Detector Physics

Ionisation Detectors I - Gas Detectors

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General Requirements

- Particle detection
- Momentum and/or energy measurement
- Position/localisation
- Time of occurrence

What can we use all these for?

- Particle identification pion - kaon - electron - WIMP...
- Reconstruction of the invariant mass of decay products $m_{\text{inv}}^2 = \left(\sum_i p_i\right)^2$
- "Missing Mass" or "Missing Energy" for undetected particles like neutrinos
- Sensitivity to lifetime or decay length
  - stable particles: protons, $\tau > 10^{32}$ y
    test of stability
  - unstable particles
    decay via strong interaction: : e.g. $\rho \longrightarrow \pi^+\pi^-$ $\quad \Gamma = 100\text{MeV}$

    $$\tau c = \frac{\hbar c}{\Gamma} = 2\text{fm} \qquad \tau \approx 10^{-23}$$

    decay via electromagnetic interaction: e.g.
    $\pi_0 \rightarrow \gamma\gamma \qquad \tau \approx 10^{-16}$
  - quasi-stable particles
    decay via weak interaction

A Few examples of decay length

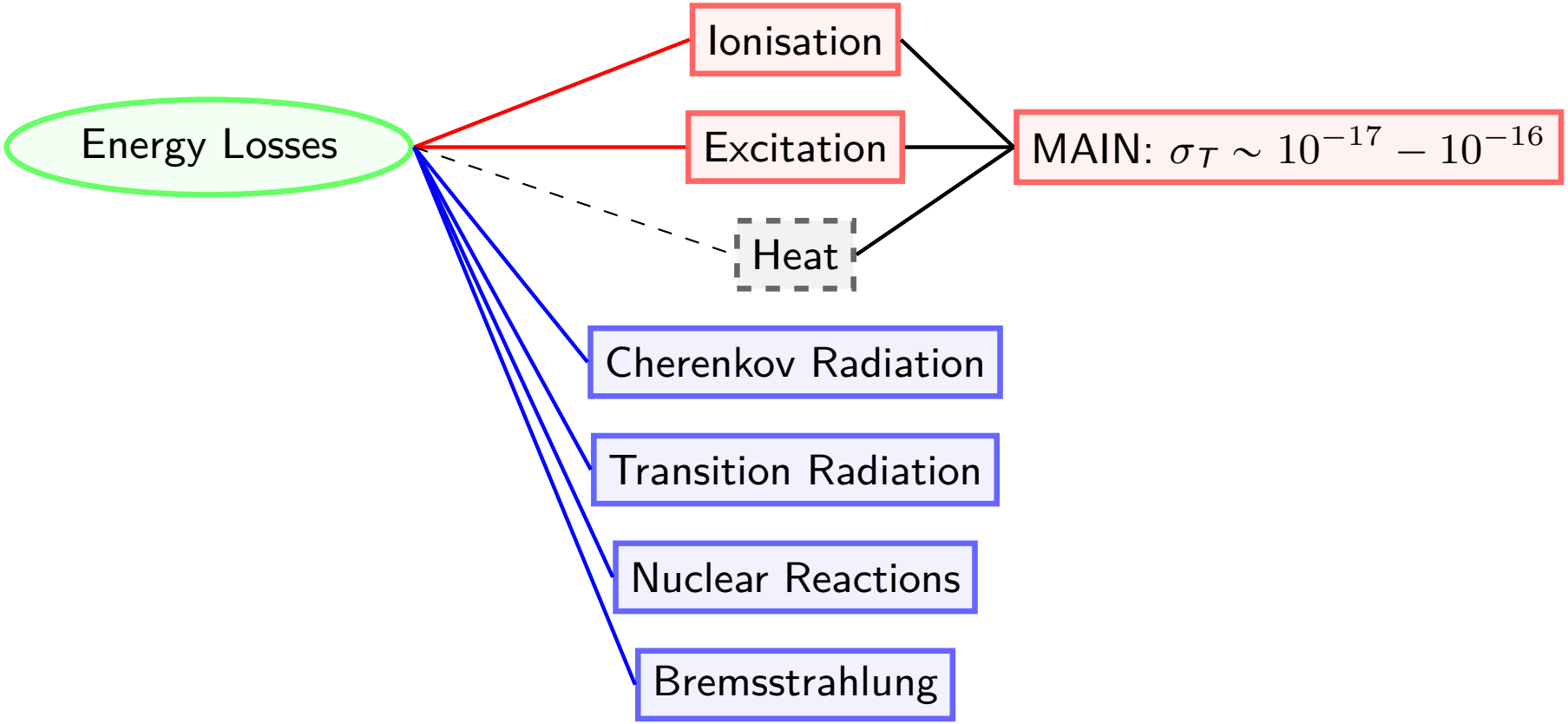
particle	τ	$c\tau$	decay length $\beta\gamma c\tau$ at $p = 10$ GeV$/c$
n	899 s	$2.7 \cdot 10^8$ km	$2.9 \cdot 10^9$ km
Λ	$2.6 \cdot 10^{-10}$ s	7.9 cm	71 cm
$\pi^{\pm}$	$2.6 \cdot 10^{-8}$ s	7.8 m	560 m
D$^{\pm}$	10^{-12} s	0.31 mm	1.6 mm
B$^{\pm}$	$1.6 \cdot 10^{-12}$ s	0.49 mm	0.93 mm
τ	$3 \cdot 10^{-13}$ s	0.09 mm	0.5 mm
H	$\sim 10^{-}22$ s	30 fm	2.4 fm

"Non-particle" decay times range from $\sim 10^{-9}$s (nuclear de-excitation γ-rays) to $\sim 10^{24}$ years ($\beta\beta$ decay w/ ν or double electron capture).

Detect particles from their effect on matter

MAIN CONCEPTS

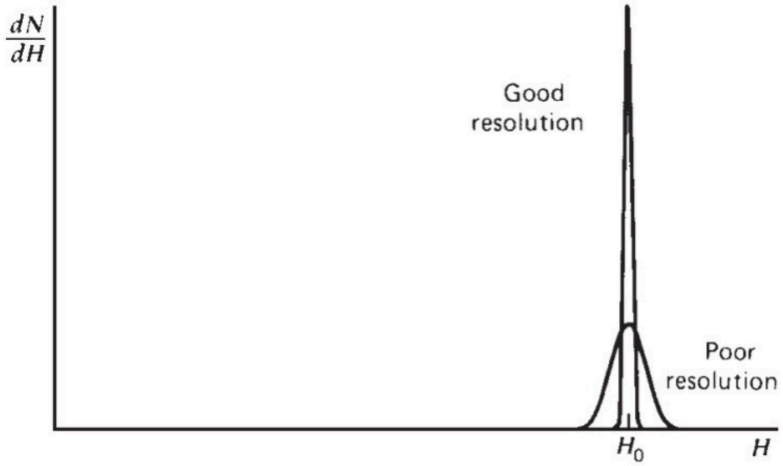
- Charged Particles (CP) can be detected only through their interaction with matter!
- Understanding the processes that are responsible for the kinetic energy losses and deflections from incident direction is crucial
- Passage of charged particles through matter is characterised by:

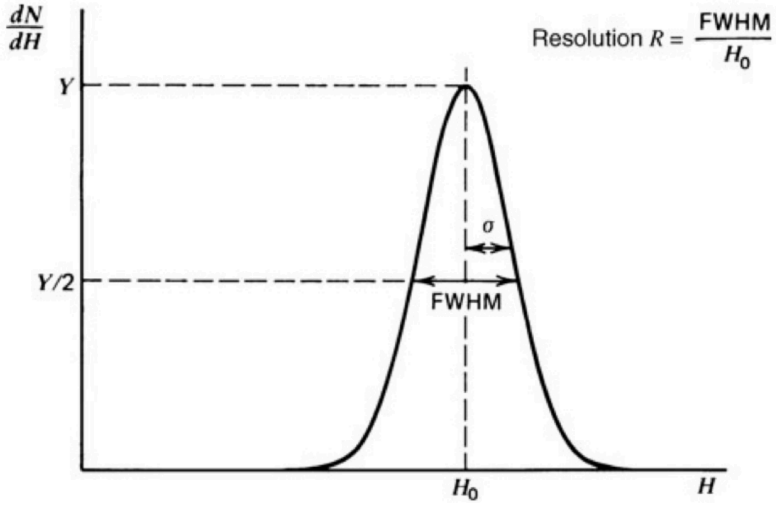


Energy Resolution

- The objective of radiation detectors application is often the measurement of the energy distribution of the incident radiation (*"radiation spectroscopy"*)
- An important characteristic of a detector devoted to radiation spectroscopy is the *"response function"* to mono-energetic radiation.
- Both "good" and "poor" resolution are centred around H_0 but the former is much narrower than the latter.
- The width reflects the amount of fluctuation in the measured signal, even though the same amount of energy is deposited in the detector and determines the ability of the detector to *"resolve"* fine details on the energy of the incident radiation.
- A formal definition of detector energy resolution is given by the ratio:

$$\boxed{\frac{FWHM}{H_0}}$$





Energy Resolution

There are a number of potential sources of fluctuation in the response:

1. Drift of the operating characteristics of the detection system.
2. Sources of random noise within the detection system.
3. Statistical noise due to the discrete nature of the measured signal (the fact that the number of charge carriers is discrete)

$$(FWHM)^2_{\text{overall}} = (FWHM)^2_{\text{statistical}} + (FWHM)^2_{\text{noise}} + (FWHM)^2_{\text{drift}} + \ldots \quad (1)$$

The third source of fluctuation is the most critical because it is *inherent to the nature of the energy loss process* that is being exploited for radiation detection.

It also depends to some extent on the efficiency with which the quanta (electrons-ions for ionisation and photons for the scintillation) are detected.

Energy Resolution

We can estimate the amount of inherent fluctuation by assuming that the formation of each quantum (e^--ion or photon) is a Poisson process:

- Given N quanta, the standard deviation is expected to be $\sqrt{N}$
- If N is a large number the response function should have a Gaussian shape.

$$G(H) = \frac{A}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(H-H_0)^2}{2\sigma}\right) \tag{2}$$

- Where $\boxed{FWHM = 2.35\sigma}$ H_0 and A are the centroid and the area of the Gaussian respectively.
- Normally the detector response is *approximately* linear, i.e. $\boxed{KH_0}$ where K is a constant
- The standard deviation σ of the peak in the PH spectrum is therefore $\boxed{\sigma = K\sqrt{N}}$

Fano factor F

- The limiting resolution R due to statistical fluctuations in N:

$$R\Big|_{\text{Poisson limit}} \equiv \frac{FWHM}{H_0} = \frac{2.35K\sqrt{N}}{KN} = \frac{2.35}{\sqrt{N}} \tag{3}$$

- Problem: variance is constrained by the energy conservation, i.e. if all the energy is lost by - say - ionisation, because the energy has to be conserved there wouldn't be any fluctuation! (Energy partition)
- Indeed in some cases R is lower than Poisson by a factor 3 or 4.
- F quantifies deviation of observed stat. fluctuation from Poisson limit:

$$R\Big|_{\text{Fano limit}} = \frac{2.35K\sqrt{N}\sqrt{F}}{KN} = 2.35\sqrt{\frac{F}{N}} \tag{4}$$

$$F \equiv \frac{\text{observed variance N}}{\text{Poisson predicted variance } (=N)} \tag{5}$$

Lecture Summary

1. Gas Detectors
   - Ionisation Chambers
   - Proportional Counters
   - Geiger-Müller Counters
   - Multi Wire Proportional Chambers (MWPC)
   - Micro-Pattern Gas Detectors - MPGD
   - Time Projection Chambers

Gas Detectors

Introduction

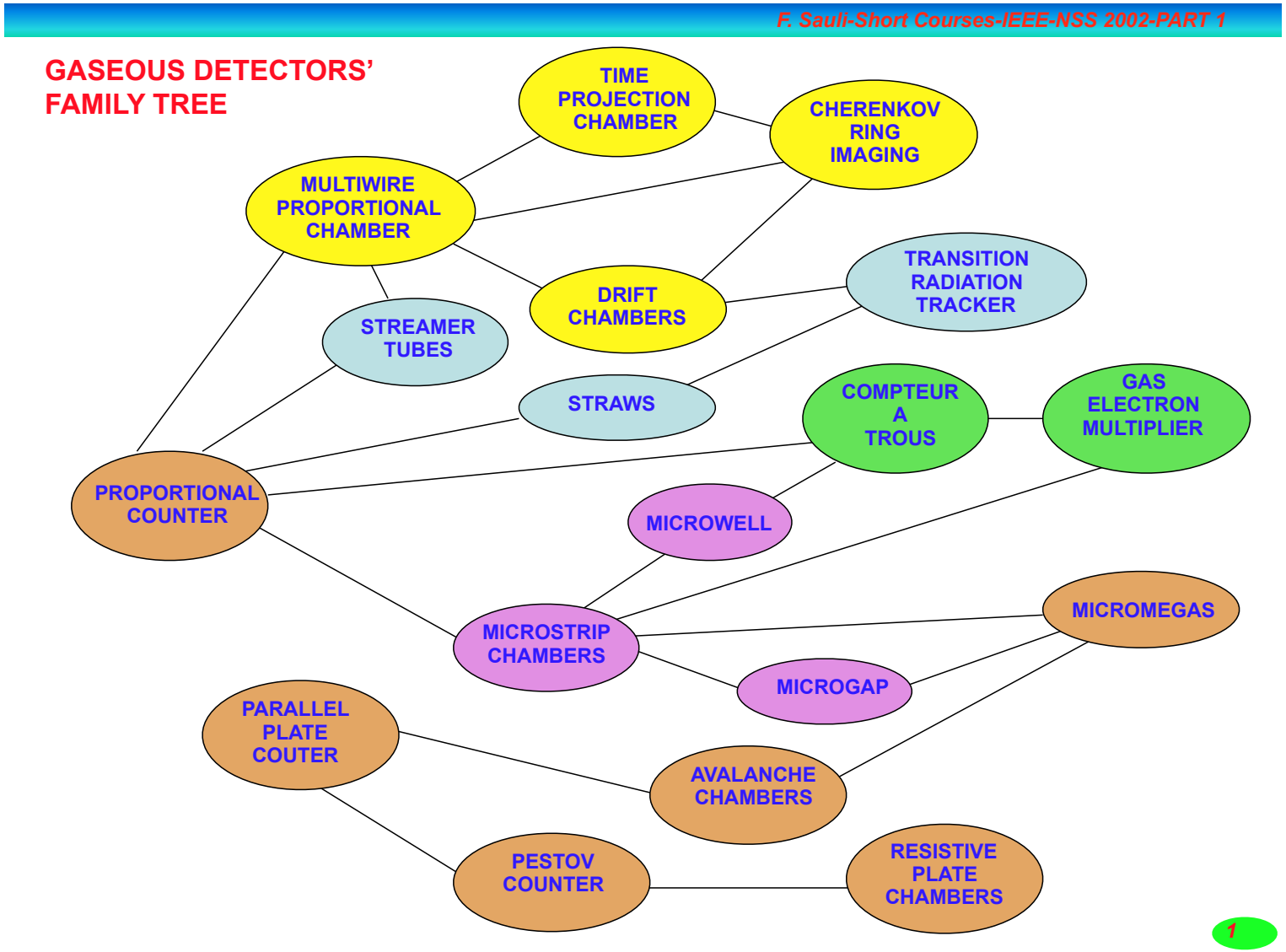
- Gas detectors are the between the oldest instruments for registering ionising radiation that are still in use.
- The primary modes of **interaction of ionising radiation** is through **ionisation and excitation**
- All (big majority!) of gas detectors are based on the detection of the ionisation generated by the interaction of the radiation.

Three main classes of gas detectors:

1. Ionization chambers
2. Proportional counters
3. Geiger-Müller counters

- In all three types of detectors an external electric field is applied between two electrodes that collect the positive and negative charges created when ionising radiation interacts with the atoms in the gas.
- The signal recorded is then the sum of the collected charges, positive and negative, and it is proportional to the deposited energy in the gas by the radiation.

Actually, our classification is a bit... reductive



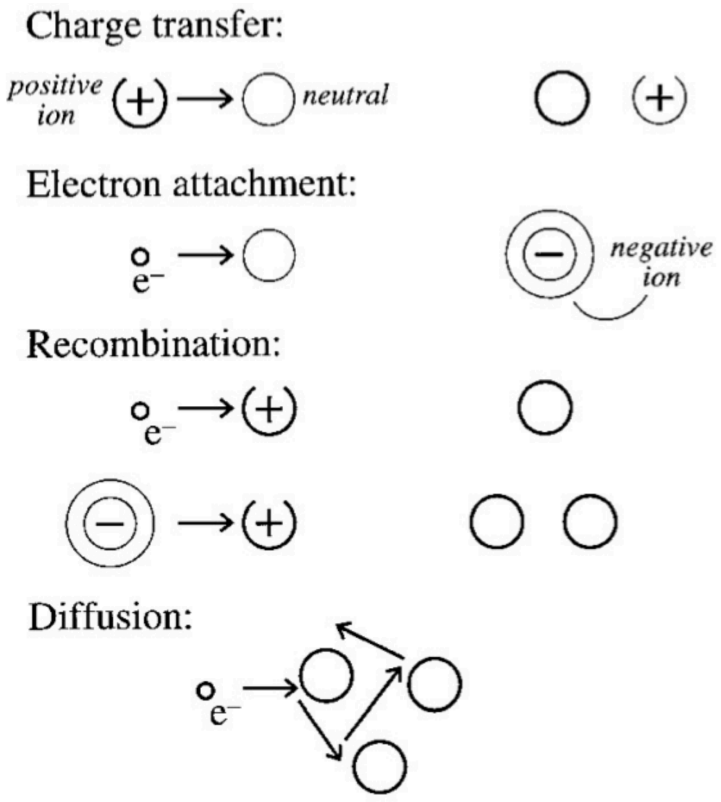
The Ionisation Process in gases

- Charged particles ionise and excite gas molecules and e^--ion pairs are created
- A minimum energy is required to ionise a certain molecule.
- The average energy spent to produce an e^--ion pair is called the W-value.
- The W-value is $\sim$ related to the ionisation energy, slightly bigger because ionisation is not the only mechanism of energy loss.
- Typical values for W-values in gas range between 25 and 40 eV.

The Ionisation Process in gases

- W-value $\neq f(E_0)$ and $\neq f(m_0, z)$.
- Mainly for gases: for scintillators and semiconductor detectors W-value has a stronger dependence on energy and type of radiation.
- For example an incident charged particle of 1 MeV, depositing all its energy in a gas-filled detector with a W-value of 25 eV would generate 40,000 electrons (on average)
- Remember the Fano factor! There is a partition of energy loss that doesn't go all into ionisation and that this is the only source of fluctuation. Otherwise the energy conservation imposes that there cannot be a free statistical fluctuation in the number of quanta.

- Free ionisation products are in thermal motion and tend to diffuse away from regions of high density.
- The diffusion is much higher for electrons than for ions
- CYGNO (and other directional dark matter searches) use "Negative Ion Drifting" (NID)
- A point-like electron cloud spreads about its original generation point into a spatial Gaussian: $\boxed{\sigma_x = \sqrt{2Dt}}$ D: diffusion coefficient and t: elapsed time.
- Charge transfer collisions can occur in which an ion meets a neutral molecule and an electron is transferred from the neutral molecule to the ion (important for gas mixtures)



Charge Migration and Collection

- The collection time should be as fast as possible to avoid recombination.
- Achieved by applying a large "external" electric field $\vec{\mathscr{E}}$.
- e^- and ions have thermal and drift ($\mathscr{E}$) motion.
- Electrons drift towards anode with a <u>constant</u> "drift" velocity: measurement of drift time Δt allows to determine point of ionization L:

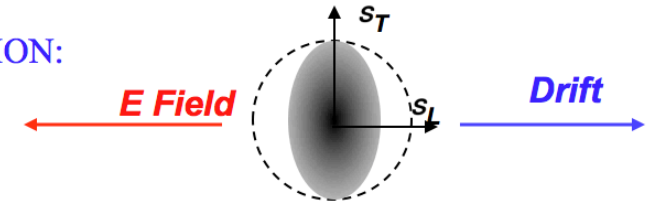
$$\Delta t = \frac{L}{\nu}$$

- Typical drift velocity of ions in a gas is $\sim$ m/s.
- The mobility of electrons is $\sim$ 1000 times greater than for ions.

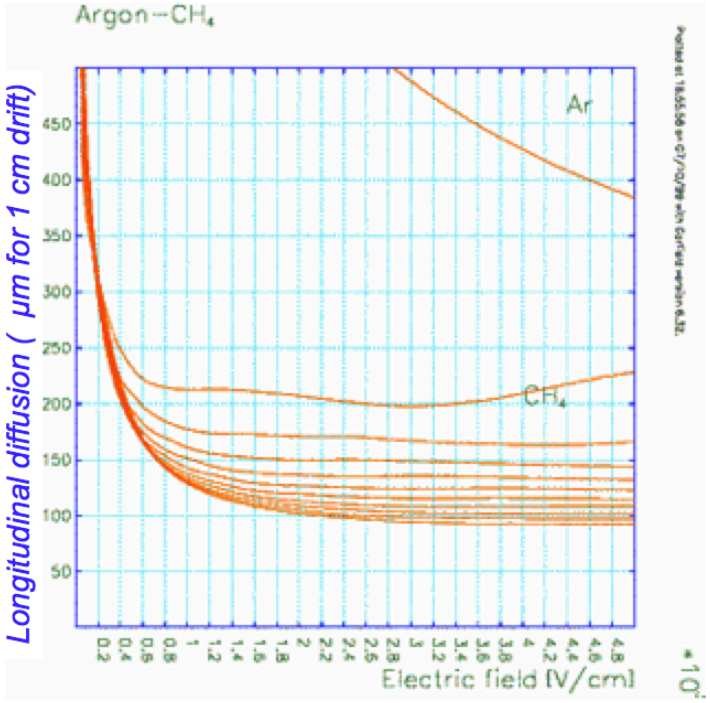
Electron diffusion

Transverse and longitudinal

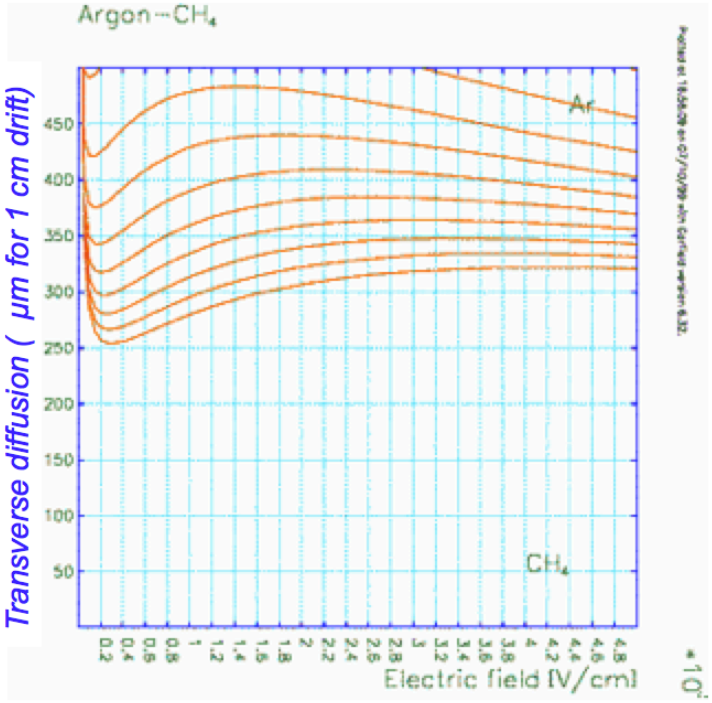
LONGITUDINAL DIFFUSION (// E)
SMALLER THAN TRANSVERSE DIFFUSION:



LONGITUDINAL DIFFUSION:



TRANSVERSE DIFFUSION:

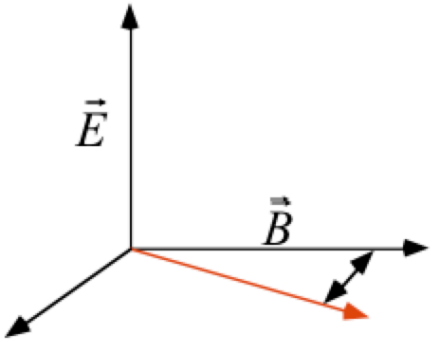


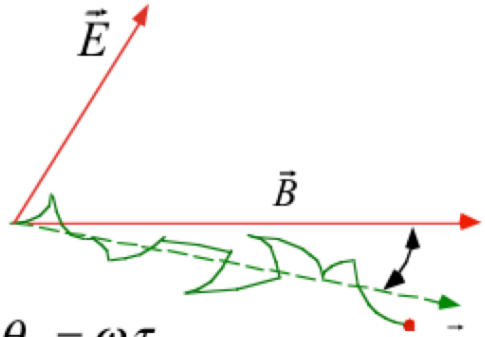
Electron diffusion

In presence of E and B

THE SWARM (cloud) IS ROTATED BY AN ANGLE θ_B
IN THE PLANE PERPENDICULAR TO E AND B

$\vec{E} \perp \vec{B}$





$$\tan\theta_B = \omega\tau$$

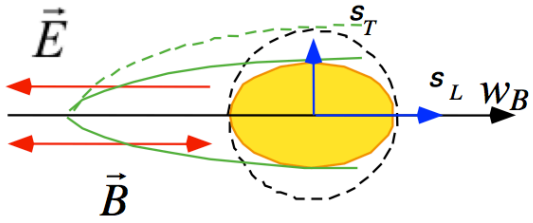
$$w_B = \frac{E}{B}\frac{\omega\tau}{\sqrt{1+\omega^2\tau^2}}$$

τ : mean collision time

$\omega = eB/m$ Larmor frequency

THE MAGNETIC DRIFT VELOCITY IS $w_B = w_0$
THE TRANSVERSE DIFFUSION IS REDUCED

$\vec{E} \parallel \vec{B}$



$$w_B = w_0$$

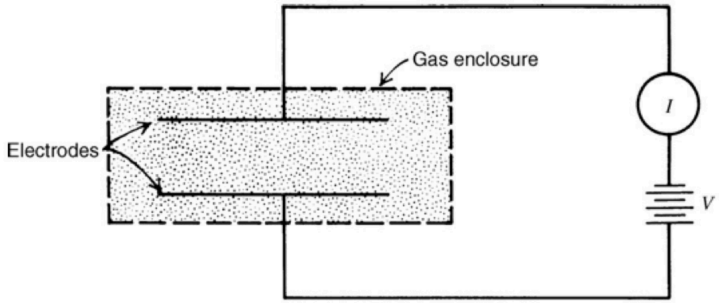
$$\sigma_L = \sigma_0$$

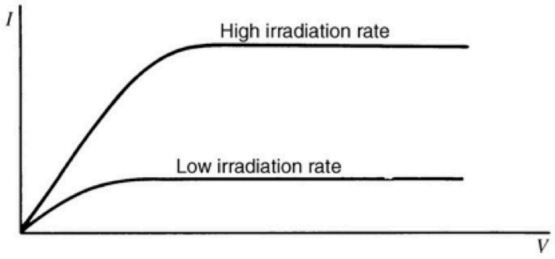
$$\sigma_T = \frac{\sigma_0}{\sqrt{1+\omega^2\tau^2}}$$

Ionisation Chambers

Design and Operation of DC Ion Chambers

- In the presence of $\mathscr{E}$, the drift of e^--ion pairs constitutes an electrical current.
- If the volume of a detector undergoes steady state radiation it will generate a constant current value (if the voltage is kept constant).
- Measurement of such ionisation current is the basic principle of DC ion chambers
- At equilibrium, the current flowing in the external circuit will be equal to the ionisation current collected at the electrodes
- A sensitive ammeter placed in the external circuit can measure the ionisation current





- DC ion chambers are operated at ion saturation current and in this conditions $I \propto$ rate
- Have we already seen something like this?

Design and Operation of DC Ion Chambers

- Need to reduce all factors that might cause the current not to be at saturation level
- The most important factor affecting the saturation current is the recombination which is minimised by using a large electric field.
- Columnar recombination for heavy charged particles is particularly difficult.
- Volume recombination increases with the dose rate.
- When ICs are used in direct current mode, it is possible to collect the negative charge as free electrons or as negative ions.
- Any fill gas can be used, even those with high electron affinity. Air is the most common one.
- The fill gas pressure is often 1 atm.
- Planar or cylindrical ICs are the emost commonly used. (Spherical ICs exist as well)
- Application of ICs range from survey instruments for radiation monitoring, radiation source calibration, radioactive gas measurements, remote sensing ionisation.

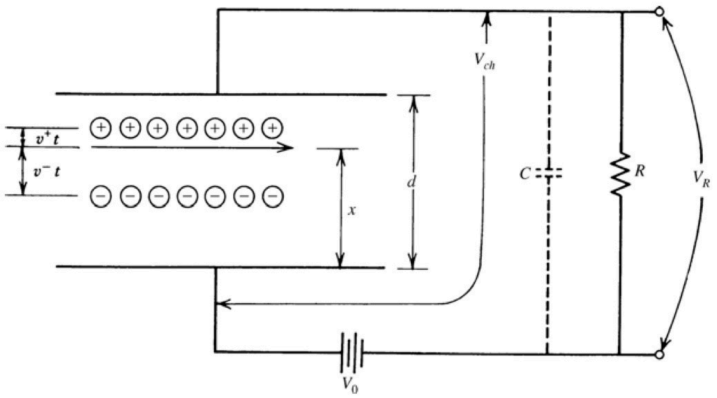
ICs in Pulse Mode Operation

- ICs are usually operated in current mode. However pulse mode is also possible.
- Pulse mode ICs are used to some extent in radiation spectroscopy, although they have largely been replaced by other more efficient detector types
- They however remain important instruments in specialised applications such as large-area alpha spectrometers or neutron detectors

- Assuming $\mathscr{E} = \frac{V_0}{d}$ uniform, no e^- capture by electronegative impurities and $RC \gg t_c$, N pairs produced
- When charges drift towards the electrodes they induce a voltage variation across R: $\boxed{V_R = V - V_0}$
- We can derive the shape of the pulse based on an energy conservation argument: the initial energy stored in the capacitor is $\boxed{\frac{1}{2}CV_0}$

- This energy gets reduced by to $\frac{1}{2}CV$ because of V_R by an amount that is:

$$N\int_x^{x'} e\mathscr{E}\,dx = Ne\mathscr{E}(x - x') \Longrightarrow$$

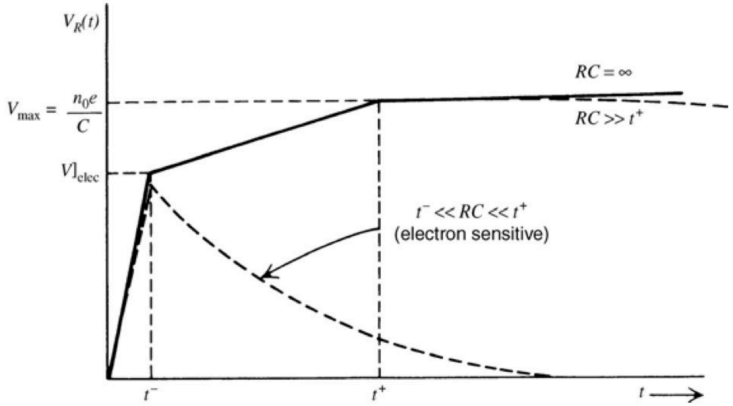


ICs in Pulse Mode

- The conservation of energy imposes that: $\longrightarrow$ $$\underbrace{\frac{1}{2}CV_0^2 - \frac{1}{2}CV^2}_{\frac{1}{2}C(V_0+V)(V_0-V)} = Ne\mathscr{E}(x' - x) = \frac{NeV}{d}(x' - x)$$
- Since $V \simeq V_0$ (i.e. $V_0 + V = 2V_0$) and that $V_R = V_0 - V$ we obtain: $\longrightarrow$ $$V_R C V_0 = \frac{NeV_0}{d}(x' - x)$$
- That reduces to:

$$\boxed{V_R = \frac{Ne}{Cd}(x' - x) \qquad (6)}$$

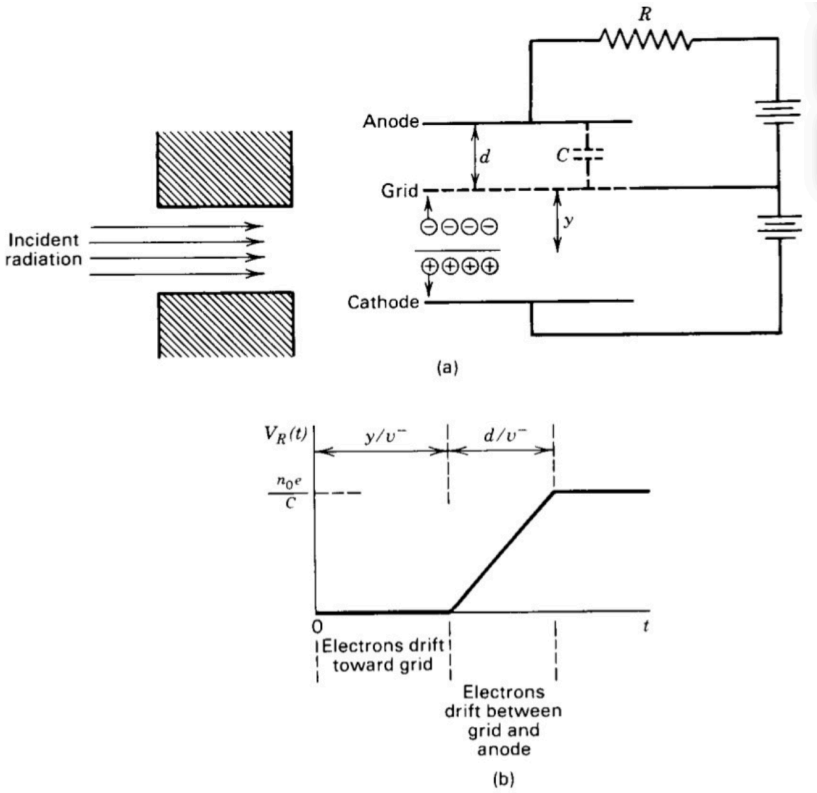
- x' is the distance travelled by both electrons and ions, thus we can rewrite the above expression as: $V_R = V^+ + V^-$
- Here $\boxed{V^+ = \frac{Ne}{Cd}\nu^+ t^+}$ and $\boxed{V^- = \frac{Ne}{Cd}\nu^- t^-}$
- Considering that $\nu^- \sim 1000 \cdot \nu^+$, and that RC can be easily chosen to be $> t^-$ but hard to make it $> t^+$ ($\sim$ ms) $\Longrightarrow$ record only V^-, BUT depends on x!



ICs in Pulse Mode

The dependence of the pulse amplitude on position of interaction can be removed through the use of an arrangement sketched in Figure

- The volume of the ion chamber is divided into two regions by a Frisch grid.
- By using an external source collimation the lower part of the chamber is used as sensitive detector volume and the upper part is used for signal read out.
- In this case indeed the signal voltage across the resistor is $V_R = \frac{Ne}{dC}\nu^- t$
- With a maximum of $V_{\max} = \frac{Ne}{C}$
- In this case the pulse amplitude is independent on the original interaction position and a proper particle spectroscopy can be done.



ICs in Pulse Mode

Let's make an example in order to better understand the performance and limitation of this technology:

- Suppose we have α particles ($E_0 = 5.5$ MeV) inside a gridded IC ($W = 30$ eV, $C = 100$ pF)
- $N = \frac{E_0}{W} = \frac{5.5\times10^6}{30} = 1.83 \times 10^5 \longrightarrow$

$$\boxed{V_{\text{max}} = \frac{Ne}{C} = \frac{(1.83\times10^5)(1.6\times10^{-19})}{10^{-10}} = 0.29 \text{ mV}}$$

- This kind of signal size can be successfully processed but requires quite sophisticated preamplifiers.
- The theoretical limit on the fluctuation related to the ionisation process can be derived for this example:
- $\sigma_N^2 = FN = 0.15(1.83 \times 10^5) = 2.75 \times 10^4 \longrightarrow \sigma_N = \sqrt{FN} = \sqrt{2.75 \times 10^4} = 166$
- And therefore the energy resolution is:

$$\boxed{R = \frac{\text{FWHM}(N)}{N} = \frac{2.35\sigma_N}{N} = \frac{2.35 \cdot 166}{(1.83 \times 10^5)} = 0.213\%}$$

This limit is hard to reach because other sources of fluctuation (especially noise from pulse processing electronics) enter. In some applications of α spectroscopy such limit has been approached.

Proportional Counters

Proportional Couters

- Gas-filled detector
- introduced in the 1940s.
- Operated in pulse mode
- Ionisation charges (mainly e^-) amplified by gas multiplication.
- Signals are much larger than for ionisation chambers.
- Suitable for spectroscopy (energy measurement)
- If $E_e^{kin} > E_i$ (ionisation energy of A) (i.e. strong $\mathscr{E}$) $\Longrightarrow$ avalanche:

$$
\begin{aligned}
& e^- + e^- + A^+ \\
& \quad \hookrightarrow e^- + A^+ \\
& \qquad \hookrightarrow e^- + A^+
\end{aligned}
$$

- If recorded charge is proportional to the initial ionisation charge $\Longrightarrow$ Townsend avalanche

Townsend Avalanche

The avalanche is governed by the Townsend coefficients α and γ:

- Let λ be the mean free path of the electrons, $\alpha = 1/\lambda$ is the probability of ionisation per unit path length
- Give n electrons, in a path length dx there will be $dn = n\alpha dx$ new electrons created and integrating we obtain:

$$n = n_0 e^{\alpha x} = n_0 \cdot M \tag{7}$$

- We derived above equation assuming $\alpha =$ const. BUT $\alpha(x)$! (see below)
- M (Multiplication factor) has a maximum of 10^8 ($\alpha = 20$) Reather limit
- Usual values for M are $10^5 - 10^6$

Townsend Avalanche

- Excitation of gas generates UV-photons which in turn can lead to photo-effect in gas and on cathode contributing thus to avalanche
- Let γ (second Townsend coefficient) be the probability for a γ of producing ionisation within the same avalanche per electron gas gain including photo-effect (A_γ):

$$N_0 A_\gamma = N_0 A + N_0 A^2 \gamma + N_0 A^3 \gamma^2 + \ldots \quad (8)$$

$$= N_0 A \cdot \sum_{k=0}^{\infty} (A\gamma)^k = \frac{N_0 A}{1 - \gamma A} \quad (9)$$

$$A_\gamma = \frac{A}{1 - A\gamma} \quad (10)$$

- For $A\gamma \to 1$: continuous discharge independent on the primary ionisation
- To prevent this, add to gas so-called quench-gas which absorbs UV photons strongly, leading to excitation and radiationless transitions
- Examples of quench gas: CH_4, C_4H_{10}, CO_2

Gas Multiplication regions

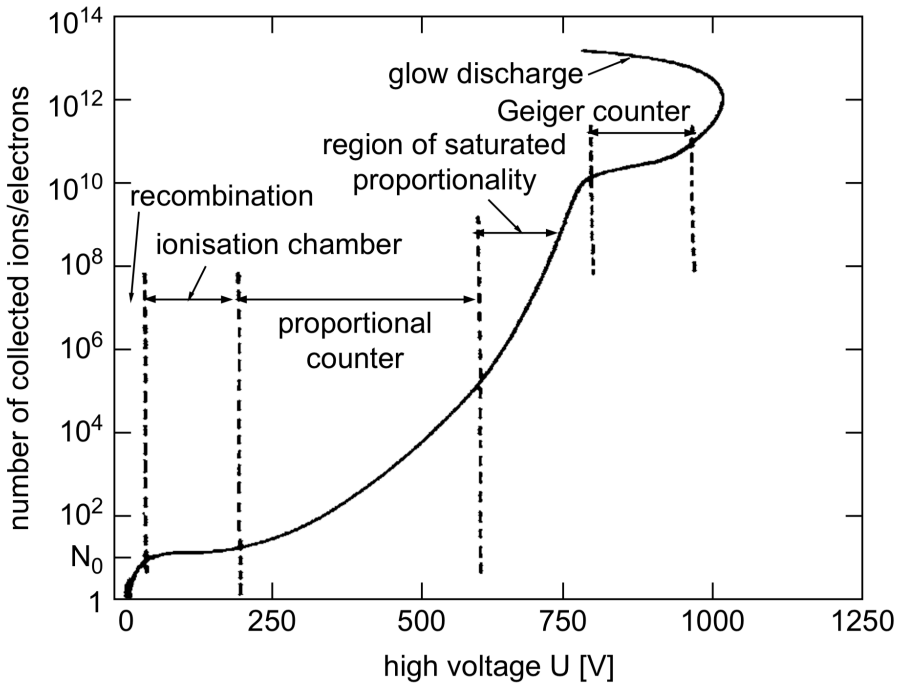


Figure: Characteristic modes of operation of cylindrical gas-filled detector

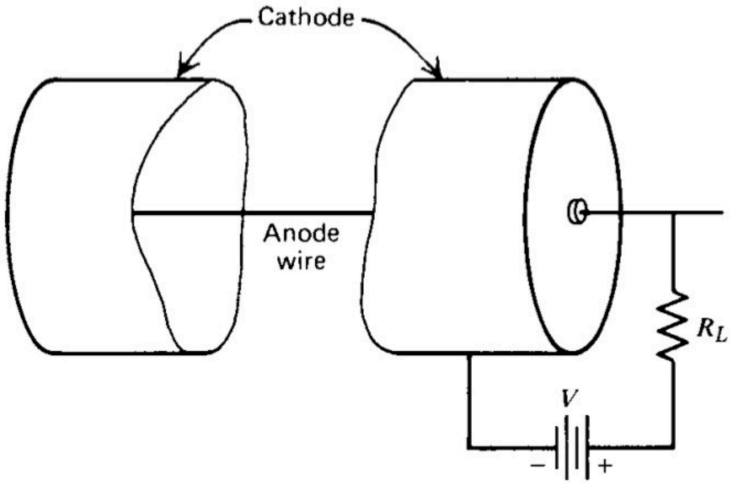
- As soon as the gas multiplication starts, a region of true proportionality is observed
- Increasing the applied voltage the slow ions produced in the avalanche generate a local field that counteracts $\mathscr{E}$, distorting its effect and determining a saturated proportionality
- When the field is higher than a certain threshold the signals created have all the same size independent on the original charge (Geiger region)

Choice of Geometry

- Typically cylindrical geometry.
- Voltage polarity is important!
- The electric field is give by:

$$\mathscr{E} = \frac{V}{r \ln(b/a)}$$

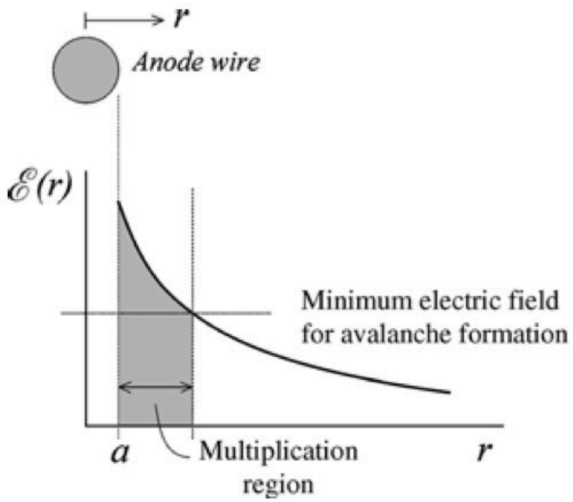
a: anode wire radius
b: cathode tube inner radius



Just for illustration lets take $V = 2000$ V, $a = 0.008$ cm and $b = 1.0$ cm:

- The value of $\mathscr{E}$ in this configuration at the anode surface is 5.18×10^6 V/cm
- A planar detector (uniform $\mathscr{E}$) would require a high voltage of 51,800 V, that is extremely impractical (if not impossible).

Choice of Geometry



- Multiplication confined to a very small volume for uniform multiplication (i.e. same for all primary e$^-$-ion pairs).
- The multiplication region begins at a distance x where $\mathscr{E}(x) > \mathscr{E}_{th}$ and extends to the anode surface.
- As above $V = 2000$ V, $a = 0.008$ cm and $b = 1.0$ cm, $\mathscr{E}_{th} = 10^6 \Longrightarrow$ $x = 0.041$ cm (0.17% of the detector volume).
- Delay time t b/w the ionisation point and signal generation:
- Drift velocity of $\nu = \mu \frac{\mathscr{E}}{p} = \frac{\mu V}{rp \ln(b/a)} \Longrightarrow$:

$$t = \int_a^r \frac{dr}{v} = \frac{p \ln(b/a)}{2\mu V} r^2 \qquad (11)$$

Note that the particle track is extended and thus the drift time may vary.

Gas multiplication Factor

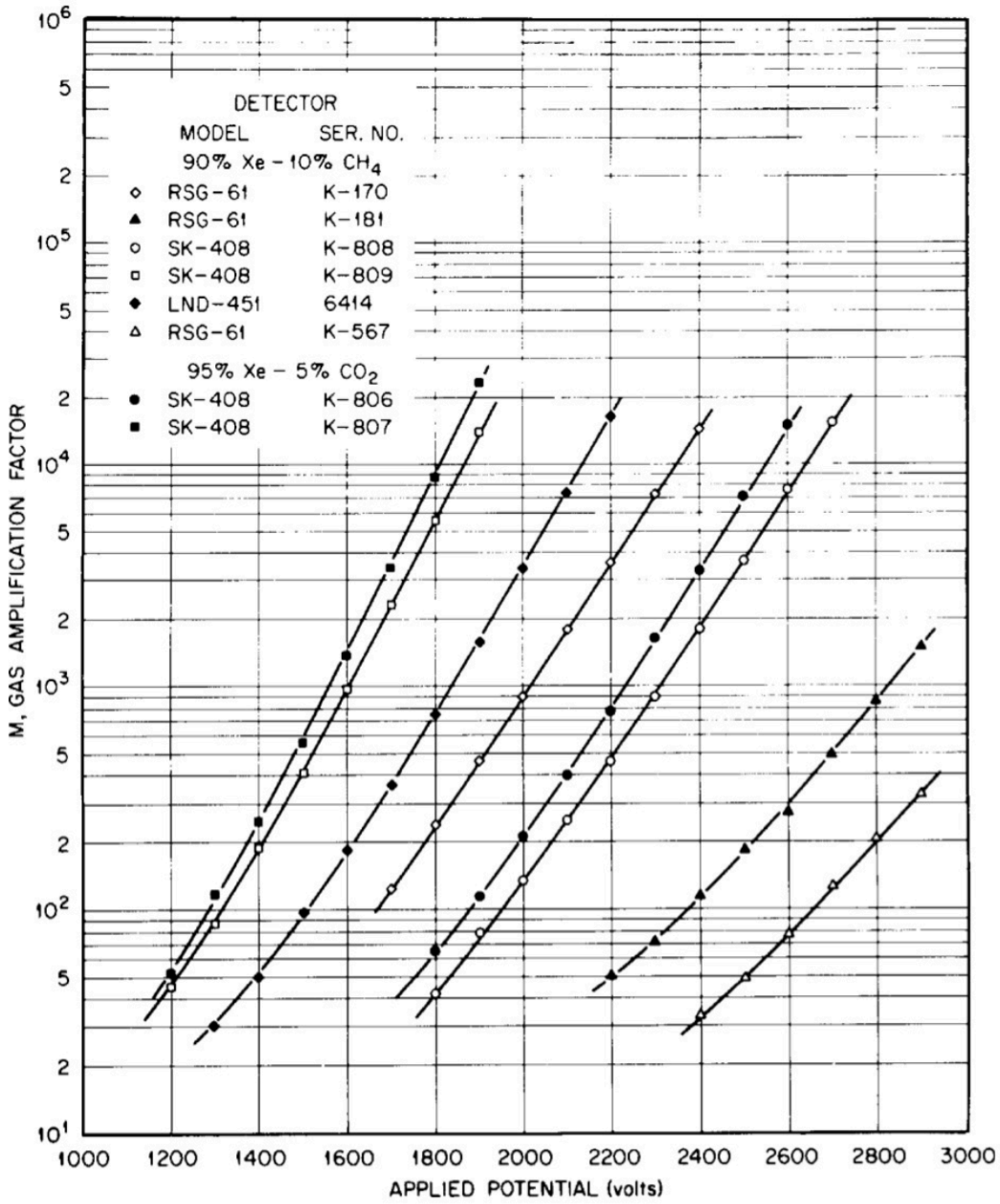
- The single-electron response is the charge generated by one free electron after charge multiplication.
- The single electron response (SER) can be measured quite effectively, especially when multiplication factors of the order of 10^5 are used
- Using the knowledge on SER, the charge generated by many original ion pairs can be estimated.
- The total charge Q generated by n_0 original ion pairs is: $\boxed{Q = n_0 e M}$ where M is the gas multiplication factor.
- Many attempt to determine analytically the multiplication factor; the most successful and widely used is by Diethorn who derived the following expression:

$$\ln M = \frac{V}{\ln(b/a)} \cdot \frac{\ln 2}{\Delta V} \cdot \left(\ln \frac{V}{pa \ln(b/a)} - \ln E_{th} \right) \qquad (12)$$

- Here a and b are the anode and cathode radii resp., V the applied voltage, p the pressure, ΔV the potential difference between successive ionising events and E_{th} is the minimum value of $\mathscr{E}/p$ above which the multiplication starts.

- The gas multiplication increases rapidly with increasing V and in many applications and gas mixtures M varies approximately as an exponential function of V.
- Proportional counters must therefore be operated with extremely stable voltage supplies.
- M is better measured than analytically described:
  - Take a X-ray source (E_γ)
  - $N_0 = \frac{E_\gamma}{W}$
  - The total measured charge is:

$$Q = eN_0M \rightarrow M = \frac{Q}{eN_0}$$



Space charge effects

- The electrons are collected quickly in the avalanche process. They leave many positive ions behind which are collected at a slower rate.
- The space charge represented by this positive charge can sometimes appreciably change the electric field in the counter.
- These effects can reduce the size of the pulses.
- Two types of space-charge effects:
  1. self-induced (related to a multiplication in a single pulse)
  2. general (high concentration of positive ions, e.g. high rates or at low gains)

Energy Resolution

- Let's try to analyse the statistics involved with proportional counters working principles in order to define the limits on the energy resolution. No non-linear effect is assumed
- Given A_i, electron multiplication factor for a specific avalanche triggered by a single electron, and M is the average multiplication factor due to n_0 avalanches:

$$M = \frac{1}{n_0} \sum_{i=1}^{n_0} A_i \equiv \overline{A} \tag{13}$$

- The charge Q collected in a pulse is $\boxed{Q = n_0 e M}$
- with an associated relative variance of:

$$\left(\frac{\sigma_Q}{Q}\right)^2 = \left(\frac{\sigma_{n_0}}{n_0}\right)^2 + \left(\frac{\sigma_M}{M}\right)^2 = \left(\frac{\sigma_{n_0}}{n_0}\right)^2 + \frac{1}{n_0}\left(\frac{\sigma_A}{\overline{A}}\right)^2 \tag{14}$$

- The different terms contributing to the variance in pulse amplitude can be analysed separately: $\longrightarrow$

Energy Resolution

- The variation in the number of ion pairs created is given by: $\left(\frac{\sigma_{n_0}}{n_0}\right)^2 = \frac{F}{n_0}$
- The variation in the single electron multiplication factor has been the topic of long and extensive theoretical and experimental investigations. For the purpose of our lectures it is enough say that there are two regimes:

  1. $\overline{A} \gtrsim 50 - 100$ the Furry distribution predicts: $\boxed{\left(\frac{\sigma_A}{\overline{A}}\right)^2 = 1}$

     Experimentally confirmed at these relatively low electric fields.

  2. $\overline{A} \gg 50$ most common regime of operation for PCs: $\boxed{\left(\frac{\sigma_A}{\overline{A}}\right)^2 = b}$

     Here b is a parameter dependent on the fraction of electrons that exceed the ionisation threshold and is usually in the range [0.4,0.7]

The variance:

$$\left(\frac{\sigma_Q}{Q}\right)^2 = \frac{F+b}{n_0}$$

The standard deviation:

$$\frac{\sigma_Q}{Q} = \sqrt{\frac{F+b}{n_0}} = \sqrt{\frac{W(F+b)}{E}} \qquad (15)$$

Energy Resolution

- For typical values of the parameters ($W = 35$ eV, $F = 0.20$ and $b = 0.61$) the energy resolution is found to be ~ 10 % at 10 keV and ~ 4 % at 100 keV of deposited energy.
- As shown in the previous equation the energy resolution scales with the inverse of the square root of the deposited energy.
- There are many factors which could deteriorate the energy resolution:
  1. The most critical of the geometric factors is the uniformity of the anode wire.
  2. Gas purity, gas pressure variations.
  3. Variations in the applied voltage.

Different anode uniformity

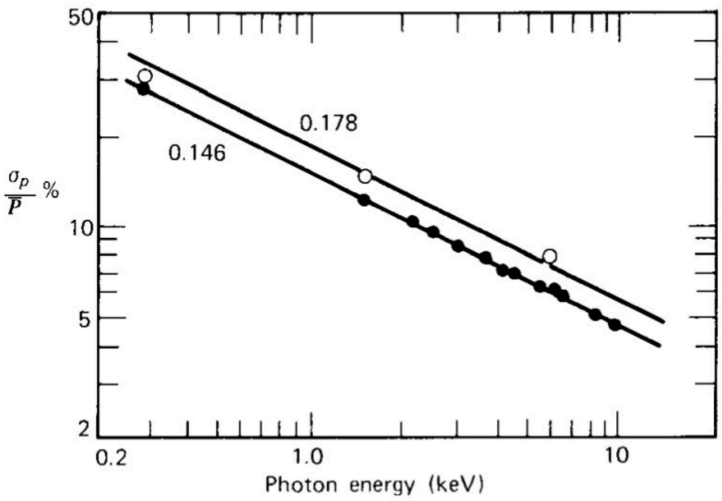


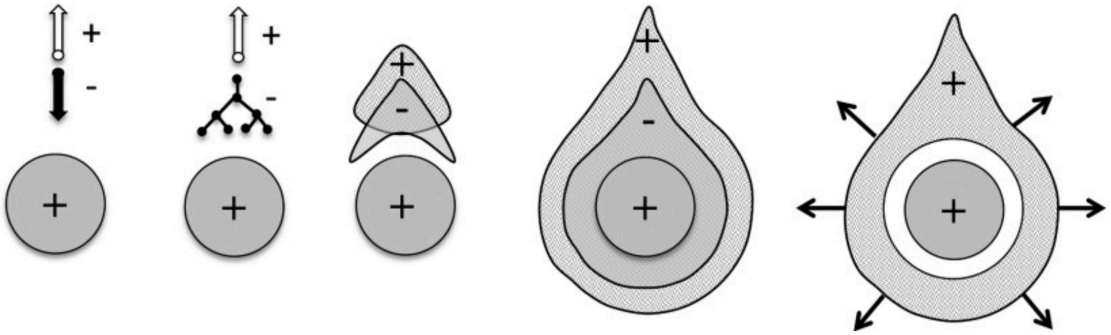
Table 6.3 Gain (Pulse Height) Variations in a Proportional Counter

Predictions of the Diethorn model for a P-10 filled proportional tube, $a = 0.03$ cm, $b = 1$ cm, $V = 1793$ V, $M = 1000$:

1% increase in	Change in M:
Applied voltage V	+17.4%
Gas pressure p	−8.6%
Anode radius a	−6.1%
Cathode radius b	−2.7%

Time development of the signal pulse

- The charge multiplication begins at a few anode wire radii, i.e. typically less than 50 μm from the anode surface.
- Assuming a value of 5 cm/μsec for the drift velocity of electrons in this high field region, it appears that the whole process of multiplication takes place in less than 1 ns.
- after this time, all electrons in the avalanche have been collected on the anode, and the positive ion sheath drifts towards the cathode at decreasing velocity



- The detected signal is the consequence of the change in energy of the system due to the movement of charges
- The bulk of the signal height is due to the drift of the positive ions since they have the highest potential energy.

- The simple electrostatic considerations discussed for the case of the Ion Chambers still hold but need to be extended to the current application.
- If a charge Q is moved by dr in a system of total capacitance C through a voltage difference $d\phi$, the work done by the field can be calculated as:

$$dE = -Qd\phi = Q\left(-\frac{d\phi}{dr}\right)dr = Q\mathscr{E}dr = Q\cdot\frac{V_0}{\ln(b/a)}\cdot\frac{1}{r}dr$$

- Assuming that all charges are produced at a distance ρ from the wire, the electron and ion contributions to the signal on the anode are, respectively:

$$E^- = -\frac{QV_0}{\ln(b/a)}\int_a^{a+\rho}\frac{1}{r}dr = \frac{QV_0}{\ln(b/a)}\cdot\ln\frac{a+\rho}{a} \tag{16}$$

$$E^+ = \frac{QV_0}{\ln(b/a)}\int_{a+\rho}^{b}\frac{1}{r}dr = \frac{QV_0}{\ln(b/a)}\cdot\ln\frac{b}{a+\rho} \tag{17}$$

- The total energy absorbed by the charge motion is therefore:

$$\Delta E = E^+ + E^- = \frac{QV_0}{\ln(b/a)}\cdot\ln\left(\frac{b}{a+\rho}\cdot\frac{a+\rho}{a}\right) = QV_0 \tag{18}$$

Time development of the signal pulse

- And the ratio between the two quantities is:

$$\frac{E^+}{E^-} = \frac{\ln(a+\rho) - \ln a}{\ln b - \ln(a+\rho)} \tag{19}$$

- Substituting in the previous expression typical values for a counter, $a = 10\mu$m, $\rho = 1\mu$m and $b = 10$ mm, one finds that the electron contribution to the signal is about 1% of the total; it is therefore, in general, neglected for most practical purposes.
- Based on energy conservation principle and in the approximation that $V_0 \simeq V$ we derive that

$$V_R = \frac{\Delta E}{CV_0} \simeq \frac{E^+}{CV_0} \tag{20}$$

- Let's see what is the time evolution of $E^+(t)$ and therefore of $V_R(t)$. First remember that:

$$E^+ = \frac{QV_0}{\ln(b/a)} \int_a^{r(t)} \frac{1}{r} dr = \frac{QV_0}{\ln(b/a)} \cdot \ln \frac{r(t)}{a} \longrightarrow$$

- The ion drift velocity is $\nu^+ = \frac{dr}{dt} = \mu \frac{\mathscr{E}}{p}$ from which, substituting the expression of $\mathscr{E}$ and integrating on both sides we get:

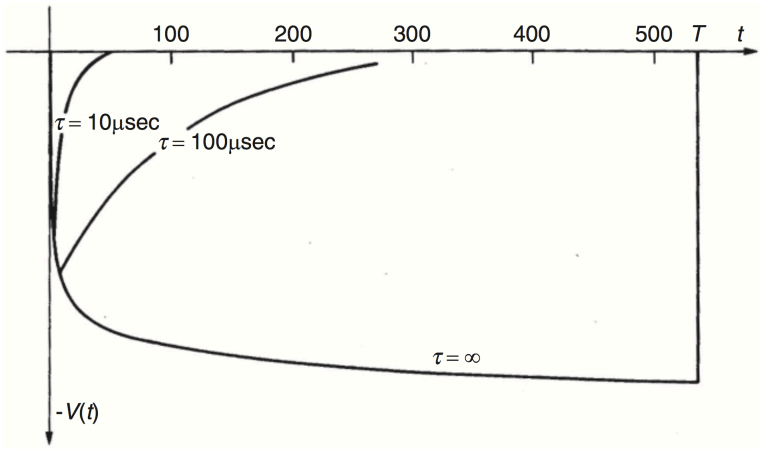
$$r(t) = \sqrt{2\frac{\mu}{p}\frac{V_0}{\ln(b/a)}t + a^2}$$

- Substituting this expression to V_R derived above we get:

$$V_R(t) = \frac{Q}{C}\frac{1}{\ln(b/a)}\ln\left(\frac{2\mu V_0}{a^2 p \ln(b/a)}t + 1\right)^{1/2} \qquad (21)$$

- The total drift time of the ions, t^+, is obtained from the condition $r(t^+) = b$.
- V_R reaches its maximum amplitude at t^+: $V_R(t+) = \frac{Q}{C}$
- Due to the high initial velocity of the ions in the field around the anode, the signal growth is very fast at short times: about one half of the signal develops in a fraction of time corresponding to the ratio of the anode to cathode radius:

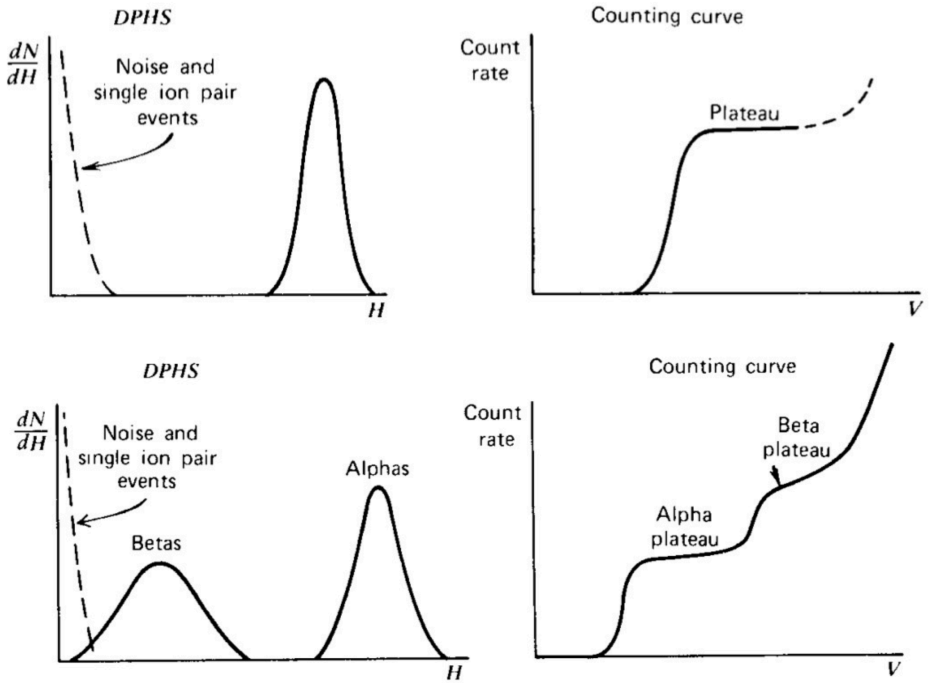
$$t\Big|_{\text{half amplitude}} = \frac{a}{a+b}t^+ \simeq \frac{a}{b}t^+$$



Detection Efficiency

Proportional counters can also be sensitive to single ion pairs, but they are normally not operated in such a mode because of the occurrence of unwanted non-linearity effects and of spurious background events.

- Lower values of the gas multiplication are normally used. Several primary ion pairs are then normally required to detect a pulse.
- A counting curve is usually recorded to select the appropriate voltage for the measurement to be carried out.
- As before, the HV is set within a "plateau" region, where the acceptance of the specific radiation is constant and maximal.
- By selecting a certain operating voltage a certain particle type can sometimes be separated/excluded from the measurement.



Geiger-Müller Counters

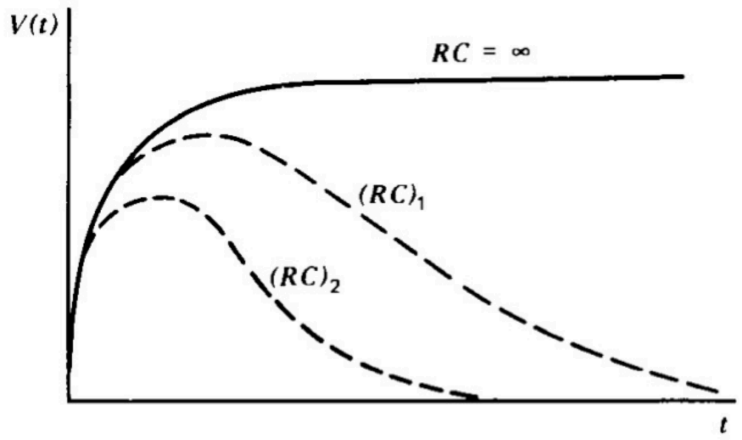
The Geiger-Müller Counter

- The Geiger-Müller Counter is one of the oldest radiation detectors and it still finds a very large use in many applications.
- It was invented by Geiger and Müller in 1928.
- It is another class of gas filled ionisation detectors. In common with proportional counters it has the fact that it is also based on gas multiplication.
- Increasing the electric field in a proportional counter leads to a high production of excitation and thus photons that can produce new electrons that initiate new avalanches and so forth and so on...
- The probability of photo-electron production becomes so high that the amount of secondary, tertiary... electron avalanches increases exponentially
- Consequently the signal is not anymore proportional to the initial amount of ionisation and all pulses have the same amplitude.
- The domain in which the liberated amount of charge does not depend on the primary ionisation is called the Geiger mode.
- Gains of the order of $10^8 - 10^{10}$ are achieved, making amplification unneeded.
- One of the main drawbacks of this detector is the large dead-time, larger than any other radiation detector.

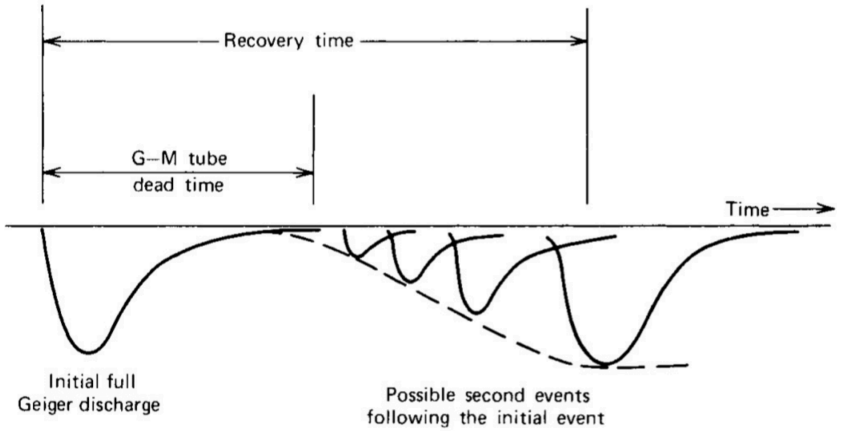
- The self-sustaining amplification of the GM needs to be interrupted. Such interruption usually comes almost automatically:
- The ions produced in the amplification are much slower than the electrons and therefore form a kind of a tube around the anode.
- When the electric field that such an extended charge produces becomes high enough to counteract the applied field between anode and cathode and the total electric field is below the critical value needed for the discharge, the pulse is over.
- The big amount of charged ions produced tend to neutralise at the cathode surface.
- The neutralisation process is accompanied by the emission of photons that can liberate new free electrons if certain conditions occur...
- This process has a very low probability to happen (that's why it's not a problem for PC). But given the high number of ions, the number of electrons produced by this process becomes sizeable.
- The newly produced electrons can now produce a new pulse.
- We need some process to "quench" the counter.
- The quenching can be achieved in two ways: $\longrightarrow$

1. external quenching:
   - adding a very high resistor in the external readout circuit ($\sim 10^8\Omega$). In this way the momentary anode voltage $U_0 - IR$ is smaller than the threshold value for the Geiger mode.
   - Together with the total capacitance C the time constant $\tau = RC$ has to be chosen in such a way that the voltage reduction persists until all positive ions have arrived at the cathode ($\sim$ ms).
   - Such long "dead times" strongly impair the rate capability of the counter.
2. internal quenching or self-quenching:
   - in this case a quench gas is admixed to the counting gas which is in most cases a noble gas.
   - These additions will absorb photons in the ultraviolet range (wavelength 100-200 nm) thereby reducing their range to a few wire radii ($\sim 100\mu$m).
   - Moreover the positive ions drifting in the direction of the cathode will collide on their way with quench-gas molecules, thereby becoming neutralised: e.g. $Ar^+ + CH_4 \rightarrow Ar + CH_4^+$
   - The molecule ions, however, have insufficient energy to liberate electrons from the cathode upon impact

- We have already derived the time variation of the signal pulse of a proportional counter and we showed that the pulse is in its majority coming from the positive ions moving away from the anode wire.
- An initial fast component (rise time $< 1\mu$s) comes from the motion of the ions in the high field region around the anode.
- A much slower rise follows that corresponds to the drift of the ions through the low field region.
- In a Geiger discharge the pulse corresponds to the cumulative of effect of many avalanches.
- Also the secondary, tertiary, ... electrons that produce further discharges produce some delayed avalanches, but in any case we do not expect a rise time much slower than a few μs.
- It is however complicated to derive a precise analytical form of the shape of the signal, given also the distortions caused by the ions space charge building up in the volume
- The net effect of all this is that the rise time of the signal of a GM tube usually exhibits a rise time of one μs or less followed by a slow rise due to slow ions.
- The time constant of the collection circuit is usually chosen to be in the order of a few up to a few tens of μs. In this way some fraction of the signal is discarded, but the pulse is still high enough that no amplification is needed.



- The presence of the slow positive ion space charge left after Geiger discharge termination also determines that a considerable amount of time must pass before a second Geiger discharge can be generated in the tube.
- As it migrates, the "ions tube" becomes less dense and the electric field slowly reestablishes.
- At some point $\mathscr{E}$ is high enough to start a new discharge, but it takes much less for the ions to quench the discharge because the ions from the previous discharge are still present.
- This gives rise to a smaller pulse than the standard one and may (or may not) be missed by our electronics.
- Only when the ions have eventually reached the cathode the $\mathscr{E}$ is fully restored and a new avalanche will take place at full amplitude.



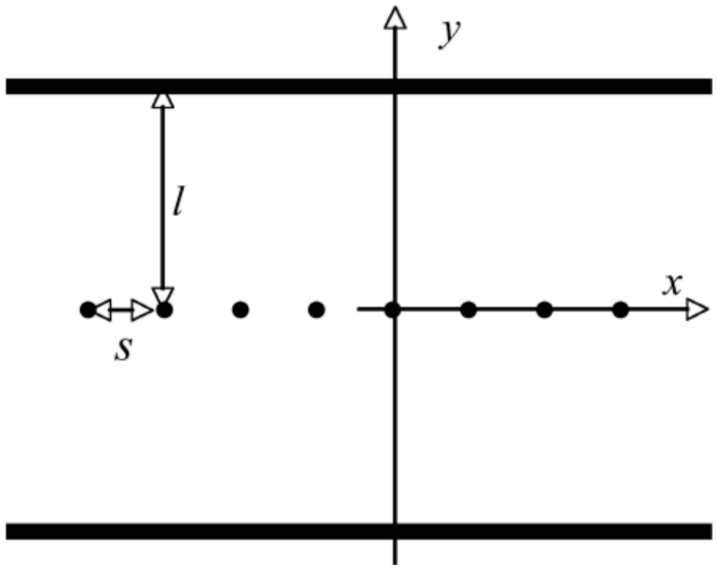
Multi Wire Proportional Chambers (MWPC)

Multi Wire Proportional Chambers

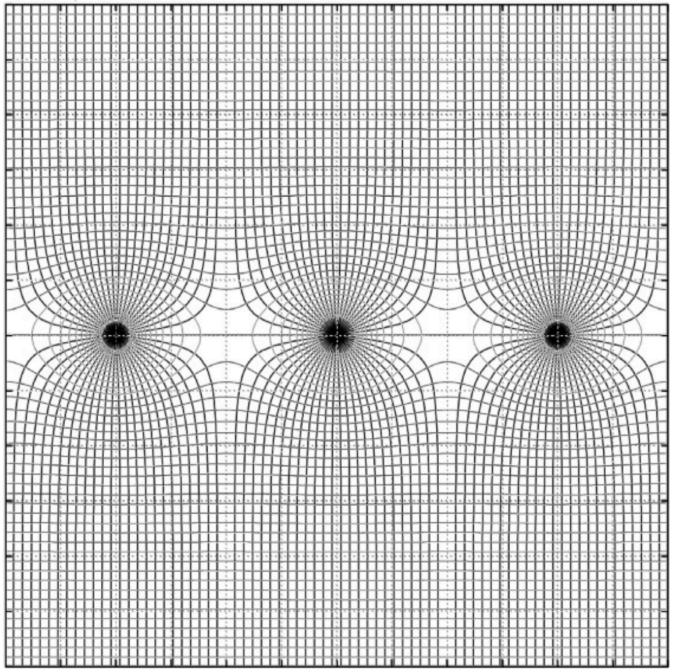
- Breakthrough application in particle physics
- Planar arrangement of proportional counters without separating walls
- G. Charpak et al. NIM 62 (1968) 202
- Nobel prize 1992, Rev. Mod. Phys. 65 (1993) 591

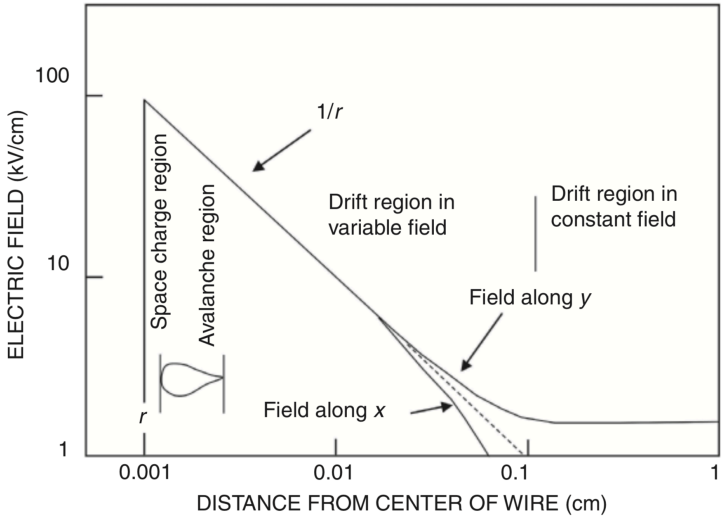
- Set of thin, parallel and equally spaced anode wires, symmetrically placed between two cathode planes (see Figure)
- Gas gaps are typically three or four times larger than the wire spacing:

  $s = 2$ mm
  $l = 7 - 8$ mm
  $a = 10 - 30\mu$m (anode radius)



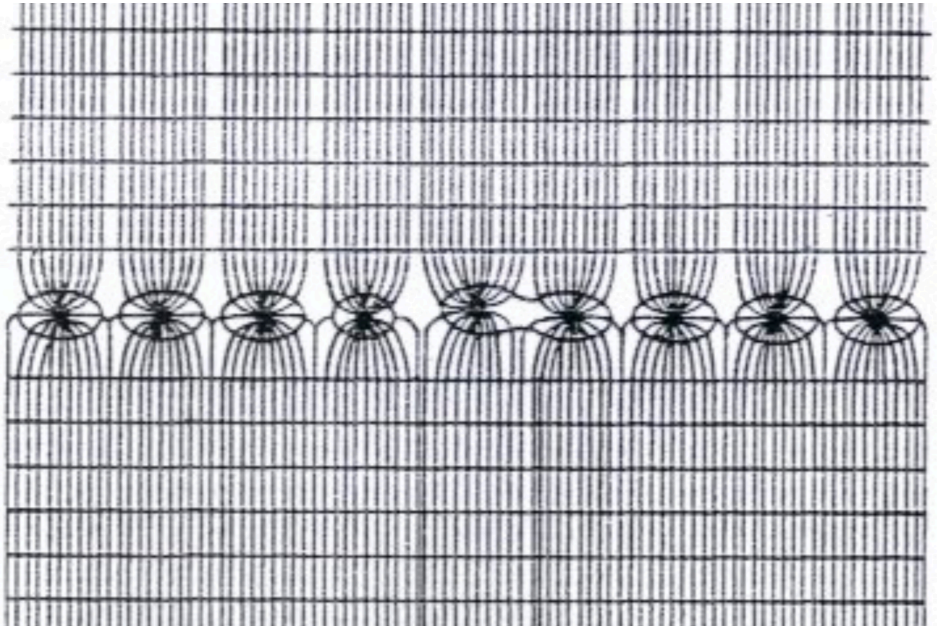
- Symmetric negative potentials applied to the cathodes, the anodes being grounded $\longrightarrow$ electric field as in Figure
- Electrons created by an ionising event drift along the field lines approaching the high field region, close to the anode wires, where avalanche multiplication can occur
- Every anode wire is read out separately $\rightarrow$ space information
- Achievable coordinate resolution: $\sigma = s/\sqrt{12} \sim 600\mu$m



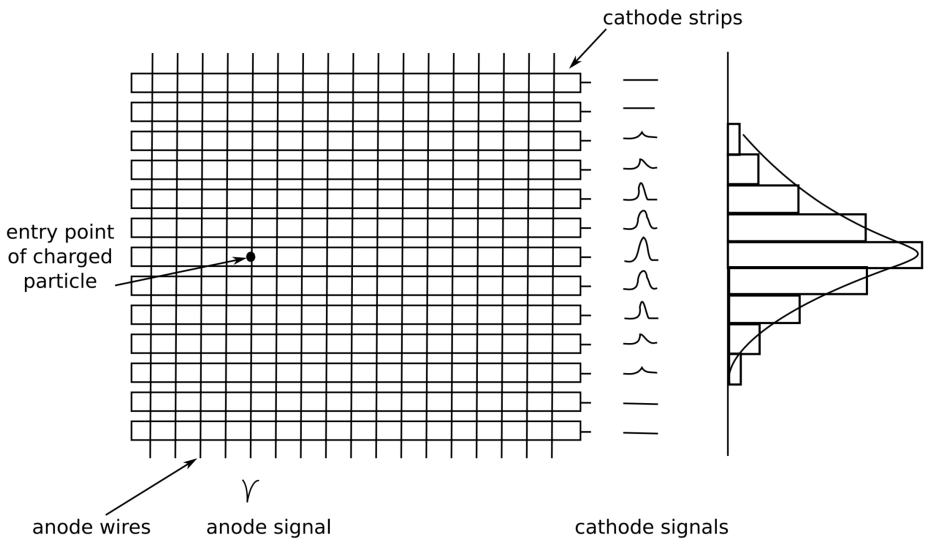


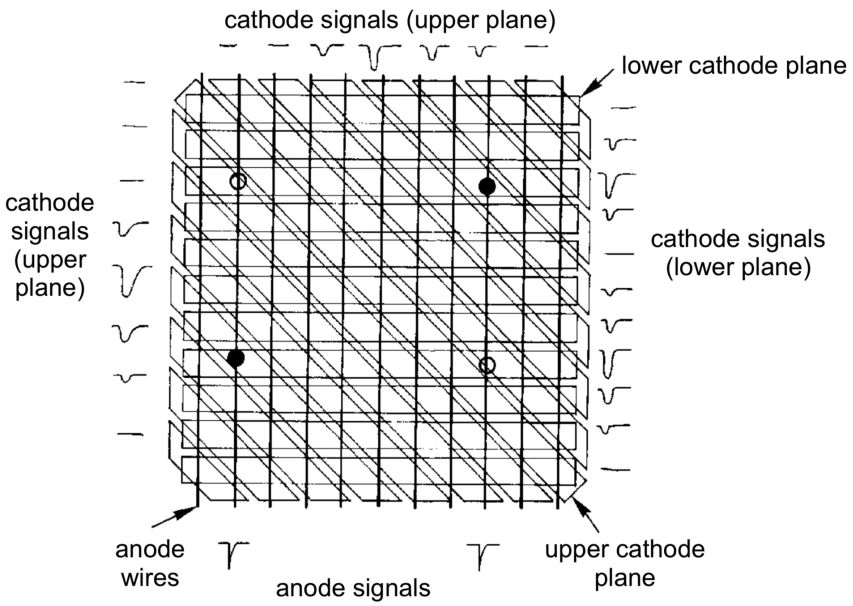
- Field lines and equipotential lines, Difficulty:

  even small geometric displacement of a single wire will affect field quality
- need of high mechanical precision, both for geometry and wire tension (electrostatic effects and gravitational wire sagging)
- The functionality of the MWPC can be significantly increased if induced signals on cathode are also recorded → second coordinate



- signal formation (as in proportional counters) is due to e^- and (mostly) slow ion-drift
- the center of gravity of signals on cathode strips can be determined with precision of $50 - 300\mu$m! Use charge sharing between adjacent strips
- Resolving ambiguities in case of 2 or more hits in one event: different orientation of segmentation in the two cathode planes



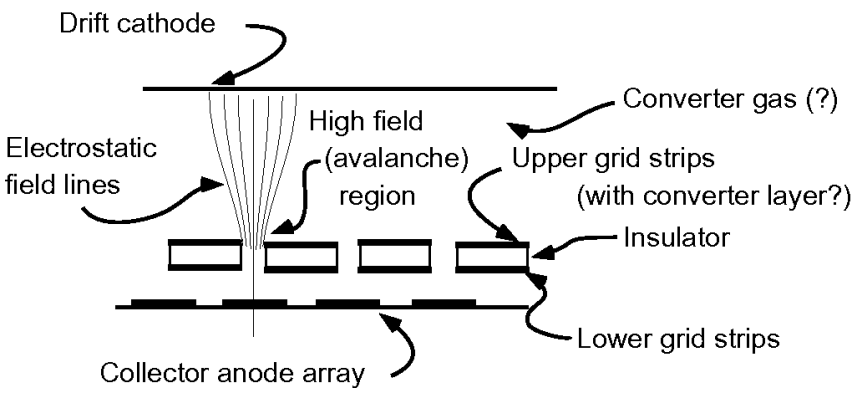


Micro-Pattern Gas Detectors - MPGD

Solution: introduce intermediate grid(s) to separate ions and gas amplification from the anode strips

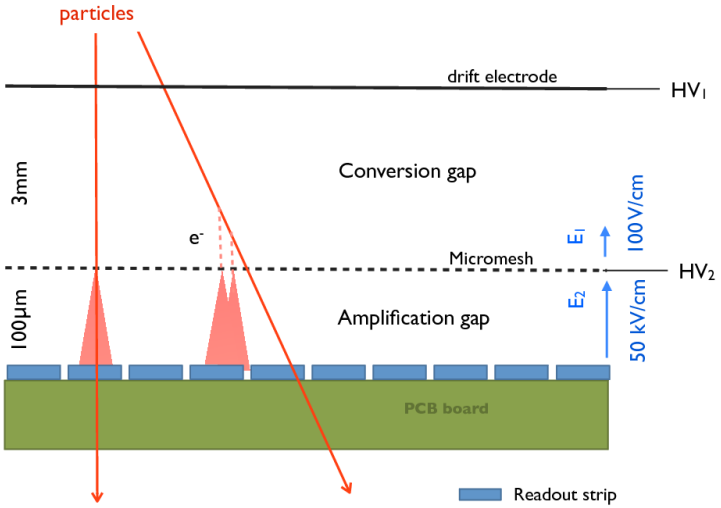
GEM (Gas Electron Multiplier) F. Sauli (CERN, 1997)

- Thin insulation foil, coated with a metal film and (100 – 200 μm) holes: electrons penetrate into the anode region (electric field at holes)
- Gas amplification in holes, separated from anode strips



Micromegas (Micromesh gaseous structure):

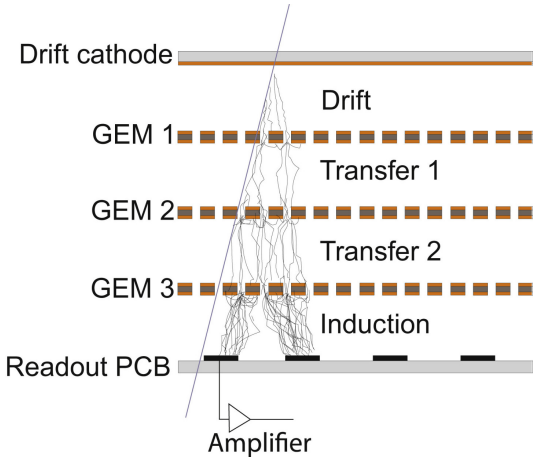
- micromesh (Frisch grid) to decouple drift region from a very short amplification region

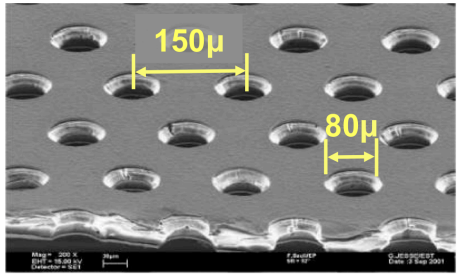


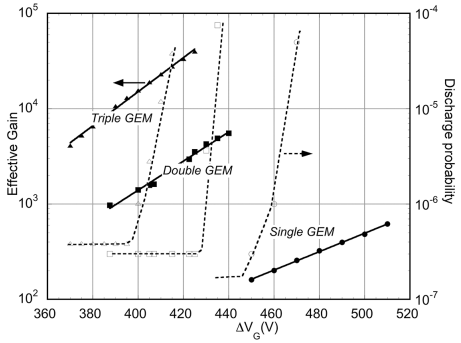
Micro-Pattern Gas Detectors - MPGD

Gas Electron Multiplier - GEM

- A two step gain reduces the spark probability
- Electrons are collected on anodes $\longrightarrow$ signal
- Positive Ions are partially collected on the GEM electrodes
- Double and Triple GEM detectors exist:
  - Large signals (Gain $10^4 - 10^5$)
  - Good spatial resolution ($\sigma \sim 60\ \mu$m)
  - Good rate capability (1 MHz / mm^2)
  - Radiation tolerant ($>$ 100 mC / mm^2) (corresponds to 1014 MIPs / cm^2)



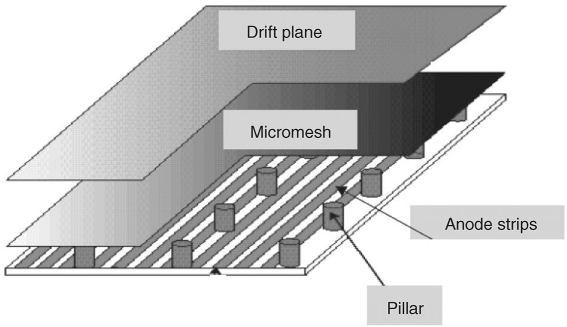


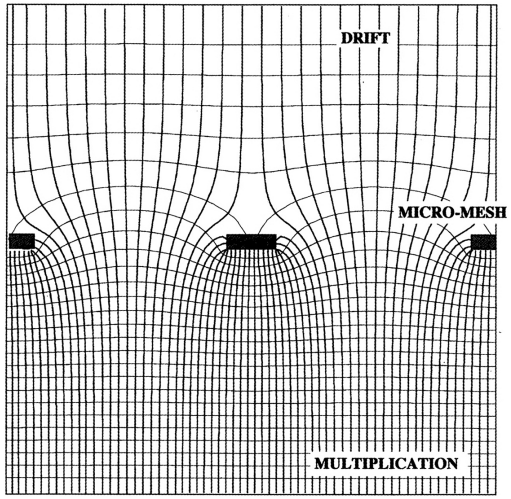


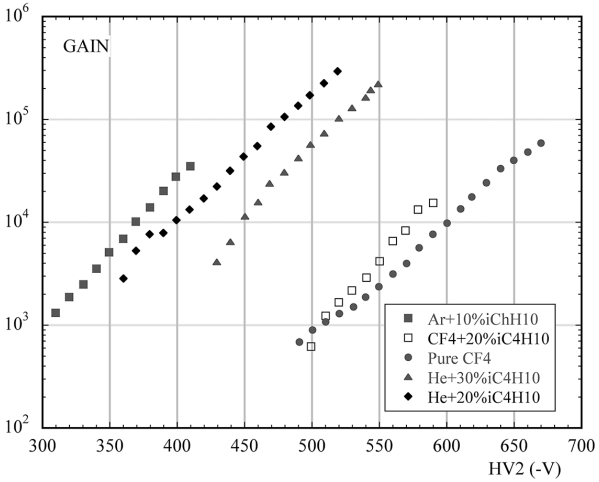
Micro-Pattern Gas Detectors - MPGD

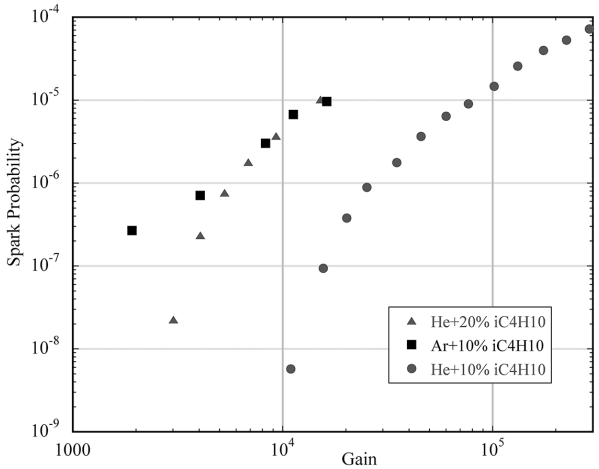
Micromegas

- Separate drift region from tiny amplification region by a micromesh
- Pillars for uniformity of the multiplying gap
- Saturation of the Townsend coefficient at high E-field → decreased sensitivity to gap variations and imperfections
- Sturdiness of the Micromegas electrodes prevents physical damages for repeated breakdowns
- But the recovery time of the voltage supply, typically of a few ms, introduces a dead time in the operation.







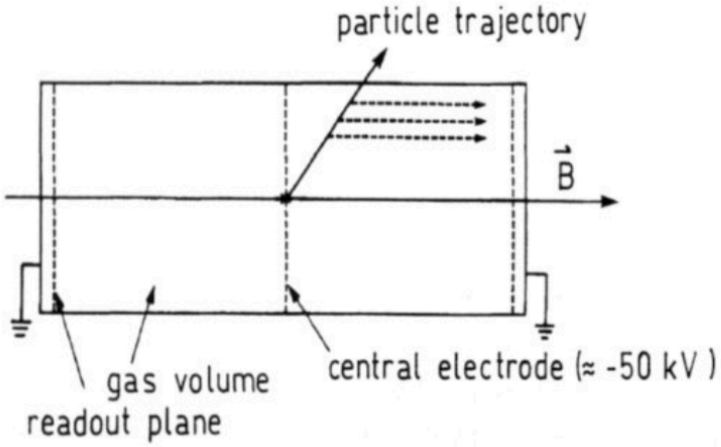


Time Projection Chambers

Time Projection Chambers (TPCs)

3-dimensional measurement of a track – 'electronic bubble chamber'
invented by D. Nygren in 1974 at Berkeley

(mostly) cylindrical detector
central HV cathode
MWPCs at the endcaps of the cylinder
electrons drift in homogenous electric fields towards MWPC, where arrival time and point and amount of charge are continuously sampled (flash ADC)
generally with $B \parallel E \rightarrow$ Lorentz angle $= 0$



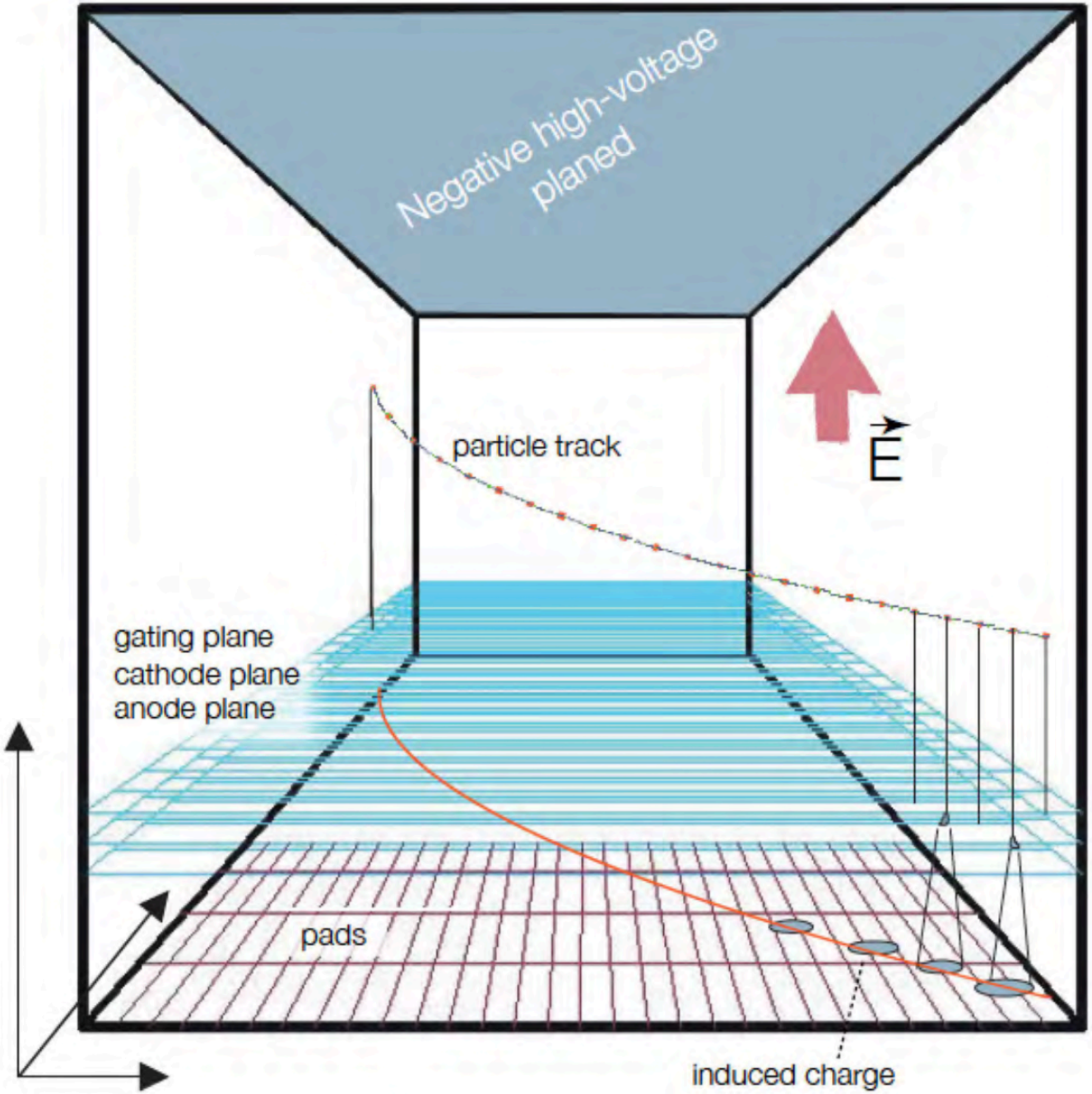
Working principle of a TPC

advantages:

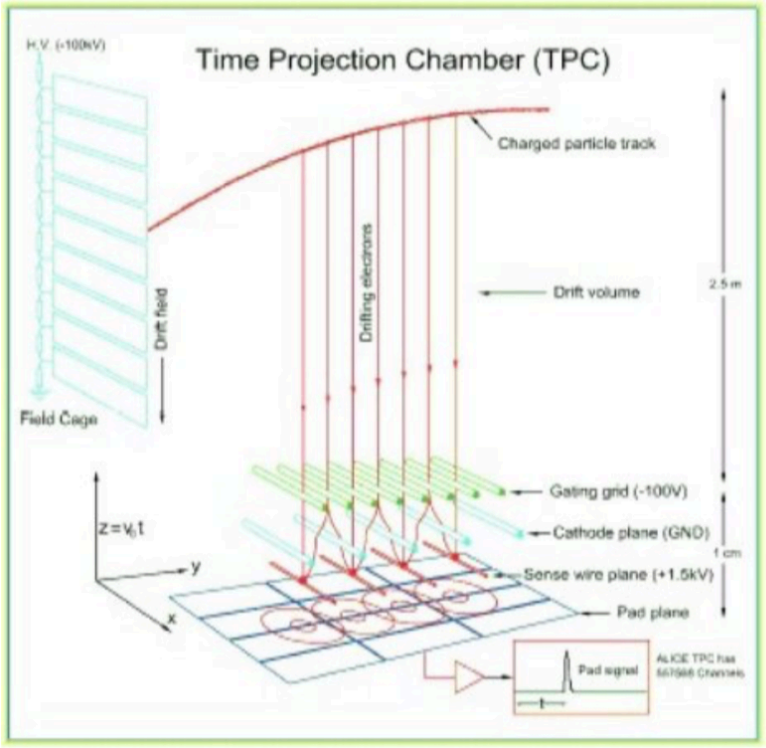
- complete track determination within one detector $\rightarrow$ good momentum measurement
- relatively few wires (mechanical advantage)
- since also charge is measured: particle identification via dE/dx
- drift parallel to $B \rightarrow$ transverse diffusion suppressed by factors $10 - 100$ (see above)

disadvantages

- drift time: relatively long - tens of microseconds $\rightarrow$ not a high rate detector
- large data volume


Negative high-voltage planed
particle track
$\vec{E}$
gating plane
cathode plane
anode plane
pads
induced charge

TPC - working principles



continuously sample induced charge or current signals in a MWPC at end of long drift path

z-dim given by drift time
x-dim given by charge sharing of cathode pads
y-dim given by wire/pad number

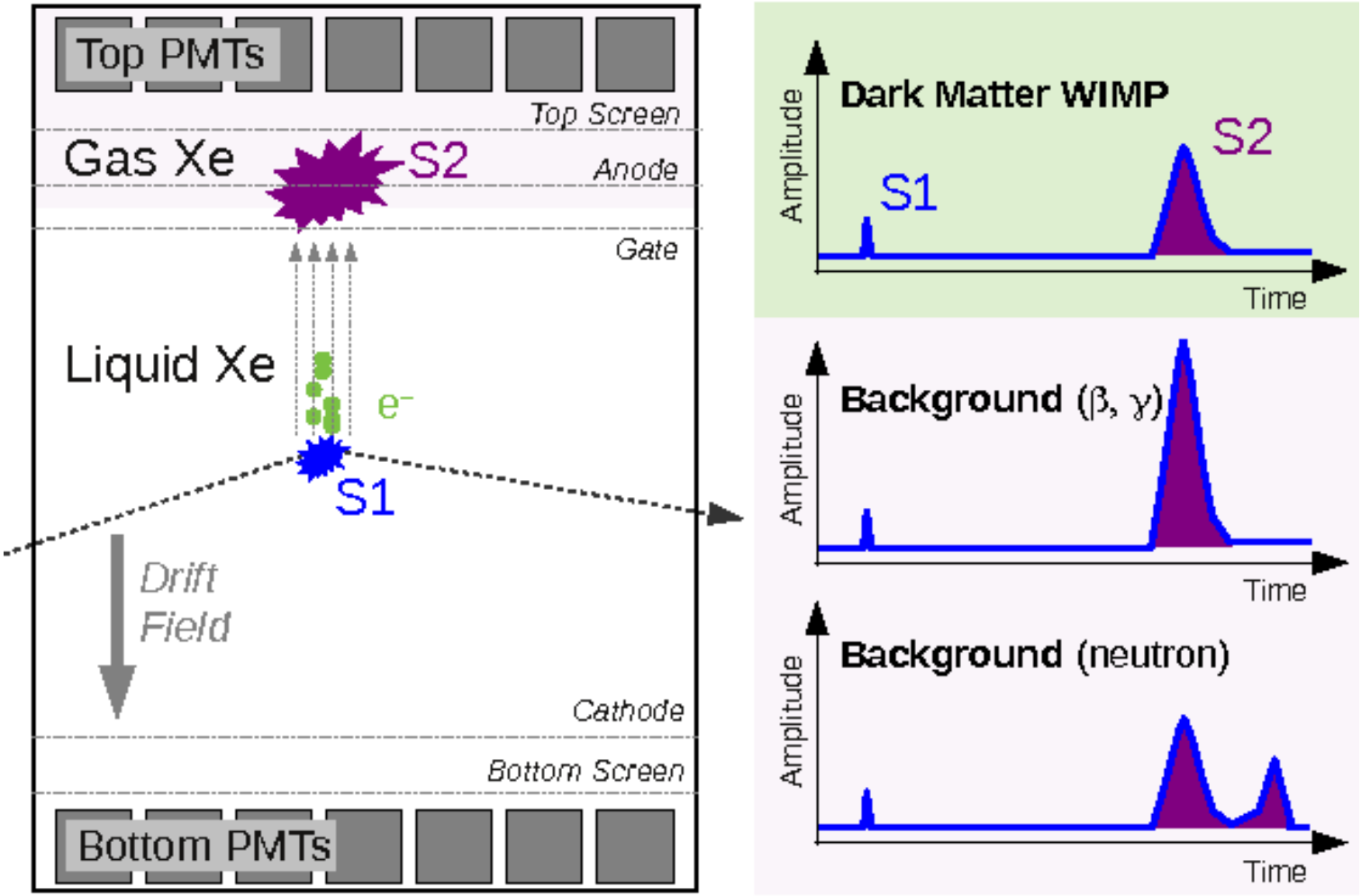
truly 3-dimensional measurement of ionization points of entire track and in fact of many tracks simultaneously

typical resolution:
z: mm
$r\phi$ or x: 150–300 μm
y: mm
dE/dx: $5-10\%$, trick:
kill Landau tail by evaluating truncated mean

challenges:

- long drift path (attachment, diffusion, baseline)
- large volume (precision)
- large voltages (discharges)
- extreme load in Pb+Pb collisions
  space charge in drift volume
  leads to distortion of $\vec{E}$
  gating grid opened (fast ~ 1 μs) for triggered events only, otherwise opaque ($\pm\Delta V$)

Dual-phase TPCs



Lecture Summary

1. Gas Detectors
   - Ionisation Chambers
   - Proportional Counters
   - Geiger-Müller Counters
   - Multi Wire Proportional Chambers (MWPC)
   - Micro-Pattern Gas Detectors - MPGD
   - Time Projection Chambers