Experimental Techniques for Nuclear and Particle Physics

Gaseous detectors

Ion chambers

Proportional counters

Geiger-Müller counters

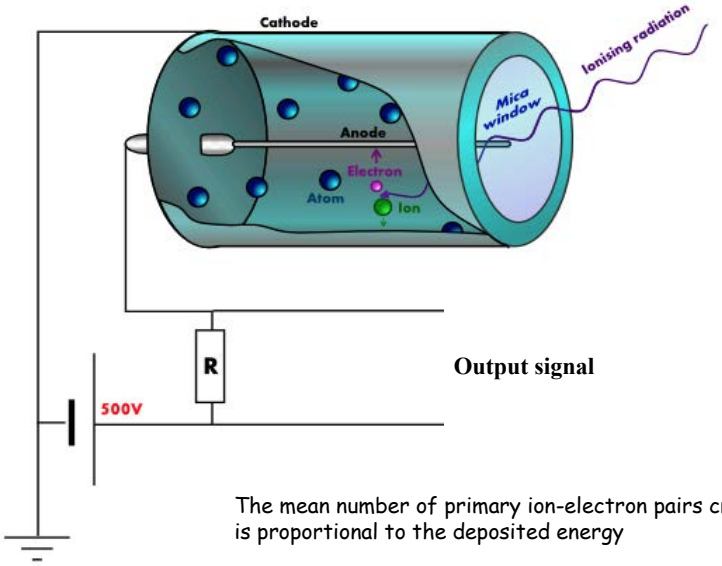
MWPC (multiwire proportional chamber)

Drift chambers

TPC (time projection chamber)

- Radiation loses energy to a gas by creating excited molecules, positive ions, and electrons or negative ions
- On average, about 30-35 eV of energy is lost per electron-ion pair created
- Without external electrical field charges would simply recombine
- With external electrical field the positive and negative charges drift in opposite directions, resulting in an electric current that can be measured externally

Basic configuration



The mean number of primary ion-electron pairs created is proportional to the deposited energy

Operational modes of gaseous detectors

I. Recombination region
Incomplete charge collection

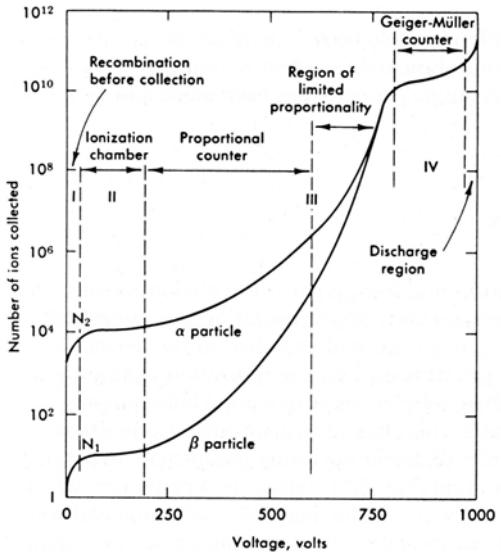
II. Ionization region
Complete primary charge collection, no multiplication or amplification
Collected charge proportional to energy, however small signal and typically used only for heavy charged particles or large fluxes of radiation

III. Proportional region
Electron energy > ionization energy → charge multiplication (secondary charge generation)
Large amplification (~10^6)
<~600V: Amplitude/ charge proportional to energy
>~600V: Region of limited proportionality due to space charge effects (positive ions reducing electrical field)

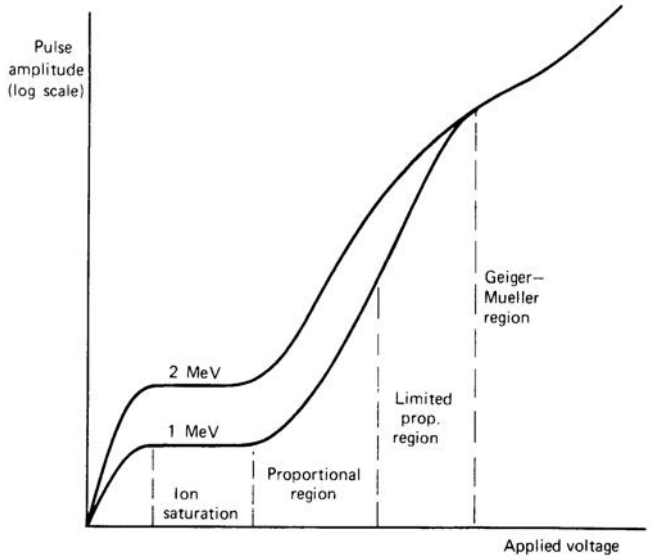
IV. Geiger Müller region
Secondary avalanches along anode wire, avalanches are created until space charge (ion charge) is sufficient to reduce electrical field and suppresses multiplication, independent of primary charge → no energy measurement possible! Only simple counter!

V. Discharge region
Continuous breakdown with or without radiation (to be avoided to prevent damage to the counter)

Total charge collected vs voltage



Energy response of gaseous detectors, ctd'



Pulse amplitude for events depositing two different amounts of energy within the gas

Choice of gases

Energy dissipated through
1) excitation
2) ionization

primary ionization

$X + p \rightarrow X^+ + p + e^-$

Penning Effect

$Ne^* + Ar \rightarrow Ne + Ar^+ + e^-$

molecular ion formation

$He^+ + He \rightarrow He_2^+$

Table 5.1 Values of the Energy Dissipation per Ion Pair (the *W*-Value) for Different Gases[a]

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

[a] Values for *W* from ICRU Report 31, "Average Energy Required to Produce an Ion Pair," International Commission on Radiation Units and Measurements, Washington, DC, 1979.

Gas mixtures

A problem with some fill gases is that ***photons can be created by gas de-excitation***.
- Gas multiplication is based on secondary ionization. In addition, collisions may occur where the gas molecule is raised to an excited state but not ionized, so secondary electrons are not created. There is no contribution of this molecule to the avalanche; it decays by ***photon emission***.
- The photons can create ionization elsewhere in the fill gas by interacting with less tightly bound electrons or interacting by the photoelectric effect in the counter wall.
- **In proportional counters this creates spurious pulses and/or loss of proportionality**. To reduce this effect ***Quench gases*** are added. These are polyatomic gases that will preferentially absorb the photons. Often this quench gas is methane.

The type of fill gas used is dependent on the function the counter is to perform. Commonly used gases for ***β measurements are the noble gases***. These often require a quench gas.
Cost dictates that argon is commonly used, usually as a mixture of 90% argon with 10% methane. This is called **P-10**.
For ***better γ-ray detection krypton or xenon*** can be used as fill gas.

Gas mixtures

The choice of a filling gas is governed by:

low working voltage

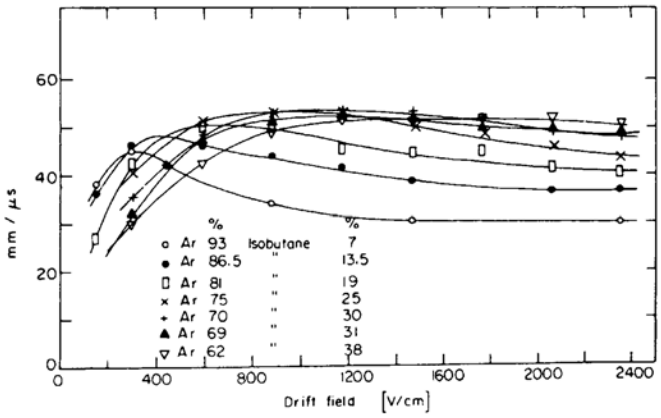
high gain

good proportionality

high rate capability

Ar: high specific ionization and low cost

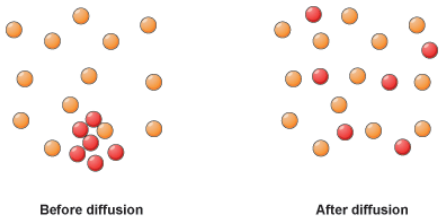
Electron drift velocity depends on the (quenching) gas mixture



Transport of electrons and ions in Gases

Mainly described by the classical kinetic theory of gases

Diffusion



Drift in an electric field

In the presence of an electric field, the electrons and ions freed by radiation are accelerated along the field lines towards the anode and cathode, respectively.

Transport of electrons and ions - diffusion

Diffusion ; thermal motion – collisions ~ 1mm/s

Thermal motion (Maxwell distribution) $v = \sqrt{\frac{8kT}{\pi m}}$

at room temp.:

$e^- \sim 10^6 cm/s, \quad ions \sim 10^4 cm/s$

charges diffusing for time t → Gaussian distribution

In one dimension: $\frac{dN}{dx} = \frac{N_0}{\sqrt{4\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right)$

spread in 1D and in 3D: $\sigma(x) = \sqrt{2Dt} \quad \sigma(r) = \sqrt{6Dt}$

diffusion coefficient $D = \frac{1}{3} v\lambda$

mean free path $\lambda = \frac{1}{\sqrt{2}} \frac{kT}{\sigma_0 p}$

Charge carrier drift velocities in an electric field

Drift: acceleration in E-field, collisions

The movement of ions and electrons is a superposition of thermal random walk and a drift along the electric field lines. For ions:

$$\bar{v} = \mu \frac{\bar{E}}{p}$$

Here μ is called the mobility and is typically ~ $1 \cdot 10^{-4}$ atm·m²/V
For electrons the mobility is typically around 1000 times larger and it is a function of the electric field.

Typical transit times for ions and electrons in a 1atm gas pressure across a 1 cm typical detector dimension are given in ms and μs, respectively.

For electrons there is also a saturation in the drift velocity for large field strengths.

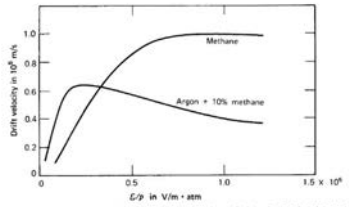
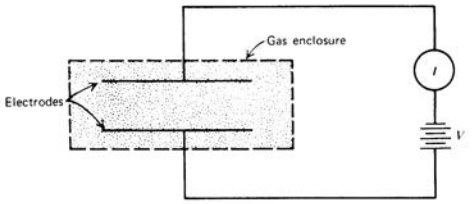


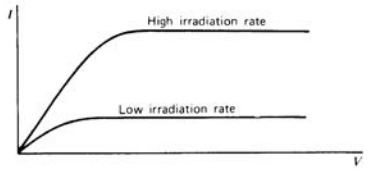
Figure 5.2 Electron drift velocity as a function of electric field $\mathscr{E}$ divided by gas pressure p. (Data from Bortner et al.[7])

Position resolution??

Ionisation chambers (Ion chambers)



At equilibrium the current flowing in the external circuit will be equal to the ionization current collected at the electrodes.

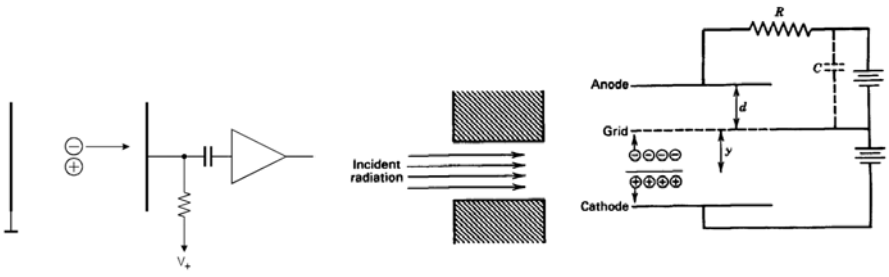


No amplification

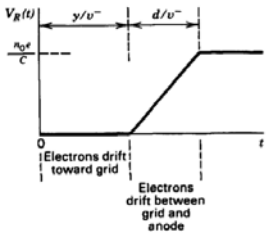
often used for dose measurements in high flux environments

Ionisation chambers (Ion chambers)

The dependence of the pulse amplitude on position of interaction in electron-sensitive ion chambers can be removed using a ***Frisch grid***



Signal on anode only generated by electrons that have passed the Frisch grid
All electrons appear at the same distance thus:
- ***no position dependence***
- ***recovery time shorter***

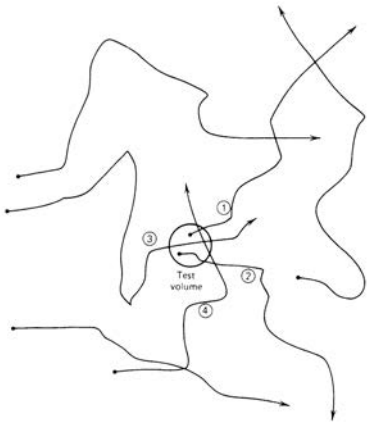


Compensation

Applications: ***gamma-ray exposure***
Exposure is defined in terms of the amount of ionization charge created in dry air.
(1R = amount of X-ray or γ-ray radiation whose associated secondary electrons create an ionization charge of 2.58×10^{-4} C/kg of dry air.

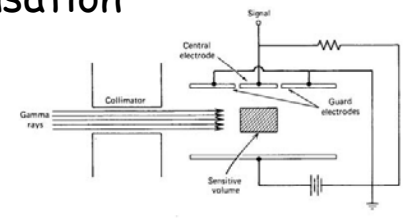
Range of a few 100 keV e- in air ≈ 1m!

If the surrounding region of the test volume is subject to the same exposure, all the charge created outside the volume from secondary electrons that were produced within the volume is balanced by charge created within the volume from secondary electrons formed in the surrounding air



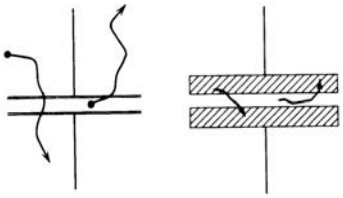
Compensation

Free-air ionization chamber
(gamma-ray energies below 100 keV)



Cavity chamber: small volume of air surrounded by a solid material (as similar as possible to air)

Secondary e^- yield
Rate of e^- energy loss/mass



Electronic equilibrium

Table 5.2 Thicknesses of Ionization Chamber Walls Required for Establishment of Electronic Equilibrium[a]

Photon Energy (MeV)	Thickness[b] (g/cm²)
0.02	0.0008
0.05	0.0042
0.1	0.014
0.2	0.044
0.5	0.17
1	0.43
2	0.96
5	2.5
10	4.9

Ordinary γ-ray energies ≈ 1 cm

Guard rings

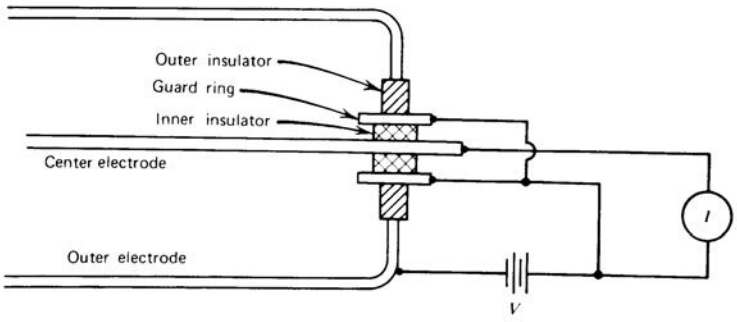


Figure 5.5 Cross-sectional view of one end of a cylindrical ion chamber that utilizes guard ring construction. Most of the applied voltage V appears across the outer insulator, for which the resulting leakage current does not contribute to the measured current I.

Exposure rate measurements using ionisation chambers

For an air-equivalent ion chamber, the exposure rate R in C/kg · s is simply given by the ratio of the saturated ion current I_s (in amperes) to the mass M (in kg) contained in the active volume:

$$R = \frac{I_s}{M} \tag{5.9}$$

The air mass M is normally calculated from a measurement of the chamber volume and the density at STP,

$$M = 1.293 \frac{\text{kg}}{\text{m}^3} \cdot V \cdot \frac{P}{P_0} \cdot \frac{T_0}{T} \tag{5.10}$$

where

V = chamber volume (in m^3)

P = air pressure within the chamber

P_0 = standard pressure (760 mm Hg, or 1.013×10^5 Pa)

T = air temperature within the chamber

T_0 = standard temperature (273.15 K)

In routine monitoring, exposure rates of the order of 10^{-3} roentgens/hour (7.167×10^{-11} C/kg · s) are of typical interest. For an ion chamber of 1000 cm^3 volume, the saturated ion current at standard temperature and pressure calculated from Eqs. (5.9) and (5.10) is 9.27×10^{-14} A. Because this signal current is very low, sensitive electrometers and careful chamber design are required to minimize leakage currents.

Simple derivation of pulse formation in ion chambers – planar geometry

The signal on an electrode produced by the flow of induced charges is described by using the Shockley-Ramo theorem

$$\nabla^2\Phi = \frac{\rho}{\varepsilon}; \qquad \overline{E} = -\nabla\Phi$$

The *weighting field* $\boldsymbol{E}_0$ *and weighting potential* Φ_0, with respect to an electrode ("contact") are introduced by setting its potential to 1 V and all others to 0 V.

The induced current and charge from a charge q moving inside the detector are then:

$i = q\bar{v}\cdot\overline{E}_0; \qquad \Delta Q = q\Delta\Phi_0$ (Change in induced charge between two points on the drift path)

Simplification: Ion chamber with parallel plate electrodes

No recombination
All pairs produced at the same position
Collecting time longer than both the ion and electrons collecting time
Small distance between the electrodes compared with the length of the electrodes

Simple derivation of pulse formation in ion chambers – planar geometry

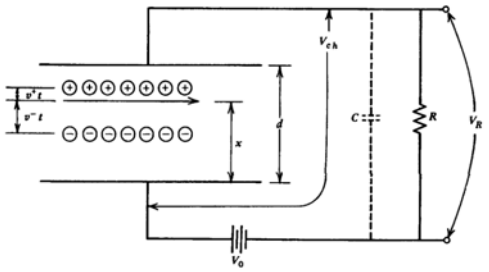
Energy conservation

original stored energy	=	energy absorbed by ions	+	energy absorbed by electrons	+	remaining stored energy
$\frac{1}{2}CV_0^2$	=	$n_0 e \mathscr{E} v^+ t$	+	$n_0 e \mathscr{E} v^- t$	+	$\frac{1}{2}CV_{ch}^2$

$$\tfrac{1}{2}C(V_0^2 - V_{ch}^2) = n_0 e \mathscr{E}(v^+ + v^-)t$$

$$\tfrac{1}{2}C(V_0 + V_{ch})(V_0 - V_{ch}) = n_0 e\left(\frac{V_{ch}}{d}\right)(v^+ + v^-)t \qquad (5.14)$$

Diagram of the derivation of the pulse shape $V_R(t)$ for an ionization chamber



Putting these substitutions in Eq. (5.14), we obtain

$$\tfrac{1}{2}C(2V_0)V_R = n_0 e\left(\frac{V_0}{d}\right)(v^+ + v^-)t$$

$$V_R = \frac{n_0 e}{dC}(v^+ + v^-)t \tag{5.15}$$

This result describes the initial portion of the signal pulse and predicts a linear rise with time. It is valid only for the period that both the ions and electrons are drifting within the chamber.

The concept of induced charge is sometimes used to describe the changes caused by the drifting charge carriers. By drifting a distance v^+t, the ions cause the chamber voltage to drop by an amount equal to $n_0 e v^+ t/dC$. The same effect would be caused by the reduction of the charge stored across the capacitance C by an amount $n_0 e v^+ t/d$. Therefore, the ion motion can be thought of as inducing a charge of this magnitude. A similar induced charge is created by the electron motion. It should be emphasized that the induced charge results only from the motion of the charge carriers within the chamber volume and does not require their collection at either electrode.

After a time $t^- \equiv x/v^-$, the electrons reach the anode. Their drift has then contributed the maximum possible to the signal voltage, and the second term in Eq. (5.15) becomes a constant equal to its value at t^-. This constant value is $n_0 e v^- t^-/dC$ or $n_0 e x/dC$. For the next period of time, only the ions are still drifting, and Eq. (5.15) takes the form

$$V_R = \frac{n_0 e}{dC}(v^+ t + x) \tag{5.16}$$

Simple derivation of pulse formation in ion chambers – planar geometry (ctd')

The ions reach the cathode after a time $t^+ \equiv (d - x)/v^+$. At this point, the signal voltage no longer increases, and Eq. (5.15) becomes

$$V_R = \frac{n_0 e}{dC}[(d - x) + x]$$

or

$$V_R = \frac{n_0 e}{C} \tag{5.17}$$

The shape of the signal pulse predicted by Eqs. (5.15), (5.16), and (5.17) is shown in Fig. 5.16. When the collection circuit time constant is very large, or $RC \gg t^+$, the maximum amplitude of the signal pulse is given by

$$V_{\max} = \frac{n_0 e}{C} \tag{5.18}$$

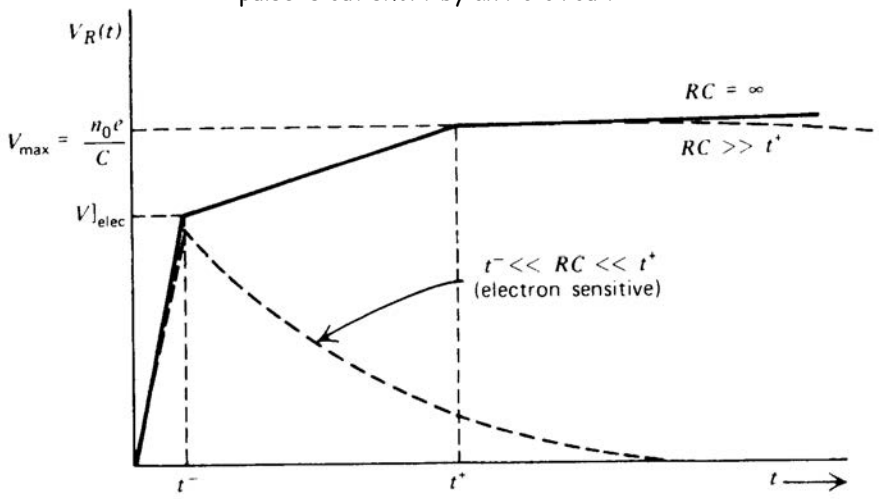
and is independent of the position at which the ion pairs were formed within the chamber. Under these conditions, a measurement of the pulse amplitude $V_{\max}$ gives a direct indication of the original number of ion pairs n_0 that contributed to the pulse.

In electron-sensitive operation, however, the portion of the pulse derived above that corresponds to drift of the ions is almost entirely lost by choosing a collection time constant that is much shorter than the ion collection time. The pulse that remains then reflects only the drift of the electrons and will have an amplitude given by Eq. (5.16) (neglecting ion drift)

$$V\big|_{\text{elec}} = \frac{n_0 e}{C} \cdot \frac{x}{d} \tag{5.19}$$

Signal formation, planar geometry, ctd'

pulse is cut short by an RC circuit



Output pulse shape $V_R(t)$ for various time constants RC

Signal formation – cylindrical geometry

Signal at the contacts is induced by the motion of electrons and ions in the detector volume (not by the collection of charges).

*E*lectric field and potential

$$E(r) = \frac{CV_0}{2\pi\varepsilon}\frac{1}{r} \qquad \phi(r) = -\frac{CV_0}{2\pi\varepsilon}\ln\left(\frac{r}{a}\right),$$

where a is the wire radius and capacitance per unit length $\frac{C}{l} = \frac{2\pi\varepsilon}{\ln(b/a)}$ with b the outer radius.

A charge q at r has the potential energy

$$W = q\phi(r), \quad dW = q\frac{d\phi(r)}{dr}dr$$

Energy contained in the field of the detector: $W = \frac{1}{2}lCV_0^2$

$$dW = lCV_0 dV = q\frac{d\phi(r)}{dr}dr \quad \Rightarrow \quad dV = \frac{q}{lCV_0}\frac{d\phi(r)}{dr}dr$$

integrating for e^- from a + r' to a and for ions from a + r' to b

$$V^- = -\frac{q}{2\pi\varepsilon l}\ln\left(\frac{a+r'}{a}\right) \qquad V^+ = -\frac{q}{2\pi\varepsilon l}\ln\left(\frac{b}{a+r'}\right)$$

Pulse amplitude

- Incident particle must transfer at least the ionization energy to generate an ion-electron pair.
- Since other mechanisms of energy loss exist (e.g. excitation) the average or mean energy for ion-electron pair creation (W-value) is always higher

	Excitation potential [eV]	Ionization potential [eV]	Mean energy for ion-electron pair creation [eV]
H_2	10.8	15.4	37
He	19.8	24.6	41
N_2	8.1	15.5	35
O_2	7.9	12.2	31
Ne	16.6	21.6	36
Ar	11.6	15.8	26
Kr	10.0	14.0	24
Xe	8.4	12.1	22
CO_2	10.0	13.7	33
CH_4		13.1	28
C_4H_{10}		10.8	23

Pulse amplitude -example

Maximum pulse amplitude:

$$V_{\max} = \frac{n_0 e}{C}$$

Example: A 1 MeV charged particle is stopped in an ion chamber:

$$n_0 = \frac{E}{W} = \frac{10^6 \text{eV}}{35 \text{ eV/ion pair}} = 2.9 \cdot 10^4$$

For a typical ion chamber the capacitance, $C = 100\text{pF}$

Then:

$$V_{\max} = \frac{2.9 \cdot 10^4 \cdot 1.602 \cdot 10^{-19}\text{C}}{100 \cdot 10^{-12}\text{F}} = 4.6 \cdot 10^{-5}\text{V}$$

Requires amplification!!!

Internal gas multiplication of the charge (later)

Energy resolution

- Fluctuations in mean number of ion pairs formed for incident particles of identical energy provide fundamental limit on the achievable energy resolution.

- In the simplest form, the formation of each ion pair can be considered a Poisson process (Poisson limit)

- However, the formation of each individual charge carrier is not independent leading to a deviation from this simple assumption (e.g. total energy from incident particle is fixed, other interaction mechanism and energy loss mechanism exist) → Fano factor

Fano factor

The Fano factor reflects the fraction of all incident particle energy that is converted into information carriers within the detector:
F=observed variance/Poisson variance

Extreme limits:

• Entire energy is converted into ion pairs only → no statistical fluctuations (F=0)!

• Only small fraction of energy is converted into ion pairs
→ Poisson distribution (F=1)!

Measured Fano factors

Ar 100%	$0.2^{+0.01}_{-0.02}$
	$<0.40 \pm 0.03$
Ar + 80% Xe	$<0.21 \pm 0.03$
Ar + 24% Xe	$<0.23 \pm 0.02$
Ar + 20% Xe	$<0.16 \pm 0.02$
Ar + 5% Xe	$<0.14 \pm 0.03$
Ar + 5% Kr	$<0.37 \pm 0.06$
Ar + 20% Kr	$<0.12 \pm 0.02$
Ar + 79% Kr	$<0.13 \pm 0.02$
Xe 100%	$<0.15 \pm 0.01$
	$<0.15 \pm 0.03$
Kr 100%	$<0.23 \pm 0.01$
	$<0.19 \pm 0.02$
Kr + 1.3% Xe	$<0.19 \pm 0.01$
Kr + 20% Xe	$<0.21 \pm 0.02$
Kr + 40% Xe	$<0.22 \pm 0.01$
Kr + 60% Xe	$<0.21 \pm 0.01$
Kr + 95% Xe	$<0.21 \pm 0.01$

Fano factor and energy resolution

Fano factor in gases: F ~ 0.2-0.4

Number of created ion pairs: N = E/W
$\sigma^2 = F \times N$ and $\sigma/N = \sqrt{(F/N)}$
$\Delta E = 2.35 \times W \times \sigma = 2.35 \times W \times \sqrt{(FN)} = 2.35 \times \sqrt{(FEW)}$
And $\boldsymbol{\Delta E/E = 2.35 \times \sqrt{(FW/E)}}$

Example:
An a-particle with E=5.5 MeV is fully stopped in Ar gas:
$N = E/W = 5.5 \times 10^6 eV / 26 eV/ion\ pair = 2.11 \times 10^5$ ion pairs

With F=0.2:
$\sigma^2 = FxE/W \rightarrow \sigma(N) = 205$ and $\sigma(E) = \sigma(N)xW =$
5.3 keV (in terms of particle energy) or $\sigma(E)/E = 0.1\%$ or 0.23% in terms of FWHM.

Such excellent energy resolution is usually not achieved due to electronic noise.

Avalanche Multiplication

Numbers of ion pairs produced are greatly amplified

After creation by radiation interaction, both electrons and ions make many collisions with neutral gas molecules until collected. When the electric field is strong enough, electrons get high kinetic energies between collisions and eventually can ionize neutral while ions have low mobility and they attain very little energy between collisions. The two electrons can then be accelerated and further ionizations can be caused. The process takes the form of a cascade (**Townsend avalanche**). The electric field must be stronger than the threshold.

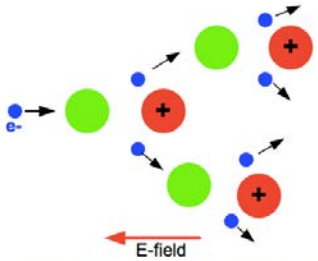


Fig. 3.8. Principle of multiplication process.

In typical gases, at atmospheric pressure, the threshold field is of the order or 10^6 V/m

Avalanche Multiplication

The fractional increase in the number of electrons per unit path length is governed by the **Townsend Equation:**

$$dN_e(x) = \alpha N_e(x)dx$$

where Ne(x) = number of electrons for the path length *x*. The constant α is called the first Townsend coefficient for the gas .

For a spatially constant field, such as parallel plates, α is a constant, which leads to:

$$N_e(x) = N_e(x=0)e^{\alpha x}$$

The number of e^- increases exponentially with distance.

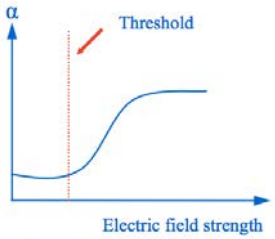


Fig. 3.9. Variation of α as a function of the electric field.

The total number of electrons can therefore be multiplied by a factor of thousands and this amplified signal at the anode is much easier to detect. The charge pulse has a much better signal to noise ratio and this reduces the requirements on external amplifiers.

Avalanche multiplication

if electrons accelerate between collisions
to sufficient energy for ionization

mean free path for a secondary ionizing collision λ

probability for ionization / length

$\alpha = 1/\lambda$ (Townsend coefficient)

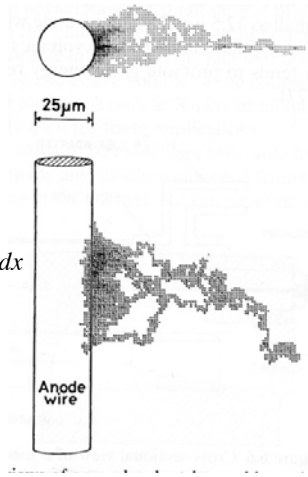
increase in number of electrons per unit path length: $dn = n\alpha dx$

total electron yield over path *x*

$n = n_0 \exp(\alpha x)$

multiplication $M = n(x)/n_0 = \exp(\alpha x)$

limited by $\sim M < 10^8, \quad \alpha x < 20$



The proper geometry for the electric field should be chosen!!!!
Planar detector with parallel electrodes:
Electric field uniform and perpendicular to the plates. Therefore for events having the same energy, the signal amplitude will vary with position and the relation between signal and energy is lost.

Cylindrical Proportional counter

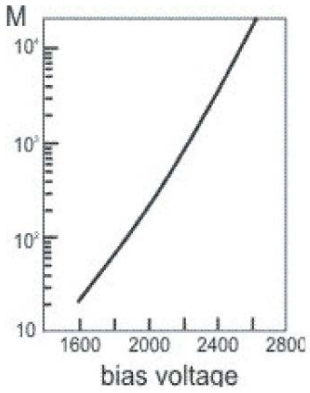
Avalanche multiplication, ctd'

- Usually, the field is not strong enough in most of the detector volume. Charges are collected from there without multiplication.
- The **avalanche** occurs close (some um) to the anode resulting in amplification just before electron collection.

Electrical field to create avalanche:

– E=dV/dr=W/λ
– With W~25 eV and λ~5 μm:
• Critical field strength: E_c~50kV/cm
• Critical radius r_c~30μm
• Critical volume Vc/Vtotal~10^{-6}
• Critical voltage difference: ~25V

M depends strongly on electric field



Fill gas and quenching

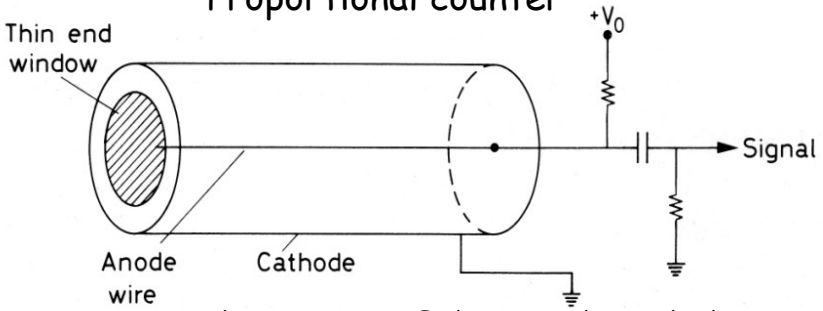
Requirements:

– Low working voltage → noble gases (e.g. Ar –"cheap")

– High gain – Noble gas limit to 10^3 before continuous discharge occurs (due to photons capable of ionizing the cathode and causing further avalanches) → Use of polyatomic gases as quencher (e.g. Methane)

• Quenching gas absorbs photons and dissipates energy through dissociation and elastic collisions.
P10 gas (mixture of 90% Ar and 10% Methane (CH_4)) mostly used and gains of up to 10^6 have been observed!

Proportional counter



• Operation in proportional region due to Townsend avalanches:
– Electrons are sufficiently accelerated between collisions by high electrical field to ionize additional atoms
• Cylindrical geometry to achieve high electrical field

- Each primary electron leads to an avalanche independently of all other avalanches
– Since all avalanches are nearly identical, the collected charge remains proportional to the number of original electrons

$$E(r) = \frac{V_0}{\ln(b/a)}\frac{1}{r} \qquad \phi(r) = -\frac{V_0}{\ln(b/a)}\ln\left(\frac{r}{a}\right)$$

where a is the wire radius and b the cathode inner radius

Signal formation in case of multiplication (cylindrical geometry)

In case of avalanche amplification, charges start very close to the anode wire resulting in a signal dominated by the motion of ions.

For motion of ions from the vicinity of the anode to the cathode:

Time development of the pulse given by integration over r(t)

$$V(t) = \int_{r(0)}^{r(t)} \frac{dV}{dr}dr = -\frac{q}{2\pi\varepsilon l}\ln\frac{r(t)}{a}$$

What is $r(t)$?

Using charge mobility

$$\frac{dr}{dt} = \mu E(r) = \frac{\mu V_0}{\ln(b/a)}\frac{1}{r} \quad \left\{= \frac{\mu C V_0}{2\pi\varepsilon}\frac{1}{r}\right\} \qquad rdr = \frac{\mu V_0}{\ln(b/a)}dt \quad \left\{= \frac{\mu C V_0}{2\pi\varepsilon}dt\right\}$$

integrating from r(0) = a to r(t) $\quad r(t) = \left(a^2 + \frac{\mu C V_0}{\pi\varepsilon}t\right)^{1/2}$

$$V(t) = -\frac{q}{4\pi\varepsilon l}\ln\left(1 + \frac{\mu C V_0}{\pi\varepsilon a^2}t\right) = -\frac{q}{4\pi\varepsilon l}\ln\left(1 + \frac{t}{t_0}\right)$$

where $t_0 = a^2\pi\varepsilon / \mu C V_0$

Total drift time $\quad T = \frac{t_0}{a^2}\left(b^2 - a^2\right)$

Proportional counters – typical energy resolution

The avalanche statistics should be accounted for (b) and will dominate the pulse amplitude variance. The fluctuations in the number of pairs are a small contributing factor.

Table 6.2 Resolution-Related Constants for Proportional Gases

Gas	W (eV/ion pair)	Fano Factor F Calculated[a]	Fano Factor F Measured	Multiplication Variance b	Energy Resolution at 5.9 keV Calculated[b]	Energy Resolution at 5.9 keV Measured
Ne	36.2	0.17		0.45	14.5%	
Ar	26.2	0.17		0.50	12.8%	
Xe	21.5		≤ 0.17			
Ne + 0.5% Ar	25.3	0.05		0.38	10.1%	11.6%
Ar + 0.5% C_2H_2	20.3	0.075	≤ 0.09	0.43	9.8%	12.2%
Ar + 0.8% CH_4	26.0	0.17	≤ 0.19			
Ar + 10% CH_4	26[c]			0.50	12.8%	13.2%

[a]From Alkhazov et al.[20]

[b]Given by $2.35[W(F + b)/5900\ \text{eV}]^{1/2}$ [see Eq. (6.22)].

[c]From Wolff.[50]

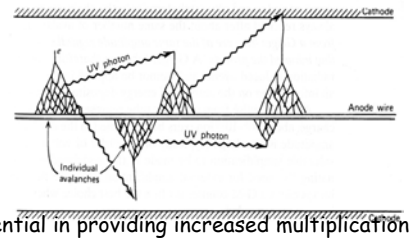
Source: Adapted from Sipila.[57]

The Geiger-Müller Counter

G-M counter – Increased electric field, otherwise similar to proportional counter

• High gas amplification with many avalanches created until space charge effects reduce effective field and terminate the chain reaction.

• Since this stage is always reached, independent of original number of ion pairs the same amplitude is observed independent of incident energy



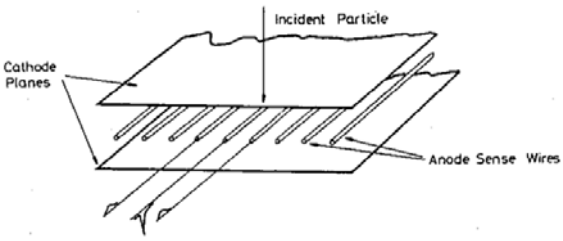
• Photons emitted from excited molecules are essential in providing increased multiplication and spread along the entire length of the wire

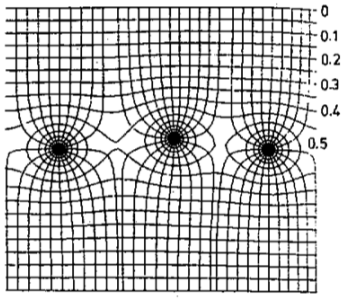
• Buildup of slow moving positive ions close to the anode wire reduces field eventually to below critical strength terminating the Geiger discharge

Multi-wire proportional counter (MWPC)

Tracking detector -> Determination of particle trajectories

Plane of equally spaced anode wires centered between two cathode planes

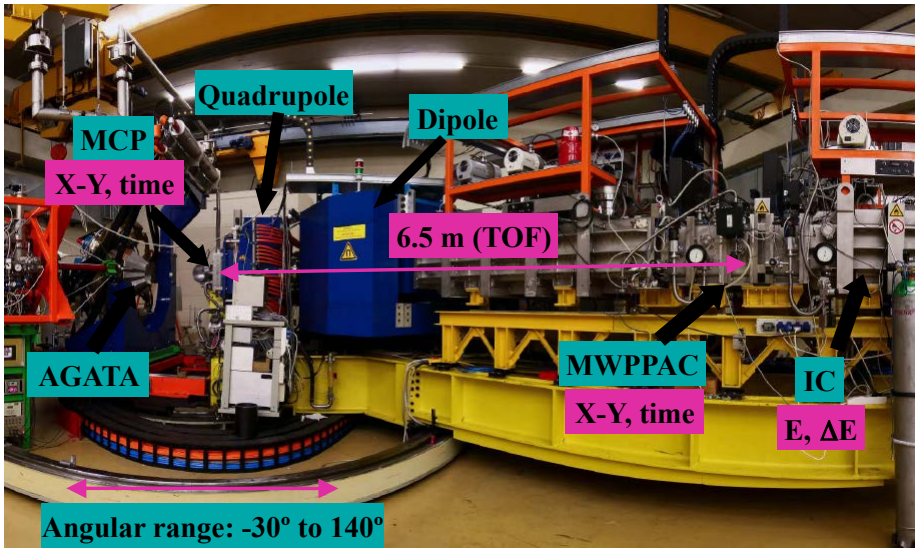




can achieve 1D position sensitivity
- charge distribution over anode wires
- induced signals distribution on segmented cathode signals

XY-MWPC: 2D position sensitivity / Multiple track resolution

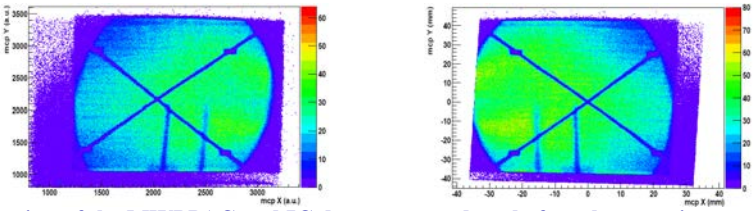
Example: Experimental setup α Laboratori Nazionali di Legnaro (Italy)



PRISMA spectrometer data analysis

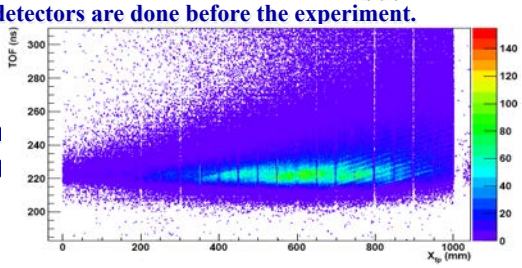
MCP detector:

Exact ion positions in X (theta) and Y (phi) directions (trajectory reconstruction)
Angle between the ion and its emitted gamma ray (Doppler correction)
Time signal as START for TOF measurement (velocity determination Dopp. correction)



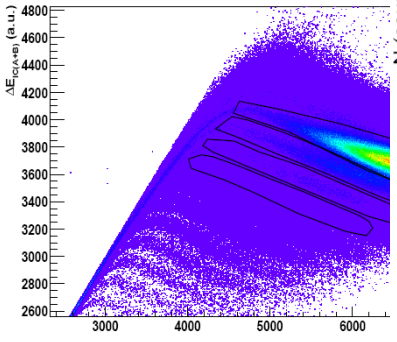
Calibration of the MWPPAC and IC detectors are done before the experiment.

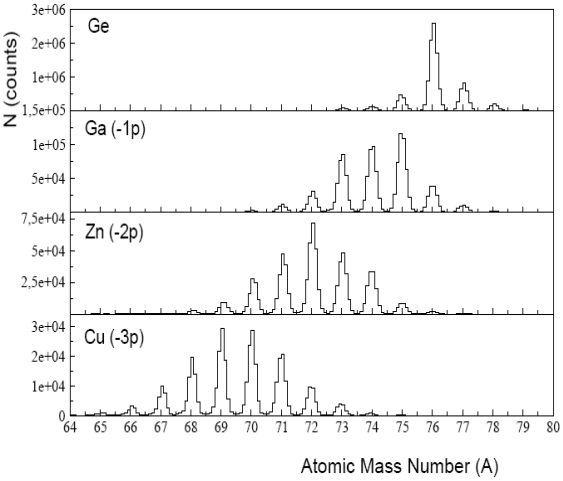
TOF: Ion flight-time between MCP (START) and MWPPAC (STOP) detectors



PRISMA spectrometer data analysis

Z identification





Charge state determination and selection

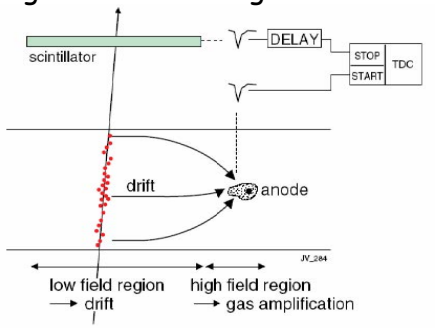
Mass separation (all distances together)

Drift chambers

Spatial information can be also obtained by measuring the drift time of the electrons coming from an ionizing event

$$X = \int_{t_0}^{t_1} v\,dt$$

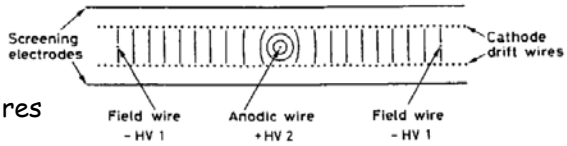
t_0: arrival time of the particle
t_1: time at which the pulse appears



Same structure as for a MWPC can be used with a larger wire spacing

Electric field not homogeneous!

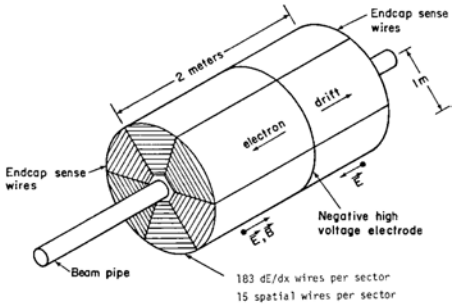
Solution: additional field wires

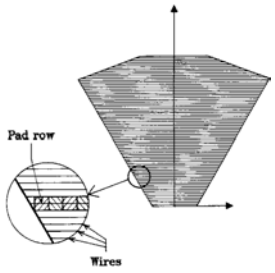


Time projection chamber (TPC)

Three dimensional tracking detector capable of providing information on many points of a particle track along with information on the specific energy loss (dE/dx) of the particle.

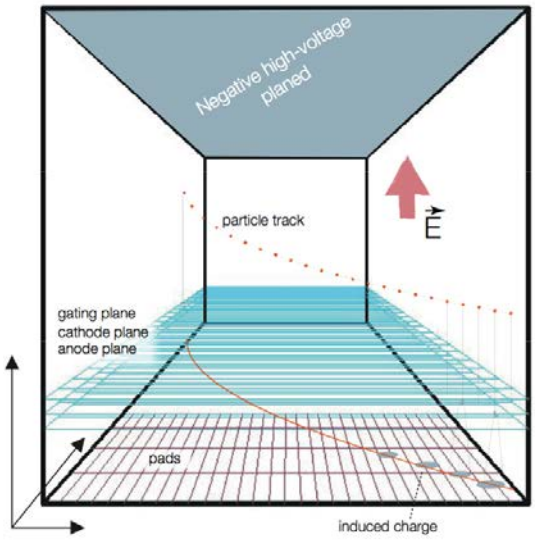
Based on MWPC and drift chamber





Long drift distance (≈ m), to avoid diffusion -> Magnetic field

Time projection chamber (TPC)



Advantages:

Complete track within one detector yields good momentum resolution

Relative few, short wires (MWPC only)

Good particle ID via dE/dx

Drift parallel to B suppresses transverse diffusion by factors 10 to 100

Challenges:

Long drift time; limited rate capability [attachment, diffusion ...]

Large volume [precision]

Large voltages [discharges]

Large data volume ...

Extreme load at high luminosity; gating grid opened for triggered events only ...

Typical resolution:

z: mm; x: 150 - 300 μm; y: mm
dE/dx: 5 - 10%

Time projection chamber (TPC)

ALICE TPC:

Length: 5 meter
Radius: 2.5 meter
Gas volume: 88 m^3

Total drift time: 92 μs
High voltage: 100 kV

End-cap detectors: 32 m^2
Readout pads: 557568

159 samples radially
1000 samples in time

Gas: $Ne/CO_2/N_2$ (90-10-5)
Low diffusion (cold gas)

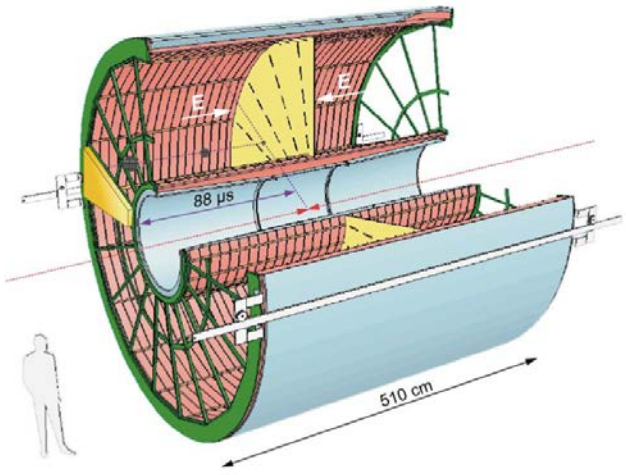
Gain: > 10^4
Diffusion: σ_t = 250 μm
Resolution: $\sigma \approx 0.2$ mm

σ_p/p ~ 1% p; ε ~ 97%
$\sigma_{dE/dx}/(dE/dx)$ ~ 6%

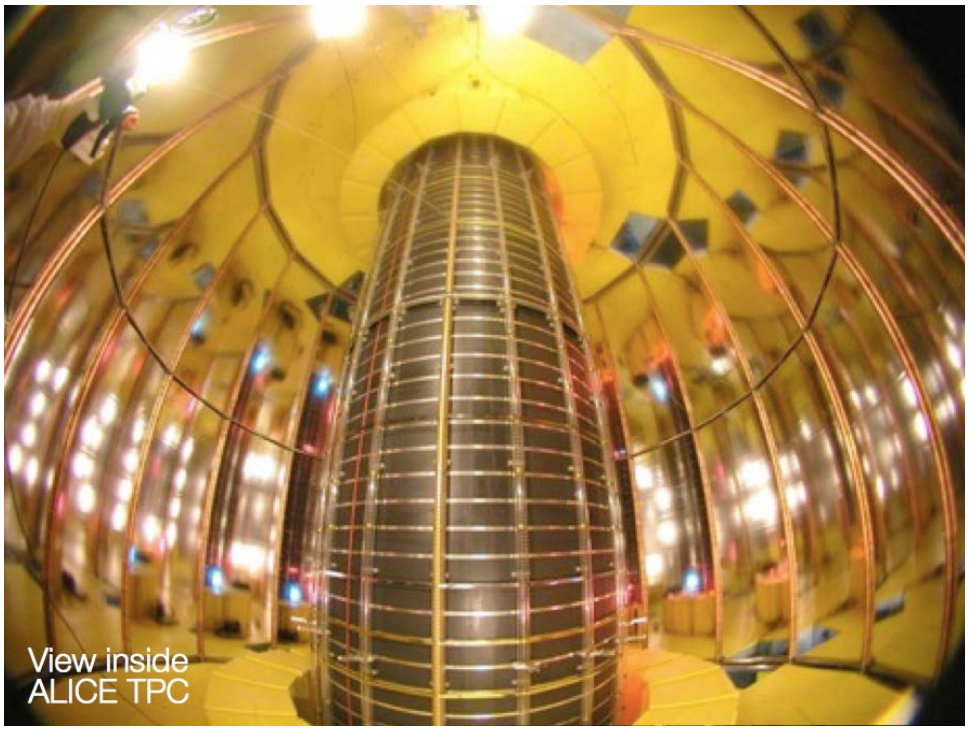
Magnetic field: 0.5 T

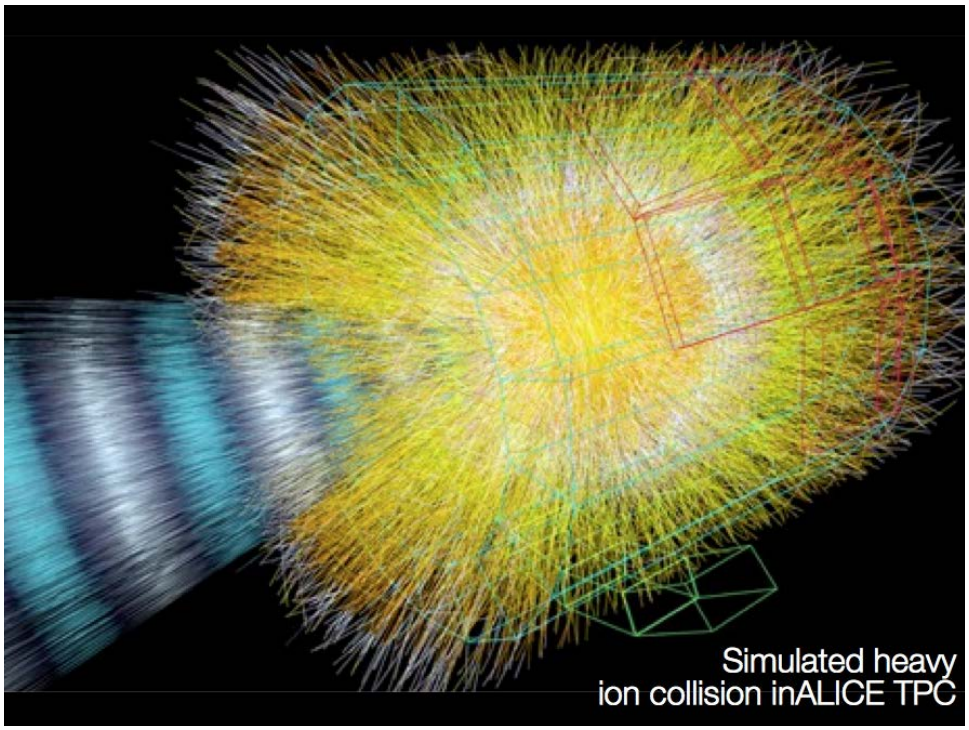
Pad size: 5x7.5 mm^2 (inner)
6x15 mm^2 (outer)

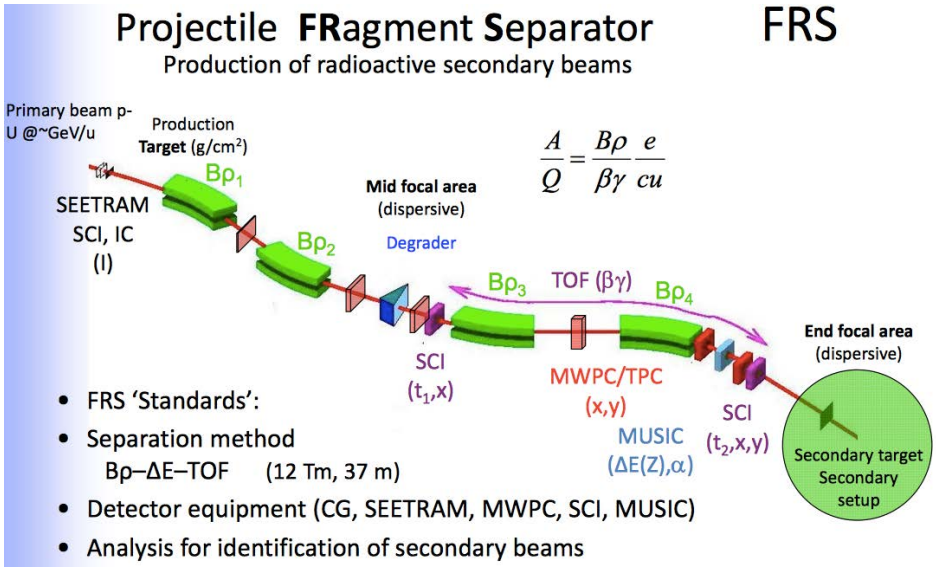
Temperature control: 0.1 K
[also resistors ...]



Material: Cylinder build from composite material of airline industry (X_0= ~ 3%)


View inside
ALICE TPC


Simulated heavy
ion collision inALICE TPC



Projectile Fragment Separator at GSI

Different systems for the combined setup

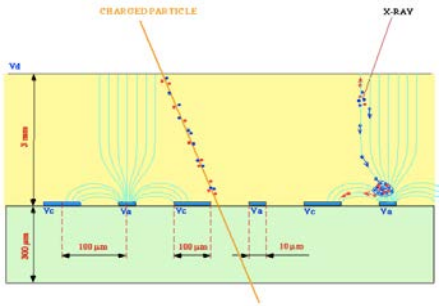
MWPC: Position identification (Tracking detectors)

TPC: dE/dx measurement (Particle Identification)

MUSIC (Multi Sampling Ionization Chambers): Identification of the Energy deposited through the charge (Z)

Micro-strip gas chambers (MSGC)

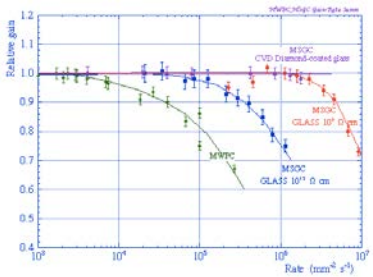
Consisting of a set of tiny metal strips engraved on a thin insulating support, and alternatively connected as anodes and cathodes.



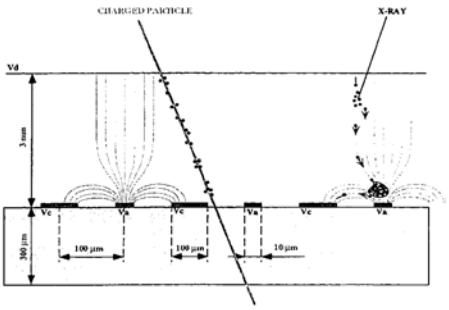
Photolithography technology permits to ***reduce the electrode spacing*** by at least an order of magnitude, correspondingly improving the ***multi-hit capability***. The fast collection of most positive ions by the nearby cathode strips reduces space charge build-up, and provides a ***largely increased rate capability***

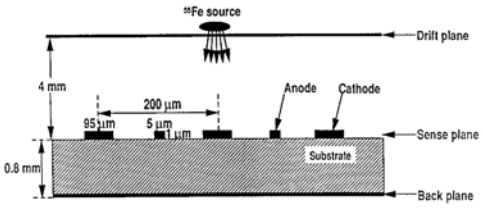
CMS experiment at CERN

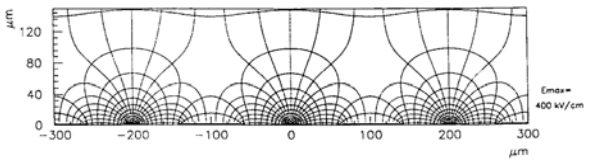
Comparison of the performance with respect to MWPC



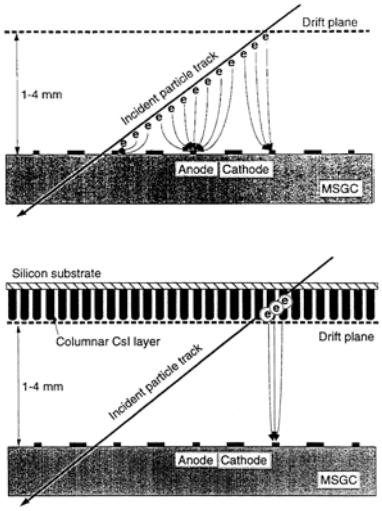
Micro-strip gas chambers (MSGC)



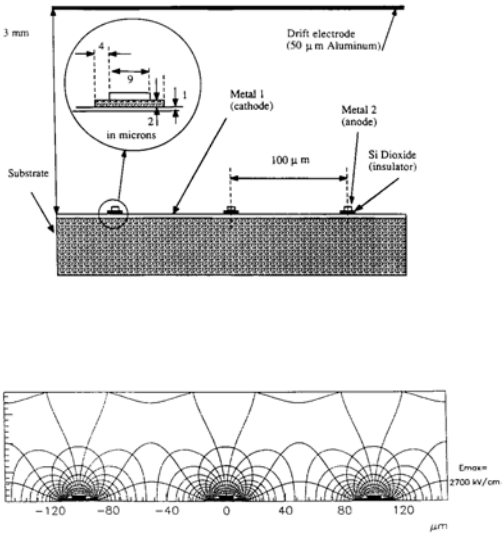




A layer of solid detector material can be used to increase dE/dx

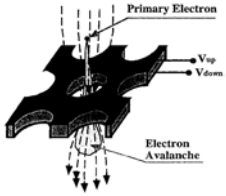


Micro-gap chamber (MGC)

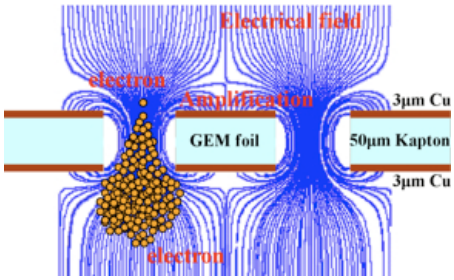


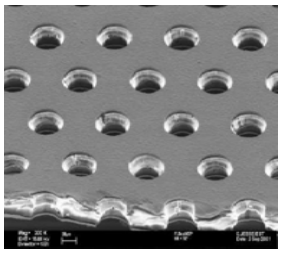
Gas electron multiplier (GEM)

Position sensitive gas detector



A thin insulating sheet is coated with a 5 μm thick copper layer on both sides. When a high voltage (~ 500 V) is applied, a strong electric field is formed inside the holes, which leads to the multiplication process.

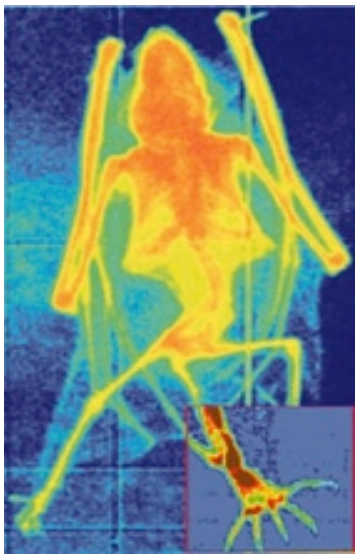




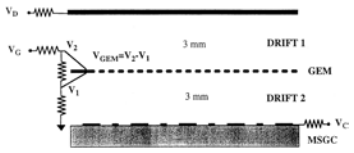
COMPASS (Common Muon and Proton Apparatus for Structure and Spectroscopy) experiment at CERN

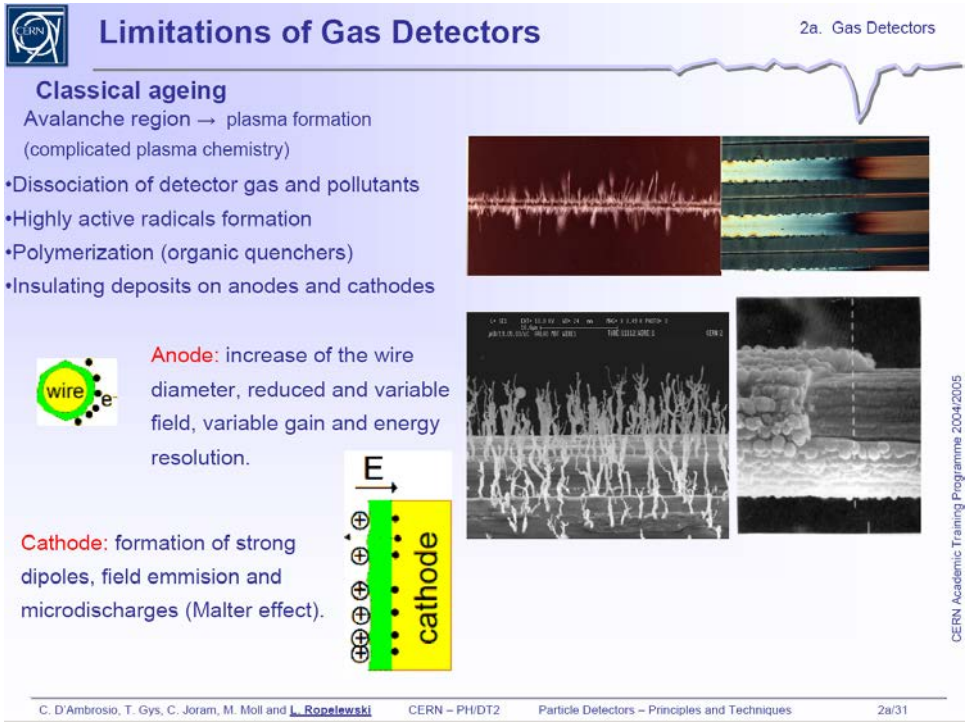
Gas electron multiplier (GEM)

Image of a small bat (width 32 mm with a pixel size of 50 μm). Two-dimensional read-out boards made using GEM technology have been made for digital absorption radiography. (F Sauli, CERN.)



A GEM foil can be used for additional amplification inside a gas detector





Gas detectors in CERN experiments

ALICE: TPC (tracker), TRD (transition rad.),

TOF (MRPC), HMPID (RICH-pad chamber), Muon tracking (pad chamber), Muon trigger (RPC)

ATLAS: TRD (straw tubes), MDT (muon drift tubes), Muon trigger (RPC, thin gap chambers)

CMS: Muon detector (drift tubes, CSC), RPC (muon trigger)

LHCb: Tracker (straw tubes), Muon detector (MWPC, GEM)

TOTEM: Tracker & trigger (CSC , GEM)

Problems

5.1 Calculate the charge represented by the positive ions (or free electrons) created when a 5.5 MeV alpha particle is stopped in helium. Find the corresponding saturated current if 300 alpha particles per second enter a helium-filled ion chamber.

Solution:

electrons = E/W = $(5.5 \times 10^6$ eV)/(42.7 eV/ion pair) = 1.29×10^5

Q = (# charge carriers)(charge per carrier)

Q = $(1.29 \times 10^5)(1.602 \times 10^{-19}$ C/e$^-$) = 2.06×10^{-14} C

I = (# α's per second)(charge per α) = (300 s^{-1})$(2.06 \times 10^{-14}$ C) = 6.19 pA

5.3 An air-equivalent pocket chamber having a capacitance of 75 pF is initially charged to a voltage of 25 V. If the active volume contains 50 cm^3 of air at STP, what value of gamma-ray exposure will reduce the chamber voltage to 20 V?

Solution:

$\Delta V = \Delta Q/C$

exposure = $\Delta Q/M = \Delta V\ C/M$

At STP, M = (1.293 kg/m^3) V = (1.293 kg/m^3) $(50 \times 10^{-6}$ m^3) = 6.465×10^{-5} kg.

exposure = (5V)(75×10^{-12} F)/$(6.465 \times 10^{-5}$ kg)

= 5.80 μC/kg or 22.5 mR.

5.4 An ion chamber is constructed using parallel plate electrodes with a spacing of 5.0 cm. It is filled with pure methane gas at a pressure of 1 atm and operated at an applied voltage of 1000 V. From the data given in Fig. 5.2, calculate the maximum electron collection time.

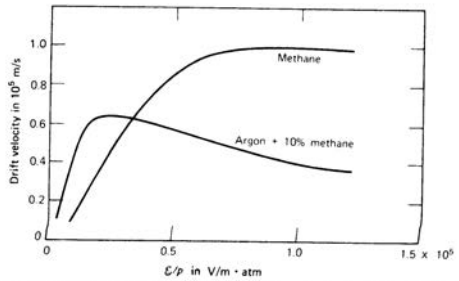


Figure 5.2 Electron drift velocity as a function of electric field $\mathscr{E}$ divided by gas pressure p. (Data from Bortner et al.[7])

Solution:

E/p = (1000 V / 0.05 m)/(1 atm) = 2×10^4 V/m·atm.
Using Fig. 5.2, v = 0.36×10^5 m/s.
t_C = d/v = (0.05 m)/(0.36×10^5 m/s) = 1.39 μs

5.8 The average beta particle energy emitted by ^{14}C is 49 keV. Calculate the saturated ion current if 150 kBq of the isotope in the form of CO_2 gas is introduced into a large-volume ion chamber filled with pressurized argon.

Solution:

$I = E_{avg}\ \alpha\ e/W$
$I = (49\times10^3\ eV/\beta)(150\times10^3\ \beta\ sec^{-1})(1.602\times10^{-19}\ C/e^-)/(27\ eV/e^-)$
$= 43.6\ pA$

5.10 A parallel plate ion chamber with 150 pF capacitance is operated in electron-sensitive mode. Calculate the pulse amplitude expected from 1000 ion pairs formed 2 cm from the anode, if the total spacing between the plates is 5 cm.

Solution:

$V = [n_0 e/C]\,[x/d]$

$V = [(1000\ e^-)(1.602 \times 10^{-19}\ C/e^-)/(150 \times 10^{-12}\ F)]\,[2/5]$

$= 0.427\ \mu V$

5.12 An air-equivalent ion chamber is constructed using aluminum walls. What is the minimum thickness of these walls if compensation is to be maintained up to a maximum gamma-ray energy of 10 MeV?

Solution:

Using Table 5-2, 10 MeV gamma rays require a wall thickness of 4.9 g/cm^2.

$t = (4.9\ g/cm^2)/(2.699\ g/cm^3) = 1.82\ cm$

6.1 Assuming that $W = 26.2$ eV ion pair and the Fano factor $F = 0.17$ for argon, find the mean and expected standard deviation in the number of ion pairs formed by the absorption of 1 MeV of radiation energy.

Solution:

$$n = E/W = (10^6 \text{ eV})/(26.2 \text{ eV/ion pair}) = 3.82 \times 10^4 \text{ ion pairs}$$
$$\sigma_n = [F\,n]^{0.5} = [(0.17)\,(3.82 \times 10^4)]^{0.5} = 80.6 \text{ (or } 0.21\% \text{ of n)}$$

6.7 A given voltage-sensitive preamplifier requires a minimum input pulse amplitude of 10 mV for good signal/noise performance. What gas multiplication factor is required in an argon-filled proportional counter with 200 pF capacitance if 50 keV X-rays are to be measured?

Solution:

$$Q = CV = n_0 eM \quad \rightarrow \quad M = CV/[n_0\,e]$$
$$n_0 = E/W = (50 \times 10^3 \text{ eV})/(26.2 \text{ eV}) = 1908$$
$$M = (200 \times 10^{-12} \text{ F})(10^{-2} \text{ V})/[(1908)(1.602 \times 10^{-19} \text{ C})] = 6540$$

6.8 A cylindrical proportional tube has an anode wire radius of 0.003 cm and a cathode radius of 2.0 cm. It is operated with an applied voltage of 2000 V. If a minimum electric field of 1.0 MV m is required to initiate gas multiplication, what fraction of the internal volume of the tube corresponds to the multiplication region?

Solution:

$$E = V/[r \ln(b/a)] \quad \rightarrow \quad r_C = V/[E \ln(b/a)]$$

$$r_C = (2000V)/[(10^6 V/m) \ln(2/0.003)] = 0.0308 \text{ cm}$$

$$V_{\text{mult region}}/V_{\text{total}} = [\pi (r_C)^2 h] / [\pi b^2 h] = [r_C/b]^2 = [0.0308/2]^2 = 0.0237\%$$

7.5 Both the proportional counter and Geiger tube are based on internal gas multiplication. Comment on each separately and contrast their behavior with regard to:

(a) Variation of pulse height with applied voltage.

(b) The need for a quench gas and its function.

(c) Ability to differentiate heavy charged particle and electron radiations.

(d) Ability to register high counting rates.

(e) Typical counting efficiency for 1 MeV gamma rays.

a) Proportional: The pulse height varies as the avalanche amplitude which, in turn, depends on voltage in an approximately exponential manner.
Geiger: The pulse amplitude corresponds to the number of ion pairs at the point at which the accumulated positive space charge is sufficient to reduce the electric field below its critical value. This number will increase in approximate proportion to the original electric field or linearly with the applied voltage.

b) Proportional: The quench gas must absorb UV photons.
Geiger: The quench gas must pick up positive charges from the original positive ions through charge transfer collisions.

c) Proportional: Because heavy charged particles tend to deposit all of their energy, and electrons only part of theirs, the two radiations can be separated by their different pulse heights.
Geiger: No differentiation can be achieved, because pulse height is independent of particle type and energy.

d) Proportional: The maximum counting rate is often set by pulse pile-up. The minimum pulse shaping time (that will minimize pile-up) is limited by the finite rise time of the pulses.
Geiger: The maximum counting rate is limited by the long dead time of the tube itself.

e) Proportional: Gamma rays produce very small amplitude pulses and are often below the discrimination level.
Geiger: Counting efficiency is a few percent due primarily to the liberation of secondary electrons from the detector walls.

7.8 In a given counter gas operated at a pressure of 0.5 atm. the mobility of a free electron is 1.5×10^{-4} (m/s) · (m/V) · atm. The threshold electric field for the onset of avalanche formation is 2×10^6 V/m. If this gas is used in a cylindrical tube with anode radius of 0.005 cm and cathode radius of 2 cm, calculate the drift time of an electron from the cathode to the multiplying region for an applied voltage of 1500 V.

Solution:

The critical radius for avalanche formation is obtained using $E_{crit} = V/[r_{crit} \ln(b/a)]$, so

$r_{crit} = V/[E_{crit} \ln(b/a)] = 1500 \text{ V}/[(2 \times 10^6 \text{ V/m})(\ln(2/0.005)] = 1.25 \times 10^{-2}$ cm

drift distance $= d = b - r_{crit} = 2.0 - 0.0125 = 1.9875$ cm

t_{drift} = (drift distance)/(drift velocity) $= d/[\mu_e E_{avg}/p] = pd/\mu_e E_{avg}$

$$E_{avg} = \frac{1}{b - r_{crit}} \int_{r_{crit}}^{b} \frac{V}{r \ln(b/a)} dr = \frac{V}{b - r_{crit}} \frac{\ln(b/r_{crit})}{\ln(b/a)} = \frac{1500 \text{ V}}{(2.0 - 0.0125) \text{ cm}} \frac{\ln(2./0.0125)}{\ln(2./0.005)}$$

$E_{avg} = 639$ V/cm

$t_{drift} = (0.5 \text{ atm})\ (2.0 - 0.0125)\text{cm} / (1.5 \times 10^{-4} \text{ m}^2 \text{ atm/s·V})\ (639 \text{ V/cm})\ (10^{-4} \text{ m}^2/\text{cm}^2)$

$t_{drift} = 1.04$ ms