

Introduction to Dosimetry

EPFL

RBPA course (PHYS-450)

26.09.2025



- What are the main biological effects of low dose radiation?
- Can you think of any type of dose measuring device?



Overview of Lecture 3



Dosimetric quantities



Ambient dosimetry



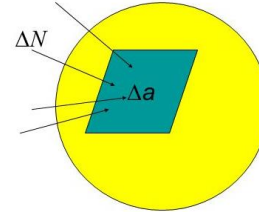
Personal dosimetry



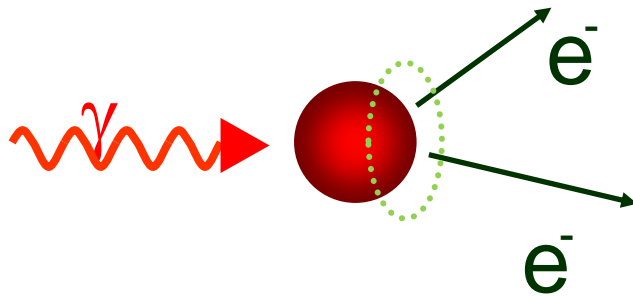
Dosimetric quantities

Primary dosimetric quantities

$$\text{Fluence} = \frac{\text{Number of particles } (\Delta N)}{\text{Area } (\Delta a)}$$



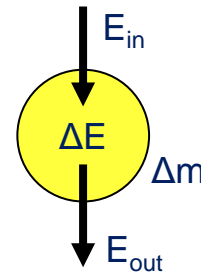
Kerma = kinetic energy released per unit mass (only for photons)



$$K = \frac{\Delta E_{tr}}{\Delta m} \quad [J \cdot kg^{-1}] = [Gy]$$

Absorbed dose = energy deposited in the medium per unit mass

$$D = \frac{\Delta E}{\Delta m} \quad [J/kg] = [Gy]$$



Primary quantities can't be used for dose limits

Why?

1) Different biological effectiveness of different types of radiation

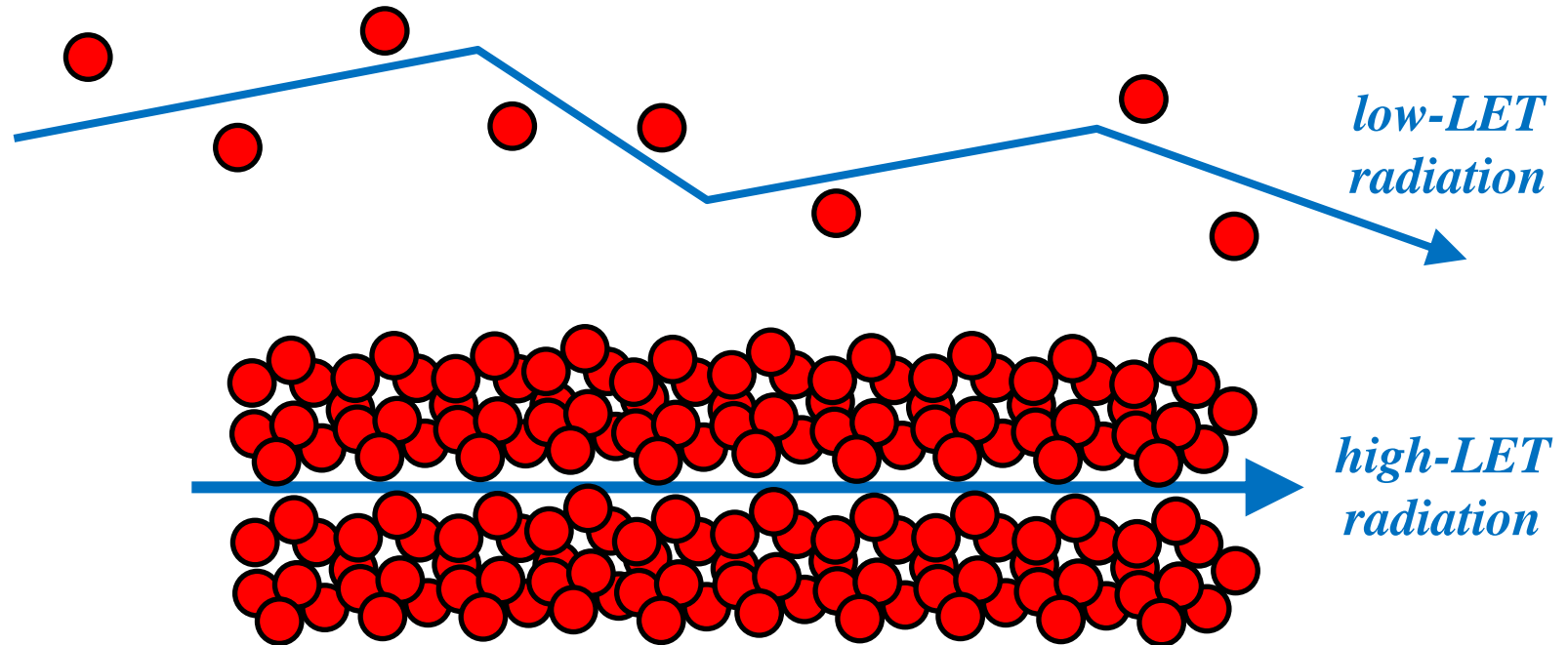
- Need for introducing radiation weighing factors, w_R

2) Different organs have different sensitivity to same radiation type

- Need for introducing tissue weighing factors, w_T

Biological effectiveness of radiation

- LET explains the difference in biological effectiveness



LET: linear energy transfer ($\sim dE_{\text{coll}}/dx$)
(energy transferred through collision to the electrons of matter)

Typical LET

Low LET

Radiation	LET [keV/ μm]
X-rays 250 kVp	2
Protons 230 MeV	2
Electrons 1 MeV	0.25
Electrons 10 keV	2.3

High LET

Radiation	LET [keV/ μm]
Neutrons 14 MeV	12
Protons Bragg peak	20
Heavy charged particles	100-200

- 10 keV/ μm is typically considered as a threshold between low and high LET radiation
- Below 10 keV/ μm RBE does not deviate much from 1

Equivalent dose to tissue/organ

- Radiation weighting factor (w_R) of the absorbed dose
- Unit for equivalent dose: **sievert [Sv]**
- Used to define dose limits for **individual tissues** (eye lens, skin) to prevent specific **deterministic effects**, e.g. cataracts

$$H_T = \sum_R w_R D_{R,T}$$

absorbed dose to the **organ T**
delivered by the radiation of
quality R

equivalent dose to
organ T

radiation weighting factor

Radiation	w_R	} related to RBE
X-rays, γ -rays, electrons	1	
protons	2	
neutrons	2-20	
α -particles	20	

1. Equivalent dose



Calculate the equivalent dose for simultaneous alpha, beta and gamma exposure to the following absorbed doses:

$$D_{\alpha} = 2.1 \text{ mGy} \quad D_{\beta} = 20.1 \text{ mGy} \quad D_{\gamma} = 10.3 \text{ mGy}$$

Effective dose E

- Sums H_T to all major organs using tissue weighing factor w_T
- Estimates long term risks of stochastic effects
- Used to define **annual dose limits**

$$E = \sum_T w_T H_T = [Sv]$$

equivalent dose to organ T

weighting factor of organ T

ICRP 103 (2007):

Tissue (sex and age averaged)	Tissue weighting factor w_T	$\sum w_T$
Bone-marrow (red), colon, lung, stomach, breast, remaining tissues(*)	0.12	0.72
Gonads	0.08	0.08
Bladder, oesophagus, liver, thyroid	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04

w_T indicates relative contribution of that tissue to **detriment**



(*) Remaining tissues: Adrenals, extrathoracic region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (♂), small intestine, spleen, thymus, uterus/cervix (♀).

Detriment

- Detriment = “Total harm”
- Deterministic effects are not considered
- Detriment is a weighted sum of several potential harmful effects:
 - Fatal cancer risk (weighted for length of life lost) ~ 4.1%
 - Non-fatal cancer risk (weighted for the loss of quality of life) ~ 1%
 - Hereditary effects ~ 0.2%

Tissue weighing factors are derived from detriment

Detriment = **probability** x **severity**

Table A.4.1. Summary of sex-averaged nominal risks and detriment. ICRP 103 (2007)

Tissue	Nominal Risk Coefficient (cases per 10,000 persons per Sv)	Lethality fraction	Nominal risk adjusted for lethality and quality of life*	Relative cancer-free life lost	Detriment (relating to column 1)	Relative detriment ⁺
a) Whole population						
Oesophagus	15	0.93	15.1	0.87	13.1	0.023
Stomach	79	0.83	77.0	0.88	67.7	0.118
Colon	65	0.48	49.4	0.97	47.9	0.083
Liver	30	0.95	30.2	0.88	26.6	0.046
Lung	114	0.89	112.9	0.80	90.3	0.157
Bone	7	0.45	5.1	1.00	5.1	0.009
Skin	1000	0.002	4.0	1.00	4.0	0.007
Breast	112	0.29	61.9	1.29	79.8	0.139
Ovary	11	0.57	8.8	1.12	9.9	0.017
Bladder	43	0.29	23.5	0.71	16.7	0.029
Thyroid	33	0.07	9.8	1.29	12.7	0.022
Bone Marrow	42	0.67	37.7	1.63	61.5	0.107
Other Solid	144	0.49	110.2	1.03	113.5	0.198
Gonads (Heritable)	20	0.80	19.3	1.32	25.4	0.044
Total	1715		565		574	1.000

Detriment

Table A.4.4. Detriment adjusted nominal risk coefficients for cancer and heritable effects (10^{-2} Sv^{-1})¹.

Exposed population	Cancer		Heritable effects		Total	
	Present	ICRP 60	Present	ICRP 60	Present	ICRP 60
Whole	5.5	6.0	0.2	1.3	5.7	7.3
Adult	4.1	4.8	0.1	0.8	4.2	5.6

¹ Values from Tables A.4.1a, A.4.1b, and *Publication 60*.

- If each person in a large population would be exposed to 1 Sv effective dose, there would be 5.7 cases of serious harm for every 100 people exposed.

Advantages and disadvantages of the effective dose concept

$$E = \sum_T w_T H_T = [\text{Sv}]$$

Advantages:

- Enables summation of organ doses due to varying levels and types of radiation
- Primary application in planning of protection, e.g. for describing dose limits
- Provides relative index of harm for various procedures in diagnostic imaging. Allows comparison of different examinations, technologies and procedures in different hospitals and countries

Disadvantages:

- It doesn't consider age at exposure, gender, body mass and size, individual radiosensitivity, etc

2. Effective dose



Compute the effective dose for the exposure consisting of:

- dose to the gonads: 1 mSv
- dose to the bone marrow: 2 mSv

Tissue/Organ	Weighting factor (2007)
Bone marrow	0.12
Breast	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.04
Esophagus	0.04
Gonads	0.08
Liver	0.04
Thyroid	0.04
Bone surface	0.01
Brain	0.01
Kidney	Remainder
Salivary glands	0.01
Skin	0.01
Remainder tissues	0.12 [†]

3. Effective dose



Calculate the effective dose for exposure of lungs to 1 mGy of gamma plus 1 mGy of protons, and thyroid to 2 mGy of beta.

$$W_{\text{lungs}} = 0.12$$

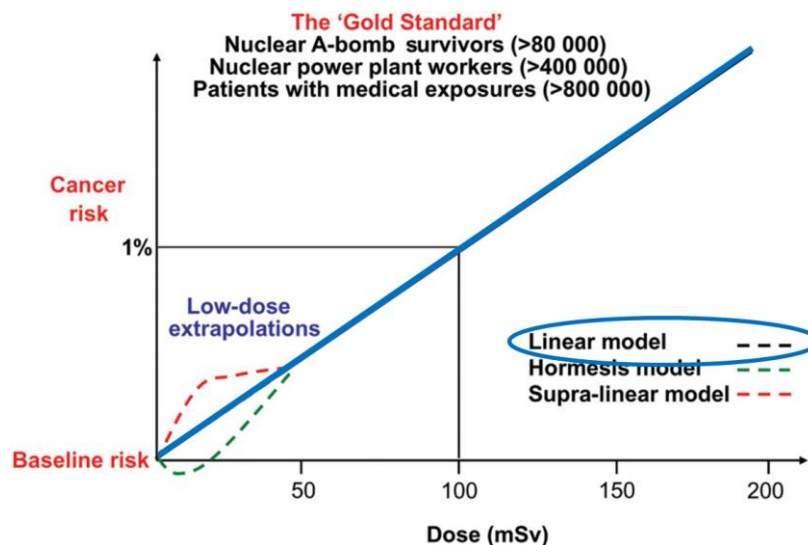
$$W_{\text{thyroid}} = 0.04$$



4. Effective dose

Which fundamental assumption allows for summation of the doses in different organs and by different radiation qualities at low doses?

Solution: The assumption of a linear no-threshold model (LNM)



Dose limits

- Defined to prevent deterministic effects and reduce stochastic effects to acceptable level
- Defined for protection quantities: **effective** and **equivalent** dose

Type of limit	Occupational	Public
<u>Stochastic limits:</u> Annual effective dose	20 mSv (av. over 5 years)	1 mSv
<u>Deterministic limits:</u> Annual equivalent dose		
Eye lens	20 mSv (av. over 5 years)	15 mSv
Skin	500 mSv	50 mSv

- Protection quantities cannot be measured directly!

Operational quantities

The **equivalent** and **effective doses** are protection quantities, but they are **not directly measurable**



Introduction of **operational quantities**

- defined in simple standardized phantoms (proxy for human body) that can be replicated in a calibration lab
- defined in a way that allows them to be measured directly
- used as a conservative estimate of protection quantities

Protection vs operational quantities

- Analogy with travel time and speedometer:

Travel time – protection quantity



- Goal: get to destination in under 2h
- Not shown on the dashboard

Speed – operational quantity



- The used is speedometer
- Speed is a measurable proxy that allows to control travel time

Main operational quantities

Operational quantity for ambient dosimetry

Ambient dose equivalent $H^*(10)$

- equivalent dose at 10 mm depth in the ICRU sphere
- used for area monitoring with survey meters
- conservative estimate of effective dose in one point

Operational quantity for personal dosimetry

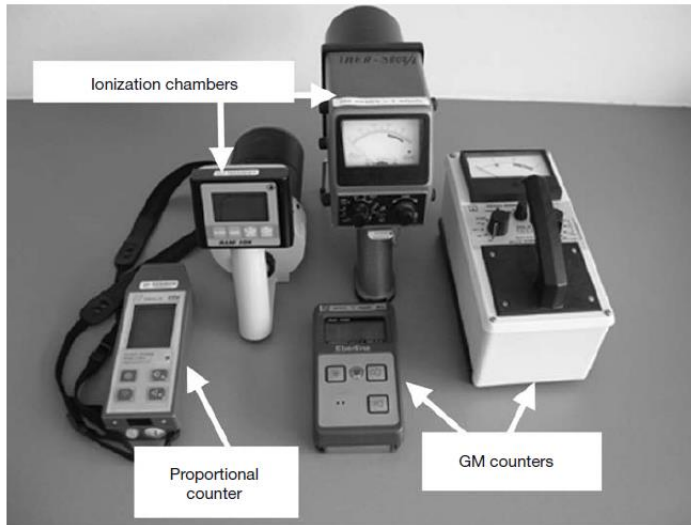
Personal dose equivalent $H_p(10)$

- equivalent dose at 10 mm depth in the ICRU slab
- used for individual monitoring with personal dosimeters
- Conservative estimate of effective dose received by a person



Operational quantities

Ambient dosimetry



- Characterizing radiation field in environment

- Ambient and personal dosimeters are calibrated in terms of operational quantities

Personal dosimetry

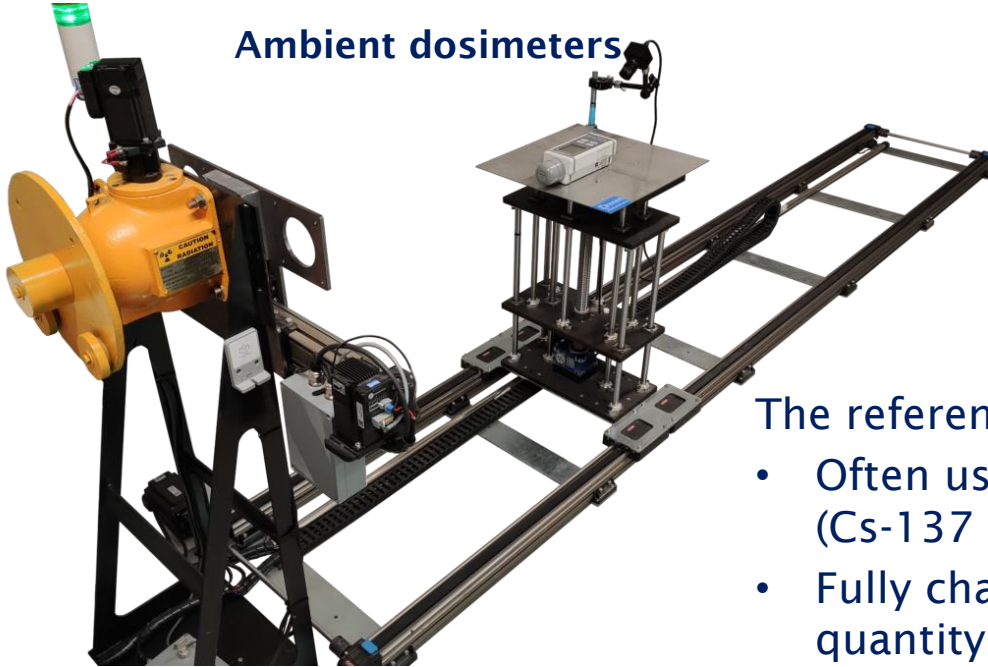


- Characterizing individual dose received by a single person

How are detectors calibrated?

- Calibration performed in highly controlled and precisely known radiation field

Ambient dosimeters



Personal dosimeters

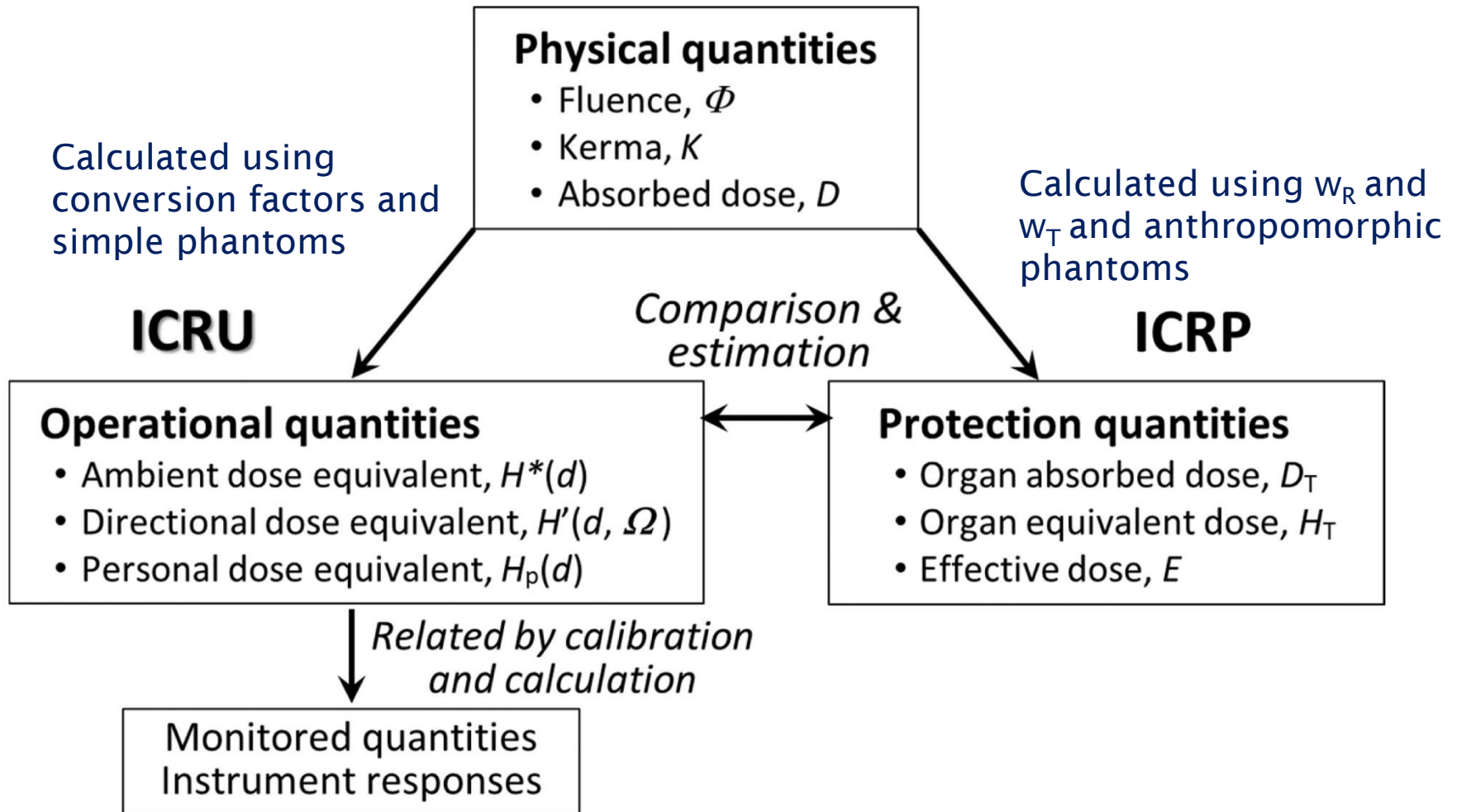
The reference field:

- Often use of standard radioactive sources (Cs-137 or Co-60)
- Fully characterized – “true” operational quantity dose rate exactly known at specific point from complex computer simulations

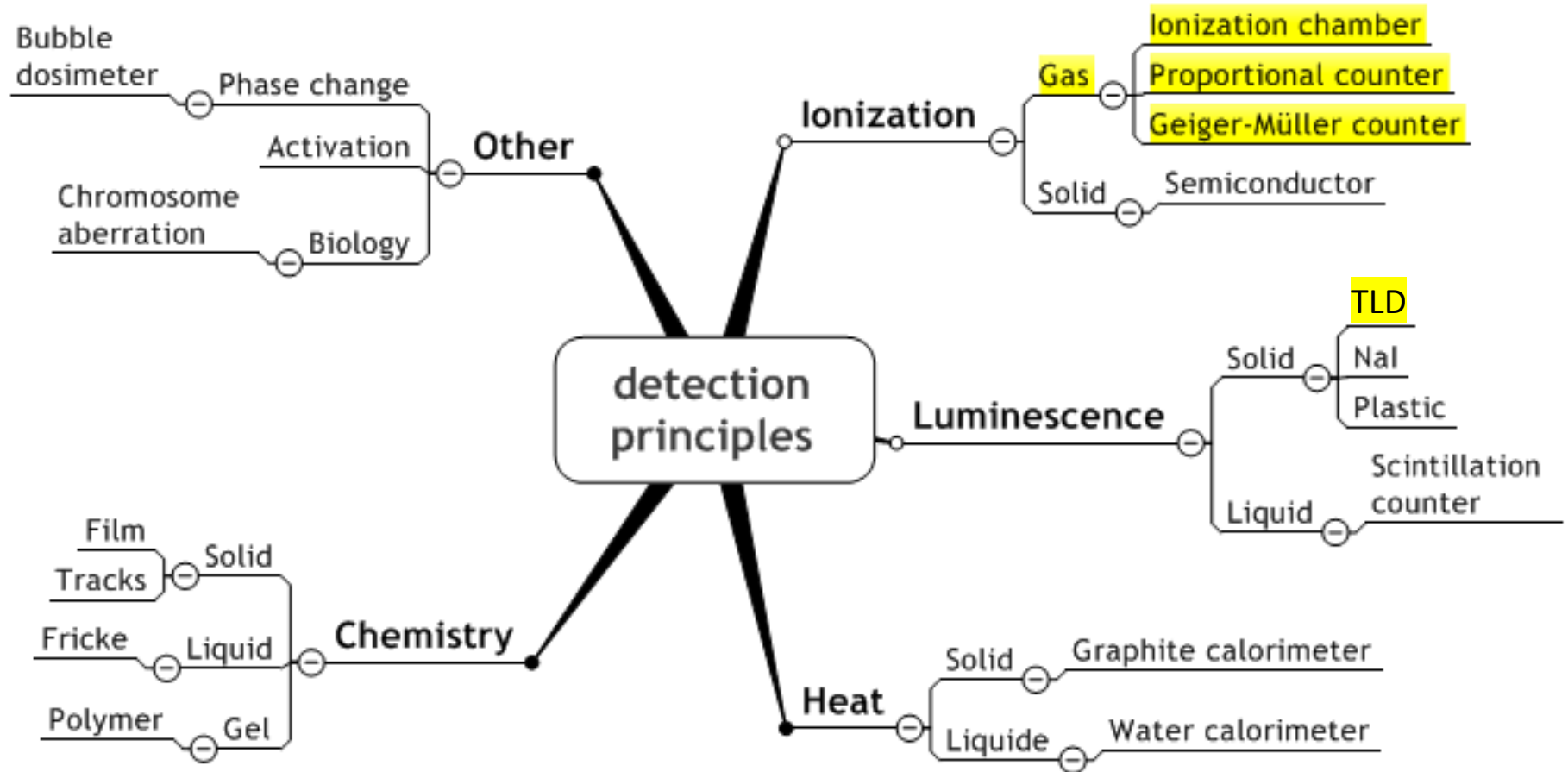
Detector is placed at exact point where dose rate is known

- **Area survey meters** placed directly in the beam
- **Personal dosimeters** placed on a phantom (typically slab of plastic or water) to reproduce backscattering from the body

Dosimetric quantities in radiation protection



Principles of dose measurement





Ambient dosimetry

Ambient dosimeters

- hand-held instruments calibrated "in air"

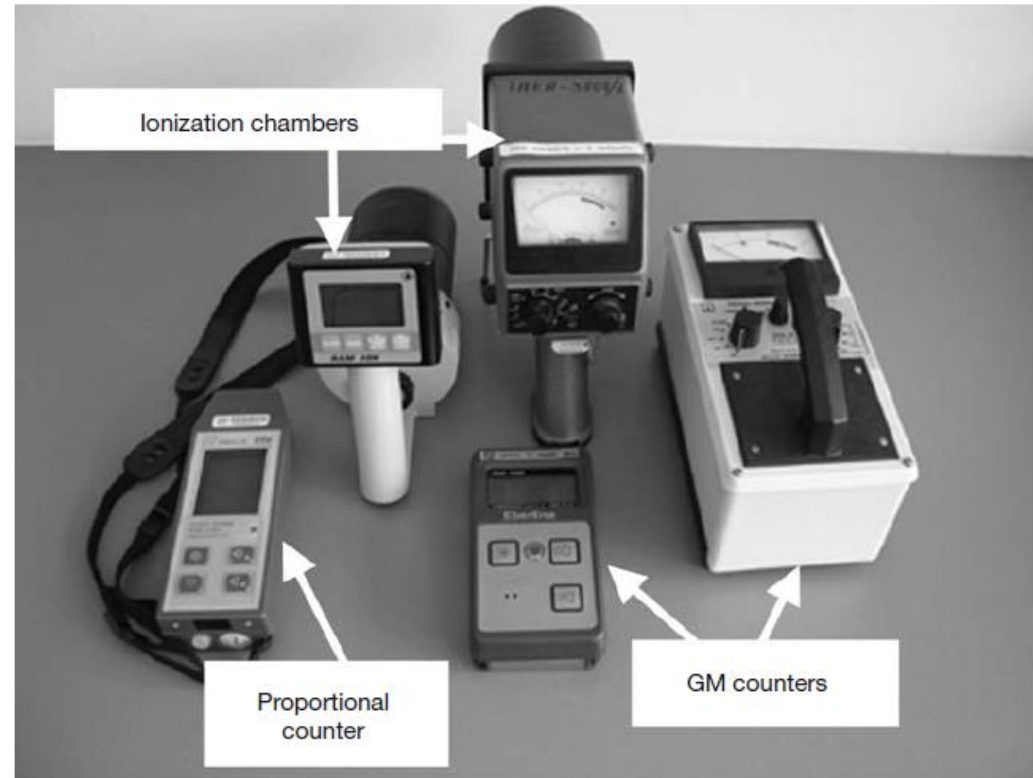
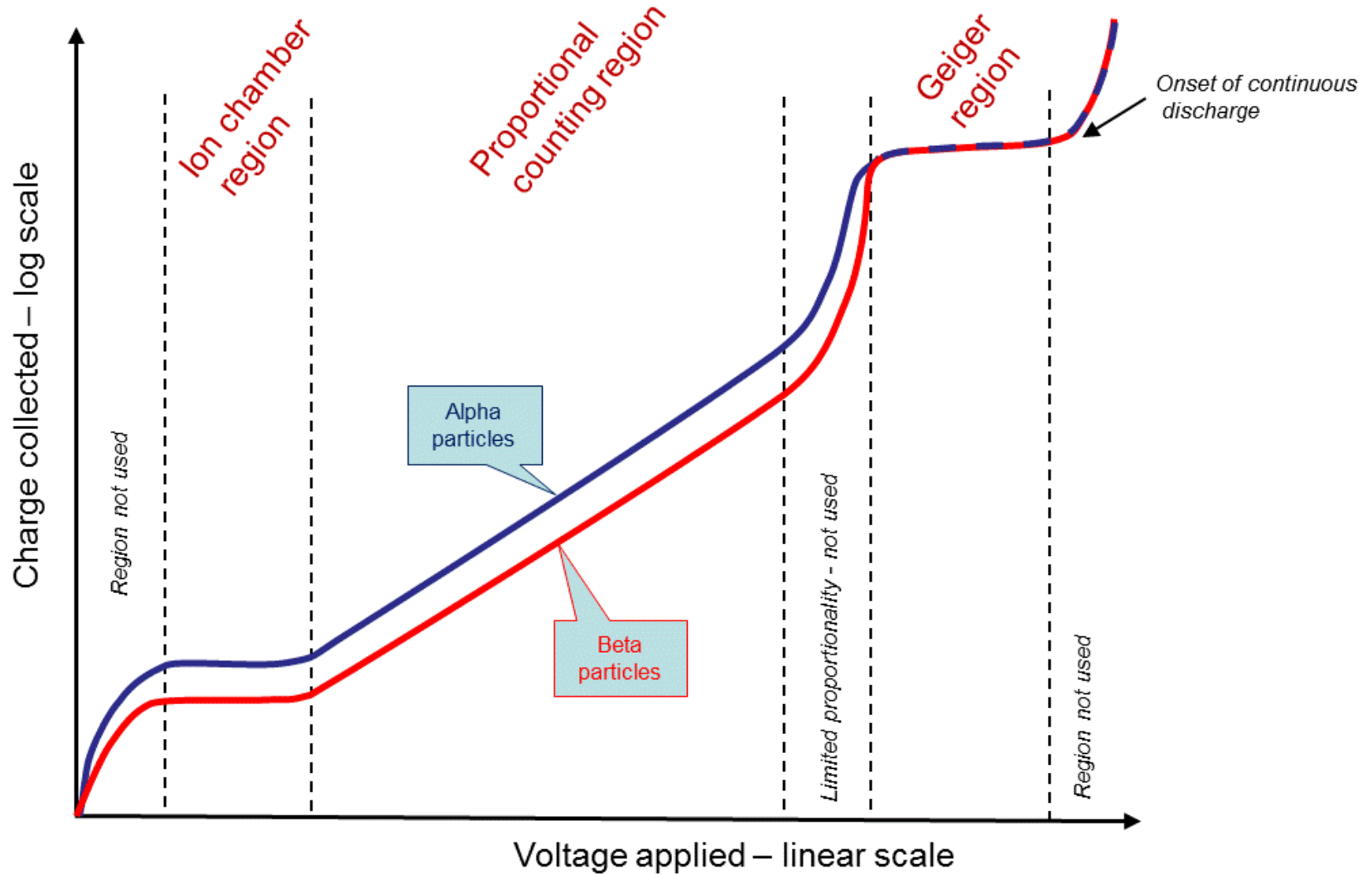


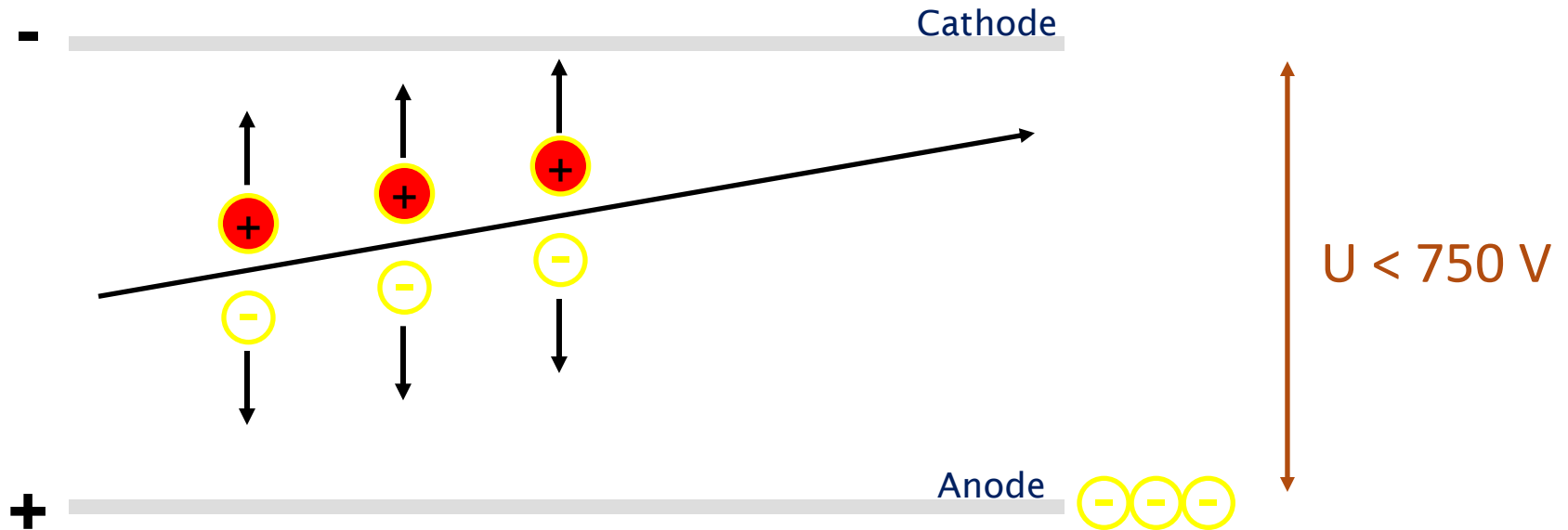
FIG. 4.2. Area survey meters commonly used for radiation protection level measurements: ionization chambers, a proportional counter and GM counters.

Properties of gas detectors



Ionization chamber

Measurement of primary ionization in a gas



- Collected charge Q is proportional to energy deposited inside the chamber

Ionization chamber: applications

Used for:

- radiation monitoring when accurate measurement of a dose rate is required
- Pulsed radiation fields such as those produced by medical LINACs

Current \mapsto **dose rate**

Environmental monitoring



Clinical dosimetry



parallel plate

5. Ionization chamber

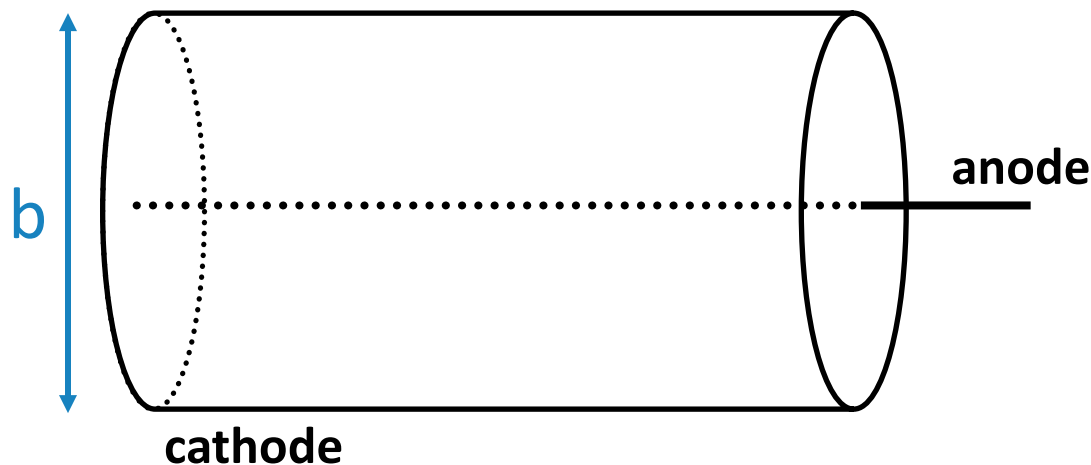


Which charge carriers contribute mostly to the induced signal in air filled ionization chamber?

- 1) Electrons and positive ions
- 2) Positive ions and negative ions
- 3) Electron and holes
- 4) Electrons and positrons

Proportional counter

- Electric field increases in the vicinity of the anode
- Operates in an intermediate voltage region between GM counters and ionization chambers
- Used to amplify signal when number of ionizations is small



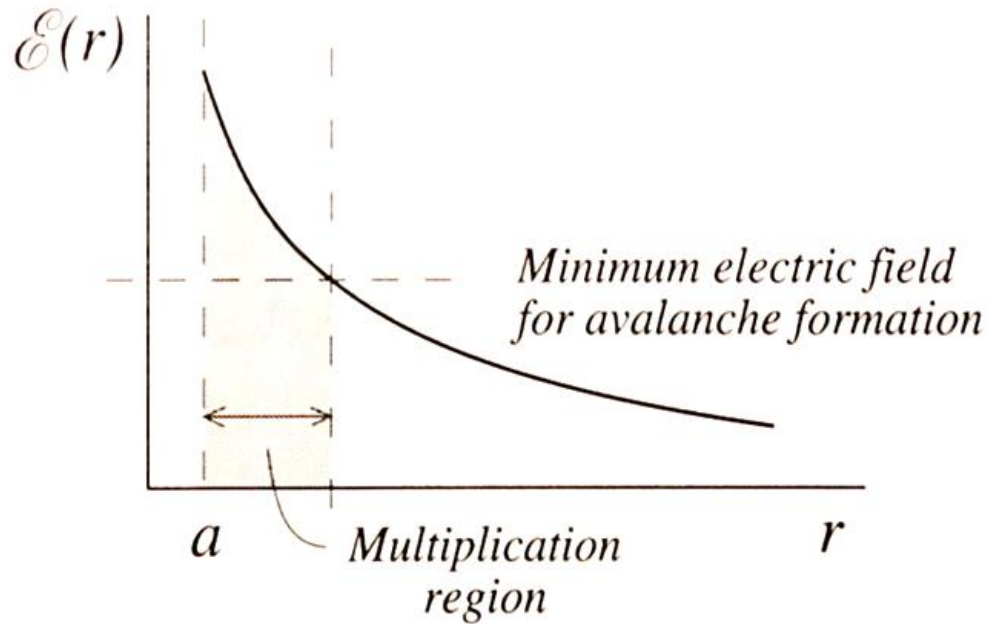
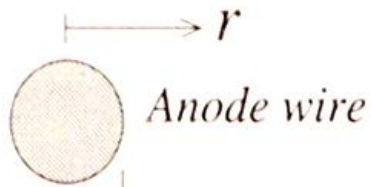
electric field

voltage

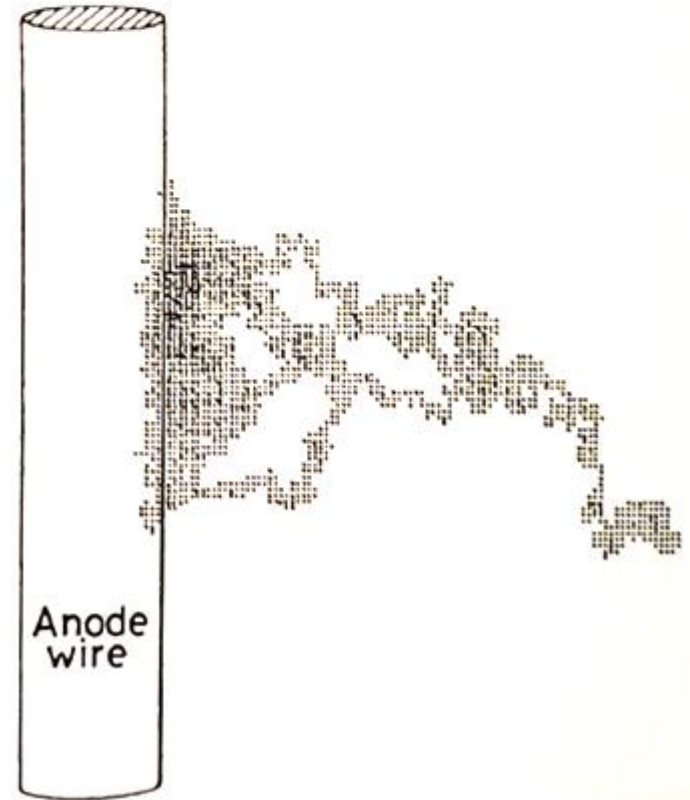
$$E(r) = \frac{U}{r \ln \frac{b}{a}}$$

anode radius

Proportional counter

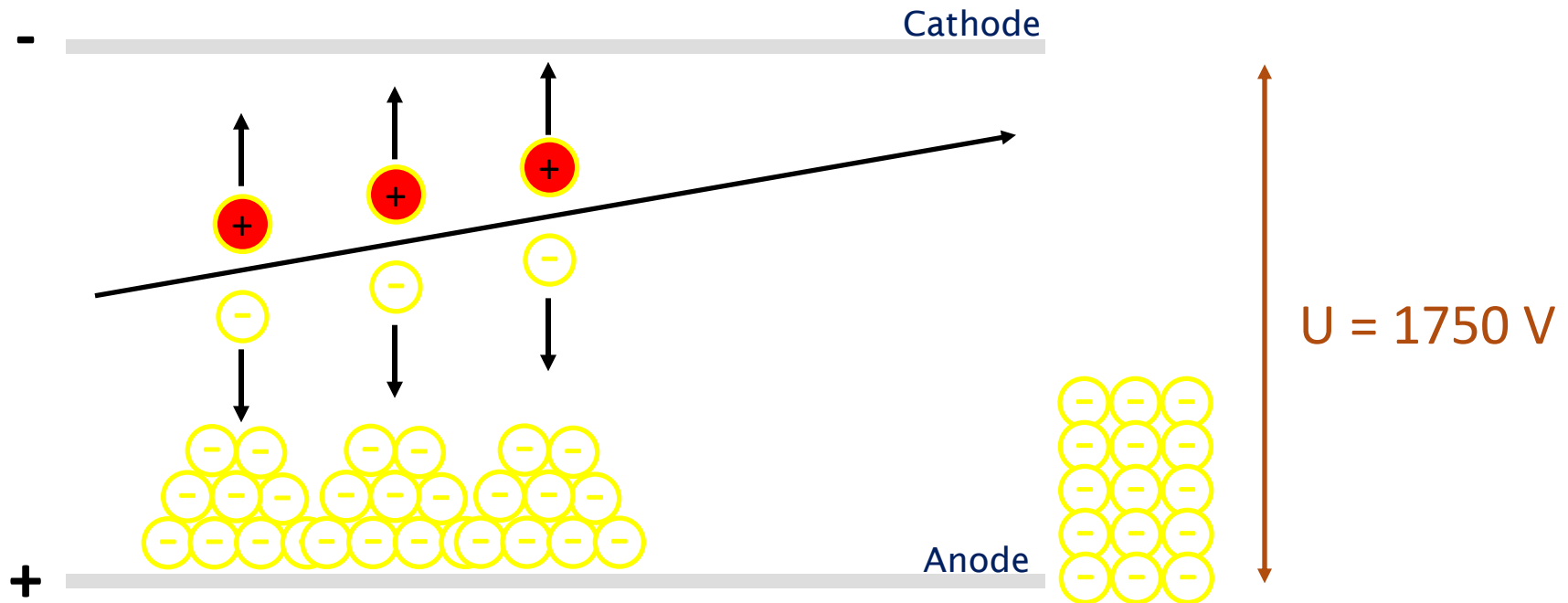


➤ Avalanche starts at $r \approx 5a$



Proportional counter

- Increased electric field inside the chamber
- True proportionality regime: charge multiplication



- Collected charge Q is still proportional to energy deposited inside the chamber

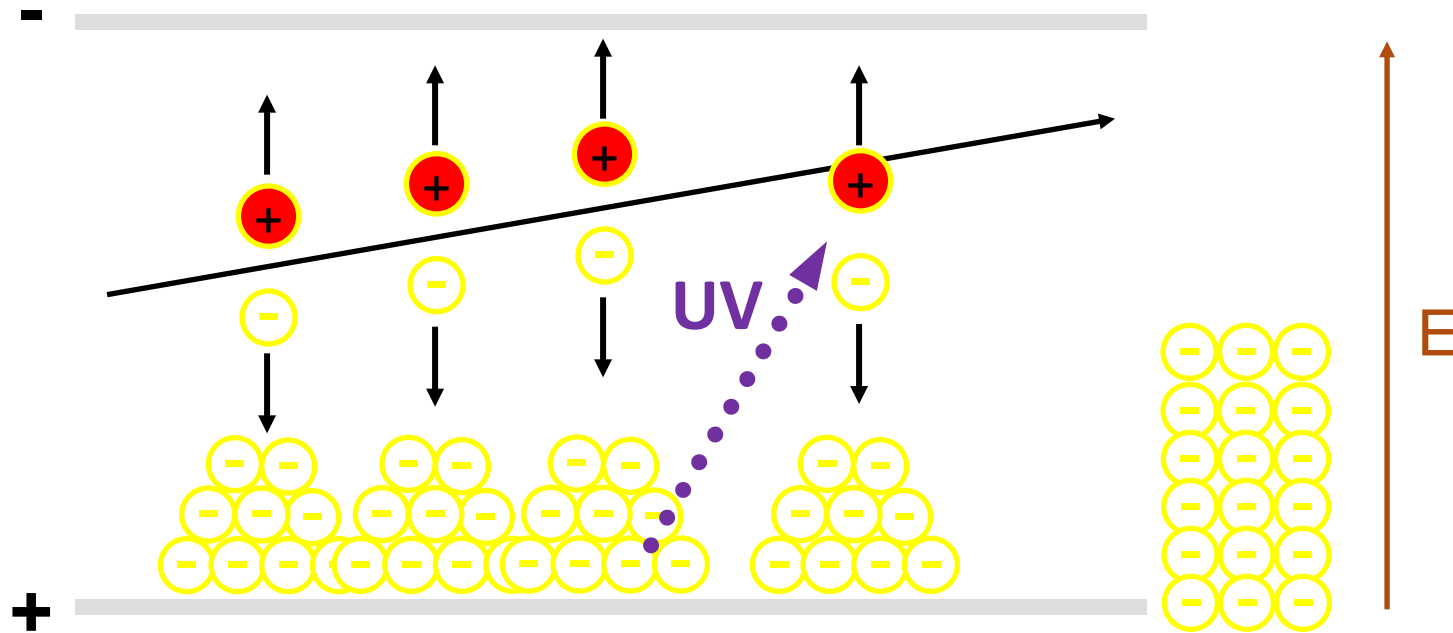
Proportional counter: the choice of the filling gas

- In principle avalanche occurs in every gas depending on the E
- However, the experimental requirements are:
 - Low operating voltage
 - High gain
 - Good proportionality
 - High rate capability
 - Long lifetime, no aging
- **Partly contradicting, no ideal gas**
- **Nobel gases** are the main component in proportional counters:
 - Avalanche occurs at lower fields than in complex molecules
- Choice of nobel gas:
 - Xe, Kr are too expensive
 - He is small → high leak rate
 - Ne and Ar are good choices
 - Ne 8x more expensive than Ar
- **Ar is a common choice**
e.g. P10 gas (90% Ar, 10% methane)

Proportional counter: the choice of the filling gas

➤ However, pure Ar would suffer from continuous discharge:

- Reason is formation of excited and ionized noble gas atoms
- Deexcitation through radiative transitions, $h\nu = E_{\text{ex}}$ (11.6 eV for Ar)
- Work function of metal (electrodes): $E_w = 4.4$ eV for Cu
- Emitted photons can extract photoelectrons \rightarrow new avalanches



➤ Solution: addition of quenching gas (CH_4 , BF_3 , CO_2)

Proportional counter: applications

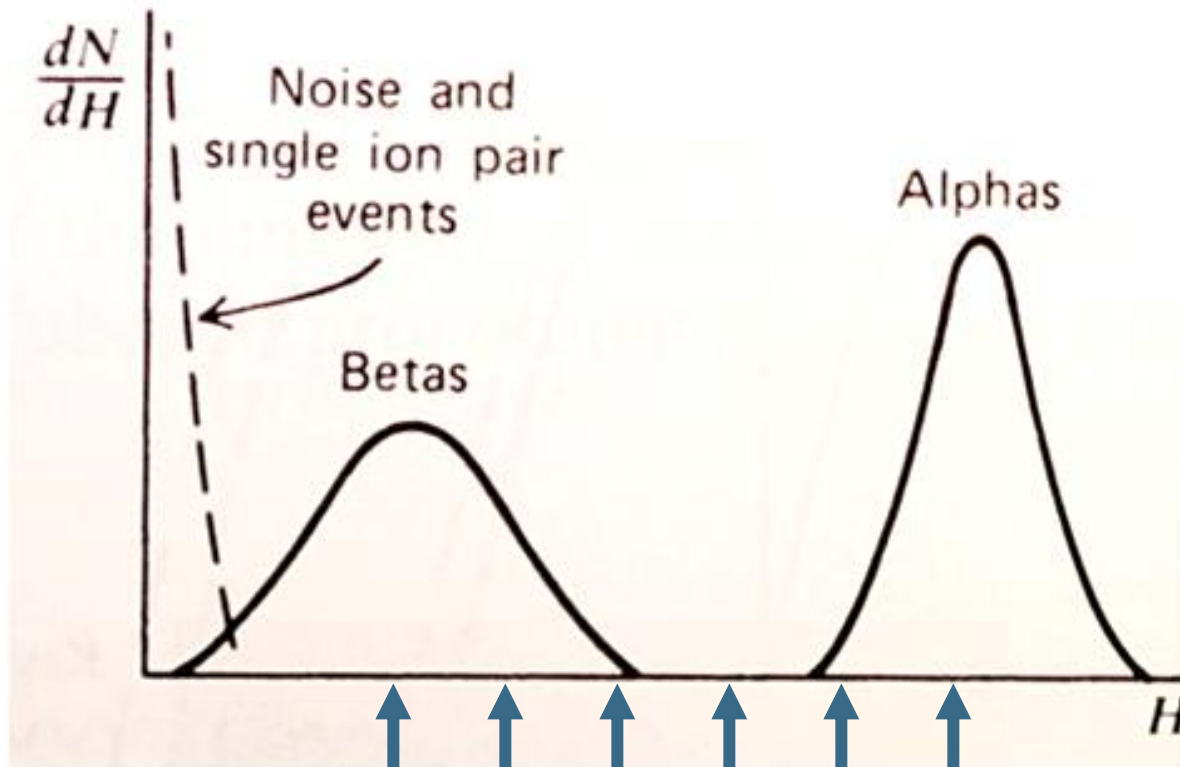
- Contamination monitor:
Counts/s \mapsto **Bq/cm²**



Berthold LB 1210B

Proportional counter: α/β discrimination

- Based on pulse height discrimination:

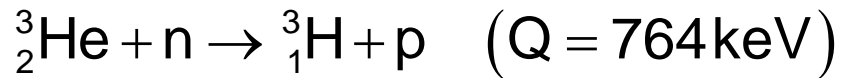


Changing the threshold allows us to discriminate different types of particles

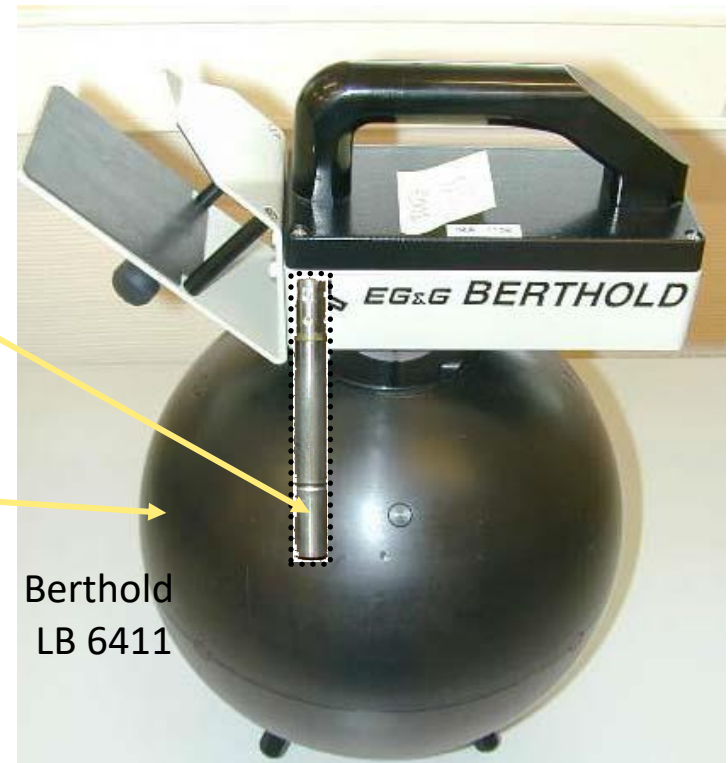
Proportional counter: applications

- Neutron dosimeter:
Counts/s \mapsto equivalent dose rate ($\mu\text{Sv/h}$)
from thermal to 20 MeV neutrons
excellent neutron/gamma discrimination

proportional
counter



moderator



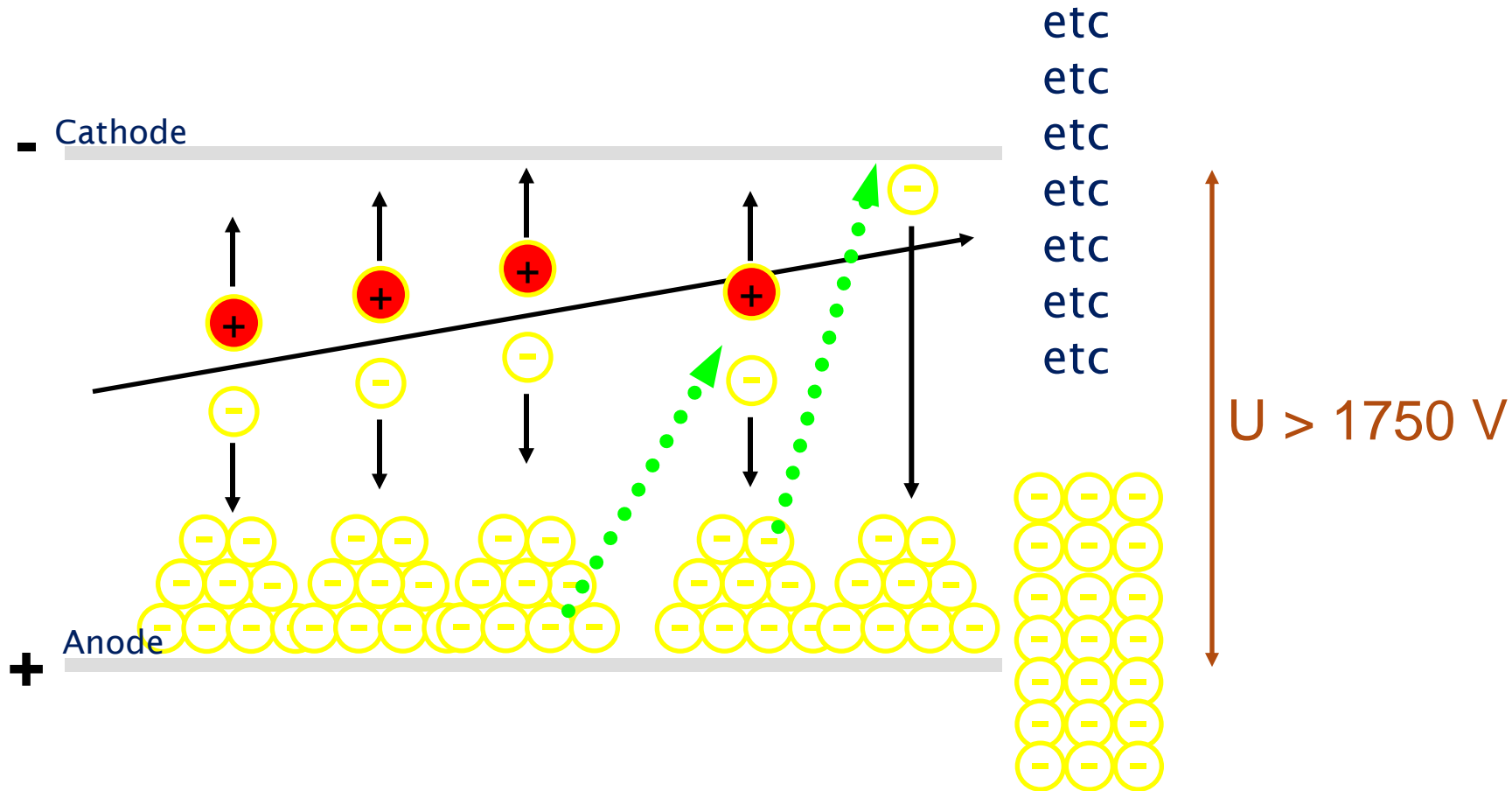
6. Proportional counter



Would you fill a proportional counter with air?

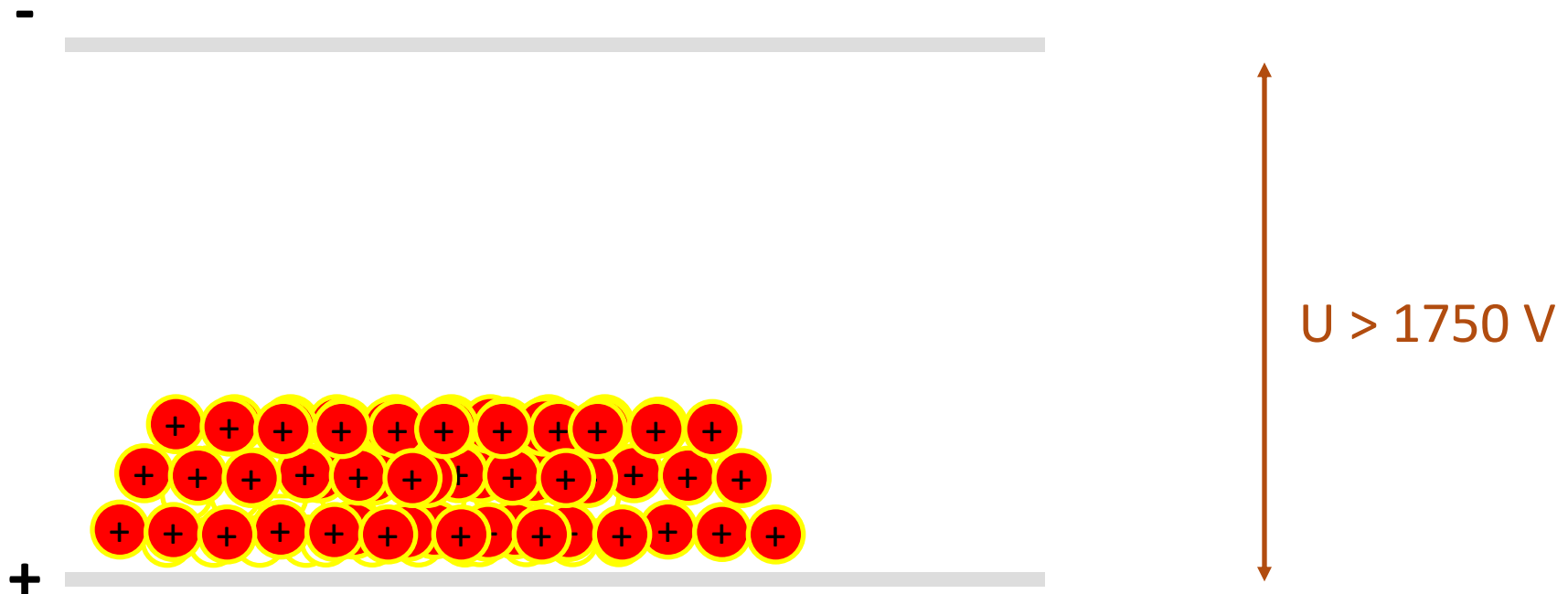
Geiger-Müller counter

- Cylindrical shape, like for proportional counters
- Complete ionization of gas around the anode takes a few μs



Geiger-Müller counter

- The process is stopped by the space charge of the ions
 - ions move slowly from the anode
 - created space charge screens the electric field, discharge stops
 - termination always after the same number of avalanches → no energy information in pulses
- Avalanche termination further improved by quenching



Geiger-Müller counter: characteristics

- Used at very low radiation levels
- Relatively inexpensive and durable
- Needs high voltage
- Geiger discharge around the anode
 - Independent** of the radiation **type**
 - Independent** of the radiation **energy**
- Can detect all types of radiation but most efficient for β
- Large dead times between counts \rightarrow false activity measurement at high rates
- Spectrometry impossible
- Closed counters
 - Quenching gas allowing charge transfer without supplementary avalanches

Geiger-Müller counter: applications

- Geiger-Müller counters can detect all types of radiation

Fixed ambient dosimeter

Counts/s \mapsto μ Sv/h



Berthold LB 1236
electrometer

Berthold LB 1236
detector

Mobile ambient dosimeter

Counts/s \mapsto μ Sv/h



GM counter with detachable
pancake probe



Personal dosimetry

Personal dosimeters

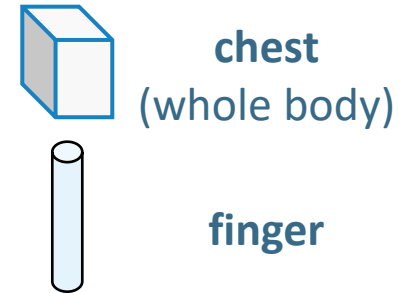
- body-worn
- calibrated on a phantom in a reference field



**whole body
personal TLD
dosimeters**



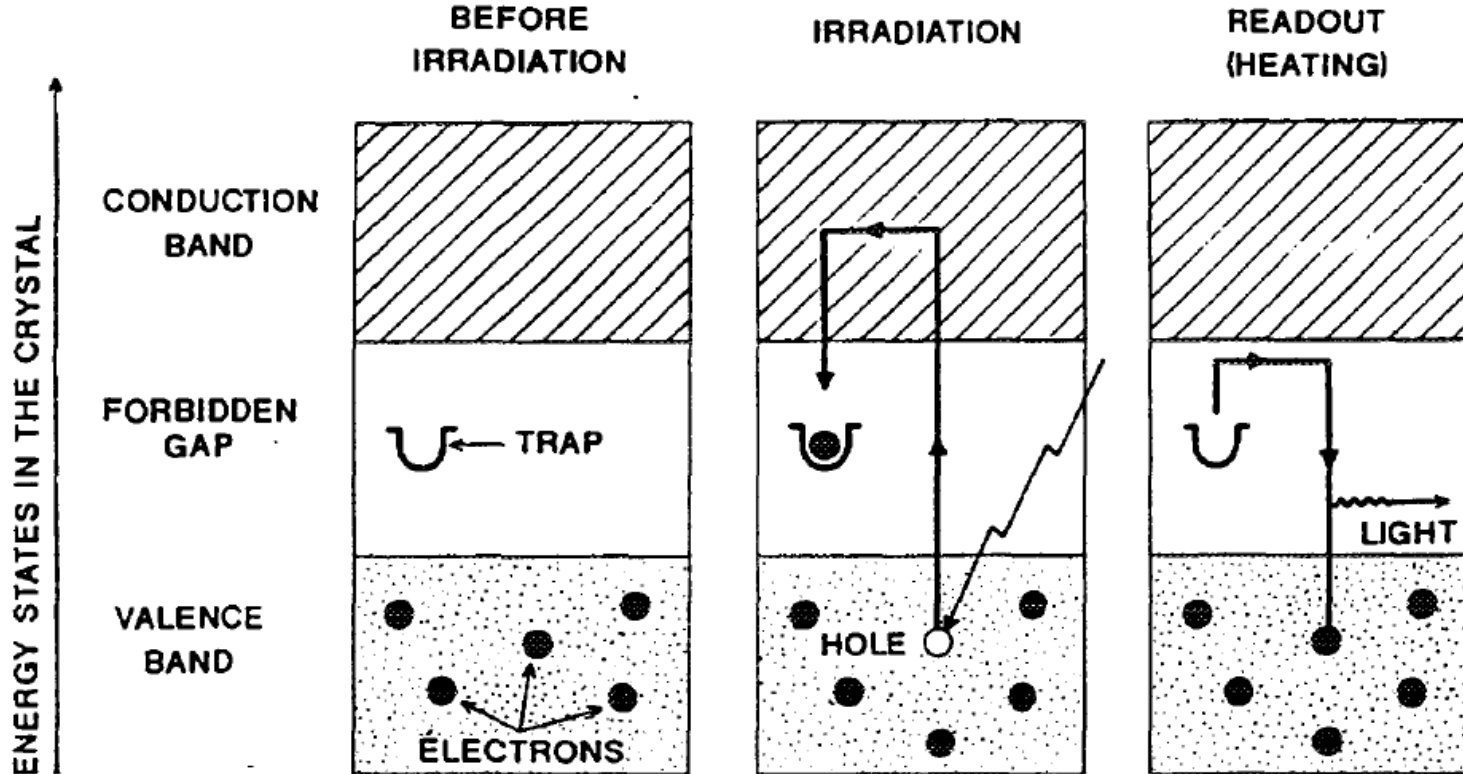
**electronic personal
dosimeters (Si diode)**



**TLD
dosimeters for
extremities**

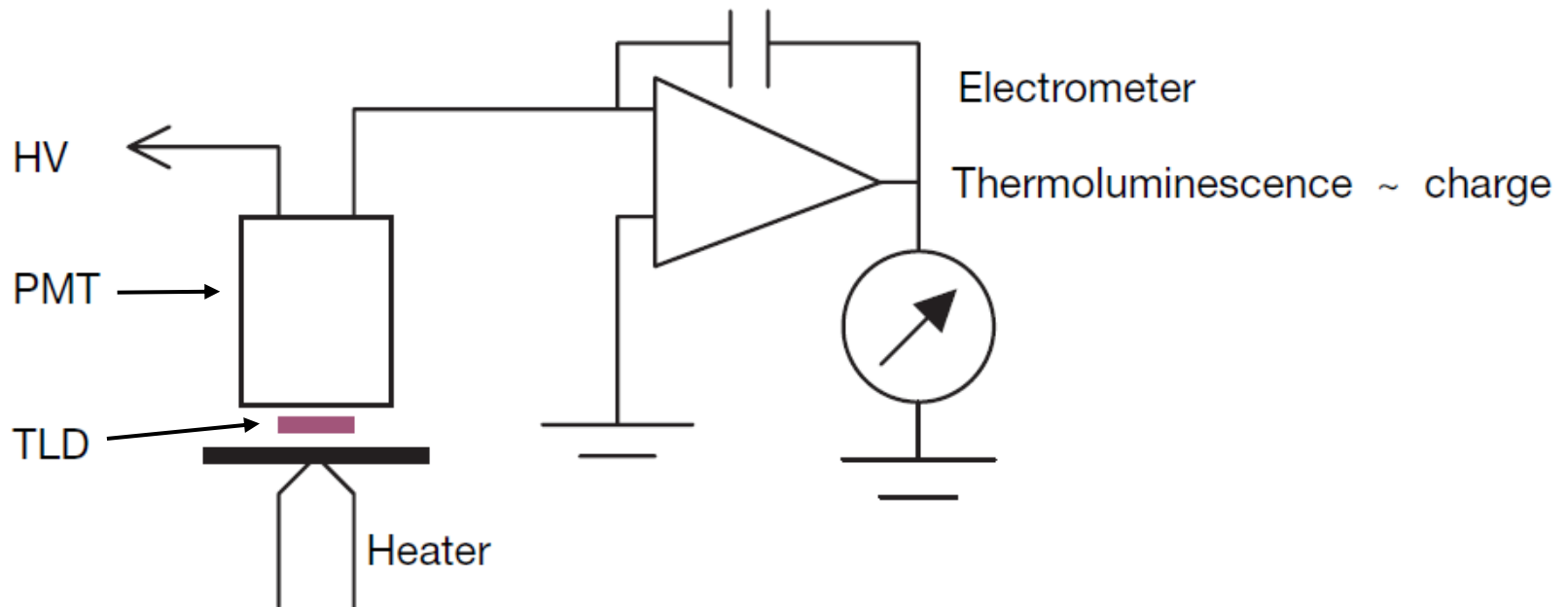
Thermoluminescence dosimetry

- Thermoluminescence dosimetry is based on the ability of crystals to absorb and store the energy of ionizing radiation and re-emit it upon heating in the form of light
- Possible mechanism referring to the band theory of crystals:



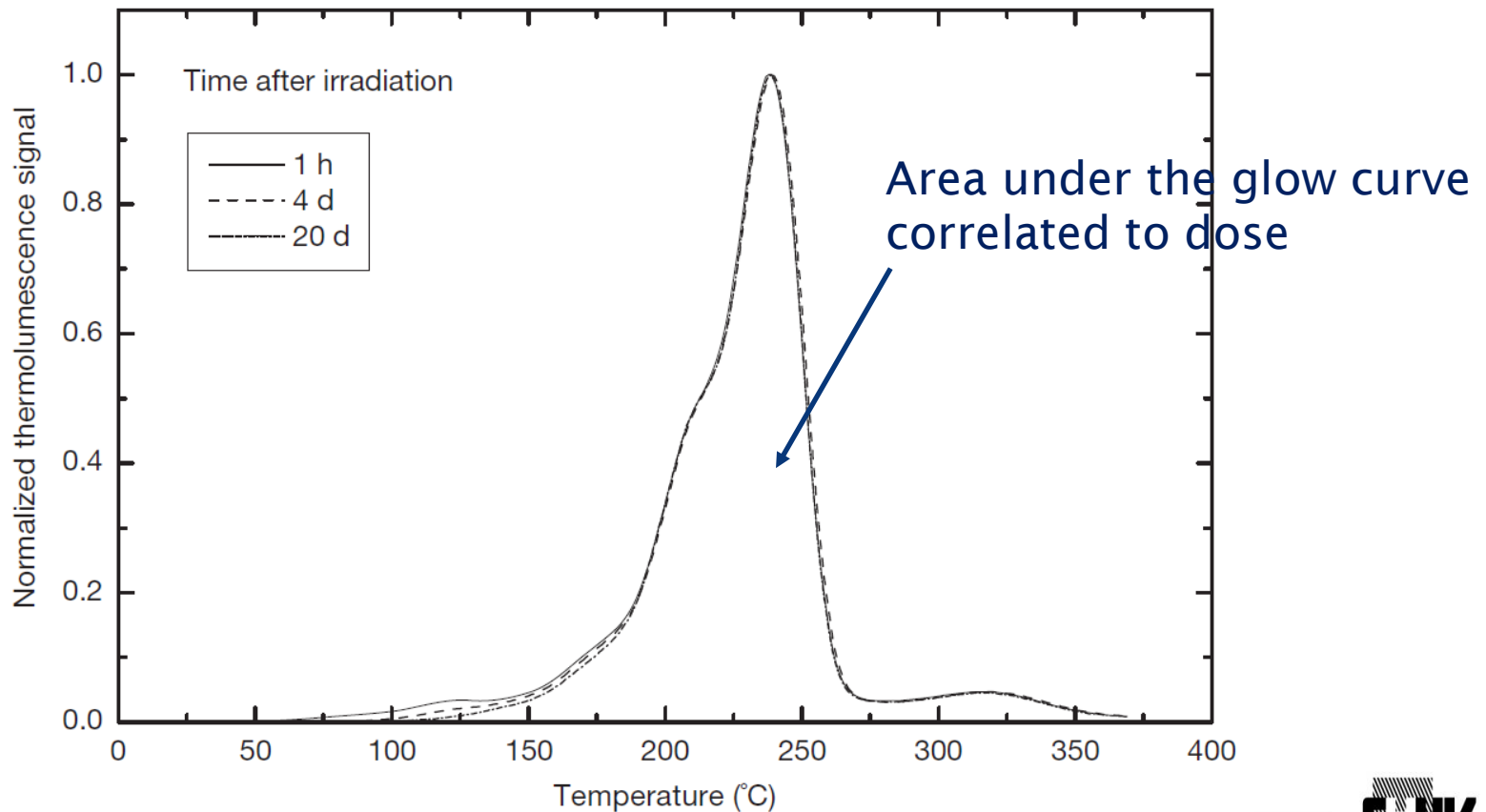
Thermoluminescence dosimetry

- Most commonly used TLDs in personal dosimetry are LiF crystals with different impurities such as Mg, Ti, Cu, etc.
- LiF has Z of 8.2 which is close to tissue (7.4)
- TLD readout system:



Thermoluminescence dosimetry

- Main dosimetric peak of LiF:Mg,Ti (TLD-100) used for personal dosimetry is between 180°C and 260°C
- typical thermogram (glow curve) of LiF:Mg,Ti:



TLD: characteristics

- TLDs need to be calibrated and annealed before they are used
- High sensitivity for low doses
- Passive dosimeters, retroactive dose assessment
- Available in various forms (powder, chips, rods, etc.)
- Can be made more sensitive to different types and energies of radiation with the use of filters and absorbers
- Signal fading after irradiation $\approx 1\%$ per month