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Introduction to Dosimetry

EPFL

RBPA course (PHYS-450)

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Questions to think about before we start with lecture:

- 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



Ambience dosimetry



Personal dosimetry



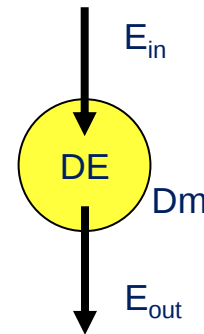
Radiation protection dosimetric quantities

Absorbed dose

Dosimetric quantity

- Absorbed dose (D) = energy deposited in the medium per unit mass:

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

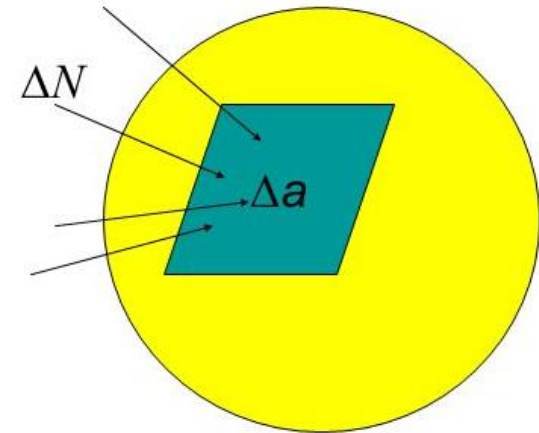


- Absorbed dose is a primary physical quantity, but it is not a sufficient indicator of the biological effect

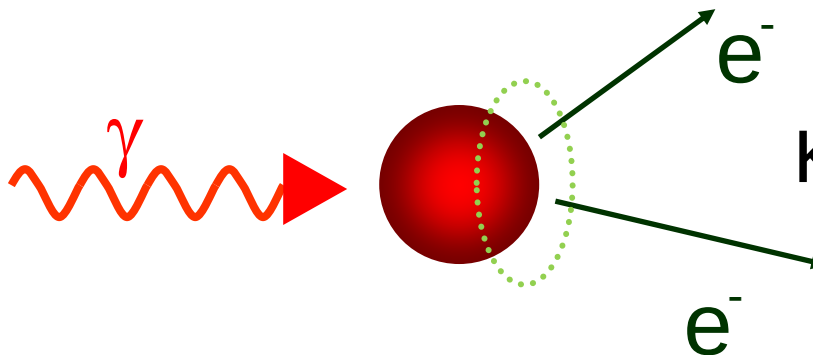
Other primary physical quantities

Radiometric quantities – describe the radiation field

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



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


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

Primary quantities can't be used for dose limits

Why?

1) Different biological effectiveness of different types of radiation

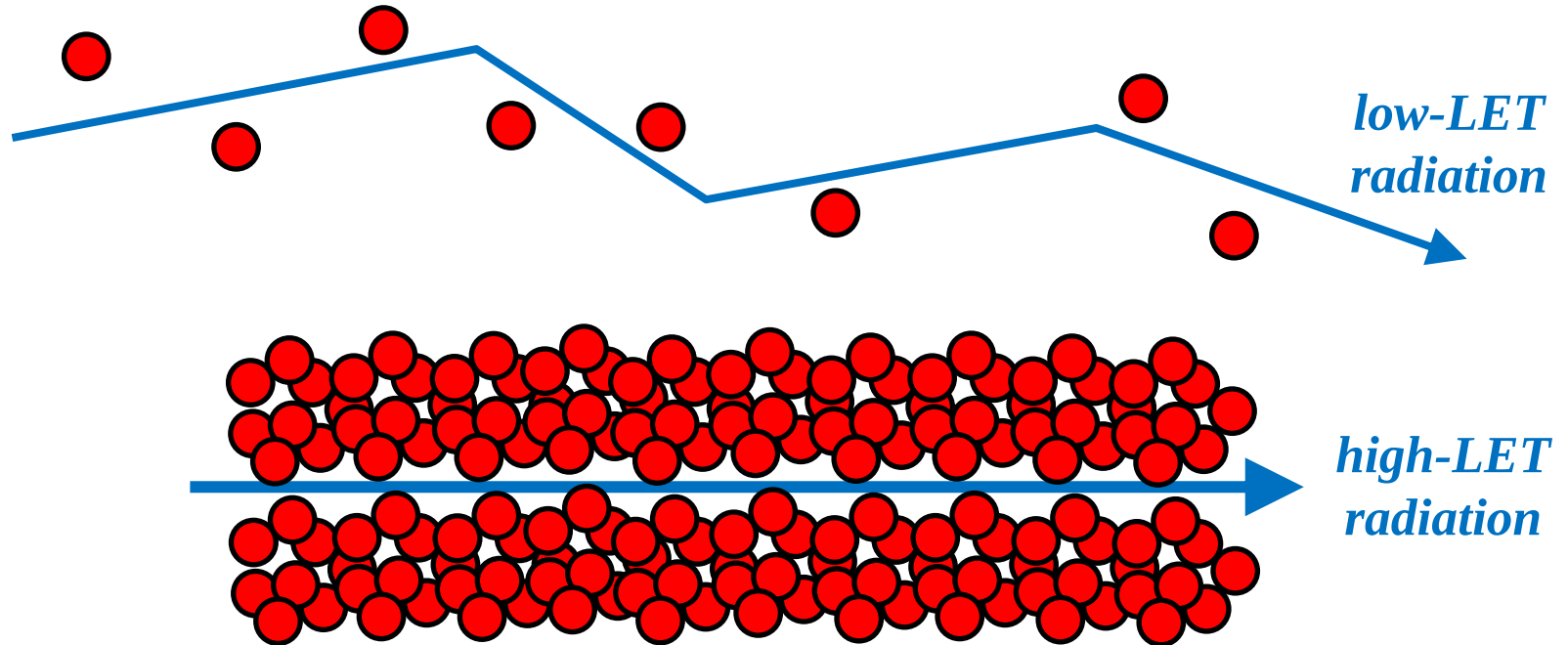
- Need for introducing radiation weighing factors, w_R

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/ μ m]
X-rays 250 kVp	2
Protons 230 MeV	2
Electrons 1 MeV	0.25
Electrons 10 keV	2.3

High LET

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

- 10 keV/ μ m typically considered as a threshold between low and high LET radiation
- Below 10 keV/ μ m RBE dose 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 limit deterministic effects

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

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

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 and beta exposure to the following absorbed doses:

$$D_{\alpha} = 1.4 \text{ mGy} \quad D_{\beta} = 10.1 \text{ mGy}$$

Effective dose E

- Tissue weighing factor w_T
- Estimates risks of health detriment at low doses
- Used to limit stochastic effects

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

equivalent dose to organ T

weighting factor of organ T

ICRP 103:

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

determined from
detriment

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



Concept of detriment

- Detriment is a concept used to quantify the harmful **stochastic effects** of low-level radiation exposure to the human population

Detriment = “Total harm”

- **Deterministic effects are not considered**
- Detriment is determined from lifetime risk of cancer for a set of tissues and organs and their severity in terms of lethality, years of life lost, quality of life...
 - **Probability** of incidence – dependent on radiation
 - **Severity** of effects – independent of radiation
- ICRP 60 and 103 use concept of detriment to derive **dose limits**

Concept of detriment

- Combination of probability of incidence and severity of effects:

*Vest changes
the
probability
of having an
accident*



*Helmet
changes the
severity of
an accident*

$$\text{Detriment} = \text{probability} \times \text{severity}$$

- Relatively easy to determine
- Incidence probability per dose

- Years of lost life
- Reduction of quality of life
- Lethality of tumor

Tissue weighing factors are derived from detriment

$$\text{Detriment} = \text{probability} \times \text{severity}$$

2005 recomm. ICRP

Tissue	Nominal Risk Coefficient (cases per 10,000 PYSv)	Lethality	Lethality-adjusted nominal risk*	Relative cancer free life lost	Detriment	Relative detriment ⁺
Oesophagus	17	0.93	17	0.87	15.0	0.023
Stomach	91	0.83	89	0.88	78.1	0.120
Colon	101	0.48	76	0.97	73.9	0.113
Liver	19	0.95	19	0.88	16.6	0.025
Lung	100	0.89	99	0.80	79.5	0.122
Bone surface	7	0.45	5	1.00	5.1	0.008
Skin	1000	0.002	4	1.00	4.0	0.006
Breast	121	0.29	67	1.29	86.5	0.133
Ovary	13	0.57	10	1.12	11.7	0.018
Bladder	43	0.29	23	0.71	16.3	0.025
Thyroid	24	0.07	7	1.29	9.5	0.015
Bone Marrow	41	0.67	37	1.63	60.8	0.093
Other Solid	214	0.49	164	1.03	169.1	0.259
Gonads / Hereditary	20	0.80	19	1.32	25.4	0.039
Total	1812		638		651.5	1.000

* Defined as $R \cdot q + R \cdot (1-q) \cdot ((1 - q_{\min}) q + q_{\min})$, where R is the nominal risk coefficient, q is the lethality, and $(1 - q_{\min}) q + q_{\min}$ is the weight given to non-fatal cancers and $q_{\min}$ is the minimum weight for nonfatal cancers. The $q_{\min}$ correction was not applied to skin cancer (see text).

+ The values given should not be taken to imply undue precision but are presented to 3 significant figures to facilitate the traceability of the calculations made.

Advantages and disadvantages of the effective dose concept

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

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 gonades: 2 mSv
- dose to the bone marrow: 1 mSv
- dose to the thyroid: 5 mSv
- dose to the remaining tissue : 0 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	0.01
Salivary glands	0.01
Skin	0.01
Remainder tissues	0.12 [†]

3. Effective dose



Calculate the effective dose for exposure of lungs and thyroid to: 1 Gy of gamma and 1 Gy of protons.

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

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

4. Effective dose



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

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**

- no laboratory standard for this quantity
- other measurable quantities were introduced for monitoring of external radiation exposure



Introduction of **operational quantities**

- can be used for practical measurements
- used as a conservative estimate of protection quantities
- dosimeters calibrated in terms of operational quantities

Operational quantities

➤ Operational quantities have the following characteristics

They are based on the equivalent dose at one point

- in the human organism
- or in a phantom

They are linked to a type of radiation and its energy at this point

They can be calculated from primary physical quantity at this point

➤ Two types of situation

Ambiance dosimetry

independent of the person, preventive

Personal dosimetry

performed on the concerned person, retrospective

Operational quantities

$$\text{operational quantities} = \text{fluence kerma dose} \times \text{conversion coefficient}$$

- Conversion coefficients are based on the reference phantom
- Ambient and personal dosimeters are calibrated in terms of operational quantities

Operational vs protection quantities

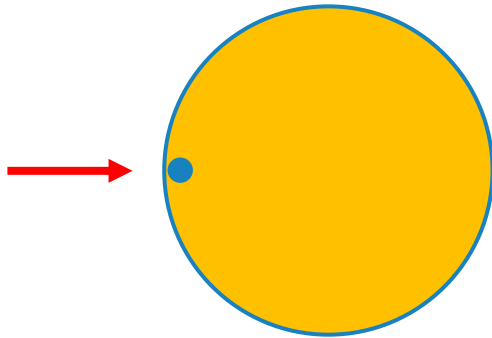
Protection quantity:
Effective dose

Operational quantity for
ambience dosimetry

Operational quantity for
personal dosimetry

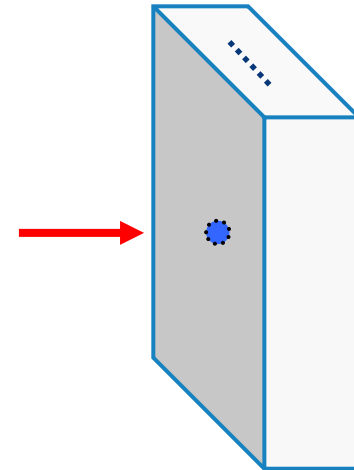
Ambient dose equivalent $H^*(10)$

- equivalent dose at 10 mm depth in the ICRU sphere

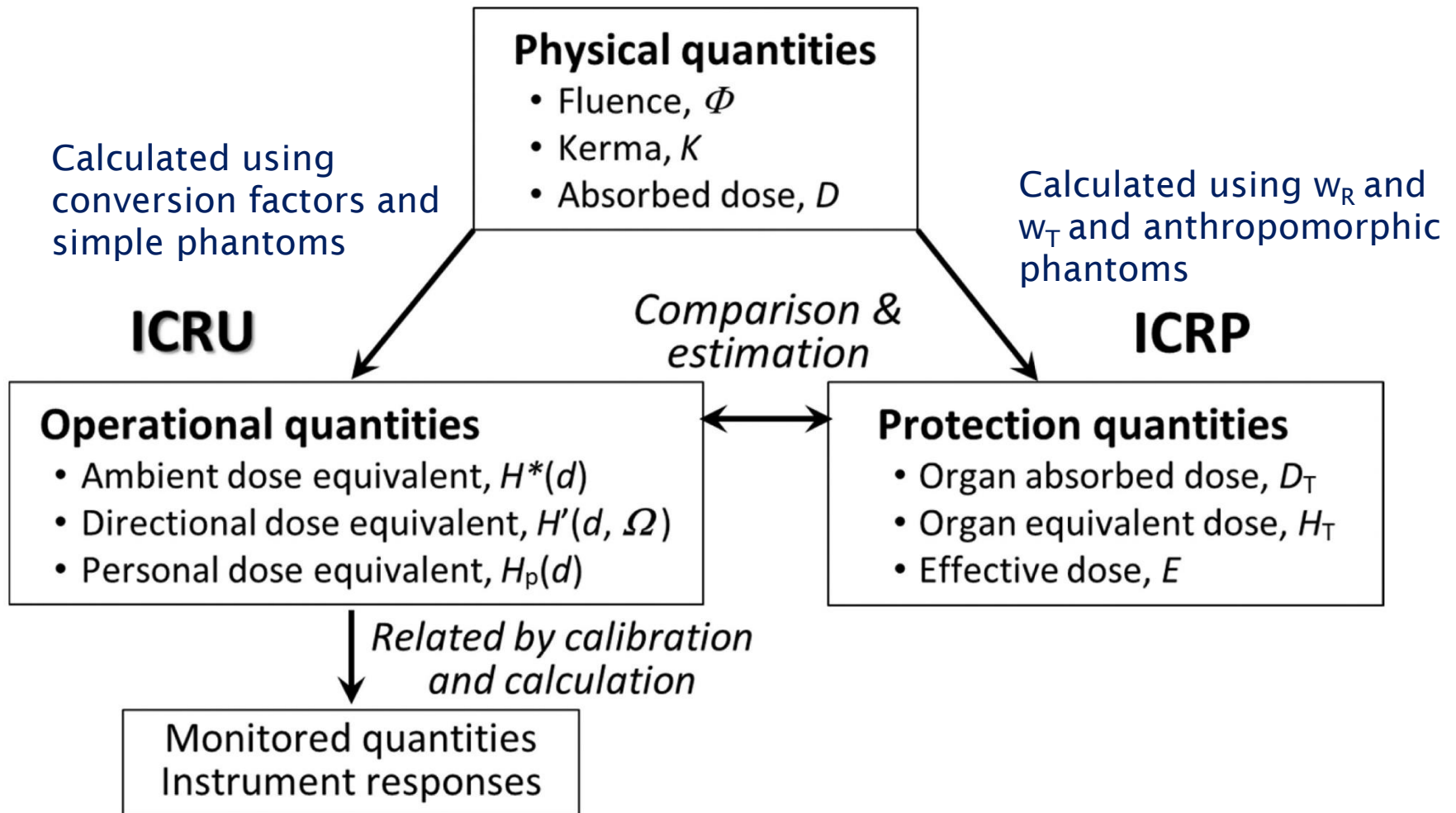


Personal equivalent dose $H_p(10)$

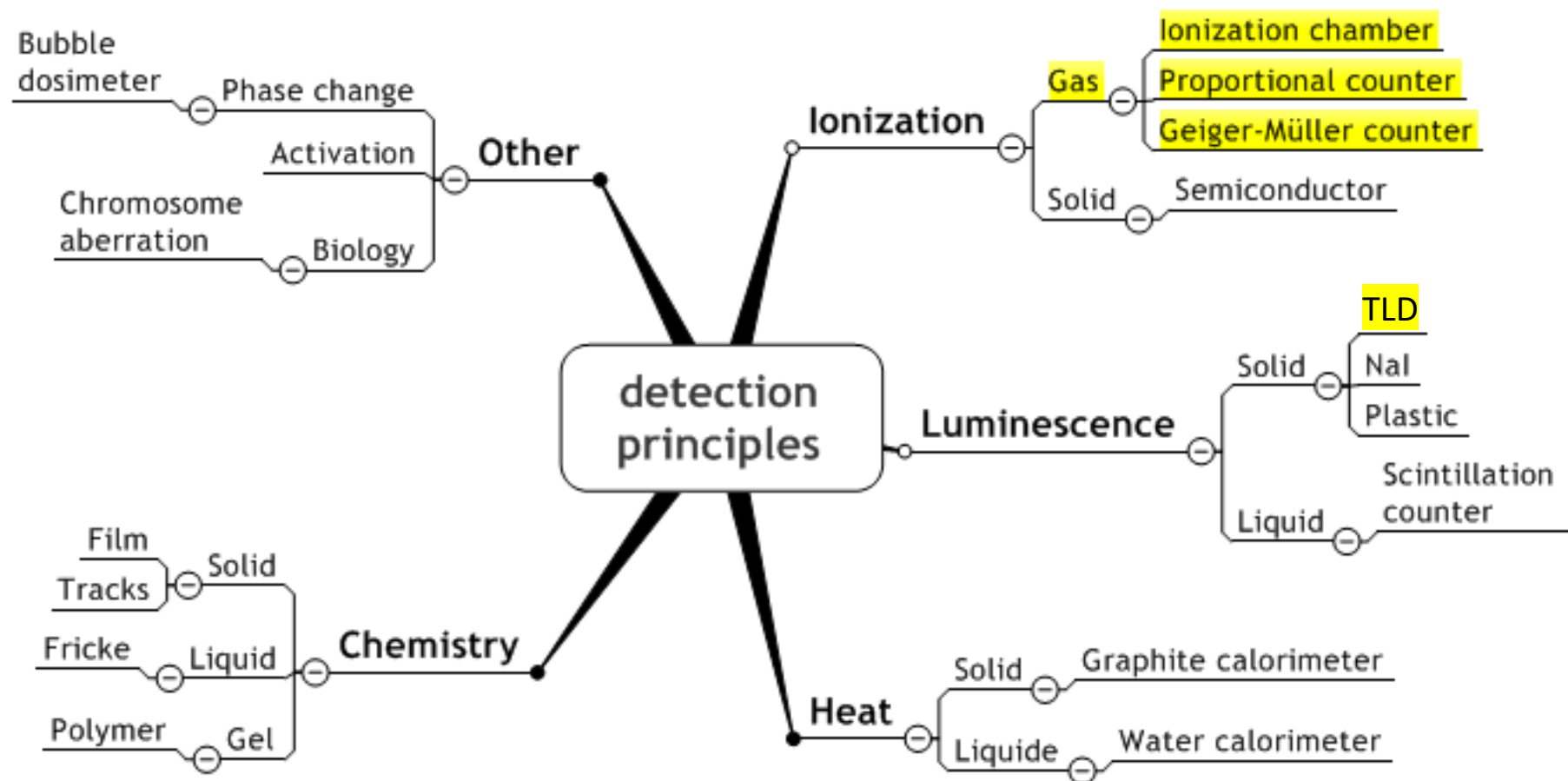
- equivalent dose at 10 mm depth in the ICRU slab phantom



Dosimetric quantities in radiation protection



Principles of dose measurement





Ambient dosimetry

Ambient dosimeters

- hand-held instruments calibrated "in air"

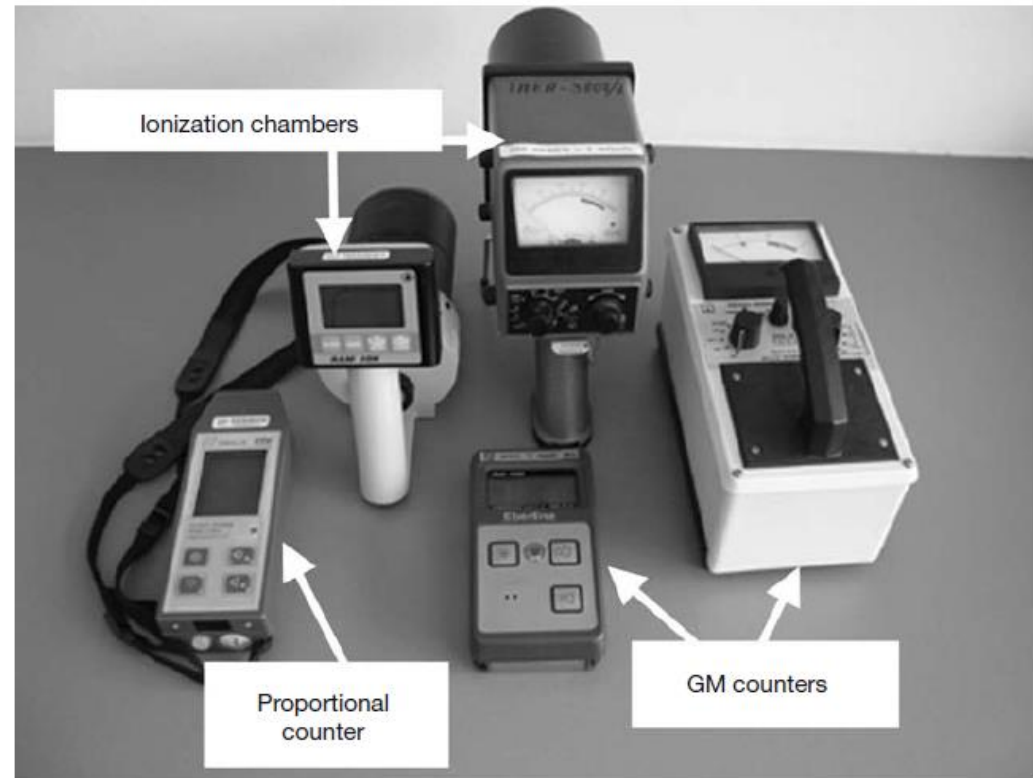
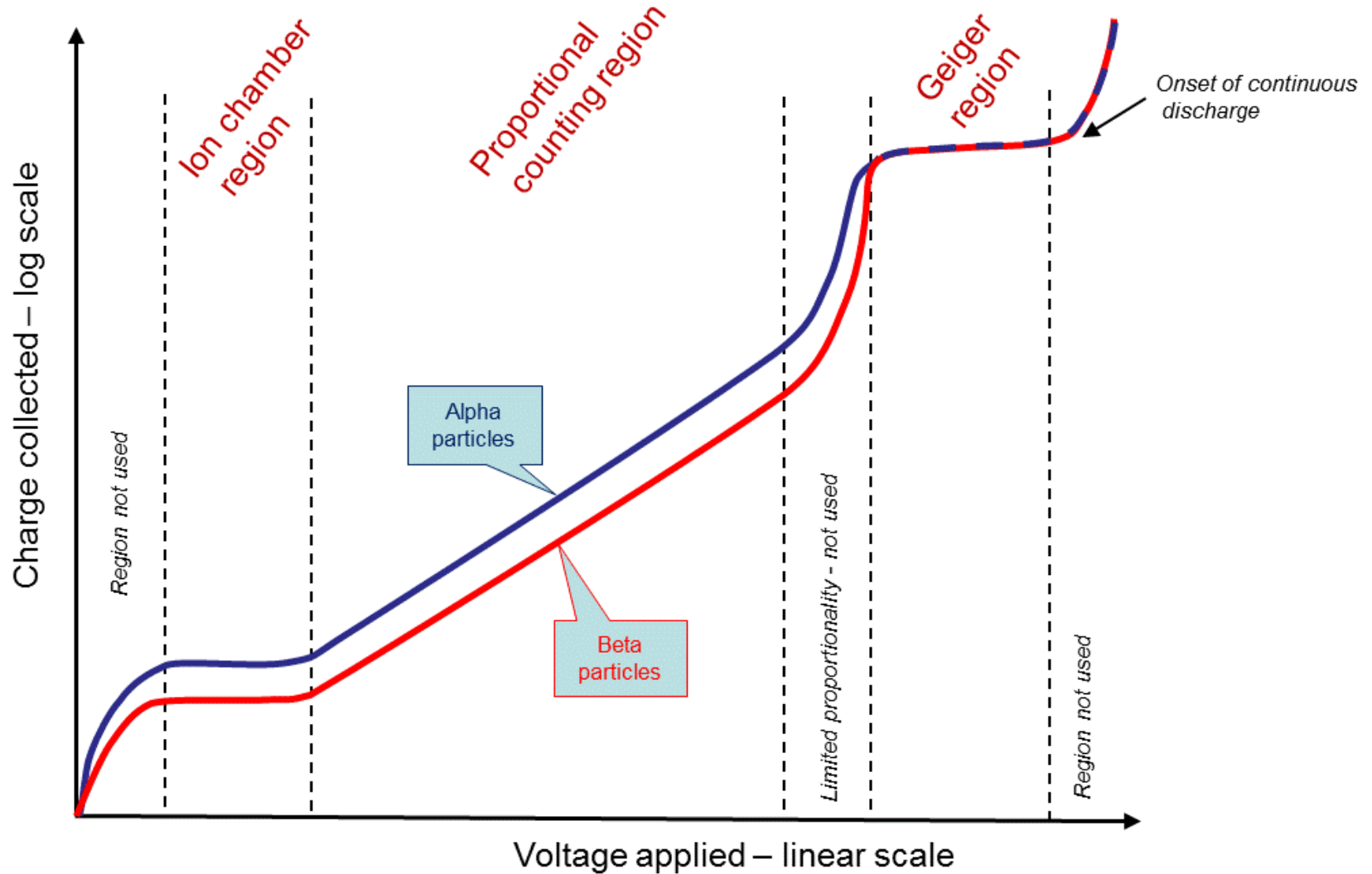


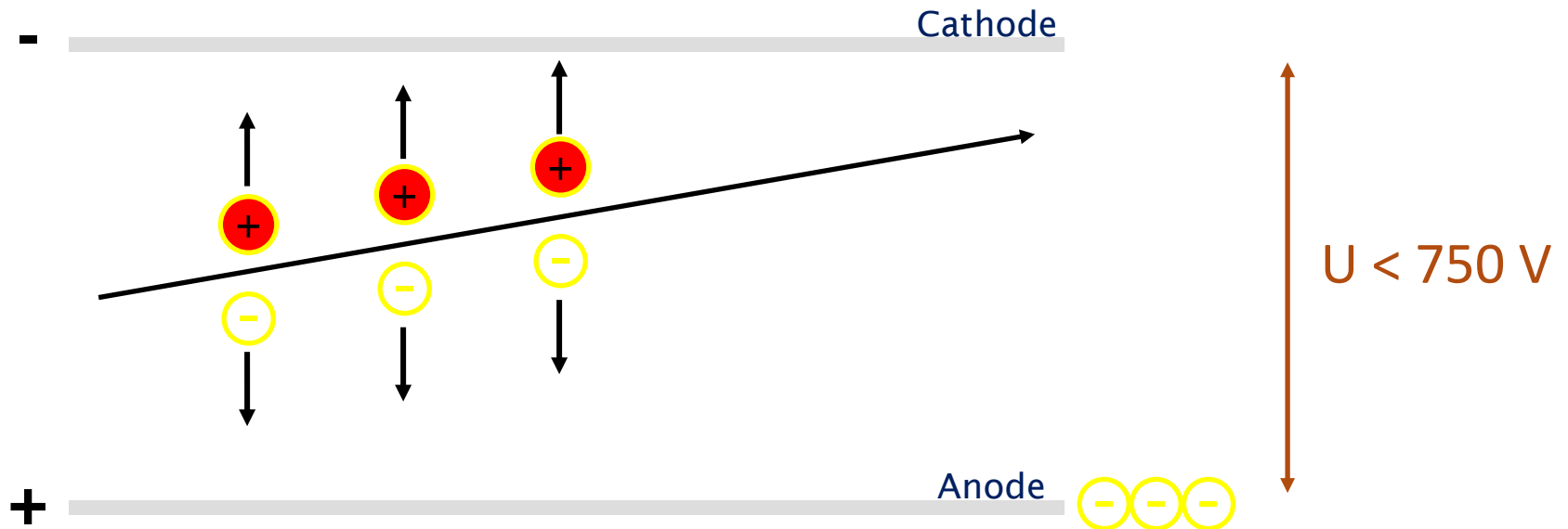
FIG. 4.2. Area survey meters commonly used for radiation protection level measurements: ionization chambers, a proportional counter and GM counters.

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

Radiology dosimeters:

current/charge $\mapsto$ kerma/dose

- Used mainly in current mode and with higher intensities of radiation, e.g. in diagnostic radiology



cylindrical



parallel plate

5. Ionization chamber

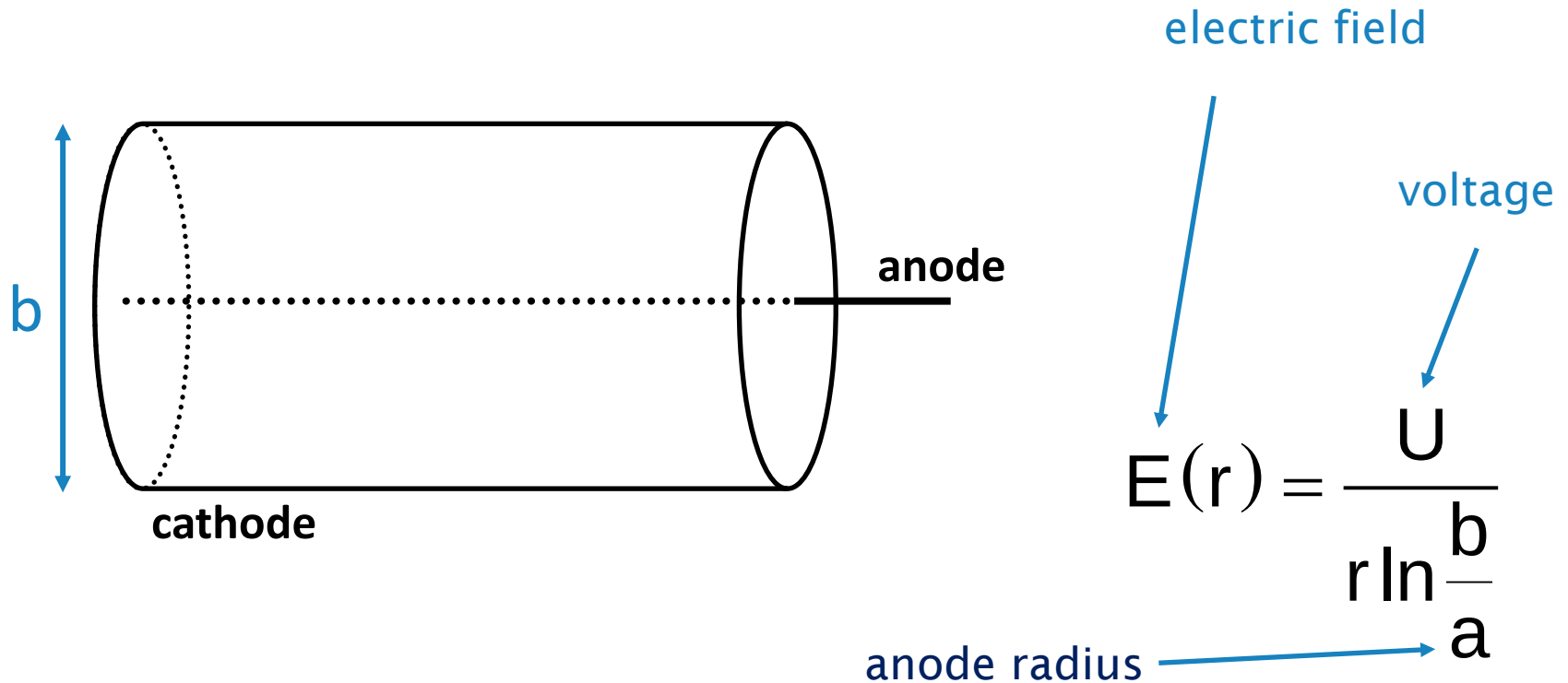


Which charge carriers contribute mostly to the induced signal in air filled ionization chamber?

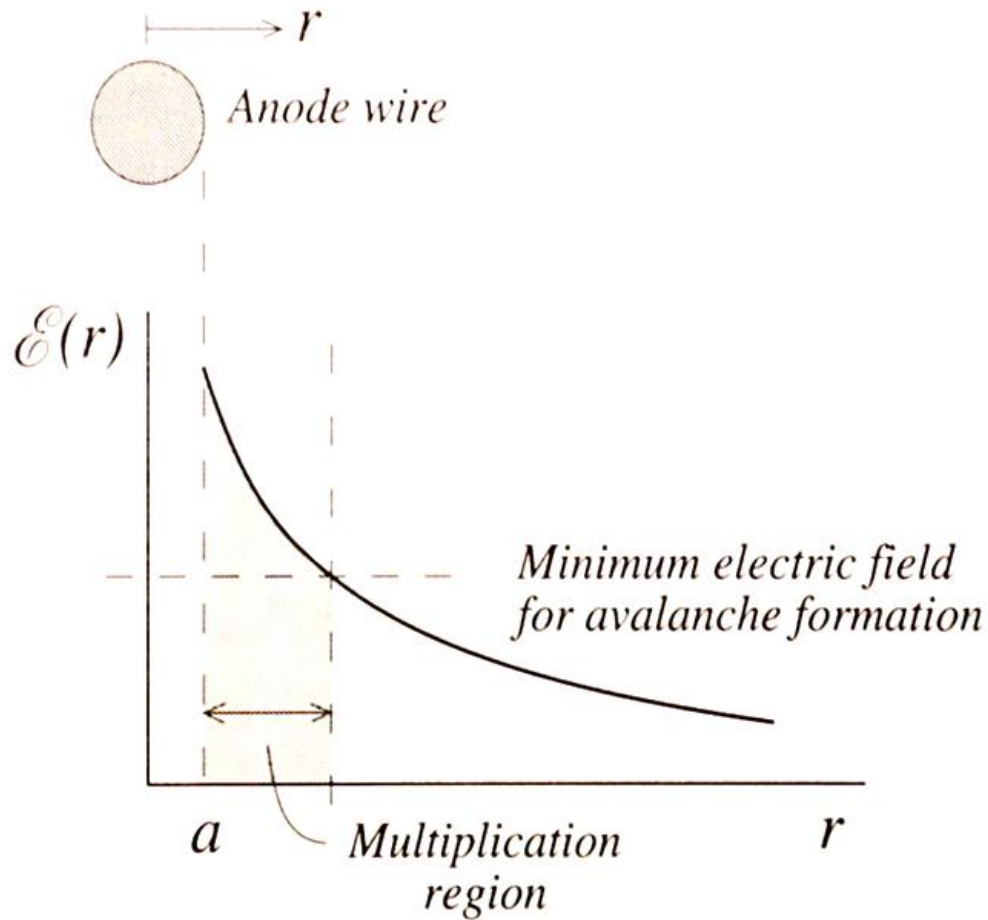
- 1) Electrons and positive ions
- 2) Positive ions and negative ions
- 3) Electron and holes
- 4) Electrons and positrons

Proportional counter

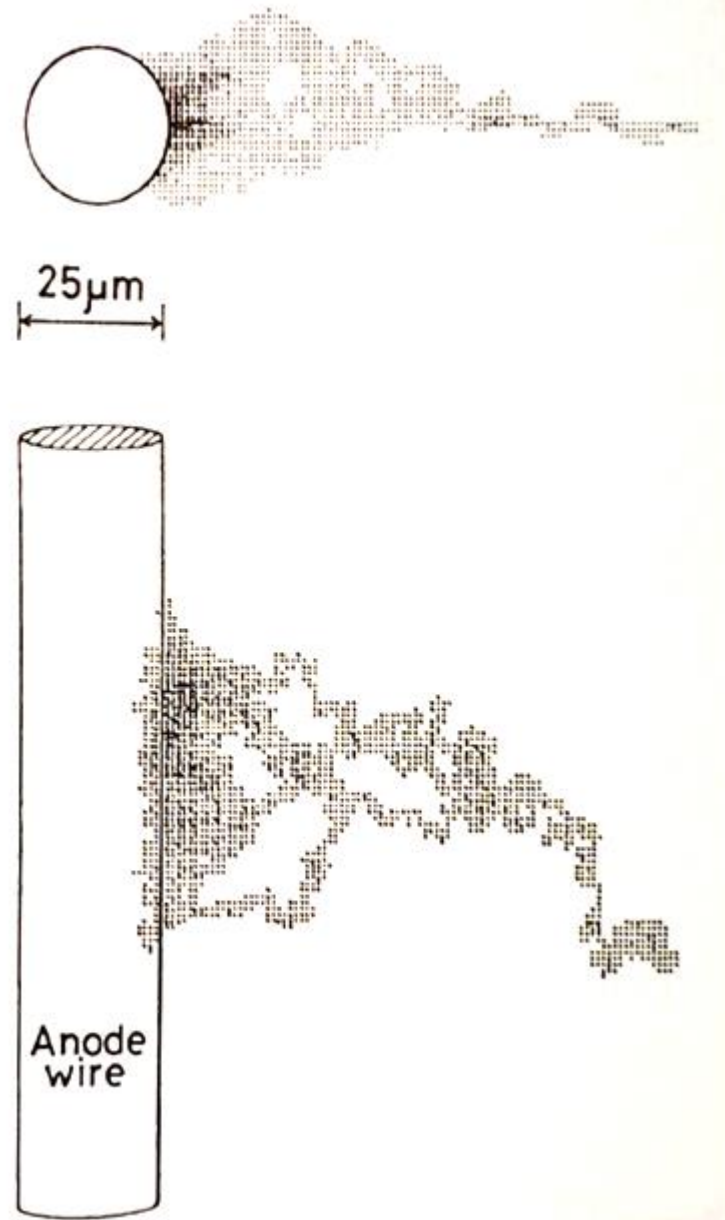
- Increase of the electric field in the vicinity of the anode
- operates in an intermediate voltage region between GM counters and ionization chambers



Proportional counter

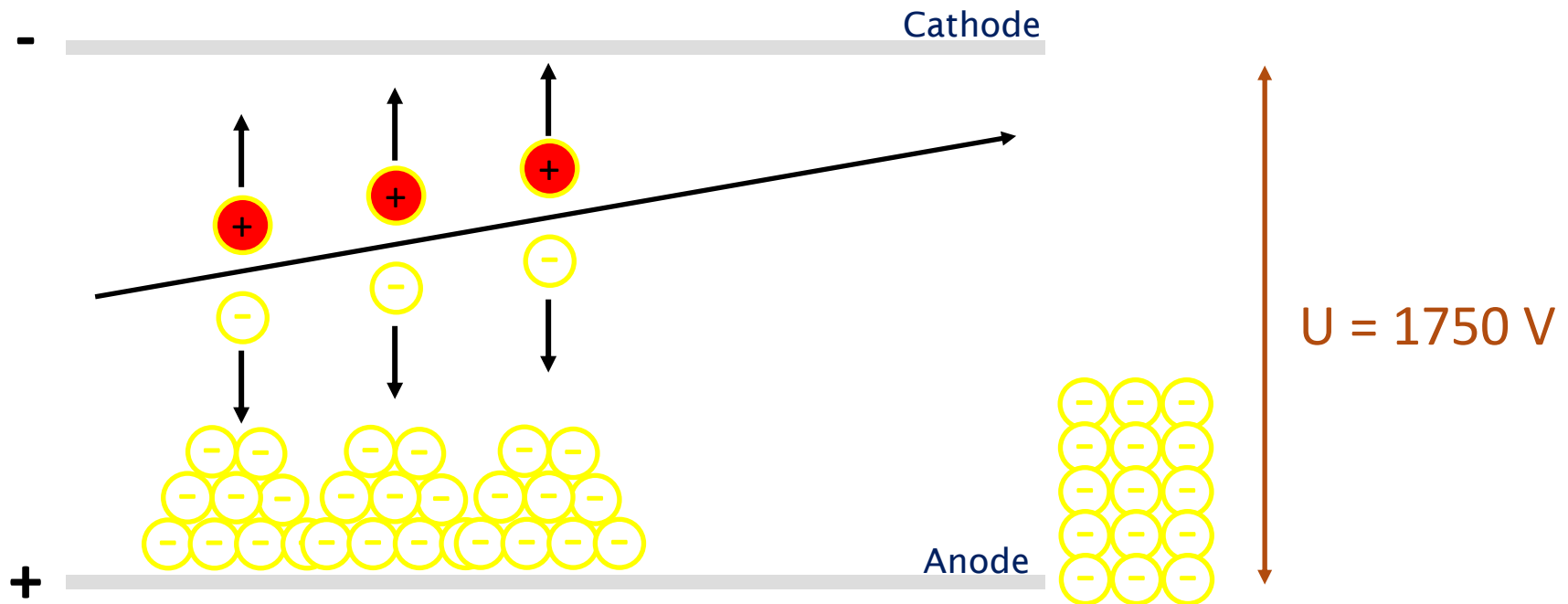


- Avalanche starts at $r \approx 5a$



Proportional counter

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



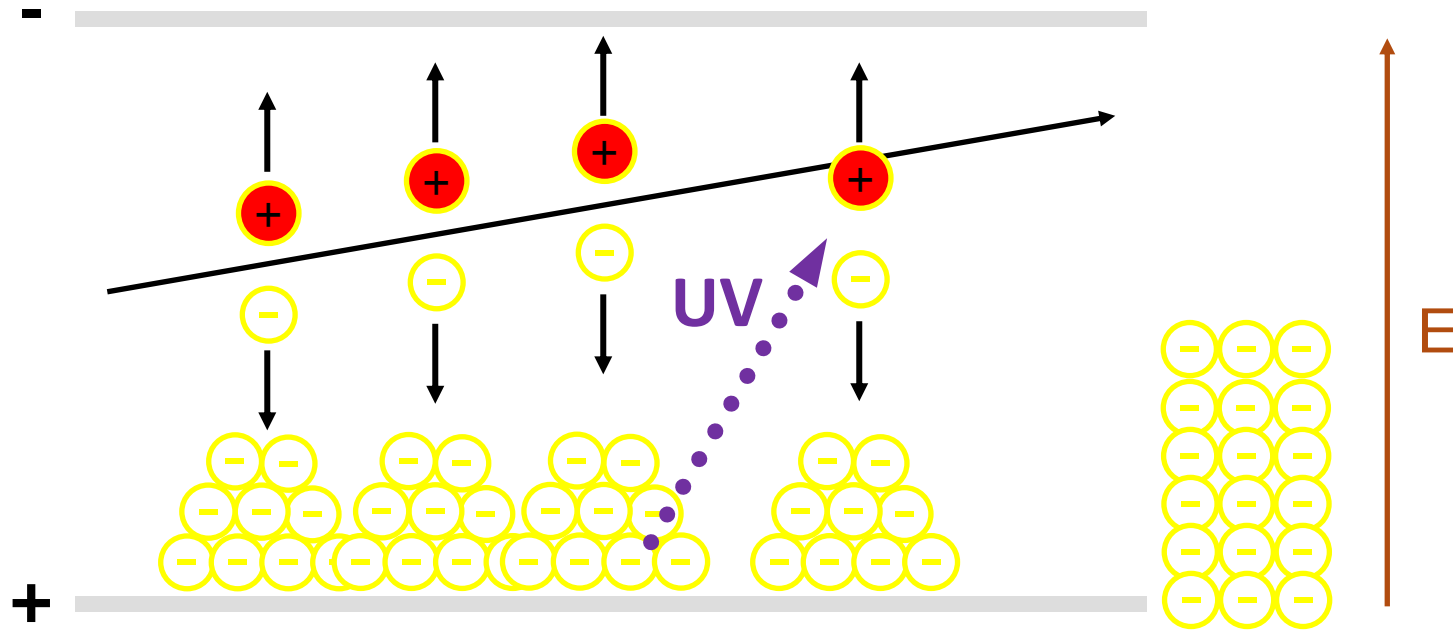
- Collected charge Q is still proportional to energy deposited inside the chamber

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
 - **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
- Partly contradicting, no ideal gas
- **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
 - Same thing happens when noble gas ions neutralize at the cathode



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

Proportional counter: role of the quenching gas

- Solution: addition of quenching gas (CH_4 , BF_3 , CO_2)
 - a) Quenching gas absorbs photons in wide energy range
 - Energy dissipation through dissociation (no new electrons)
 - b) Charge exchange with noble gas
 - Emission of secondary radiation at cathode unlikely
- In addition:
 - anode material with large work function

Proportional counter: characteristics

- Suitable for low intensity radiation fields (more sensitive than ionization chambers)
- Signal proportional to the energy deposited in the gas
 - One (identical) avalanche per primary electron
 - Secondary avalanches negligible
 - Total charge proportional to the number of primary electrons
i.e. the energy deposited in the gas
- Filled gas typically combination of noble gas and quenching gas
- Voltage usually high but not too high to maintain proportionality
- Mostly used in pulsed mode
- α/β discrimination possible
 - α amplitude higher

Proportional counter: applications

- Contamination monitor:
Pulse/s $\mapsto$ activity / cm²

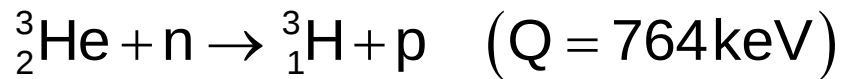


Berthold LB 1210B

Proportional counter: applications

- Neutron dosimeter:
 - pulse/s $\mapsto$ equivalent dose
 - from thermal to 20 MeV neutrons
 - excellent neutron/gamma discrimination

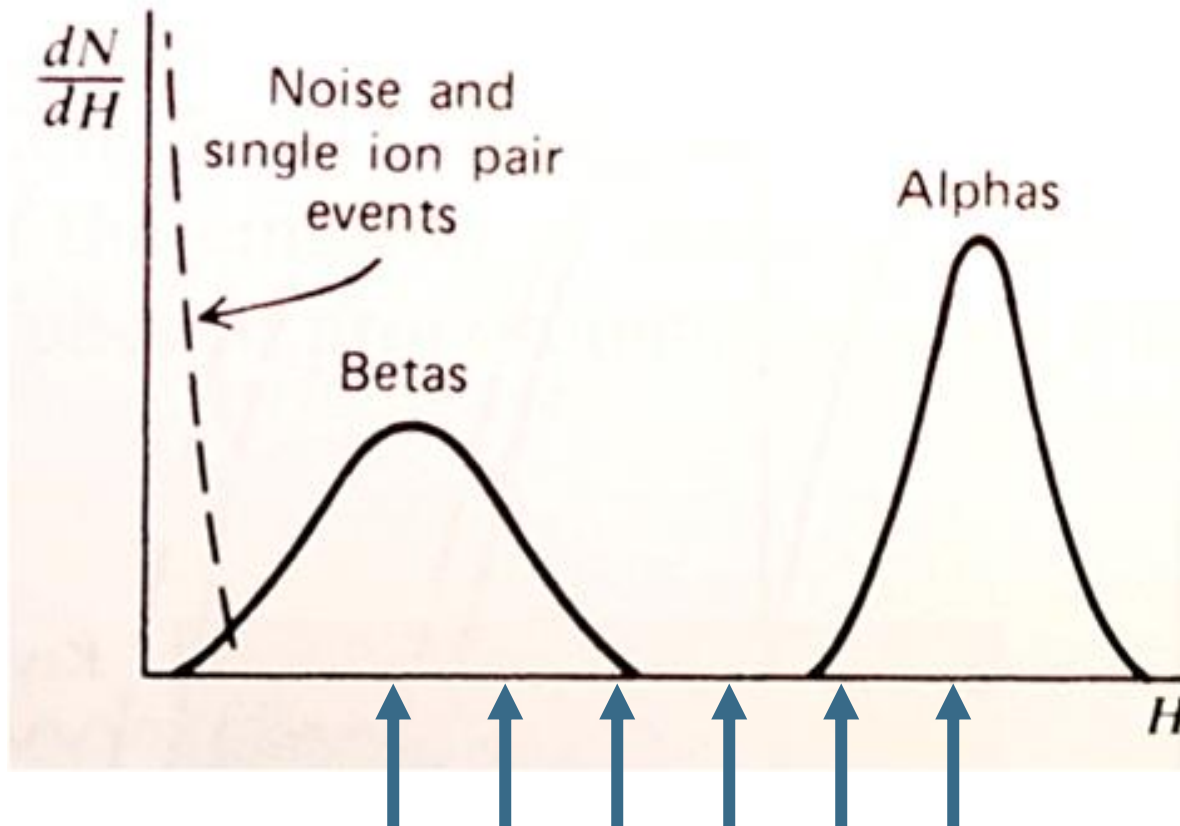
proportional
counter



moderator



Proportional counter: α/β discrimination



Changing the threshold allows us to discriminate different types of particles

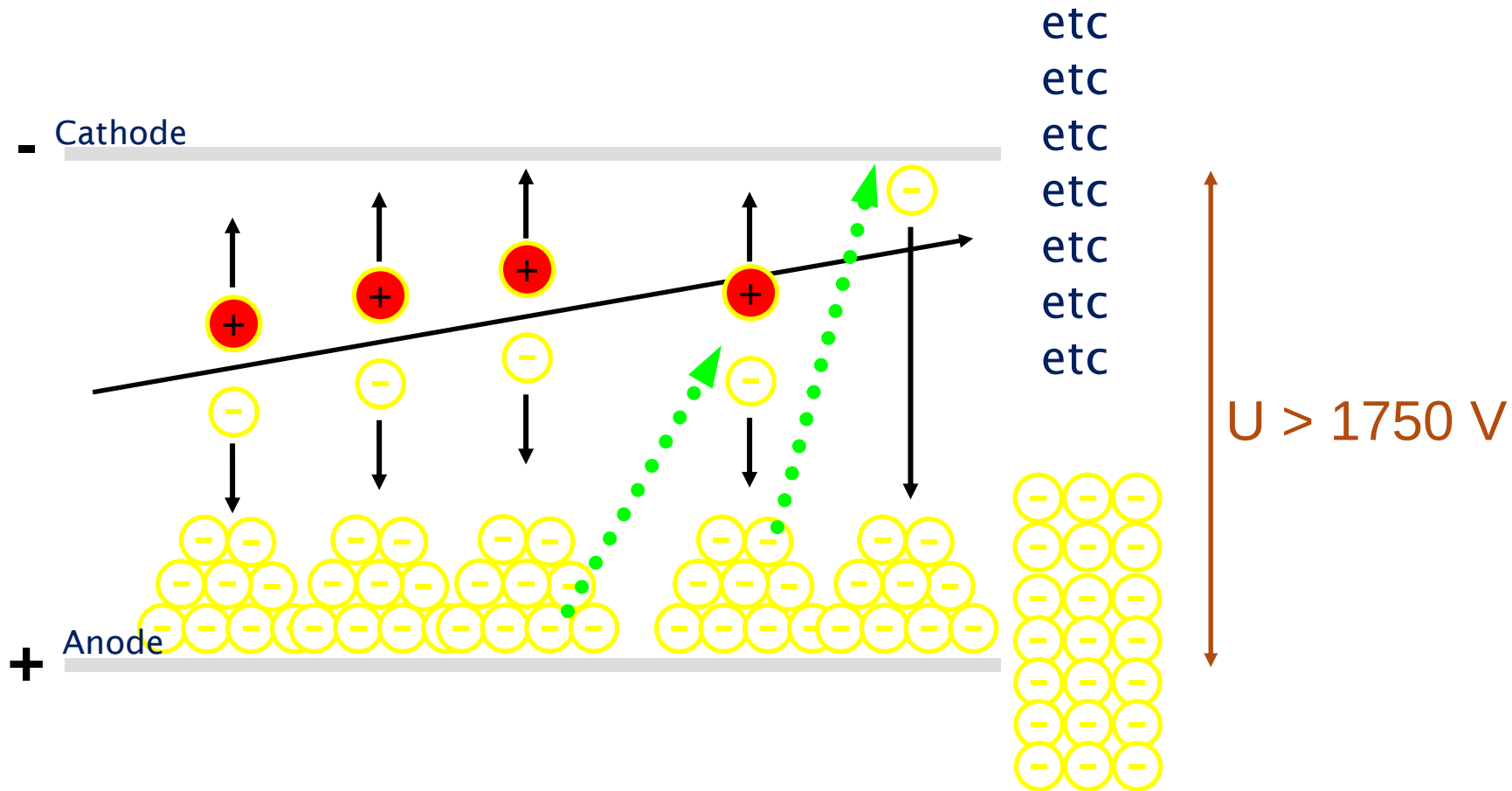
6. Proportional counter



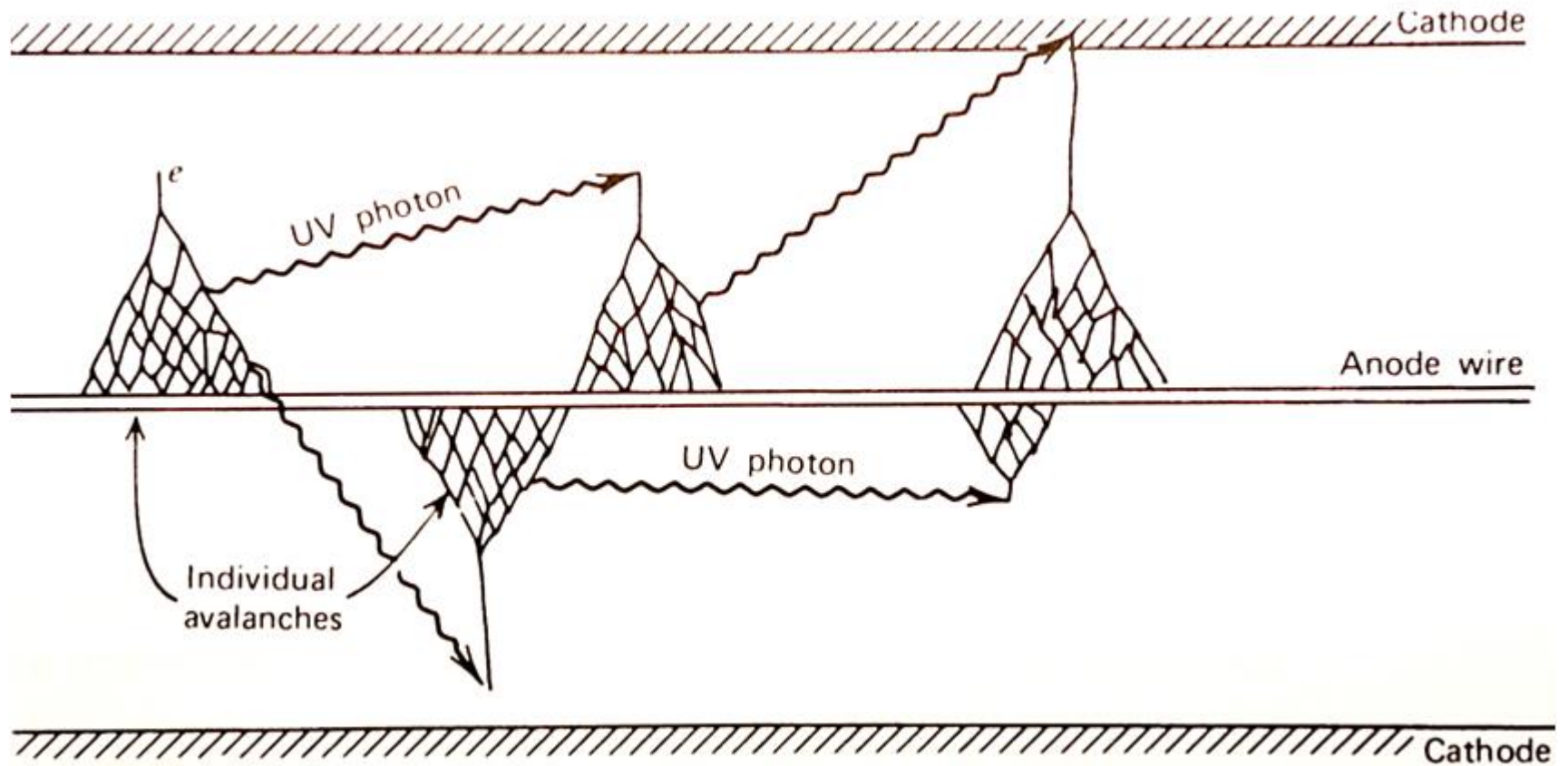
Would you fill a proportional counter with air?

Geiger-Müller counter

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

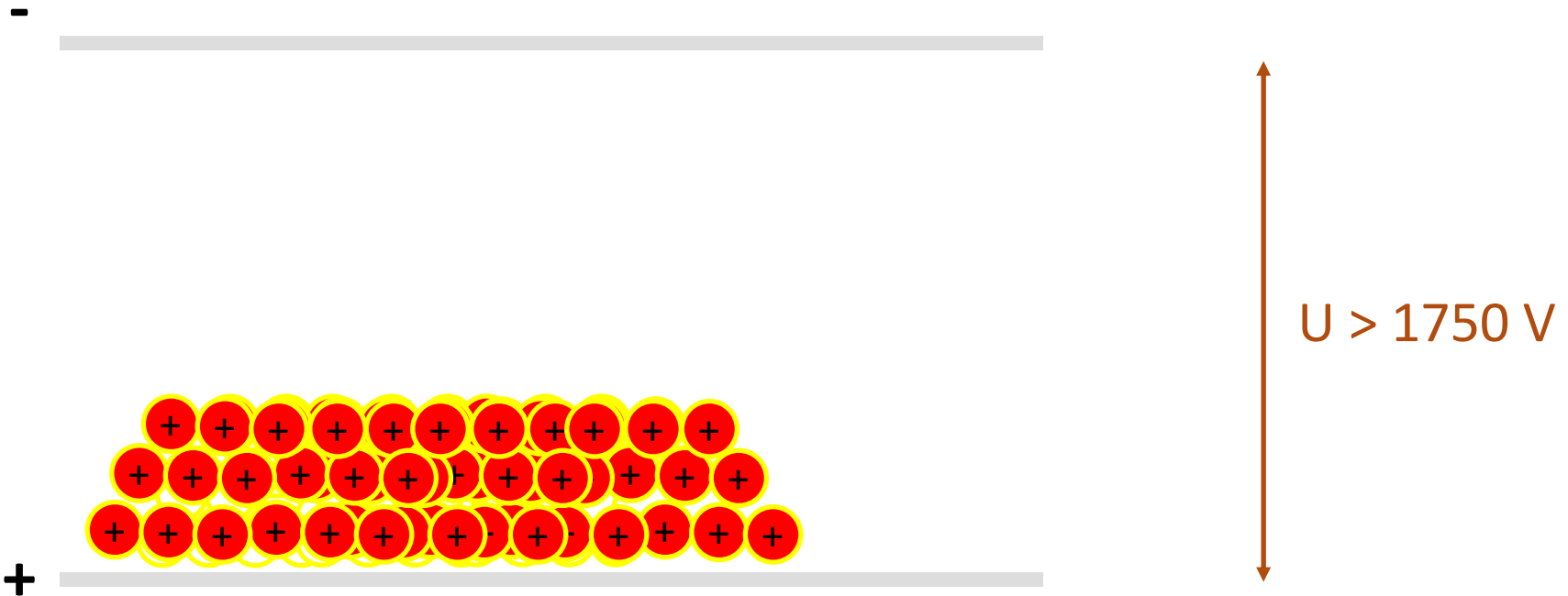


Geiger-Müller counter



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 → 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 ambience
dosimeter

pulse/s $\mapsto$ dose/s



Berthold LB 1236
detector

Mobile ambience dosimeter

pulse/s $\mapsto$ dose/s



Berthold LB 1236
electrometer



Personal dosimetry

Personal dosimeters

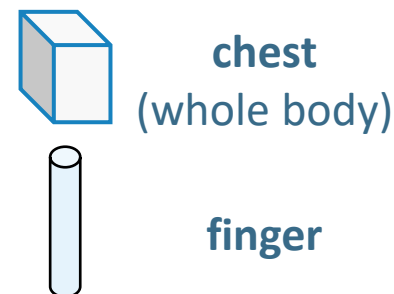
- body-worn
- calibrated on a phantom in a reference field



**whole body
personal TLD
dosimeters**



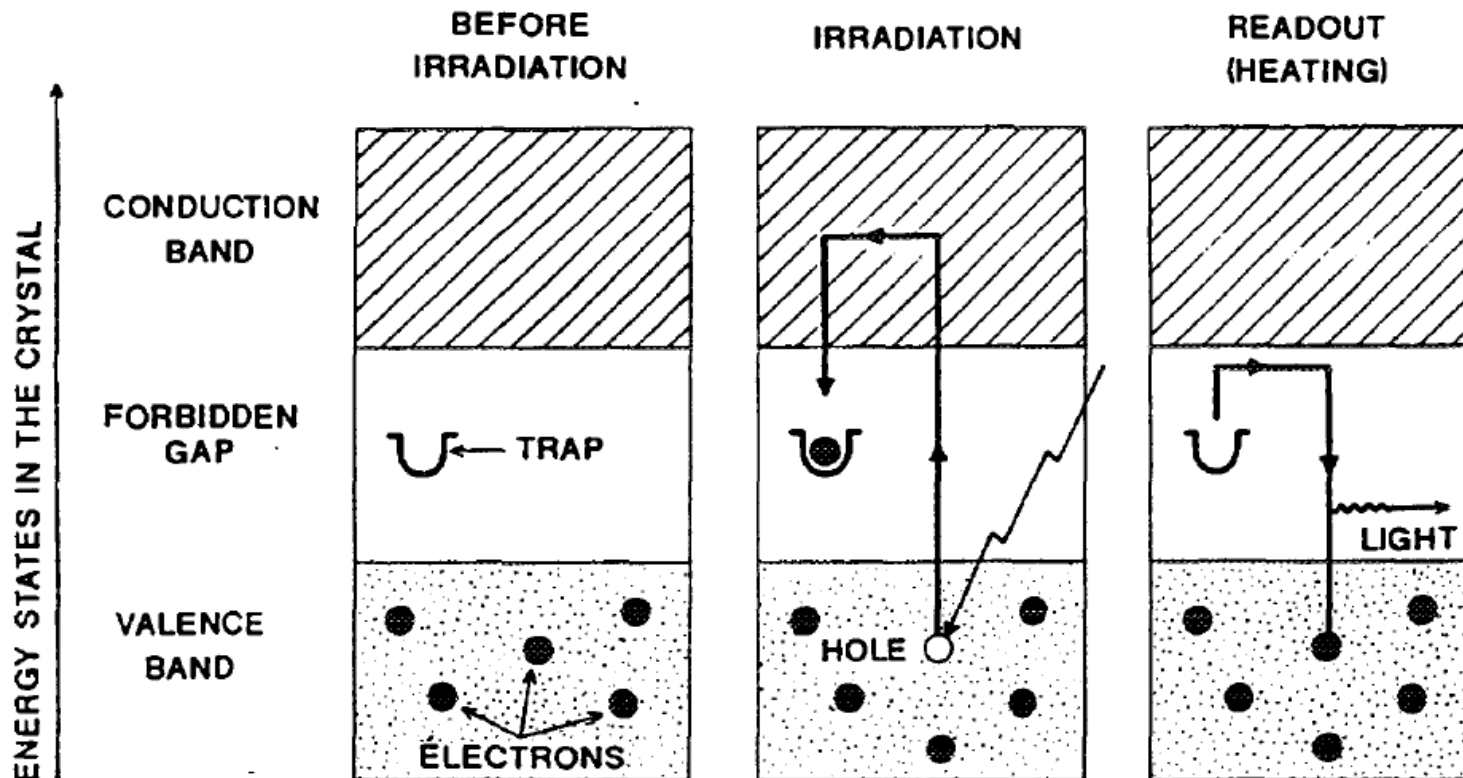
**electronic personal
dosimeters (Si diode)**



**TLD
dosimeters for
extremities**

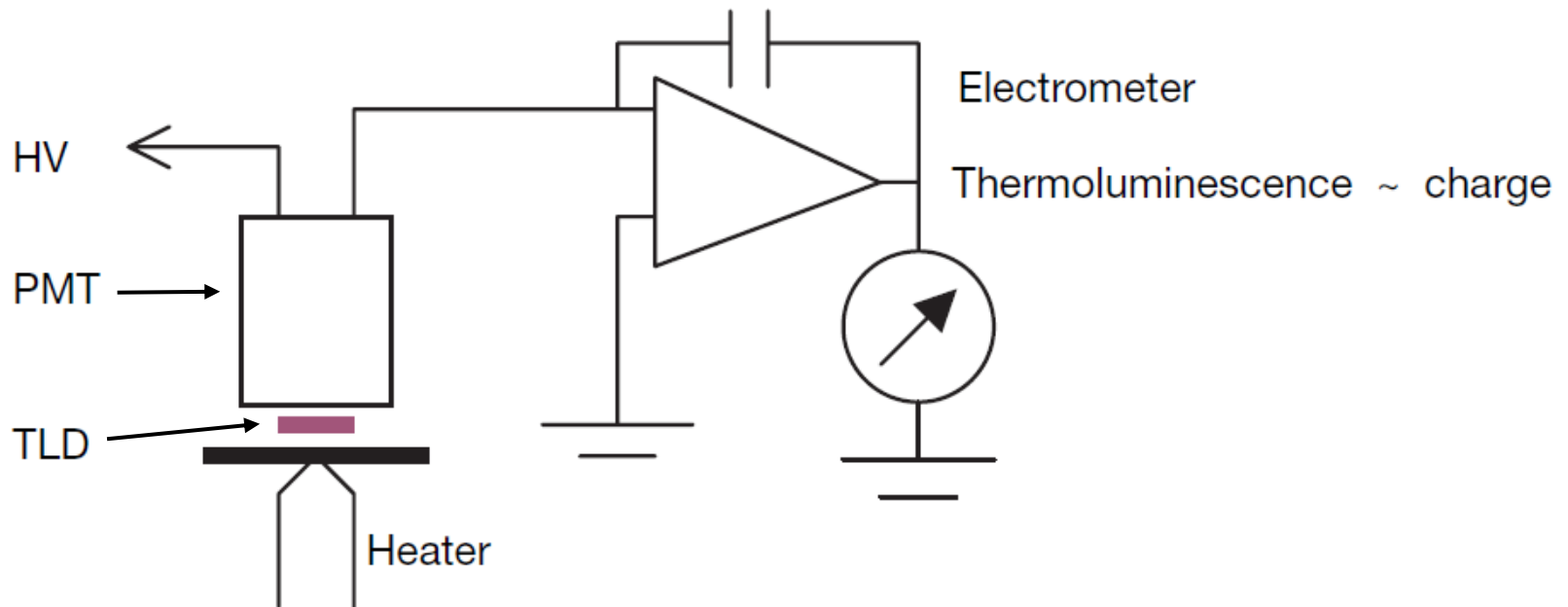
Thermoluminescence dosimetry

- 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:



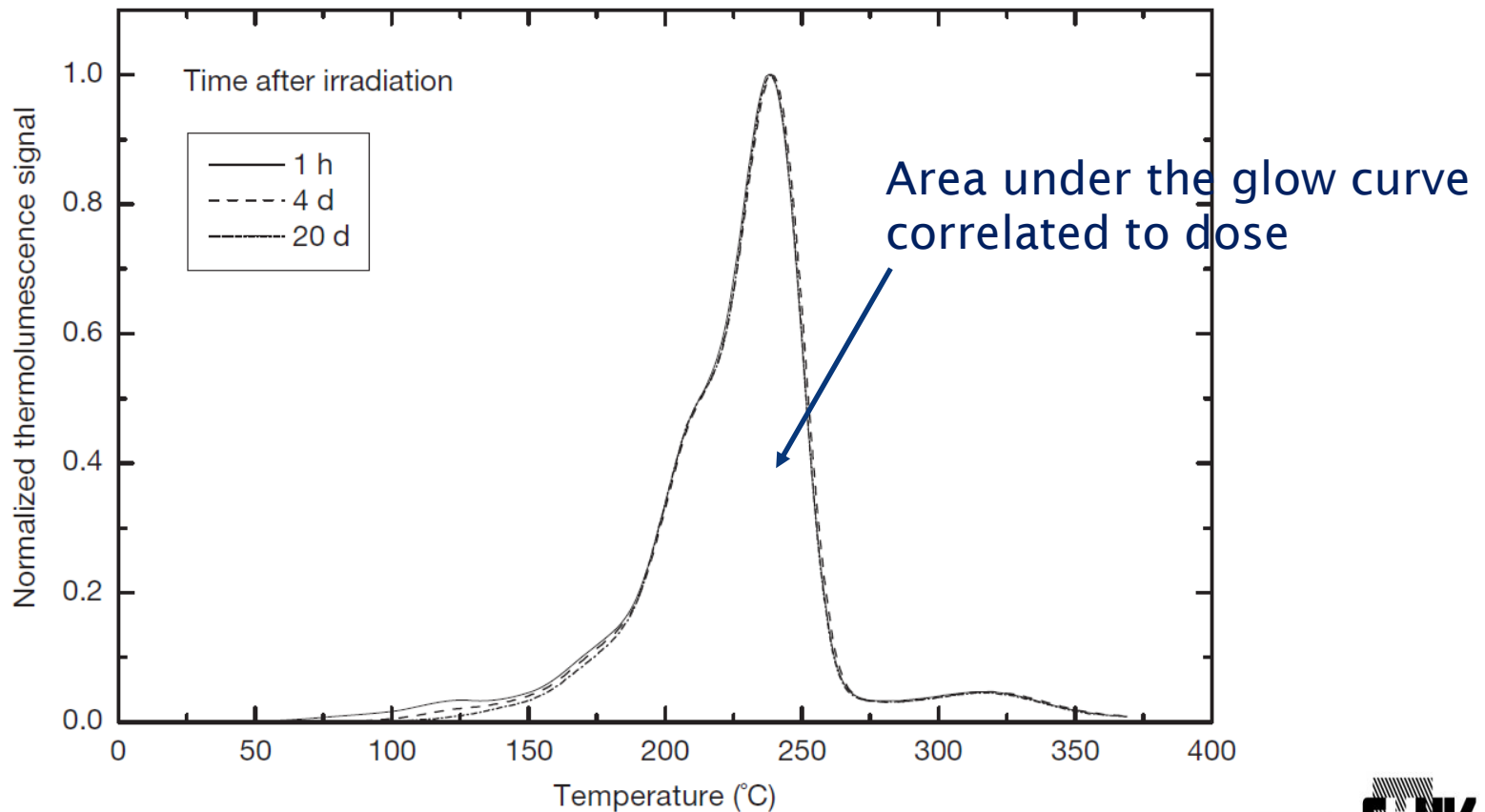
Thermoluminescence dosimetry

- 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) between 180°C and 260°C used for dosimetry
- 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