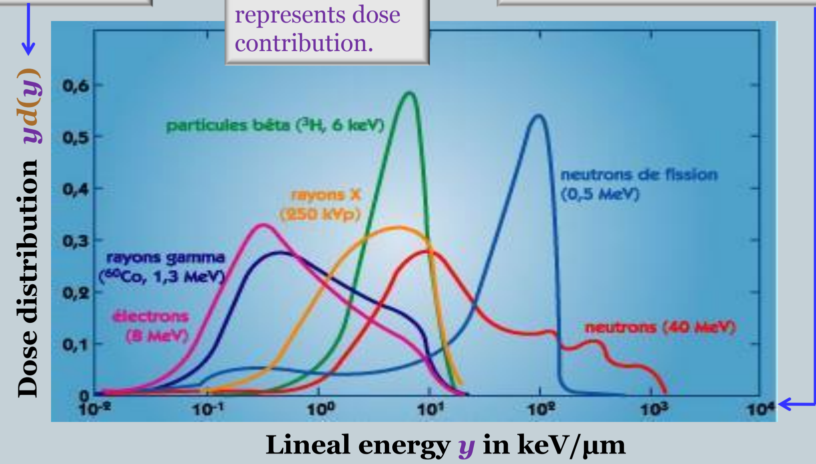
Microdosimetric spectra of various radiation qualities

68

ordinate: *yd(y)* → Area under curve represents dose contribution. ← logarithmic scale of *y* (abszissa)



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Summary: Concepts of Microdosimetry

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- Microdosimetry studies the spatial distribution and the stochastics of energy deposition in irradiated matter.
- Fundamental quantities are the statistical distributions of
  - Specific energy z (corresponding to absorbed dose)
  - Lineal energy y (corresponding to linear energy transfer)

  which are *stochastic* quantities.
- The frequency-mean and dose-mean values of z and y are *deterministic* quantities.

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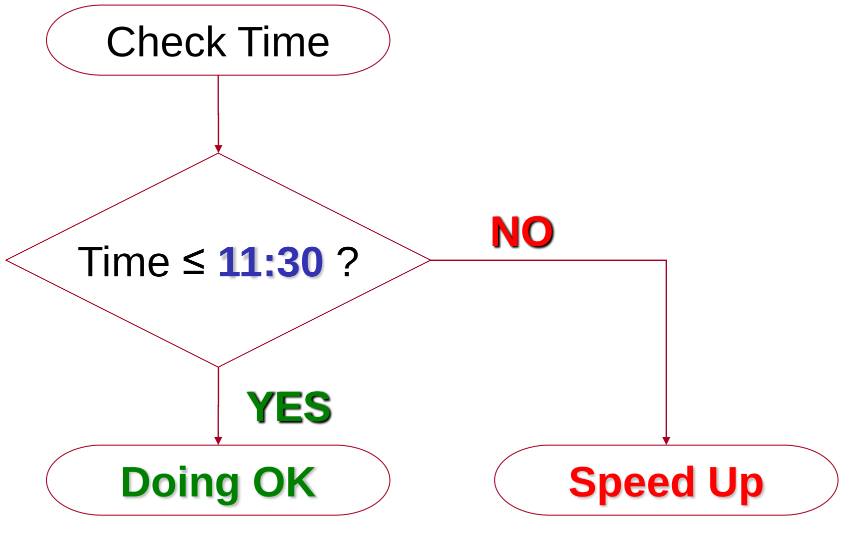

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Radiobiological Effectiveness

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Radiation quality: Size of the critical biological target?

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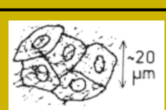
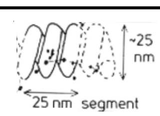
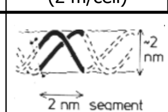
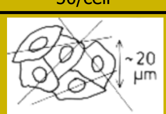
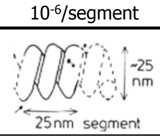
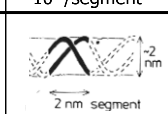
10^{-2} Gy	Tissues	Cells	Chromatine (-5 cm/cell)	DNA (2 m/cell)	
Gamma (1 MeV)					0,001 lethal lesions /cell
z	$\bar{z} \approx z$	$\bar{z} \approx z$	$\bar{z} \neq z : 0 - 10^3$ Gy	$\bar{z} \neq z : 0 - 10^6$ Gy	
n	>>	50/cell	10^{-6}/segment	10^{-8}/segment	
Neutrons (10 MeV)					0,005 lethal lesions /cell
z	$\bar{z} \approx z$	$\bar{z} \neq z : 0 - 5x10^{-2}$ Gy	$\bar{z} \neq z : 0 - 5x10^3$ Gy	$\bar{z} \neq z : 0 - 10^6$ Gy	
n	>>	1/cell	~4 10^{-6}/segment	10^{-8}/segment	

Taken from Goodhead, 1987

Lineal energy spectra of different radiation qualities and their associated *RBE* for cell killing

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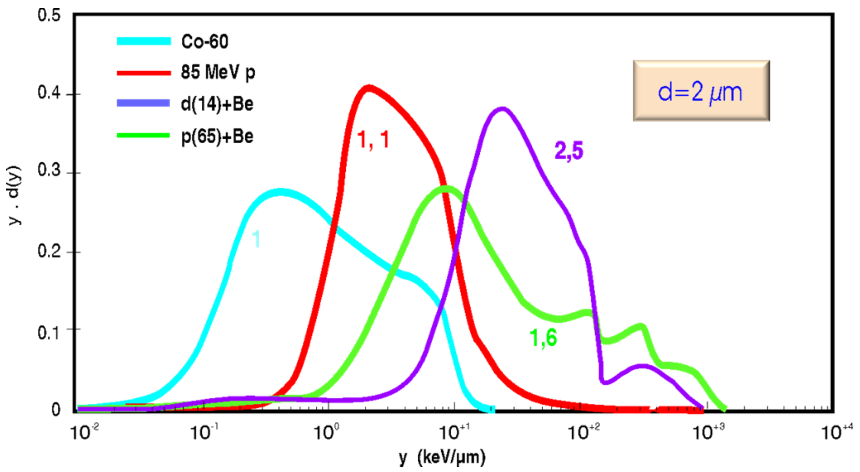

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Determination of the microdosimetric weighting function *r(y)* based on *RBE* data

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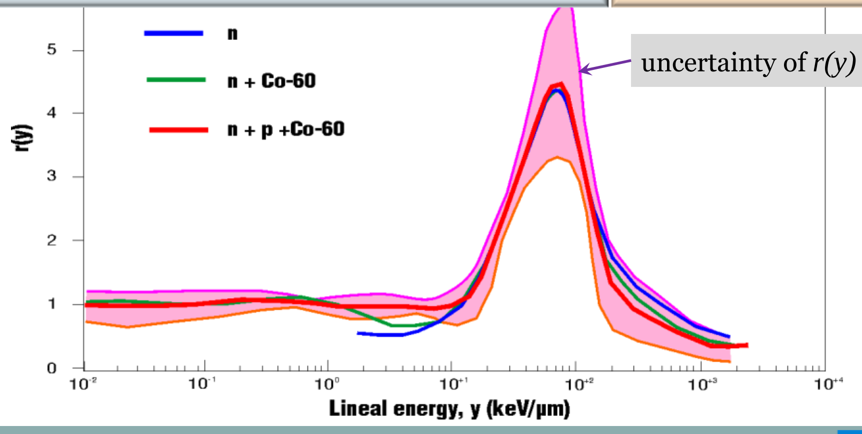
Task: Find function *r(y)* that gives *RBE* when used for weighting the dose frequency distribution of *y*.

$$\int r(y) d_i(y) dy \approx RBE_i$$



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What is the size of the critical biological target?

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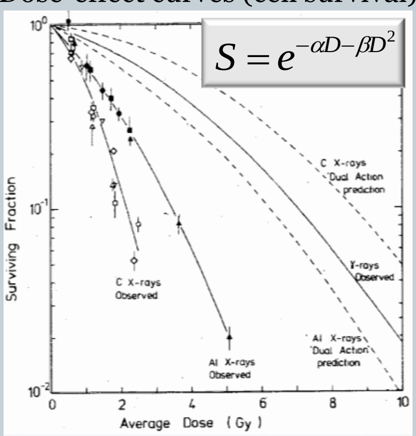
Dose-effect curves (cell survival)



$$S = e^{-\alpha D - \beta D^2}$$

Source: Goodhead, 1980

Reminder:

- Specific energy z is a stochastic quantity.
- Its mean $\bar{z}$ is equal to absorbed dose D.
- Frequency mean and dose mean specific energy are
  - deterministic quantities,
  - related to single events,
  - dependent on site size.

What is the size of the critical biological target?

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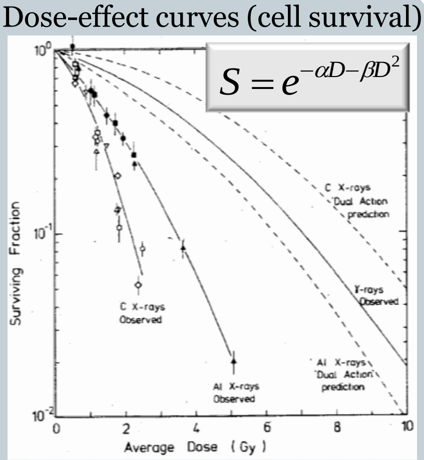
Dose-effect curves (cell survival)

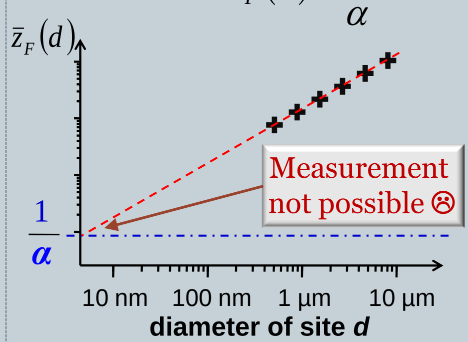


$$S = e^{-\alpha D - \beta D^2}$$

Source: Goodhead, 1980

Question:

- For which value of site size d do we have $\bar{z}_F(d) \approx \frac{1}{\alpha}$?



Summary: Microdosimetry and Biology

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- Microdosimetric characterisation of radiation quality adapted to cell dimensions in the micrometer range.
- This was considered in the past to derive radiation quality factors (ICRU report 40).
- Lineal energy spectra may be linked to relative biological effectiveness by a universal biological response function.
- There are hints that microdosimetric quantities relate to biological dose-response parameters when determined in sites of few nanometer size.

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Nanodosimetry

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Radiation interaction in nanometer dimensions

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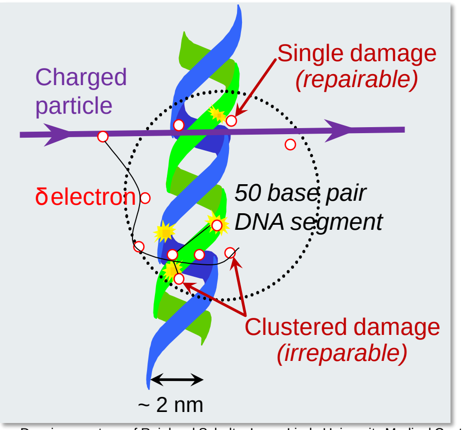
- DNA is the primary target for radiation-induced damage
- Random event
- Single damage easily repaired (breaks, base damages)
- Clustered damage difficult to repair → mutation, apoptosis



Drawing courtesy of Reinhard Schulte, Loma Linda University Medical Center

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Importance of particle track structure

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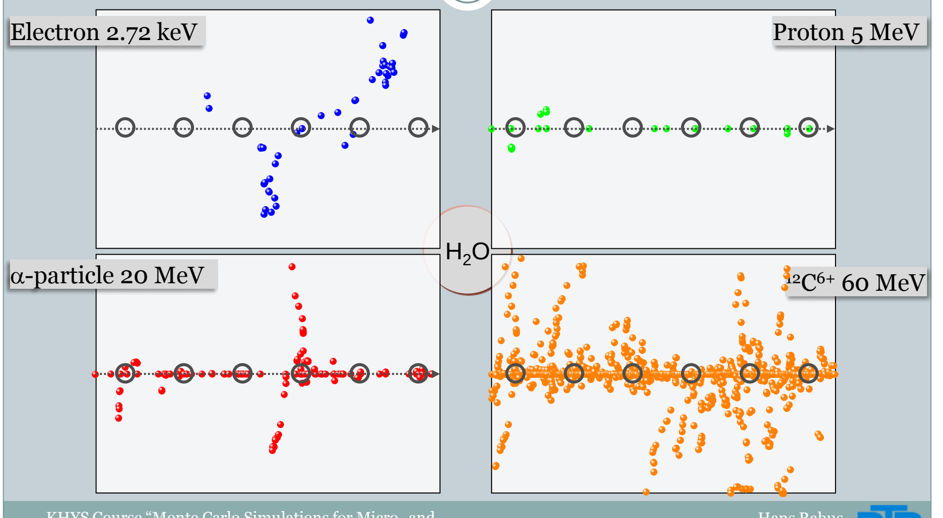

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Microdosimetry in sub-micrometer dimensions?

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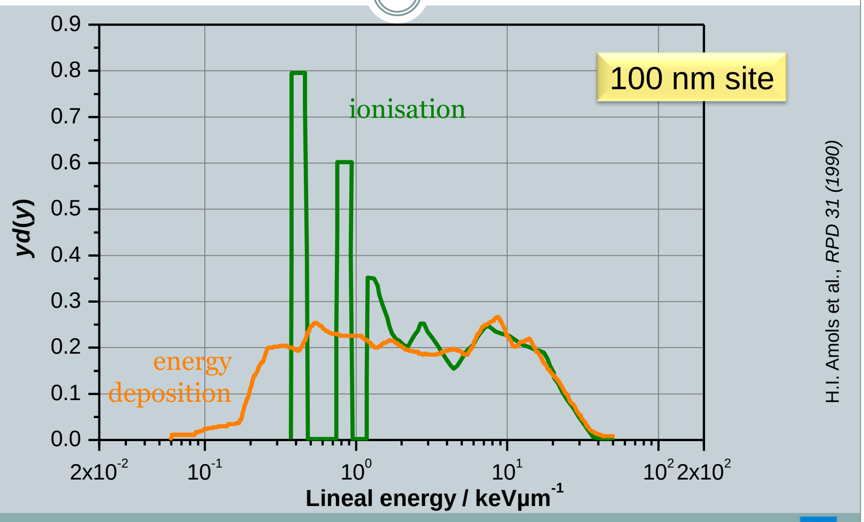

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Microdosimetry in sub-micrometer dimensions?

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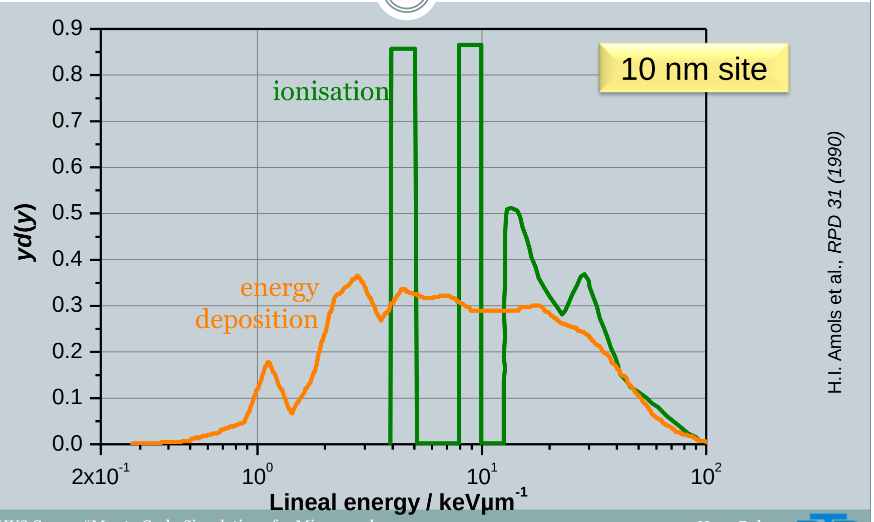

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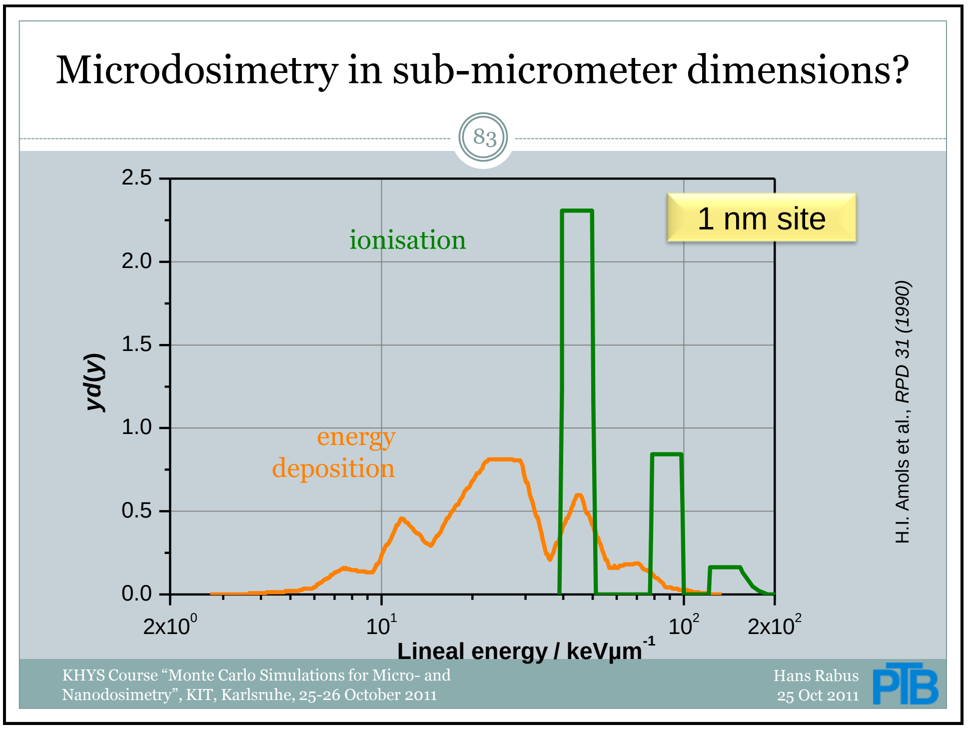
Microdosimetry in sub-micrometer dimensions?
83
1 nm site
ionisation
energy
deposition
yd(y)
2.5
2.0
1.5
1.0
0.5
0.0
2x10^0
10^1
10^2
2x10^2
Lineal energy / keVμm^-1
H.I. Amols et al., RPD 31 (1990)
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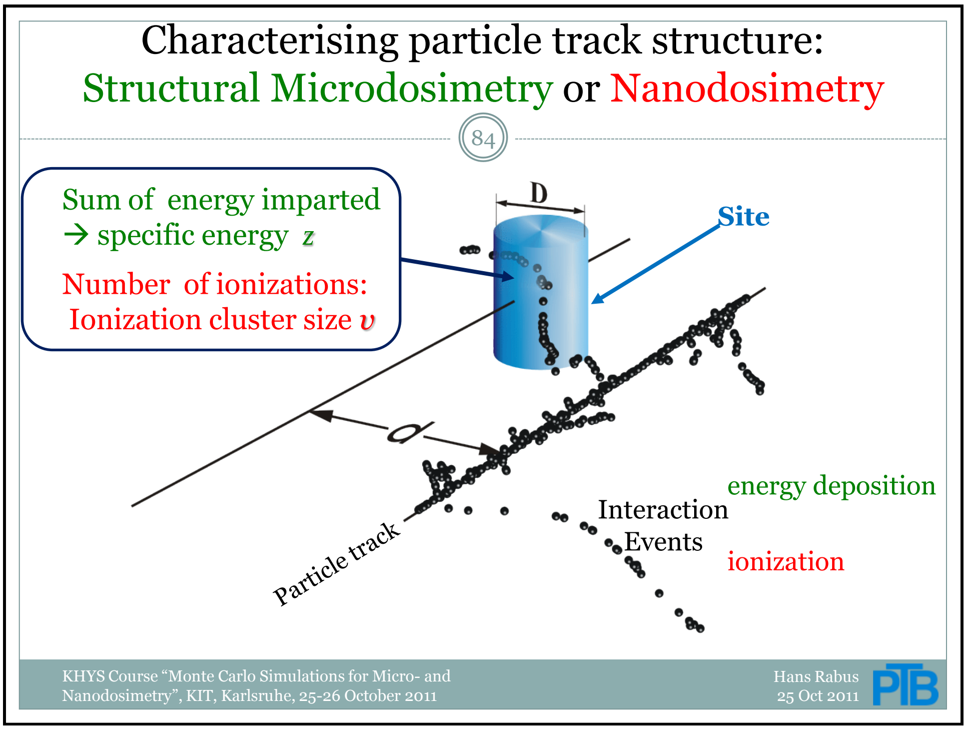
Characterising particle track structure:
Structural Microdosimetry or Nanodosimetry
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Sum of energy imparted
→ specific energy z
Number of ionizations:
Ionization cluster size ν
D
Site
d
Particle track
Interaction
Events
energy deposition
ionization
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Ionisation cluster size distributions

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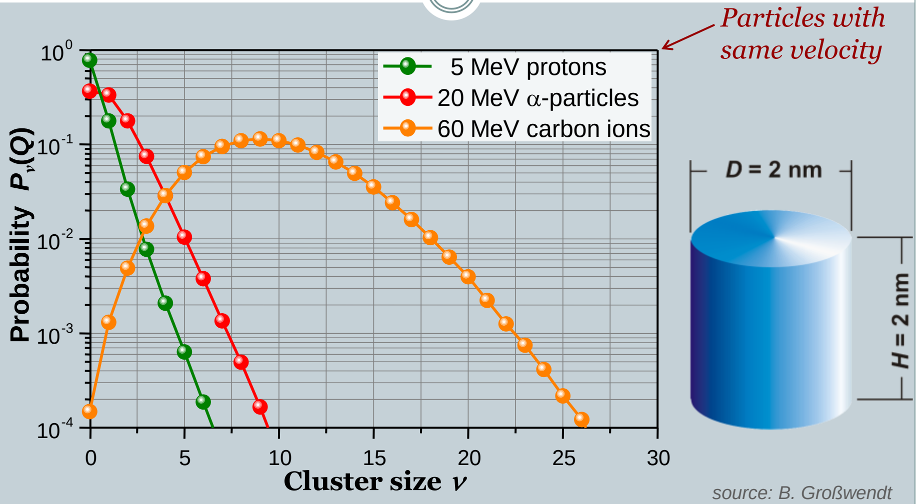

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Measuring ionisation cluster size

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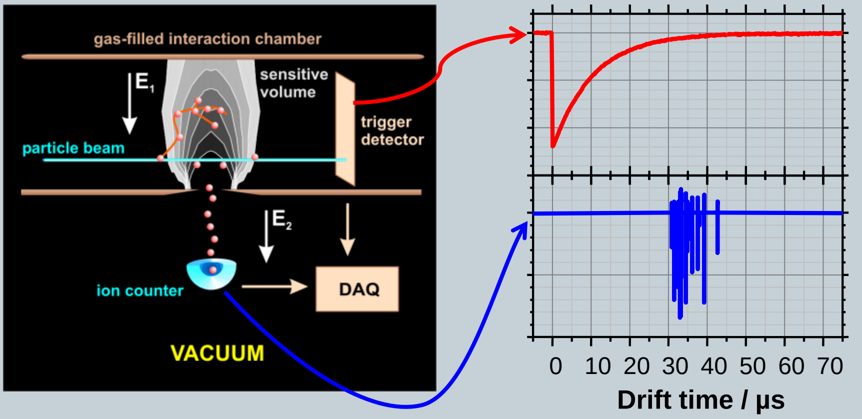

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Ionization cluster-size distributions

Measurement in a gas target equivalent to a DNA segment

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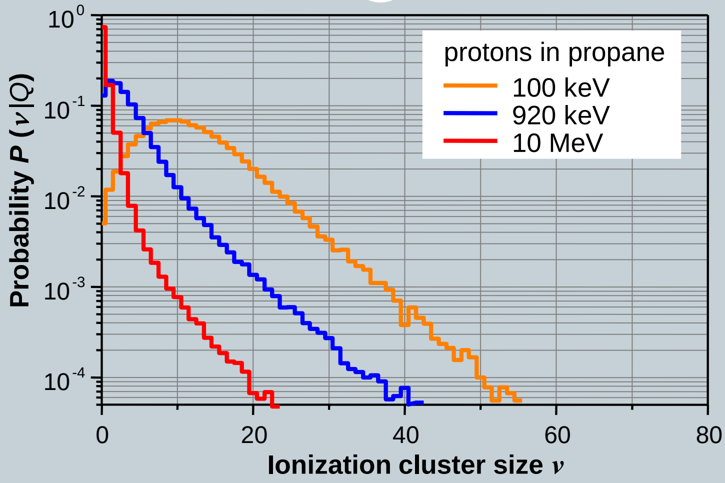
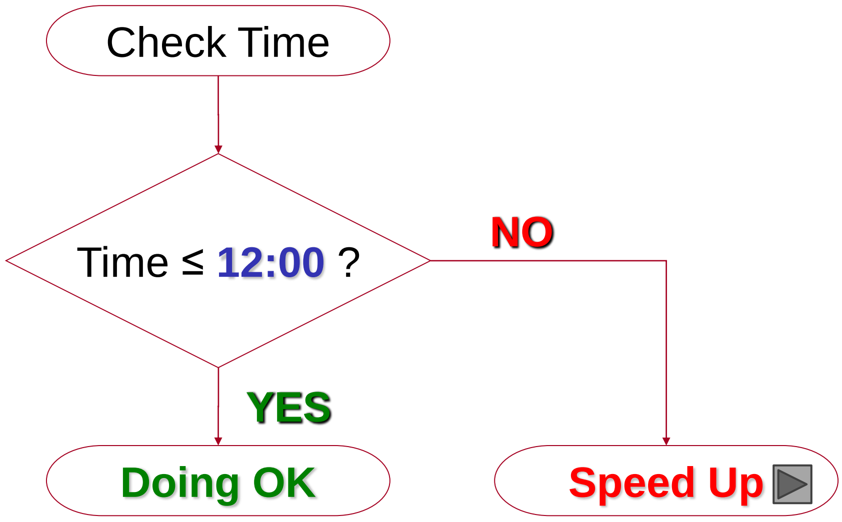
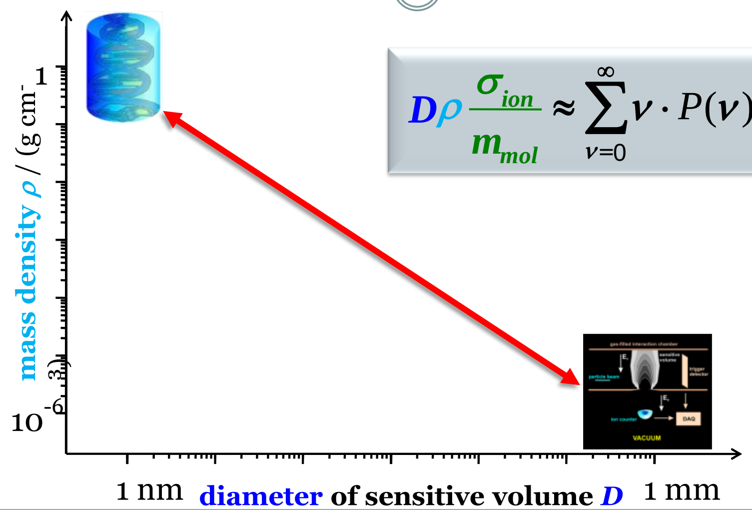




Scaling of track structure characteristics

89



$$D\rho \frac{\sigma_{ion}}{m_{mol}} \approx \sum_{\nu=0}^{\infty} \nu \cdot P(\nu)$$

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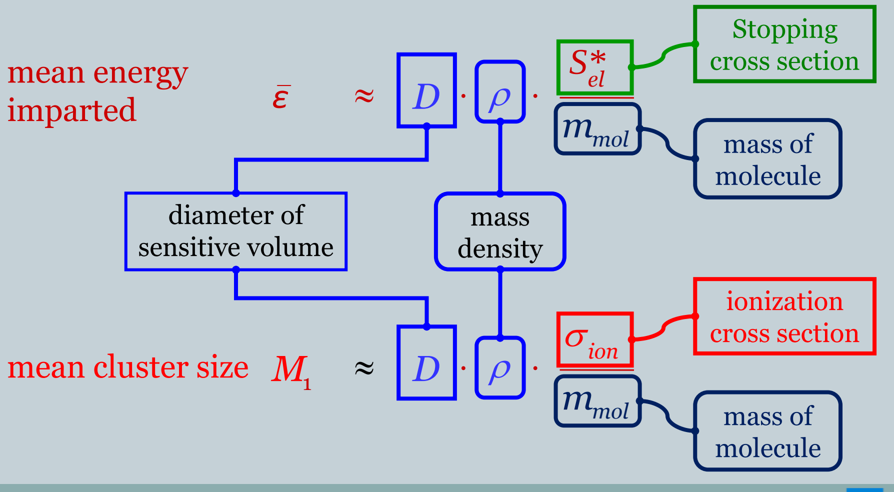
Measurement of track structure using gas detectors relies on scaling relations

90



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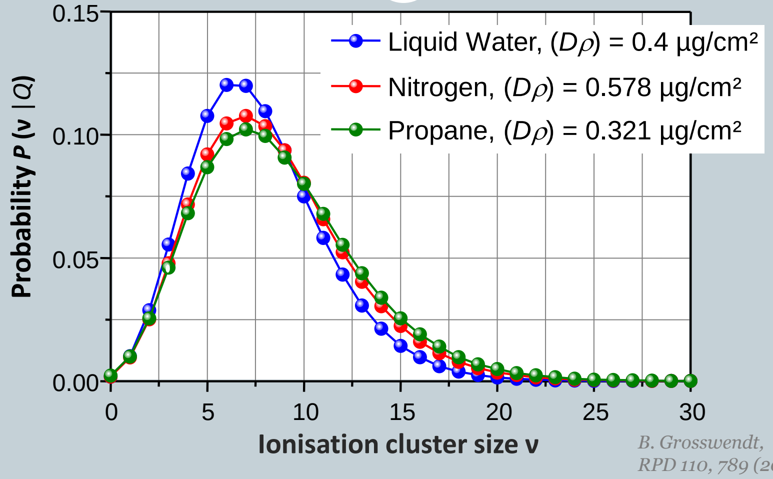
Scaling ionization cluster-size distributions

for 4.6 MeV α-particles



B. Grosswendt, RPD 110, 789 (2004)

Nanodosimetry and Radiobiological Effectiveness

Nanodosimetry and biological effectiveness

Two different approaches:

1. *Initial biological effectiveness of a radiation quality is directly related to physical track structure parameters.*

   B. Grosswendt, Radiat. Prot. Dosim. 115, 1-9 (2005)

2. *Each ionisation (in DNA or its vicinity) has a fixed probability to be converted into a strand break.*

   G. Garty et al., Phys. Med. Biol. 55, 761-781 (2010)

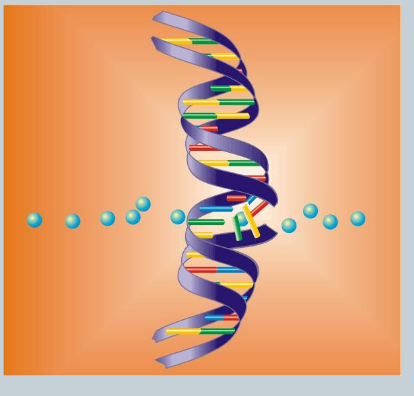
Estimators of biological effectiveness from nanodosimetry: (1) Grosswendt's approach

Hypothesis 1:

The probability P_1 to produce an ionisation cluster of size $\nu = 1$ in a short DNA segment

is proportional to

the probability P_{SSB} for a single strand break.



Estimators of biological effectiveness from nanodosimetry: (1) Grosswendt‘s approach

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Hypothesis 2:

The probability F_2 to produce an ionisation cluster of size $\nu \geq 2$ in a short DNA segment

is proportional to

the probability P_{DSB} for a double strand break.

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Estimators of biological effectiveness from nanodosimetry: (1) Grosswendt‘s approach

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Hypothesis 1:

The probability P_1 to produce an ionisation cluster of size $\nu = 1$ in a short DNA segment

is proportional to

the probability P_{SSB} for a single strand break.

Hypothesis 2:

The probability F_2 to produce an ionisation cluster of size $\nu \geq 2$ in a short DNA segment

is proportional to

the probability P_{DSB} for a double strand break.

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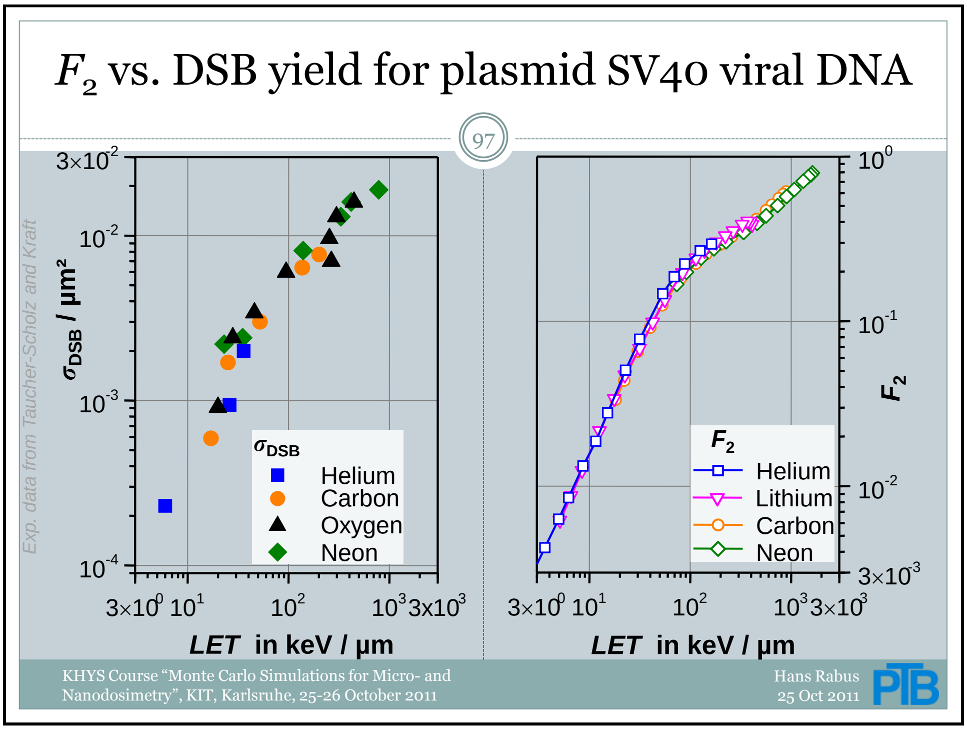
F2 vs. DSB yield for plasmid SV40 viral DNA
97
Exp. data from Taucher-Scholz and Kraft
σDSB / µm²
3×10-2
10-2
10-3
10-4
σDSB
Helium
Carbon
Oxygen
Neon
3×10^0 10^1 10^2 10^3 3×10^3
LET in keV / µm
F2
Helium
Lithium
Carbon
Neon
10^0
10-1
10-2
3×10-3
3×10^0 10^1 10^2 10^3 3×10^3
LET in keV / µm
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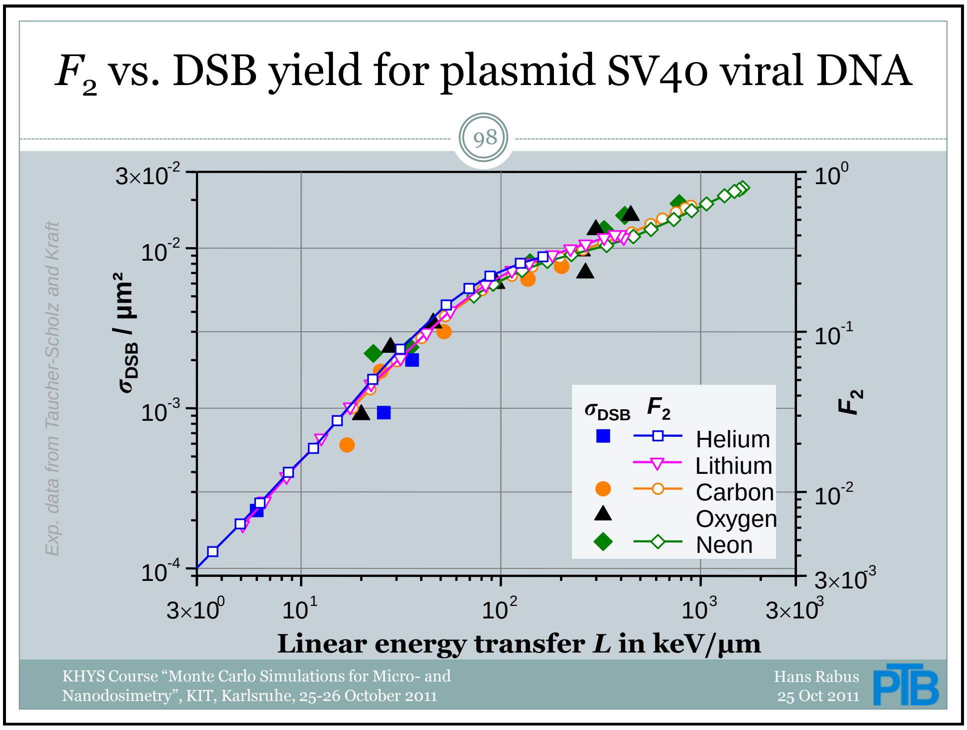
F2 vs. DSB yield for plasmid SV40 viral DNA
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σDSB / µm²
3×10-2
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σDSB F2
Helium
Lithium
Carbon
Oxygen
Neon
10^0
10-1
10-2
3×10-3
F2
3×10^0 10^1 10^2 10^3 3×10^3
Linear energy transfer L in keV/µm
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Estimators of biological effectiveness from nanodosimetry: (2) Garty's approach

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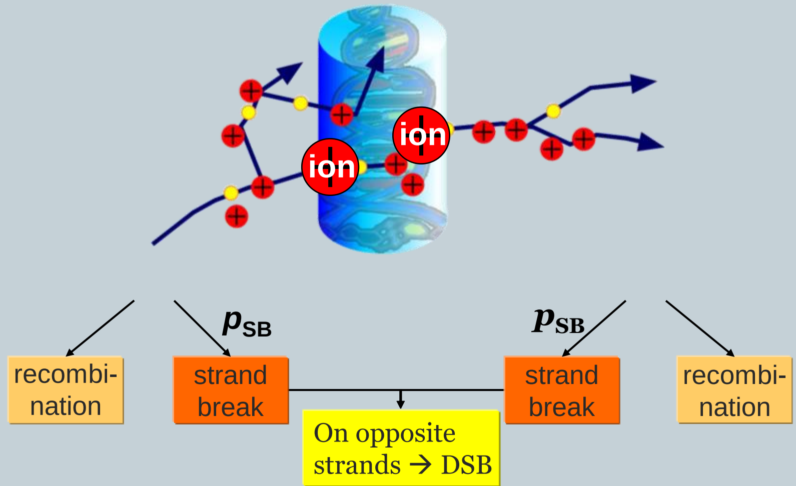
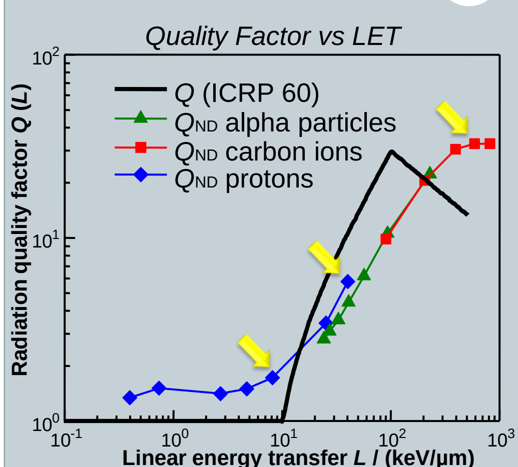


Nanodosimetric radiation quality factor Q_{ND}

100



Q_{ND} is the ratio of complex DSBs to those for 100 keV electrons derived from

- simulated ionisation cluster-size distributions
- Garty's model and a plasmid DNA assay

Reproduces ICRP 60 curve, *except…*

Outlook: Micro- *and* nanodosimetry

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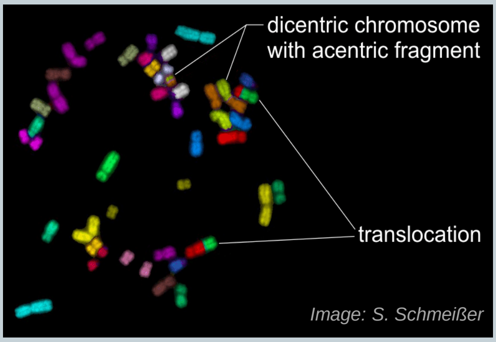
- Improving particle track structure codes

  → *Cross sections for DNA constituents instead of water*

- Relate track structure properties (e.g. F_2) to radiobiological yields
- Multi-scale characterisation of track structure



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Overall Summary:

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- Microdosimetry and nanodosimetry properties of radiation quality (particle track structure) are statistical distributions.
- Microdosimetric and nanodosimetric simulation should score these distributions, not only the deterministic mean values.
- Be aware that these distributions depend on the choice of the target volume (called the 'site').
- There is no 'official' link between micro-/nanodosimetry and radiation protection quanties, even though nanodosimetry-based quality factors can reproduce the ICRP60 curves.
- If you do micro-/nanodosimetric simulations and want to derive radiation protection quantities, be aware of their definitions (w_R and w_T factors) and describe explicitly and clearly what you derived and how.

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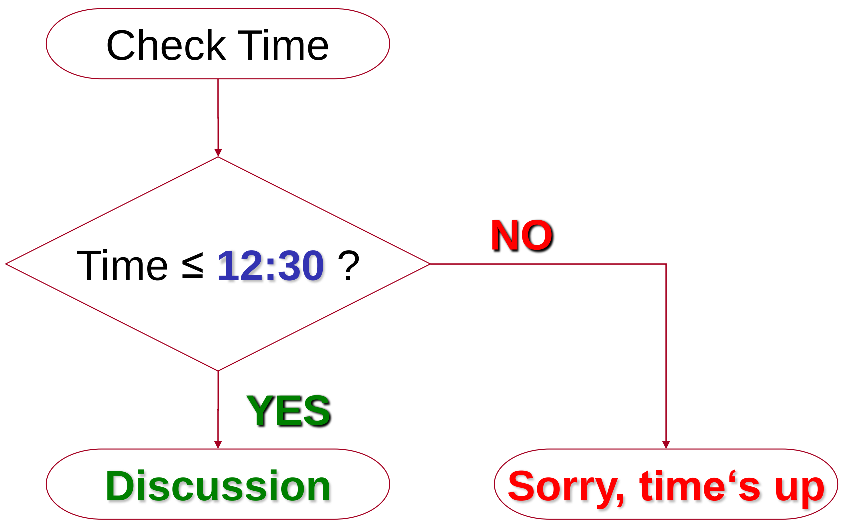

Thank you

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FOR YOUR ATTENTION!