

Nuclear measurement techniques. Dosimetry, radiation protection.



Basic definitions

Reminder

- Nuclear radiation:
 - Produced in the transition of the nucleus
 - α (He^{2+}), β (e^{-}, e^{+}), γ (em.), ... radiation
- Isotope (same atomic number, different mass number)
- Radioactive isotope (unstable, decays, emits radiation)
- Activity ($\text{Bq} = \text{decay/s}$)
- Exponential decay law

Interaction of the nuclear radiation with the matter

nuclear radiation — absorption
detection

interaction \Rightarrow energy transfer

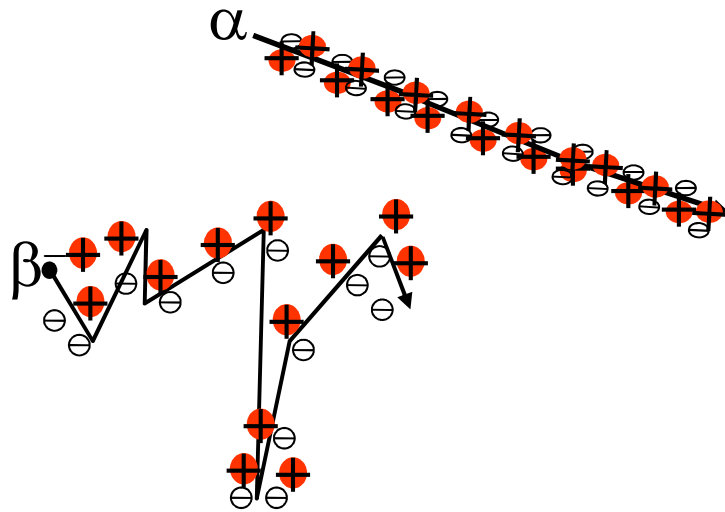
$\left. \begin{matrix} \alpha \\ \beta \end{matrix} \right\}$ charged \rightarrow direct ionisation

γ
x-ray } uncharged \rightarrow indirect ionisation

Reminder

Attenuation of nuclear radiations

charged

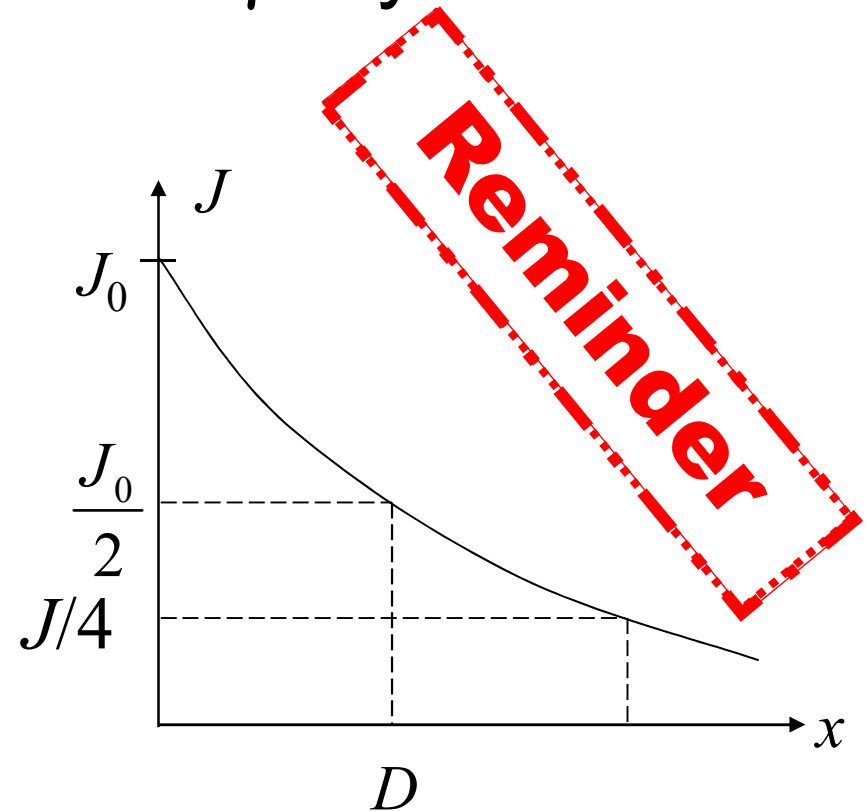


Ionisation \Rightarrow energy loss:

Runs out of the energy
on a finite distance.

effective range

γ -ray



Exponential attenuation law
no effective range

Detection of the ionizing radiation

scintillation based methods

gas-ionization detectors

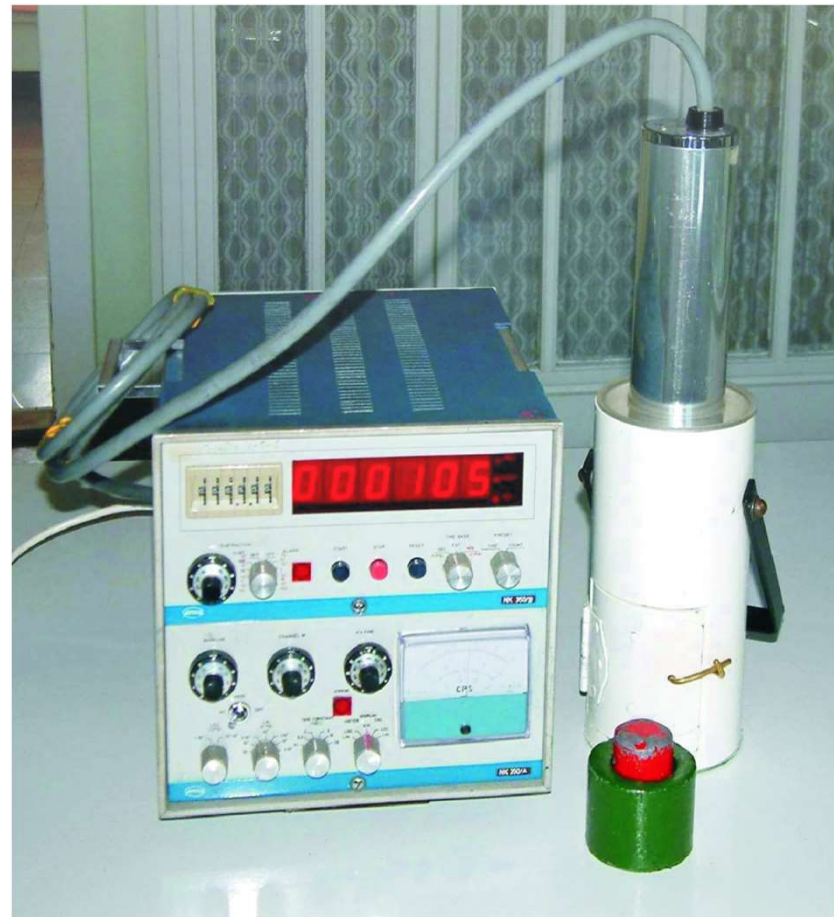
thermoluminescent dosimeter

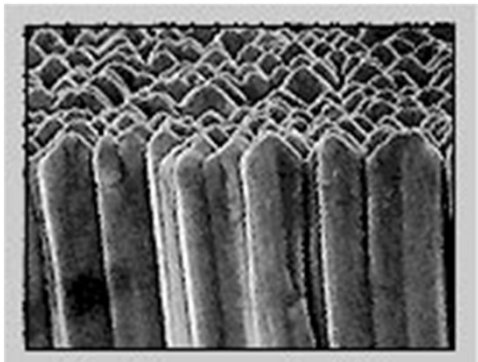
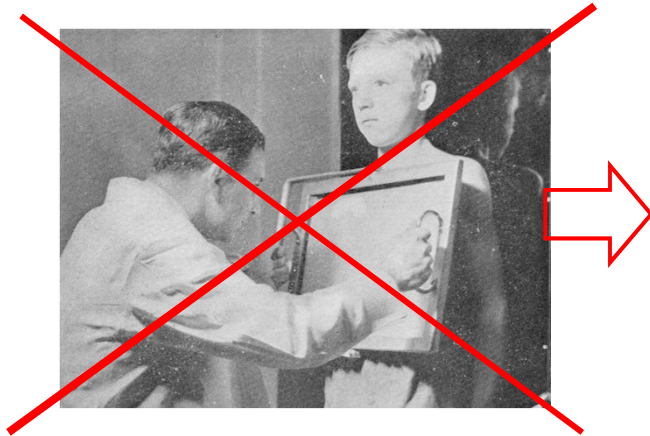
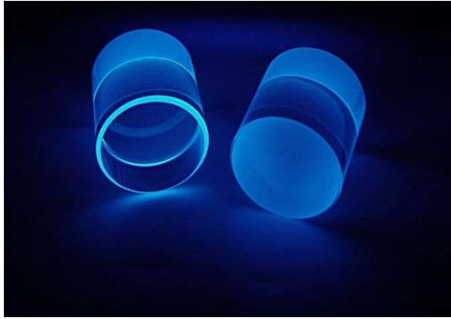
~~photographic methods (film)~~

semiconductor detectors

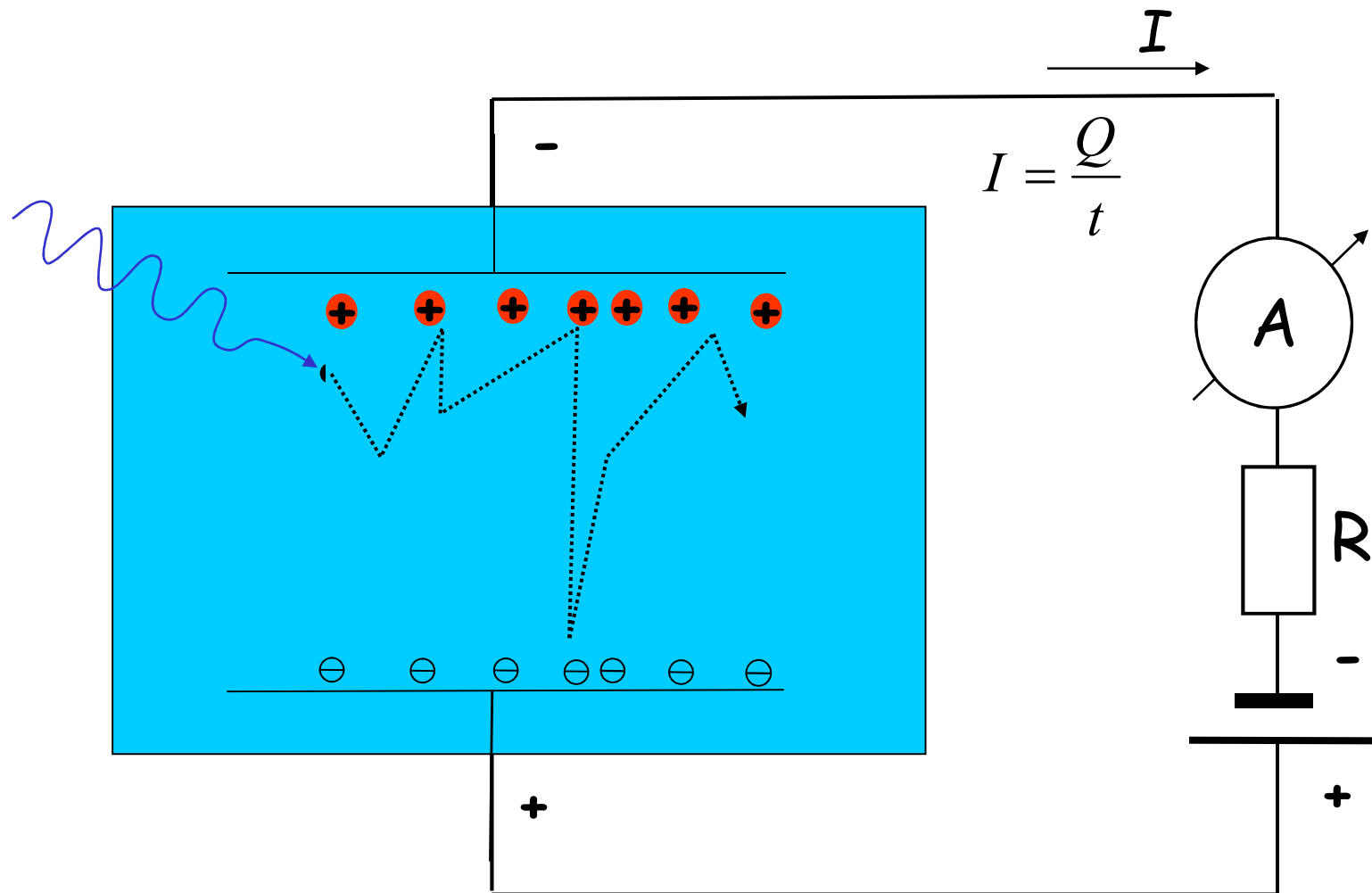
Scintillation counter

see practical
exercises!



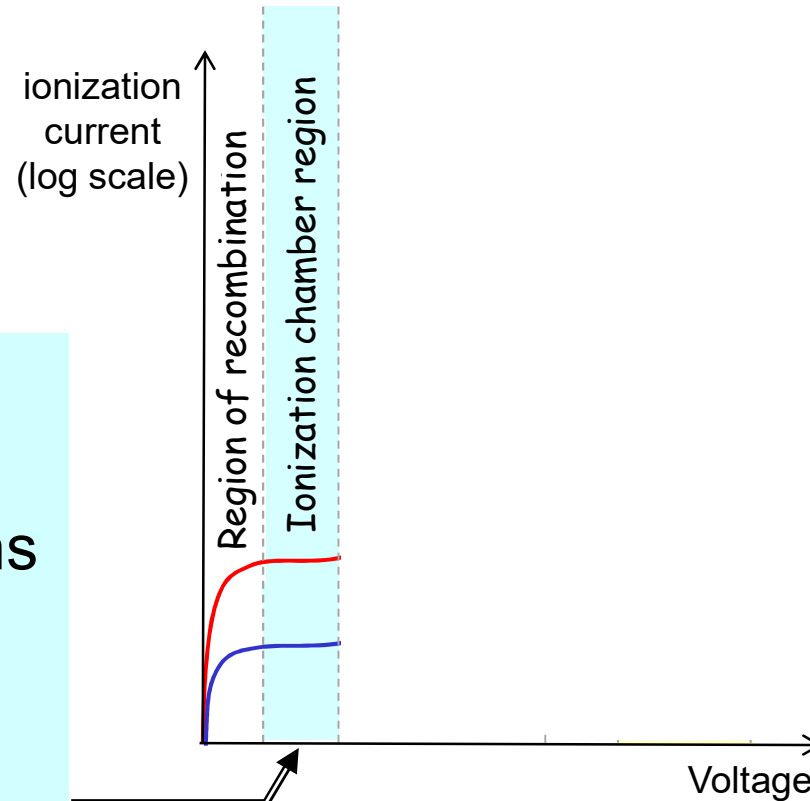


Gas-ionization detectors

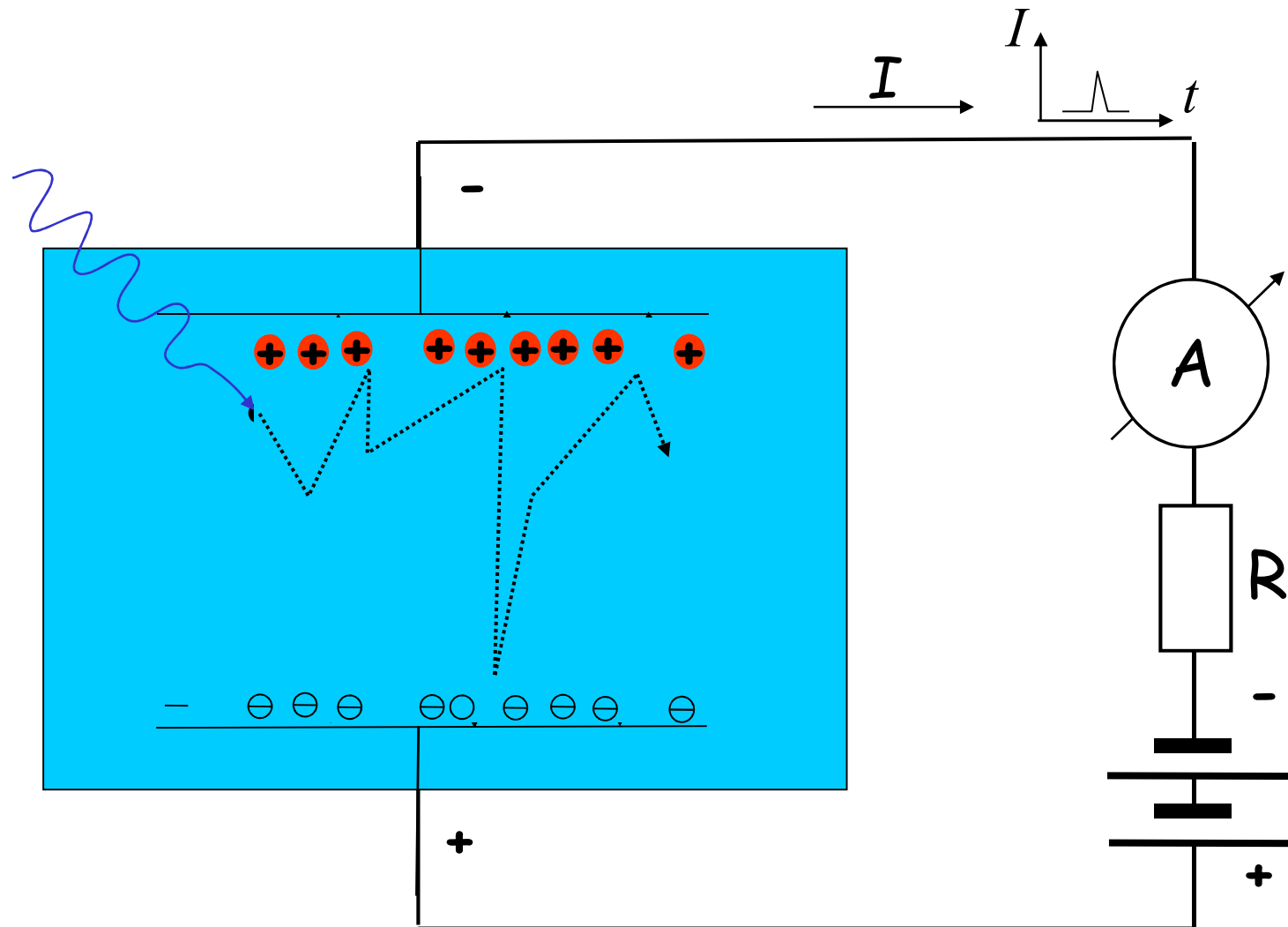


Gas-ionization detectors

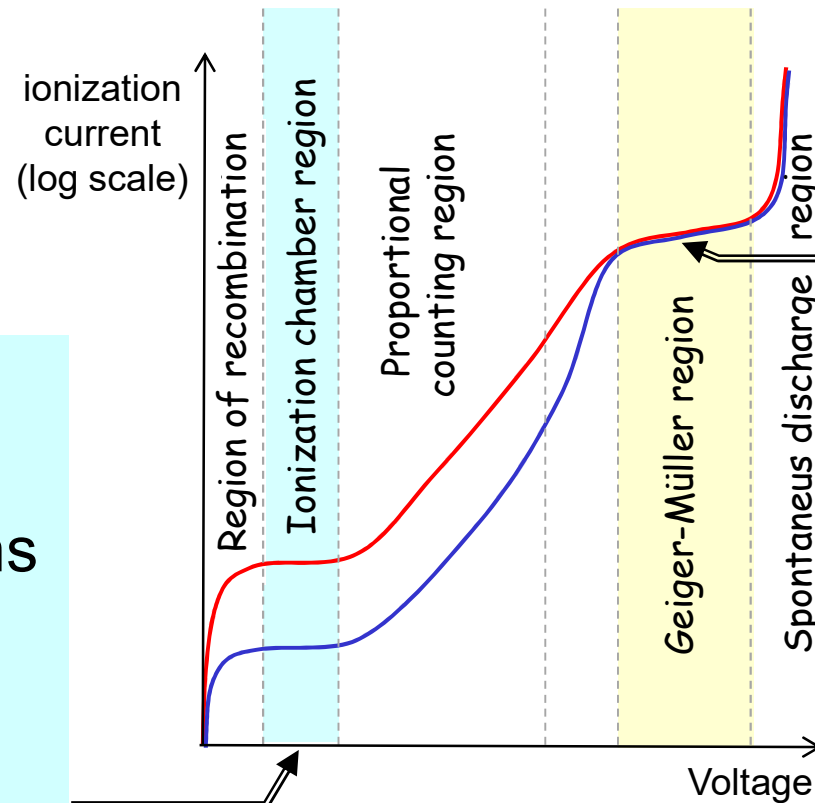
Ionization chamber:
collects all the ions
Measures the
ionizing effect
of the radiation
see: dosimetry



Gas-ionization detectors



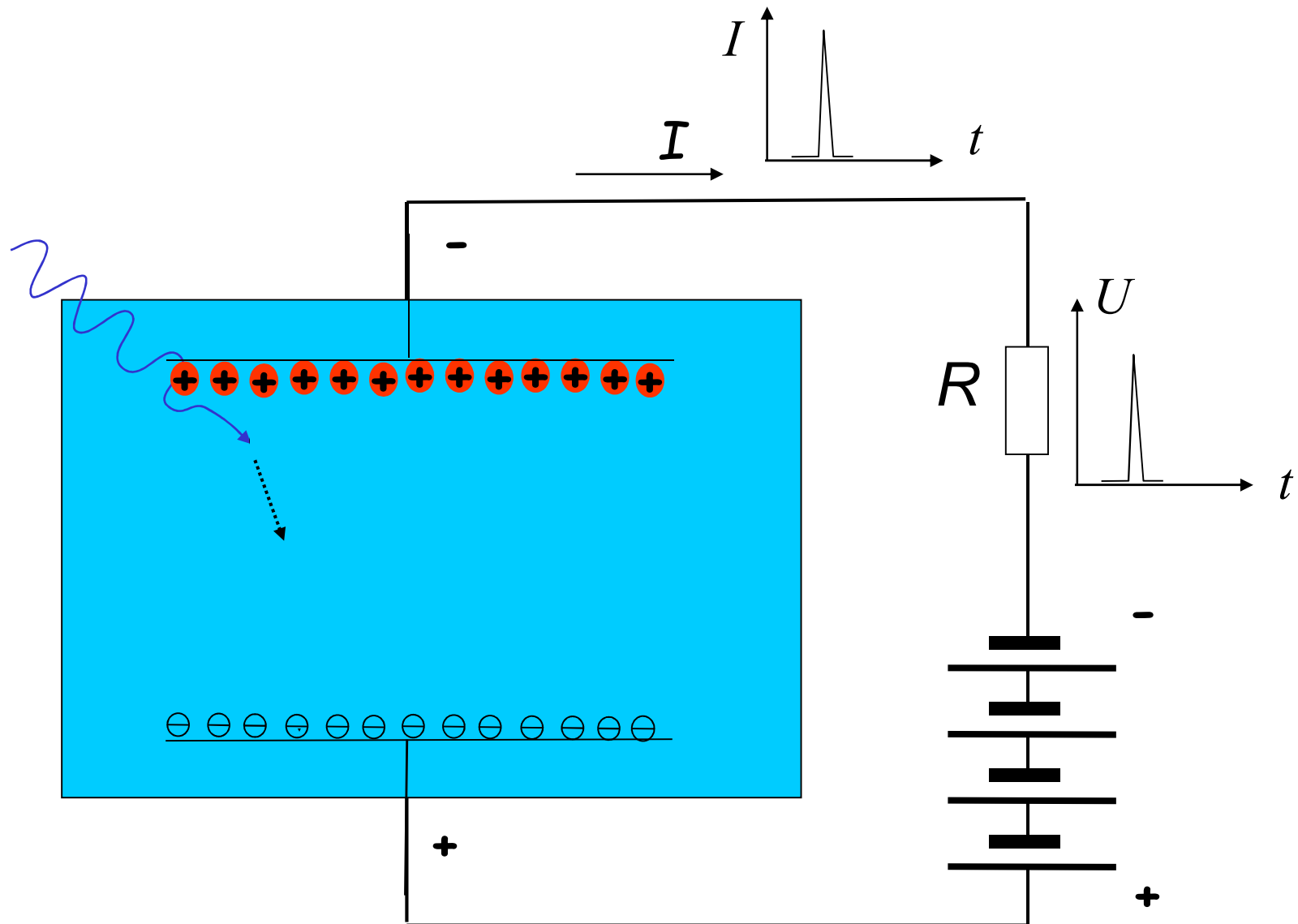
Gas-ionization detectors



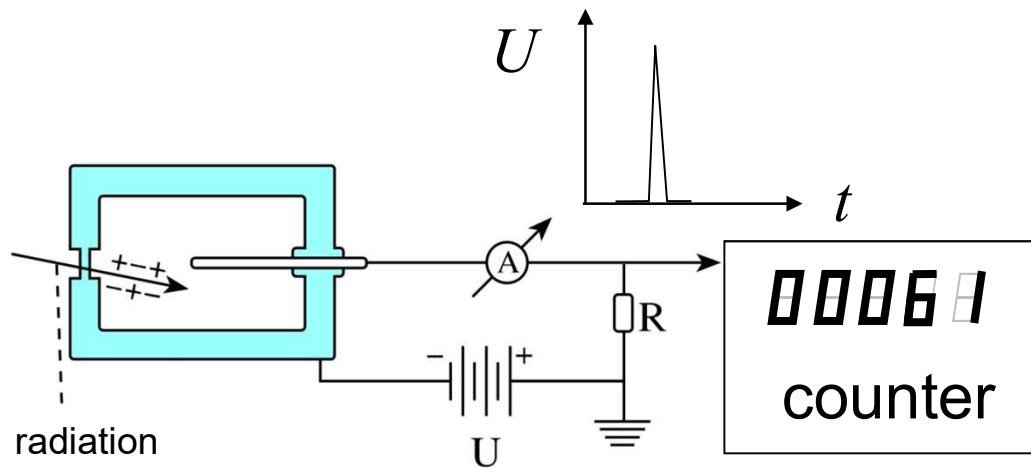
Ionization chamber:
collects all the ions
Measures the ionizing effect of the radiation
see: dosimetry

Geiger-Müller
range:
avalanche-effect:
particle
↓
voltage pulse

Geiger-Müller tube



G-M tube

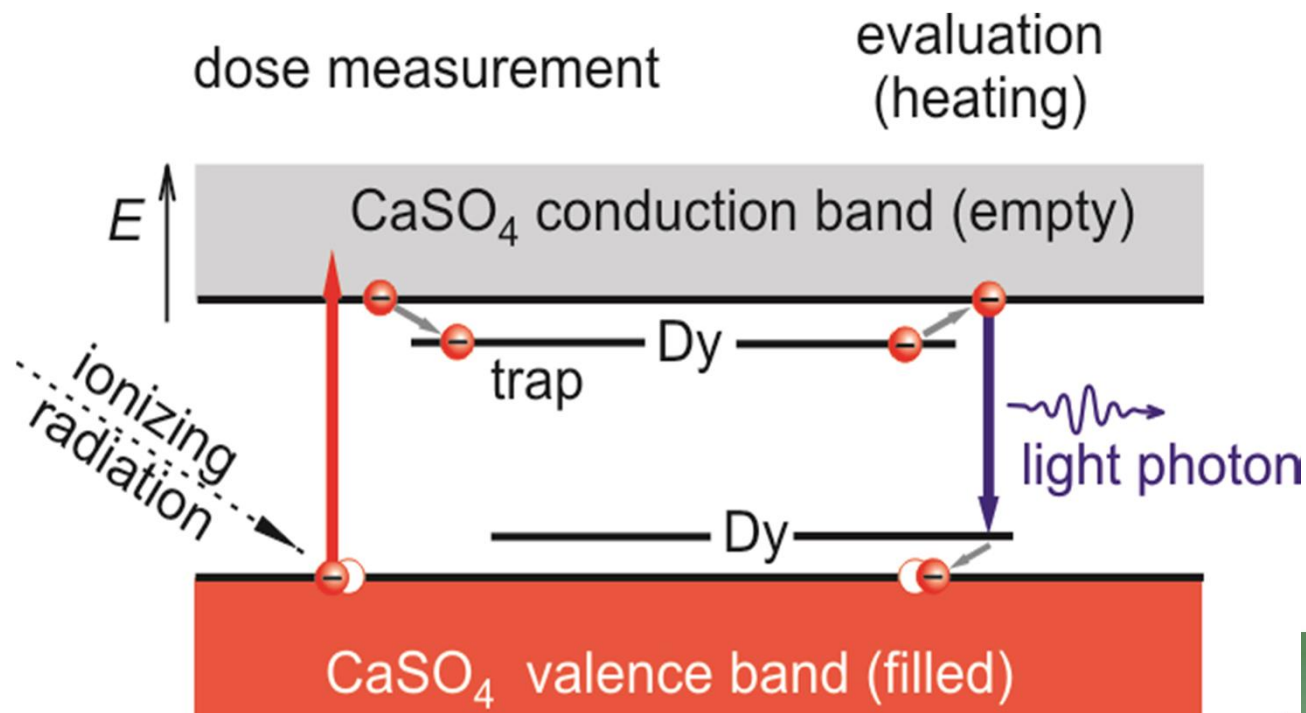


advantage: simple construction,
disadvantage: no energy selectivity,
low efficiency for γ -ray

usage: mainly in dosimetry



Thermoluminescent dosimeter (TLD)





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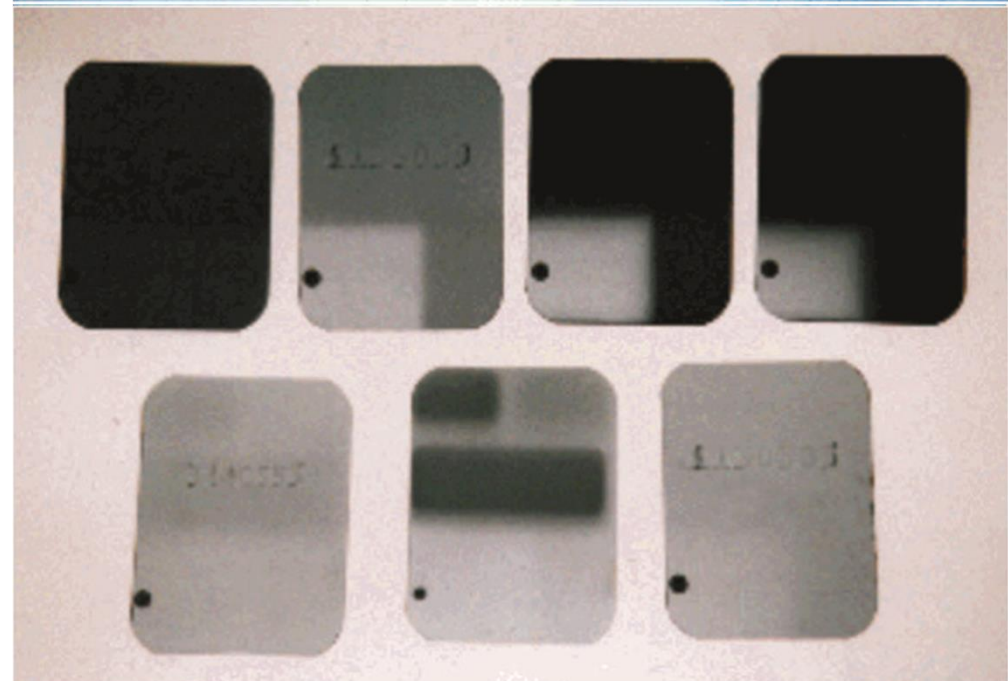
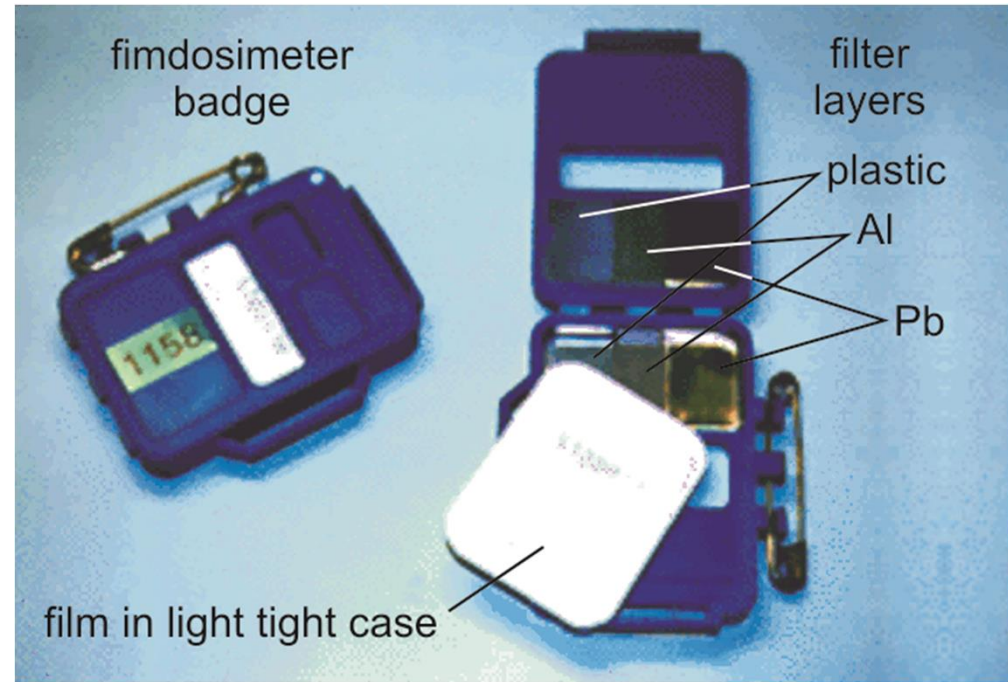
**An american astronaut uses the TLD dosimeter „Pille” produced by KFKI Budapest
(Photo: NASA ISS002E7814)**

Personal dosimeters



Photochemical detection

obsolete

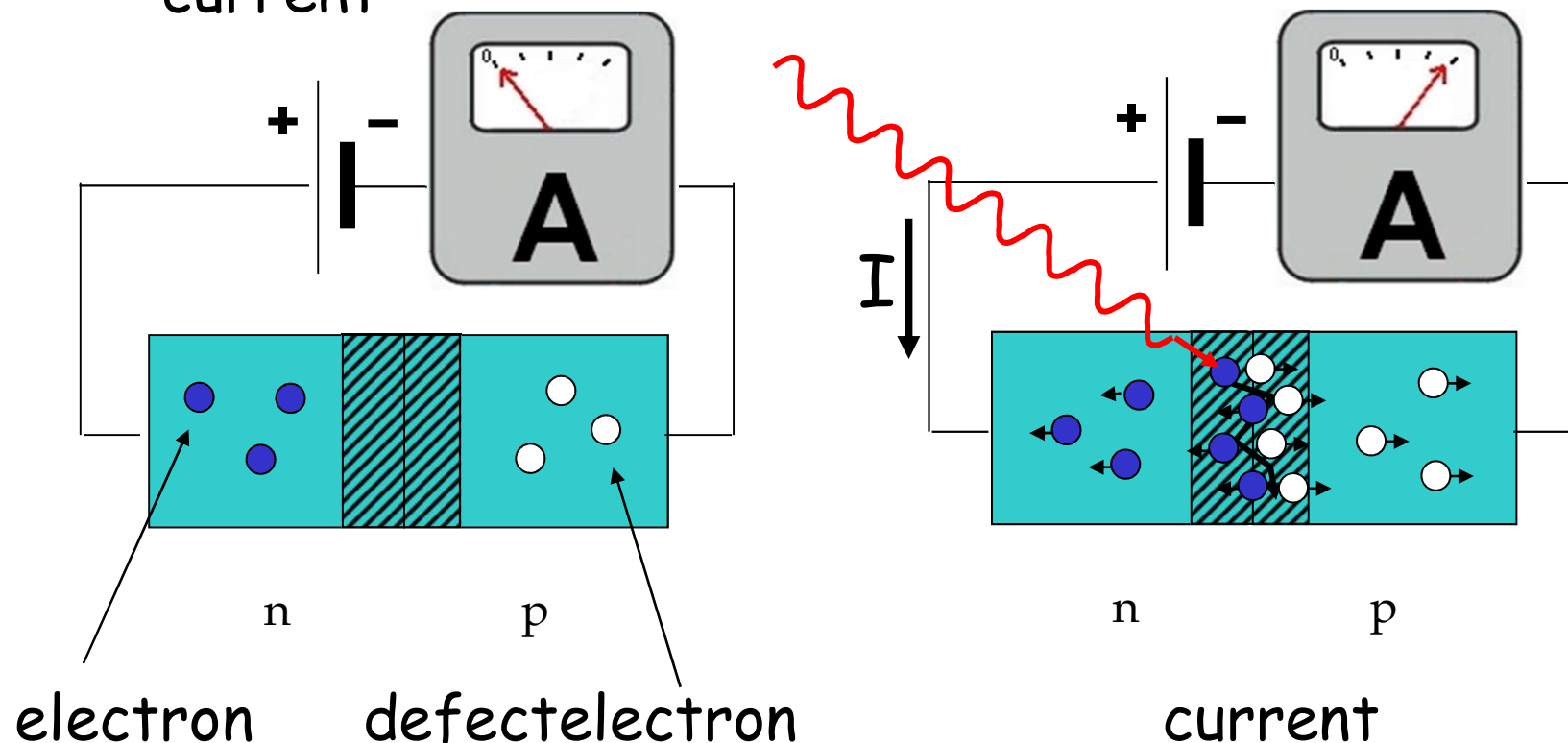


Semiconductor detector

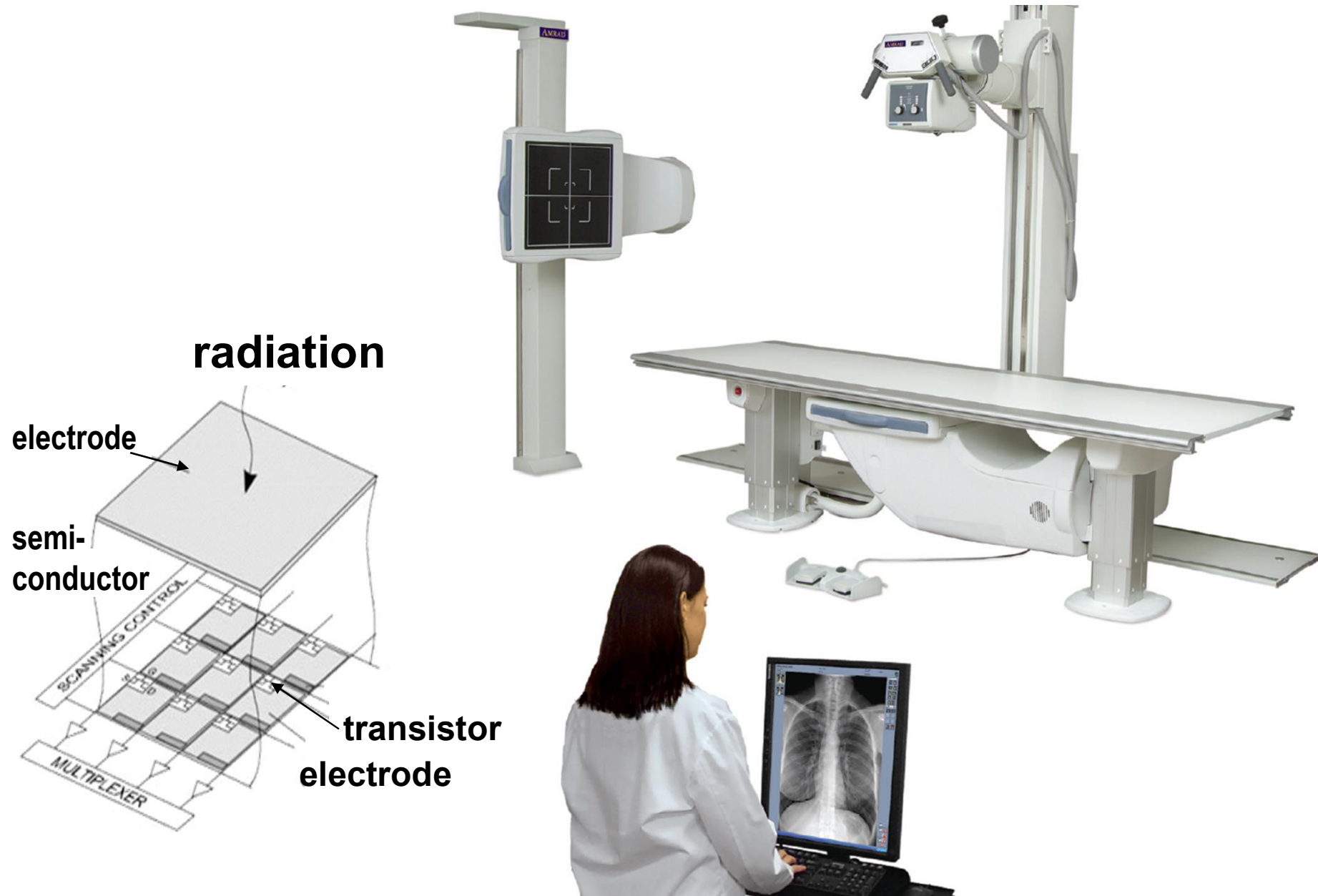
Principle:

Semiconductor diode connected reverse biased

The radiation induces free charges and consequently current



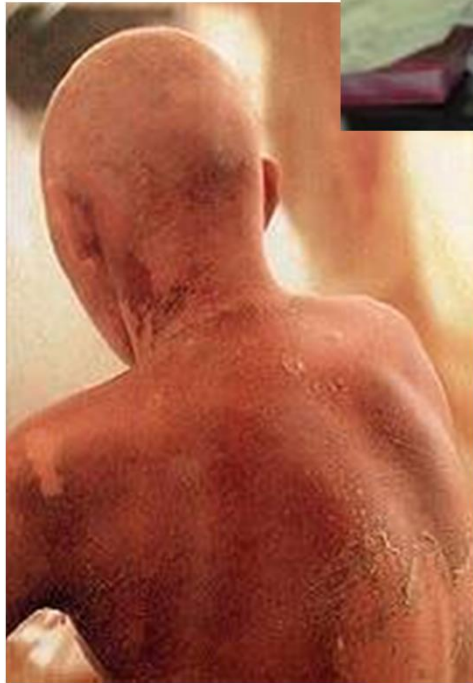
Semiconductor detectors in the diagnostics



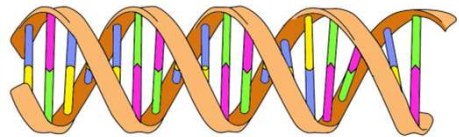
Semiconductor based dosimeters



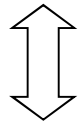
Biological effect of the ionizing radiation



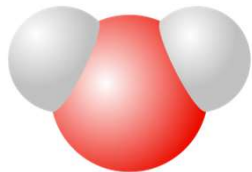
The mechanism of the radiation damage



direct



indirect



Physical phase:

10^{-17} - 10^{-12} s ionisation

Chemical (biochemical) phase:

10^{-10} - 1s: free radical reactions

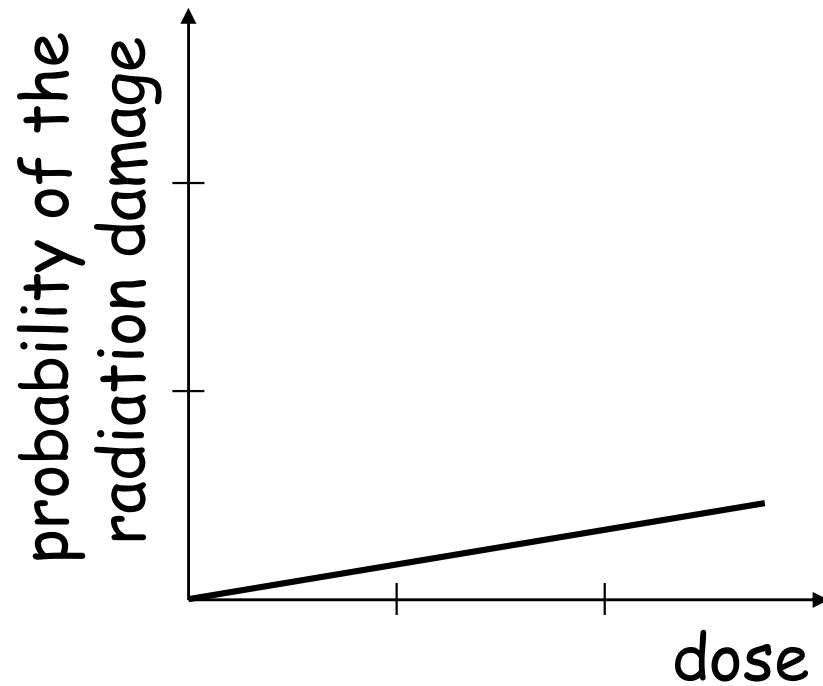
Biological phase:

hours: alteration in the tissues

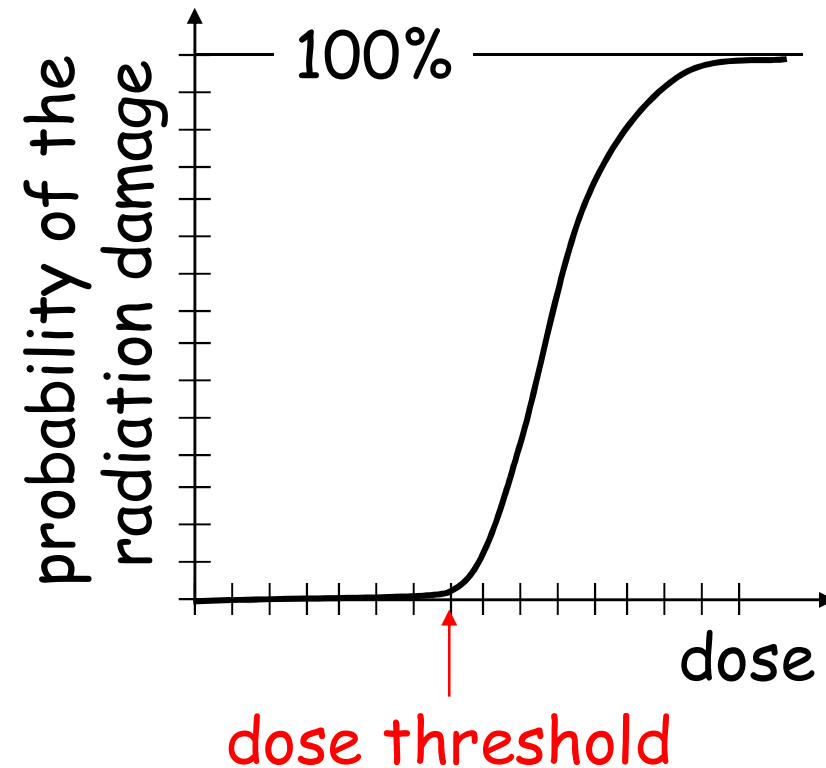
days-years: stomach-bowel
damage of the
haematogenesis
somatic damage

Mechanism of radiation damage

Stochastic

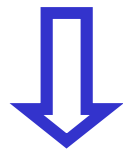


Deterministic



Stochastic

already at low dose level
small number of targets
no dose threshold
severity is independent
of the dose



personnel at workplaces
using ionisation
radiation,

patients of X-ray and
nuclear imaging
investigations

Deterministic

High dose (>threshold)
many targets should be hit
only above the threshold
severity increases with the
increasing dose



accidents

Radiotherapy

Dose concepts

Absorbed dose:

$$D = \frac{\Delta E}{\Delta m}$$

The energy
absorbed from
the radiation by
the mass Δm

unit J/kg = Gy

⇒ absorbed energy by unit mass of
absorbing medium

can be used for all types of radiations



Luis Harold Gray

Absorbed dose :

$$D = \frac{\Delta E}{\Delta m} \quad [\text{Gy}]$$

How to measure:

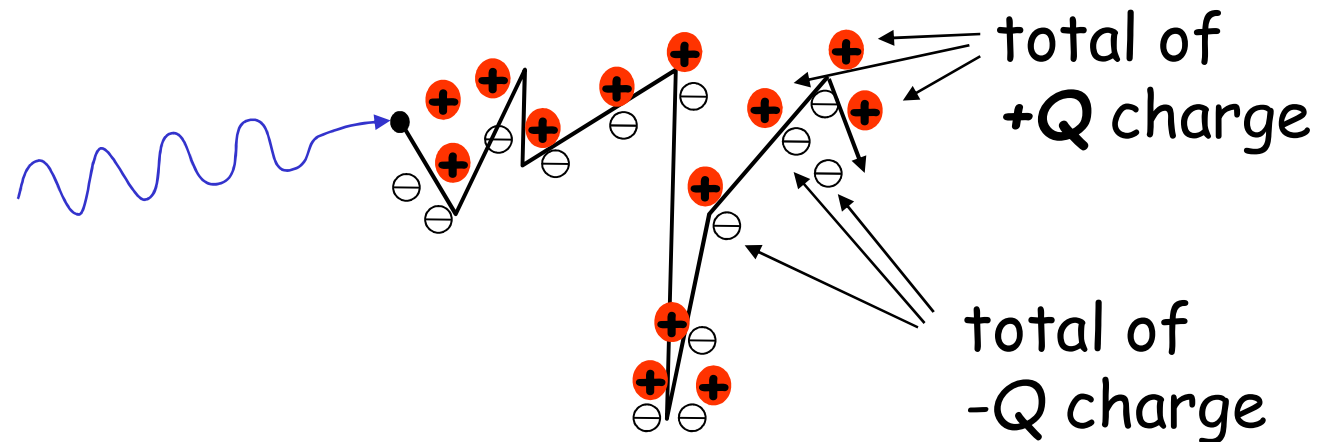
- hard to measure directly (unmeasurably small temperature change $\Delta T = 0,006^\circ\text{C}/4 \text{ Gy}$)
- indirect detection methods:
 - ionisation chamber
 - semiconductor detector
 - thermoluminescent detector
 - ...

Exposure:

$$X = \frac{\Delta Q}{\Delta m}$$

*the positive charge
produced in the air
of mass Δm*

unit: C/kg

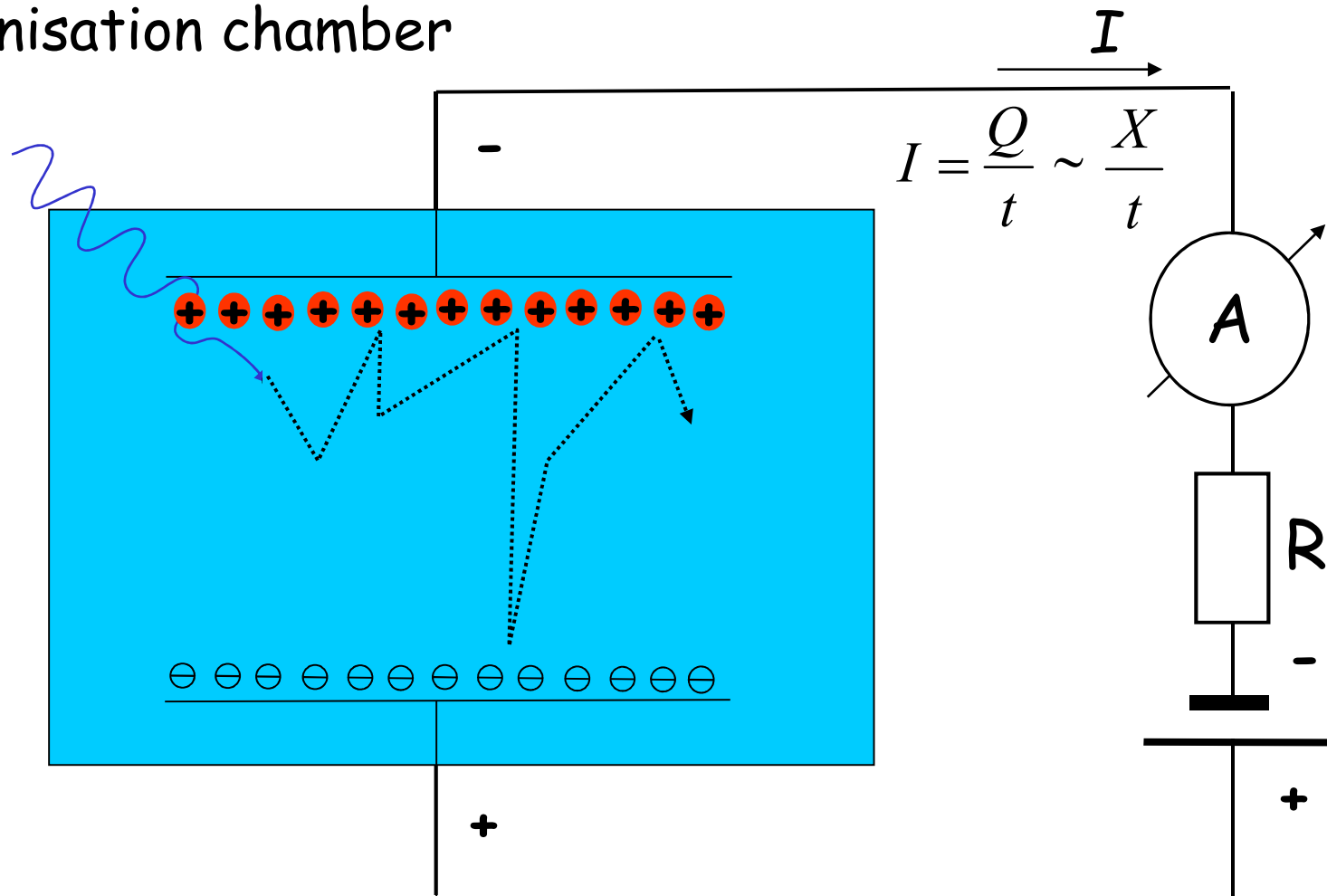


Olny for γ - and x-ray in air!

How to measure the exposure:

$$X = \frac{\Delta Q}{\Delta m}$$

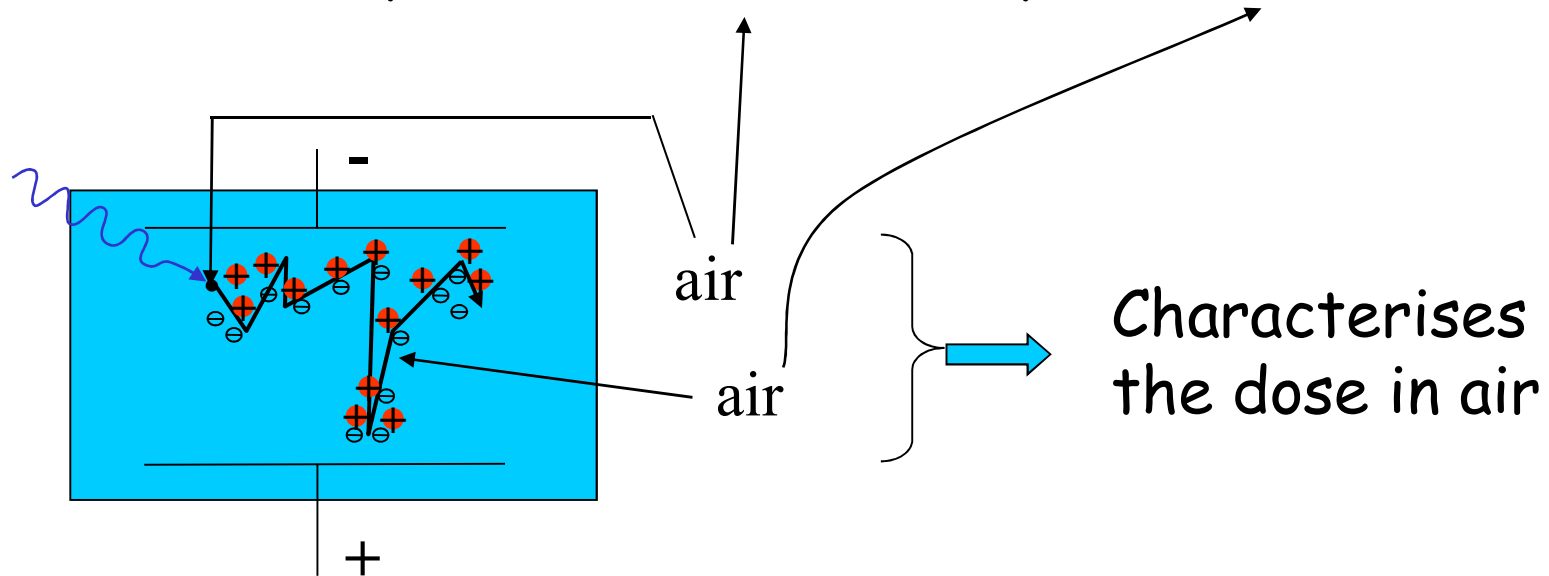
Ionisation chamber



Exposure:

$$X = \frac{\Delta Q}{\Delta m}$$

The location of the detection and of the ionization



How to convert it to absorbed dose?

Exposure was measured in air

how to convert it to the dose in the tissue?

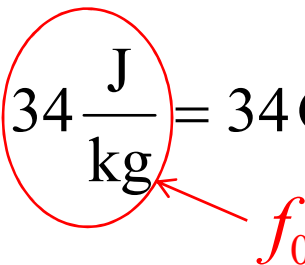
Exposure:

$$X = \frac{\Delta Q}{\Delta m}$$

Conversion to absorbed dose:

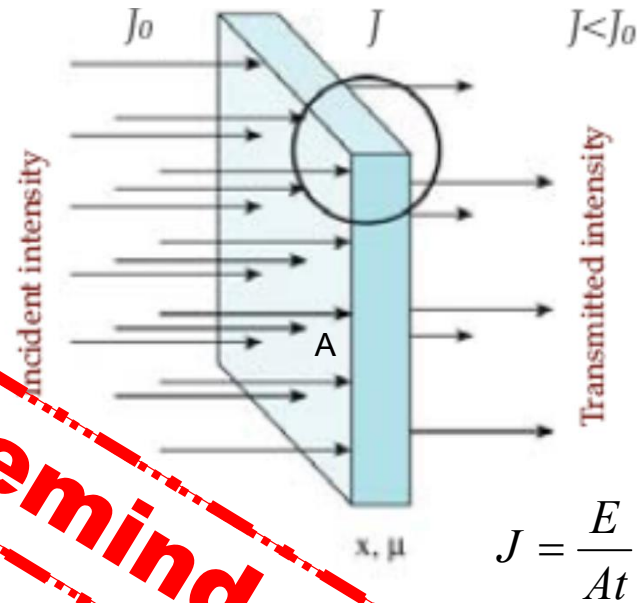
To produce 1 pair of ions one needs 34 eV energy in air*

$$\begin{array}{ll} 34 \text{ eV} = 34 \cdot 1.6 \cdot 10^{-19} \text{ J} & \longrightarrow 1.6 \cdot 10^{-19} \text{ C} \\ 34 \text{ J} & \longrightarrow 1 \text{ C} \end{array}$$

$$1 \frac{\text{C}}{\text{kg}} \Rightarrow 34 \frac{\text{J}}{\text{kg}} = 34 \text{ Gy}_{\text{air}}$$


* In case of electrons. For protons and α particles $\approx 35 \text{ eV}$

Conversion of absorbed dose measured in air to absorbed dose expected in tissue



Reminder

A given quantity (J) and its change (ΔJ) are proportional:

$$\Delta J = -\mu \Delta x J$$

Exponential function:

$$J = J_0 e^{-\mu x}$$

$$\Delta J = -\mu \Delta x J$$

$$J = \frac{E}{At}$$

$$\Delta E = |\Delta J| At$$

$$D = \frac{\Delta E}{\Delta m} = \frac{|\Delta J| At}{\rho A \Delta x} =$$

$$= \frac{\mu \Delta x J t}{\rho \Delta x} = \mu_m J t$$

$$D \sim \mu_m$$

Conversion of absorbed dose measured in air to absorbed dose expected in tissue

$$\frac{D_{tissue}}{D_{air}} = \frac{\mu_{m,tissue}}{\mu_{m,air}} \quad \Rightarrow \quad D_{tissue} = \frac{\mu_{m,tissue}}{\mu_{m,air}} D_{air}$$

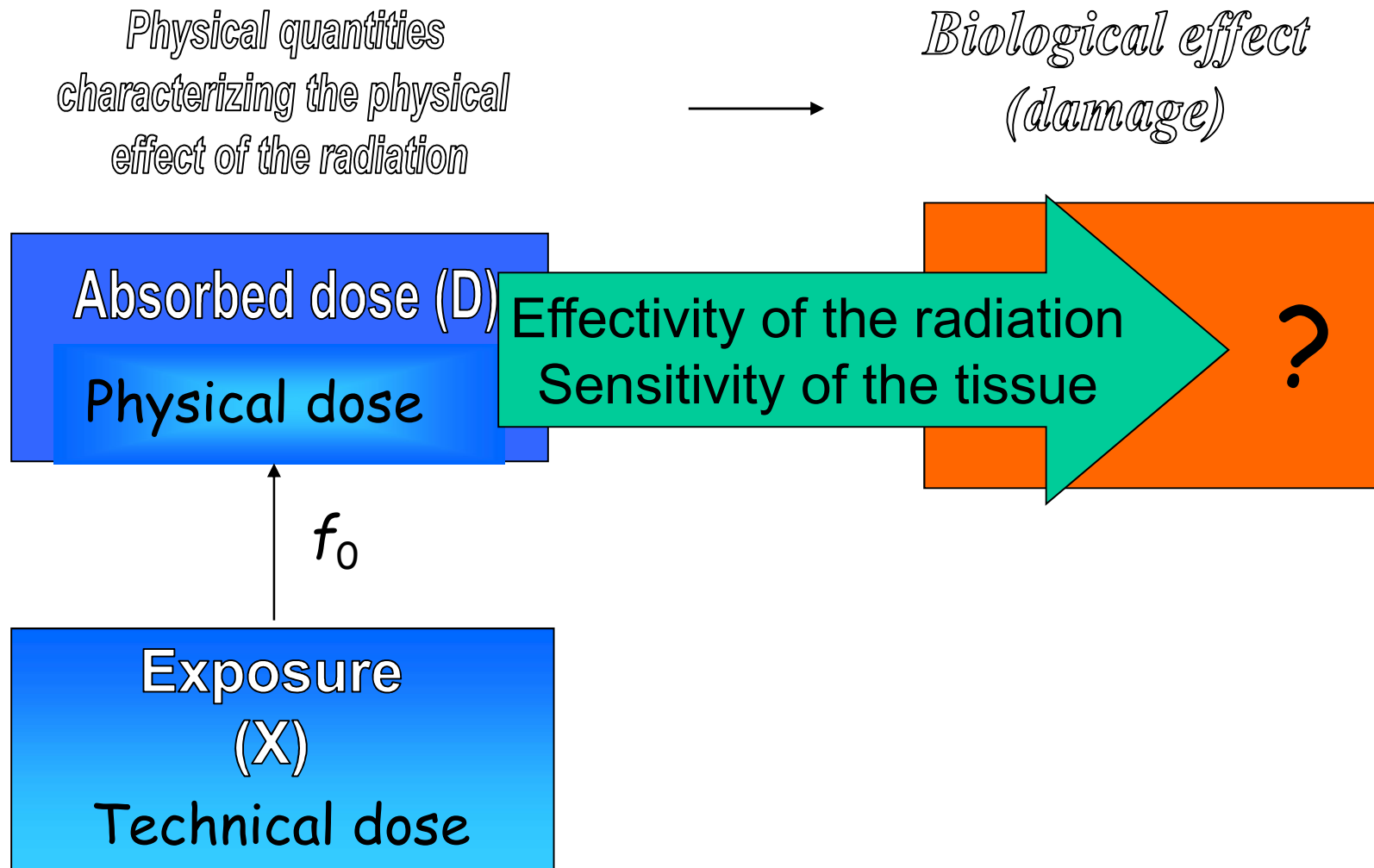
$$\Downarrow$$

$$D_{tissue} = \frac{\mu_{m,tissue}}{\mu_{m,air}} f_0 X$$

$f_0 = 34 \frac{J}{C}$

If $E_{\text{photon}} < 0,6 \text{ MeV}$, for soft tissue: $\frac{\mu_{m,tissue}}{\mu_{m,air}} \approx 1.1$

Dose concepts so far:



In case of...

→ **Deterministic effect** (e.g. radiotherapy)

typically

- single type of radiation is used
- single type of tissue is irradiated

Absorbed dose

proportional

Biological effect

→ **Stochastic effect** (e. g. in diagnostics, radiation protection)

typically

- several types of radiations are absorbed
- several different tissues are irradiated

Absorbed dose

weighted
summation

Biological effect



+



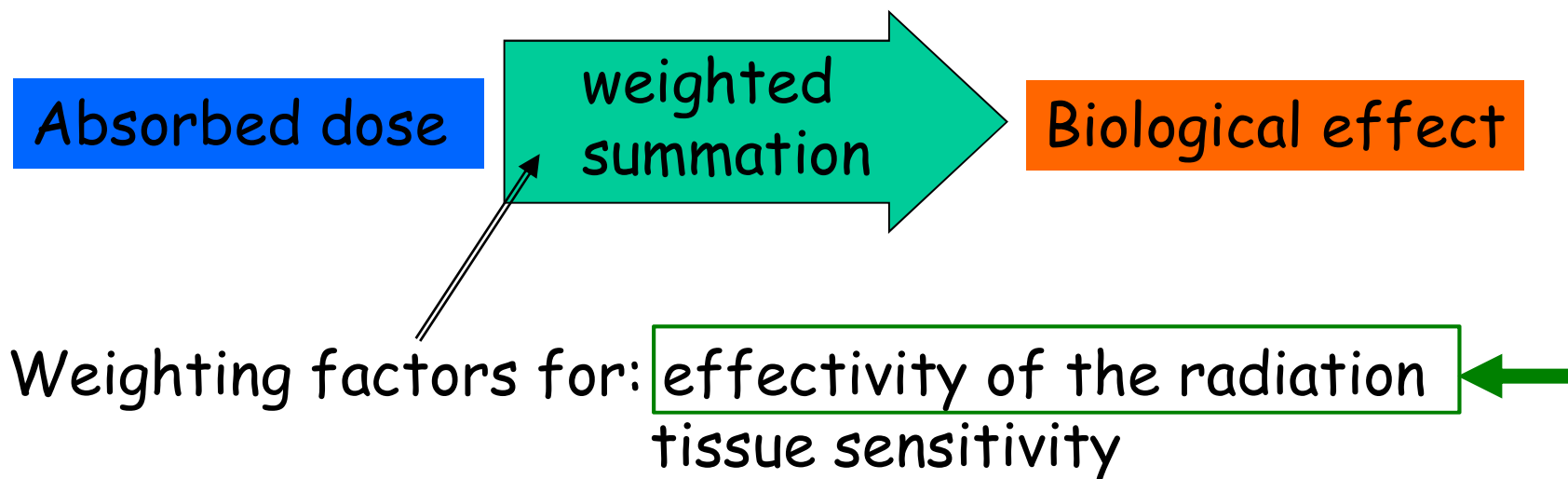
+



=



Equivalent dose



Equivalent dose: $H_T = \sum_R w_R D_{T,R}$ [Sv]

Weighted sum of the absorbed doses from the different radiations (R) in a given tissue (T).

w_R : radiation weighting factor

E.g.:

$$H_{\text{skin}} = w_{\alpha} D_{\text{skin},\alpha} + w_{\beta} D_{\text{skin},\beta} + w_{\gamma} D_{\text{skin},\gamma}$$

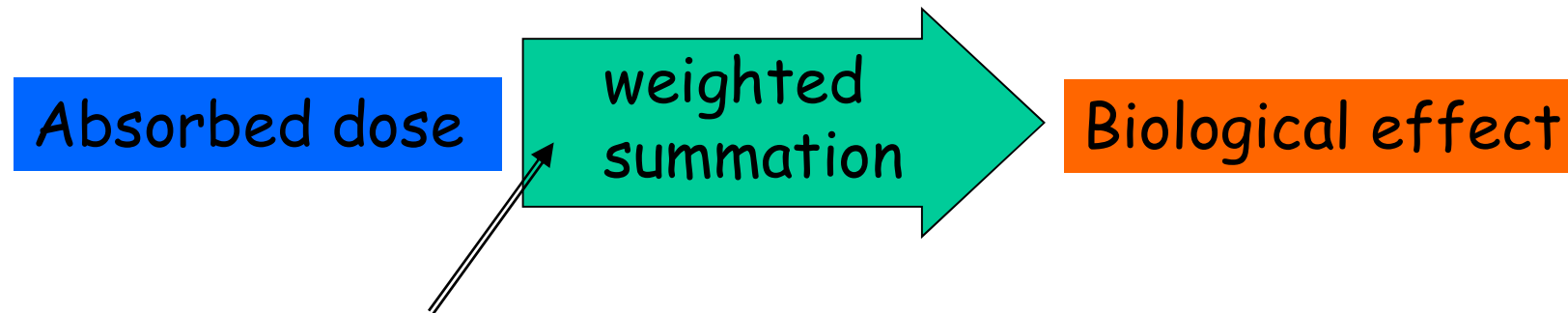
The w_R radiation weighting factors

How many times greater is the effectivity (considering stochastic effects) of the given radiation compared to the x-ray or γ -radiation.

Radiation and energy range		Radiation weighting factor
Photons, at every energy		1 ← by definition
Electrons, muons, at every energy		1
Neutrons, if the energy is	< 10 keV	5
	10 keV–100 keV	10
	100 keV–2 MeV	20
	2 MeV–20 MeV	10
	> 20 MeV	5
Protons, if the energy is	> 2 MeV	5 2
α -particles, nuclear fission products, heavy nuclei		20

*Continuous
function for
neutrons*

Effective dose:



Weighting factors for: effectivity of the radiation
tissue sensitivity

Effective dose: $E = \sum_T w_T H_T$ [Sv]

Weighted sum of the equivalent doses
of the irradiated tissues (T)

$$\sum_T w_T = 1$$

$w_T H_T$ gives the contribution of the H_T dose
to the damage of the whole body.

In case of homogenous irradiation $E = H_T$

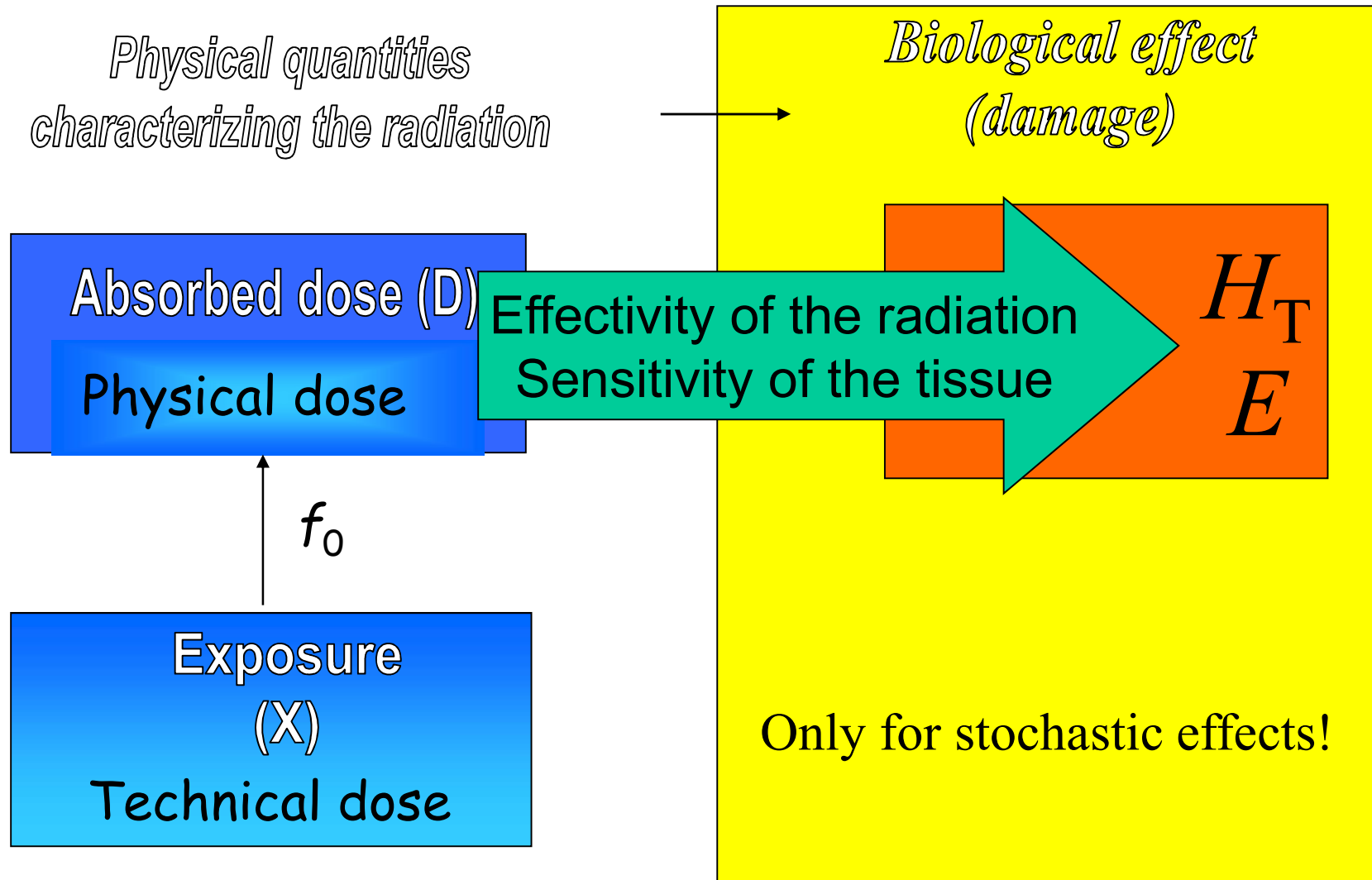
The w_T weighting factor

represents the relative contribution of that organ or tissue to the total damage in case of stochastic effects resulting from uniform irradiation of the whole body

Tissue	w_T	Tissue	w_T
Red bone marrow	0,12	Oesophagus	0,04
Large intestine	0,12	Liver	0,04
Lungs	0,12	Thyroid gland	0,04
Stomach	0,12	Surface of the bones	0,01
Breast	0,12	Brain	0,01
Other tissues*	0,12	Salivary glands	0,01
Gonads	0,08	Skin	0,01
Bladder	0,04		

*Other tissues: adrenal glands, upper respiratory tracts, gall-bladder, heart, kidney, lymph nodes, muscle, mucus membrane, pancreas, prostate, small intestine, spleen, thymus, uterus.

Summary of dose concepts



Radiation protection

For personnel:

Justification

Rule out the deterministic effect

Dose limits

Reduction of the stochastic effect on a
rationally acceptable level

Patients:

Justification

Cost-benefit principle

Measurement and documentation of patient
dose values

Calculation of absorbed dose from γ radiation of an isotope

In case of point radiator:

$$D = \frac{K_{\gamma} \Lambda t}{r^2}$$

K_{γ} : dose constant $\left[\frac{\mu\text{Gy} \cdot \text{m}^2}{\text{h} \cdot \text{GBq}} \right]$

Λ : Activity [Bq]

r : distance from the isotope [m]

t : time [s,h]

E.g $K_{\gamma} = 80 \frac{\mu\text{Gy} \cdot \text{m}^2}{\text{h} \cdot \text{GBq}}$ for ^{137}Cs

1GBq ^{137}Cs gives 80 $\mu\text{Gy/h}$ in 1 m distance

↑
800 x background radiation level

Dose limits

(\neq allowed dose!)

For personnel at radiation workplace

- whole body: 20 mSv/year

(c.a. $10 \mu\text{Sv}/\text{working hour}$)*

- eye lens: 20 mSv/year
- skin: 500 mSv/year
- limb: 500 mSv/year

*compare: background dose rate: $\approx 0,1 \mu\text{Sv}/\text{h}$

Threshold doses for deterministic effects

bone-marrow:

Reduction of blood production

0,5 Gy

Testis:

temporary sterility

0,15 Gy

permanent sterility

3,5-6 Gy

Eye lens

obscurity

0,5-2 Gy

Cataracta

5 Gy

Skin:

temporary erythema

2 Gy

erythema

6 Gy

temporary epilation

3 Gy

For whole-body irradiation: median lethal dose (LD_{50}) :

4 Gy

lethal dose

6 Gy

A few characteristic dose values

Background radiation: 2,4 mSv/year

half of it from Radon.

Medical investigations (patient dose)

conventional x-ray image: 0,2-1 mSv

CT scan: 2-8 mSv

Treatment:

Intervention radiology

doctor: hand: 100 mSv/2 month

eye: 30 mSv/2 month

knee: 20 mSv/2 month

gonad (under
the lead apparel): 0,5 mSv/2 month

Patient: up to 1 Gy!!



Radiotherapy: typically 45-60 Gy (in fractions, localized)

Some of the above presented values are taken from:

Damjanovich et al.: Medical Biophysics

Köteles György: Sugáregészségtan (Medicina)

Fehér István, DemeSándor: Sugárvédelem (ELTE Eötvös kiadó)

Turák O., Osvay M.: A személyzet dózisa az intervenciós radiológia területén.

OSSKI www.sugarvedelem.hu/sugarvedelem/docs/kulonsz/.../szemelyzet.pdf

Pellet Sándor, Giczi Ferenc, Gáspárdy Géza, Temesi Alfréda: Az intervenciós radiológia sugár-egészségügyi vonatkozásai. Magyar Radiológia 81 (2007) 32–39.