Gas Detectors

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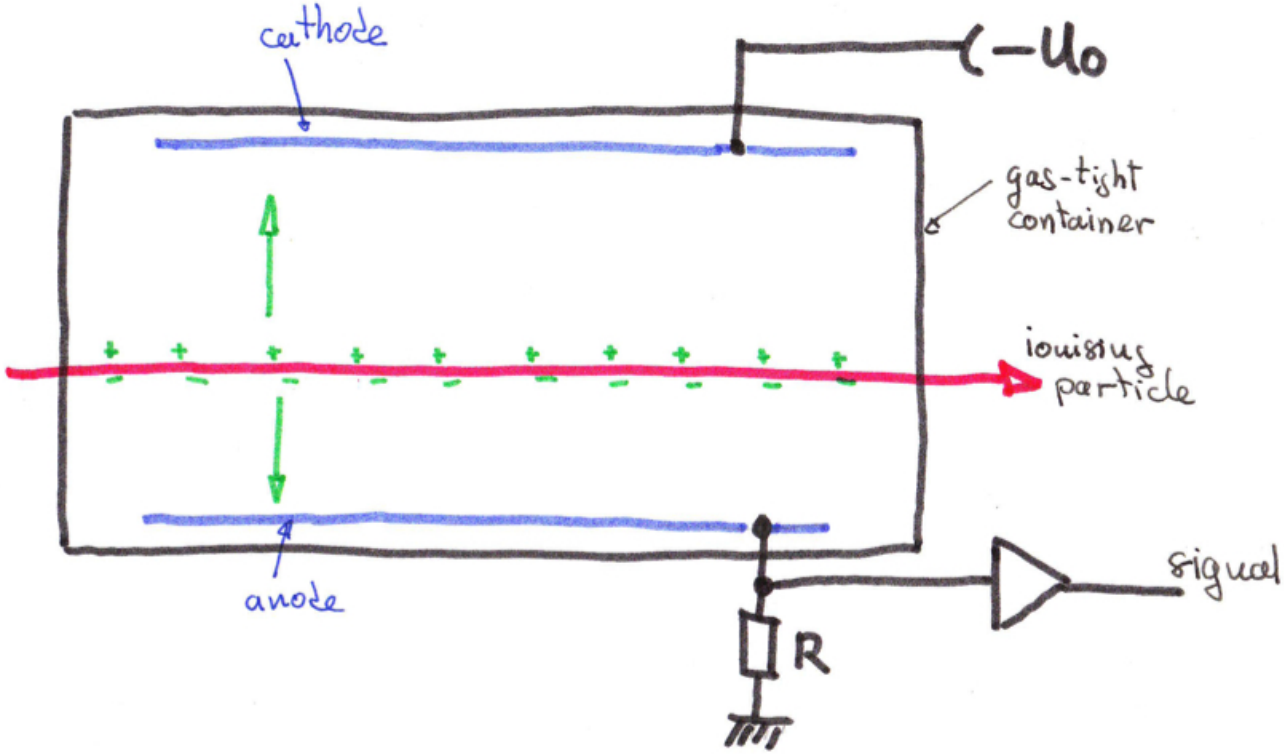
1. General Principles
2. Ionization and Transport Processes in gases
3. Ionization chambers
4. Proportional counters
5. Geiger-Müller counters
6. Summary and test

Section 1

General Principles

Introduction

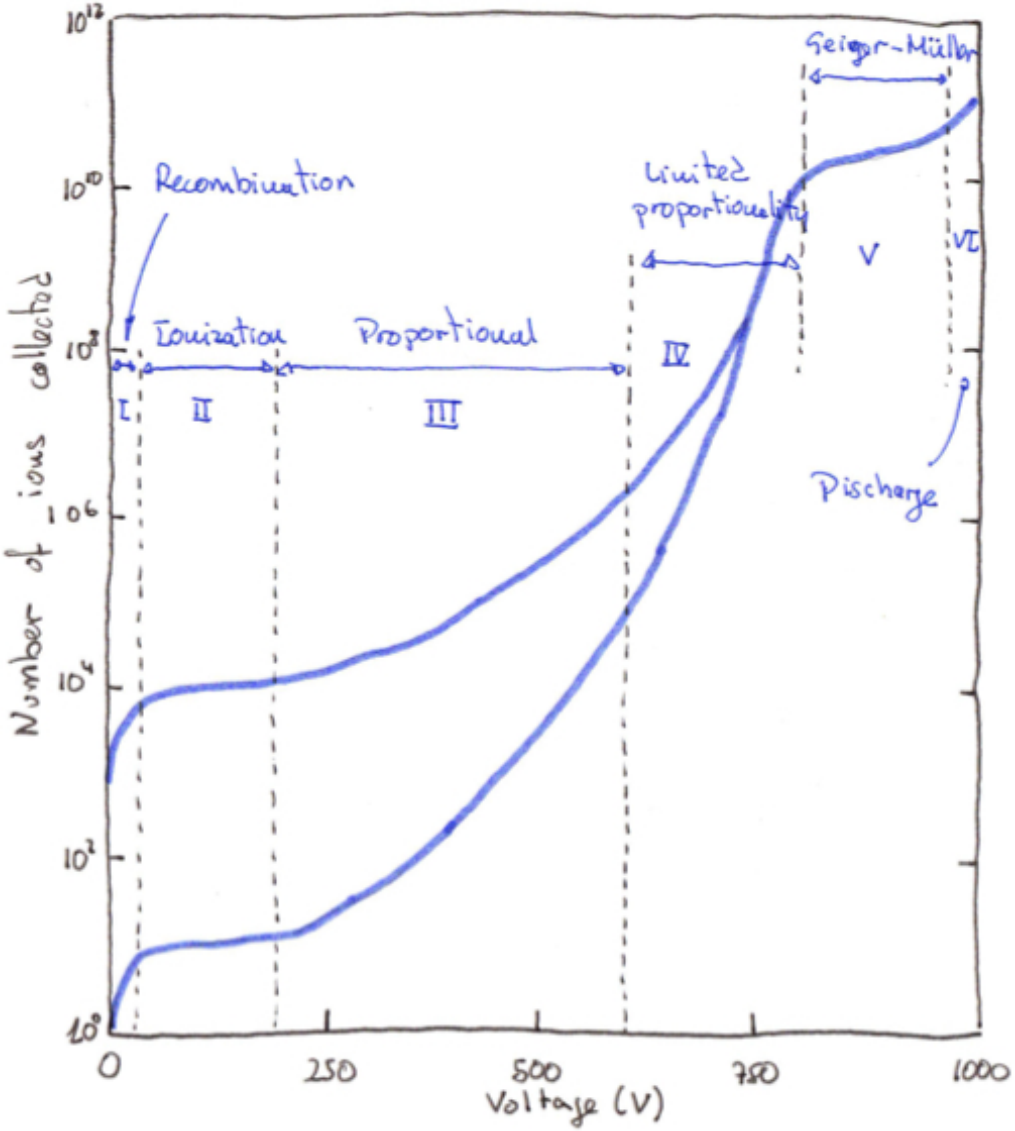
- Gas detectors are those in which the active media is a gas
- Radiation passing through a gas can ionize the gas molecules.
- Ion-electron pairs drift in opposite directions if an electric field is applied through electrodes
- A typical gas detector would be as:



Operation regimes of Gas detectors

- Based on the applied voltage, a gas detector can be operated in various modes
- These modes differs by the amount of charges produced and their movement inside the detector volume
- Choice of operation depends on the application
- We will distinguish SIX regimes or regions
  - Recombination region
  - Ionization region
  - Proportional region
  - Limited Proportionality region.
  - Geiger-Muller region
  - Discharge region

Operation regimes of Gas detectors



Operation regimes of Gas detectors

- Recombination region
  - If $V = 0$ ion pairs recombine before they arrive to electrodes
  - When increasing V
    - → recombination rate decrease
    - → more and more charge carriers can reach electrodes
  - The output does not reflect the energy deposited.
  - Not used for radiation detection

- Ionization region
  - In this region all ion pairs reach electrodes
  - Increasing the voltage does not change number of ions collected
  - Current proportional to ionization
  - Operation zone of Ionization Chambers

Operation regimes of Gas detectors

- Proportional region
  - In this region primary ions (n) can generate new ions(N).
  - Gain factor k linear with V

$$N = kn \qquad \rightarrow \qquad k = 10^2 - 10^6$$

  - Signal is then amplified IN the gas
  - Operation zone of Proportional Counters

- Limited proportionality region
  - Gain factor is no longer linear with increasing voltage
  - The reason is that density of ions change locally the electric field
  - As linearity is not conserved this regime is not used for radiation detection

Operation regimes of Gas detectors

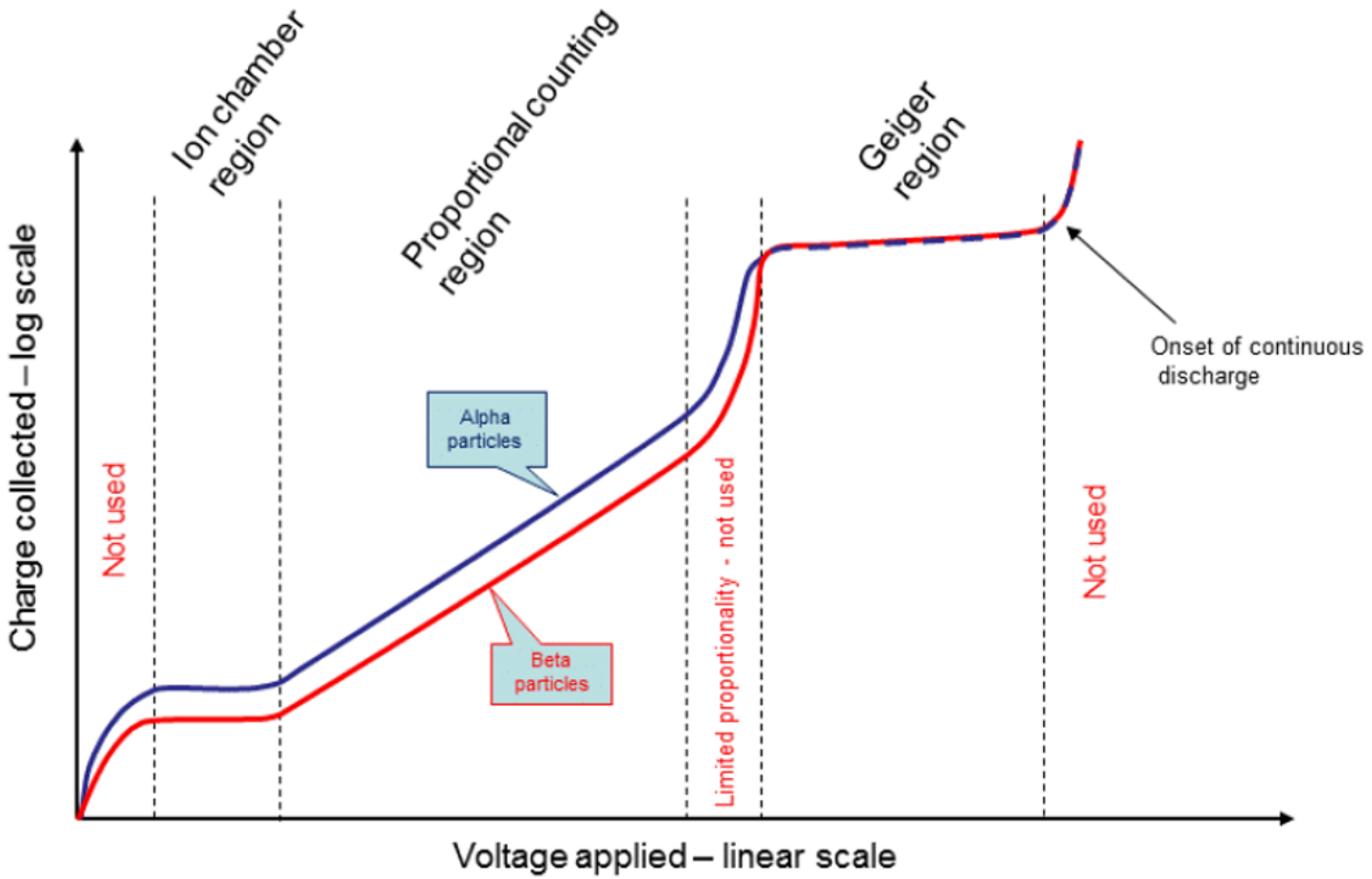
- Geiger-Müller region
  - After a certain voltage $V > V_{GM}$ an avalanche occurs even if only one ion pair is generated
  - Gain factors $\sim 10^8 - 10^9$
  - Once the ionization disappears the avalanche also disappears
  - Information about ionization is lost but sensitivity is high
  - Due to the high quantity of ion-pairs generated, the recovery time is large
  - Regime of operation of Geiger-Müller counters.

- Discharge region
  - When voltage is high enough, the electric field can ionize gas molecules
  - A continuous discharge avalanche appears.
  - Only way to stop the avalanche is to low the voltage
  - Radiation detectors cannot operate in this region.

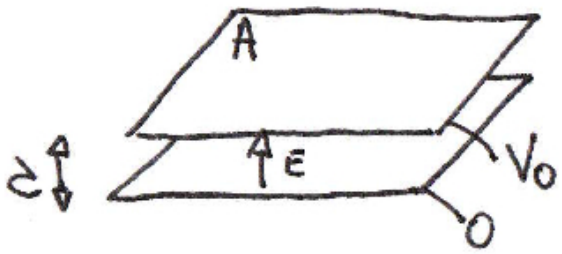
Practical Gaseous Ionisation Detector Regions

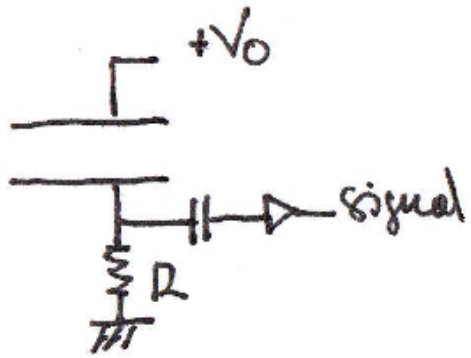
Variation of ion pair charge with applied voltage in a co-axial wire anode gaseous ionisation detector subject to constant and equal count rate of alpha and beta particles.

(regions with non-linear behaviour are not used)



Useful geometries: Planar Parallel Plates





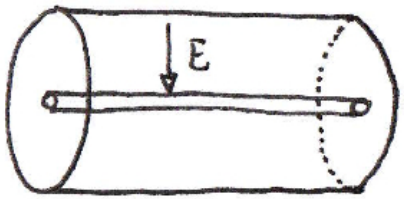
$$\vec{E} = \frac{\sigma}{\varepsilon}\hat{n} \xrightarrow{\sigma = Q/A} \vec{E} = \frac{Q}{\varepsilon A}\hat{n}$$

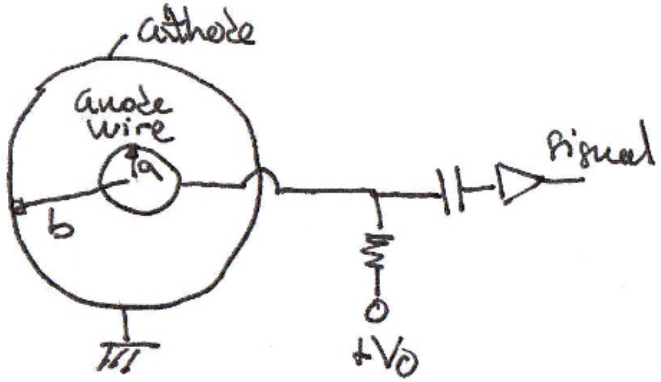
$$V(x) = -\frac{\sigma}{\varepsilon}x = -\frac{Q}{\varepsilon A}x = -\frac{Q}{Cd}x$$

$$V_0 = -\frac{Q}{\varepsilon}d$$

$$C = \frac{Q}{V_0} = \varepsilon\frac{A}{d}$$

Useful geometries: Cylindrical geometry





$$\vec{E}(r) = \frac{1}{r}\frac{V_0}{\ln\left(\frac{b}{a}\right)}$$

$$V(r) = -\frac{CV_0}{2\pi\varepsilon}\ln\left(\frac{b}{a}\right)\ln\frac{r}{b} = -\frac{V_0}{\ln\left(\frac{b}{a}\right)}\ln\frac{r}{b}$$

$$C = \frac{2\pi\varepsilon}{\ln\left(\frac{b}{a}\right)}$$

Section 2

Ionization and Transport Processes in gases

2. Ionization and Transport Processes in gases

- Production of Electron-Ion Pairs
- Transport processes of electron and ions
- Drift of charged particles
- Drift of ions
- Drift of electrons
- Diffusion
- Factors affecting Charge Transport
- Gas multiplication

Production of Electron-Ion Pairs

- Radiation interacting within a gas will produce ionization in the gas molecules but also excitation
- Ionization can be:
  - Primary: produced directly by the radiation
  - Secondary: produced by the electrons (δ-rays) or the ions
- The relevant quantity in which we are interested is the effective ionization=number of ion pairs created
- Regardless of the type of radiation and energy, effective ionization is

$$N_{eff} = \frac{\Delta E}{w} \rightarrow \#\text{ion-pairs} \qquad n_{eff} = \frac{dE/dx}{w} \rightarrow \#\text{ions-pairs/cm}$$

  where w is the average energy to produce an ion pair
- For gases, $w = 25 - 40$ eV (ionization potential = 10-20 eV)

Production of Electron-Ion Pairs

Gas	First Ionization Potential (eV)	w-value (eV/ion-pair)	
		Fast Electrons	Alpha Particles
Ar	15.7	26.4	26.3
He	24.5	41.3	42.7
H_2	15.6	36.5	36.4
N_2	15.5	34.8	36.4
Air		33.8	35.1
O_2	12.5	30.8	32.2
CH_4	14.5	27.3	29.1

Production of Electron-Ion Pairs

- The formula of n_{eff} gives us the total ionization produced n_t
- From dedicated experiments the primary ionization n_p has been measured for certain gases.
- $n_p \neq n_t$ because of inevitable presence of secondary ionization
- The effective ionization for a gas mixture is:

$$n_t = \sum_i x_i \frac{(dE/dx)_i}{w_i}$$

$$n_p = \sum_i x_i n_{p,i}$$

where x_i is the fraction by volume of gas i

- This is an statistical approach ... huge variations (up to 30%) can take place!!

Production of Electron-Ion Pairs

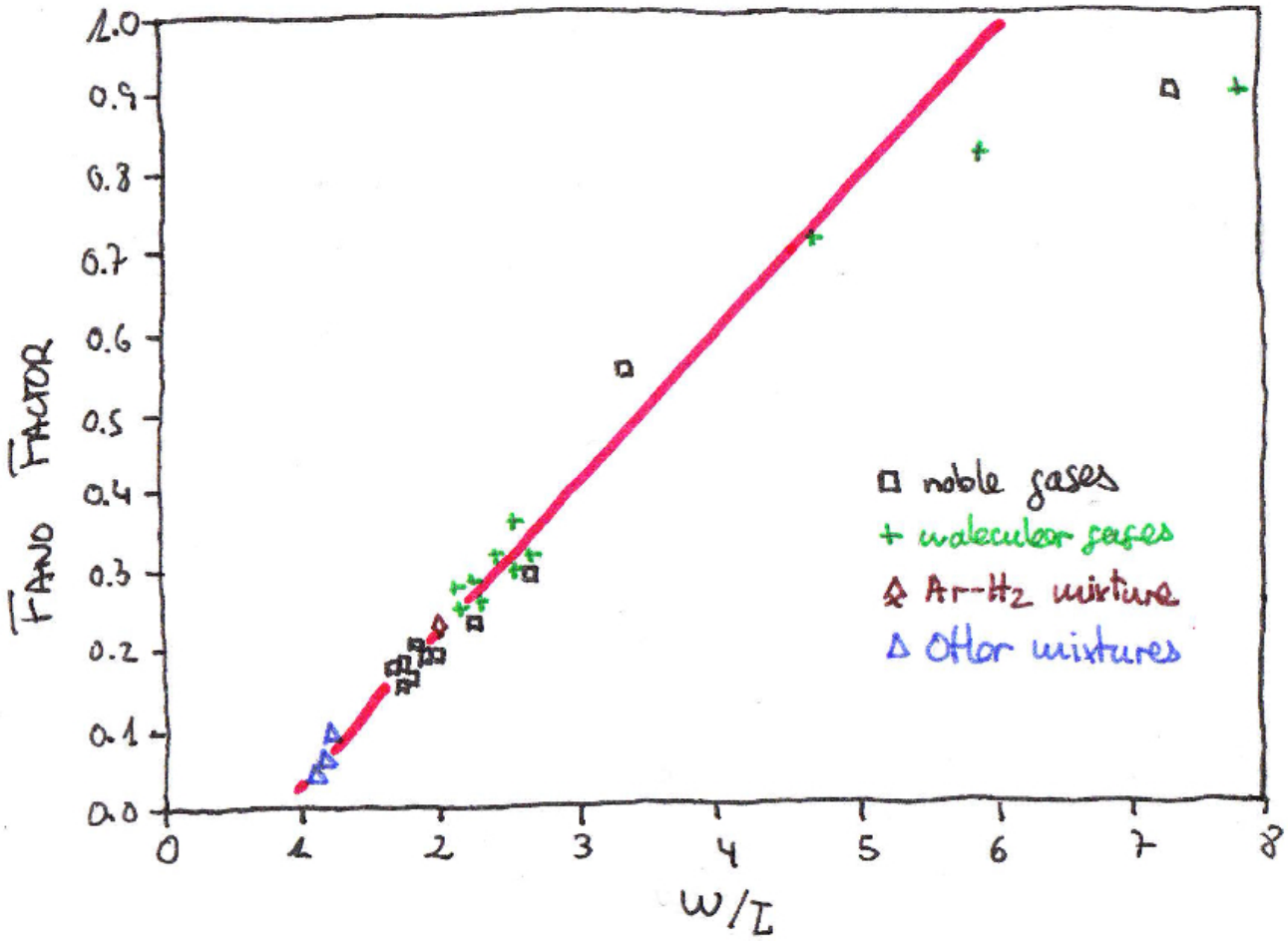
Gas	I_e (eV)	w (eV/ip)	dE/dx (keV/cm)	n_p (ip/cm)	n_t (ip/cm)
H_2	15.4	37	0.34	5.2	9.2
He	24.6	41	0.32	5.9	7.8
N_2	15.5	35	1.96	10	56
O_2	1.2	31	2.26	22	73
Ne	21.6	36	1.41	12	39
Ar	15.8	26	2.44	29	94
Kr	14.0	24	4.60	22	192
Xe	12.1	22	6.76	44	307
CO_2	13.7	33	3.01	34	91
CH_4	10.8	28	1.48	46	53

Fano factors

- Fano factors are < 1.
- It has been proven experimentally a linear relation between the Fano factor and the w/I:

$$F = a\frac{w}{I_e} + b$$

$$a = 0.188 \pm 0.006$$
$$b = -0.15 \pm 0.02$$



Diffusion and drift

- Charges generated by radiation passage in a gas moves due to two phenomena
  - Diffusion: Spread because of random (thermal) motion
  - Drift: forced movement thanks to the presence of an electric field
- During their movement electrons and ions collide with gas molecules
- On average, drift process will be done in a coherent way in the direction of the electric field.
  - If a magnetic field is present, it should be taken in consideration to determine the drift velocity
- Diffusion will randomize the direction on each collision with gas molecules
  - In the simplest case this randomization will be isotropic

Drift of charged particles

- The motion of charged particles under the influence of electric and magnetic fields is described by equation of motion:

$$m\frac{d\vec{u}}{dt} = e\vec{E} + e(\vec{u}\times\vec{B}) - K\vec{u}$$

where $\vec{u}$ velocity of a particle of mass m and charge e
K describes "friction" caused by the interaction with gas

- The ratio $\tau = \frac{m}{K}$ has dimension of time:
  - Its a characteristic time, depending on the gas and its pressure
  - It represent the mean time between two collisions
- The solution for $t >> \tau$ is a steady state ($\frac{d\vec{u}}{dt} = 0$):

$$\frac{1}{\tau}\vec{u} - \frac{e}{m}(\vec{u}\times\vec{B}) = \frac{e}{m}\vec{E}$$

Drift of charged particles

- If we write: $w_i = \frac{e}{m} B_i$
  $\epsilon_i = \frac{e}{m} E_i$

  The solution for the equation of motion can be written in matrix form:

$$M\vec{u} = \vec{\epsilon} \qquad M = \begin{bmatrix} 1/\tau & -w_z & w_y \\ w_z & 1/\tau & -w_x \\ -w_y & w_x & 1/\tau \end{bmatrix}$$

$$\vec{u} = M^{-1}\vec{\epsilon}$$

$$\vec{u} = \frac{e}{m}\tau|E|\frac{1}{1+w^2\tau^2}\left(\hat{E} + w\tau[\hat{E}\times\hat{B}] + w^2\tau^2(\hat{E}\cdot\hat{B})\hat{B}\right)$$

where $\hat{E}, \hat{B}$ = unit vectors in the directions of the fields
$w = \frac{e}{m} B$ = cyclotron frequency dimension $[T]^{-1}$

Drift of charged particles

- The solution is governed by the dimensionless parameter $w\tau$
- In case of $B = 0 \quad \rightarrow \quad w\tau = 0$:

$$\vec{u} = \frac{e}{m}\tau\vec{E} = \mu\vec{E}$$

- This equation define the mobility $\mu = \frac{e}{m}\tau$
  - It's an scalar.
  - Depends on the particle (e and m)
  - Depends on the gas through τ
- In case of gases, τ scales with pressure, and the velocity is written as:

$$\vec{u} = \mu\frac{E}{p}$$

- Usual units of mobility are $\frac{m^2\,atm}{V\,s}$

Drift of charged particles

- μ remains fairly constant over wide ranges of electric field and gas pressure.
- Typical values of mobility:

  Ions $\quad \mu \sim 10^{-4} \frac{m^2\, atm}{V\, s} \quad u = 1 m/s \rightarrow 10 ms/cm$

  electrons $\quad \mu \sim 10^{-1} \frac{m^2\, atm}{V\, s} \quad u = 10^4 m/s \rightarrow 1 \mu s/cm$
- In case of a gas mixture we can define an effective mobility of an ion i that can be written as:

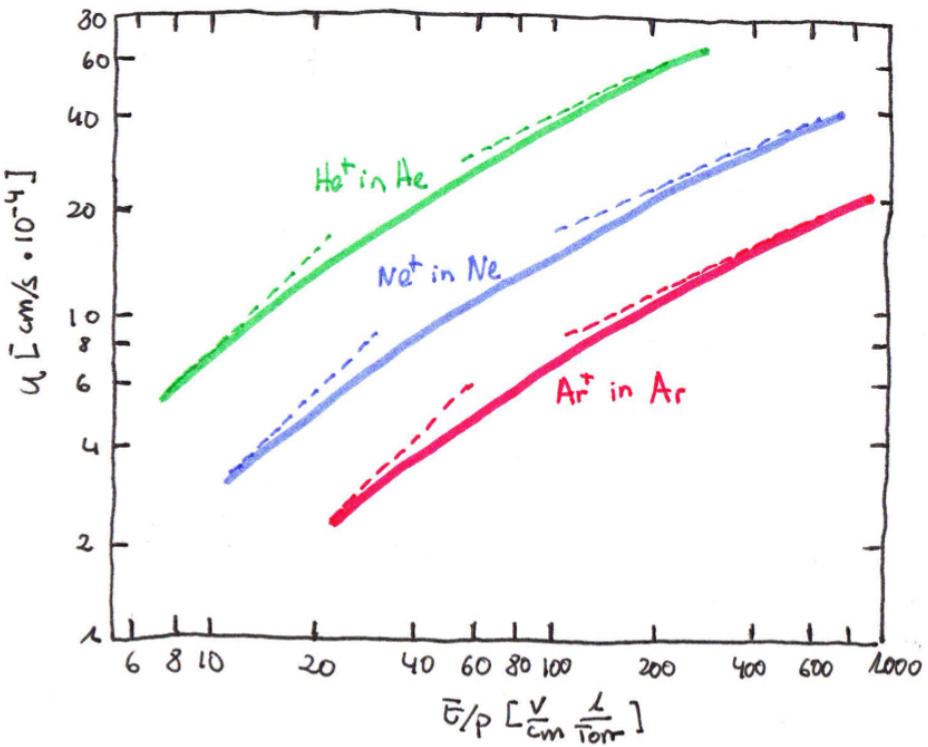
$$\frac{1}{\mu_i} = \sum_j \frac{c_j}{\mu_{ij}} \qquad \text{Blanc's formula}$$

where c_j = volume concentration of gas j in the mixture

μ_{ij} = mobility of ion i in gas j

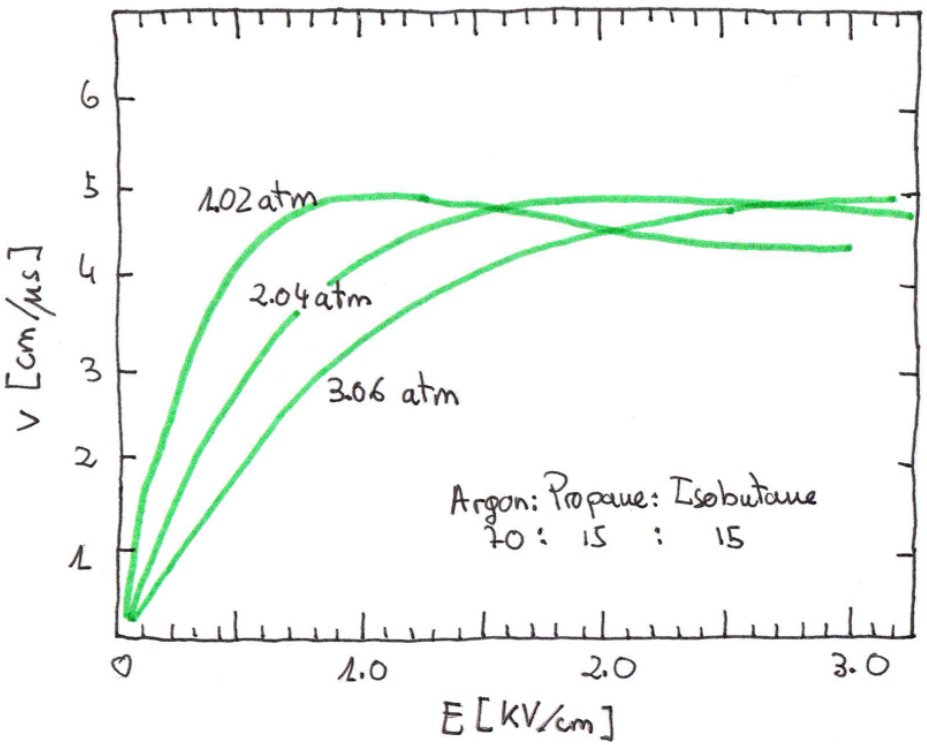
Drift of ions

- Ions are much heavier than electrons
- They will quite rarely reach the saturation velocity
- All the expressions given before will apply.
- Two regimes wrt thermal energy of the ions ($= \frac{3}{2}kT$)
  - At low field $u \propto E$
  - At high field $u \propto E^{\frac{1}{2}} \rightarrow \mu \propto \frac{1}{\sqrt{E}}$



Drift of electrons

- Electrons move much faster than ions because of its mass $v_e >> v_{th}$
- Collisions are quite different of those of ions
- "Saturation" effects appears quite fast
- Only in low field region velocity is proportional to the electric field
- After a threshold voltage velocity stays constant or even decrease
- There is still a strong dependence with the pressure



Diffusion

- Diffusion is the movement of charges due to thermal motion
- In absence of an electric field electrons and ions can be characterized by a Maxwellian energy distribution:

$$F(E) = \frac{2}{\sqrt{\pi}}(kT)^{-3/2}\sqrt{E}e^{-E/kT}$$

where k = Boltzmann's constant
T = absolute temperature

- The average energy is given by

$$\overline{E} = \frac{3}{2}kT \xrightarrow{T=300\,K} \sim 0.04\,eV$$

Diffusion

- Since there is no electrical field,
  - There is no preferred direction for the motion of charges
  - At a time t the number of particles at a distance x (or r) is:

$$dN = \frac{N}{\sqrt{4\pi Dt}} e^{-x^2/4Dt} dx \qquad \text{1-dim} \quad \sigma_x = \sqrt{2Dt}$$

$$dN = \frac{N}{\sqrt{12\pi Dt}} e^{-r^2/6Dt} dr \qquad \text{3-dim} \quad \sigma_r = \sqrt{6Dt}$$

where N = The total number of particles at x, r=0
D = diffusion coefficient (units: cm^2/s)

- Diffusion coefficient depends on the gas but also on the particle
  - Electrons diffuse faster than ions
- There is a relationship between mobility and diffusion coefficient:

$$\mu = \frac{e}{kT} D \quad \text{Nerst-Einstein relation}$$

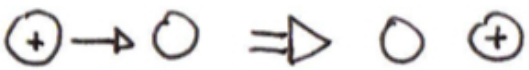
Charge carrier removal

- Ion pairs are in constant movement (diffusion and drift)
- The quality of the signal obtained is directly proportional to the number of ion pairs present
- Most of the time gaseous detectors are filled with a mixture of gases
  - Ratio of gases depends on the detector type and application
- In addition to these gases, there are also impurities
  - Unwanted gases present in the mixture
  - i.e. air, water vapor, oxygen, etc..
- Main effect of certain gases in the mixtures or impurities:
  - Absorption of electron or positive ions
  - Most of the time is an unwanted effect that will degrade the signal
  - Sometimes, this effect is wanted = Quenching gas
  - Quenching gases are NEEDED for the operation of proportional chambers and Geiger-Müller.
- The shorter the drift time to electrodes the smaller the losses of charge carriers

Charge carrier removal phenomena

There is a set of phenomena that can remove charge carriers.

- Charge transfer collisions:

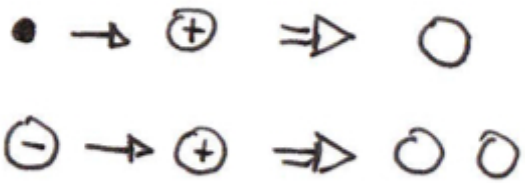


- Important in gas mixtures
- Tendency to transfer the net positive charge to the gas with the lowest ionization energy

- Electron attachment:

- Electronegative gases have tendency to attach free electrons
- i.e. oxygen attaches electrons easily

- Recombination:



- Two types of collisions considered:
  - Positive ion and electron → e^- is captured
  - Positive ion and negative ion → electron is transferred and both ions became neutral. Orders of magnitude higher than the other process.

Recombination

- In both cases, collision frequency is proportional to concentrations of positive and negative ions

$$\frac{dn^+}{dt} = \frac{dn^-}{dt} = -\alpha n^+ n^- \qquad n^+ = n^- = n(t) = \frac{n_0}{1 - \alpha n_0 t}$$

where n^+ = density of positive species
n^- = density of negative species
α = recombination coefficient

- There are two types of recombination losses:
  - Columnar (or local) recombination:
    Recombination formed along the path of the particle
    Higher ionization → Higher ion density → Higher recombination
    It does not depend on the irradiation rate
  - Volume recombination:
    Recombination far from track
    Positive and negative species can come from different tracks
    More important with higher irradiation rates

Gas multiplication

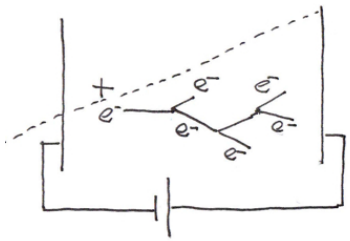
- Increasing electric field will have two main effects:
  - Decrease of charge collection time → less recombination
  - Charge multiplication. Ionization charges are multiplied by avalanche phenomena
- The net effect is the multiplication of the primary ionization

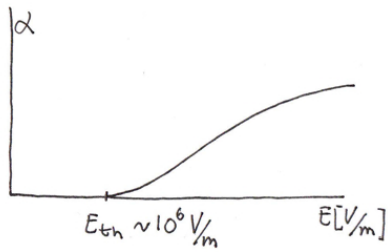
$$\Delta V = -\frac{eN}{C}M \qquad M = \text{multiplication factor}$$

- We are going to study two multiplication phenomena:
  - Townsend avalanche (→ proportional counters)
  - Geiger avalanche (→ Geiger-Müller)

Townsend Avalanche

- When electric field is higher than a threshold values ($E_{th} \simeq 10^6$ V/m):
  - Primary electrons originated by ionization acquire sufficient energy between collisions to produce new ionization.
  - Secondary electrons produces tertiary and so on, so forth
  - Townsend avalanche: each electron can potentially creates new electrons





- In this conditions, the number of charge pairs per unit length is proportional to the total number of charged pairs.

$$\frac{dN}{dx} = \alpha N \quad \rightarrow \quad N = N_0 e^{\alpha x} \quad \text{Townsend equation}$$

where N_0 = number of primary ion-pairs
α = First Townsend coefficient

First Townsend coefficient

- First Townsend coefficient (α) represents the number of collisions leading to ionization per unit length of the particle track.
- Let's compute α from a single model:
  - Energy gain between two collisions: $\Delta E_{kin} = eE\lambda_0$
    $\Delta E_{kin} < I_{ion}$: electrons loose energy without ionization
    $\Delta E_{kin} > I_{ion}$: ionization always occurs
  - The probability for an electron to pass the distance $\lambda > \lambda_{ion}$ without collision is:

$$P(\lambda > \lambda_{ion}) = e^{-\lambda_{ion}/\lambda_0} \qquad \text{where} \qquad \lambda_{ion} = \frac{I_{ion}}{eE}$$

  - As there are $\frac{1}{\lambda_0}$ collision per unit length, the total number of ionizations is:

$$\alpha = \frac{1}{\lambda_0} e^{-\lambda_{ion}/\lambda}$$

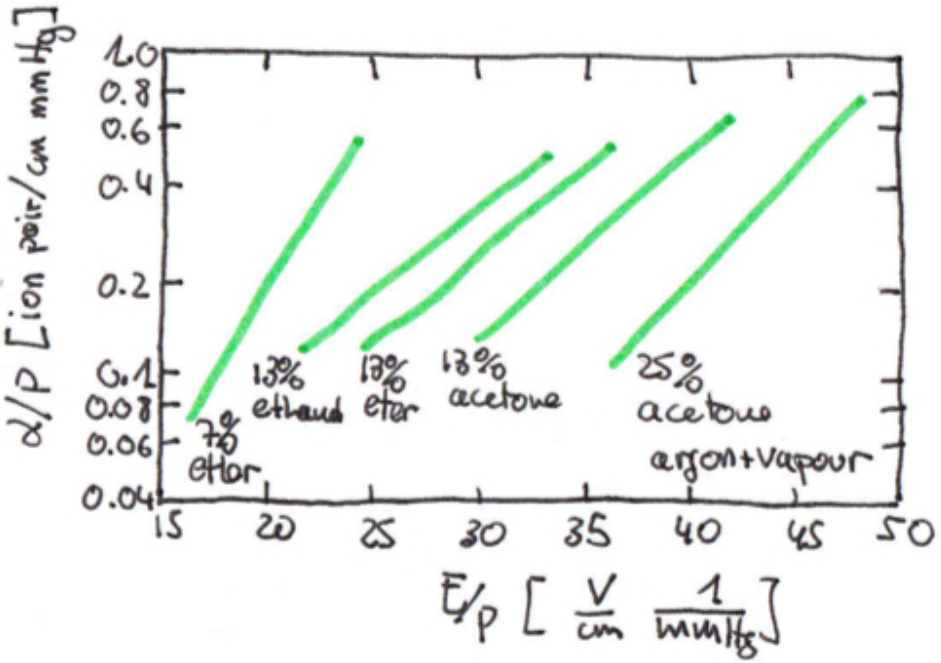
  - Taking into account that λ_0 is inversely proportional to pressure ($\lambda_0 \propto 1/p$)

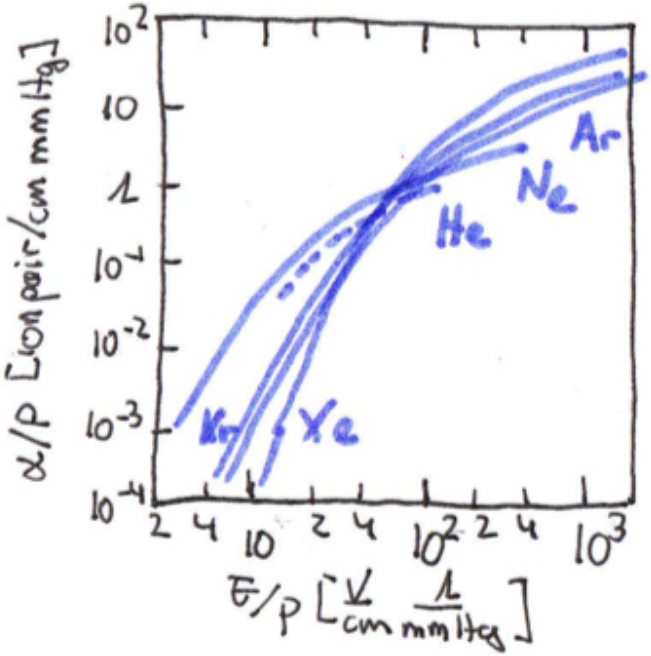
$$\frac{\alpha}{p} = ae^{\frac{b}{E/p}}$$

First Townsend coefficient

$$\frac{\alpha}{p} = ae^{\frac{b}{E/p}}$$

Gas	a [cm^{-1} $Torr^{-1}$]	b [$V\ cm^{-1}$ $Torr^{-1}$]
He	3	34
Ne	4	100
Ar	14	180





Multiplication factor

- If the electric field is uniform the multiplication factor $M = \frac{N}{N_0}$ can be obtained from the Townsend equation:

$$N(x) = N_0 e^{\alpha x} \qquad \rightarrow \qquad M = e^{\alpha x}$$

- This is the case for instance in a parallel plate geometry
- In case of a non-uniform field the multiplication factor will depend also with the position.
- In a more general way:

$$N(x) = N_0 e^{\int \alpha(x) dx} \qquad \rightarrow \qquad M = \exp \int_{x_i}^{x_k} \alpha(x) dx$$

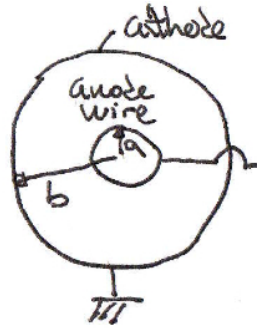
where x_i = position where $E > E_{th}$
x_k = positon of the cathode

- Typical values of gas amplifications are $\sim 10^4 - 10^6$

Multiplication factor: Diethorn formula

- In case of a cylindrical geometry the electric field is non-uniform:

$$E(r) = \frac{V}{r \ln\left(\frac{b}{a}\right)}$$



- We have to apply the most general formula:

$$\ln M = \int_a^{r_c} \alpha r dr = \int_{E(a)}^{E(r_c)} \alpha(E) \frac{\partial r}{\partial E} dE$$

- For cylindrical electric field we have:

$$\frac{\partial r}{\partial E} = \frac{V}{\ln\left(\frac{b}{a}\right)} \frac{-1}{E^2(r)} \quad \rightarrow \quad \ln M = \frac{V}{\ln\left(\frac{b}{a}\right)} \int_{E(a)}^{E(r_c)} \frac{\alpha(E)}{E} \frac{dE}{E}$$

Multiplication factor: Diethorn formula

- Assuming a linear relation between α and E we obtain:

$$\ln M = \frac{V}{\ln\left(\frac{b}{a}\right)} \frac{\ln 2}{\Delta V} \left[\ln\left(\frac{V}{pa \ln\left(\frac{b}{a}\right)} \right) - \ln K \right]$$

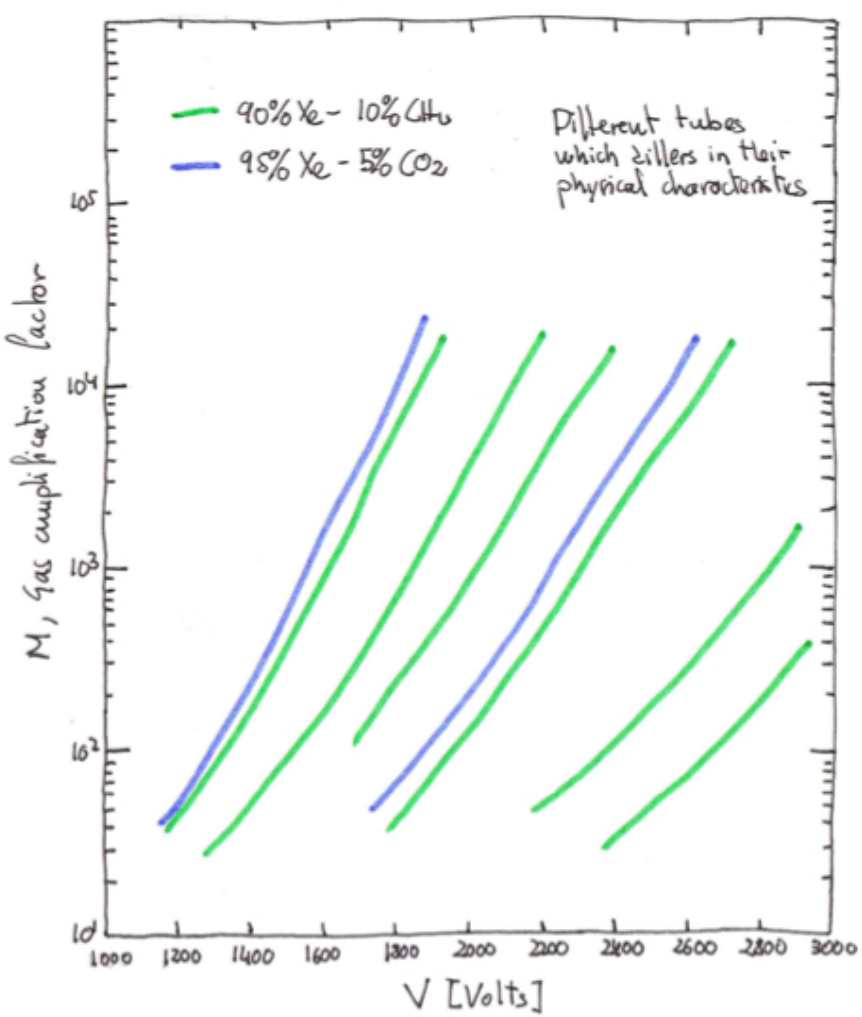
Diethorn formula

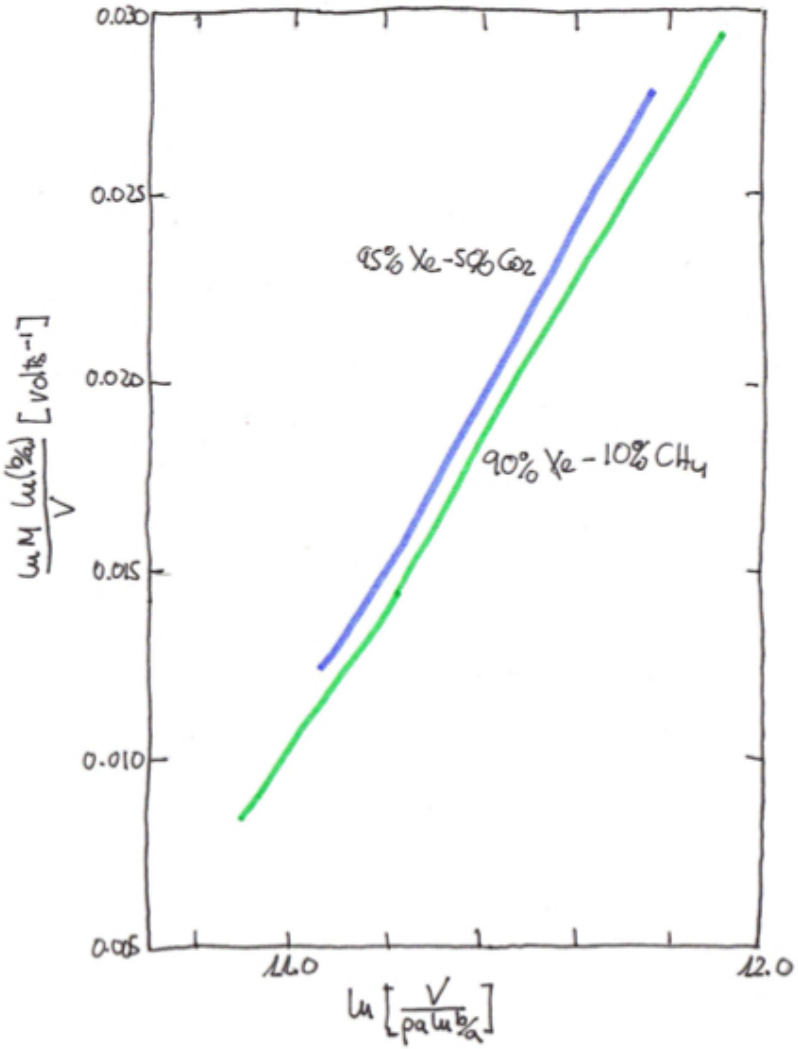
ΔV = Average potential difference needed to produce a ionization.
K = Minimum value of $\frac{E}{p}$ below which multiplication cannot occur

- Both ΔV and K are constants for any given gas.

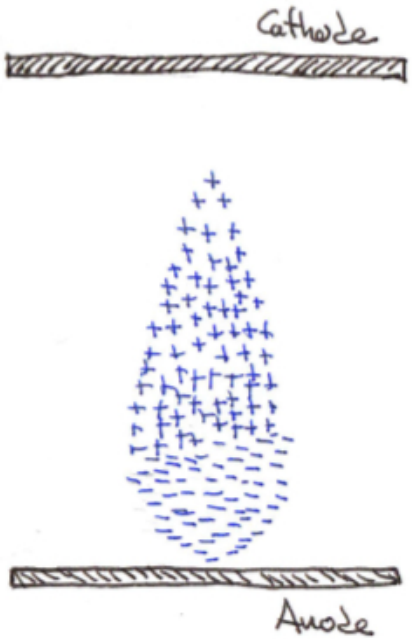
Gas mixture	K[10^4V/(cm·atm)]	ΔV [V]
90% Ar, 10% CH_4 (P-10)	4.8	23.6
90% Ar, 5% CH_4 (P-5)	4.5	21.8
100% CH_4 (methane)	6.9	36.5
100% C_3H_8 (propane)	10.0	29.5
96% He, 4% isobutane	1.48	27.6
75% Ar, 15% Xe, 10% CO_2	5.1	20.2
69.4% Ar, 19.9% Xe, 10.7% CH_4	5.45	20.3
64.6% Ar, 24.7% Xe, 10.7% CO_2	6.0	18.3
90% Xe, 10% CH_4	3.62	33.9
95% Xe, 5% CO_2	3.66	31.4

Multiplication factor: Diethorn formula





Avalanche geometrical progression



- Avalanches have the shape of a liquid-drop
- On each ionization electron-ion pairs are produced
- $\mu_e >> \mu_{ion}$
  - Electrons move faster to the anode than ions to the cathode
  - Electrons are concentrated near the head of the drop, leaving a "tail" of the slower ions

Geiger avalanche

- At high field collisions of electrons with atoms and molecules in the gas, in the electrodes or in the walls, can create not only ionization but also excitation
- De-excitation is often followed by a photon emission.
- Some of these photons, in the UV region, can produce secondary ionization by photoelectric effect.
- Avalanche development is modified by secondary avalanches produced by these secondary processes.
- We define the Second Townsend Coefficient (γ) as the probability that one photoelectron per electron is produced

$$
\begin{aligned}
1^{st} &\text{ generation } N_0 M \\
2^{nd} &\text{ generation } \gamma(N_0 M)M = \gamma N_0 M^2 \\
3^{rd} &\text{ generation } \gamma(\gamma N_0 M^2)M = \gamma^2 N_0 M^3 \\
&\cdots \\
n^{th} &\text{ generation } \gamma(\gamma^{n-2} N_0 M^{n-1})M = \gamma^{n-1} N_0 M^n
\end{aligned}
$$

Geiger avalanche

- We can then define the gas amplification including γ as:

$$N_0 M_\gamma = N_0 M + N_0 M^2 \gamma + \cdots$$
$$= N_0 M \sum_{k=0}^{\infty} (M\gamma)^k$$

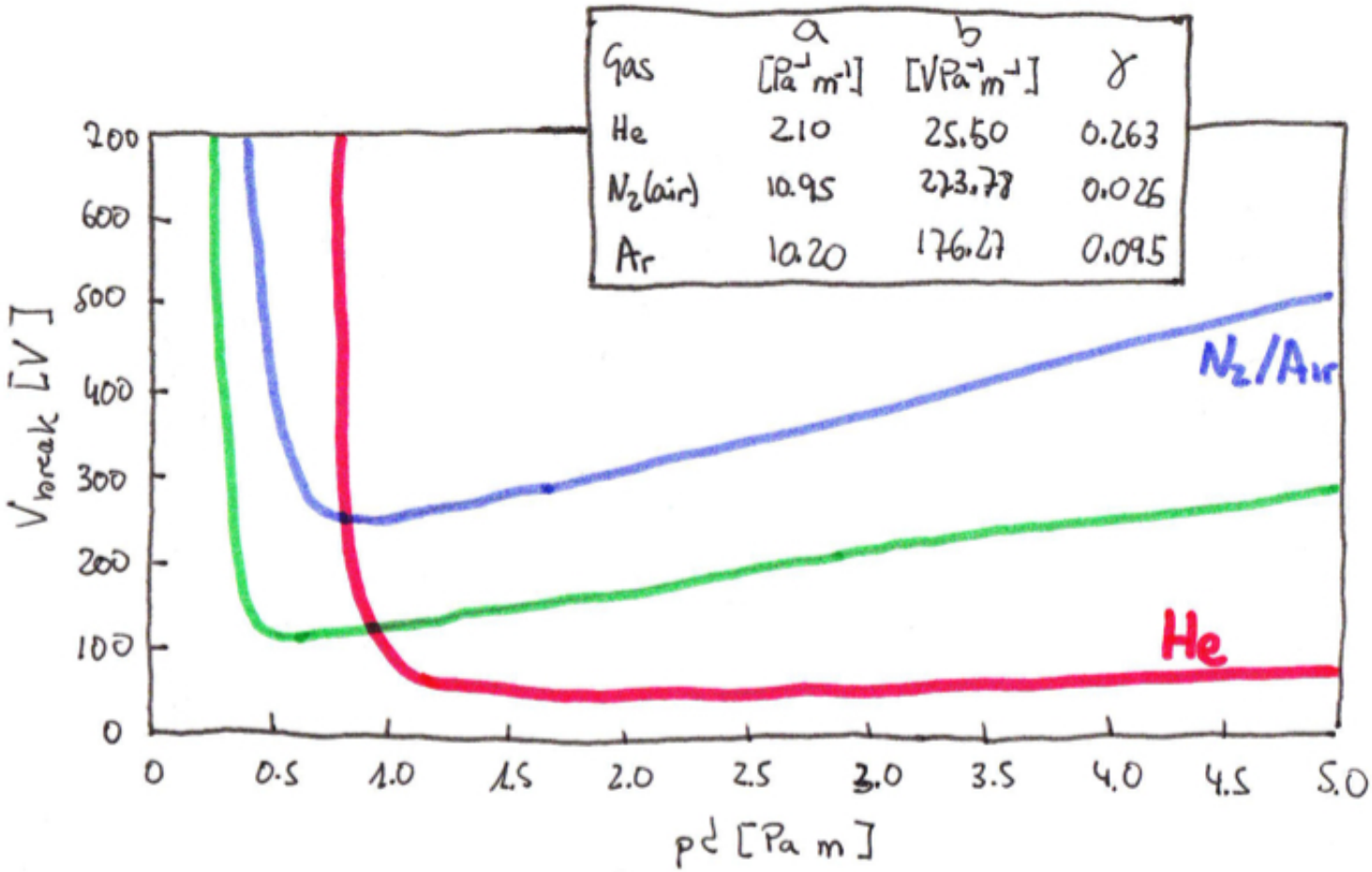
$$\text{If } M\gamma < 1 \rightarrow \sum_{k=0}^{\infty} (M\gamma)^k = \frac{1}{1-\gamma M}$$

$$M_\gamma = \frac{M}{1-\gamma M}$$

- A complete calculation gives

$$M_\gamma = \frac{M}{1-\gamma(M-1)} = \frac{e^{\alpha x}}{1-\gamma(e^{\alpha x}-1)}$$

Breakdown: Paschen law



$$(pd)_{min} = \frac{e}{a}\ln\left(1+\frac{1}{\gamma}\right)$$

e=natural logarithm number

Section 3

Ionization chambers

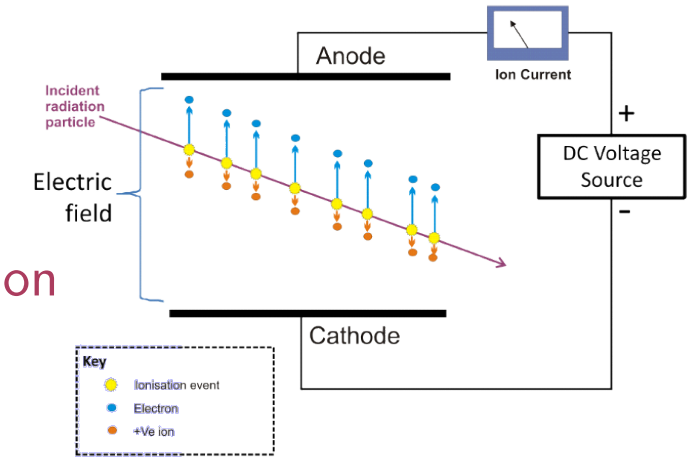
3. Ionization chambers

- General characteristics
- Operation in current mode
- Pulse mode Operation
- Types of ionization chambers
- Applications
- Advantages and Disadvantages of Ionization Chambers

Ionization chambers

an e^- cross the detector in $\sim 1\mu s$

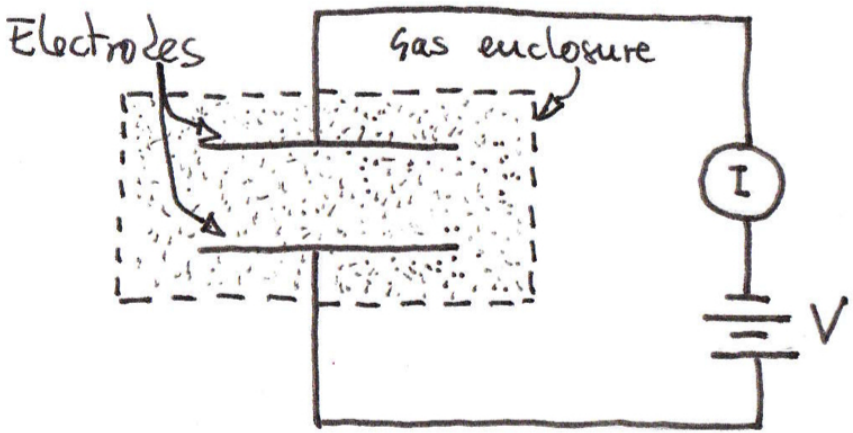
and an ion in 1-10 ms

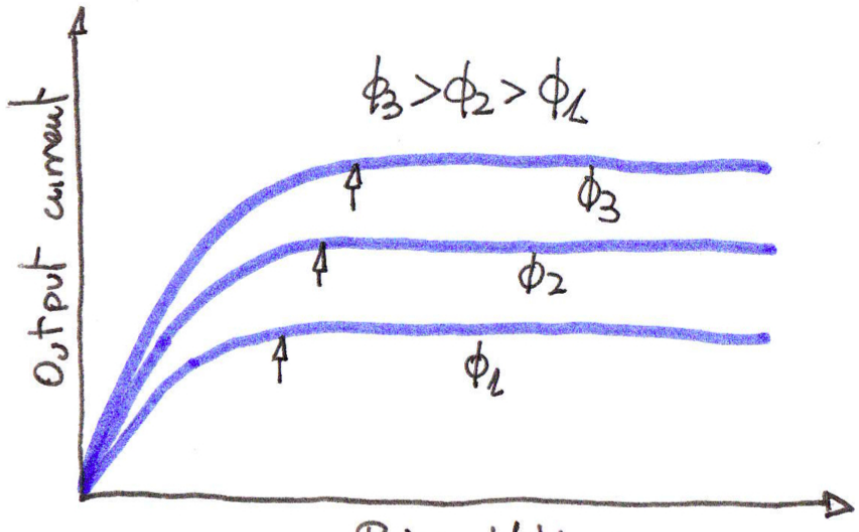


- Ionization chambers are gas detectors working in ionization regime
  - Collected ions $\simeq$ ions generated by ionization
  - No multiplication in the gas
- Gases of choice are:
  - Almost any gas can be used
  - For low resolution measurement (low pressure) $\rightarrow$ air. Fluctuations of few %.
  - For high pressure $\rightarrow$ use of noble gases to avoid recombination
- Important detector in radioprotection
  - Only gas detector providing a direct lecture of absorbed dose
  - Used frequently in current mode, but it can be used also in pulse mode

Current-Voltage characteristics

- Measured current in ionization chamber is proportional to ionization rate
- Current-voltage characteristics of ionization chambers is:





Operational remarks

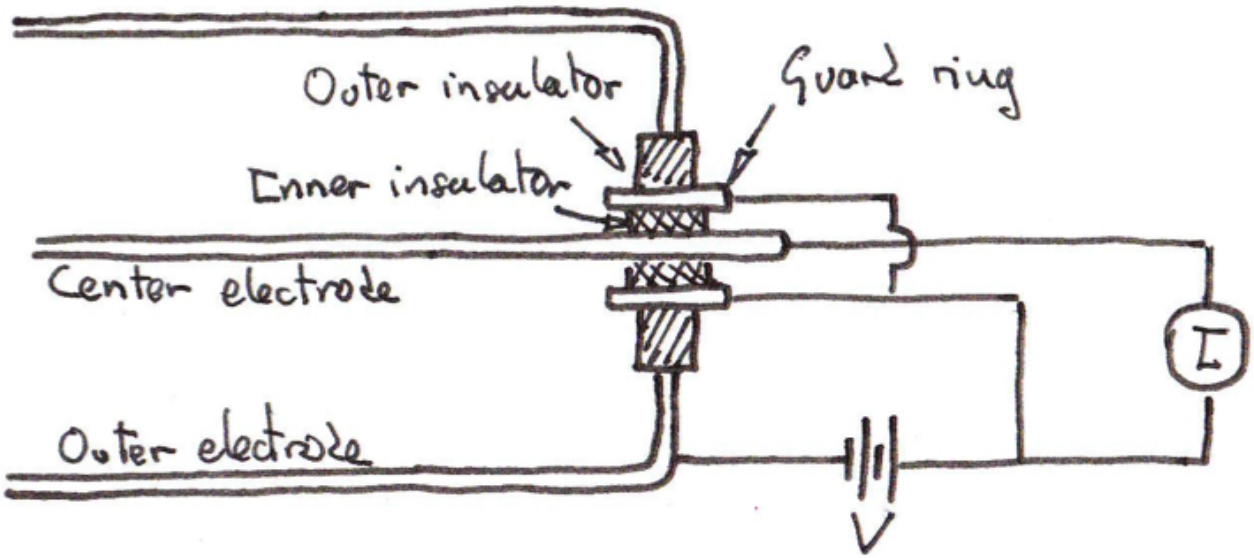
- Used in the middle of plateau to avoid influence of voltage variation. Voltage can be modified by electron-ion densities in case of high flux
- Currents are tiny $I \simeq 10^{-12}$ A
- Typical voltages applied is $\simeq 10^2$ V
- Leakage current should be limited
- If we want to limit leakage currents to ~1% signal current:

$$R = \frac{V}{I_{leak}} = \frac{10^2 \text{ V}}{10^{-12}\text{A}\, 10^{-2}} = 10^{16}\Omega$$

- Measurements of such small currents requires special measurement techniques: electrometers

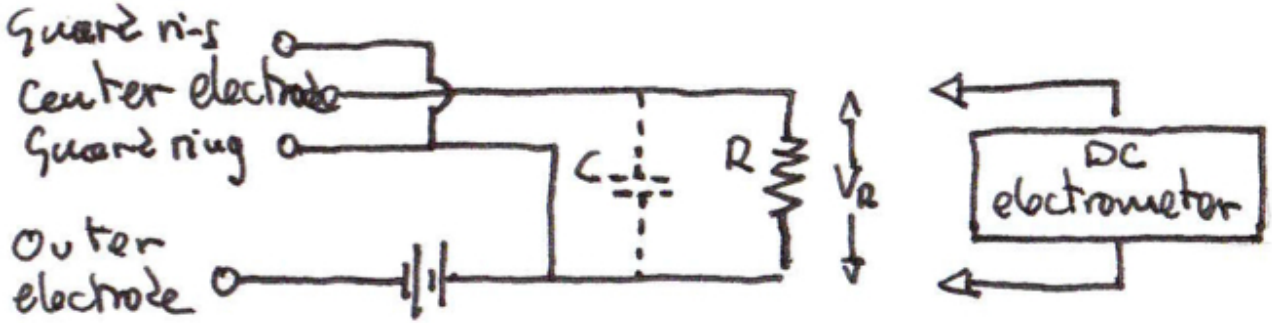
Operational remarks

- In order to obtain such large resistance, high insulation between anode and cathode should be achieved:
  - Using the right materials: teflon for weak fields
    ceramics for high fields
  - Use of guard-rings: Most of leakage does not cross measurement instruments
  - Main leakage comes from moisture in insulators



Measurement of ion current

- DC electrometers measure indirectly currents through the ΔV in a resistance ($\sim 10^9 - 10^{12}\Omega$ in series with electrodes.



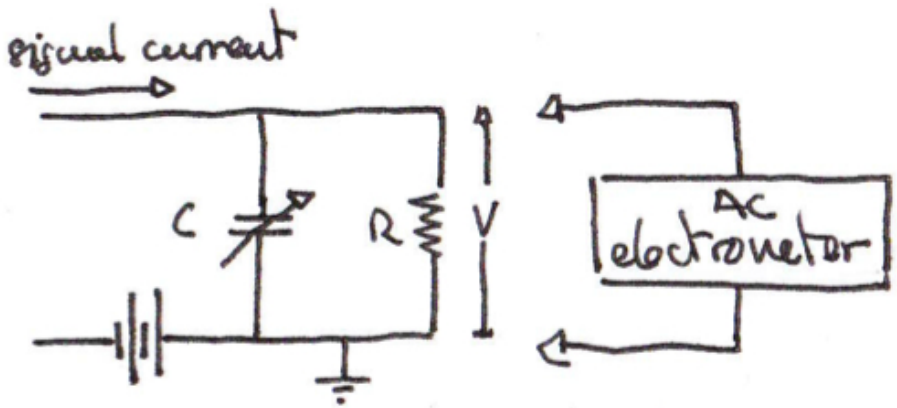
- This ΔV can be amplified
- Drawback: DC coupling and drifts are quite usual (solved short circuiting input)

Measurement of ion current

- Vibrating-reed electrometers: conversion from dc to ac + ac amplification
- Used a RC readout circuit
- In case of a steady ionization-current $V = IR$
- A charge $Q = CV$ is stored in the capacitance
- If capacitance change rapidly wrt RC time constant, voltage change accross C is

$$\Delta V = \frac{Q}{C^2}\Delta C = I\frac{R}{C}\Delta C$$

- If ΔC varies sinusoidally $\rightarrow$ ac-amplitude $\propto$ ionization current



Measurement of ion current

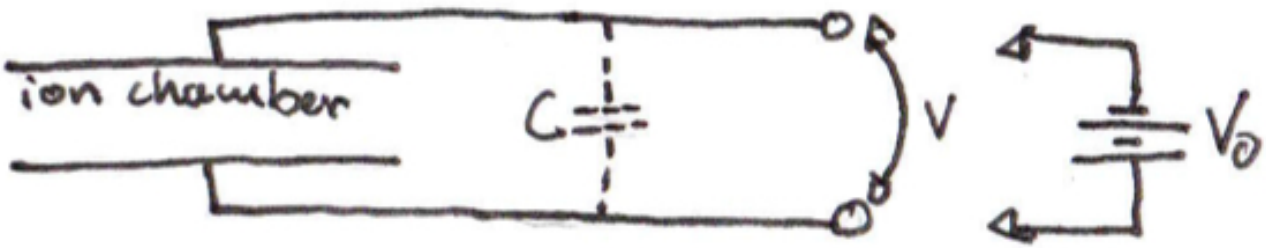
- Measurement over finite periods of time by integration methods
- RC circuit with $R = \infty$:

$$I = \frac{dQ}{dt} = C\frac{dV}{dt}$$

$$\int I\,dt = \int dQ = C\int dV = C\Delta V$$

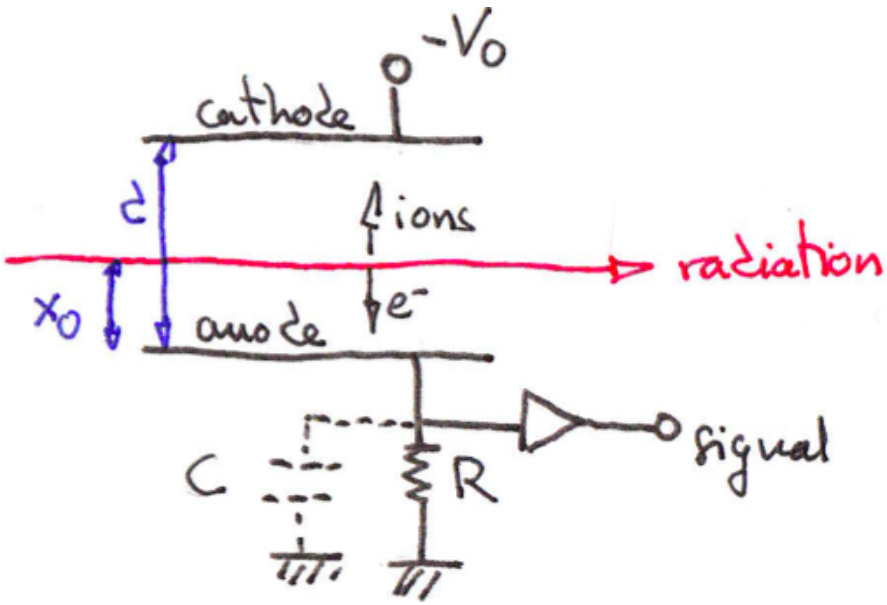
$$\Delta V = \frac{\Delta Q}{C}$$

- A measurement of ΔV thus gives the total ionization charge or the integrated ionization current over the period of the measurement



Pulse mode Operation

- Ionization can also be operated in pulse mode
- Operated in pulse mode ionization chambers can be used in radiation spectroscopy
  - Replaced largely by scintillators and semiconductor detectors
  - Still important in specialized applications
    - large area alpha spectrometers
    - neutron detectors



- R=load resistance
  U=ΔV across R
- C= Total capacitance: includes detector + stray capacitances

Energy resolution

- What's the energy resolution expected from counting statistics for ionization detectors
- First step is to calculate the expected average of ion pairs (N) produced if an energy E_d is deposed: $N = \frac{E_d}{w}$
- The variance is given by $\sigma_N^2 = FN \rightarrow \sigma_N = \sqrt{FN}$
  $FWHM = 2.35\sqrt{FN}$
- The energy resolution is:

$$R = \frac{FWHM}{N} = 2.35\sqrt{\frac{F}{N}} = 2.35\sqrt{\frac{Fw}{E_d}}$$

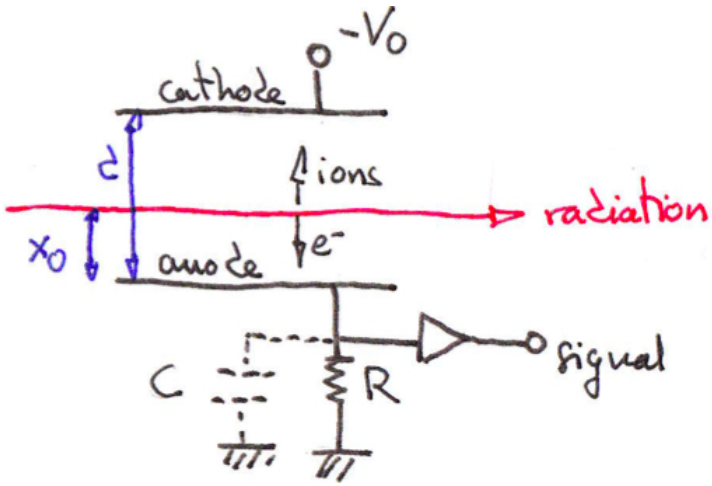
- in case of a α of energy 5.5 MeV fully absorbed in a gas of w=30 eV and a Fano factor 0.15

$$R = 2.35\sqrt{\frac{0.15 \times 30}{5.5 \times 10^6}} = 0.213\%$$

- This excellent energy resolution is never achieved in practice because the sources of electronic noise are much larger.

Signal formation in parallel plate geometry

- Let's consider the equivalent circuit of an ionization chamber traversed by a radiation where N pairs at a distance x_0 du anode.
- The voltage U_0 applied to the electrodes provides a uniform electric field



$$|\vec{E}| = E_x = \frac{U_0}{d}$$

- The shape of the pulse can be obtained by applying the Shockley-Ramo theorem.

$$\Delta U = \Delta U^+ + \Delta U^- = \frac{Nq}{Cd}(v^+ + v^-)t$$

where $v^{\pm}$ are the drift velocities of electrons and ions.

Signal formation in parallel plate geometry

- Electrons moves faster than ions ($v^- \sim 1000 v^+$)
  - While electrons are moving they will dominate the signal
  - After a time $T^- = \frac{x_0}{v^-}$ all electrons reach the anode and they will no longer contribute to the signal
  - After a time $T^+ = \frac{d-x_0}{v^+}$ ions reach the cathode

- We are going to discuss three cases:
  - Case 1: $RC >> T^+, T^-$
  - Case 2: General case
  - Case 3: $T^- << RC << T^+$. Electron sensitive mode

Signal formation in parallel plate geometry

Case 1: $RC >> T^+, T^-$

- As electrons are faster than ions $\Delta U^- >> \Delta U^+$
- As $RC >> T^-$ the capacitor cannot charge and the signal grows linearly in the interval $[0, T^-]$ from $\Delta U = 0$ up to

$$\Delta U^- = \frac{Nq}{Cd} x_0$$

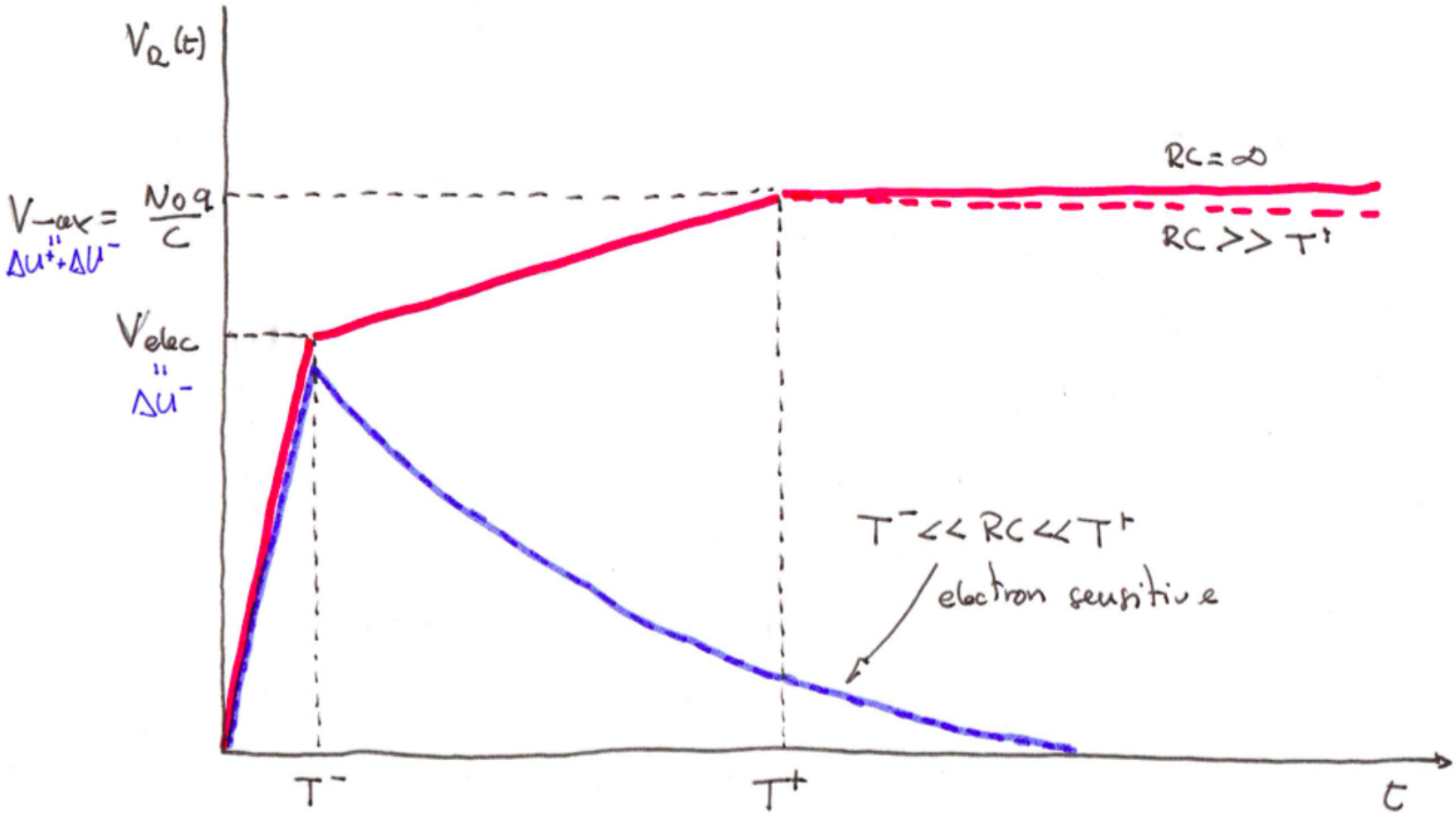
- After T^- only ions are still drifting and the voltage will increase slowly

$$\Delta U^+ = \frac{Nq}{Cd}(d - x_0)$$

- The maximum signal amplitude is achieved when $t > T^- + T^+$

$$\Delta U = \Delta U_1 + \Delta U_2 = \frac{Nq}{C}$$

Signal formation in parallel plate geometry



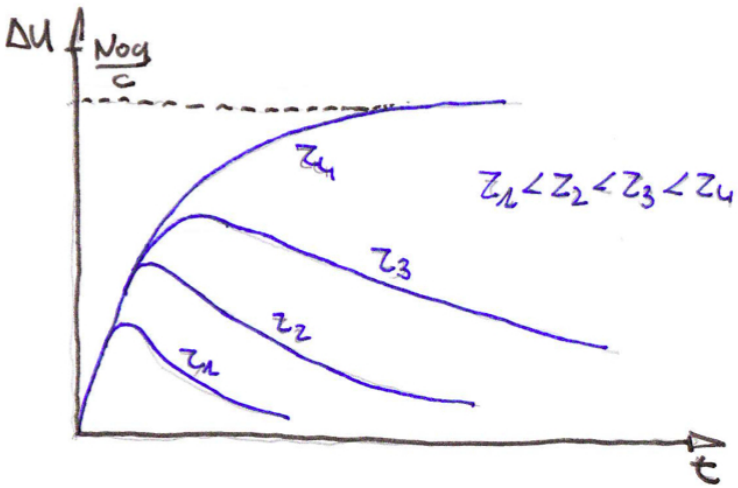
Signal formation in parallel plate geometry

Case 2: General case

- The most general expressions are

$$\Delta U^+ = \frac{Nq}{d} v^+ R\left(1 - e^{-\frac{\Delta t}{RC}}\right)$$

$$\Delta U^- = \frac{Nq}{d} v^- R\left(1 - e^{-\frac{\Delta t}{RC}}\right)$$



$$\Delta U = \frac{Nq}{Cd} v \Delta t$$

$$\left.\begin{aligned} I &= C\frac{\Delta U}{\Delta t} \\ \frac{\Delta Q}{\Delta t} &= C\frac{\Delta U}{\Delta t} \\ \Delta U &= \frac{\Delta Q}{C} \end{aligned}\right\} \Rightarrow \begin{aligned} \Delta Q &= \frac{Nq}{d} v \Delta t \\ V = IR &= \frac{\Delta Q}{\Delta t} R = \frac{Nq}{d} vR \end{aligned}$$

Charge of a capacitance: $V(t) = V_0(1 - e^{-t/RC})$

Signal formation in parallel plate geometry

Case 3: $T^- << RC << T^+$. Electron sensitive mode

- For practical cases, wait till T^+ is too much long
- If RC fulfill the condition $T^- << RC << T^+$ we have:
  - Ion contribution is almost entirely lost for $t << RC$
  - Only electron contribution is important
  - A maximum is obtained at T^-
  - Signal vanishes with RC constant

$$\Delta U_{max} = \frac{Nq}{Cd} x_0$$

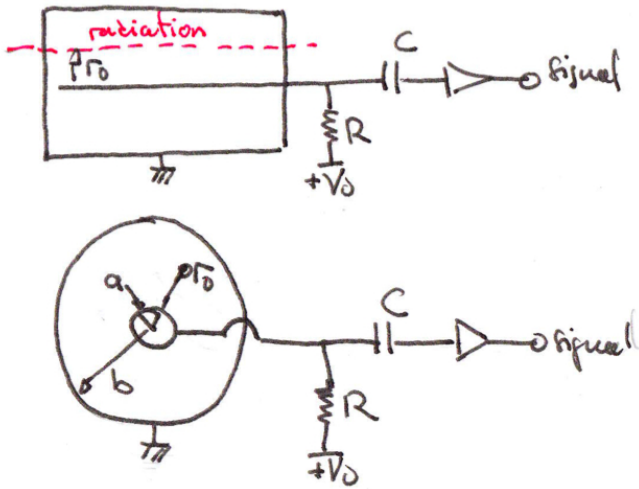
- Beware: Signal depends on x

Signal formation in cylindrical geometry

- We are going to apply the same formulas obtained for parallel plate geometry with cylindrical geometry

$$V(r) = -\frac{V_0}{\ln\left(\frac{b}{a}\right)} \ln\frac{r}{a}$$

$$\vec{E}(r) = \frac{1}{r}\frac{V_0}{\ln\left(\frac{b}{a}\right)}$$



- Collection times depends on mobility

$$T^- = \int_{r_0}^{a} \frac{dr}{v^-(r)} = \int_{a}^{r_0} \frac{p\,dr}{\mu^- V_0} r \ln\left(\frac{b}{a}\right) = \frac{p \ln\left(\frac{b}{a}\right)}{2\mu^- V_0}(r_0^2 - a^2)$$

$$T^+ = \int_{r_0}^{b} \frac{dr}{v^+(r)} = \int_{r_0}^{b} \frac{p\,dr}{\mu^+ V_0} r \ln\left(\frac{b}{a}\right) = \frac{p \ln\left(\frac{b}{a}\right)}{2\mu^+ V_0}(b^2 - r_0^2)$$

- Mobility for electrons depends on electric field strength. The previous expressions are only a rough approximation

Signal formation in cylindrical geometry

- Signal height can be calculated from Ramo-Shockley theorem:

electrons $$\Delta U^- = \frac{Nq}{C \ln\left(\frac{b}{a}\right)} \ln\left(\frac{r_0}{a}\right)$$

ions $$\Delta U^+ = \frac{Nq}{C \ln\left(\frac{b}{a}\right)} \ln\left(\frac{b}{r_0}\right)$$

$$\frac{\Delta U^+}{\Delta U^-} = \frac{\ln\left(\frac{b}{r_0}\right)}{\ln\left(\frac{r_0}{a}\right)}$$

$$\Delta U = \Delta U^+ + \Delta U^- = \frac{Nq}{C \ln\left(\frac{b}{a}\right)} \left[\ln\left(\frac{b}{r_0}\right) + \ln\left(\frac{r_0}{a}\right)\right] = \frac{Nq}{C}$$

Signal formation in cylindrical geometry

- $\frac{\Delta U^+}{\Delta U^-}$ depends on the position r_0 where the radiation hits.

$a = 80\,\mu$ m, $b = 1$ cm

r_0	$\frac{\Delta U^+}{\Delta U^-}$
81 μm	387.674
82 μm	194.537
85 μm	78.643
90 μm	39.993
100 μm	20.638
500 μm	1.635
1 mm	0.912
5 mm	0.168
8 mm	0.048

- All these calculations are independent of L
  - L can be as large as possible
  - Ex. SLAC, beam loss monitor was L=3.5 km!!!

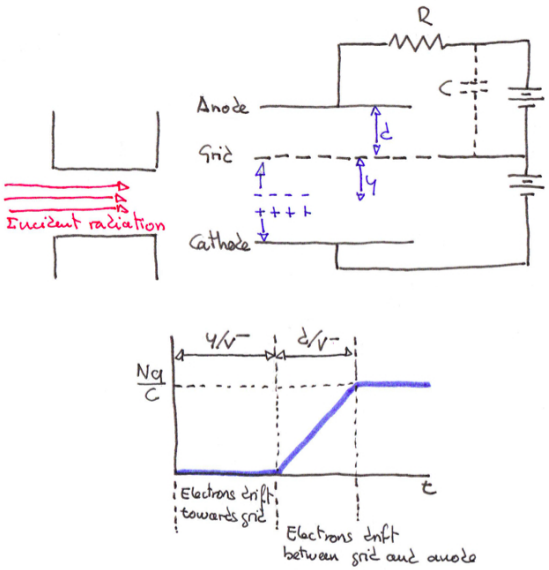
Some types of ionization chambers

Ionization chambers are widely used radiation detectors. These are ones of the most used:

- Parallel Plate Frisch Grid Chamber:
  Used to avoid position dependent amplitude in electron sensitive operation
- Boron Lined Ion Chamber: (chapter 7)
  Ionization chambers where walls are coated with enriched ^{10}B. Used for neutron detection.
- Compensated Ion Chamber: (chapter 7)
  Used to detect low neutron flux accompanied by a high γ-ray flux.
- Direct reading electroscope:
  Used extensively in personal dosimetry
- Babyline:
  Standard portable ionization chamber in radiation protection measurement

Gridded chamber

- In order to overcome the position dependence of ΔU when operating in electron mode, the setup known as FRISCH GRID can be used:



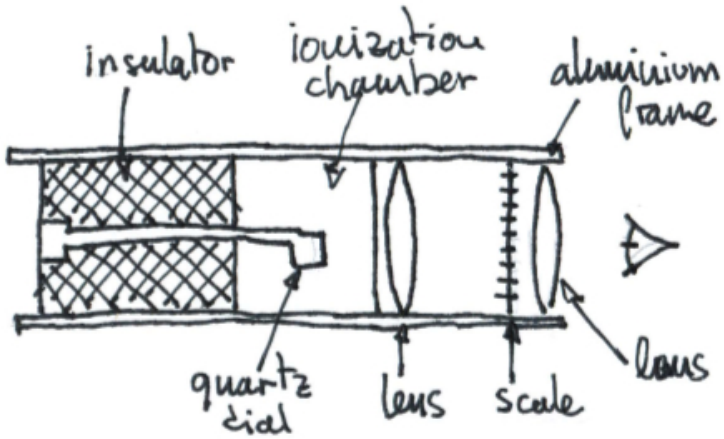
  - A grid is placed in the detector at a distance d from the anode
    - The grid is "transparent" to the electrons
    - The grid is placed at an intermediate voltage
  - Detection region (cathode → grid)
    - ions drift to cathode and electrons drift to grid
    - grid screens charge induction in the anode
  - Signal region
    - As soon as electrons pass through the grid → induced signal in the anode
    - Drift distance = cte → induced signal is cte

$$\Delta U = \frac{Nq}{Cd} v^- t \rightarrow \Delta U_{max} = \frac{Nq}{C}$$

  - Ion component is discarded → fast readout.

Direct Reading Electroscope

- Portable electroscope with pencil shape



- Operated in current mode. Integration read out method
- Composed of two quartz fibers embedded in an ionization chamber
- When charged they are separated and indicate "0" in an optical scale
- When radiation pass through → electroscope discharge and quartz moves
- Measures doses between 0-100 mrad with 5-10% precision
- It discharges ~5 mrads/week

Babyline

- Portable ionization chamber
- Volume = 515 cm^3
- It has two windows
  - 7 mg/cm^2 (silk paper) = epidermis
  - 300 mg/cm^2 (capuchon), H:10.2% C:61.1% F:17.5% = crystalline
- Voltages up to 300 V with batteries (very stable)
- Readout impedance $\simeq 10^{15}\Omega$
- Always operated in current mode
- 6 operation operation scales:
  - 1 mrad/h (10 μGy/h)
  - 10 mrad/h (100 μGy/h)
  - 100 mrad/h (1 mGy/h)
  - 1 rad/h (10 mGy/h)
  - 10 rad/h (100 mGy/h)
  - 100 rad/h (1 Gy/h)

Applications of ionization chambers

- Perfectly adapted as moinitor for X- and γ-rays:
  - Instantaneous measurement of dose rate
  - Efficiency $< 10\% \rightarrow$ better to measure high rates
- If equipped with a thin entrance window:
  - α and β detection possible
  - efficiency may reach 100%, depending on the range
- Widely used in:
  - Nuclear industry
  - Radiology
  - Environmental monitoring

Advantages of Ionization Chambers

- Insensitivity to applied voltage:
  As they are operated in the ionization region, small changes in the applied voltage do not deteriorate the system performance.
  Less expensive power supplies can be used with ionization chambers.
- Proportionality:
  Saturation current is directly proportional to the energy deposited by incident radiation
- Less Vulnerability to Gas Deterioration:
  As there is no multiplication, gas quality (presence of electronegative ions) is not important.
  Almost any gas can be used.
- Uniform response for γ: accurate overall dose reading
- Measurement of high radiation rate

Disadvantages of Ionization Chambers

- Low current: Current flowing through an ionization chamber is usually very small.
  Needed to use low noise electronics
  Difficult to perform measurements for low radiation environments.

- Vulnerability to atmospheric conditions.
  Response of the chamber may change with atmospheric conditions (pressure, temperature), specially with air-filled chambers.
  These effects are only important in high resolution systems.

- Solution: Amplify charge → **Proportional Counters**

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- Solution: Amplify charge → **Proportional Counters**

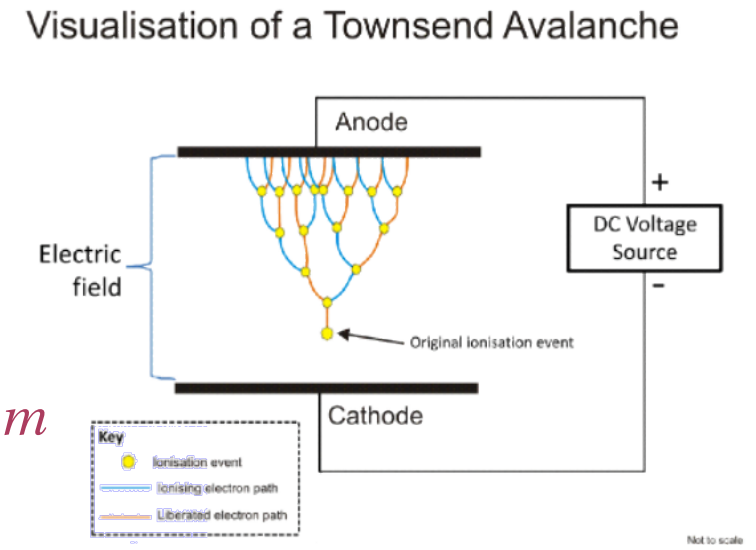
Section 4

Proportional counters

4. Proportional counters

- General characteristics
- Gases
- Special proportional counters types

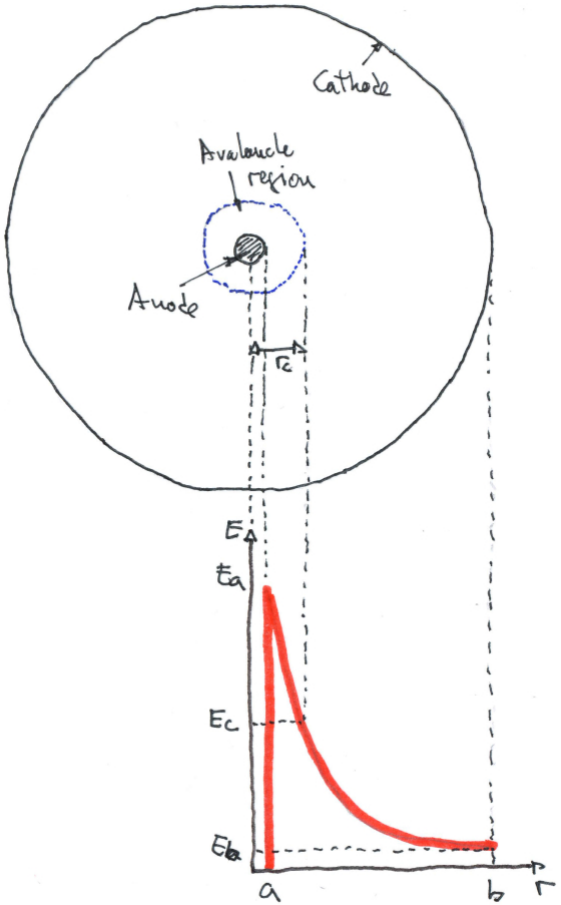
General characteristics



- Gas detectors working in the proportional mode:
  - Townsend avalanches
  - Multiplication if $E > 10^6\, V/m = 10^4\, V/cm$
- Electric field increased
  - electrons accelerated
  - sufficient kinetic energy to cause secondary ionizations
- Avalanches (higher ionization current)
  - detection much more sensitive
  - better signal/noise ratio
- Current is still proportional to the number of ion pairs
  - Higher energy of radiation
  - greater avalanche
  - higher current

Proportional counters

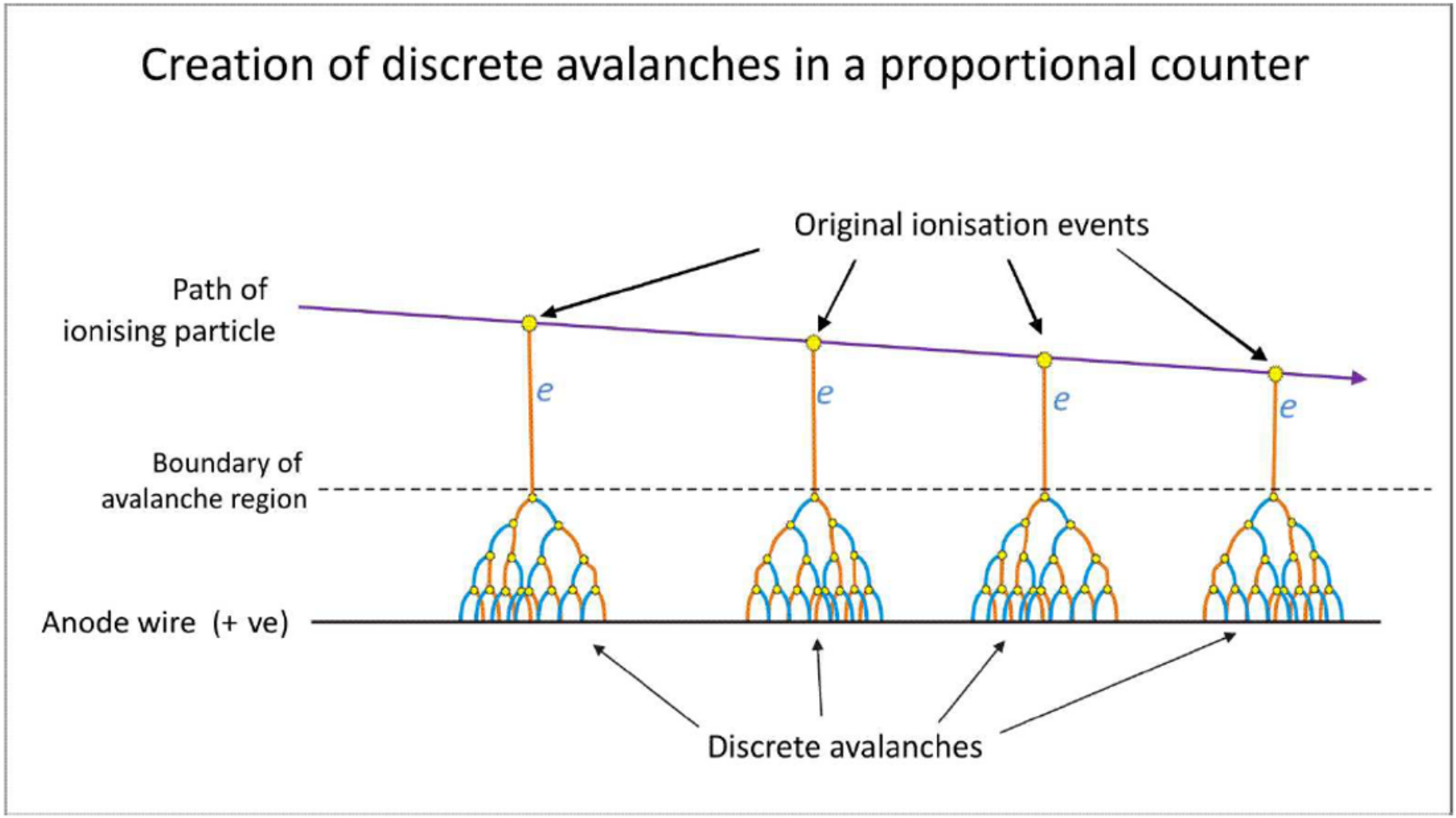
- Preferred cylindrical geometry



$$E = \frac{V}{r \ln \frac{b}{a}}$$

Ex. $a = 80\,\mu$m, b=1cm, and V=2000V

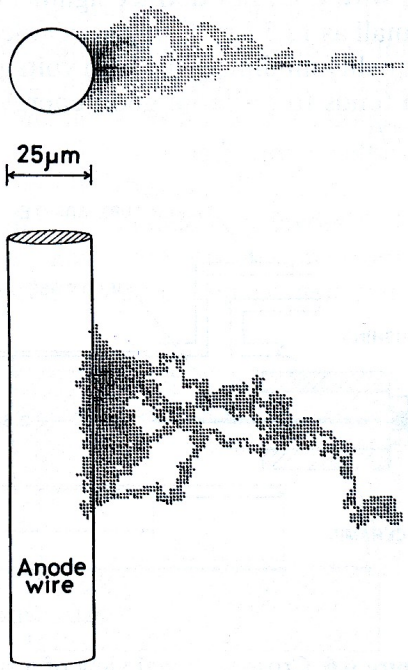
r	E (V/cm)
1 cm	414
0.5 cm	828
1 mm	4142
500 μm	8284
400 μm	10335



- Each ionization event is detected separately
- Energy information preserved:

General characteristics

- Avalanches are then confined around the anode wire
  - We can distinguish two zones
    - Drift region: from cathode to ~5x wire radius
      Electrons drift towards anode wire
    - Avalanche region: r <5x radius
  - Signal formation:
    - Same pulse form as with ionization chambers
    - Signal formed in avalanche region. $\Delta U^{+} >> \Delta U-$
    - Only difference → change N by MN
  - In the timing we have to take into account
    - e^{-} migration to the avalanche zone
    - Avalanche formation → electron signal (fast)
    - Drift of ions to the cathode



Gases

- Gas multiplication depends CRITICALLY on the migration of free electrons
  - Avoid gas species with high electronegativity (i.e. Oxygen)
  - Air should be avoided → proportional counters hermetic to avoid contaminations
- Primary choice: Noble gases
- Gas multiplication can produce also excitation:
  - Excitation → UV γ → photoelectrons → new avalanches
  - Addition of small quantities of gases that absorbs UV γ
  - The presence of this quench gas stabilize the gain M
  - Typical quench gases: polyatomic hydrocarbures(CH_4, isobutane,...)
- Usual gases mixes used in proportional counters:

90% Ar + 10% CH_4	P-10 gas. General purpose
95% Xe + 5% CO_2	
64% CH_4 + 32% CO_2 + 4% N_2	biological tissue equivalent
$^{10}BF_3$, ^3He	Detection of thermal neutrons
75% Ar + 24.5% iso-C_2H_8 + 0.5 freon	Charpak magic gas

Sealed and continuous flow counters

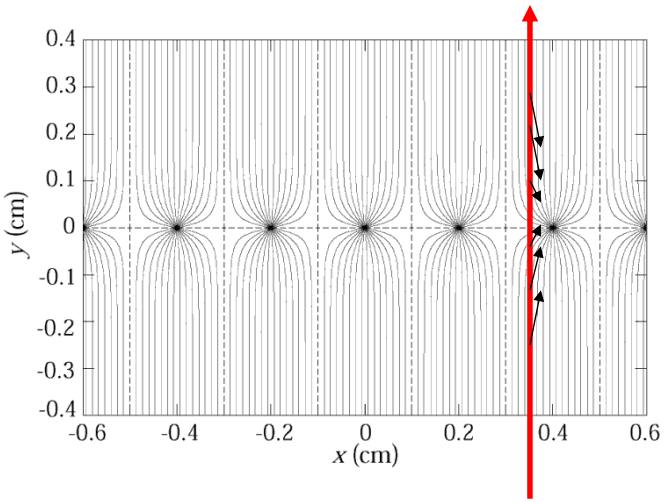
- We can distinguish two types of proportional counters:
  - Sealed
  - Continuous flow counters

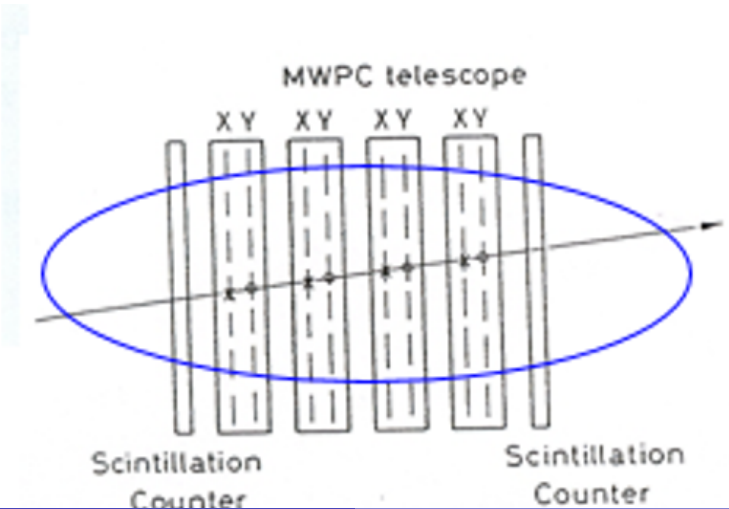
- In sealed counters the gas is not renewed
  - Limited lifetime because of microscopic leakages
  - Convenient because it can be used in portable equipments

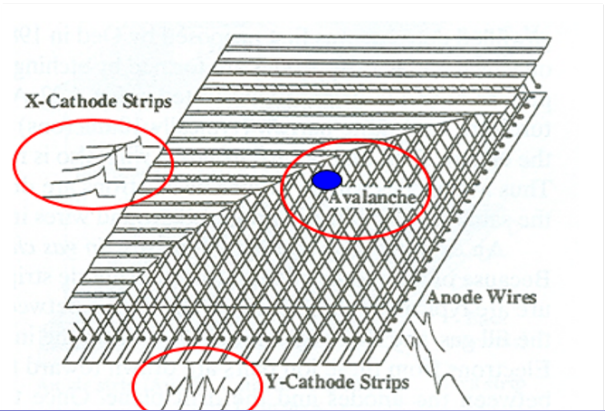
- In continuous flow counter the gas is renewed/purified constantly
  - It allow to change gas composition
  - This is the choice for precision measurements
  - Cumbersome equipment (filtration plant + ...)

Special types of proportional chambers

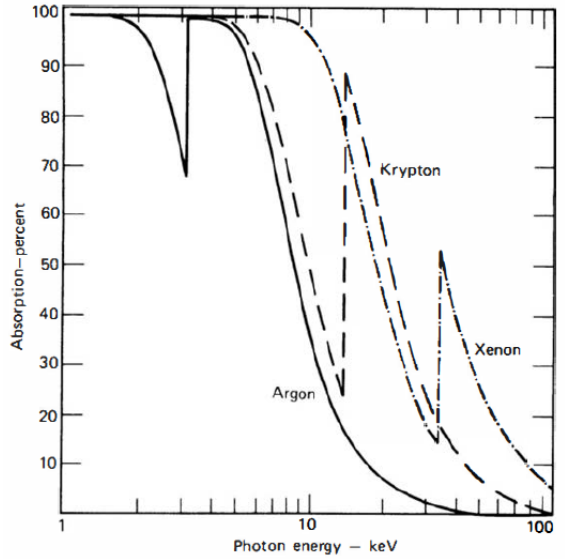
- Tissue equivalent Proportional counter
- Parallel Plate Avalanche Counters (PPAC)
- BF_3 and ^3He counters for neutron detection
- Position sensitive Proportional Counters
  - Multiwire proportional chambers
  - TPC. Time Projection Chamber
  - Microstrip Gas Chamber. (MSGC)
  - Gas Electron Multiplier (GEM)
  - Micromegas
  - Resistive Plate Chambers (RPC's)





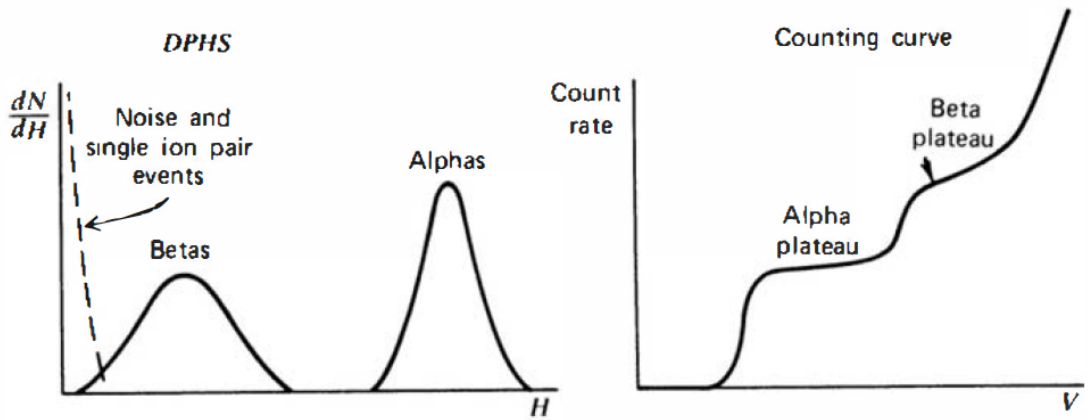


Applications



- X rays and γ-rays up to about 100 keV
- protons and α-particles: counting&spectrometry
- Counting of β's

- Widely used in:
  - Spectroscopy
  - Contamination
  - Particle tracking



- Advantages:
  - Measures energy
  - Discriminate particles
- Disadvantages:
  - Efficiency affected by O_2 contamination
  - Entrance windows easily damaged

Section 5

Geiger-Müller counters

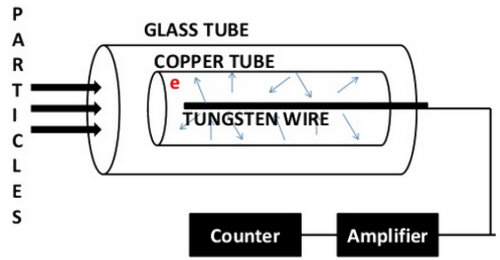
5. Geiger-Müller counters

Gases. Quenching

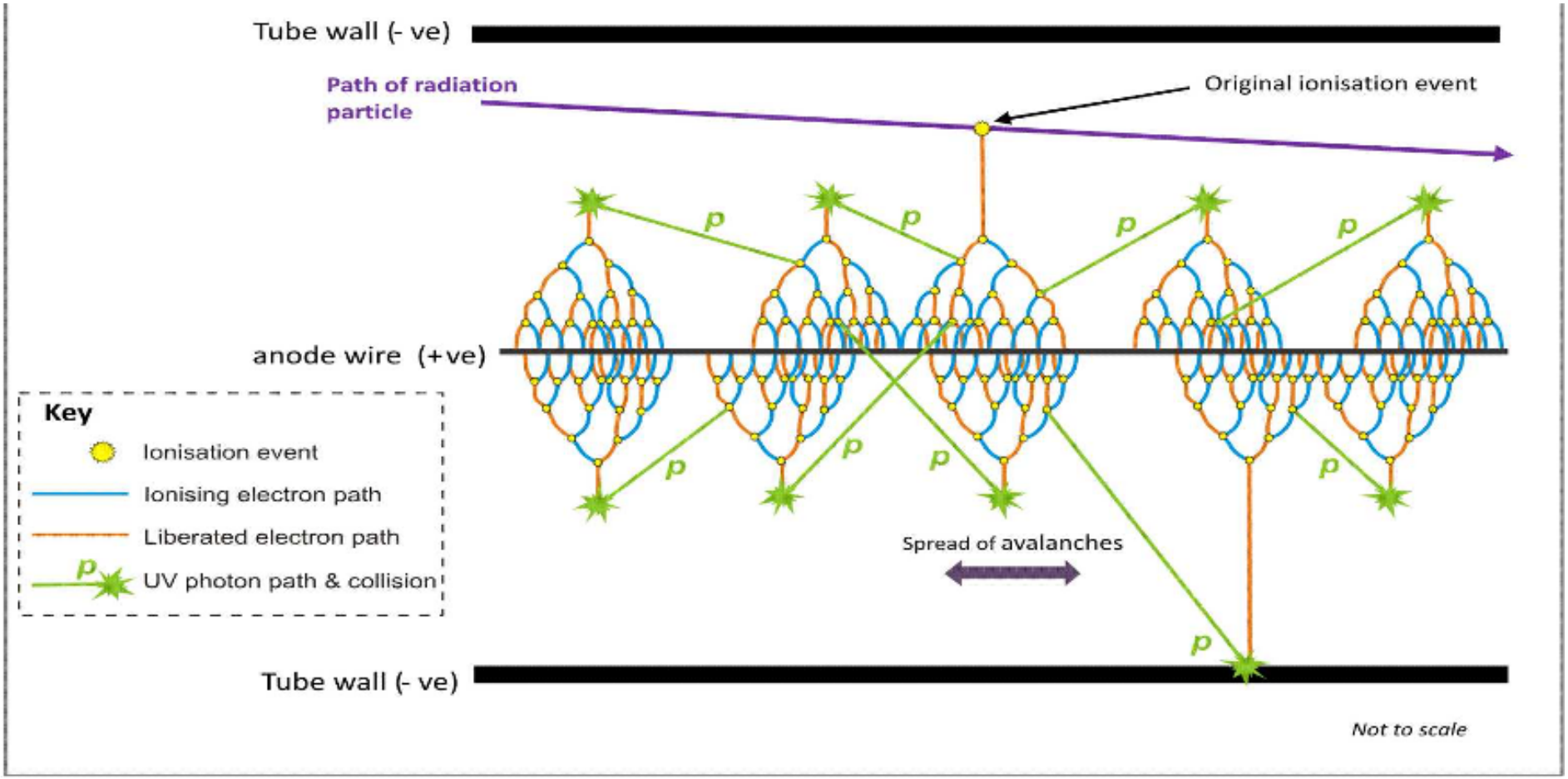
Advantages and Disadvantages of GM counters

General characteristics

- This is one of the oldest electronic counters: introduced in 1928 by Geiger and Müller
- Geiger-Müller counters (GM) operates in the the Geiger region
  - Proportional region each e^- produces an avalanche: signal $\propto$ energy
  - Geiger region, the avalanche is a collective phenomena: G$> 10^8$
  - Same signal if 1 electron or 1000 electrons generated by radiation
- The critical condition for GM operation is:
  - Proportional region: $N\gamma < 1$
  - Geiger region: $N\gamma > 1$



- Because of the large number of charge carriers generated, GM present a huge dead time ~few 100's μs
- Gases used: mainly noble gases (Ar). Gases that form negative ions (i.e. O_2) should be avoided.


Tube wall (- ve)
Path of radiation particle
Original ionisation event
anode wire (+ve)
Key
Ionisation event
Ionising electron path
Liberated electron path
UV photon path & collision
Spread of avalanches
Tube wall (- ve)
Not to scale

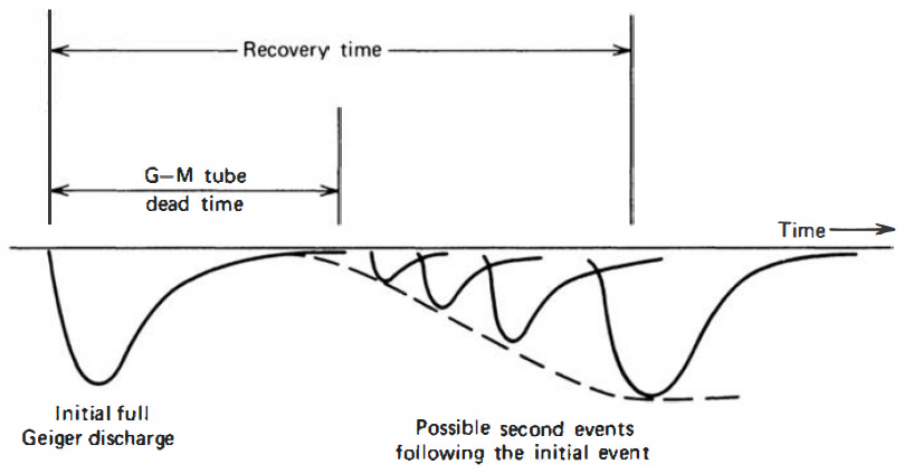
Quenching

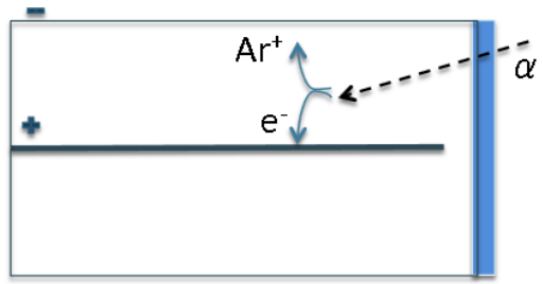
- As with proportional counters quenching is needed in GM counters
  - Limit and extinguish the avalanche formation
- Internal quenching:
  - Positive ions reduce the electric field below the critical value
  - Add a small amount of polyatomic gas (5-10%)
    - Low ionization potential
    - Does not de-excite emitting electrons or UV-γ
    - Transfer the positive charge to these polyatomic gases.
- External quenching
  - Stop the avalanche just by reducing the anode voltage once the Geiger discharge is detected
  - It reduces dead time

Dead time

- After a Geiger discharge a considerable amount of time is needed before a second Geiger discharge can be generated:
  - Drift of positive charges reduce the electric field
  - No more discharges possible
  - Dead Time: 100-200 μs
- The time to allow the system to detect as second discharge, even if the signal amplitude is not fully developed is called the resolving time

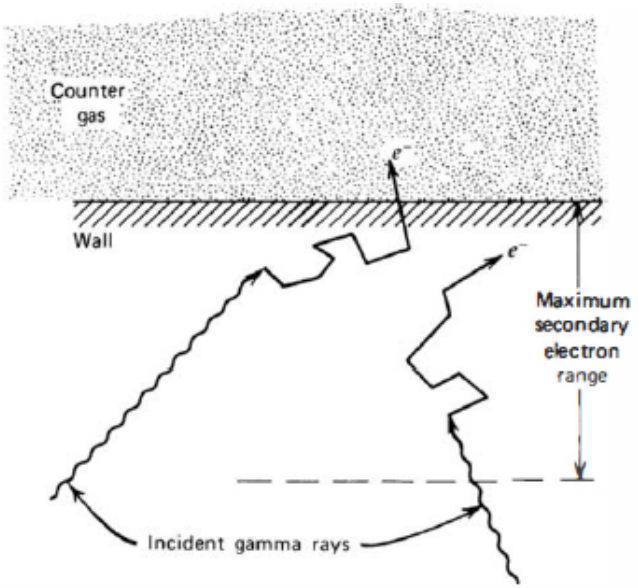
- The time needed by the counter to develop a signal with a full amplitude is the recovery time

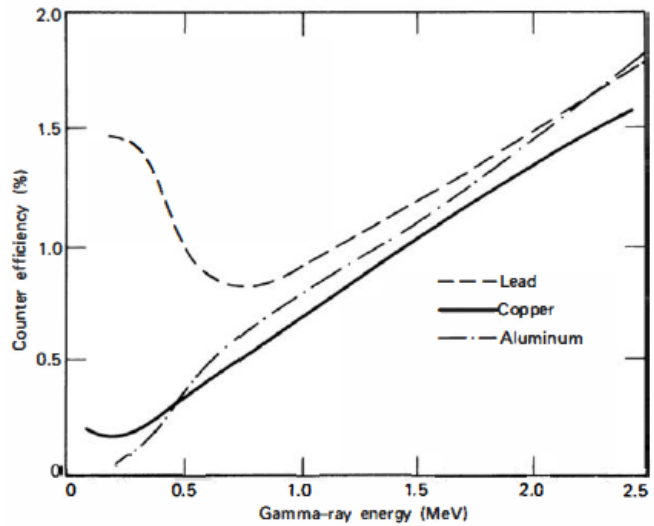




Detection features

- Charged particles:
  - $\varepsilon \simeq 100\%$ if particles cna get into the active volume (thin window)
- Neutrons: Seldom used
- Gamma-rays: detection of secondary electrons.
  - Interaction with the wall (electron range, material)
  - The electron should reach the gas volume.





Applications

- For detection of α and β particles
- To check for environmental levels of radioactivity
- On-field radioactivity detection
  - Industry: mineral prospection
  - Military purpose
- Fire and Police: initial determination of radiation risks

Advantages and Disadvantages of GM counters

Advantages:

- Simplicity in design:
  GM are the easiest to built and operate of electronic counters
- Invulnerability to environmental changes:
  Output pulse does not depends on external factors as temperature or pressure

Disadvantages:

- Large dead time ($\sim 100\mu s$)
- No Energy/Particle discrimination:
  Pulse height is not proportional to energy deposited or particle type
- Low dynamic range:
  Dead time increases with rate. This can be cured reducing the size at the cost of reduce sensitivity.

Section 6

Summary and test

6. Summary and test

Summary of applications of gas detectors

- Ionization chamber
  - dosimetry (all particles),
  - detection of α's and β's
  - possibly of γ's when a high pressure is considered
- Proportional counters
  - Spectroscopy of α and protons (size larger than range)
  - X-ray spectroscopy
  - detection of neutrons (Gas sensitive to neutrons ^{3}He $^{10}BF_3$
- Geiger-Müller counters
  - Detection of α, β and γ

What is the best detector for:

1. Very high rate X-rays exposure
2. Weak β source counting
3. Detection of α's
4. Spectrometry of 10 keV X-rays
5. α-β identification
6. Spectrometry of 10 MeV γ