chap.4 Ionization Detectors

Ionization Detectors:

Based on the direct collection of the ionization electrons and ions produced in a gas by passing radiation

First electrical devices developed for radiation detection.

- First half of the 20th century;Three basic types

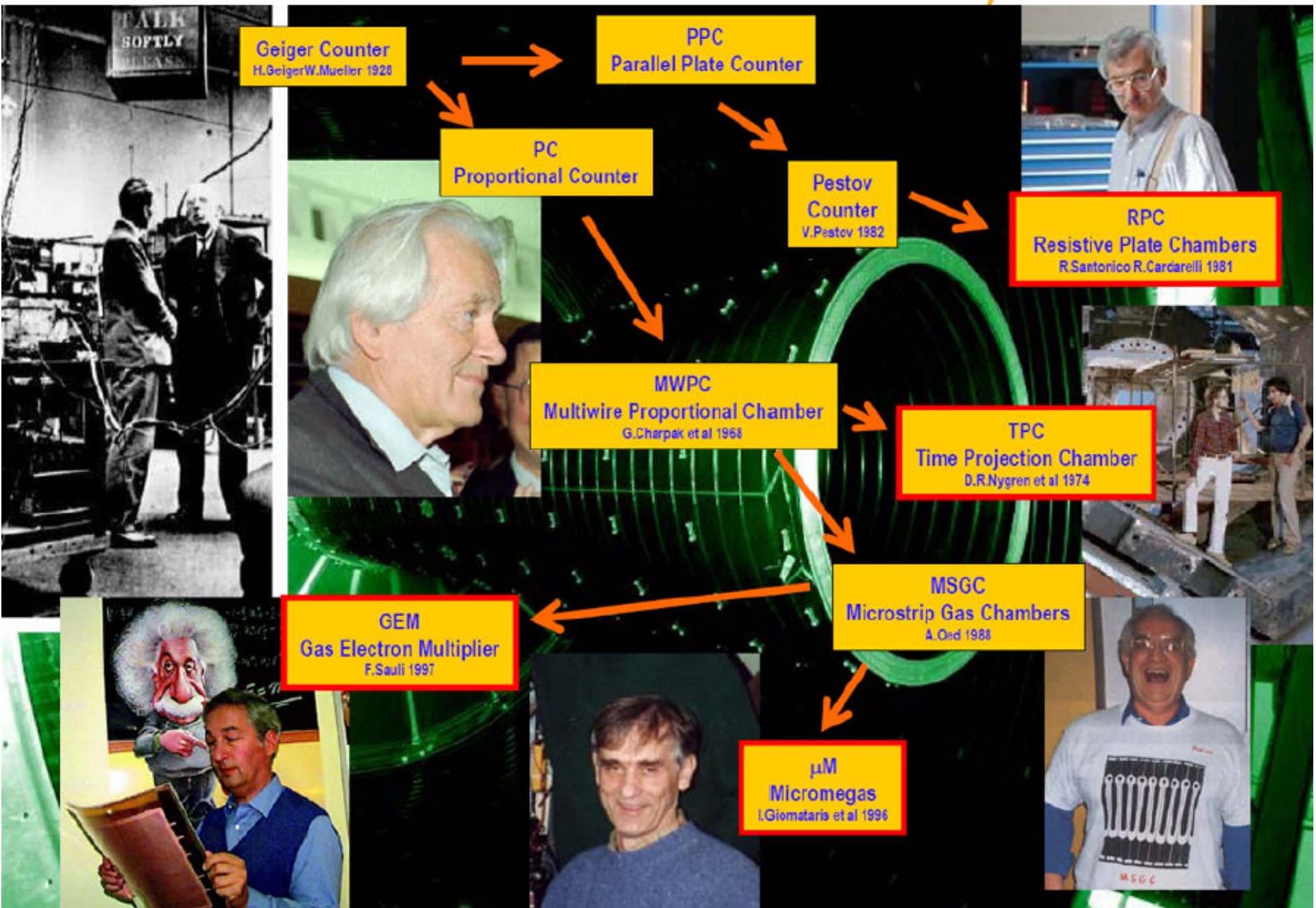
  Ionization Chamber ,Proportional Counter and Geiger Müller

  Not in widespread use in modern nuclear and particle physics experiments today; Still very much employed in the laboratory as radiation monitors ; Cheap, simple to operate and easy to maintain

- During the late 1960s; Invention of the multi-wire proportional chamber
  - Quickly adopted in high energy experiments
  - Capable of localizing particle trajectories to less than a millimeter

- Later; Development of Drift Chamber and Time Projection Chamber
  - Operate on the same basic principles as the simple Proportional Counter
  - Require more sophisticated electronics and data acquisition by computer
  - Used extensively in high energy particle physics experiments

Gas detectors History

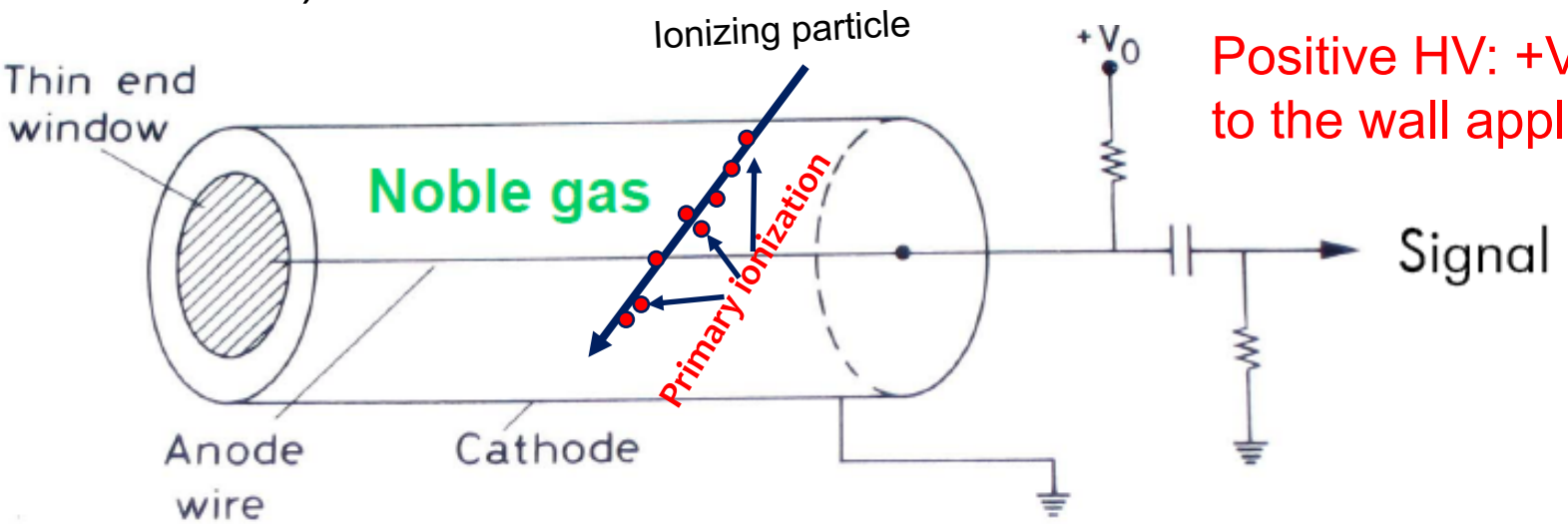


Gaseous Ionization Detectors

•Great mobility of electrons and Ions in gas →gas is a obvious medium to measure ionizing radiation

•Ionization in gas has been studied thoroughly over the years, gas mixtures have been optimized for efficiency, devices have been optimized for fastness and resolution

•Basic construction of a simple gas detector (ion. chamber, prop. counter, GM-counter)

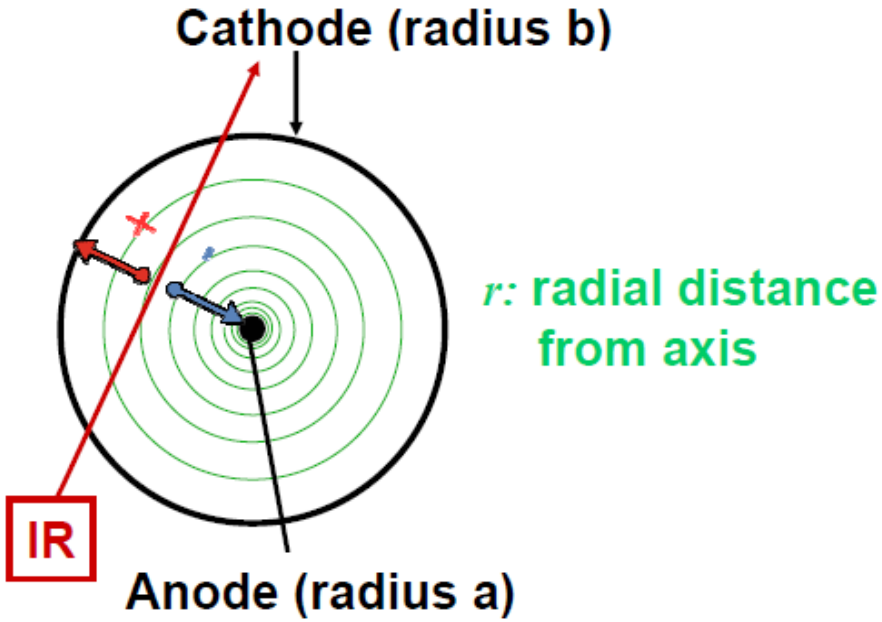


Positive HV: $+V_0$ relative to the wall applied

Filled with a suitable gas, usually noble gas(argon,..)

•Conducting walls

•Thin end window



Radial Electric Field

$$E = \frac{1}{r}\frac{V_0}{\ln(b/a)}$$

What happens if radiation penetrates the active volume?

- Certain number of pairs created
- Mean number of pairs proportional to the energy deposited in the counter
- Electrons will be accelerated towards the anode and ions toward the cathode
- Current signal observed depends on the field intensity

Ionization and Transport Phenomena in Gases

- **Two types of energy loss of a charged particle in matter:**

(1) excitation: $\mathbf{X + p \rightarrow X^* + p}$

$\sigma \approx 10^{-17}$ cm^2, exact resonant energy required

(2) ionization: $\mathbf{X + p \rightarrow X^+ + p + e^-}$

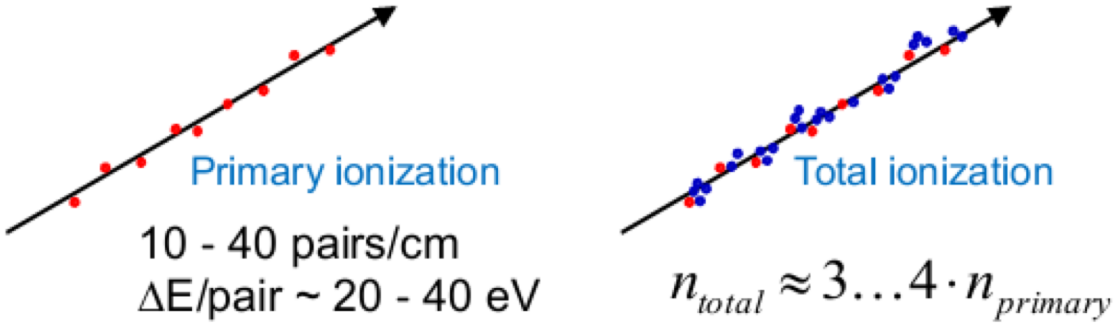
$\sigma \approx 10^{-16}$ cm^2, no exact energy requirement, $E > I_0$, higher energy threshold

- Primary ionization:

  The electrons and ions created by the incident radiation itself

- Secondary ionization:

  Sufficiently large energy is transferred to the electron (delta-rays), such that it creates electron-ion pairs itself, secondary ionization electrons may also ionize untill threshold for ionizing reactions is reached



•Second mechanism of ionization:

Penning Effect:

- Excited metastable states in certain atoms are unable to deexcite immediately to the ground state by emission of photon
- Deexcitation may occur through a collision with a second atom resulting in the ionization of latter

EX: $\mathbf{Ne^* + Ar \rightarrow Ne + Ar^+ + e}$

•Third important mechanism:

Formation of molecular ions:

Positive gas ions interacts with a neutral atom of the same type to form a molecular ion

EX: $He^+ + He \rightarrow He_2^+$

Mean Number of Electron-Ion Pairs

• Ionization is of statistical nature

• For gases: of the order of 1 ion-electron pair per 30 eV, so for example for 3 keV particle an average of 3000/30=100 ion-electron pairs is created.

• This average value ***w*** does not depend very strongly on particle type and only weakly on the gas type.

• Fano factor: Not well determined for most gases, 0.2-0.4

Table 1.3. *Fano factors for typical detector materials [54]*

source	energy	absorber	F
X-rays	5.9 keV	Ar + 10 % CH_4	0.21
"	2.6 keV	"	0.31
α	5.03 MeV	"	0.18
α	5.68 MeV	Ar + 0.8 % CH_4	0.19
p	1 . . . 4.5 MeV	Si	0.16

$$R = 2.35\sqrt{\frac{Fw}{E}}$$

Ionization processes

Characteristics of common gases

Gas	ρ [g/cm^3]	I_0 [eV]	W_i [eV]	$\frac{dE}{dx}$ [$\frac{\text{kev}}{\text{cm}}$]	n_P [$\frac{\text{I.P}}{\text{cm}}$]	n_T [$\frac{\text{I.P}}{\text{cm}}$]
H_2	8.38×10^{-5}	15.4	37	0.34	5.2	9.2
He	1.66×10^{-4}	24.6	41	0.32	5.9	7.8
N_2	1.17×10^{-3}	15.5	35	1.96	10.0	56.0
O_2	1.33×10^{-3}	12.2	31	2.26	22.0	73.0
Ne	8.39×10^{-4}	21.6	36	1.41	12.0	39.0
Ar	1.66×10^{-3}	15.8	26	2.44	29.4	94.0
Kr	3.49×10^{-3}	14.0	24	4.60	22.0	192.0
Xe	5.49×10^{-3}	12.1	22	6.76	44.0	307.0
CO_2	1.86×10^{-3}	13.7	33	3.01	34.0	91.0
CH_4	6.70×10^{-4}	13.1	28	1.48	16.0	53.0

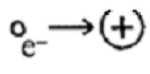
Table: Characteristic numbers of common gases: a.o. the average energy to produce electron-ion pair W_i, the number of primary and total electron-ion pairs per length n_P, n_T and the energy loss per length dE/dx. Values extracted from K. Kleinknecht, *Detektoren für Teilchenstrahlung*, Teubner (2005)

Note: Factor 2 – 6 between n_P to n_T.

Recombination and Electron Attachment

When there is no electric field, ion-elctron pairs will generally recombine under force of their electric attraction emmitting a photon in the process

$$X^+ + e^- \rightarrow X + h\nu$$



For molecular ions:

$$X^- + Y^+ \rightarrow XY + h\nu$$

Rate of recombination

$$dn = bn^- n^+ dt$$

b : recombination coefficient, constant depending on gas type;

n^-,n+ : ion concertation

$$n = n_0 \frac{n_0}{1 + bn_0 t}$$ for $n^- = n^+ = n$

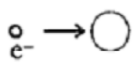
n_0: initial concentration at t=0

The recombination coefficient is normally orders of magnitude larger between positive ions and negative ions compared with that between positive ions and free electrons.

Electron attachment:

Capture of free electrons by electronegative atoms to form negative ions

$$e^- + X \rightarrow X^- + h\nu$$

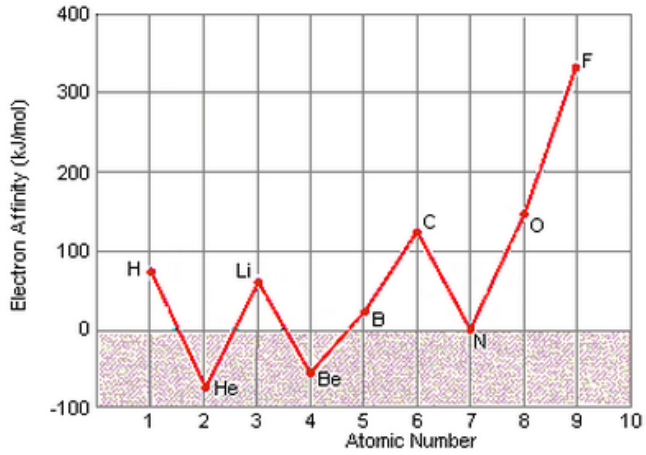


Atoms which have an almost full outer electron shell so that the addition an extra electron actually results in the release of energy. The negative ion consequently stable. The energy released in this capture is known as *electron affinity*. 电子亲和势

Examples of electronegative gases are O_2, H_2O, CO_2 etc.

Presence of any electronegative gases in the detector will diminish the efficiency of electron-ion collection by trapping the electrons before they reach the electrodes

Noble Gases; He, Ne, Ar, in contrast, have negative electron affinities



Electron Affinities and Electron Configurations for the First 10 Elements in the Periodic Table

Element	*Electron Affinity (kJ/mol)*	*Electron Configuration*
H	72.8	$1s^1$
He	<0	$1s^2$
Li	59.8	[He] $2s^1$
Be	<0	[He] $2s^2$
B	27	[He] $2s^2\ 2p^1$
C	122.3	[He] $2s^2\ 2p^2$
N	<0	[He] $2s^2\ 2p^3$
O	141.1	[He] $2s^2\ 2p^4$
F	328.0	[He] $2s^2\ 2p^5$
Ne	<0	[He] $2s^2\ 2p^6$

Transport of Electrons and Ions in Gases

The neutral atoms or molecules of the gas are in constant thermal motion, a mean free path of typical gases under standard conditions ~10^{-6}-10^{-8} m

Positive ions or free electrons created within gas also take part in the radom thermal motion and therefore have some tendency to diffuse away from regions of high density.

Diffusion

In the absence of electric field, electrons and ions liberated by passing radiation

- diffuse uniformly outward from their point of creation
- suffer multiple collisions with the gas molecules, loses their energy
- come quickly into thermal equilibrium with the gas and eventually recombine

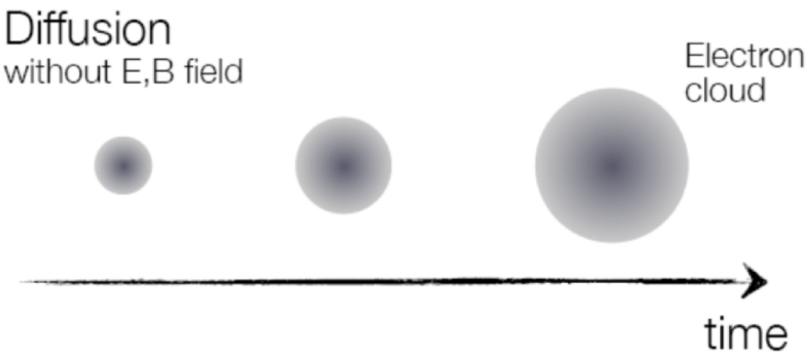
At thermal energies, velocity of charges are described by Maxwell distribution

$$v = \sqrt{\frac{8kT}{\pi m}}$$, k: Boltzmann, T: temperature, m: particle mass

At room temp.: electrons: ~ 10^6cm/s, ions ~ 10^4cm/s

From kinetic theory: distribution of charges after diffusing for a time t is gaussian

$$\frac{dN}{dx} = \frac{N_0}{\sqrt{4\pi Dt}} exp(-\frac{x^2}{4Dt})$$



N_0 : total number of charges

x : distance from point of creation

D : the diffusion coefficient

after a diffusion time t the electrons/ions are Gaussian distributed with a spread

$$\sigma(r) = \sqrt{6Dt}$$ for ions under normal conditions about 1mm after 1sec

Diffusion coeff. is:

$$D = \frac{1}{2} v\lambda$$ for an ideal gas: $$\lambda = \frac{1}{\sqrt{2}} \frac{kT}{\sigma_0 p}$$ $$D = \frac{2}{3} \frac{1}{p\sigma_0} \sqrt{\frac{(kT)^3}{m}}$$

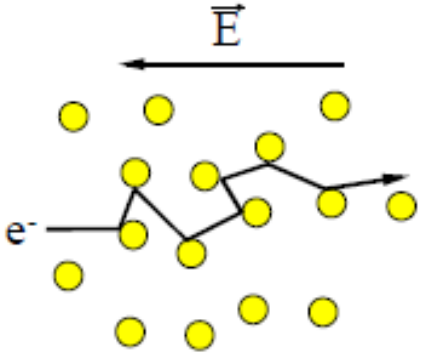
λ: the mean free path of particle

σ_0: total cross section for a collision with a gas molecule

p: pressure

- diffusion of ions is almost gas independent
- diffusion of electrons is strongly gas dependent

Drift



- In the presence of an electric field, the electrons and ions are accelerated along the field lines
- Acceleration is interrupted by collisions with the gas molecules which limit maximum average velocity, known as drift velocity v 漂移速度

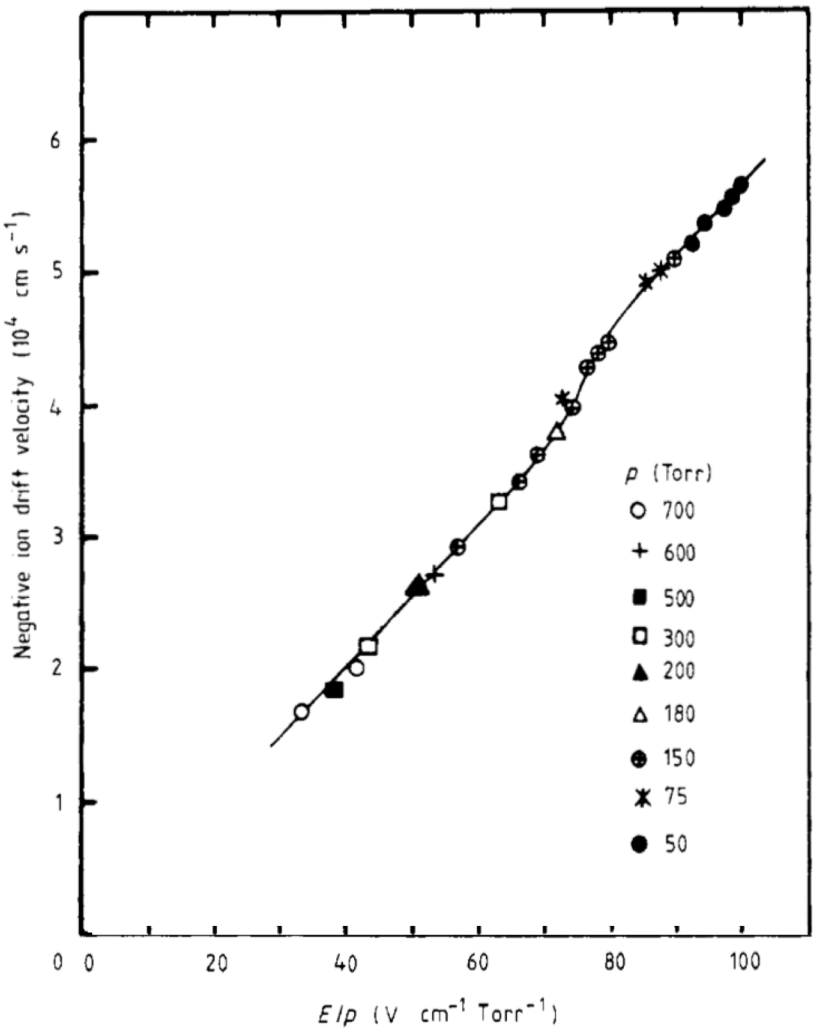
For positive ions

约化场强

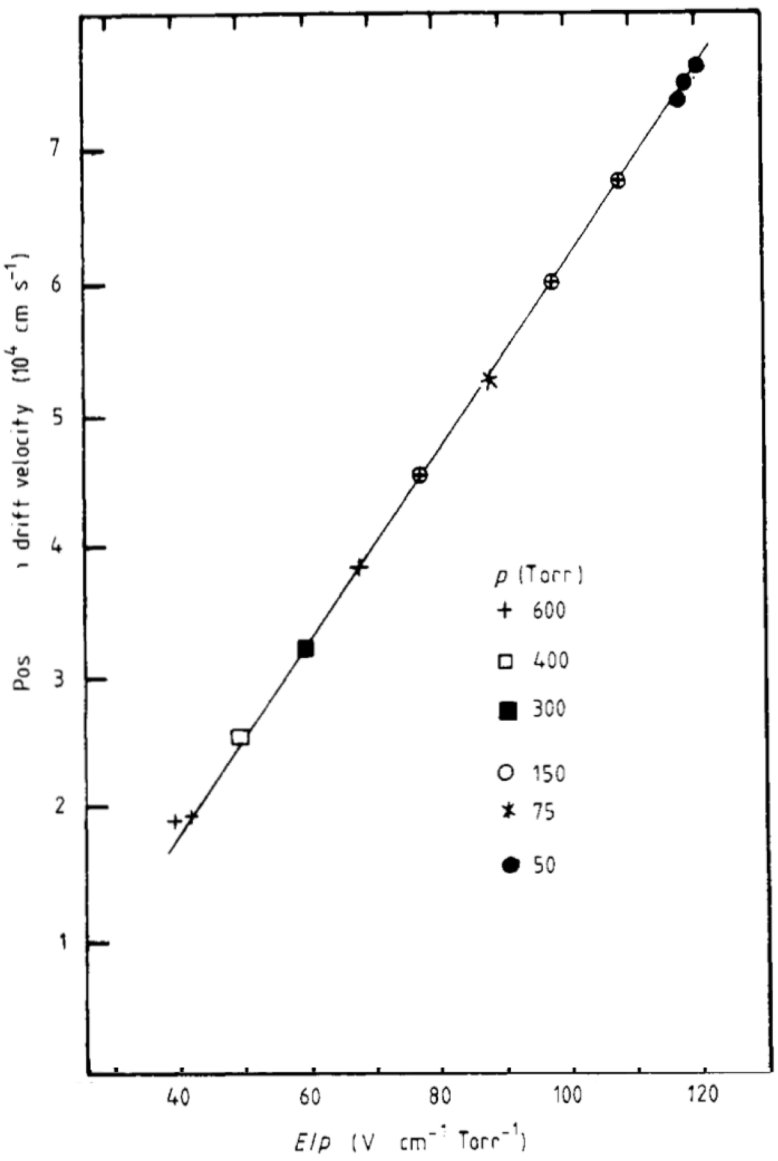
- Drift velocity depends linearly on the ratio E/p (called *reduced electric field*) up to relatively high E, $v=\mu \cdot E/p$ μ: *mobility of charge* 迁移率

At 1 atm pressure, a typical electric field of 1KV/cm will result in a drift velocity of the order of 10^3cm/s. Ion transit times over typical detector dimensions of a cm will therefore be approximately 1ms. By most standards, this is a very long time.

Drift velocities were measured for ions of both polarities in unpurified cylinder SF_6, at pressures ranging from 50 to 700Torr.



Negative ion drift velocities.



Positive ion drift velocities.

http://iopscience.iop.org/article/10.1088/0022-3727/22/6/006/pdf

For electrons

• mobility is ~1000 times higher than ions and is function of E. velocities of a few times 10^6 cm/s at electric fields of 1 kV/cm-atm.

•No linear dependence on electric field strength. Saturation effects, even decreasing possible.

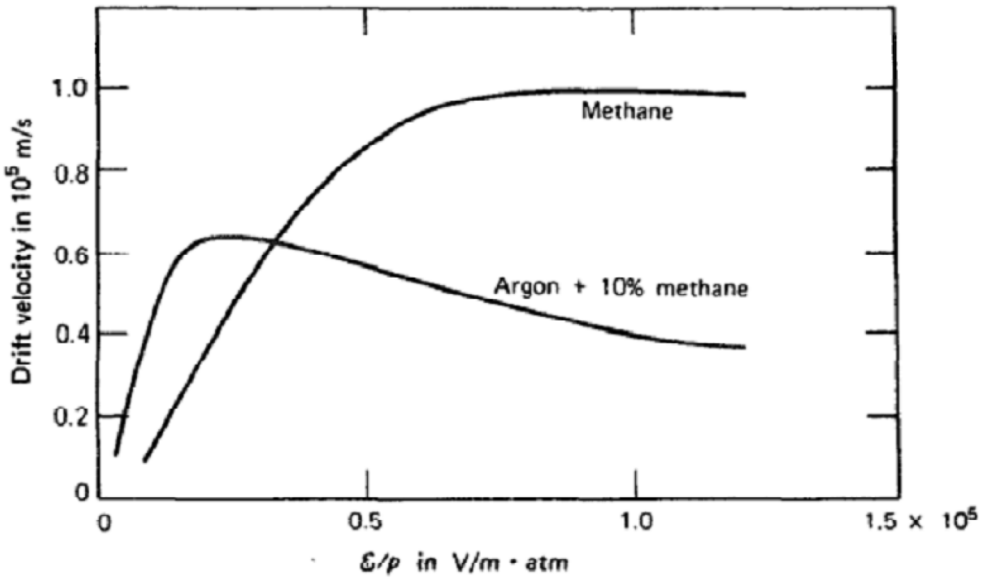
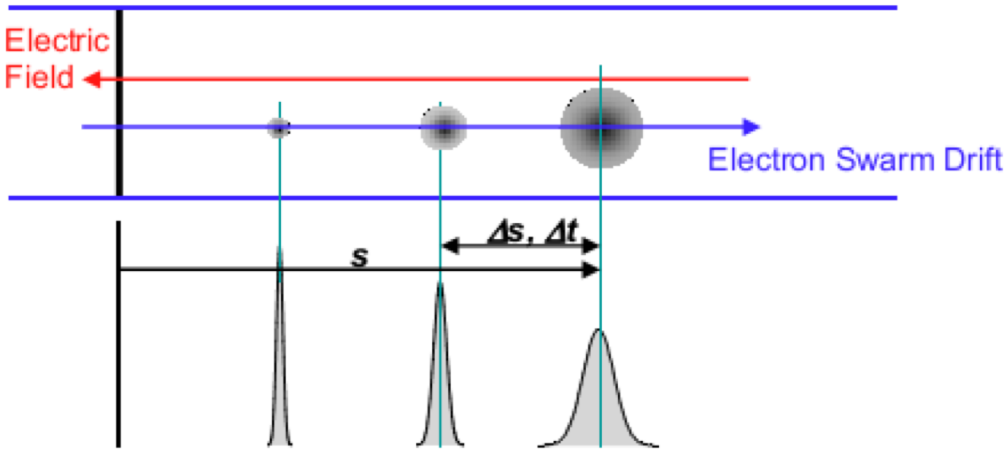


Figure 5.2 Electron drift velocity as a function of electric field $\mathcal{E}$ divided by gas pressure p. (Data from Bortner et al.[7])



Avalanche multiplication 雪崩放大

Multiplication in gas detectors occurs when the primary ionization electrons gain sufficient energy from the accelerating E field to also ionize gas molecules. The resulting secondary electrons then produce tertiary ionization etc. This result in the formation of anavalanche.

Because of the greater mobility of electrons: avalanche has the from of a liquid drop: Electrons grouped near the head; Ions (slower) trailing behind

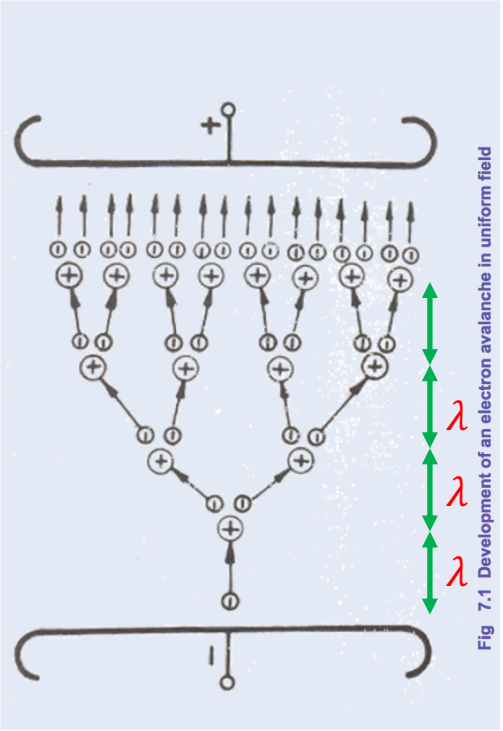
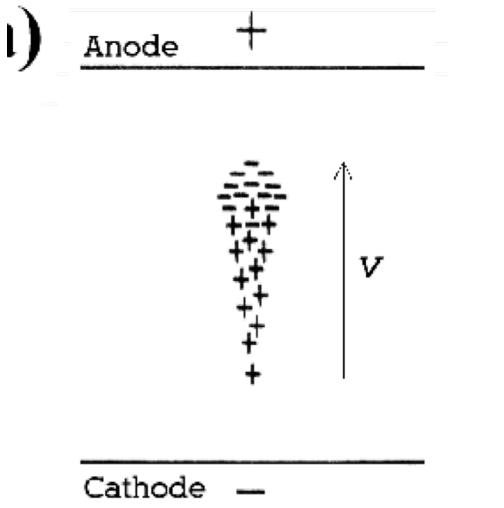
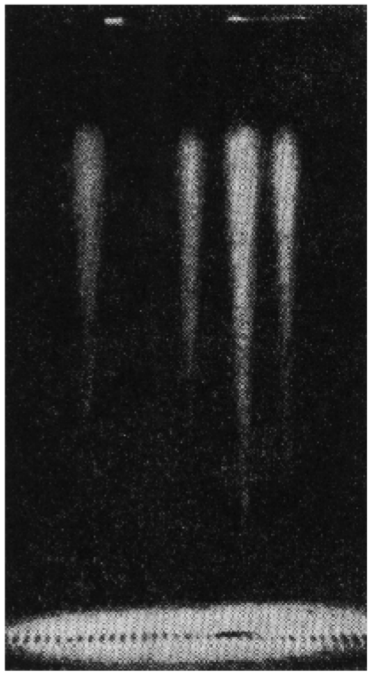


Fig 7.1 Development of an electron avalanche in uniform field



Electron avalanche in a laboratory experiment


An actual photograph of individual electron avalanches.

Mean free path $\lambda = \frac{1}{N\sigma}$ N: molecules/cm^3

- the probability of ionization per unit length $\alpha = \frac{1}{\lambda}$
- For n electrons, there will be $dn = n\alpha dx$ new electrons created in a path d*x*

$$n = n_0 e^{\alpha x}$$ α: first Townsend coefficient

- Multiplication factor M:

$$M = \frac{n}{n_0} = exp[\int_{r_1}^{r_2} \alpha(x)dx]$$ α is function of x (in non uniform electric fileds)

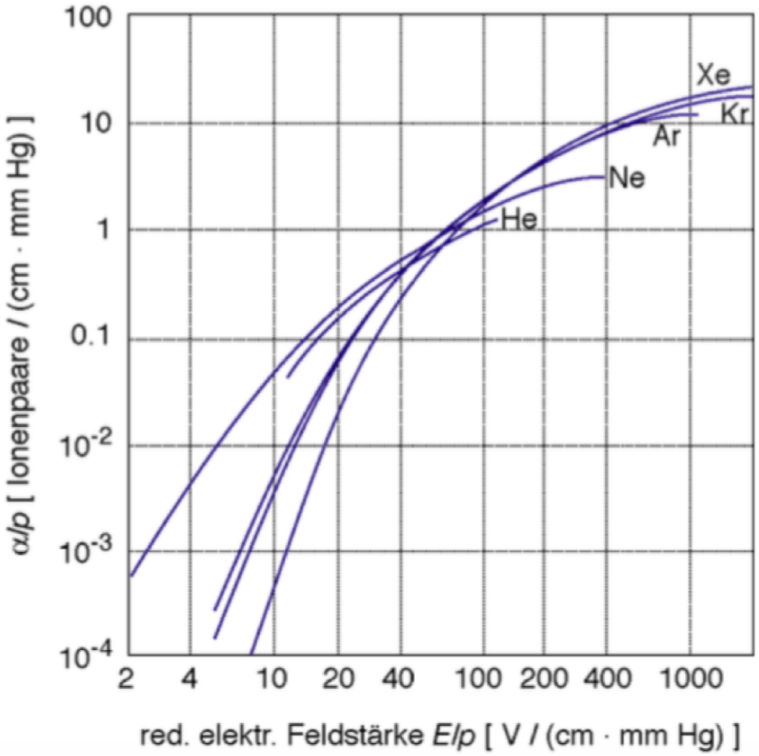
- Limitation of M: M < 10^8 or α(x) < 20, α(x)> 20 → breakdown
- Calculating α for different gases (model by Rose and Korff)

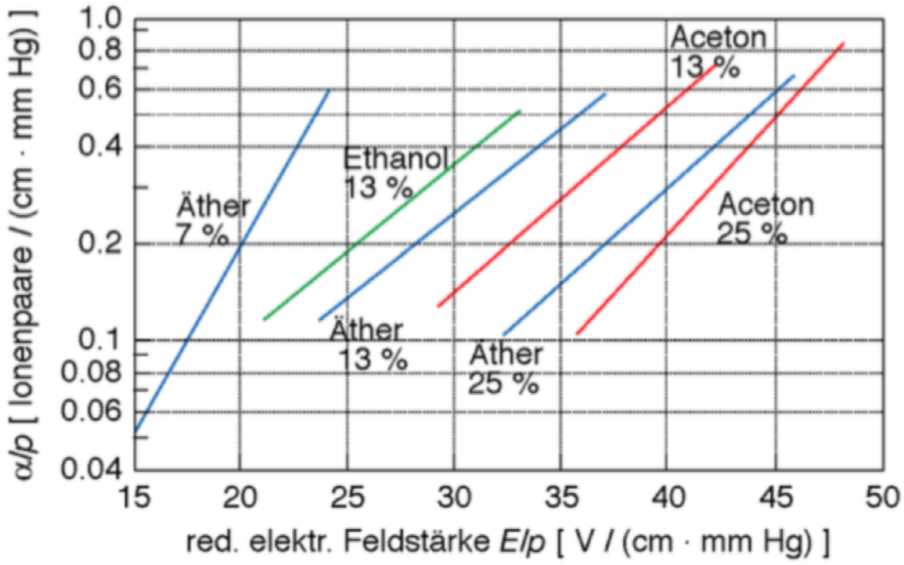
$$\frac{\alpha}{p} = A\, exp(\frac{-Bp}{E})$$ A,B: constants depending on gas

Charge amplification within a detector itself reduces the demands on external amplifiers

First Townsend coefficient – Examples

- First Townsend coefficient as function of the reduced electric field strength for various noble gases and Argon with different admixtures:





F. Sauli, *Principles of Operation of Multiwire Proportional and Drift Chambers*, CERN 77-09, 1977

The Townsend coefficient is proportional to the gas density and therefore to the pressure P.
The ratio α/P is a function of the reduced electric field

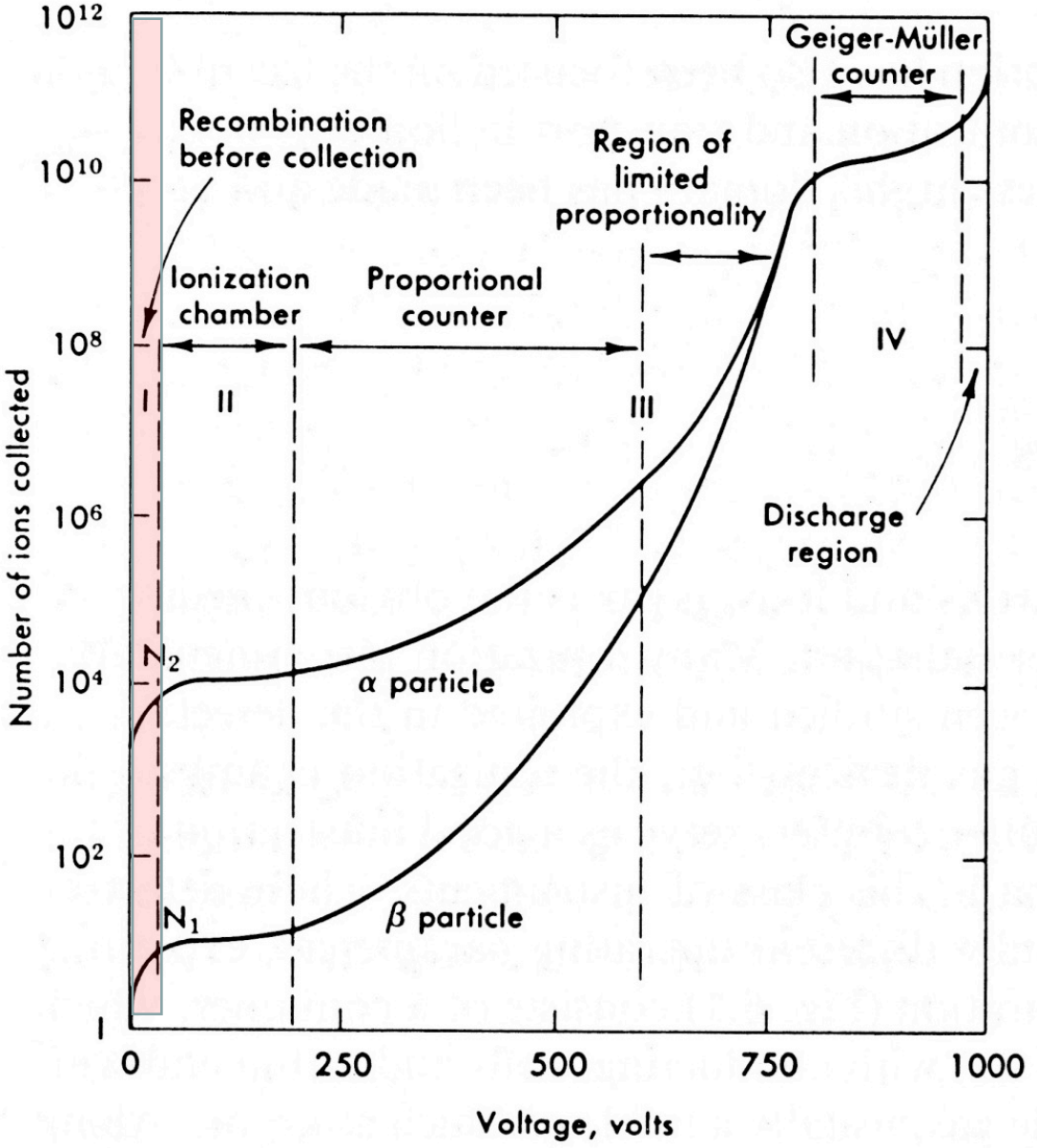
At zero voltage

No charge is collected

I. Recombination region

Incomplete charge collection:

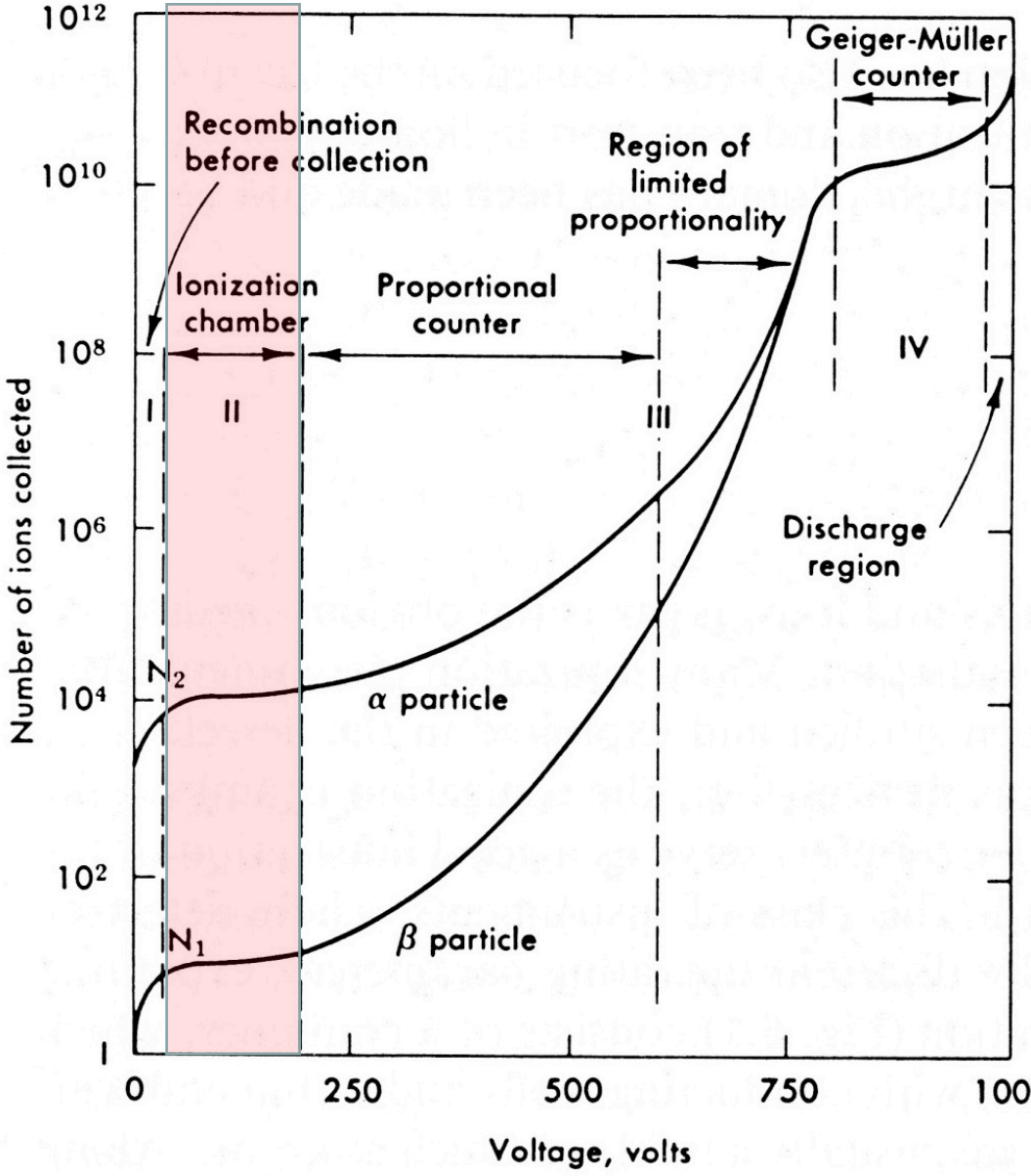
- Recombination before collection as the voltage raised
- Currents begins to increase
- More and more electron-ion pairs are collected



II. Ionization region

Complete primary charge collection, no multiplication or amplification

- Collected charge proportional to energy, small signal, typically used only for heavy charged particles or large fluxes of radiation



III. Proportional region

Avalanche multiplication.

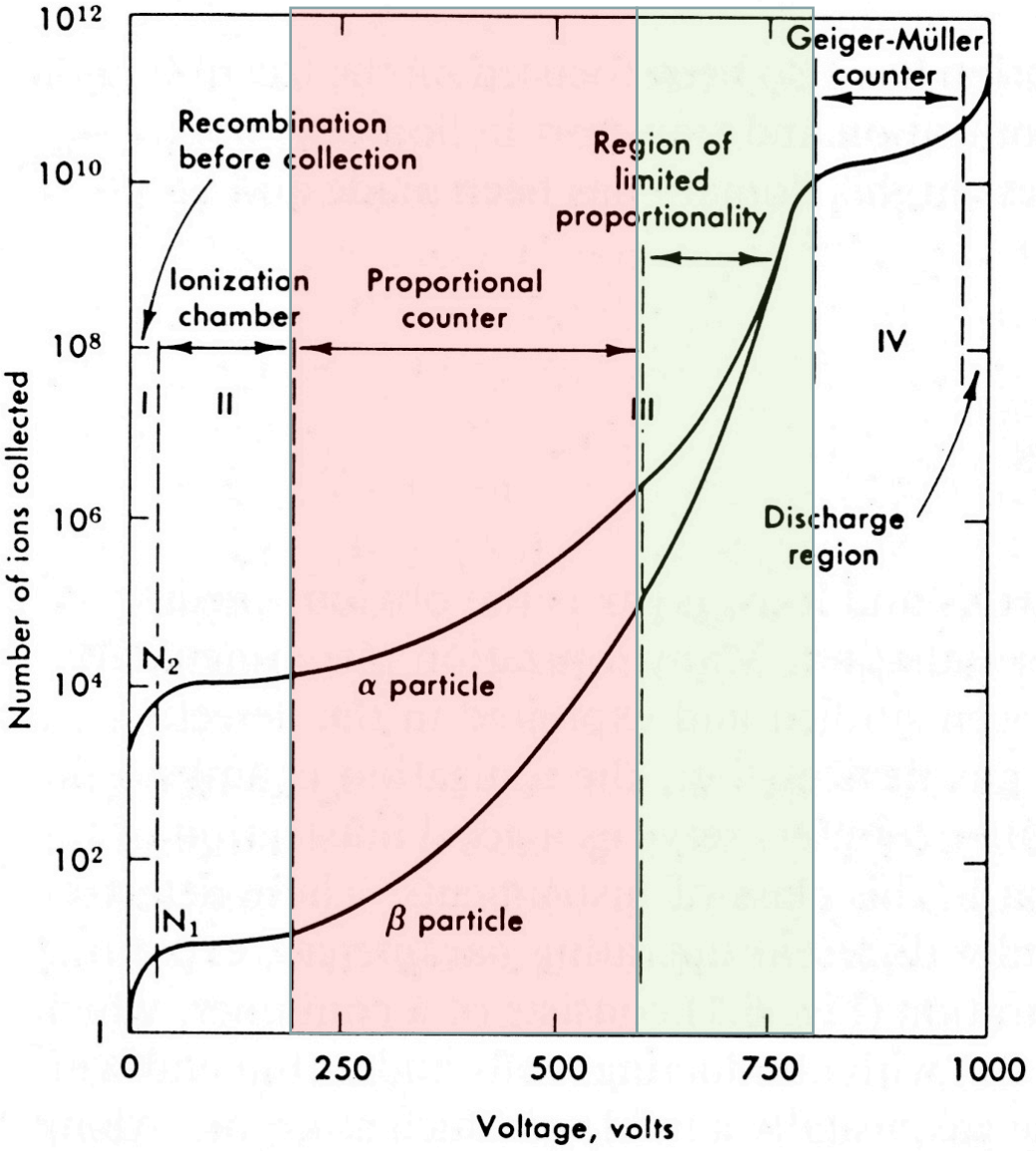
- The multiplication is linear.
- Measured pulse amplitude ∝ incident particle energy (at fixed applied voltage)
- Large amplification (~10^6)

IV. Region of limited proportionality

- Motionless cloud of positive ions is created which is slow to disperse.
- If the positive ion concentration is high, the electric field is distorted, which leads to distortion in gas multiplication. Space charge results in non-linear effects.

$$E(r) = \frac{V}{ln(b/a)}\frac{1}{r} - \boxed{\frac{\rho e b^2}{4\pi\epsilon_0 ln(b/a)}\frac{1}{r}}$$

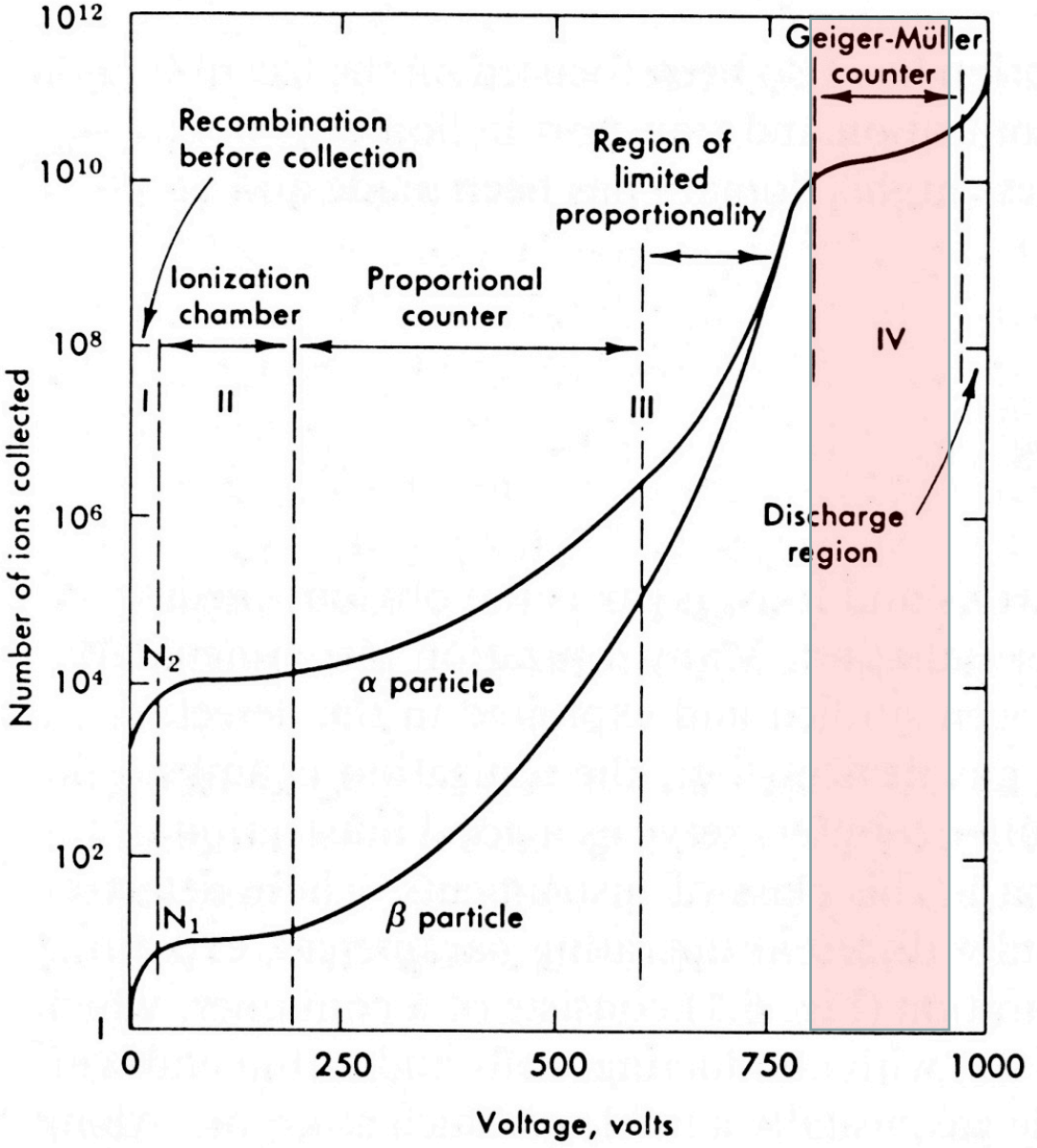
ρ :space charge density



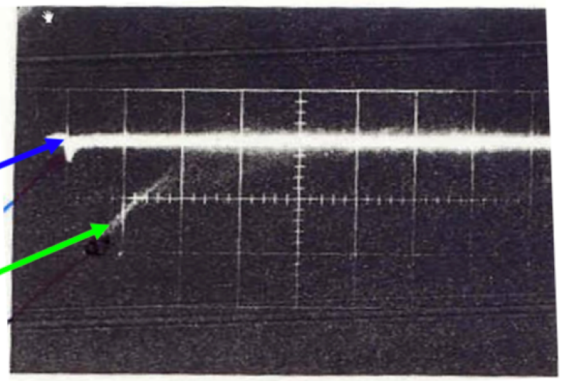
IV. Geiger Müller region

- Secondary avalanches along anode wire, avalanches are created until space charge is sufficient to reduce electrical field and suppresses multiplication
- independent of primary charge no energy measurement possible!

Geiger Müller counter



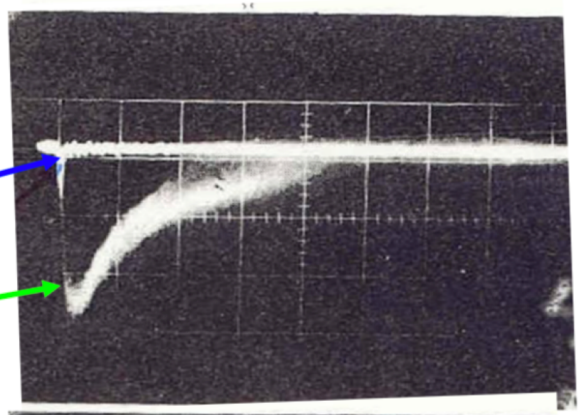
proportional → limited propotional → Geiger



proportional

prop. signal

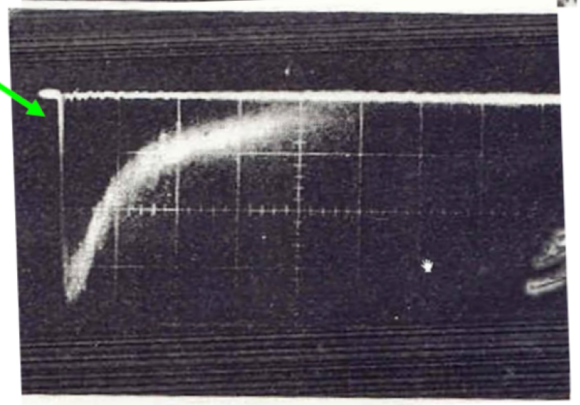
start of
Geiger pulses



limited prop.

prop. signal

Geiger pulses

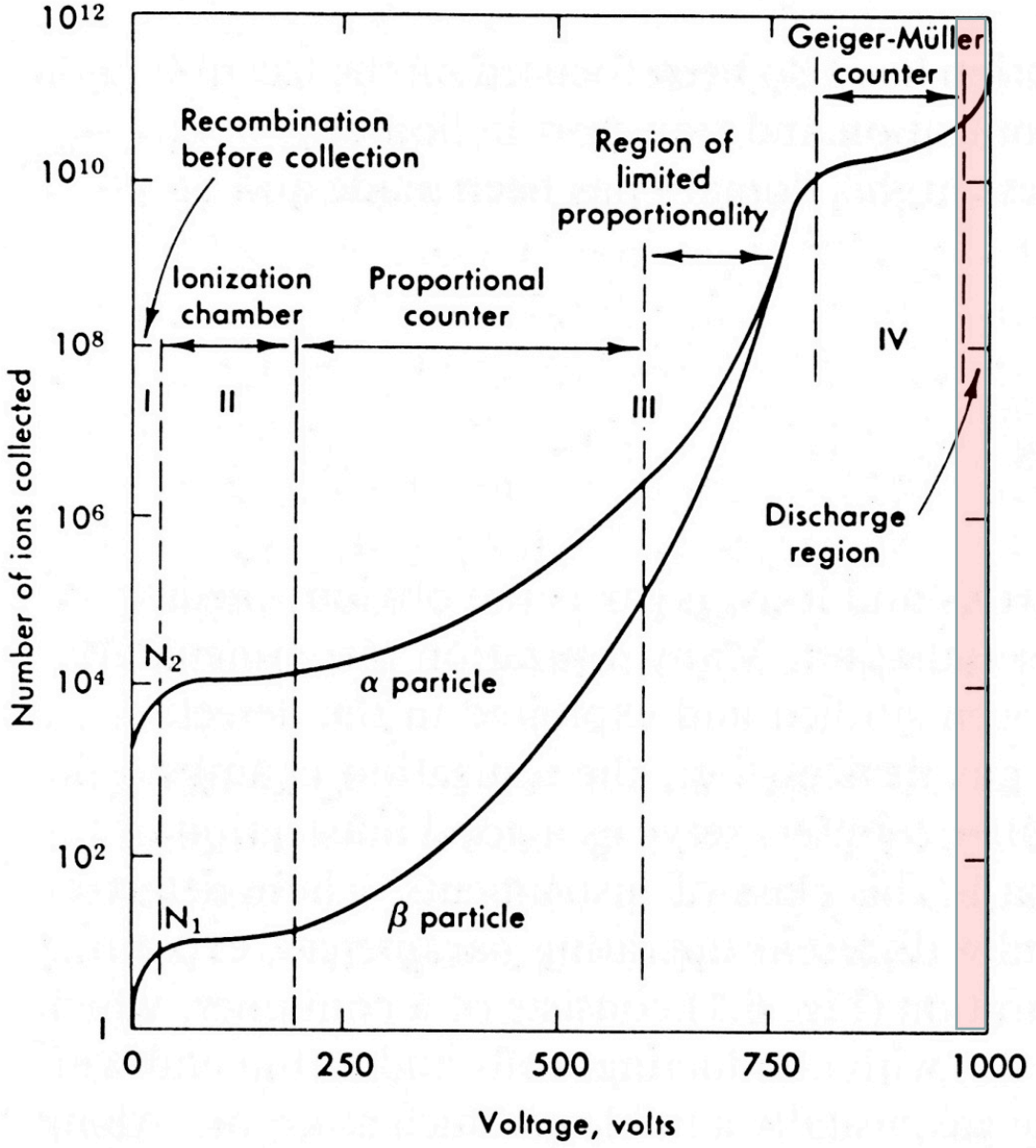


Geiger

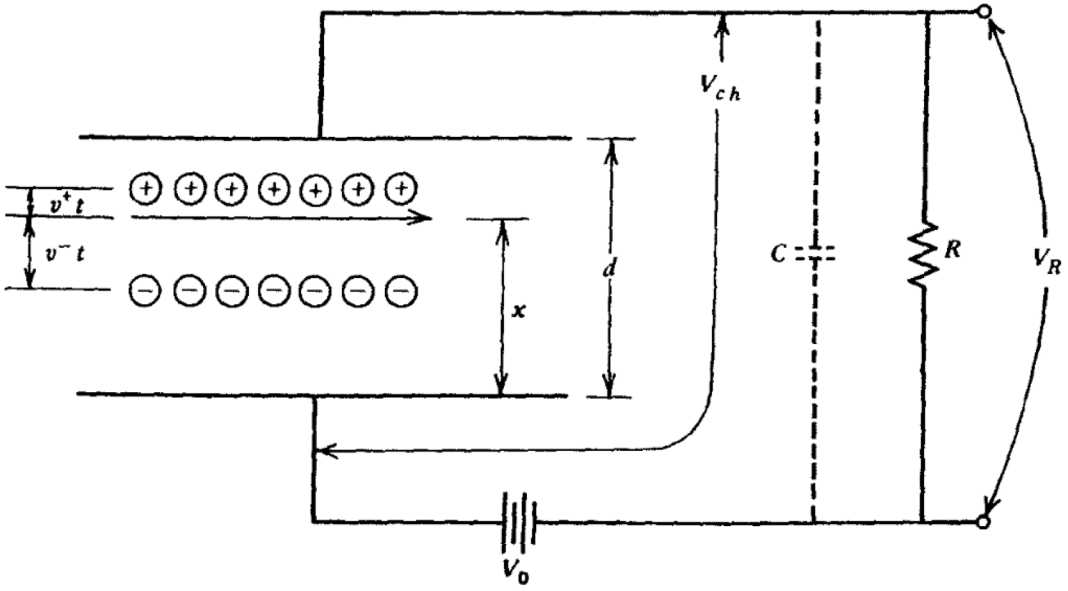
Transition between the proportional and the limited Geiger operation in a multiwire chamber as seen directly on a 50 Ω termination[52]). Horizontal and vertical scales are, respectively, 200 nsec/div. and 10 mV/div. In (a) the small peak at the left shows the detection of 5.9 keV X-rays still in the proportional (or semiproportional) region, while limited Geiger pulses begin to appear; Figs. 74b and c, obtained at increasingly high voltages, show that all detected pulses enter the limited Geiger mode. The time extension of the signal (less than a μsec) proves the limited extension of the Geiger streamer (around 1 cm).

V. Discharge region

Continuous breakdown with or without radiation (to be avoided to prevent damage to the counter)

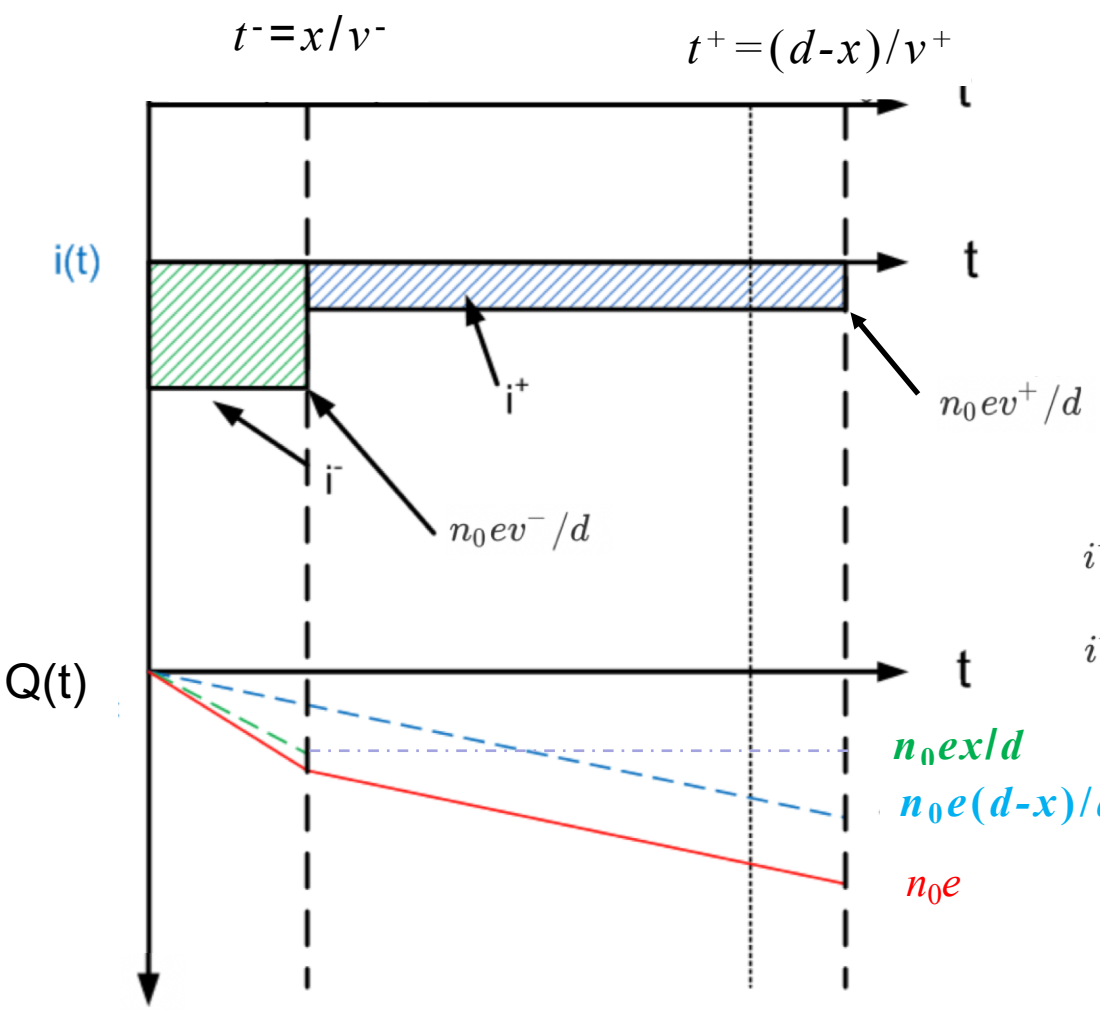


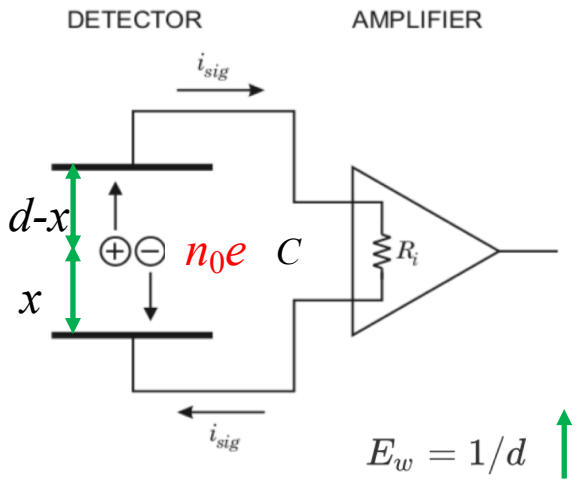
Ion Chamber - Pulse mode



Ionization chamber made by Pierre Curie, c 1895-1900

- V_0 across the load resistance R
- Gas spacing d
- Generation of ion pairs at x





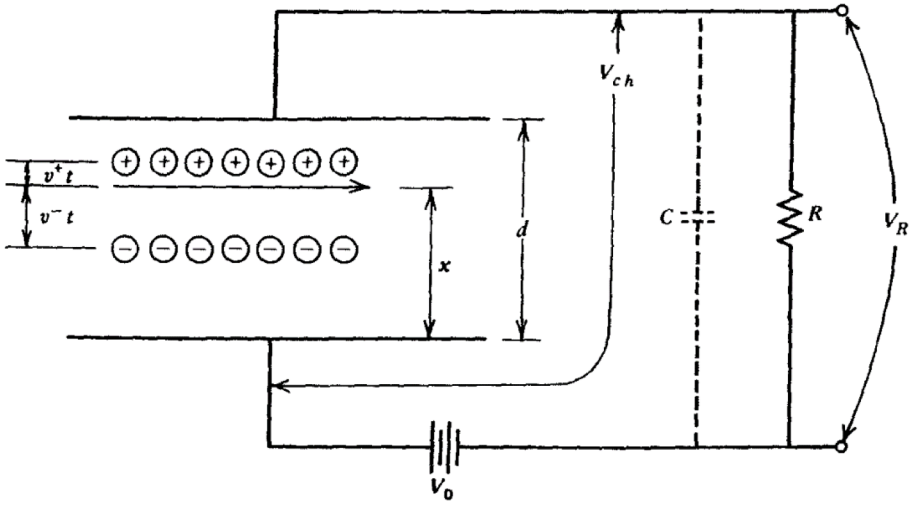
$$i^-(t) = q\vec{E}_w \cdot \vec{v}^- = -n_0 e(-E_w v^-) = n_0 e v^-/d$$

$$i^+(t) = q\vec{E}_w \cdot \vec{v}^+ = n_0 e(E_w v^+) = n_0 e v^+/d$$

$$Q(t) = \frac{n_0 e}{d}(v^- + v^+)t \qquad t \leqslant \frac{x}{v^-}$$

$$Q(t) = \frac{n_0 e}{d} v^+ t \qquad \frac{x}{v^-} < t \leqslant \frac{d-x}{v^+}$$

$$v(t) = Q(t)/C \qquad v_R = \frac{n_0 e}{dC}[(d-x)+x] = \frac{n_0 e}{C}$$

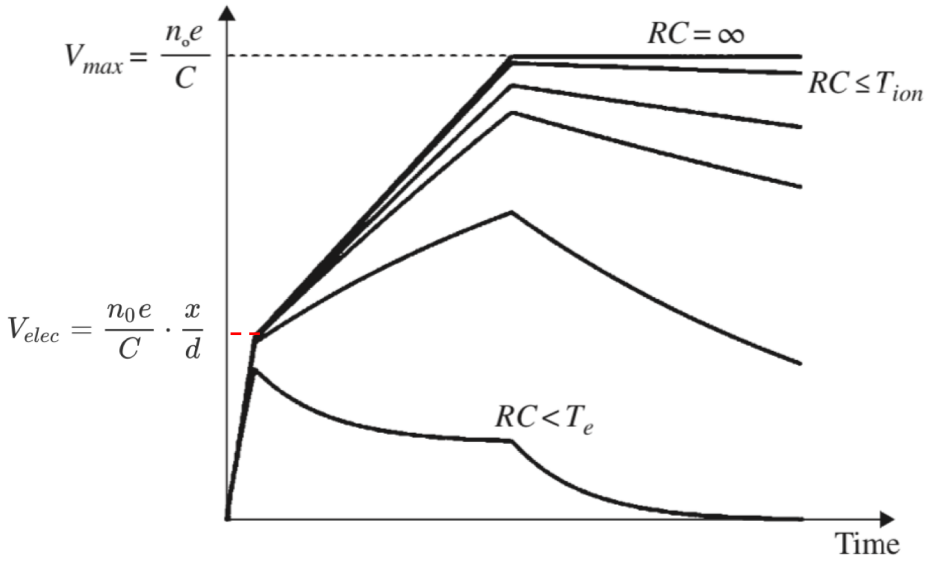


Typical:
v^- = 4 cm/μs; v^+ = 4 cm/ms

Example: 2 x 2 x 10 cm^3 chamber
Electron drift time:
$t^-_{max} = d/v^- = 2cm/(4cm/\mu s) = 500$ ns
Ion drift time:
$t^+_{max} = d/v^+ = 500$ μs

When the collection circuit time constant is very large $RC \gg t^+ \rightarrow V = V_{max} = \frac{n_0 e}{C}$

V: Independent of position of incident ionization

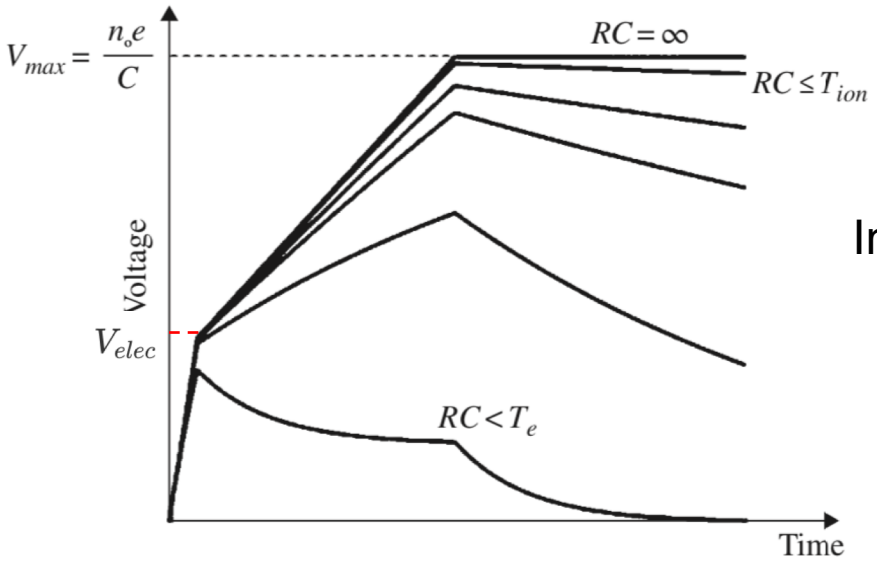


If a 1 MeV charged particle loses all its energy within the chamber,

$$n_0 = \frac{E_0}{W} \cong \frac{10^6 \text{ eV}}{35 \text{ eV/ion pair}} = 2.86 \times 10^4$$

$$V_{max} = \frac{(2.86 \times 10^4)(1.60 \times 10^{-19} \text{ C})}{(10^{-10} \text{ F})} = 4.58 \times 10^{-5} \text{ V}$$

An ionization chamber collects the generated charge (from ionization) without amplification. If we want to see a single ionization(n_0=1) we need an amplification of at least 10,000 times without amplification of the noise.



In electron-sensitive operation, $t^- \ll RC \ll t^+$

- Pulse shape given by electrons

$$V_{elec} = \frac{n_0 e}{C} \cdot \frac{x}{d}$$ (neglecting ion drift)

$V_{elec.}$: sensitive to position of incident radiation

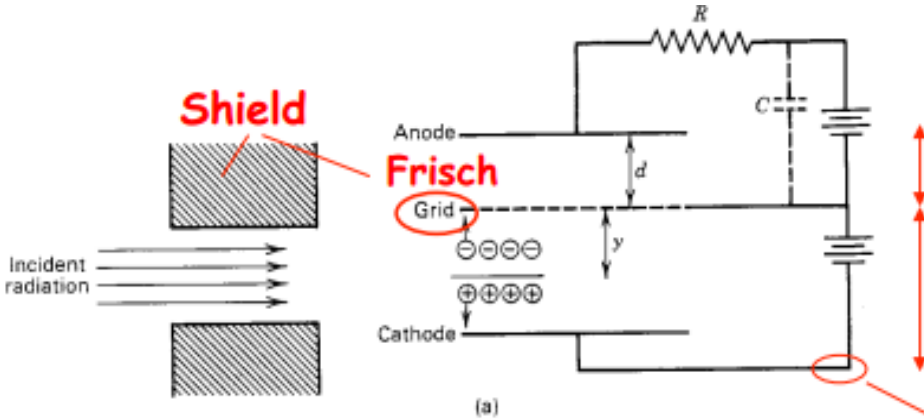
The gridded Ion Chamber

Add a grid at position between the anode and cathode but closer to the anode.

The grid has a high transmission but it shields the anode electrically from the primary ionization.

- The grid is maintained to intermediate potential and is transparent to electrons
- Incident radiation directed only into active volume Cathode-Grid

Signal on anode only generated by electrons that have passed the Frisch grid

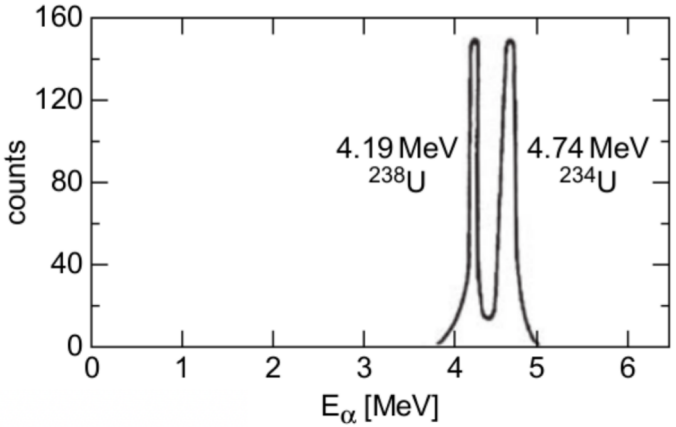


d = 1.6 cm

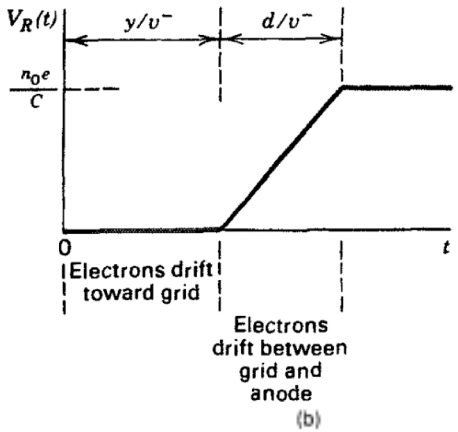
d = 16 cm

(b)

FWHM: ~30keV

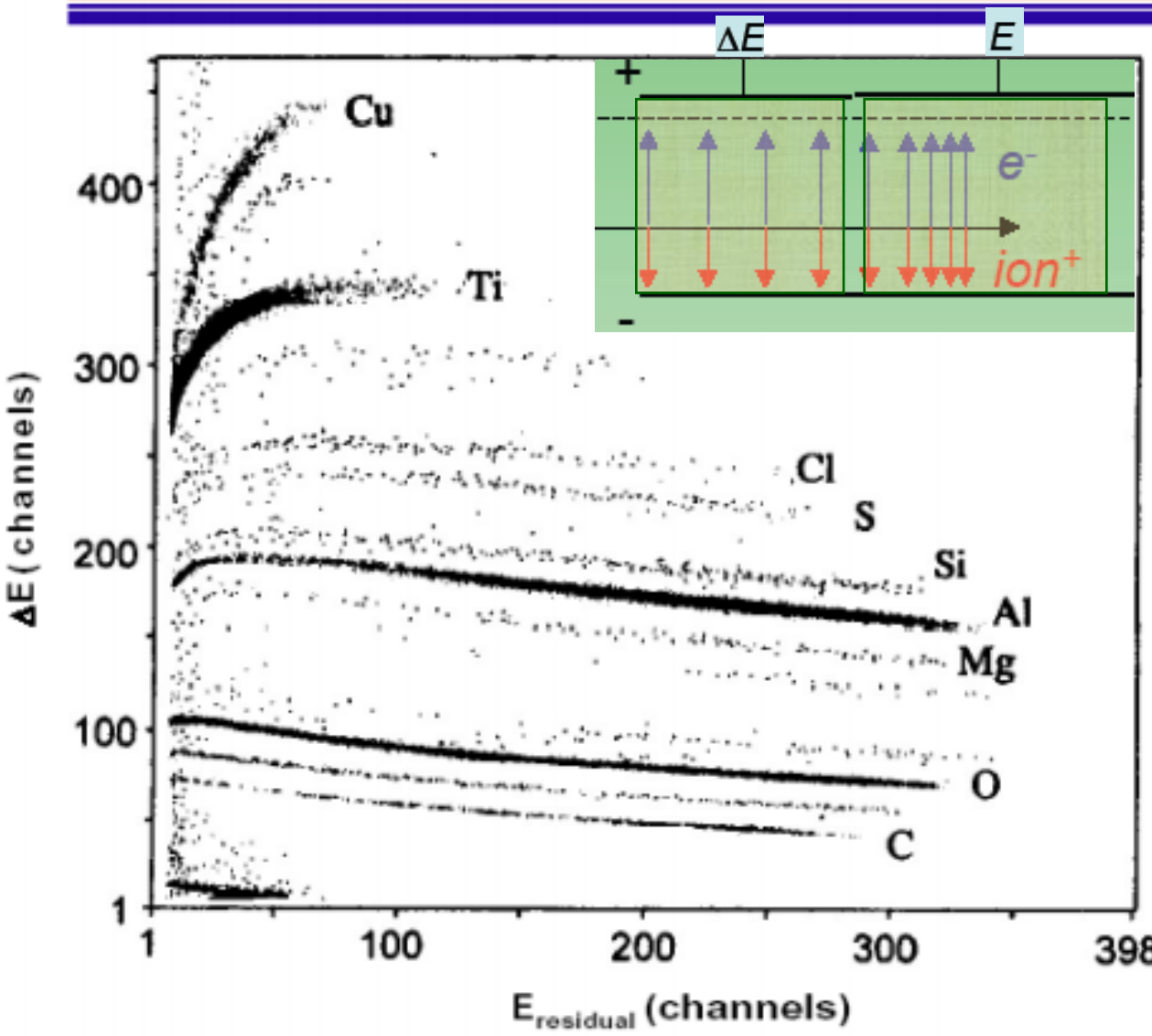


NO resistor
⇒ NO measurable signal



The signal derives from electrons drift only
⇒ NO dependence on slow ion motion !!!

IC for Z identification of reaction products



ICs have excellent resolution in E, Z of charged particles but are slow detectors. Gas IC need very stable HV and gas handling systems.

Energy resolution

$$\sigma_\varepsilon^2 = F\langle n_{ip}\rangle = F\frac{\Delta\varepsilon}{I}$$

F<1 Fano factor

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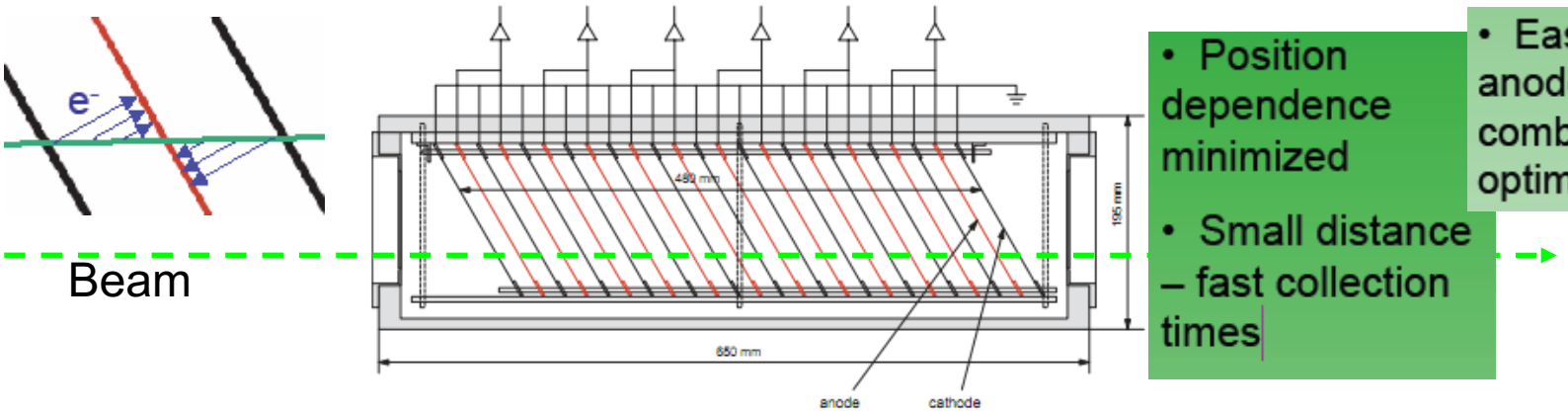
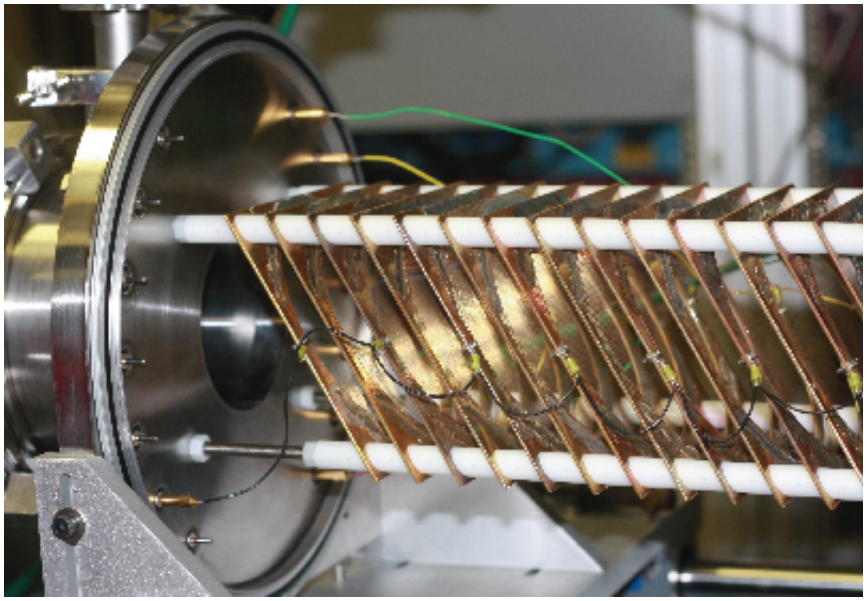
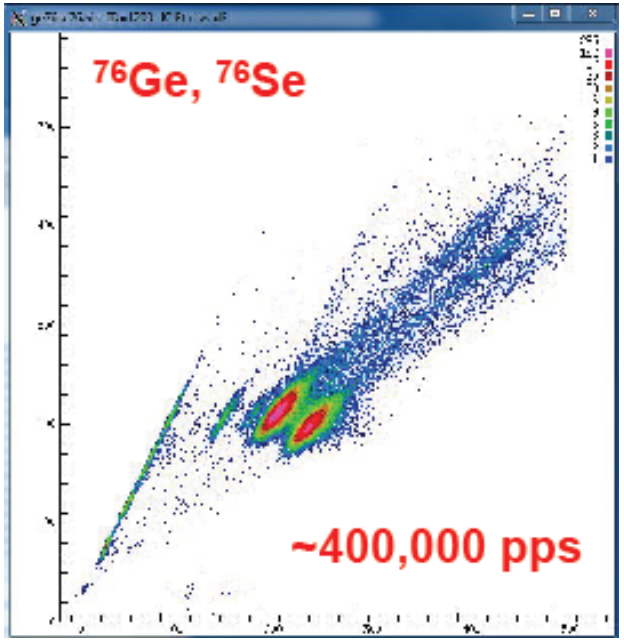


- Position dependence minimized
- Small distance – fast collection times
- Easy to adjust anode combinations to optimize ΔE -E

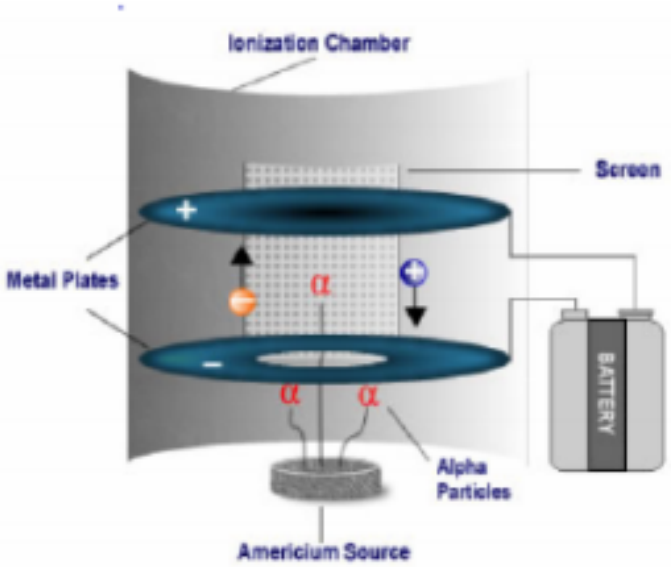
Fig. 1. Cross-sectional view of the tilted electrode gas ionization chamber (TEGIC).

In the TEGIC, electrons and positive ions have an equal potential drop. Only the electron part of the anode pulse is sufficient to obtain ΔE information, and so the positive ion part can be completely disregarded.

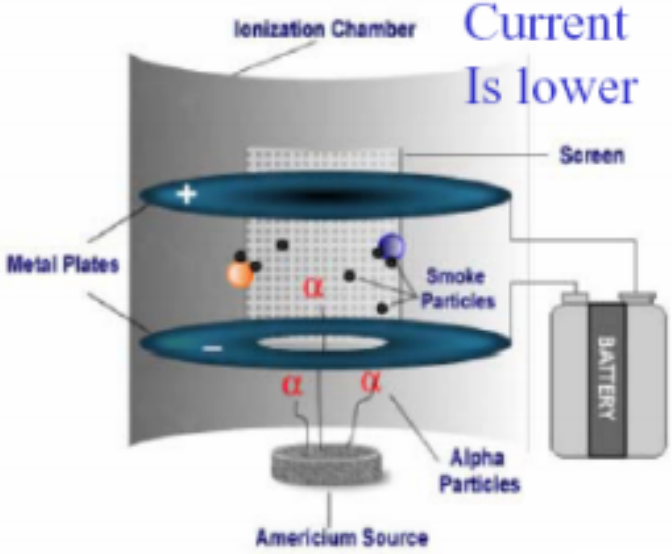




Ionisation chamber as Smoke Detector



Measured Current Is lower

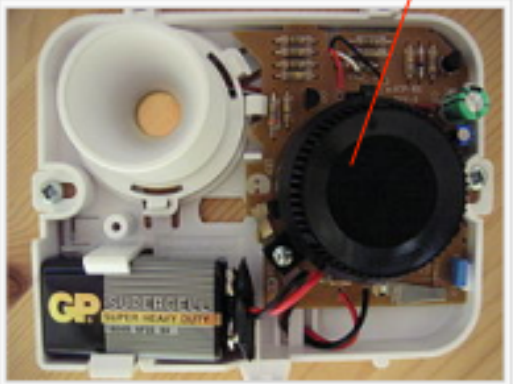


Detect the decrease of induced charge by the alpha source

1 μCu (~ 0.3 μg) of ^{241}Am
τ = 432 y

- α passing through ionization air-chamber produce costant current
- **smoke absorbes α's ⇒ reduced ionization, lower signal, allarm ..**
- α' a have low penetrability: they are stopped by the plastic of detector

Ionization chamber



Inside a basic ionization smoke detector. The black, round structure at the right is the ionization chamber. The white, round structure at the upper left is the piezoelectric buzzer that produces the alarm sound.

Proportional Counter

Choice of Geometry

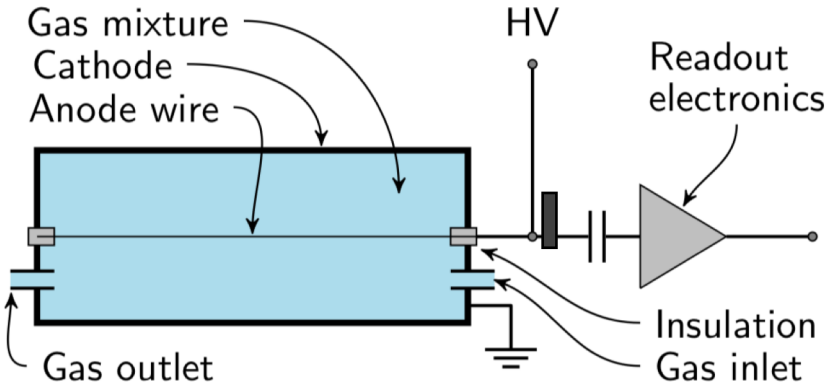
Typical proportional counters are constructed with the cylindrical geometry.

The anode consists of a fine wire that is positioned along the axis of a large hollow tube that serves as cathode.

The electric filed at a radius r is given by

$$E = \frac{1}{r}\frac{V_0}{\ln(b/a)}$$

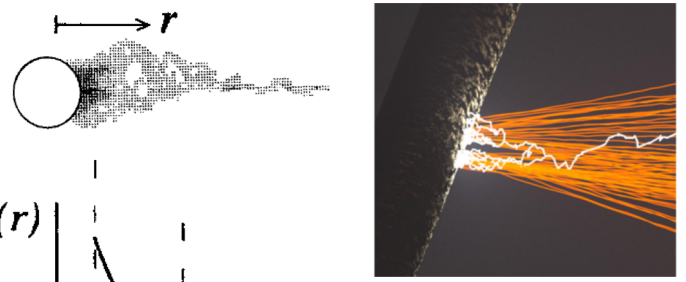
a= anode wire radius.
b= cathode inner radius.

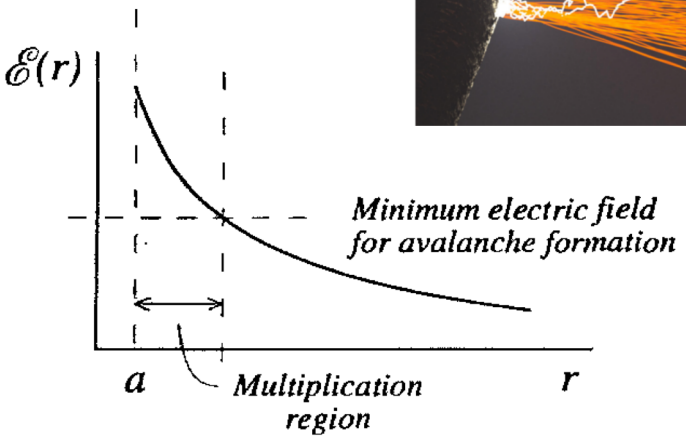


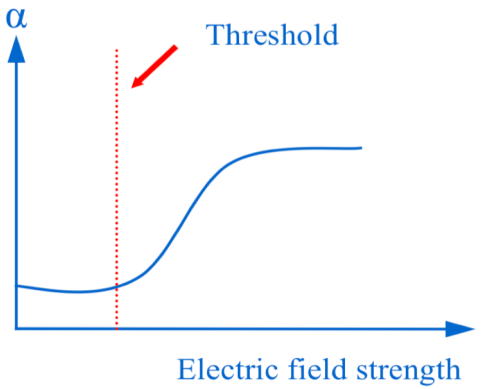
Suppose a voltage V of 2000V is applied with a=80μm and b=1.0cm.

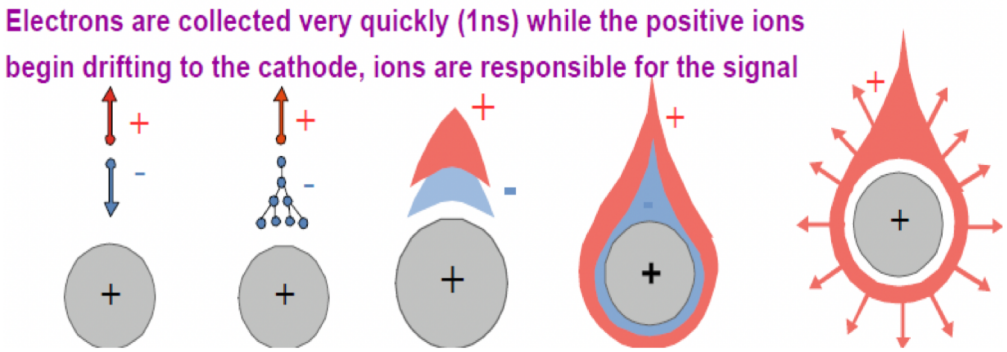
The electric filed at anode surface is 5.18 x 10^6 V/m

- The region of gas multipilication is confined to a very small volume compare to the total volume of the gas. The avalanche occurs very quickly.
- almost all primary ion pairs are formed outside the multiplying region, and the primary electron simply drifts to that region before multiplication take place.
- each electron undergoes the same multiplication precess regardless of its original positon of formation, and the multiplification factor will be same for all original ion pairs.

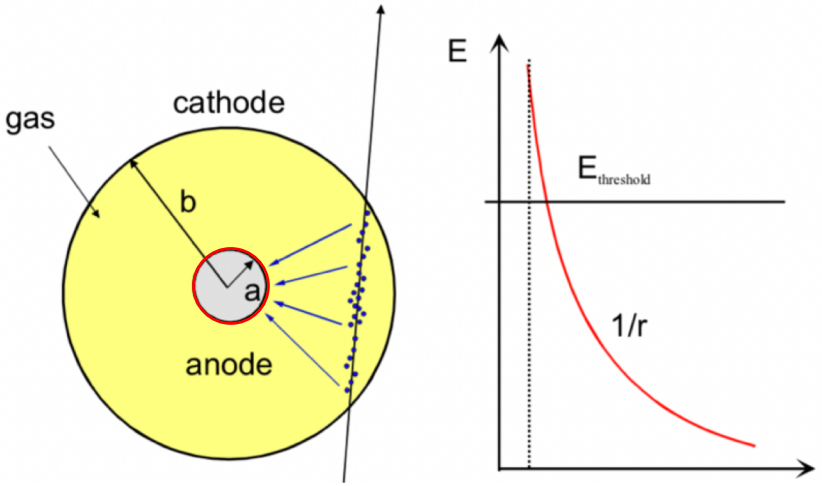








Induced signal in a tube



$$E = \frac{1}{r}\frac{V_0}{\ln(b/a)} \qquad E_w = \frac{1}{r}\frac{1}{\ln(b/a)}$$

Induced current

$$i = Ne \cdot v(r)E_w = Ne \cdot E_w \mu(E)E/p$$
$$= Ne\mu(E)\frac{V}{(ln(b/a))^2}\frac{1}{r^2} \propto \frac{\mu(E)}{r^2}$$

Electron current orders of magnitude greater than ion current because of greater mobility and smaller radii but very fast (down to less than 1ns)

Induced charge

$$Q(t) = \int_0^t i(\tau)d\tau = Ne\int_0^t \frac{dx}{dt}E_w dt$$
$$= Ne\int_{x1}^{x_2} E_w dx$$

$$Q^- = Ne\frac{1}{ln(b/a)}\int_a^x \frac{1}{r}dr = Ne\frac{ln(x/a)}{ln(b/a)}$$

$$Q^+ = Ne\frac{1}{ln(b/a)}\int_x^b \frac{1}{r}dr = Ne\frac{ln(b/x)}{ln(b/a)}$$

For a=25μm, b=1cm, x=28μm

$$Q^-/Q_+ = Ne\frac{ln(x/a)}{ln(b/x)} = 1.9\%$$

- neglect the electron contribution in the pulse formation

The drift velocity of the ions $v^+(r) = \mu E/p = \frac{\mu}{p}\frac{V_0}{ln(b/a)}\frac{1}{r}$

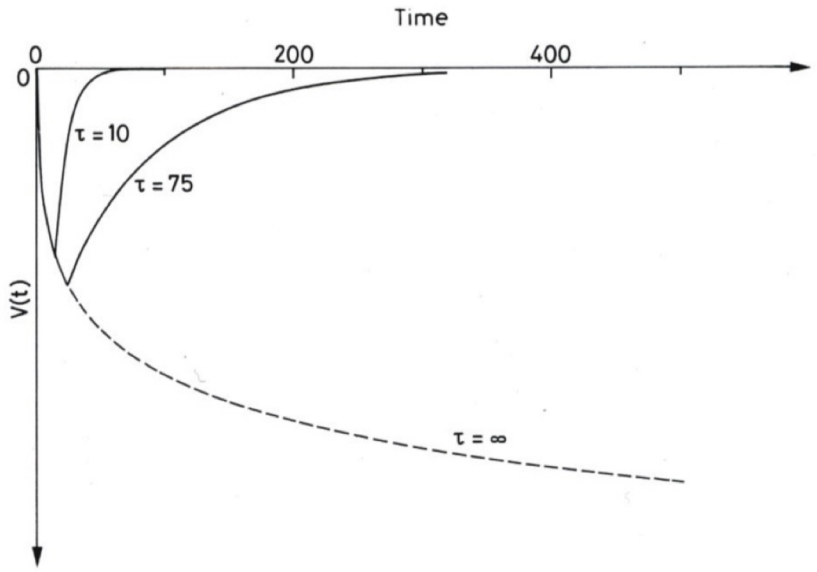
$$\int_a^{r(t)} \frac{dr}{v^+(r)} = \int_0^t dt \quad \Rightarrow \quad r(t) = (2\frac{\mu}{p}\frac{V_0}{ln(b/a)}t + a^2)^{1/2}$$

The time required to collect ions $r(t^+) = b \Rightarrow t^+ = \frac{(b^2 - a^2)ln(b/a)p}{2\mu V_0}$

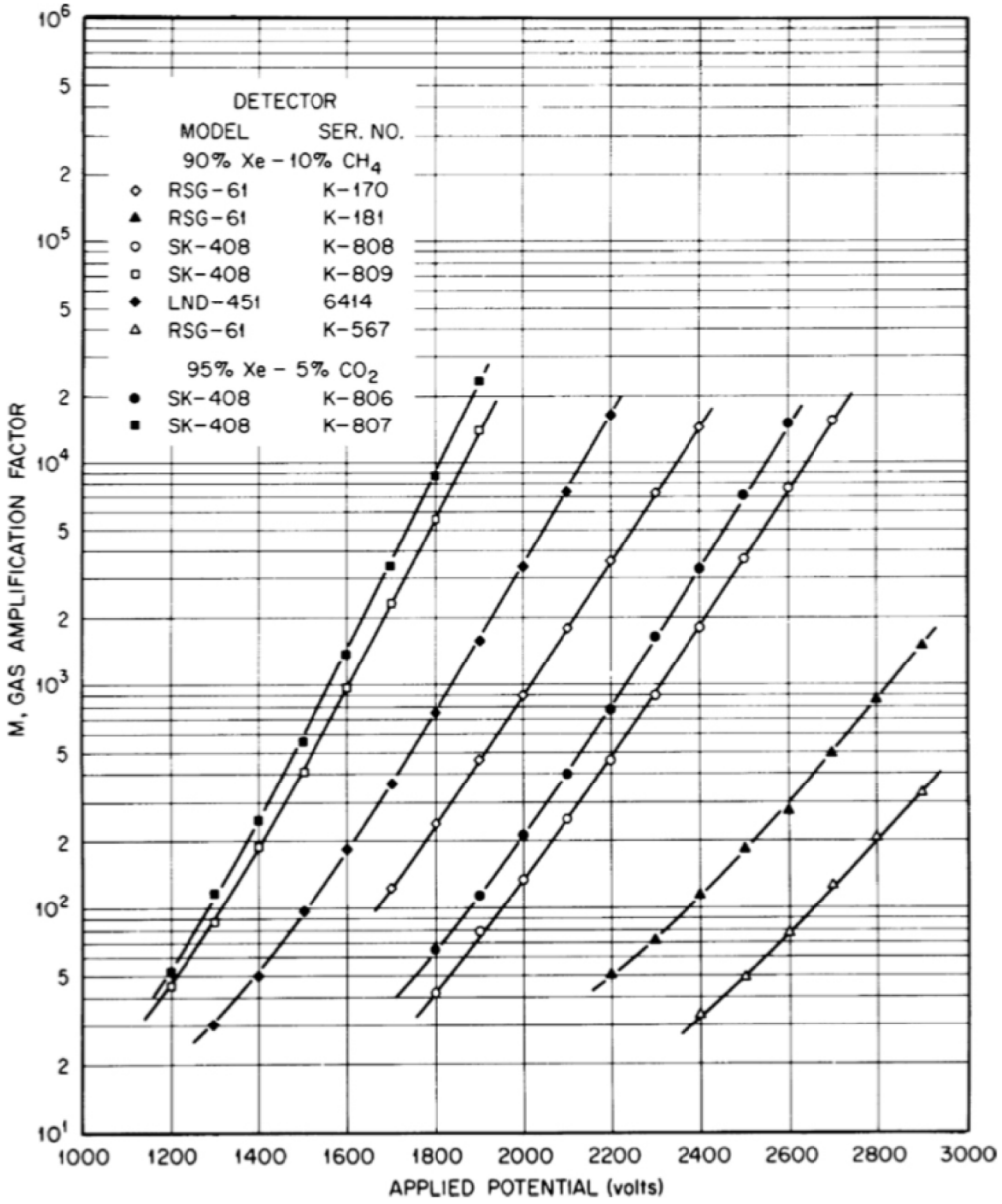
~several hundred μs

$$\mathrm{V}(t) = \frac{Q(t)}{C} = \frac{1}{C}\int_0^{t+} i(\tau)d\tau = \frac{Ne}{C}\frac{1}{\ln(b/a)}\ln\left(\frac{2\mu V_0}{a^2 pln(b/a)}t + 1\right)^{1/2}$$

Pulse shape with different time constants



Gas multiplication factor



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

ΔV=the potential difference through which an electron moves between successive ionization events.

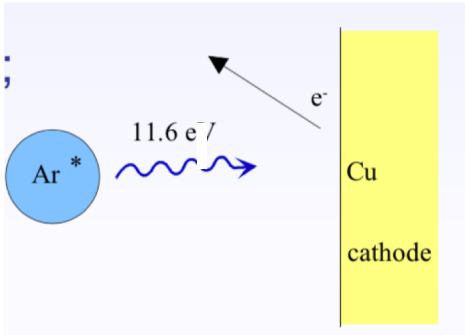
K=minimum value of E/p below which multiplication cannot occur.

Choice of Fill Gas

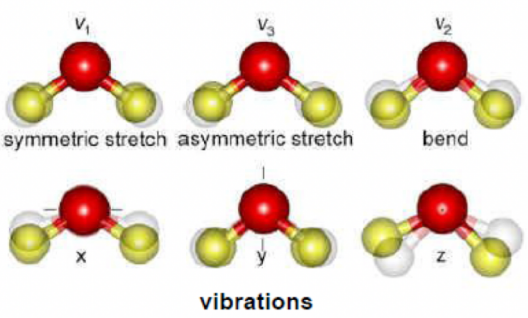
Choice is governed by several factors:

- Low working voltage
- High gain
- Good proportionality
- High rate capability

- Usually these conditions are met by gas mixtures rather than pure gases
- Preferred usually: Argon→ high specific ionization and low cost
- Pure Argon cannot be operated at gains of more then 10^3-10^4 , above that continuous discharge will occur, photons will be emitted by the excited Argon atoms in the avalanche with high enough energy to ionize the cathode by photo-electric effect →further avalnches->Permanent discharge!)



- Remedy of discharge: Mix in a small amount of a small molecule – molecules have vibrational modes that can absorb energy and they tend not to radiate UV photons and also tend to collect the charge due to charge-exchange reactions.



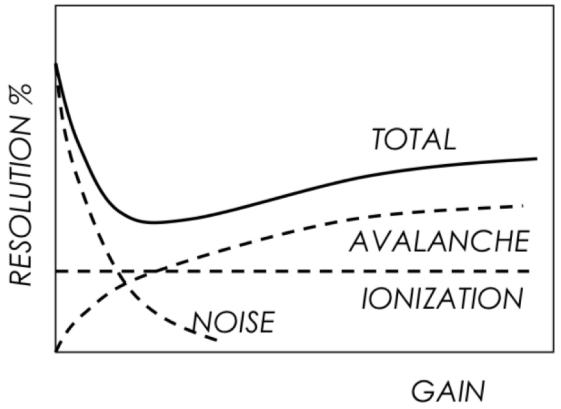
猝灭剂

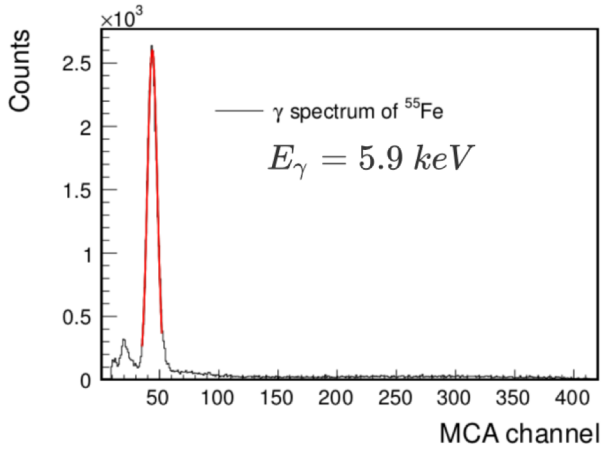
- Quencher: addition of polyatomic gas like Methane, Alcohol, isobutane, CO_2, or BF_3, which absorb the emitted photons and then dissipate their energy through dissociation or elastic collisions
- Conventional proportional counters filled with P10 gas (90% Argon+ 10% Methane) have gains of 10^6
- Gain can be further increased to 10^7 by adding electronegative gas such as freon(CF_3Br), these gases do not only absorb photons but can also trap electrons extracted from the cathode (because of the high electric field) before they reach the anode and cause avalanches

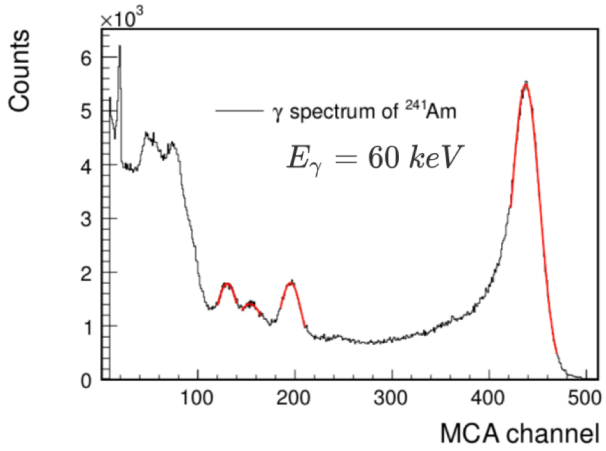
Energy resolution

* The energy resolution is a convolution of ionization statistics, avalanche spread and electronics noise:

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{\sigma_N}{N}\right)^2 + \left(\frac{\sigma_M}{M}\right)^2 + \left(\frac{\sigma_{el}}{M}\right)^2$$



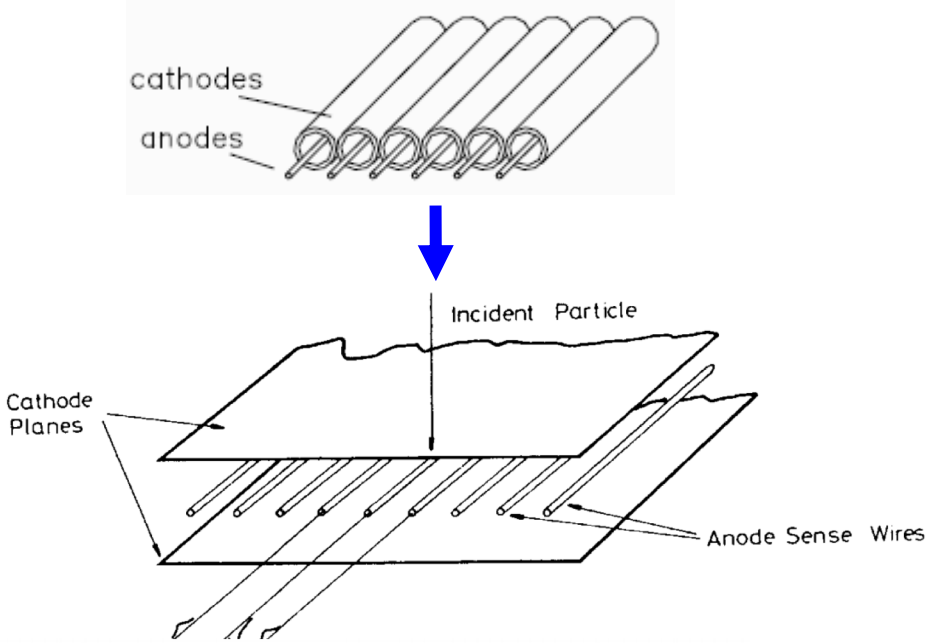




Detector at moderate voltage of 2.25 kV.

The Multiwire Proportional Counter(MWPC)

Charpak showed that an array of many closely spaced anode wires in the same chamber act like independent prop. counters



–Plane layer of proportional chambers without intermediate walls

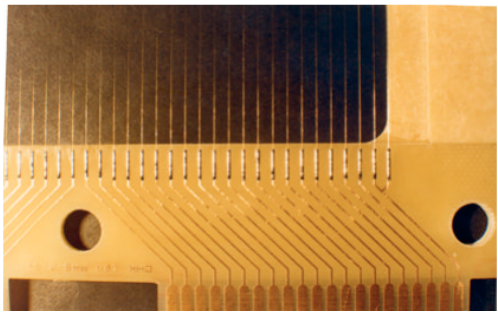
–Anode wire, typ. gold plated tungsten (10-30 μm)

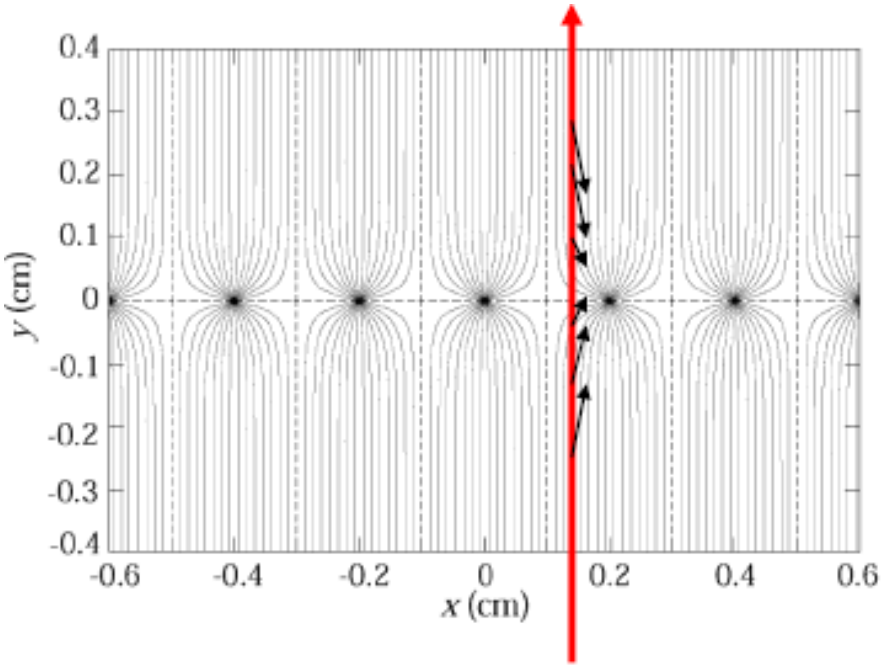
–Typ. distance d = 2 mm

–Gains of 10^7

Large size MWPC (1972)

Compared to spark chamber and bubble chamber, MWPC are much faster, improving spatial resolution and time accuracy, no significant dead time and radiation hardness.





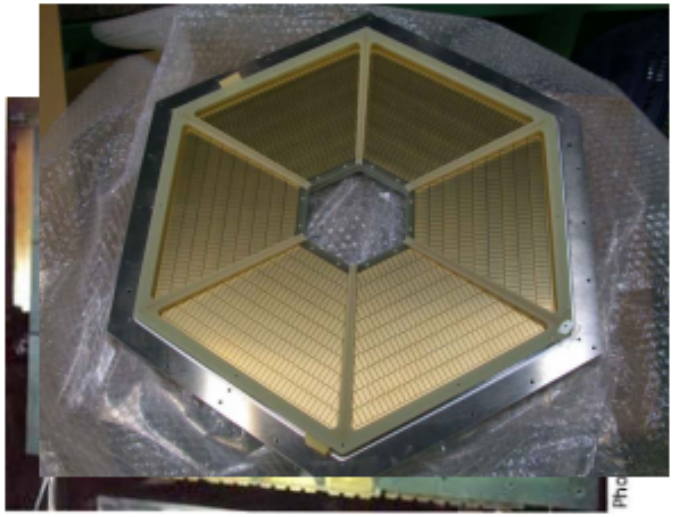
Electrons (v≈5cm/μs) are collected within ≈ 100ns. The ion tail can be eliminated by electronics filters → pulses of <100ns length.

→ 1MHz/wire rate capabiliy !

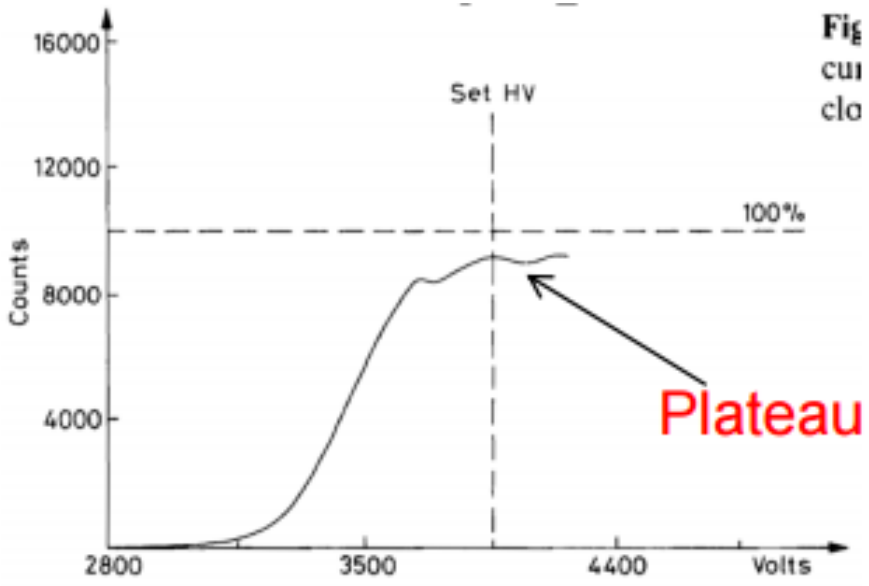
Bubble Chamber with 10 Hz !

tracking of charged particles,
some PID capabilities via dE/dx
Large area coverage, high rate capability

Picture of MWPC wire frame (5 layers)
With cathodes removed



MWPCs can have very high efficiencies



Chamber Gas

Pressure: usually 1atm

Depends on the purpose:

P10 for energy measurement

magic gas for time measurement

Magic gas: Ar(75%), isobutane(24.5%) and freon-^{13}B1 (0.5%)

Gains of 10^7 → at this level of multiplication the signals are saturated and independent of energy

The magic gas increases the path length of the electrons

(ultraviolet photons emitted in the avalanches near the anode can extend the avalanche radially outward)

→ contribution of electron signal becomes significant

→ fast signal due to short drift time of electrons

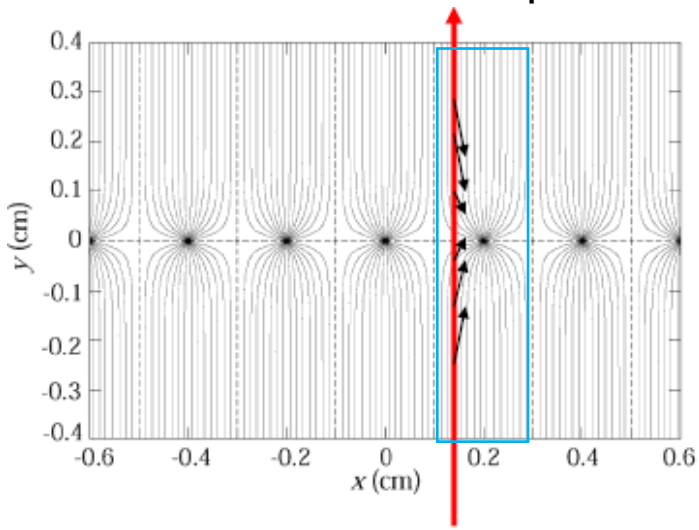
→ good timing resolution (~ ns)

Readout methods

$\leftarrow d \rightarrow$

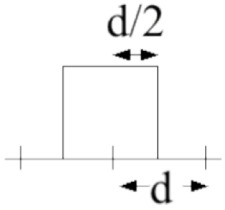
Standard method:

each anode wire is considered a separate detector connected to its own electronics



- Resolution: know only hit wire

Flat probability distribution



$$\langle x \rangle = 0; \text{ where } x = x' - x'_{\text{wire}}$$

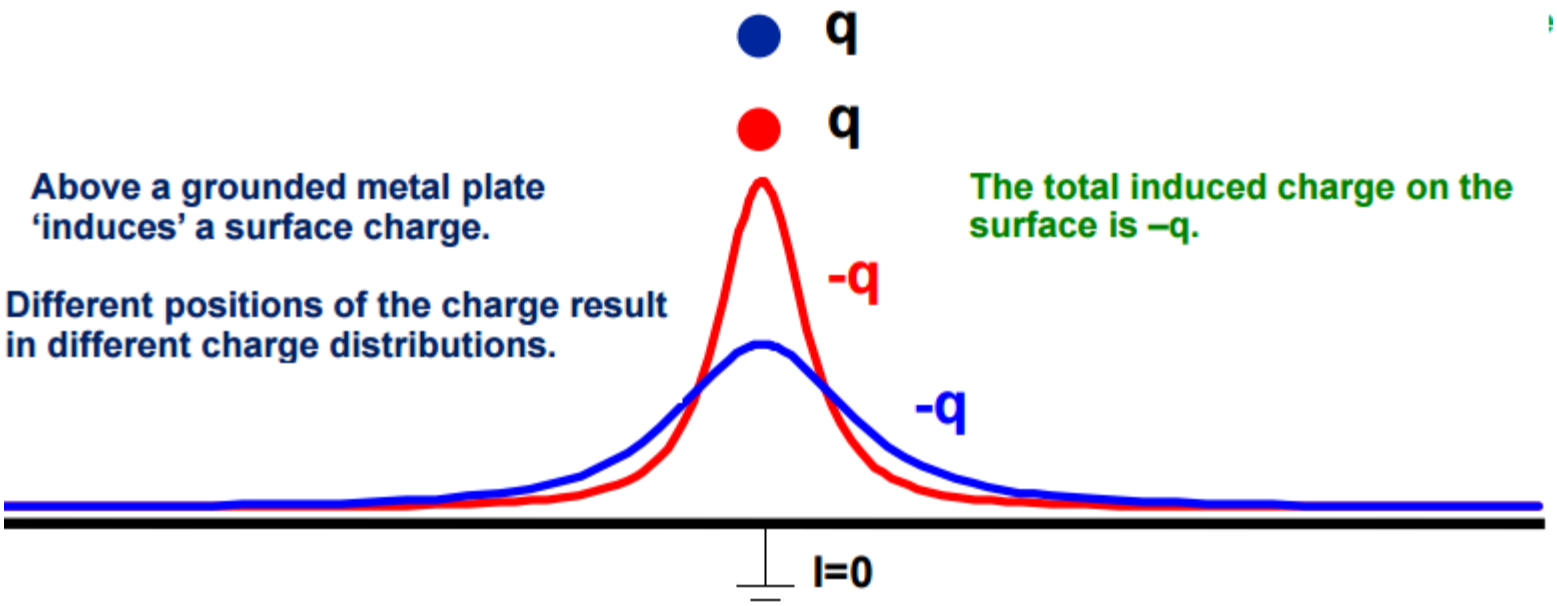
$$\langle x^2 \rangle = \frac{\int_0^{d/2} x^2 dx}{\int_0^{d/2} dx} = \frac{2}{d}\frac{x^3}{3}\Big|_0^{d/2} = \frac{d^2}{12}$$

Gaussian equivalent:

$$\sigma = \sqrt{\langle x^2 \rangle} = \frac{d}{2\sqrt{3}}$$

$$\approx 600\mu,\ d = 2\,\text{mm}$$

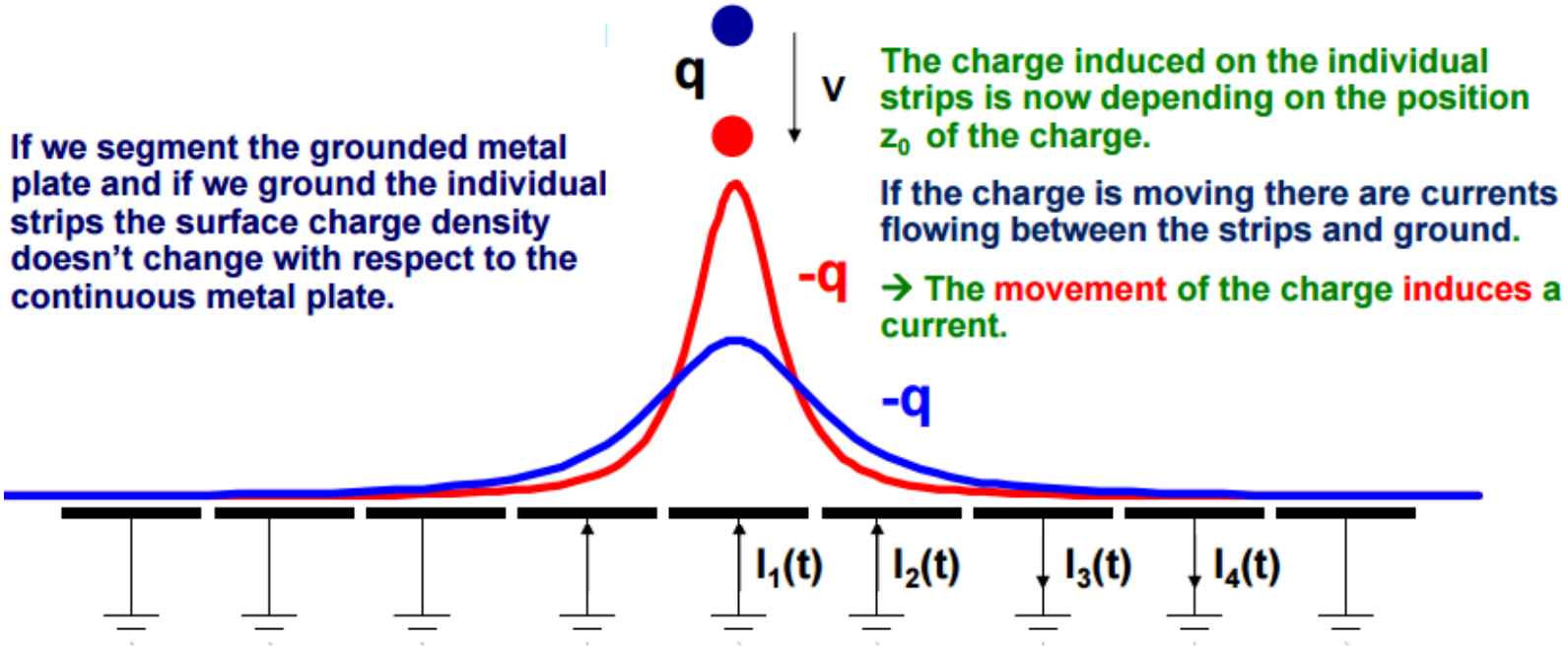
Principle of Signal Induction by Moving Charges



Above a grounded metal plate 'induces' a surface charge.

Different positions of the charge result in different charge distributions.

The total induced charge on the surface is –q.



If we segment the grounded metal plate and if we ground the individual strips the surface charge density doesn't change with respect to the continuous metal plate.

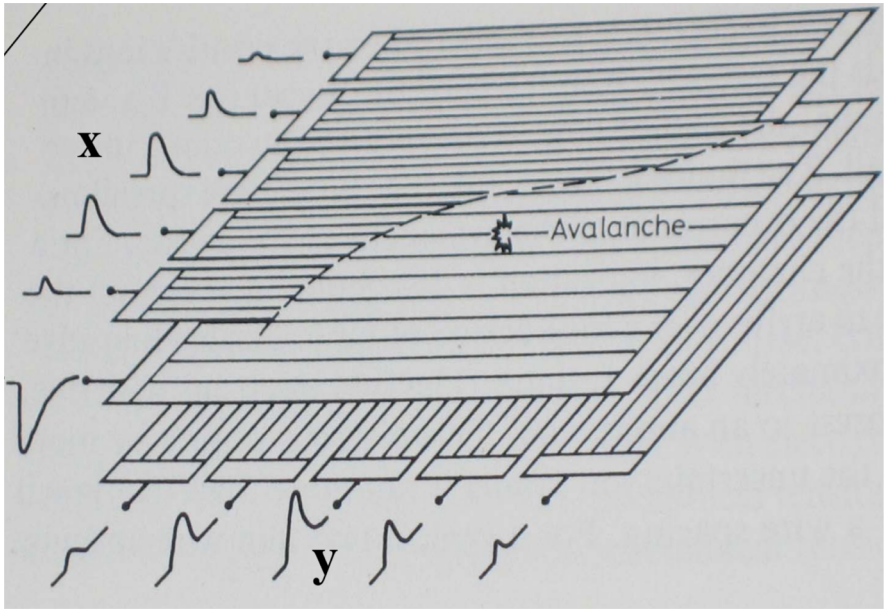
The charge induced on the individual strips is now depending on the position z_0 of the charge.

If the charge is moving there are currents flowing between the strips and ground.

→ The movement of the charge induces a current.

Center of gravity method:

Read-out not only on anode wires, but also on cathodes - segmentation of cathodes. Charge sharing allows for more precise measurement of center of gravity resolution of y coordinate (along the wire) of ≥ 50 µm possible

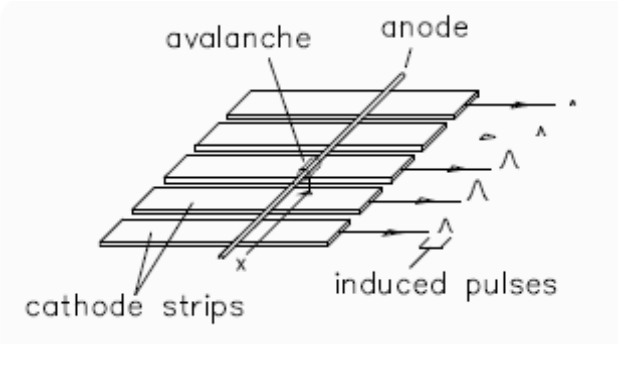


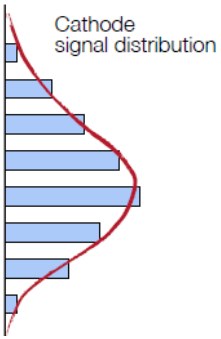
$$\bar{x} = \sum_i x_i P(x_i) / \sum_i P(x_i)$$

The center of gravity of the induced charge distribution on cathode strips provides the X and Y projections of the avalanche position:

$$X = \frac{\sum_i X_i A_i(X)}{\sum_i A_i(X)} \qquad Y = \frac{\sum_i Y_i A_i(Y)}{\sum_i A_i(Y)}$$

- X_i, Y_i: Coordinates of the strips
- $A_i(X)$, $A_i(Y)$: Charge on strips





σ_y = 50 - 300 µm

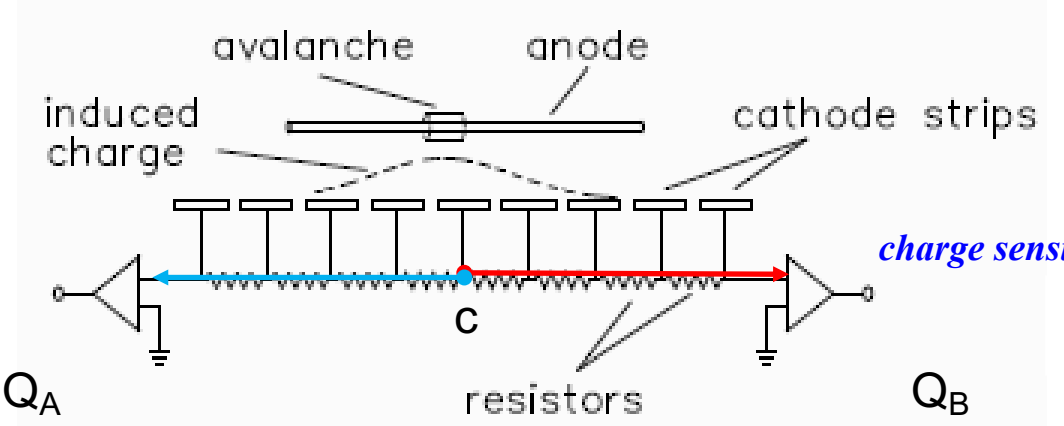
Direct readout method

- readout channel per resolution element

Interpolating readout method

- less electronics

- **Charge division: Resistive wires**

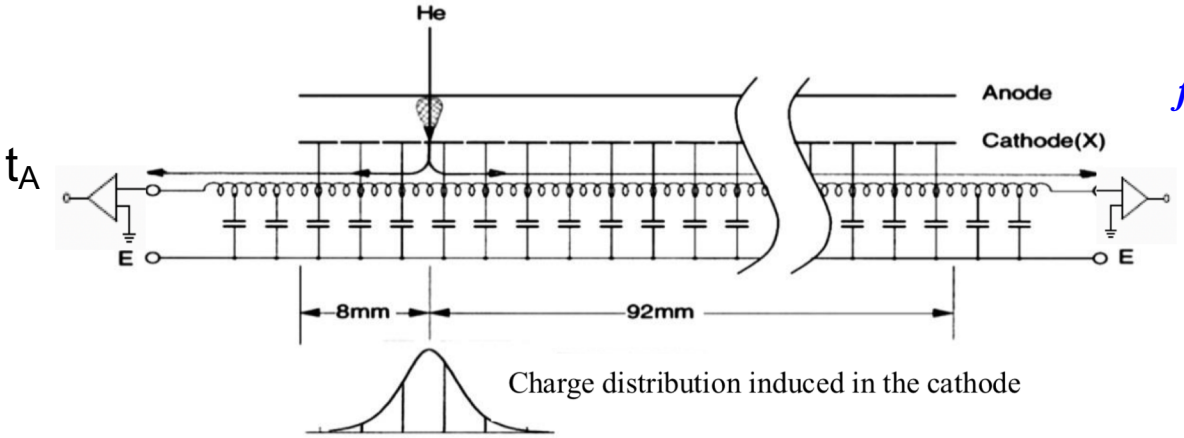


charge sensitive preamplifier

$$v_c = i_A R_A = i_B R_B$$

$$x = \frac{Q_B - Q_A}{Q_A + Q_B} L$$

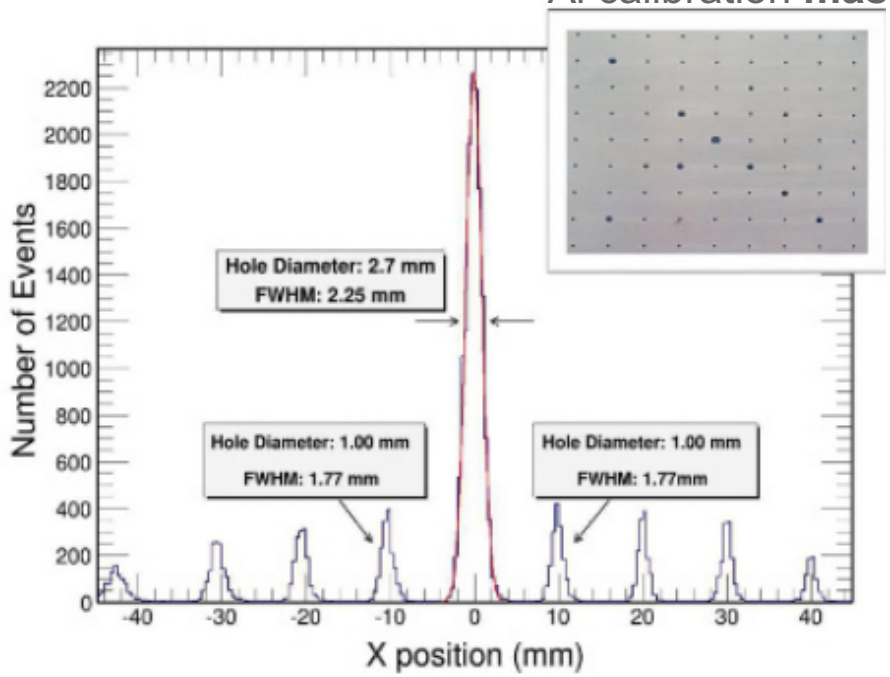
- **Time difference : Delay lines**



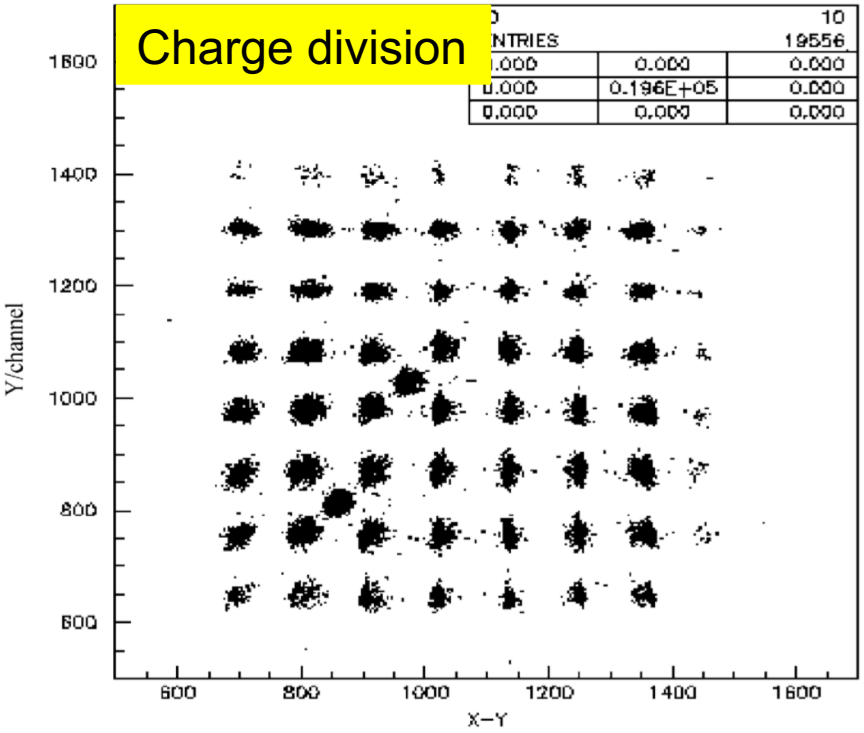
fast time amplifier

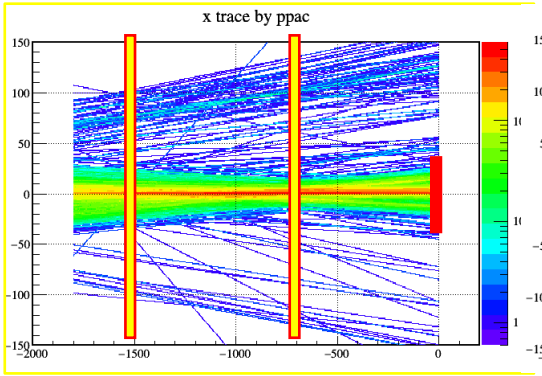
$$x = (t_A - t_B)\frac{L}{2T_{delay}}$$

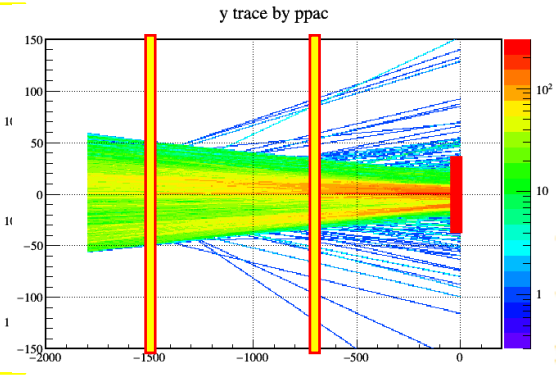
Al calibration **mask**

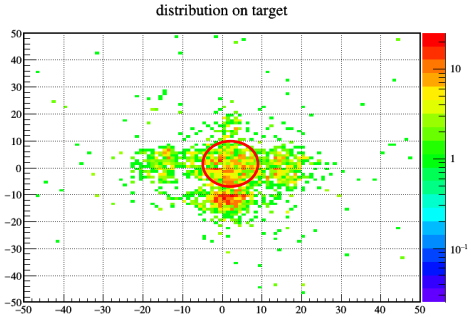


Charge division

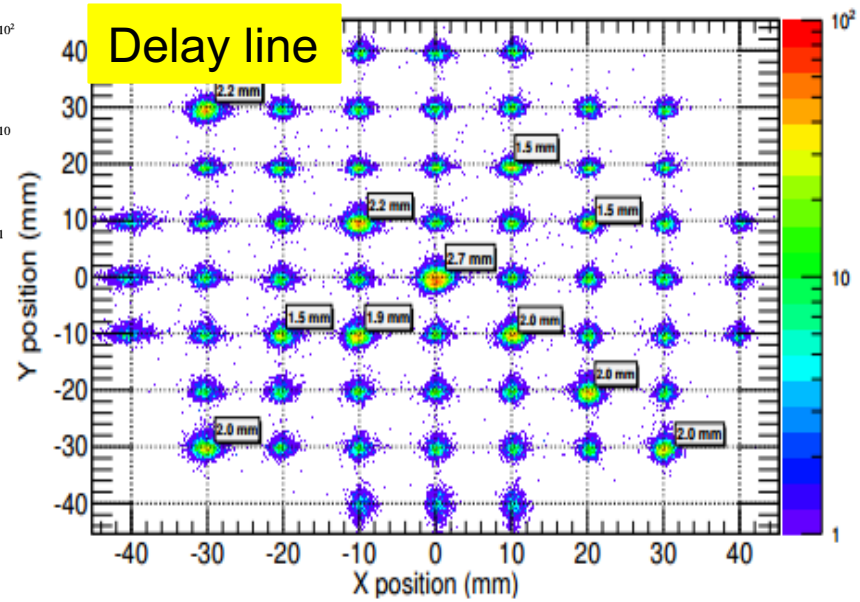


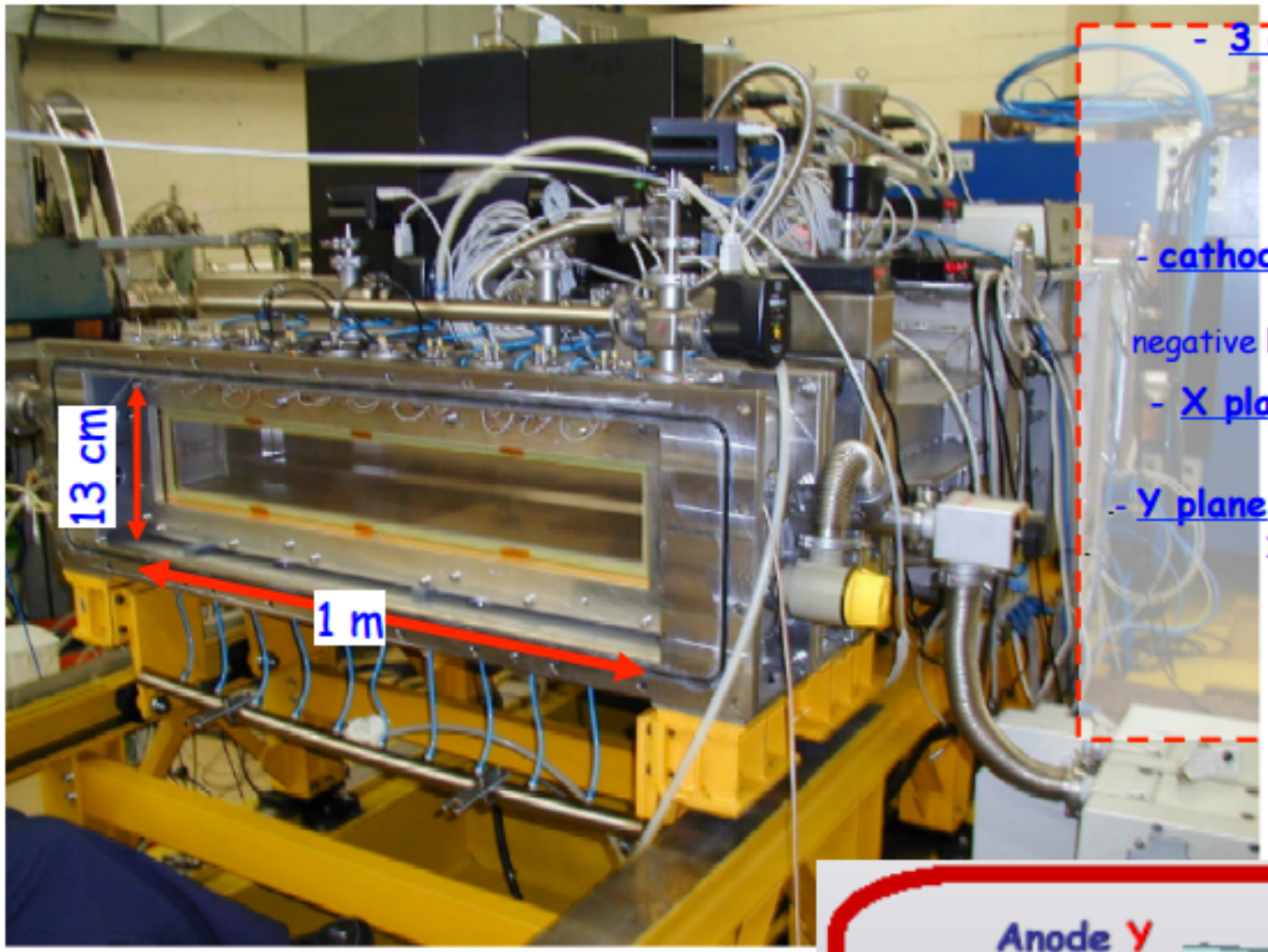




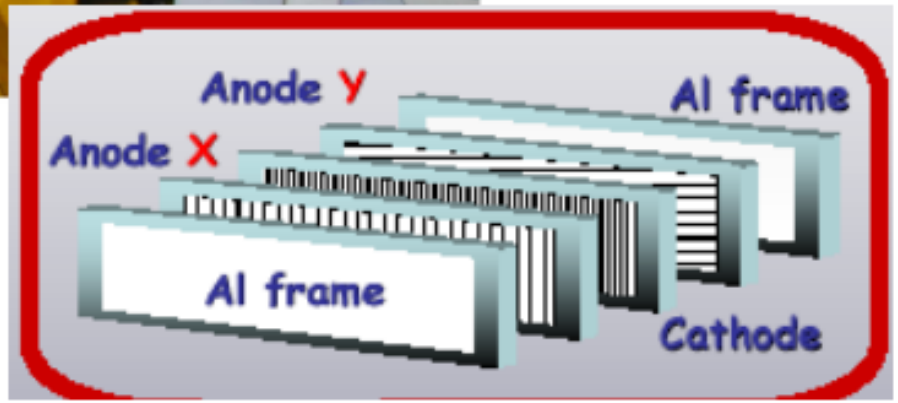


Delay line





- **3 electrode structure**:
  central cathod
  2 anodic wire planes
  (X and Y)
- **cathode**: 3300 wires of 20μm
  0.3 mm spacing
  negative high voltage: 500-600 V
- **X plane**: 10 x 100 wires each
  1mm spacing
- **Y plane**: common to all cathode,
  130 wires, 1 m long, 1mm steps
- **spatial resolution**:
  ΔX ~ 1mm,
  ΔY ~ 2mm



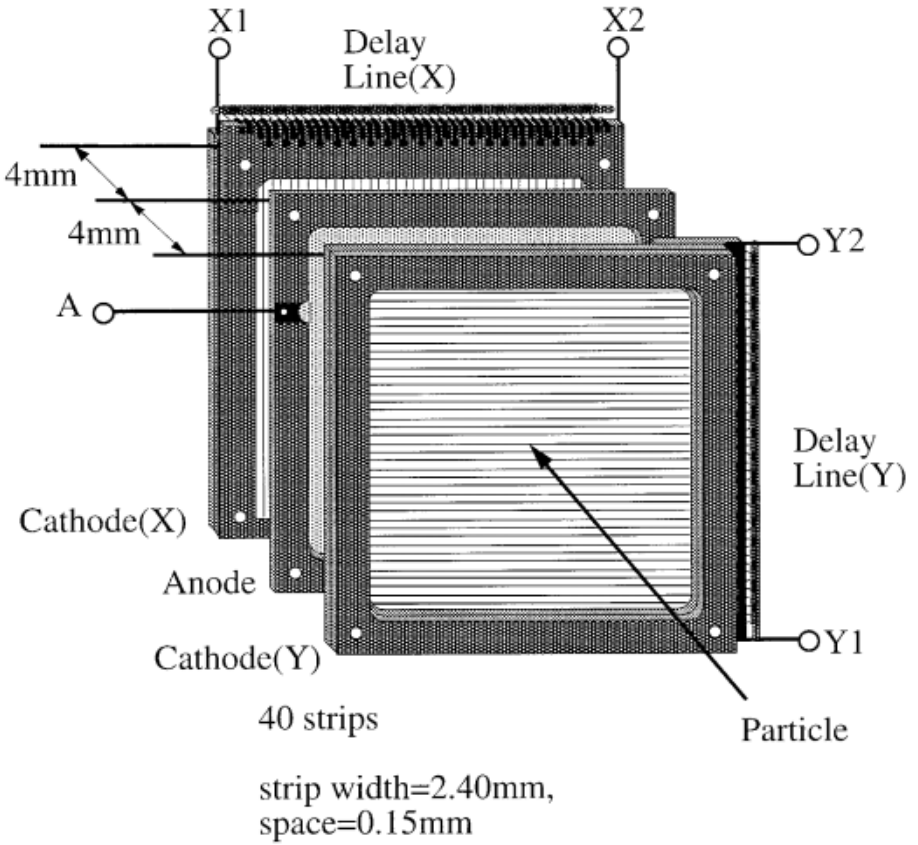
MWPPAC: the Focal plane detector of the PRISMA spectrometer at LNL Laboratory (Padova)

The Parallel Plate Avalanche Chamber(PPAC)

A PPAC consists of two thin parallel stretched foils with a very low gas pressure in between.

Under low pressure condition: p: 1 - 20 mbar; V: a few hundred volts

Typically E/P~ 300V/cm-mbar,
sufficient to ensure the proportional regime



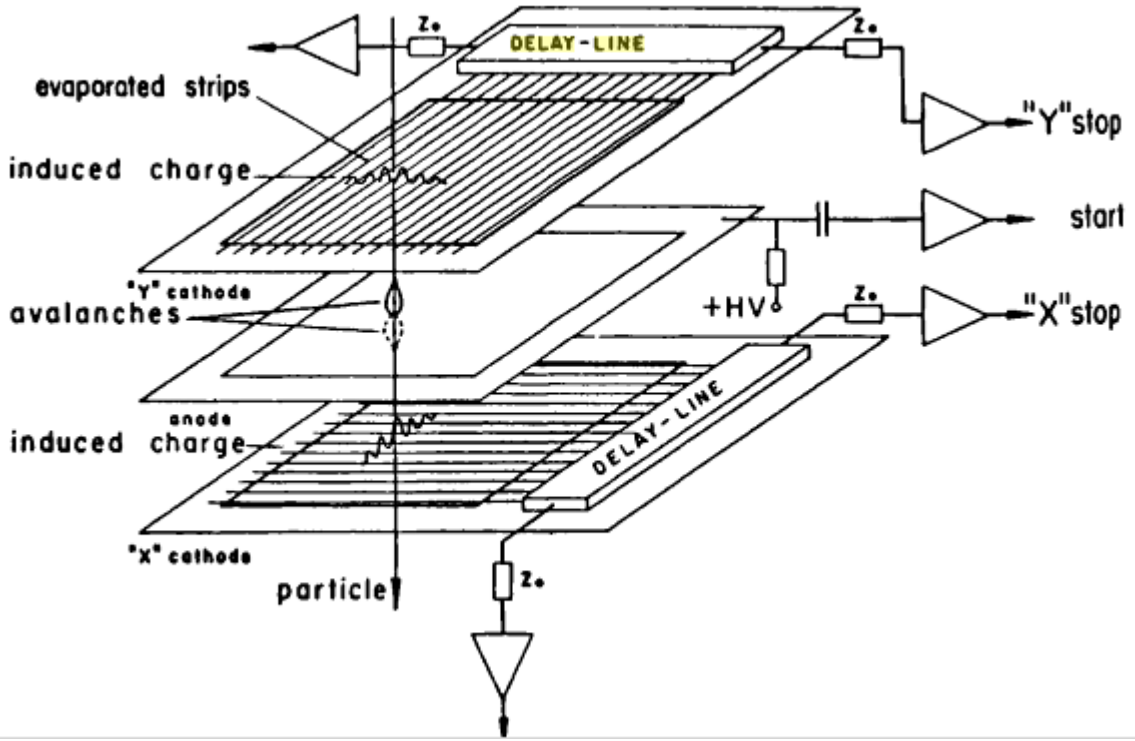
Electrons released gain enough energy to induce immediate secondary ionization in the homogeneous electric field, and a Townsend avalanche is formed

Gas: isobutane ;Gain: a few thousands

mainly used for heavy ion detection:
charged particle tracking

Higer gain: Low pressure multiwire proportional counter

Nucl. Instr. and Meth. A 431 (1999) 476.

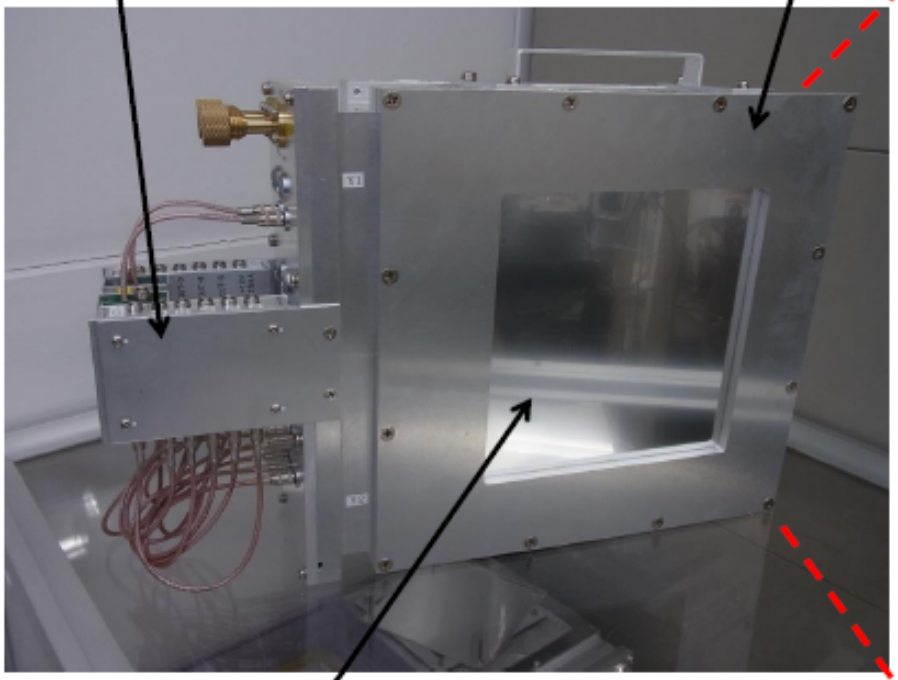


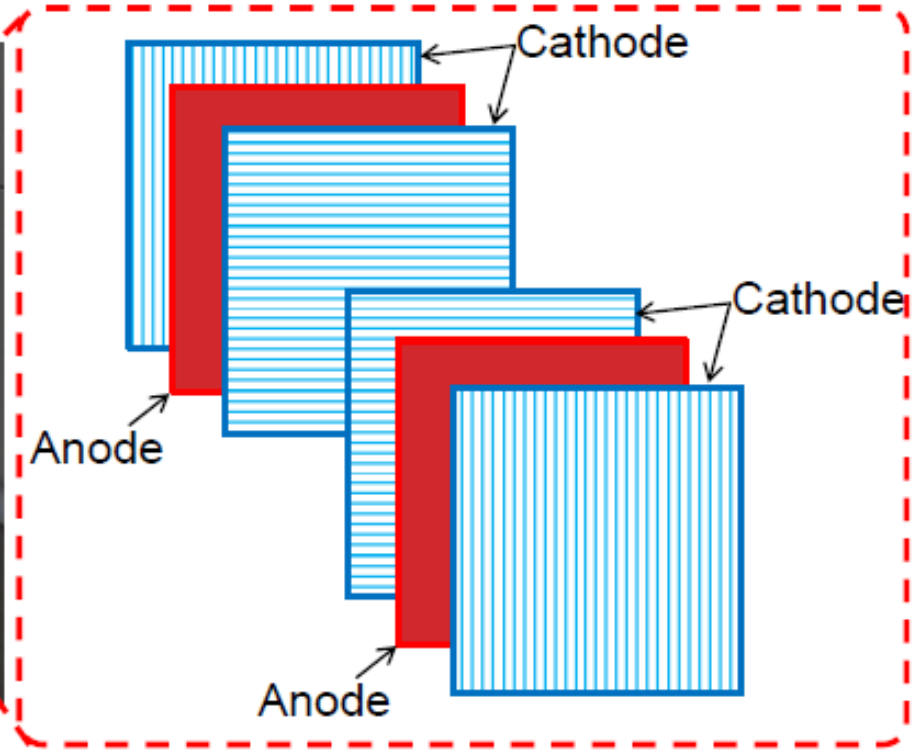
Nuclear Instruments and Methods in Physics Research A 470 (2001) 562–570

Measurements of the detection efficiencies (Y), the position and time resolutions for the PPAC at GSI. Applied bias voltages and beam-conditions are given. C_3F_8 gas with 30 Torr at a flow rate of 14 1/h was used. Beam conditions and applied bias voltages are given in the table. Results for the mixed (^{8}B and ^{7}Be) beam apply to the mixture of ions

Ions	Energy (A MeV)	Count rate (Hz)	Bias voltage (V)	Detection efficiency η_y (%)	Position resolution (FWHM) (mm)	Time resolution (FWHM) (ns)
^{12}C	174	3.0×10^3	1800	> 99	1.3	1.2
^{12}C	335	3.0×10^2	1810	> 99	0.9	1.2
(^{8}B, ^{7}Be)	(254, 216)	1.0×10^3	1820	~ 94	1.2	1.4
(^{8}B, ^{7}Be)	(254, 216)	2.0×10^4	1820	~ 94	1.4	1.3

Photos of PPAC detector

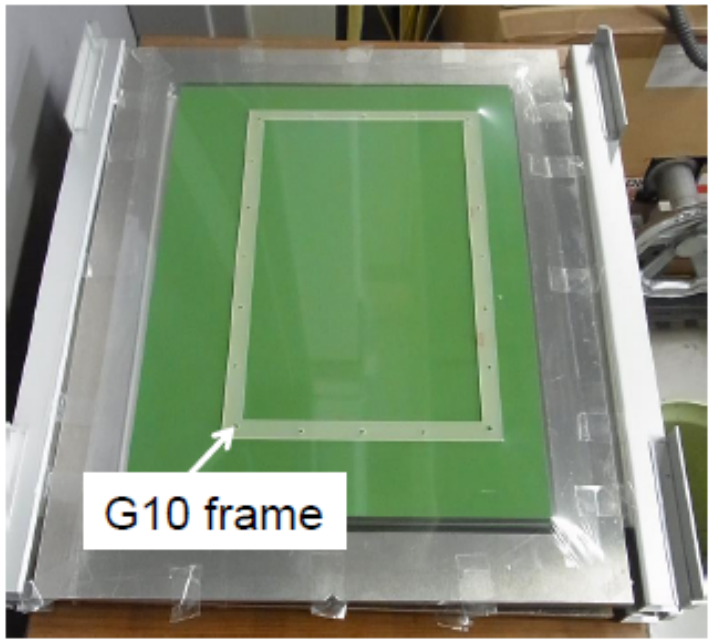




Double PPAC
for BigRIPS

Electrode-foil fabrication

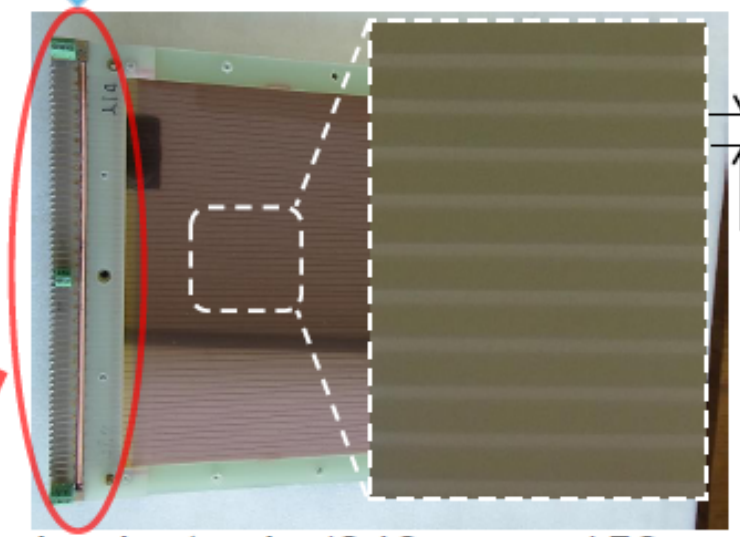
4 μm-thick-mylar is pasted and stretched on the G10 frame.



Evaporation mask

+

Vacuum metalizing

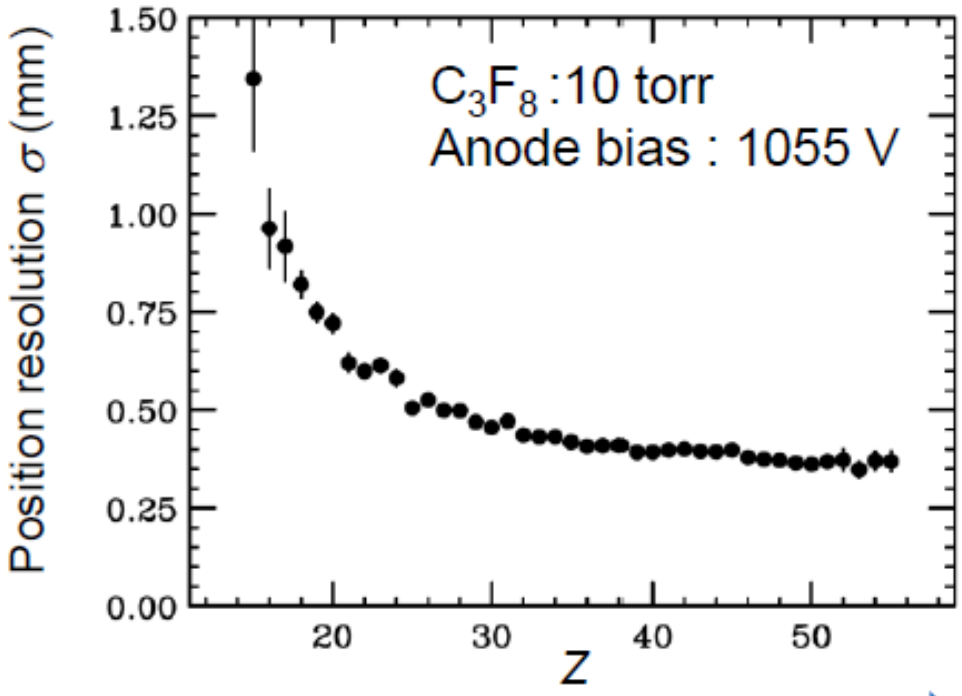


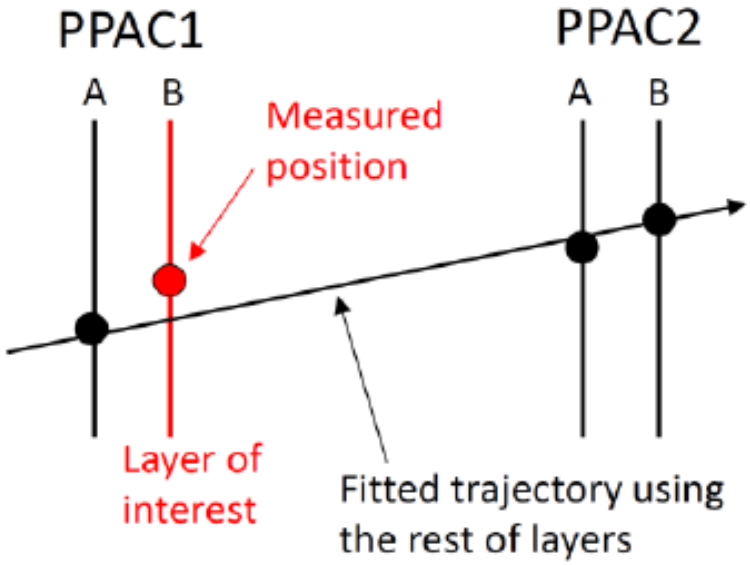
Delay line was attached.

Cathode electrode (240 mm × 150 mm Y-axis)

Position resolution for heavy ions

Fragment ions (reaction: $^{238}U + {}^{9}Be$ at 345 MeV/nucleon)





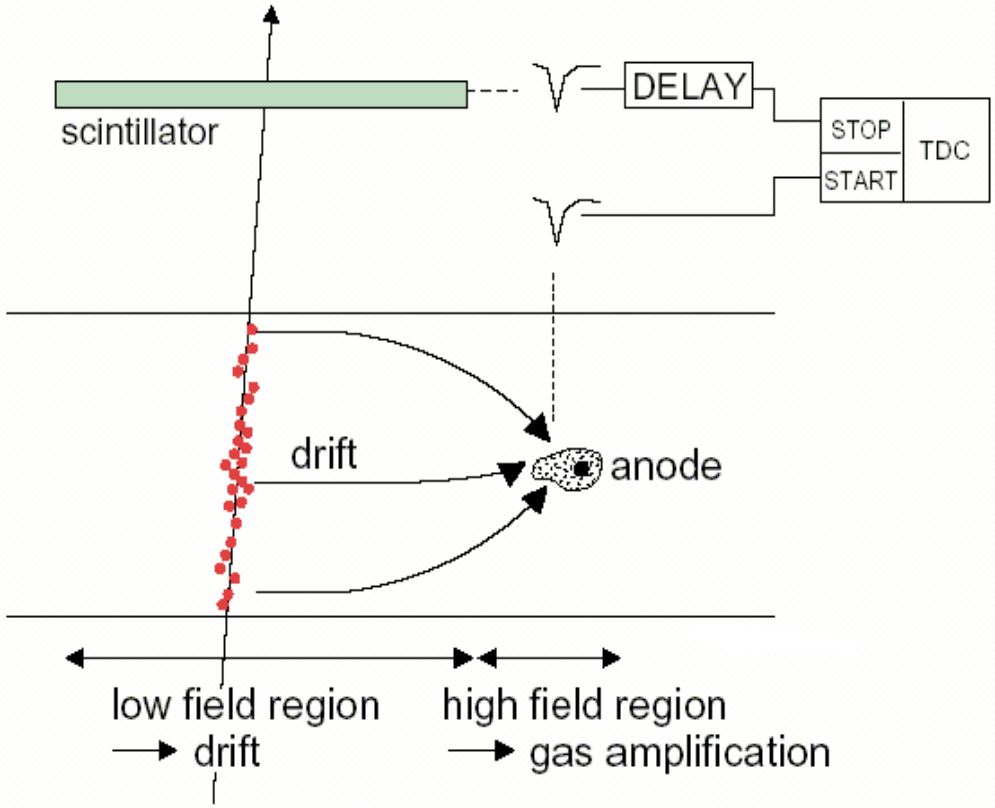
Signal intensities are increasing.
($Q \propto Z^2$)

Position resolutions improved.

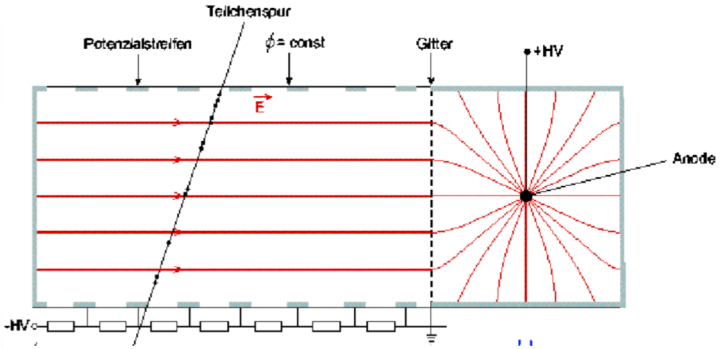
σ~350 μm at $Z \approx 50$ ions.

Drift Chamber

Drift Chambers are MWPCs where the time it takes for the ions to reach the sense wire is recorded. This time info gives position info:



TDC: Time to Digital Converter



Get external time reference t_0 (scintillator)

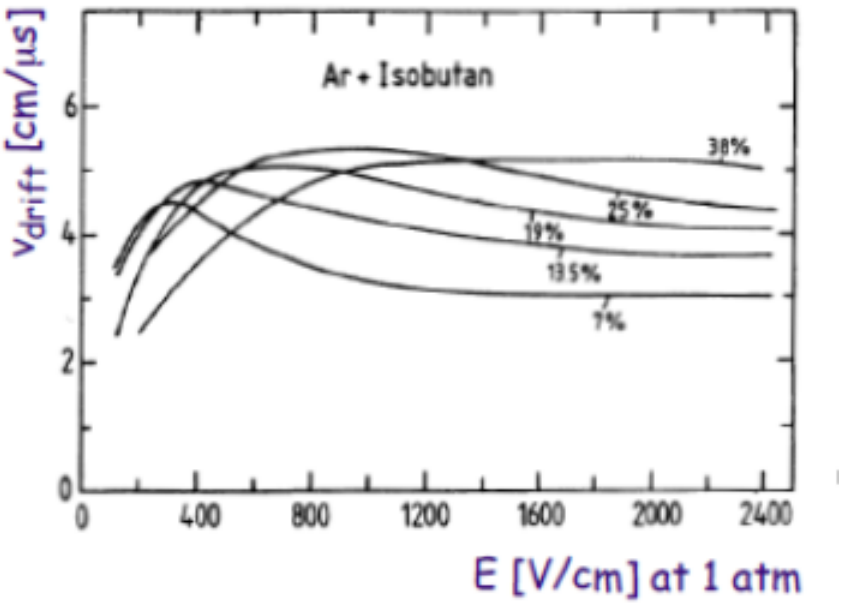
Measure arrival time of electrons at anode t_1

x- coordinate given by $x = \int_{t_0}^{t_1} v_D(t)\ dt$

- advantage of drift chamber: much larger sensitive volume per readout channel.

drift velocity

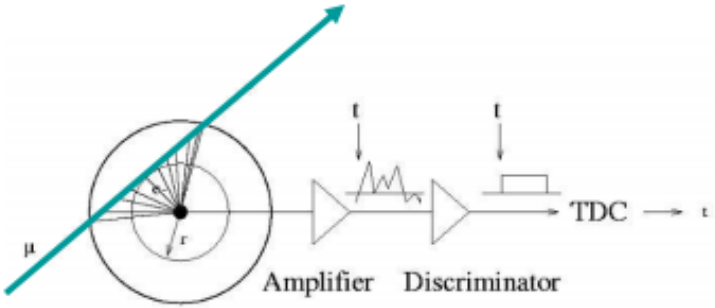
For some gas mixtures the drift velocity is ~constant (independent of the electric field): $x = v\,(t-t_o)$



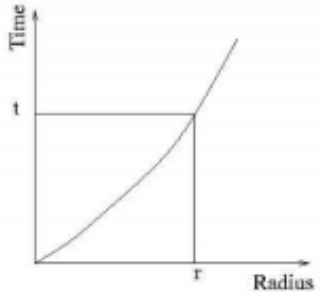
A gas with almost constant drift velocity is
50-50 Argon-Ethane, drift velocity ≈ 50μm/nsec

Primary electrons are drifting to the wire.

ATLAS MDT R(tube) =15mm



Calibrated Radius-Time correlation

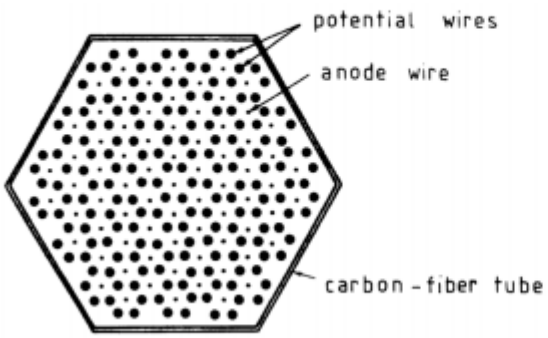


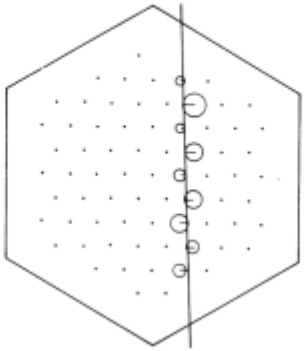
Electron avalanche at the wire.

The measured drift time is converted to a radius by a (calibrated) radius-time correlation.

By using the drift time information we can improve our spatial resolution by a factor of 10 over MWPCs (1mm →100 μm).

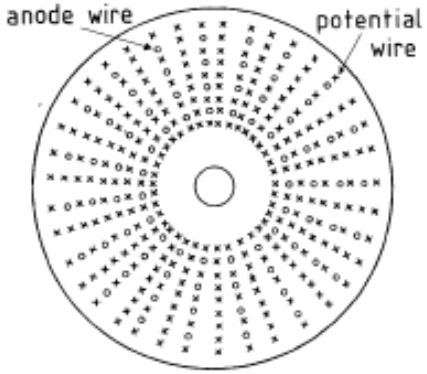
Hex-cell drift chamber

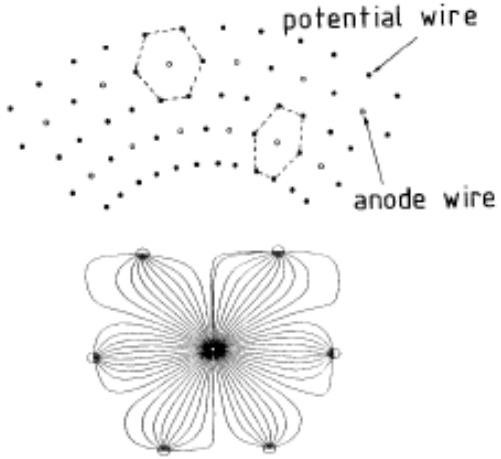


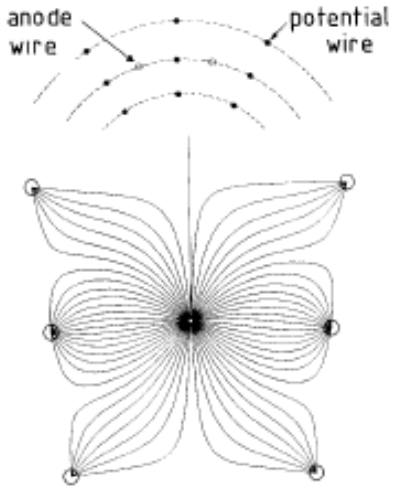


Many of these circles define the particle track.

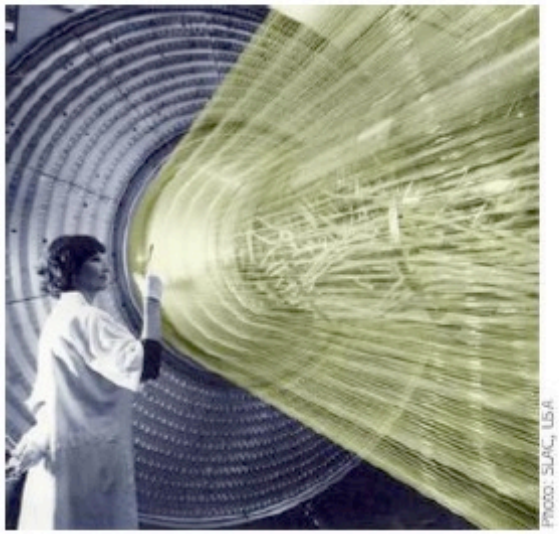
Cylindrical Driftchamber

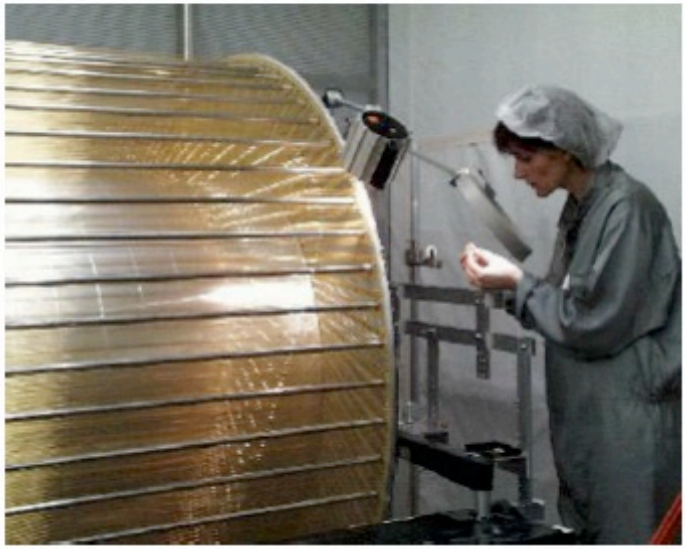






H1 Central Jet Chamber

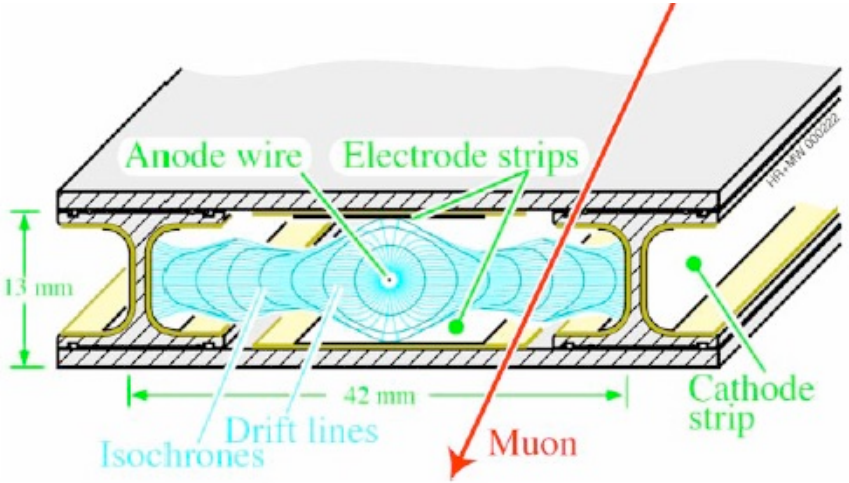


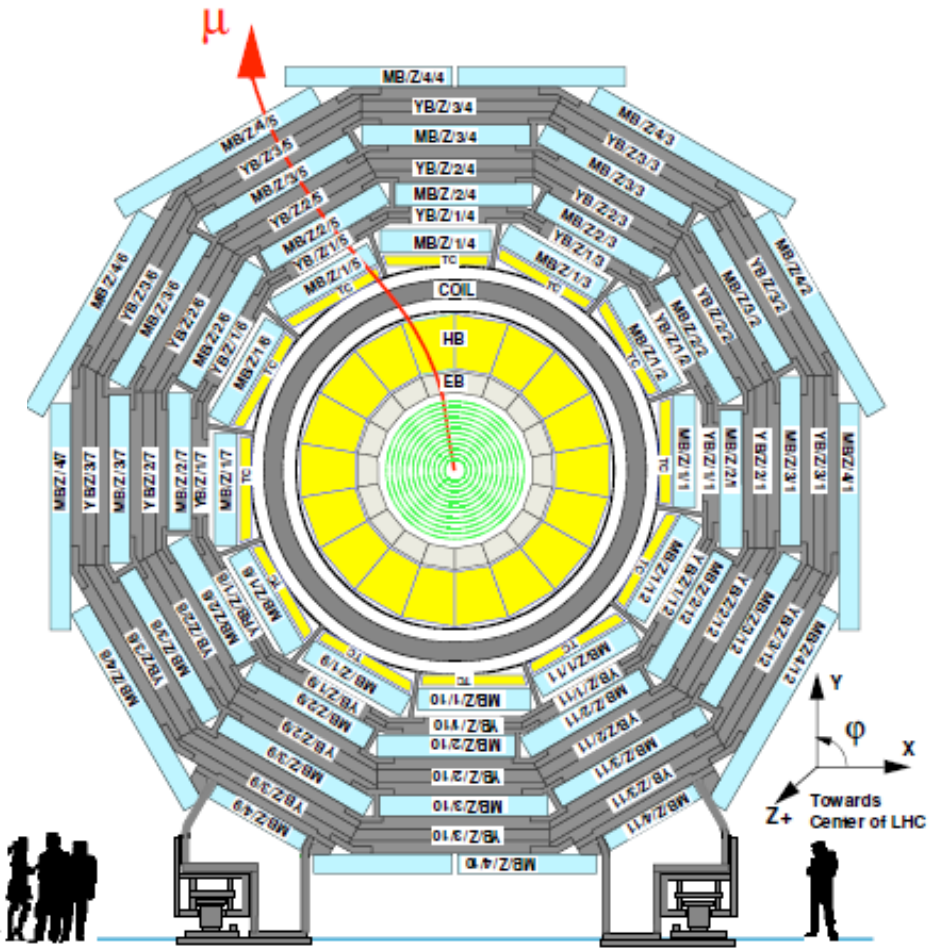


- ≈ 15000 wires
- total force from wire tension ≈ 6 tons

CMS Muon Drift Tube System

CMS Muon Drift Tubes Chambers





Drift Chamber Spatial Resolution

$$\sigma_x^2 = \underbrace{\left(\frac{1}{64N^2}\right)\cdot\frac{1}{x^2}}_{\text{1st ionization statistics}} + \underbrace{\frac{2D}{v_d}\cdot x}_{\text{diffusion}} + \underbrace{\sigma^2_{\text{const}}}_{\text{electronics}\ \delta\text{-electrons}}$$

Possible improvements:

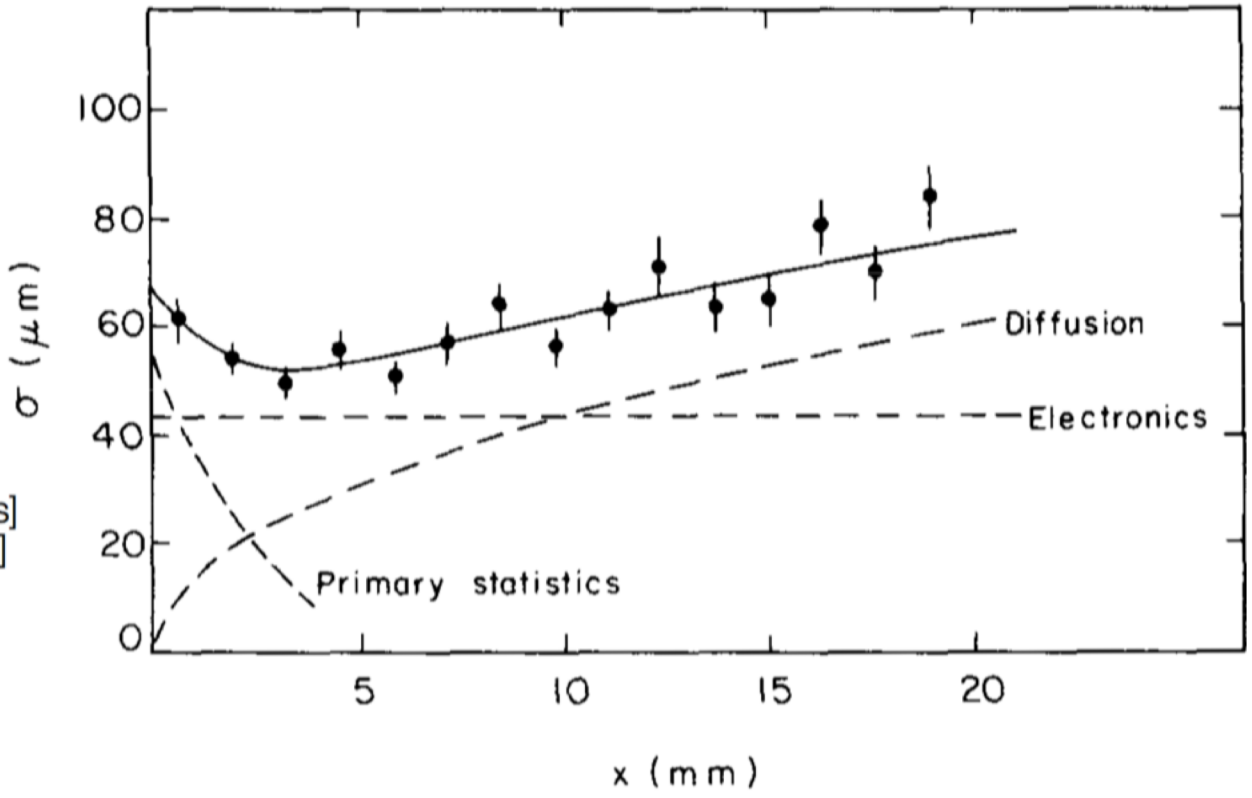
Increase N by increasing pressure ...

Decrease D by increasing pressure ...

$$D \sim \frac{\lambda_0^2}{\tau} \sim \frac{1/n^2}{1/n} \sim \frac{1}{n}$$

[n: particle density in gas]
[increases with pressure]

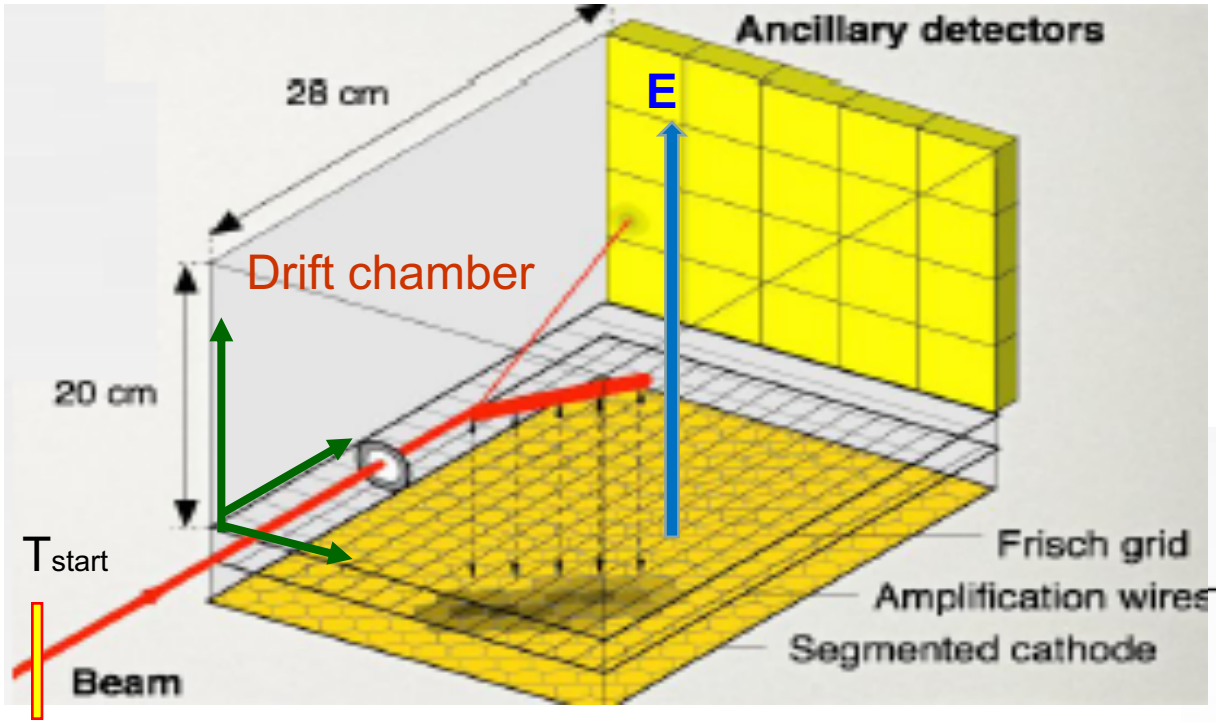
i.e.: increase pressure ...
[up to 4 atm possible]



Time Projection Chamber → full 3-D track reconstruction

- x-y from wires and segmented cathode of MWPC
- z from drift time
- in addition dE/dx information

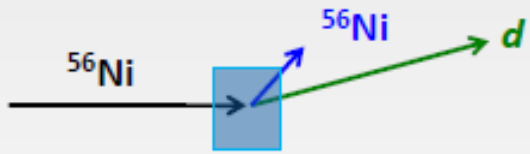
- the drift time to the amplification wires allows the determination of the reaction plane
- the recoil leaves enough energy to induce an image of its trajectory in the segmented cathode.



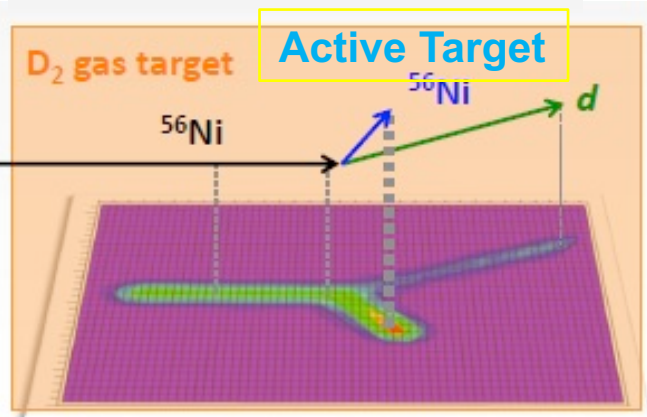
C.E. Demonchy et al., Nucl. Instrum. and Meth. A 583 (2007) 341

- Low beam energy (~ 3 MeV/u)
- Low transferred energy

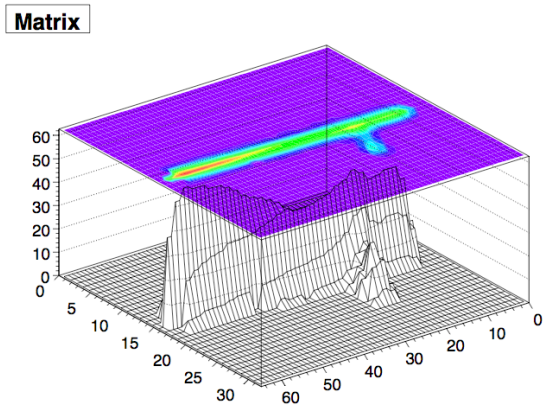
$^{56}Ni(d, d')^{56}Ni$

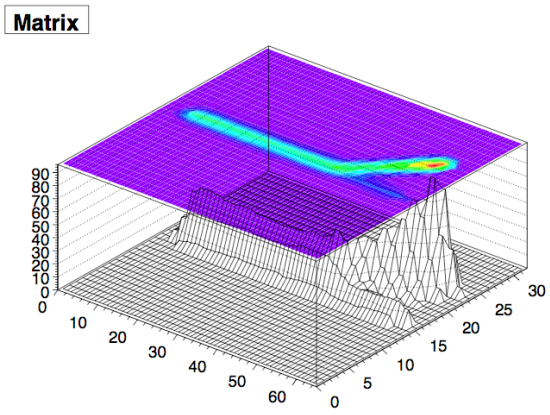


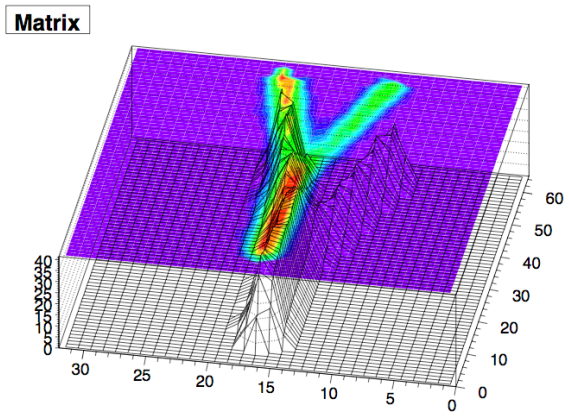
CD_2 solid target

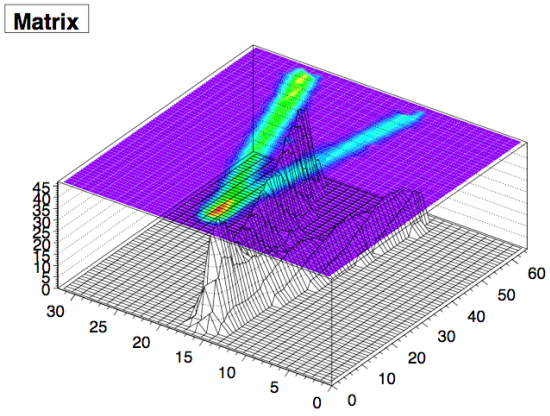


MAYA random selected events

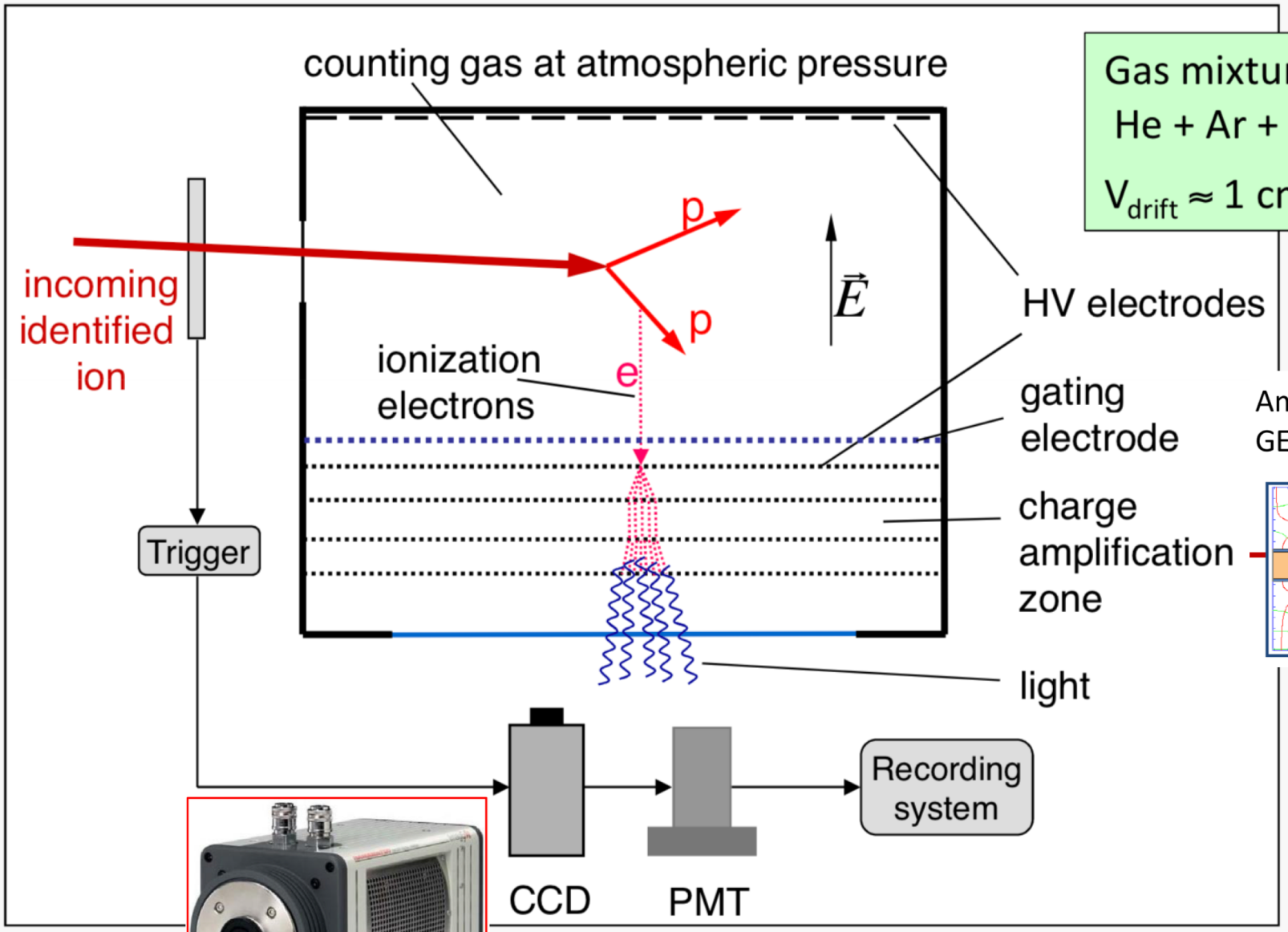




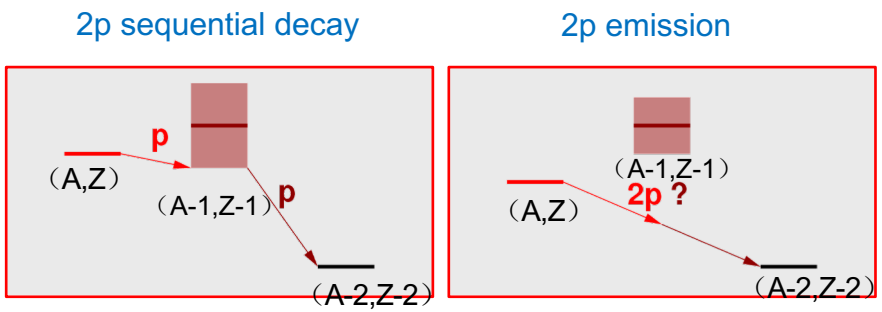


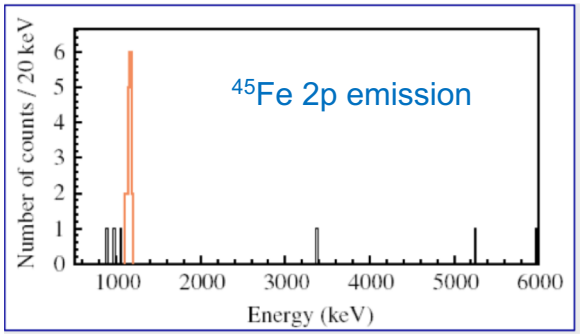


OTPC: Optical Time Projection Chamber

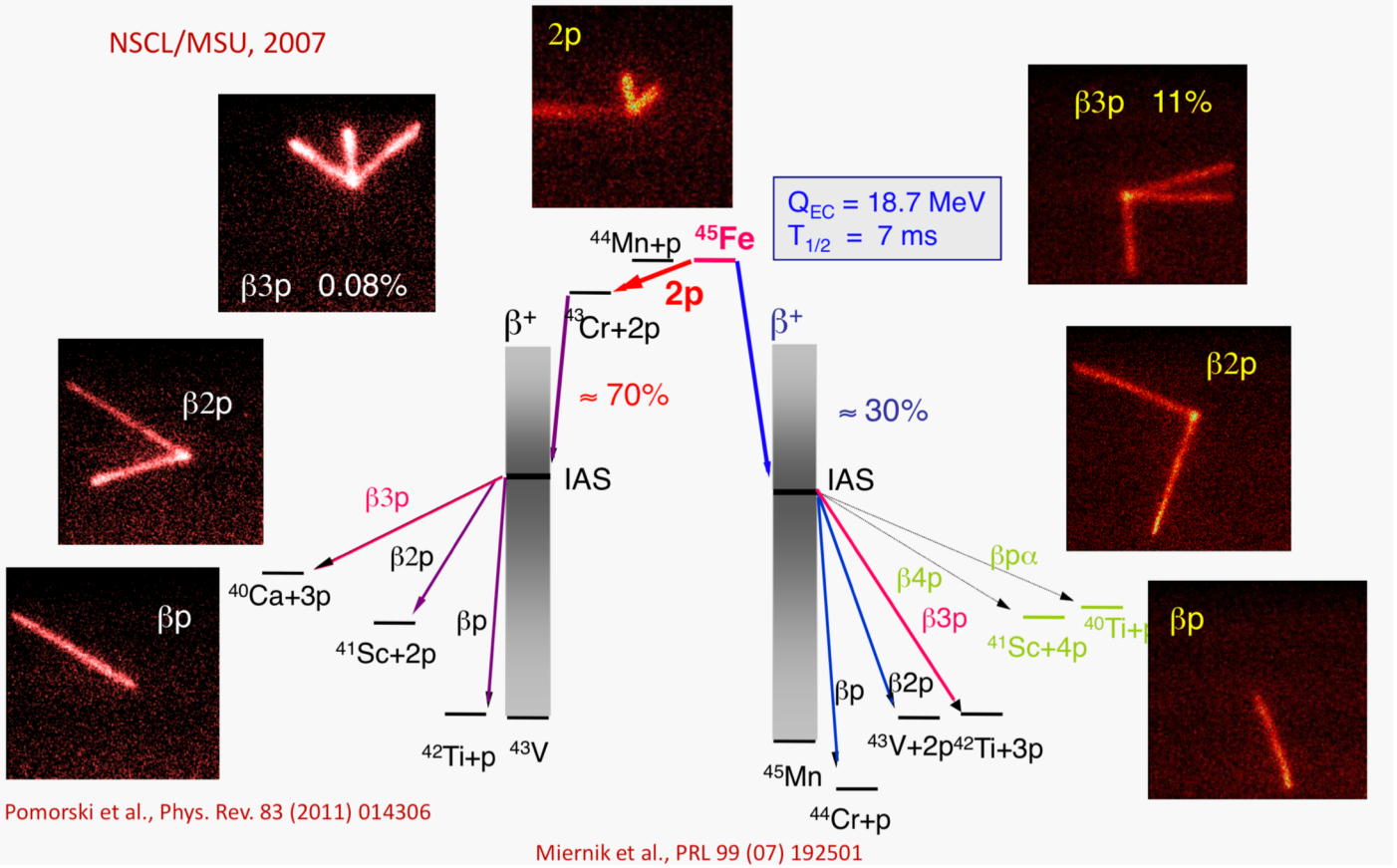


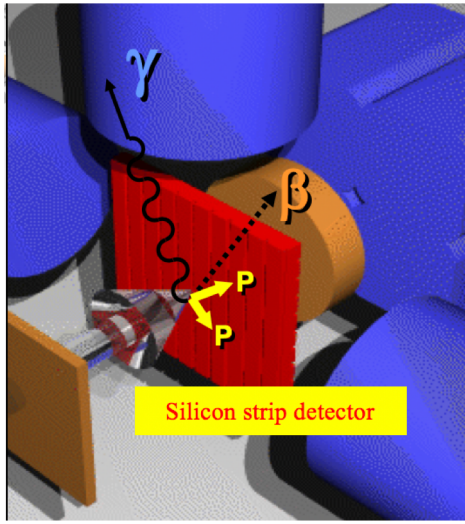
M. Ćwiok et al., IEEE TNS, 52 (2005) 2895
K. Miernik et al., NIM A581 (2007) 194



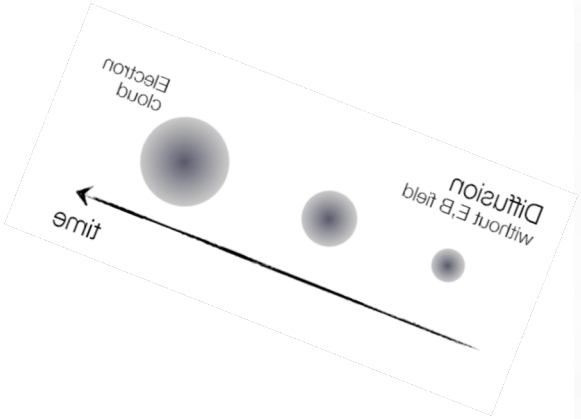


Decays of ^{45}Fe and ^{43}Cr





- For longer drift distance, larger diffusion(particularly in the lateral direction) →resolution!
- Remedy: magnetic field parallel to E-field→confines electrons to helical trajectories about the drift direction →reduces diffusion by a factor of 10



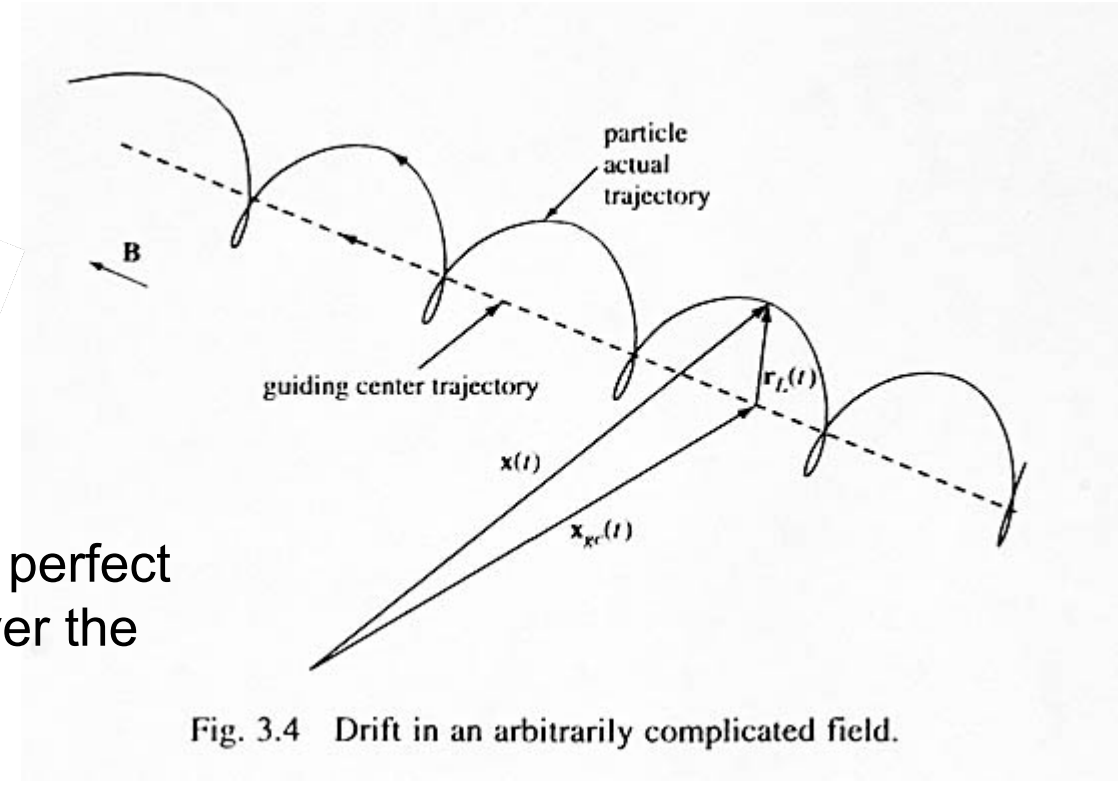
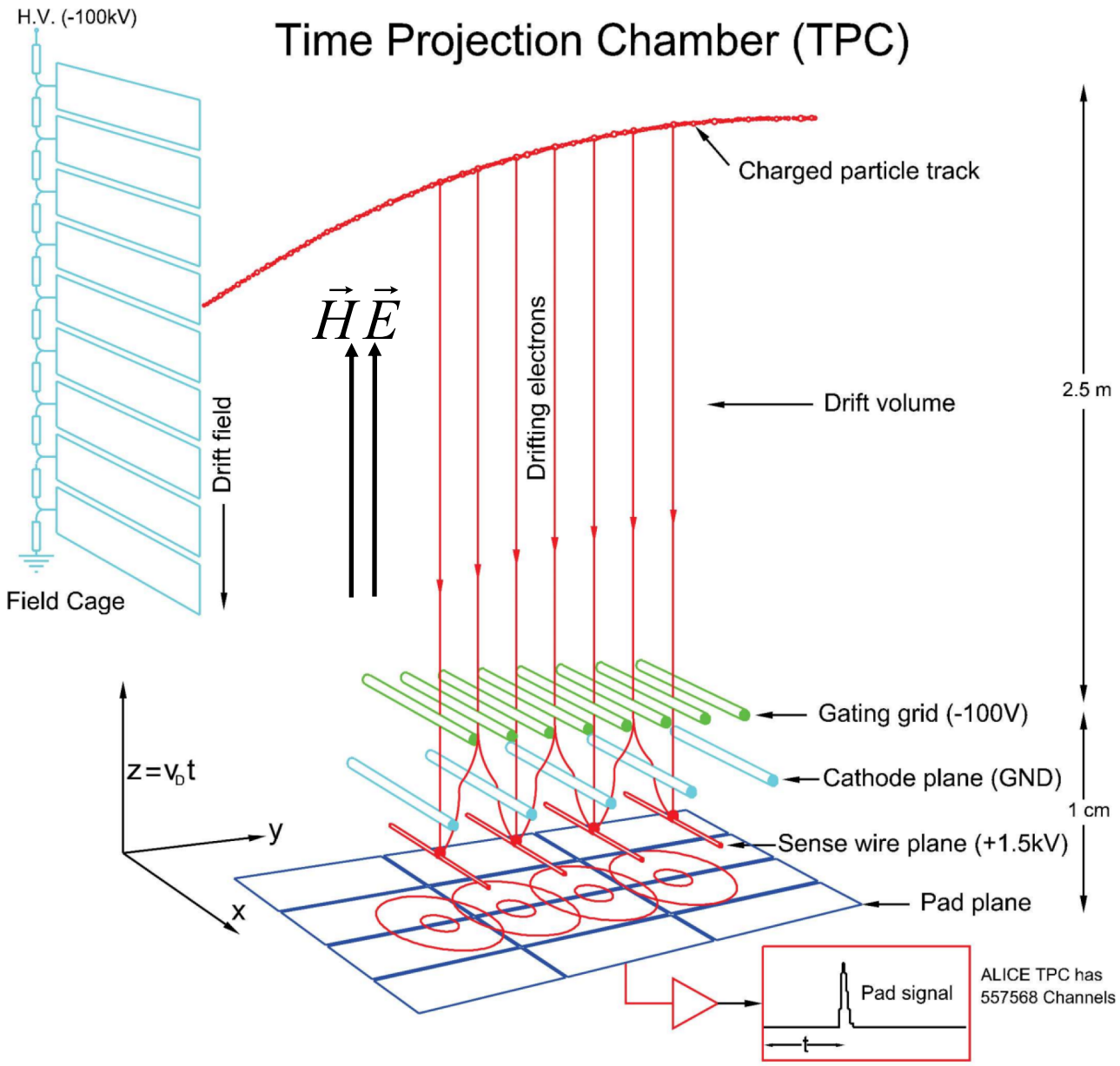
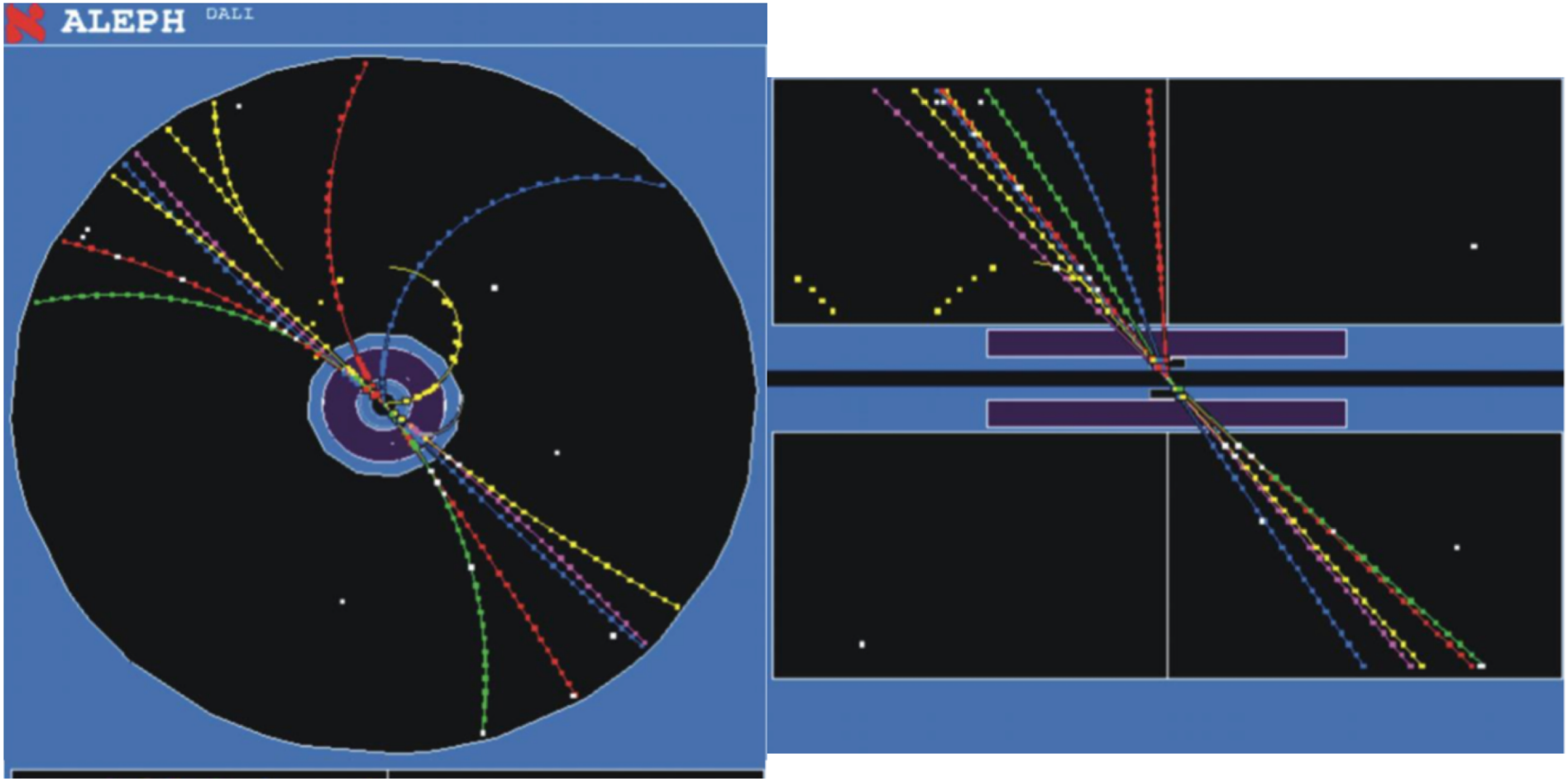


Fig. 3.4 Drift in an arbitrarily complicated field.

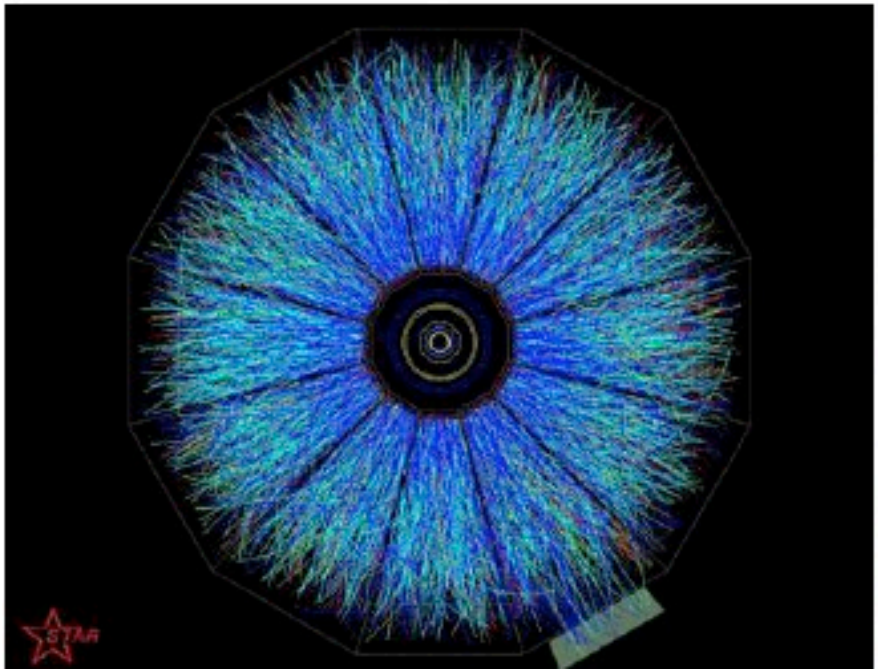
- E and B fields must be in perfect alignment and uniform over the volume of the drift zone ($1/10^4$ accuracy).



- Space charge from positve ions drifting from anode wires to the central cathode
- prevented by grid at ground potential just before the anode wires, capture ions


ALEPH
DALI

Solenoidal Tracker At RHIC

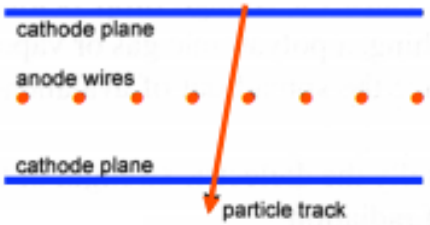


Proportional Counters – Wires → Stripes

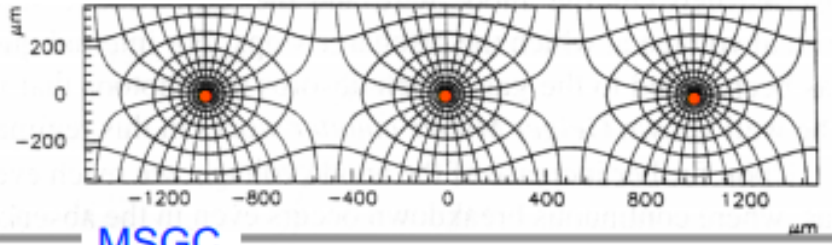
More sensitive detectors require more amplification – smaller "wires." Tiny anodes can be made by photoetching techniques but they must be supported on substrates (thick materials). Importantly the distance to the cathode traveled by the slow cations can be reduced enormously.

Multi-wire proportional chamber

Charpak

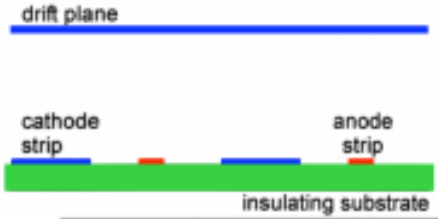


MWPC

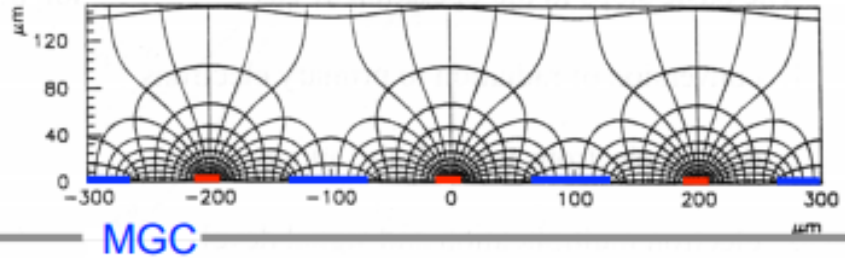


Micro-strip gas chamber

Oed

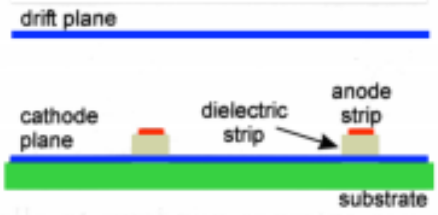


MSGC

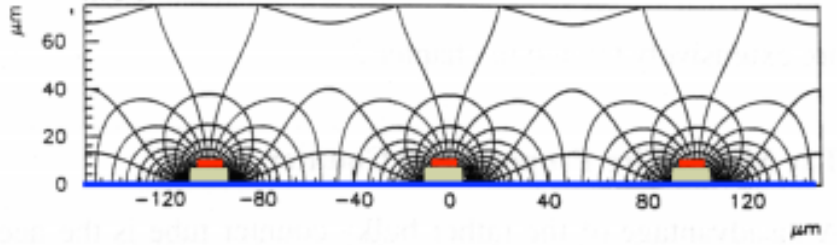


Micro-gap chamber

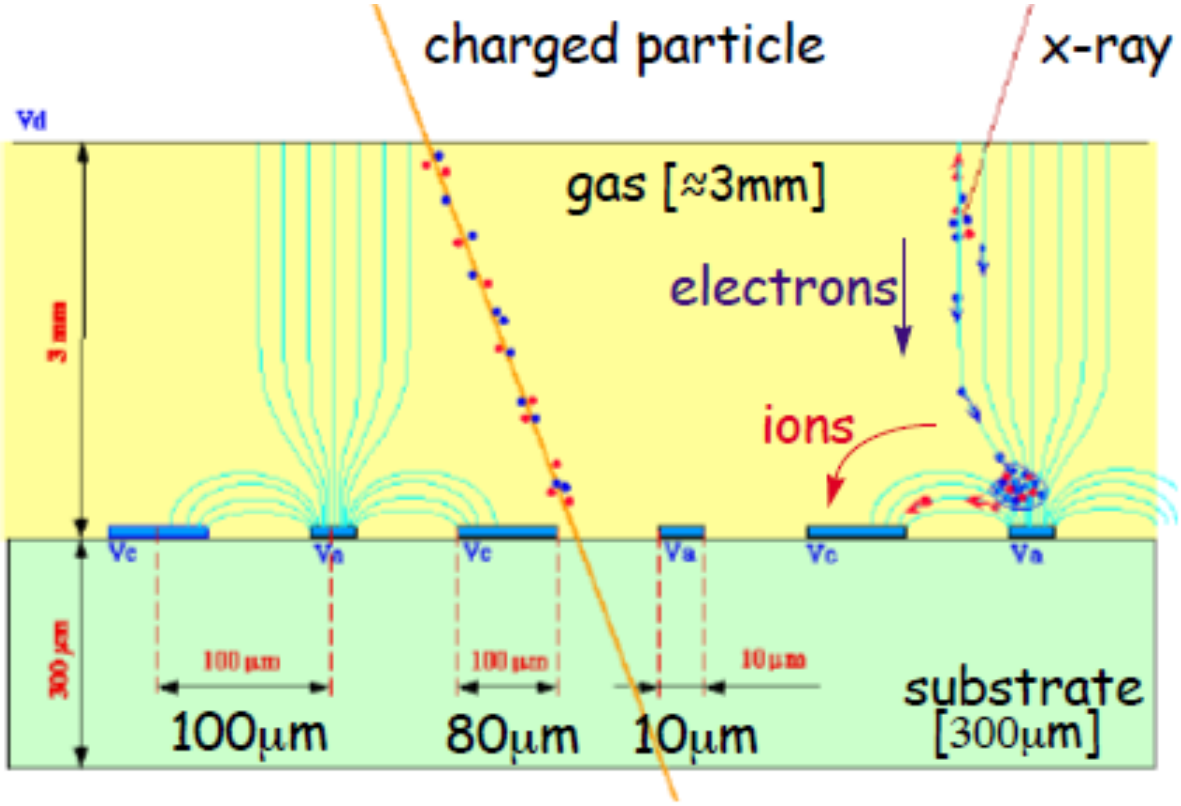
Bellazini



MGC



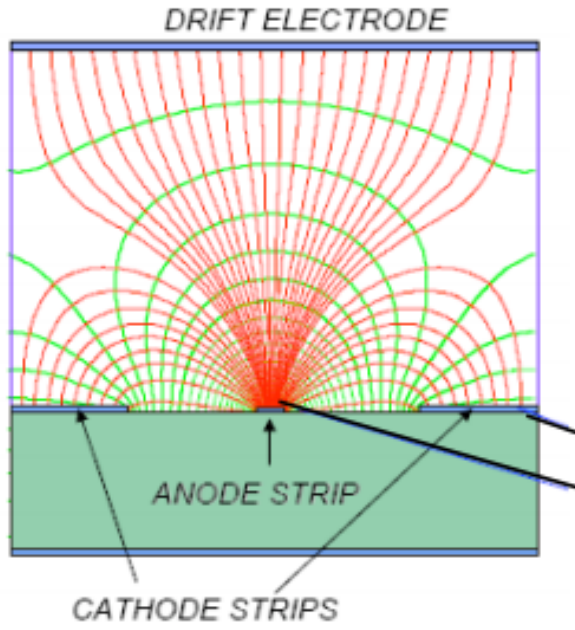
Microstrip Gas Chamber (MSGC)



Advantages:

- Very precise and small anode/cathode structures can be produced with lithographical methods. Thus very good position resolution is possible.
- MSGC provide high mechanical stability
- small drift distance for ions, thus high rate capability.
- reduction of the size of the detecting cell (limitation of the length of the ion path) using chemical etching techniques developed for microelectronics and keeping at same time similar field shape.

Thin metal strips on insulating support, generally resistive glass have a very high rate capability due to high fields and short distance of travel for the cations.



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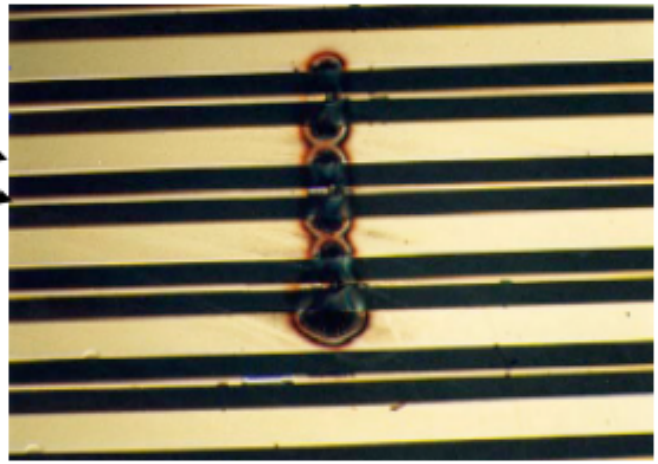
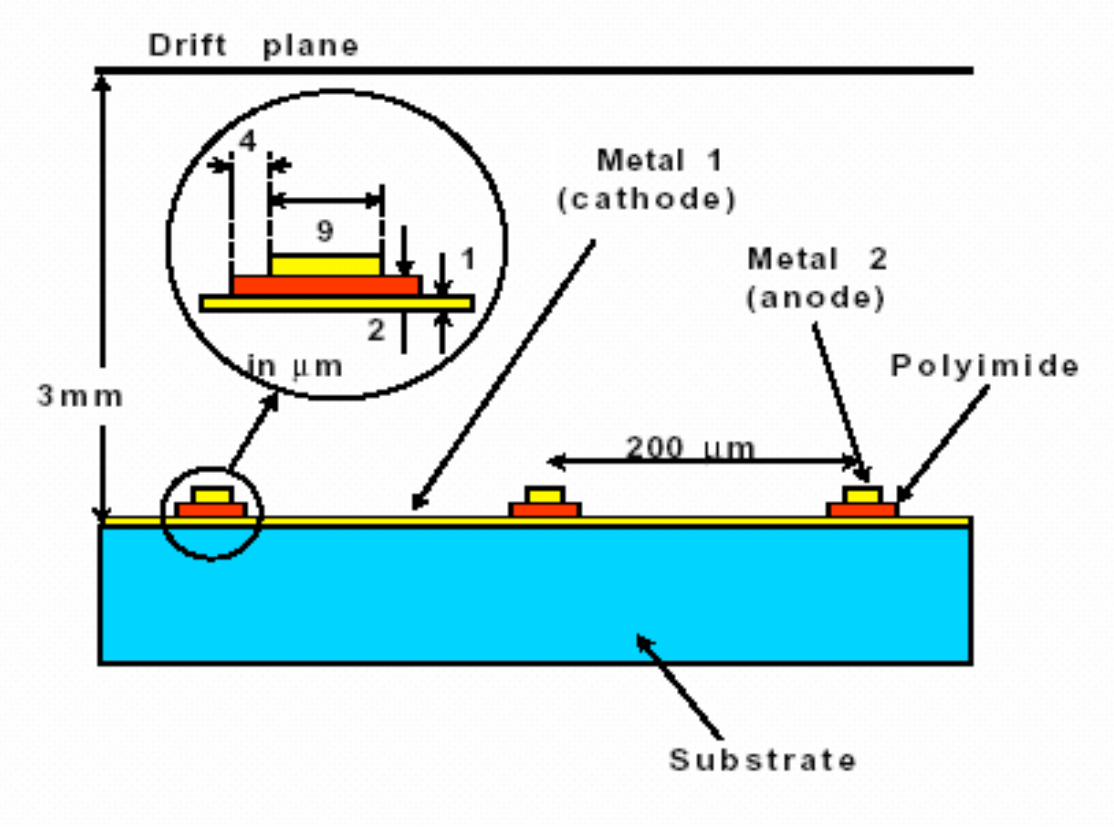
However, strips are permanently damaged by sparks or other discharges which kills the detector.



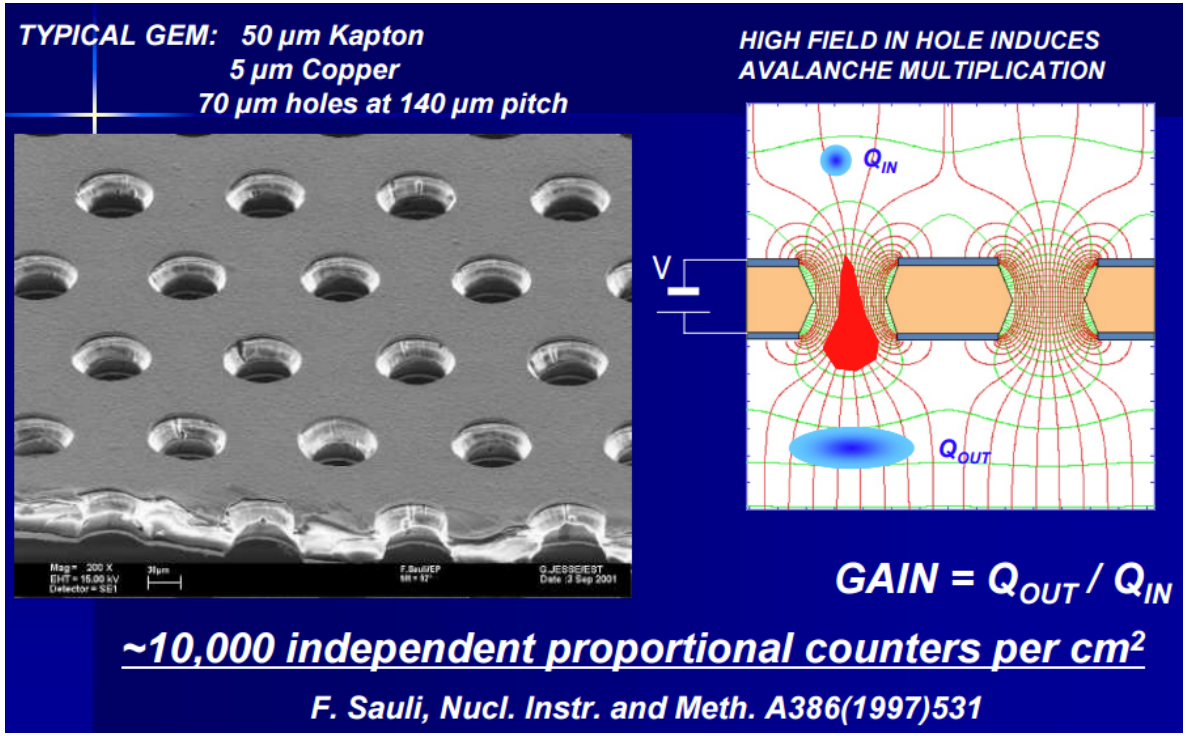
Micro-Gap Chambers

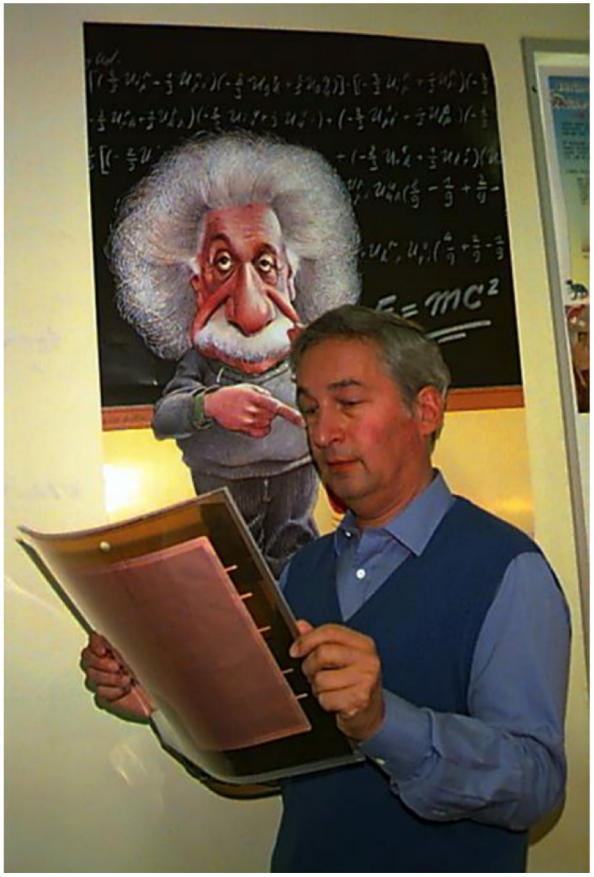
- Enhanced type of MSGC with anode and cathode separated by a layer of insulating film



Gas Electron multipliers(GEM)

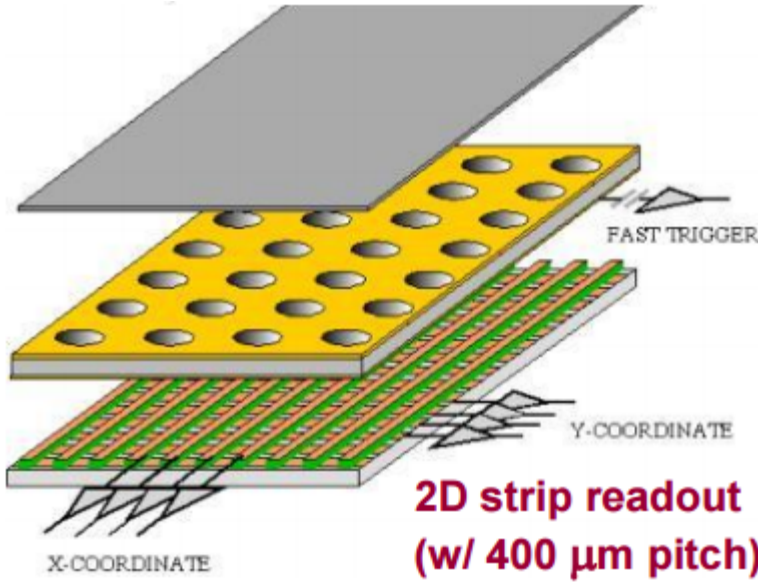
- Get rid of the wires and use holes in an insulator
- Thin layer of insulating foil coated on both sides with metal film
- Contains chemically produced holes of size ~50-100μm
- The two metal films are have different voltages, creating a strong E field in the holes
- Gas multiplication avalanche occurs when a charge passes through a hole

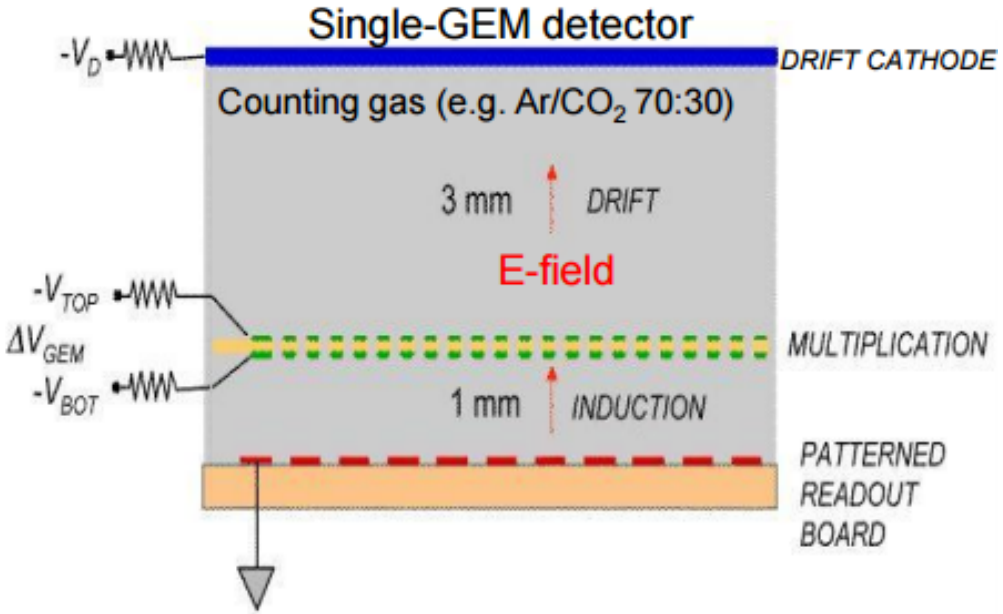




- Electrons produced in the avalanche's front leave the multiplication region and transfer to lower section of the structure, where they can be collected by the two dimensional-patterned charge collection anode.
- The signal on the anode is only generated by the collection of electrons（very fast）.

A typical resolution is ~70 μm





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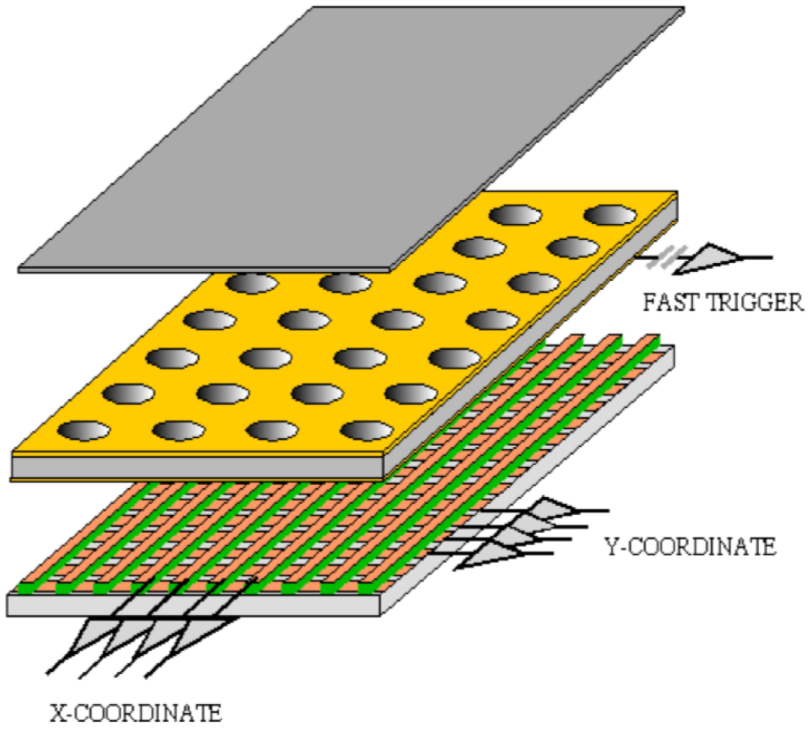
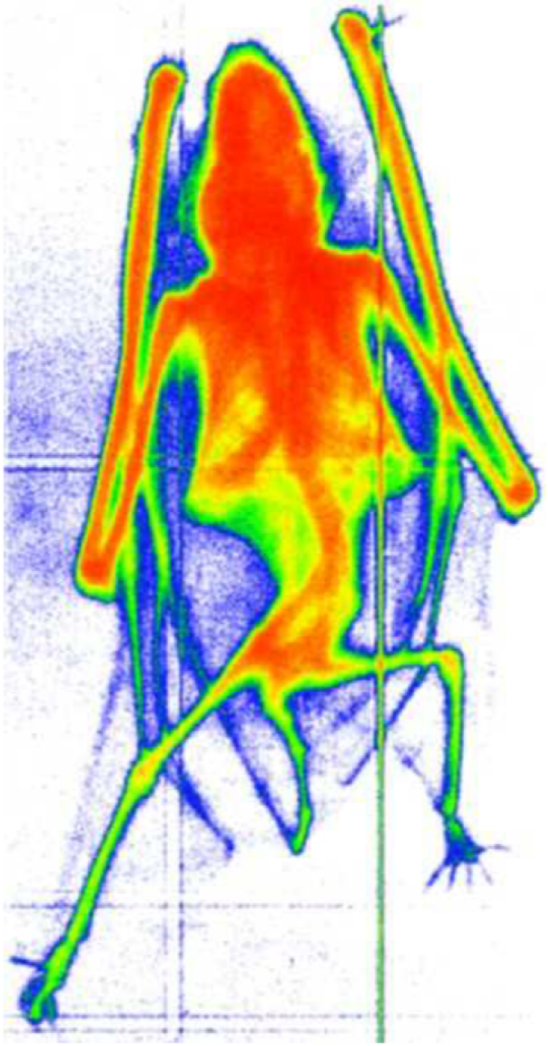


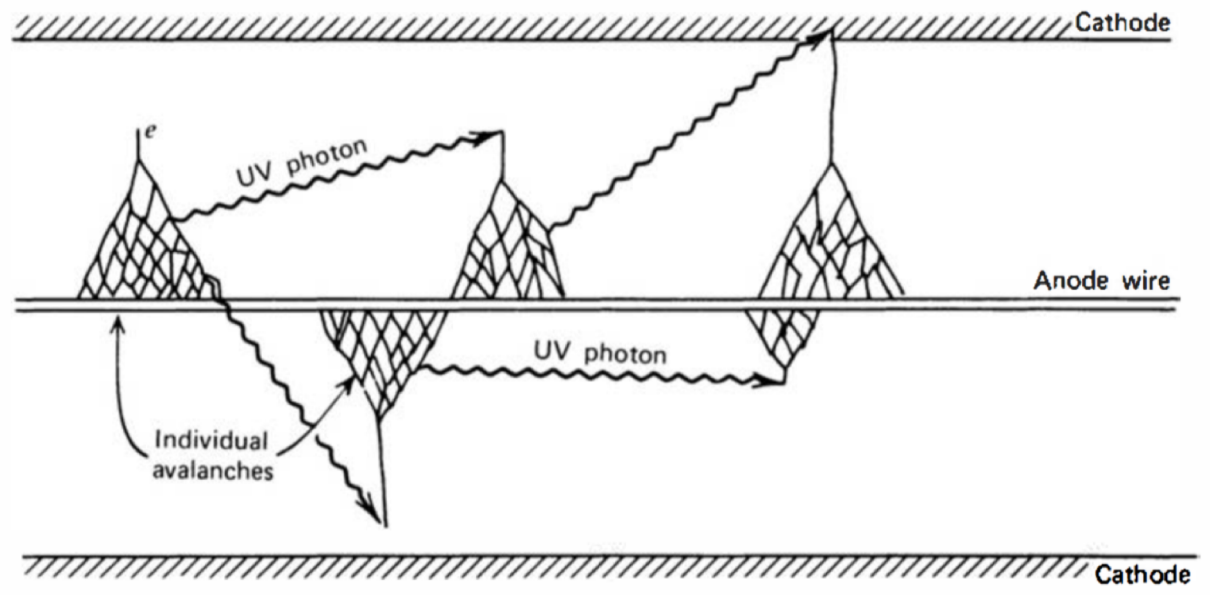


9-keV absorption radiography of a bat (30 × 60 mm^2)

The Geiger-Müller Counter

Principle

- Usage of similar gases as in proportional counter.
- Configuration of detector such that operates above the proportional region.
- In avalanches surrounding atoms get excited and radiate soft photons that generate via photoelectric effect electron-ion pairs that form additional avalanches.
- Within a few microsecond we get a total discharge and a large signal.



advantages: can detect α β radiation (if window thin!)

large signals:

$\Delta V = \Delta Q / C \approx 10^4$ fC/ 10 pF = 1 V !

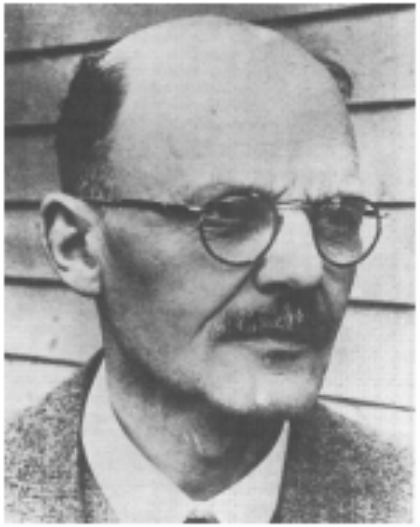
det. eff. $\approx$ 100%

operate in center of plateau !

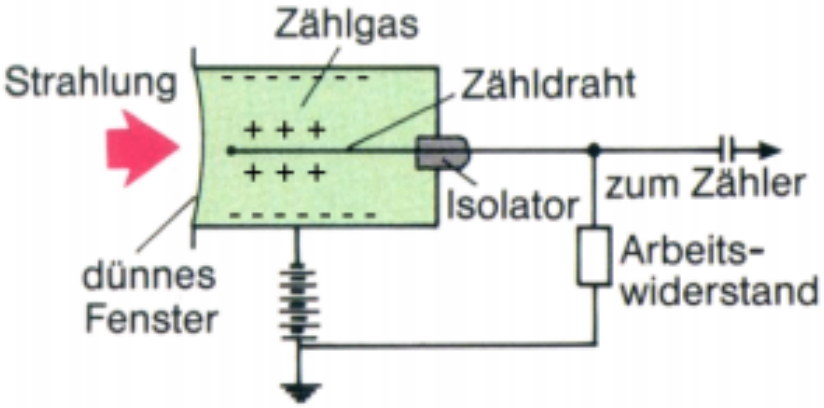
disadvantages: no space resolution

large dead time

→ low rate capability

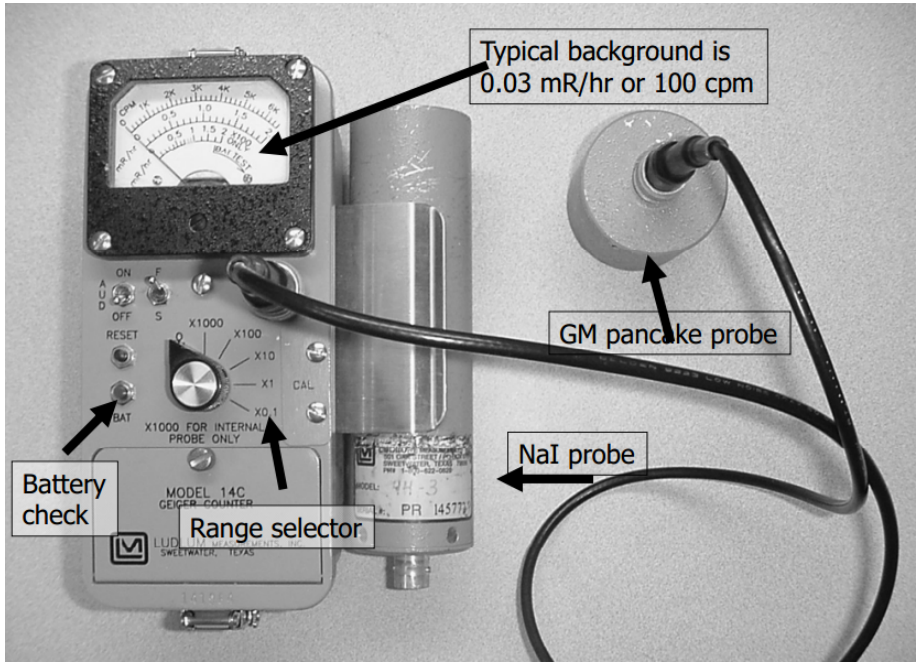


Geiger-Müller-Zählrohr:



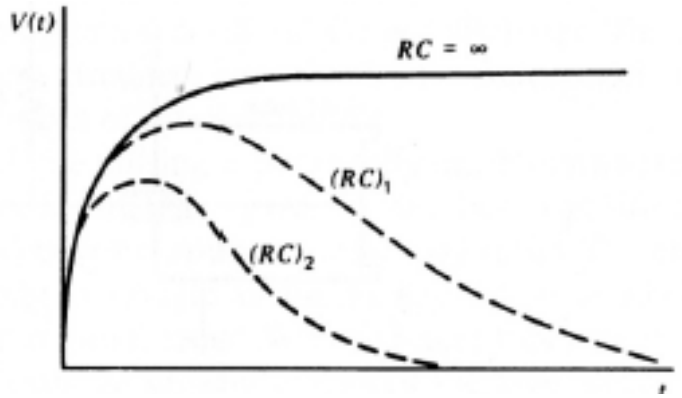
- Two window types:
  - Glass — Resistant, no α detection
  - Mica — Fragile, possible α detection

Hans Geiger (1882-1945) was a German physicist who introduced the first reliable detector for alpha particles and other ionizing radiation.His basic design is still used, although more advanced detectors also exist.
His first particle counter was used in experiments that identified alpha particles as being the same as the nucleus of a Helium atom.He accepted his first teaching position in 1925 at the University of Kiel, where he worked with Walther Müller to improve the sensitivity and performance of his particle counter.



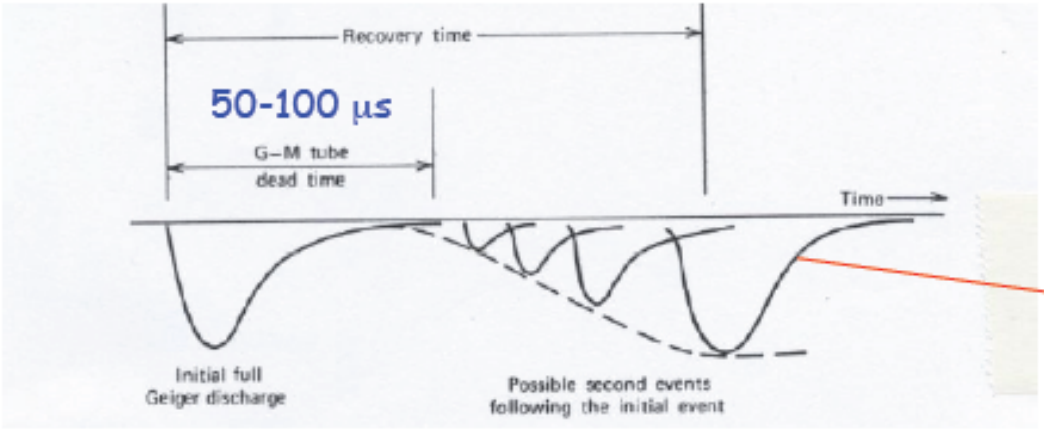
Signal Shape and Dead Time

Pulse shapes in G-M counter
RC typically ~ 100 μs



Dead Time

The Geiger discharge stops when an **high ions (+) concentration** reduces the field E below the moltiplication threshold



Second full pulse appears when **ALL** ions (+) are collected to the cathode

⇒ G-M tubes are limited to application with **low counting rates**