Ionisation counters

Primary and secondary ionisation

Drift and diffusion of electrons and ions

Gas multiplication

Signal development

Multiwire proportional chamber

Drift chamber

Microstrip gas chamber

Wire chamber based photon (UV, X, γ) detectors

Literature

- F. Sauli: *Principle of operation of multiwire proportional counters and drift chambers*, CERN 77-09, in Experimental techniques in high energy physics, T. Ferbel (editor), World Scientific, 1991; scanned copy also at http://lhcb-muon.web.cern.ch/lhcb-muon/documents/Sauli_77-09.pdf
- W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, 2nd edition, Springer, 1994
- C. Grupen, Particle Detectors, Cambridge University Press, 1996

Interaction of charged particles with matter

Energy loss due to ionisation: depends on $\beta\gamma$, typically about

2 MeV/cm $\rho/(\text{g cm}^{-3})$.

Liquids, solids: few MeV/cm

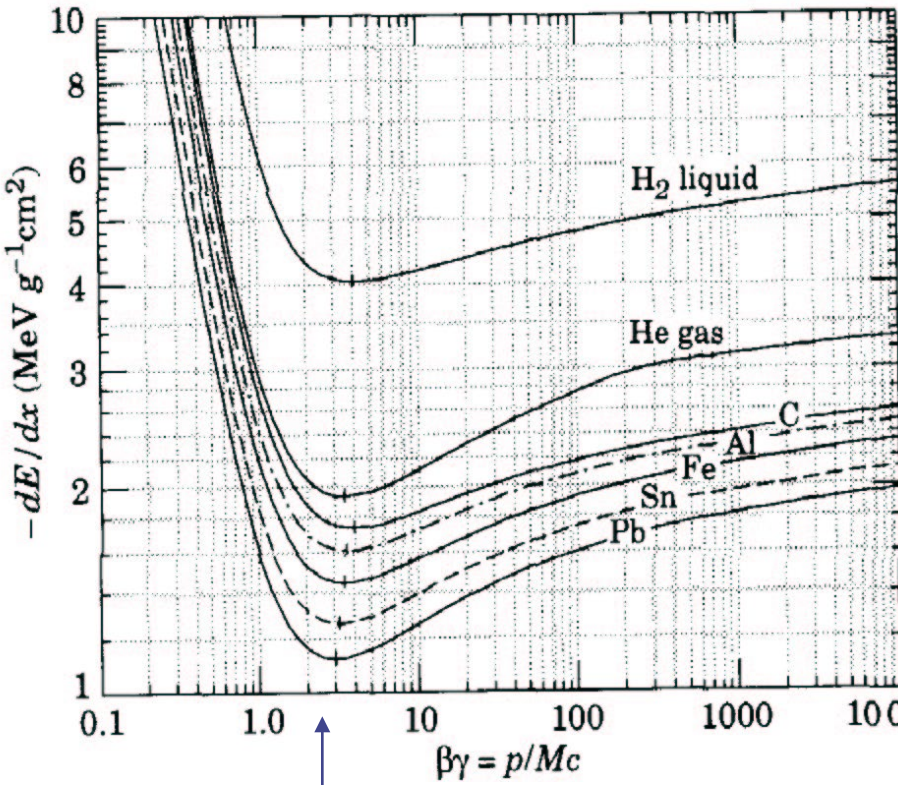
Gases: few keV/cm

Primary ionisation: charged particle kicks electrons from atoms.

In addition: excitation of atoms (no free electron)

→ On average need W_i (>ionisation energy) to create an e-ion pair.

W_i typically 30eV → per cm of gas about 2000eV/30eV=60 e-ion pars



Minimum ionizing particles (MIP)

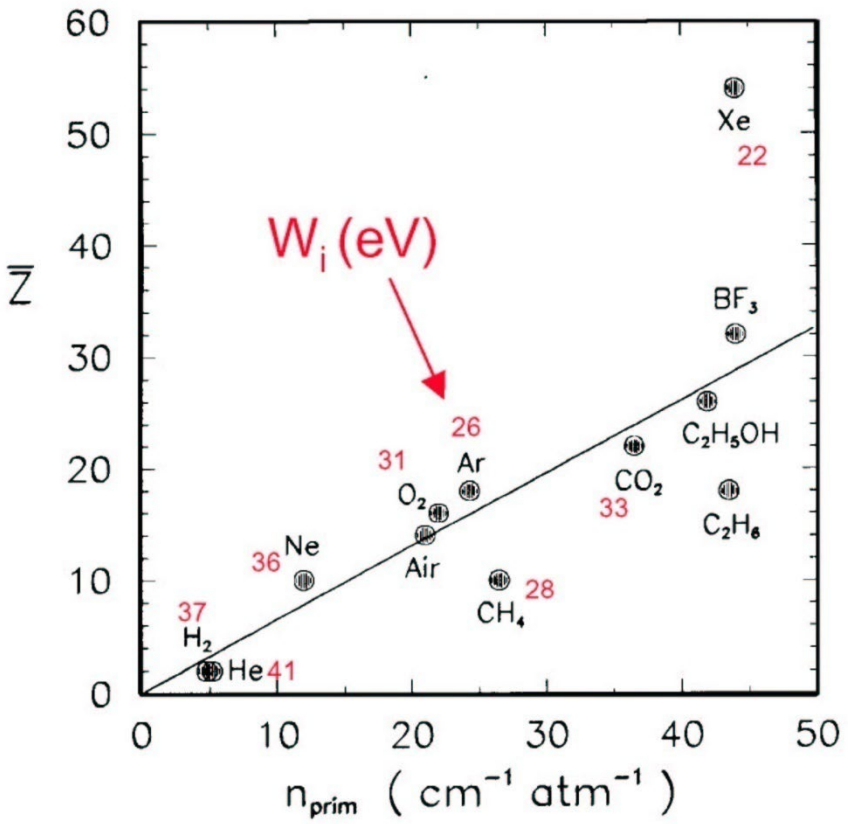
Ionisation

n_{prim} is typically 20-50 /cm

(average value, Poisson like distribution – used in measurements of n_{prim})

The primary electron ionizes further: secondary e-ion pairs, typically about 2-3x more.

Finally: 60-120 electrons /cm



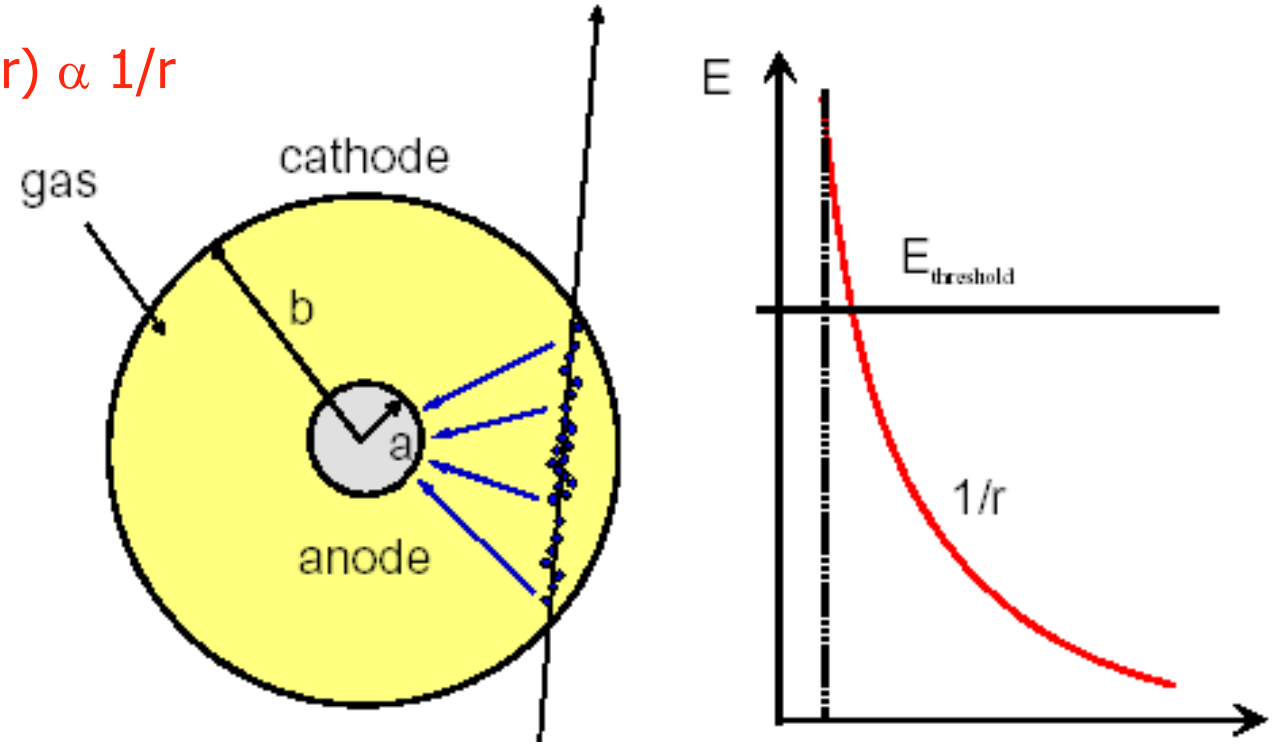
Can this be detected? 120 e-ion pairs make a pulse of $V=ne/C=2\mu V$ (at typical C=10pF) → NO

→ Need multiplication in gas

Multiplication in gas

Simplest example: cylindrical counter, radial field, electrons drift to the anode in the center

$E = E(r) \alpha 1/r$



If the energy eEd gained over several mean free paths (d around 10μm) exceeds the ionisation energy → new electron
Electric field needed → E = I/ed = 10V/μm = 10kV/cm

Diffusion and mobility of ions

Diffusion: ions loose their enegy in collisions with the gas molecules, thermalize quickly (mean free path around 0.1μm) ; Maxwellian energy distribution.

Localized charge distribution diffuses: fraction of charges in dx after time t

$$\frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}} e^{-\frac{x^2}{4Dt}} dx$$

D, diffusion coefficient: typically around 0.05 cm^2/s

The r.m.s. of the distribution for 1D and 3D cases:

$$\sigma_x = \sqrt{2Dt}, \sigma_V = \sqrt{6Dt}$$

Electric field: the Maxwellian distribution changes by very little, ions drift in electric field with an average net (drift) velocity (not instant velocity!) depending linearly on the electric field:

$$\mathbf{v_D}^+ = \mu^+ (\mathbf{E/p})$$

μ^+: mobility, related to D, $D^+/\mu^+ = kT/e = 0.026V$

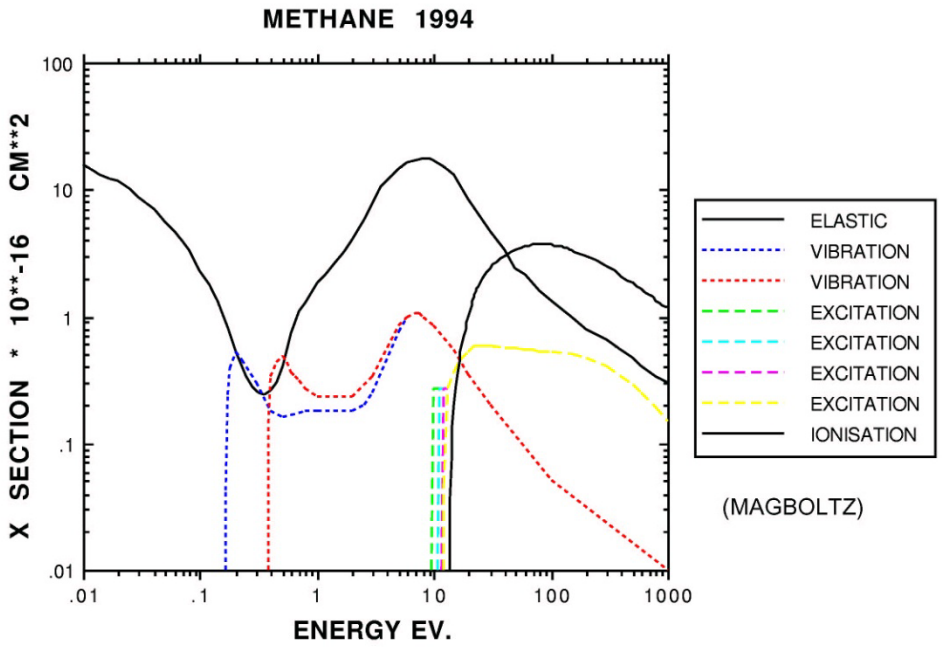
Typical values for μ^+: 1-2 cm^2 atm/Vs; at 1kV/cm: 1cm/ms

Diffusion and mobility of electrons

Diffusion of electrons in electric field:

Energy distribution far from the Maxwellian energy distribution.

Wavelength of the accelerated electrons becomes comparable to the atomic dimensions, interactions with atoms (Ramsauer effect).



Typical values for diffusion r.m.s. after 1cm of drift:
200 μm for argon-isobuthane (75%-25%) mixture, 70 μm for CO_2

Drift velocity of electrons

No simple relation to E field, typical value 5cm/μs

Few examples:

Argon changes drastically with additives

Methane, ethane, CO_2

Methylal, Ethylene

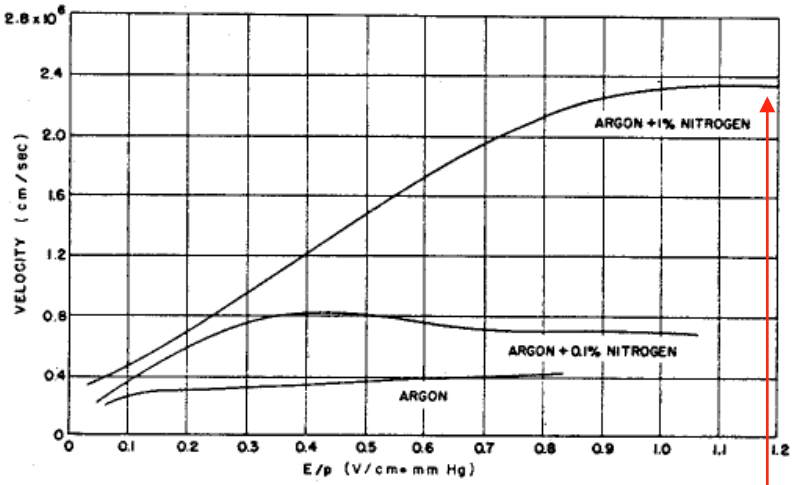


Fig. 25 Drift velocity of electrons in pure argon, and in argon with small added quantities of nitrogen. The very large effect on the velocity for small additions is apparent[22].

Very useful: in some gas mixtures v_D gets saturated

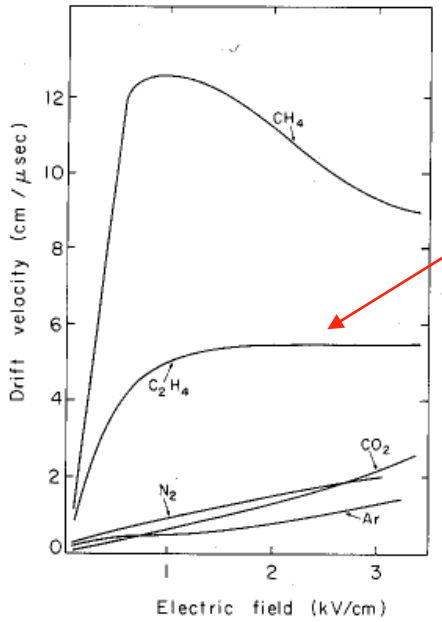


Fig. 26 Drift velocity of electrons in several gases at normal conditions[12,22,23]

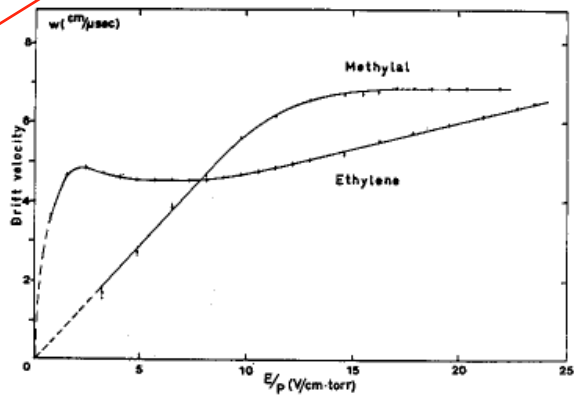
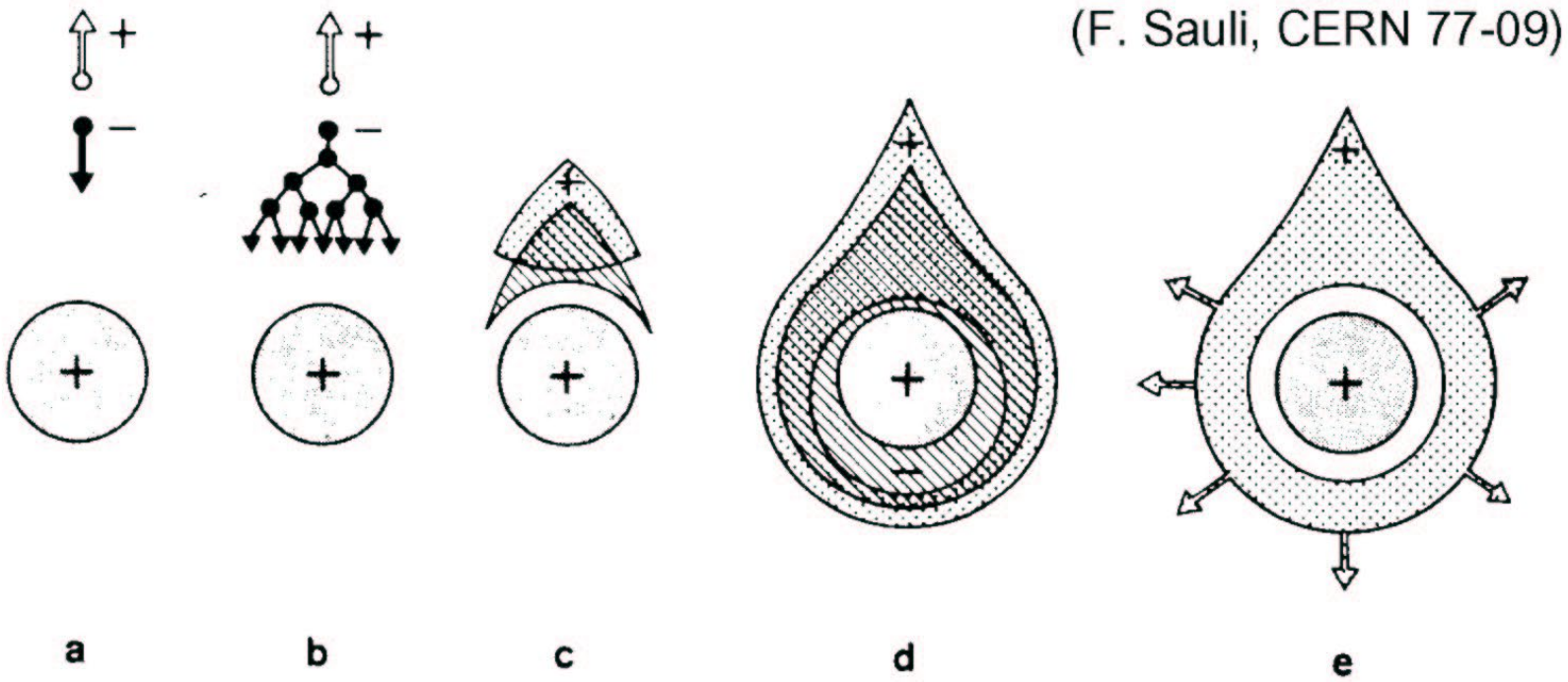


Fig. 27 Drift velocity of electrons in methylal $[(OCH_3)_2CH_2]$ and in ethylene (C_2H_4) [24]

Multiplication in gas

Electron travels (drifts) towards the anode (wire); close to the wire the electric field becomes high enough (several kV/cm), the electron gains sufficient energy between two subsequent collisions with the gas molecules to ionize -> start of an avalanche.



Multiplication in gas

α: first Townsend coefficient, probability per unit length that the electron ionizes an atom; α is a steep function of electron energy ->

The number of electrons n increases in dx by: $dn = \alpha\, n\, dx$

If α were constant, the multiplication would be $M = \exp(\alpha x)$

In general $\alpha = \alpha(x)$ and

$$M = \exp\left(\int_{x_1}^{x_2} \alpha(x)dx\right)$$

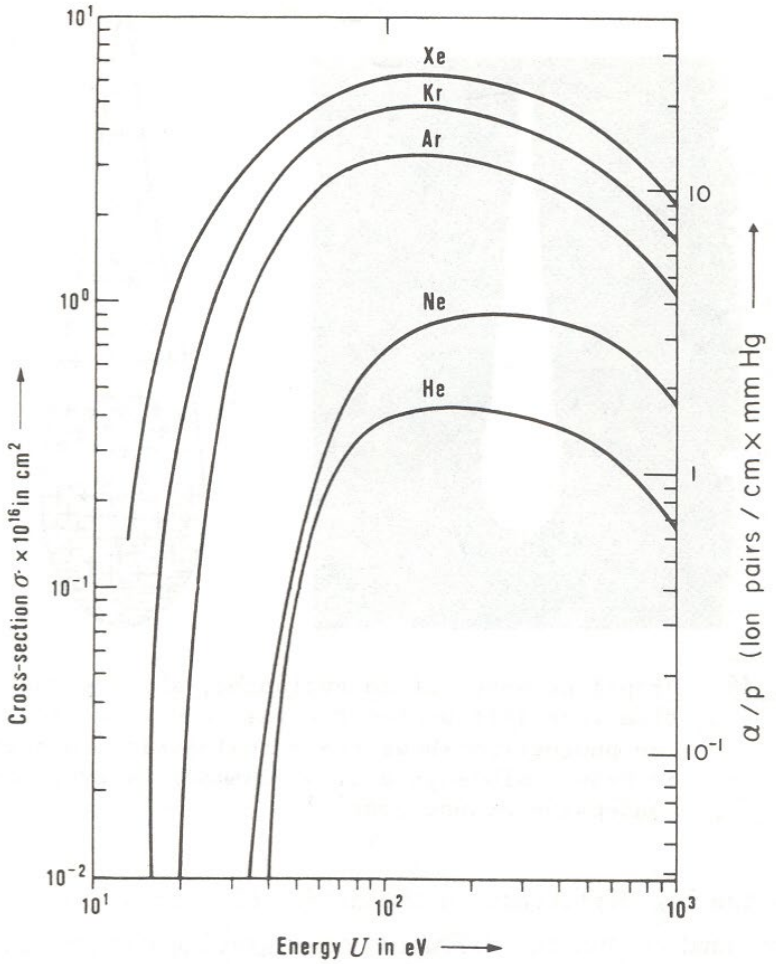
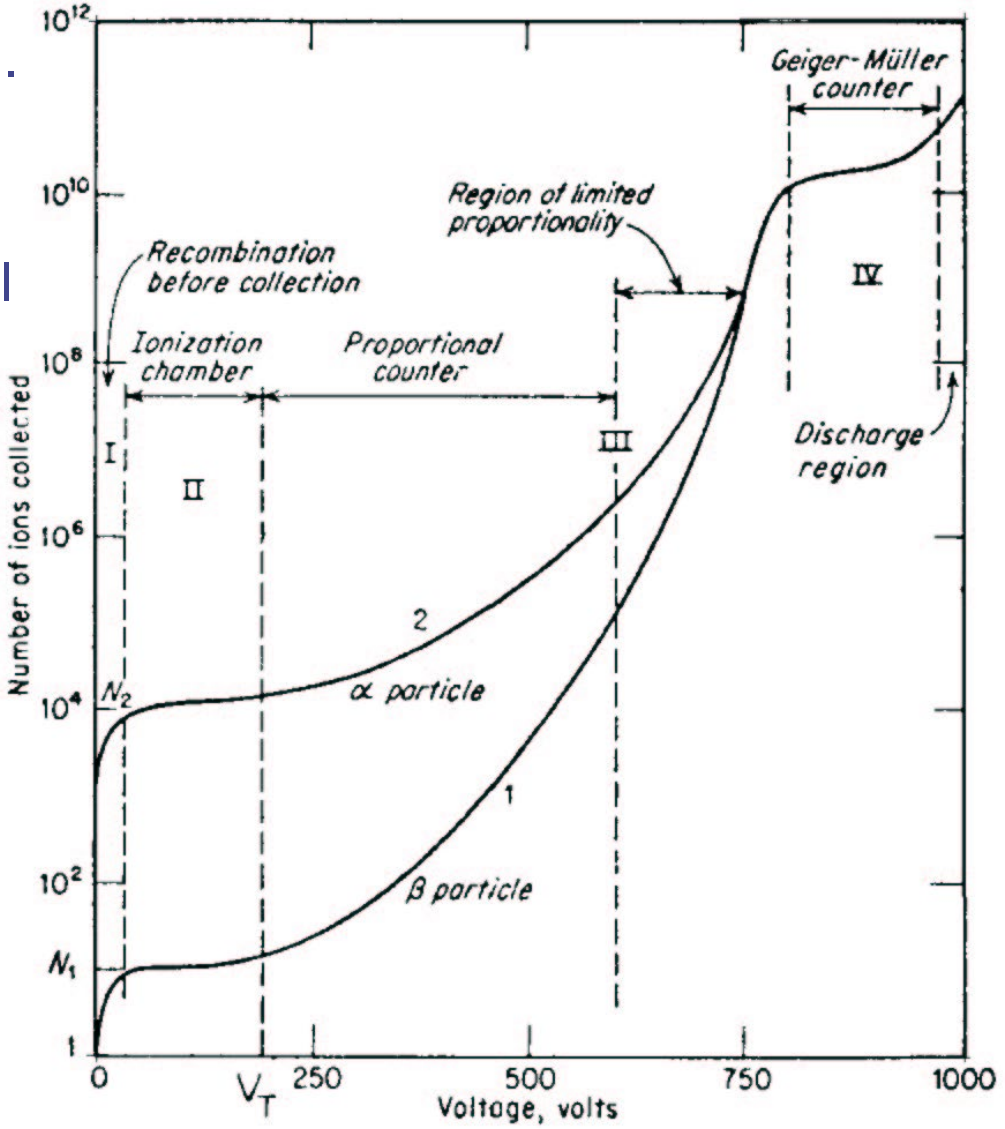


Fig. 45 Cross-section and first Townsend coefficient as a function of electron energy, for noble gases[28]

A useful parametrisation: $M = \exp(U/U_1)$, U_1 is a parameter, depends on gas, chamber geometry.

Multiplication in gas: operation modes

- Ionization mode: full charge collection, but no charge multiplication.
- Proportional mode: above threshold voltage V_T multiplication starts. Detected signal proportional to original ionization → energy measurement
- Limited Proportional → Saturated → Streamer mode: Strong photo-emission. Secondary avalanches, merging with original avalanche. Requires strong quenchers or pulsed HV. High gain (10^{10})
- Geiger mode: Massive photo emission. Full length of anode wire affected. Stop discharge by cutting down HV. Strong quenchers needed as well. Huge signals → simple electronics.

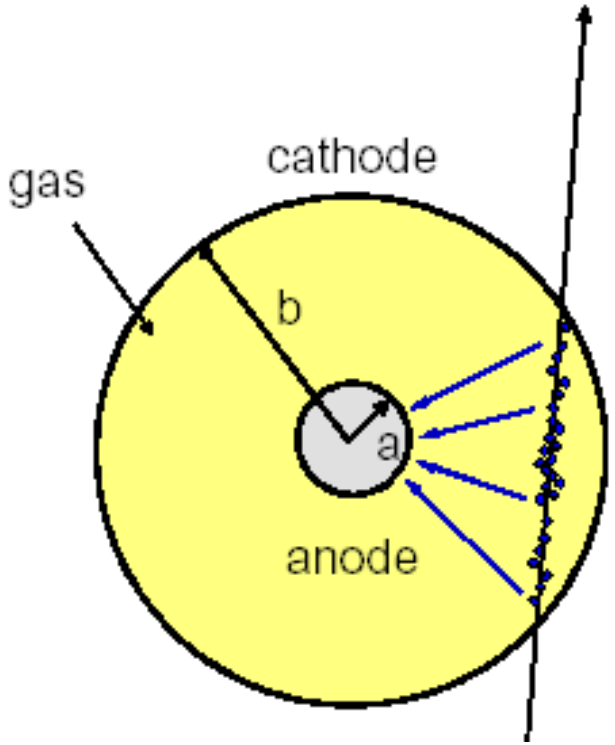


Signal development 1

Take the simplest example: the cylindrical counter.

Assume that:

- The contribution of electrons to the signal is negligible.
- All ions are produced at the anode (at r=a).



Signal development 2

The work of the electric force on the ions drifting in the electric field, *Qedr*, is supplied by the generator: charge *Cldu* flows through the HV source with high voltage U_0 (*C* = capacitance per unit length).

$$QdU = dW_e = d(\frac{1}{2}U_0^2 Cl)$$

$$-QEdr = U_0 Cldu$$

$$E = \frac{U_0 C}{2\pi\varepsilon_0}\frac{1}{r}$$

$$Q = nMe_0$$

$$u(t) = \int_0^t du = -\frac{Q}{2\pi\varepsilon_0 l}\ln\frac{r(t)}{a}$$

Signal development 3

$$u(t) = \int_0^t du = -\frac{Q}{2\pi\varepsilon_0 l}\ln\frac{r(t)}{a}$$

$$\frac{dr}{dt} = v = \mu^+\frac{E}{p} = \frac{\mu^+}{p}\frac{U_0 C}{2\pi\varepsilon_0}\frac{1}{r}$$

$$\int_a^r r dr = \frac{\mu^+}{p}\frac{U_0 C}{2\pi\varepsilon_0}\int_0^t dt$$

$$r(t) = \sqrt{a^2 + \frac{\mu^+}{p}\frac{U_0 C}{\pi\varepsilon_0}t} = a\sqrt{1+\frac{t}{t_0}}$$

$$t_0 = \frac{\pi\varepsilon_0 p a^2}{\mu^+ U_0 C}$$

$$T_0 = t_0\frac{(b^2 - a^2)}{a^2} \approx 500\,\mu s$$

T_0 = total drift time for ions

$$u(t) = -\frac{Q}{4\pi\varepsilon_0 l}\ln(1+\frac{t}{t_0})$$

Note: Electrons are produced very close to the anode, drift over a small potential difference → contribute very little to the signal (1%)

Signal development 4

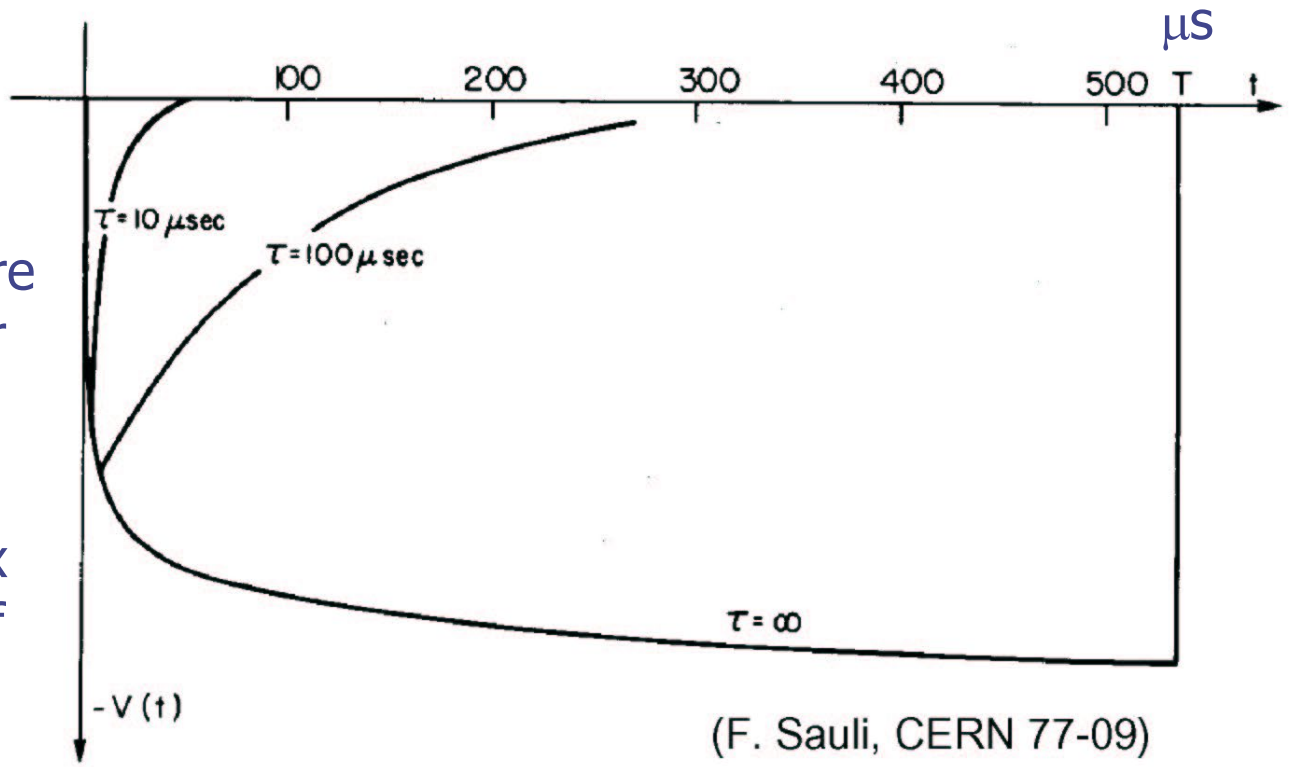
Time evolution of the signal

$$u(t) = -\frac{Q}{4\pi\varepsilon_0 l}\ln(1+\frac{t}{t_0})$$

Plot signal evolution with no RC filtering (τ = inf., above equation), and with RC filters with time constants 10μs and 100μs.

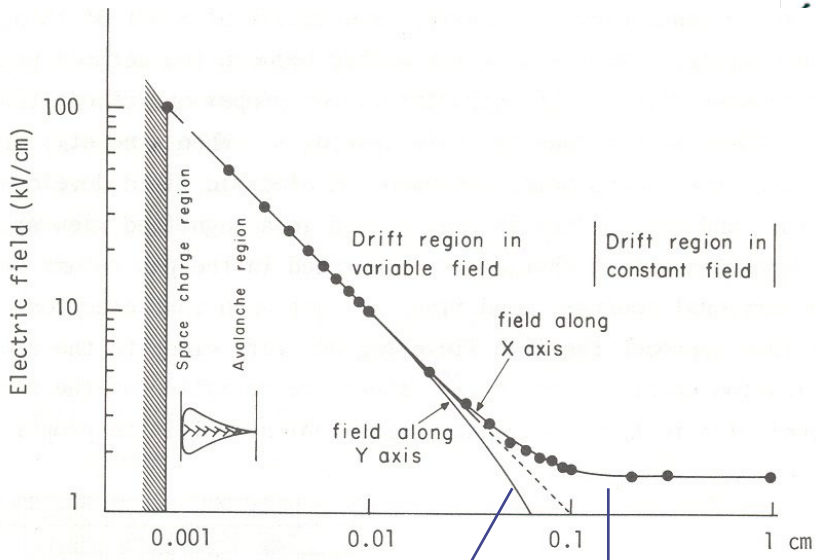
If faster signals are needed → smaller time constants→ smaller signals

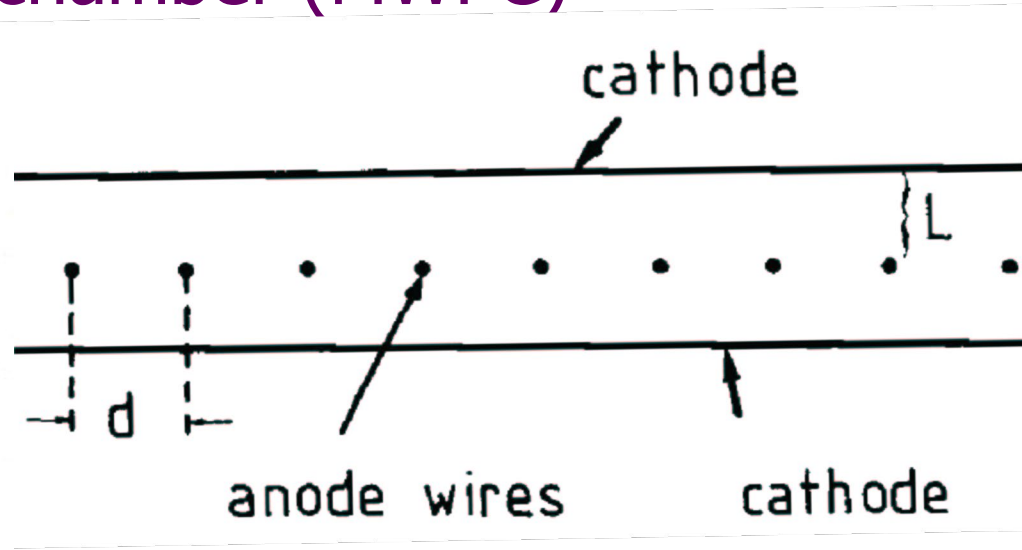
e.g. τ =40ns: max u(t) is about ¼ of the τ = inf. case



(F. Sauli, CERN 77-09)

Multiwire proportional chamber (MWPC)

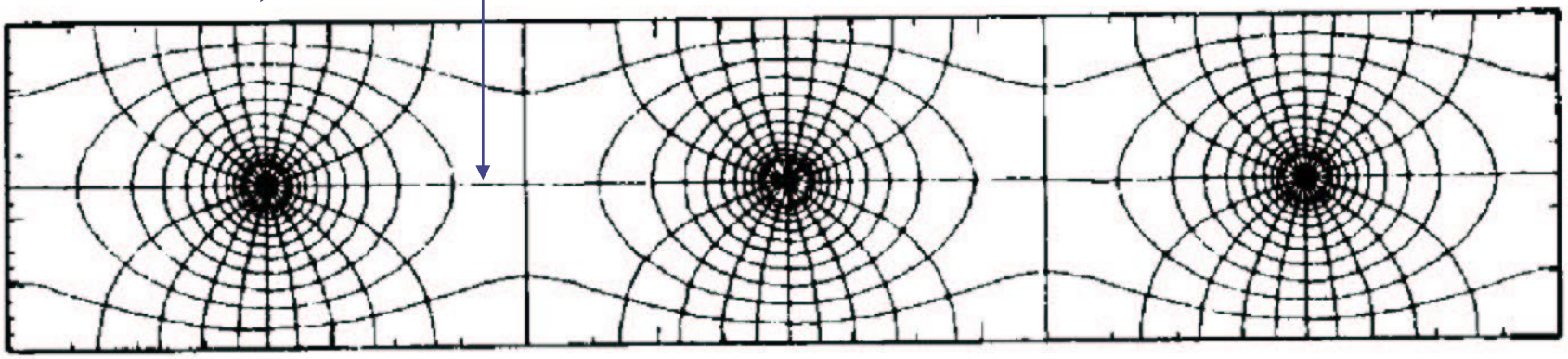




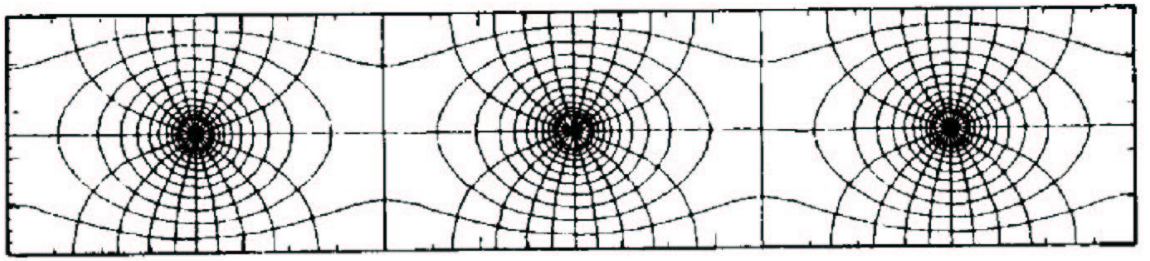
Typical parameters:

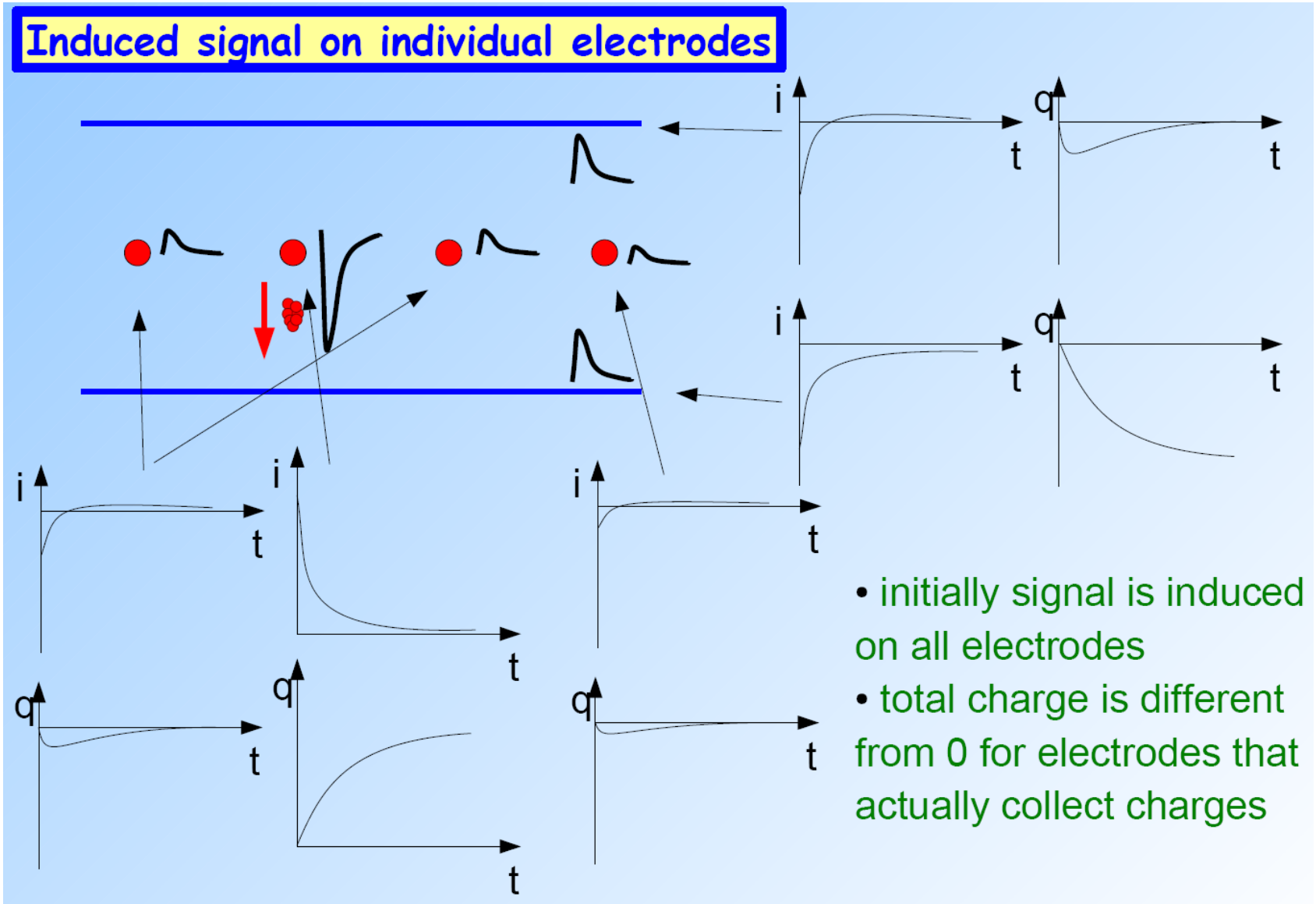
L=5mm, d=1-2mm,

wire radius =20 μm



MWPC: signal development





Multiwire proportional chamber: mechanical stability 1

Gain: strong dependence on the geometric parameters:

$\Delta M/M = 3\ \Delta a/a$ radius of the wire

$\Delta M/M = 12\ \Delta l/l$ distance to the cathode plane

All wires equally charged → repulsion → metastable

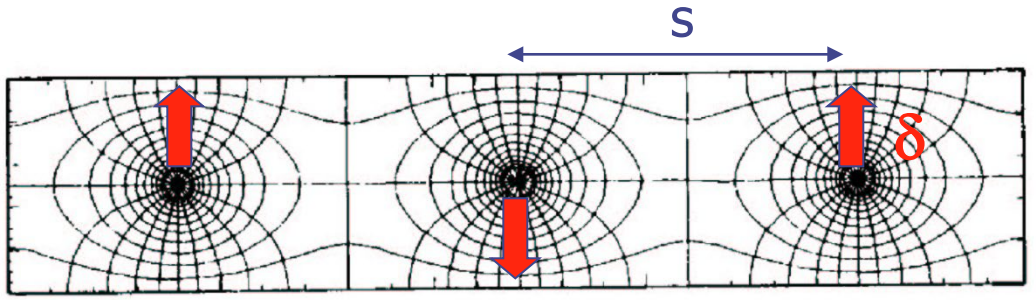
$$\sum F_T = 2\frac{(CU_0)^2}{2\pi\varepsilon_0}\left(\frac{1}{s}\frac{2\delta}{s}+\frac{1}{3s}\frac{2\delta}{3s}+\ldots\right)=\frac{(CU_0)^2}{4\pi\varepsilon_0}\frac{\delta}{s^2}$$

$$F_w\frac{d^2\delta}{dx^2}=-\frac{(CU_0)^2}{4\pi\varepsilon_0}\frac{\delta}{s^2}$$

$$\delta(0)=0,\delta(L)=0$$

$$\delta(x)=\delta_0\sin\left(\frac{CU_0}{2s}\sqrt{\frac{\pi}{F_w\varepsilon_0}}x\right)$$

$$F_w^{\ c}=\frac{1}{4\pi\varepsilon_0}\left(\frac{CU_0L}{s}\right)^2$$



If $F_W > F_W^c$ (critical wire tension)→

only trivial solution → $\delta(x)=0$

Multiwire proportional chamber: mechanical stability 2

Tension cannot be extended at will!

Tungsten: $F_{W,max}$=0.16N for wires with 2a=10μm,
$F_{W,max}$=0.65N for wires with 2a=20μm

$$F_w^{\,c} = \frac{1}{4\pi\varepsilon_0}\left(\frac{CU_0L}{s}\right)^2$$

$$L_{\max} = \left(\frac{s}{CU_0}\right)\sqrt{4\pi\varepsilon_0 \mathrm{F}_{\mathrm{W,max}}}$$

With s=2mm, l=8mm, 2a=20μm: **L_{max}=85cm**!

For longer wires: support.

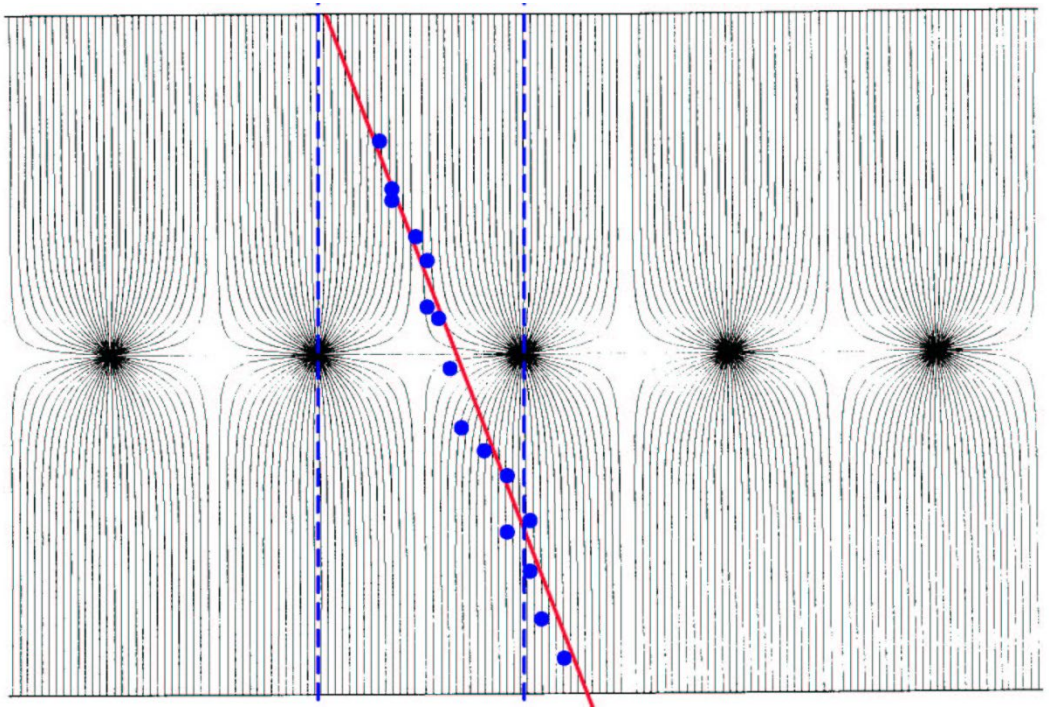
Multiwire proportional chamber (MWPC)

Address of fired wire gives only 1-dimensional information.

Normally digital readout: spatial resolution limited to

σ = d/sqrt(12)

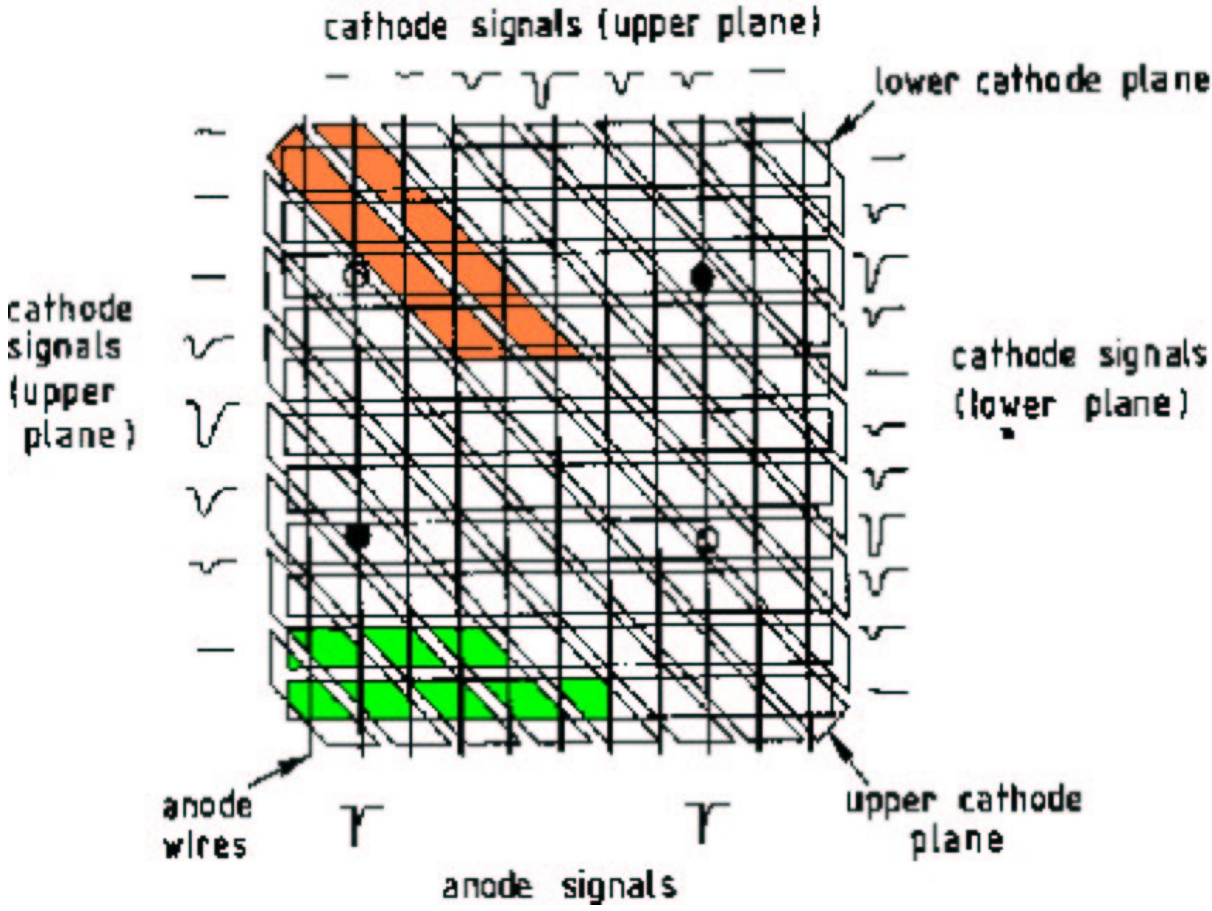
for d=1mm, σ =300 μm



Multiwire proportional chamber (MWPC)

More than one coordinate per single chamber

Remove ambiguities



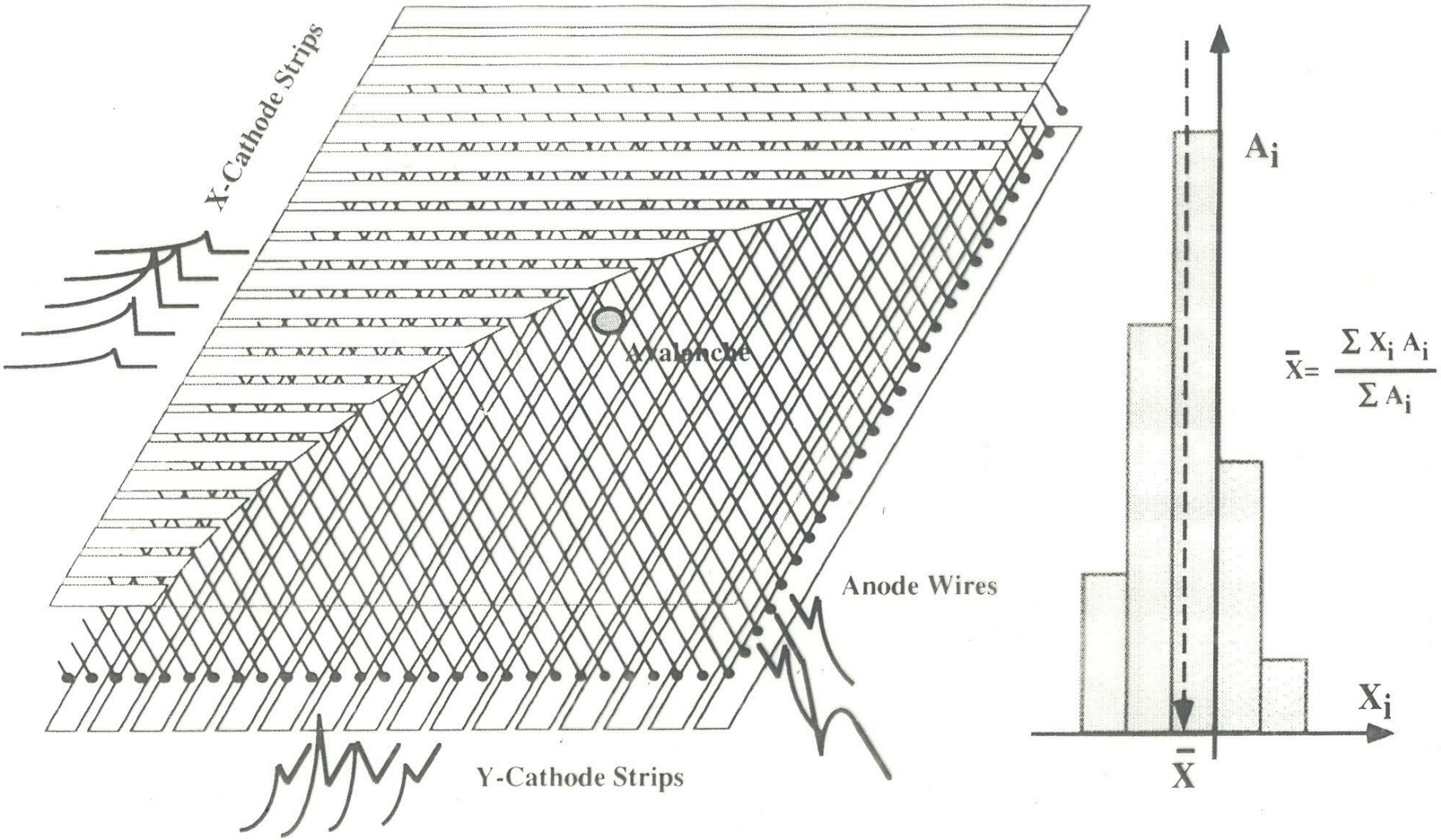
Use signals from the

-anodes

-sliced upper cathode

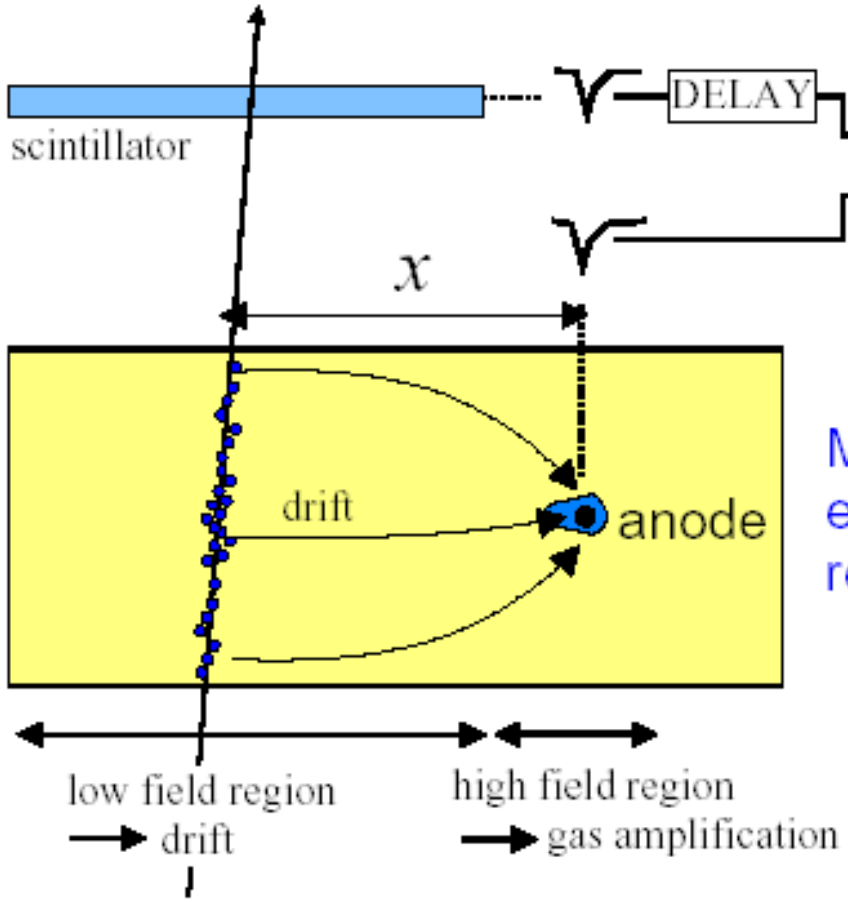
-sliced lower cathode

CENTER OF GRAVITY OF INDUCED CHARGE



Drift chamber

Improve resolution by measuring the drift time of electrons

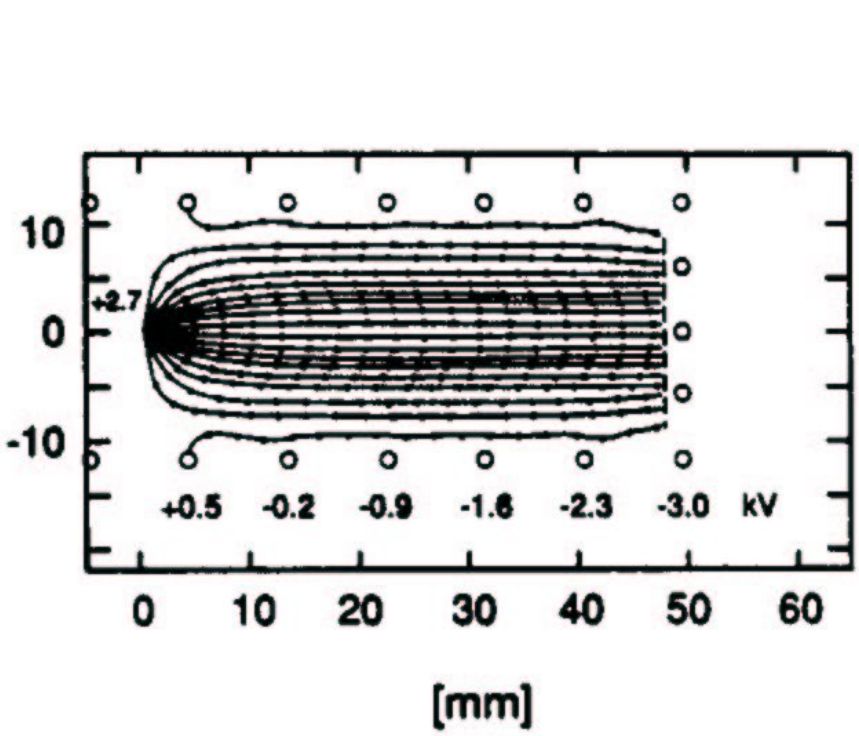


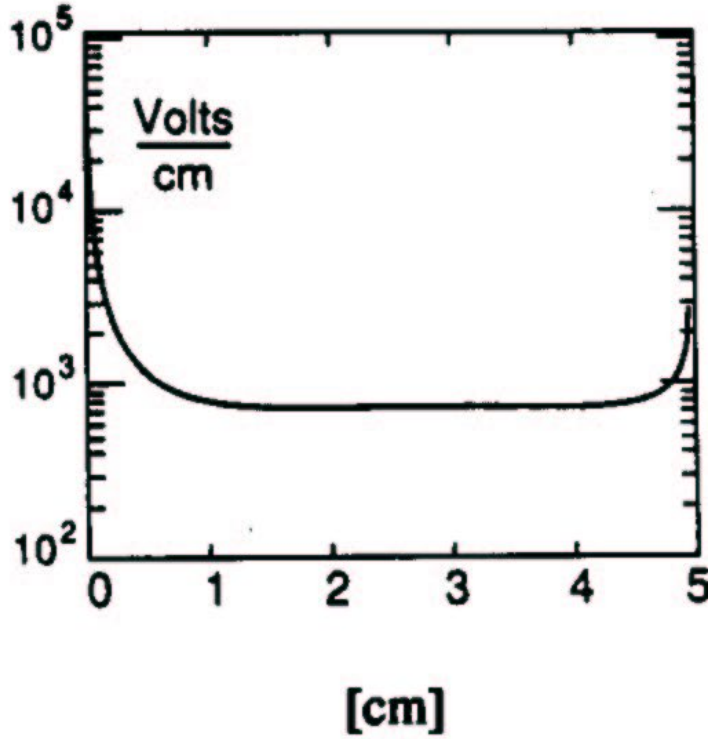
Measure arrival time of electrons at sense wire relative to a time t_0.

$$x = \int v_D(t)dt$$

Drift chamber

The name of the game: transform drift time to distance: need constant E (field shaping) and constant drift velocity (gas mixture)





Drift chamber: resolution

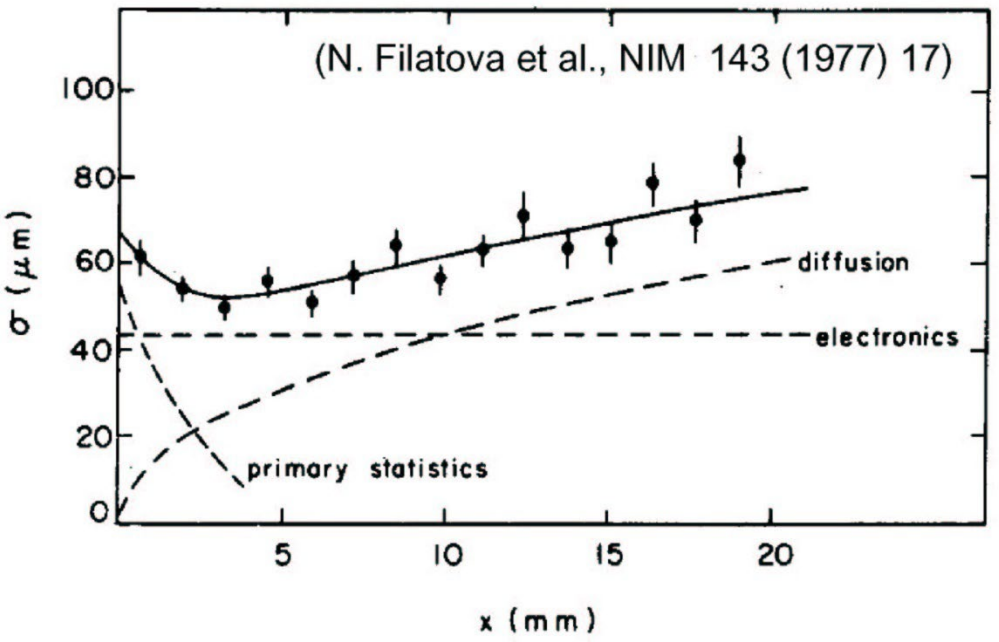
Resolution determined by

- diffusion,
- primary ionisation statistics,
- electronics,
- path fluctuations.

Diffusion: $\sigma_x \propto \sqrt{Dt} \propto \sqrt{x}$

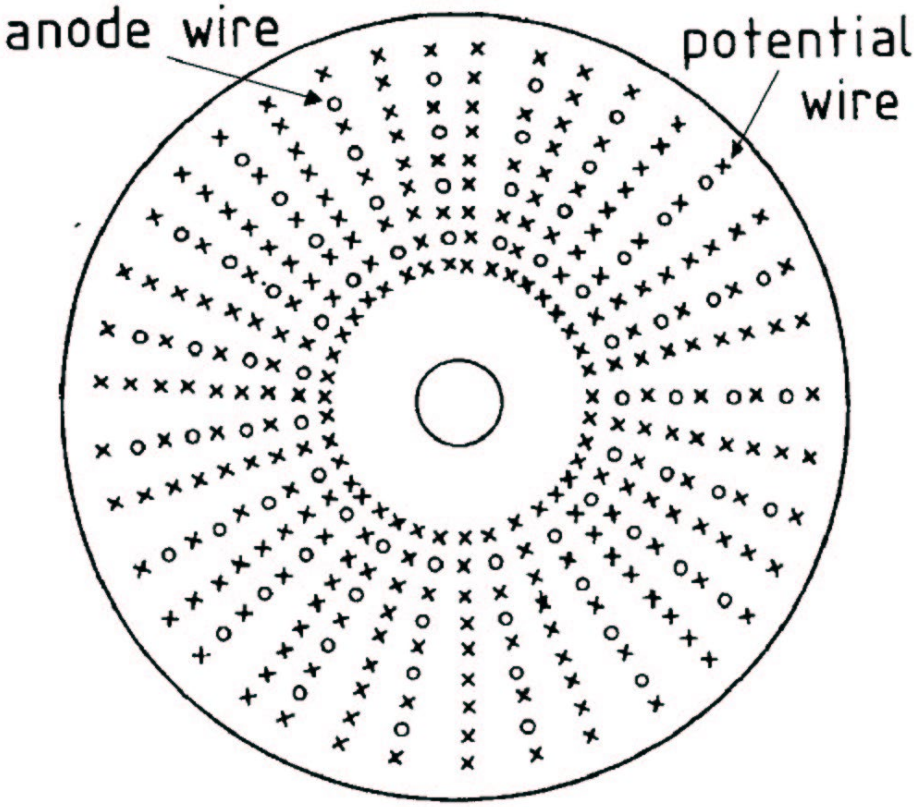
Primary ionisation statistics: if n e-ion pairs are produced over distance L, the probability that the first one is produced at x from the wire is $e^{-nx/L}$

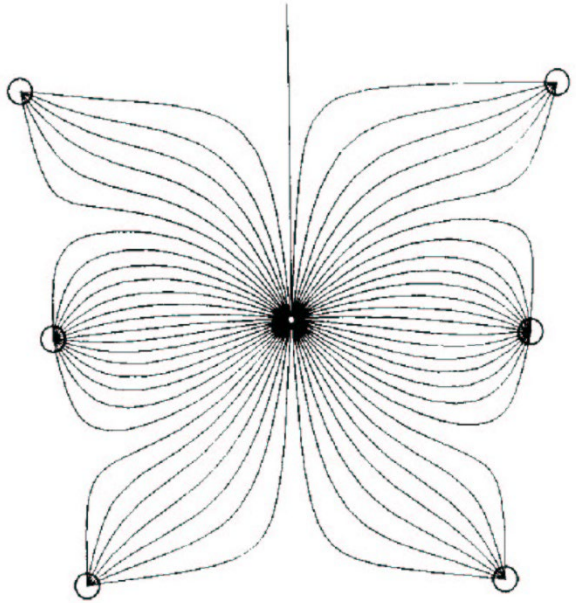
Resolution as a function of drift distance



Drift chamber with small cells

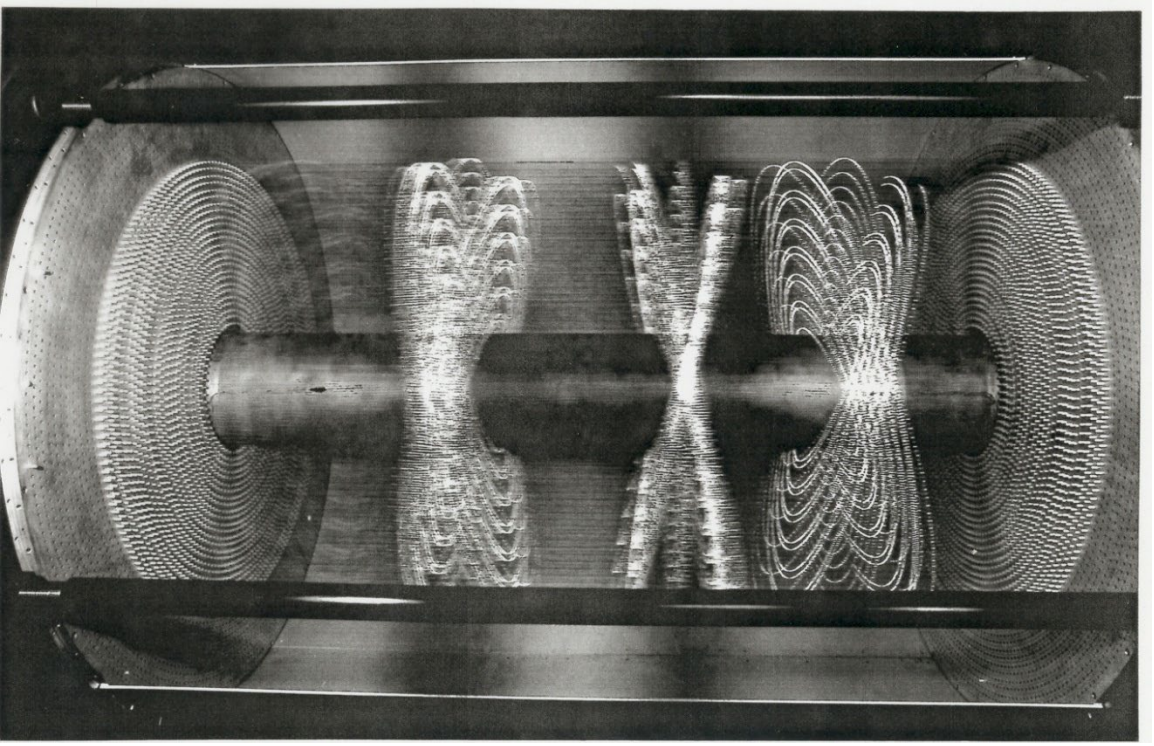
One big gas volume, small cells defined by the anode and field shaping (potential) wires

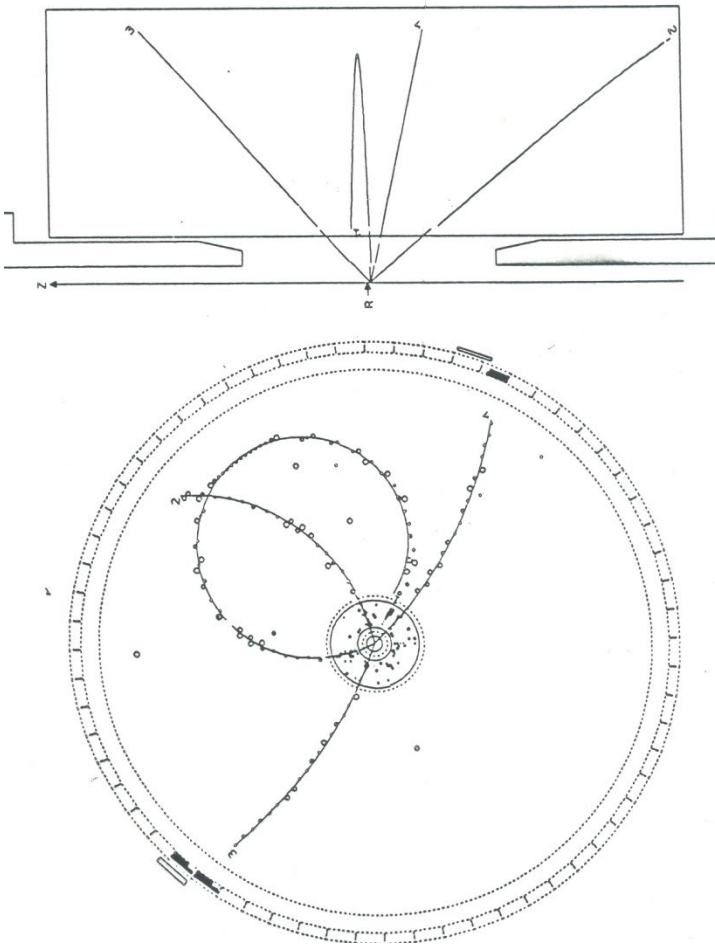




Drift chamber with small cells

Example: ARGUS drift chamber with axial and 'stereo' wires (at an angle to give the hit position along the main axis)

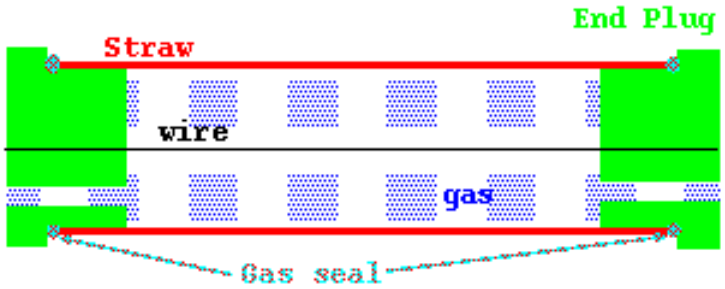




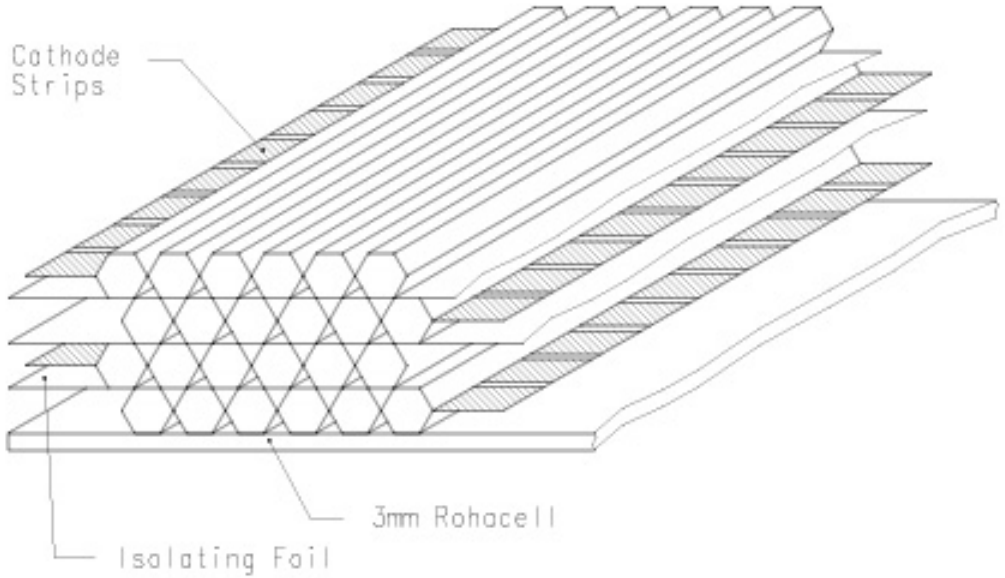
Typical event in two projections

Single cell drift chamber

Simplify manufacturing: put each wire in a tube (straw or hexagonal); useful for large areas.



Cells can be several meters long!



Diffusion and mobility of electrons in magnetic field

E perpendicular to B

Lorentz force perpendicular to B → net drift at an angle α to E

$\mathrm{tg}\alpha = \omega\tau$

α: Lorentz angle

ω: cyclotron frequency, ω=eB/m

τ: mean time between collisions

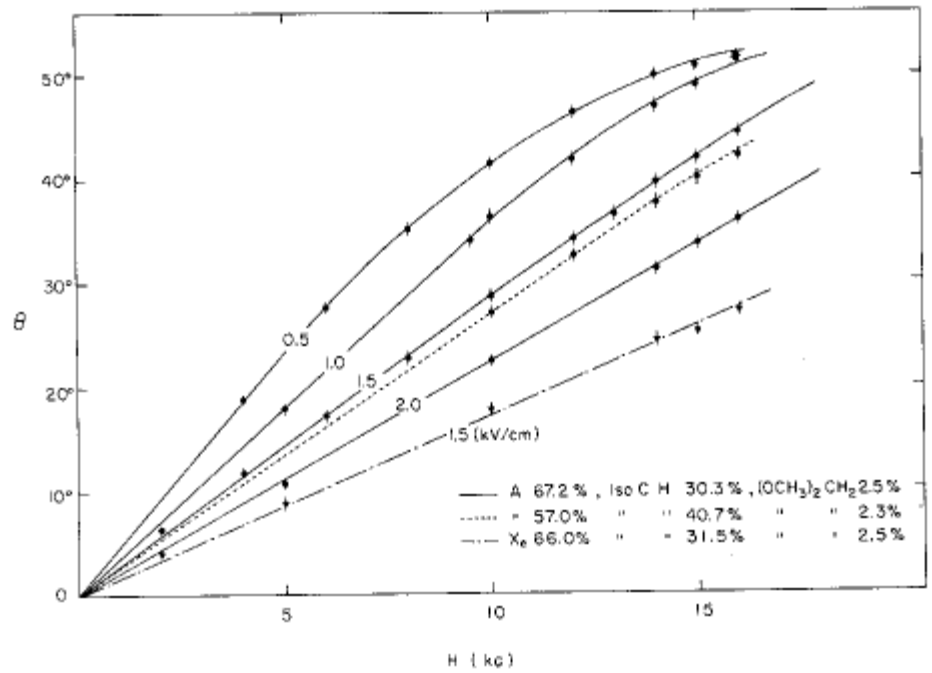
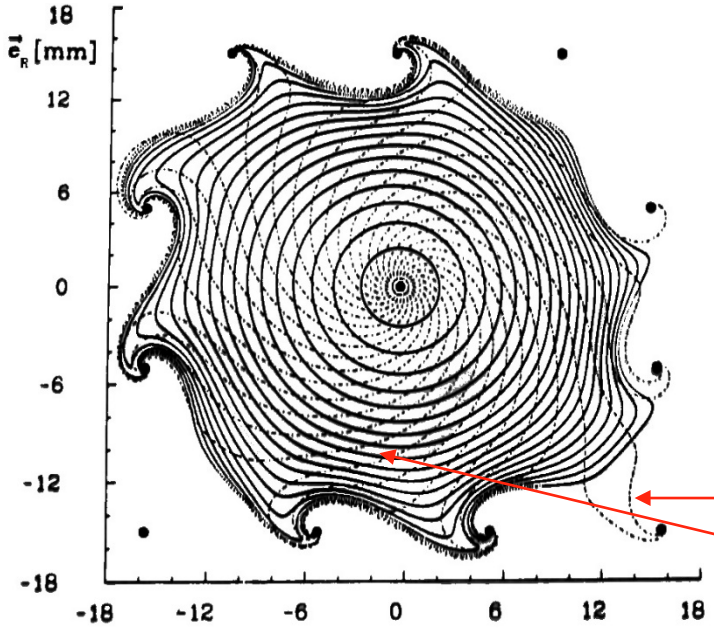


Fig. 38 Measured drift angle (angle between the electric field and the drift directions) as a function of electric and magnetic field strength[9].



Drift lines in a radial E field (dash-dotted)

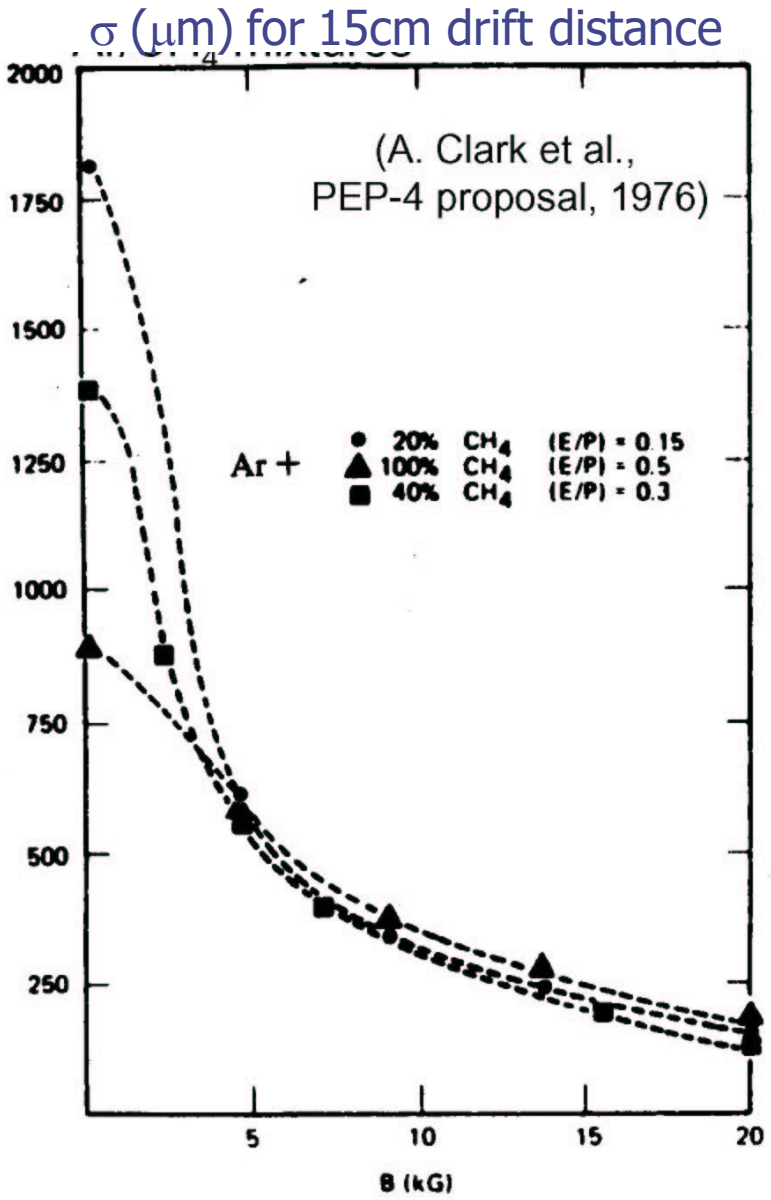
Isochrones (full lines)

Diffusion and mobility of electrons in magnetic field 2

E and B parallel:

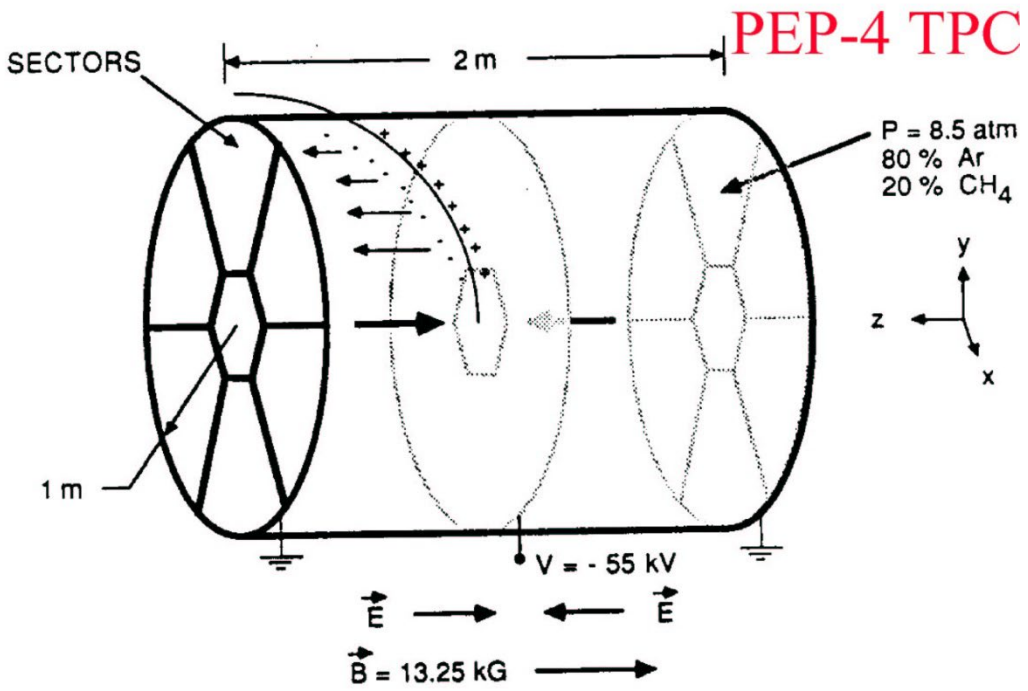
drift along E, diffusion in the transverse direction reduced! – departing electrons get curled back:

$$D_T(B) = D_0/(1 + \omega^2\tau^2)$$



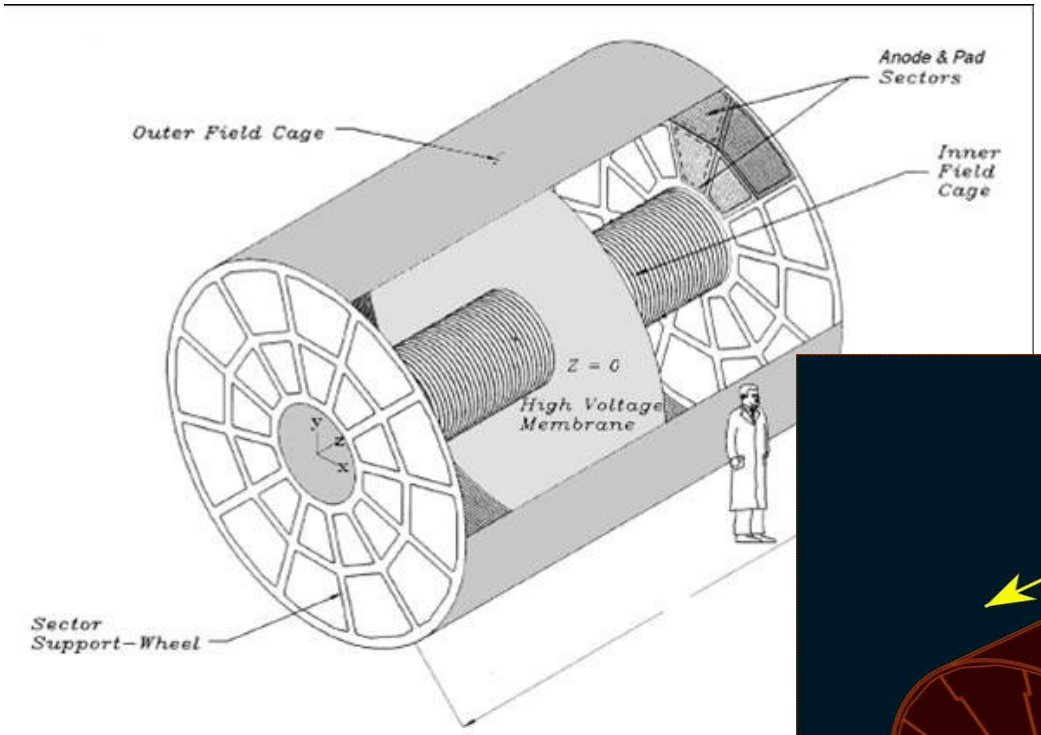
Drift chamber: TPC – time projection chamber

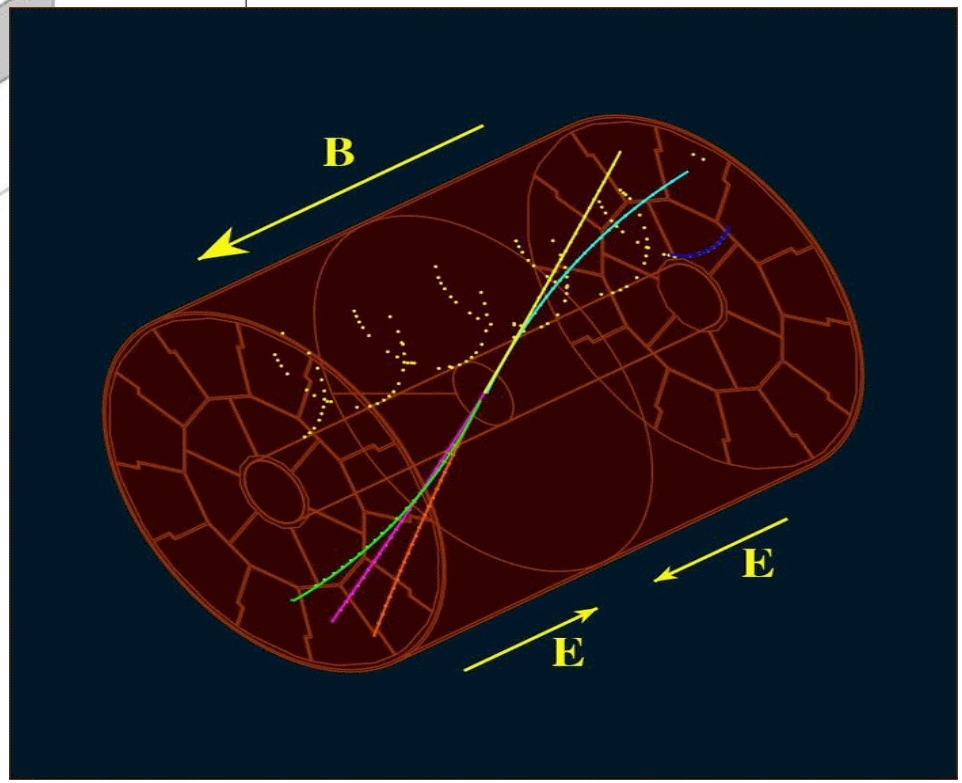
3-dimensional information: drift over a large distance, 2 dim. read-out at one side



Diffusion: no problem for the tranverse coordinate in spite of the very long drift distance because B parallel to E (drift direction).

TPC principle





Drift chamber: TPC – time projection chamber

z coordinate (along the E, B field): from drift time

2 dim. read-out at one side:

- Anode wires and cathode pads
- Anode wires and cathode strips (perpendicular)

Resolutions for the ALEPH TPC (d=3.6m, L=4.4m):

in x,y: 173 μm, in z: 740 μm.

Potential problems:

- need an excellent drift velocity monitoring (long drift distance)
- high quality gas (long drift distance)
- space charge: ions drifting back to the cathode

Gas mixtures for drift chambers and MWPCs

Main component: a gas with a low average ionisation energy W_i - nobel gases have less degrees of freedom.

Add to this:

- A component which absorbs photons ('quencher') produced in the avalanche (deexcitation of atoms and ions) – an organic molecule with a lot of degrees of freedom: isobutane, methane, CO_2, ethane
- A component which prevents that ionized organic molecules would travel to the cathode, stop there, and polymerize to form poorly conductive layers: a gas which has a low ionisation energy - methylal
- A small concentration of an electronegative gas (freon, ethylbromide) which prevents the electrons travel too far (to prevent that electrons which escaped from the cathode start new avalanches) allows to work at high gains (10^7)

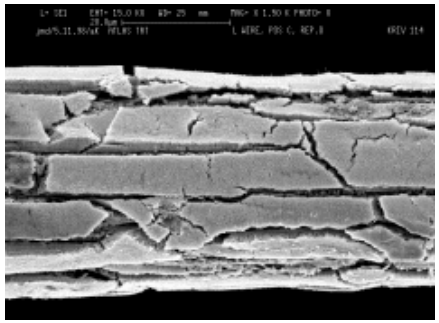
'Magic mixture': 72% Ar, 23.5% isobutane, 4% methylal, 0.5% freon

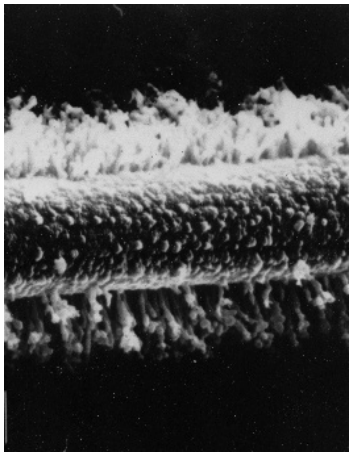
Gas mixtures for drift chambers and MWPCs 2

For drift chambers in addition:

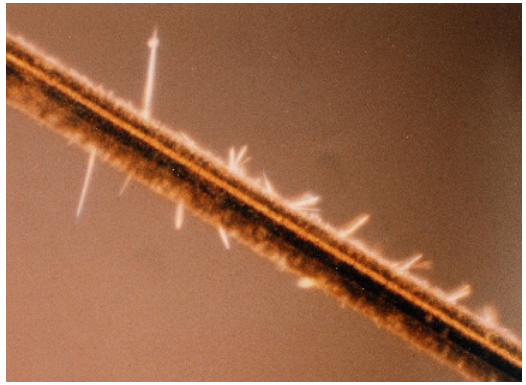
- Need a gas with constant drift velocity (to simplify the drift time -> distance relation)
- Sometime low density (to reduce multiple scattering): add He
- Long drift distances: no electronegative gas
- Gas with a small diffusion coefficient ('cool' gas): CO_2, DME
- To prevent anode wire ageing (a poorly conductive layer on the anode – redices gain): add very little water or freon CF_4.

Ageing of wire chambers

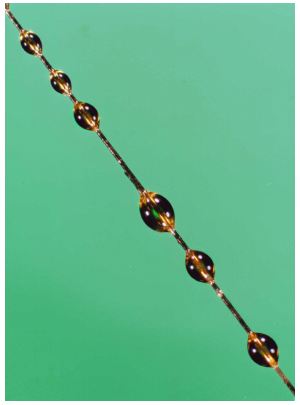




Mainly due to accumulation of polymerisation deposits on the anodes and cathodes.



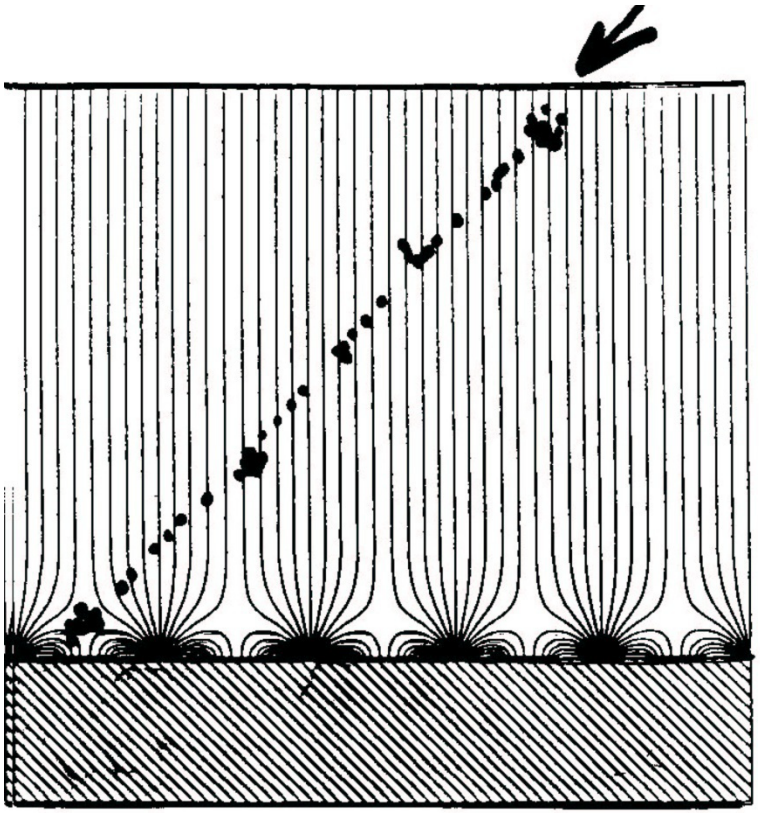
Anode wire ageing, consequence: gas amplification drops as a function of deposited charge (wire is thicker, and the amplification process is stopped earlier).

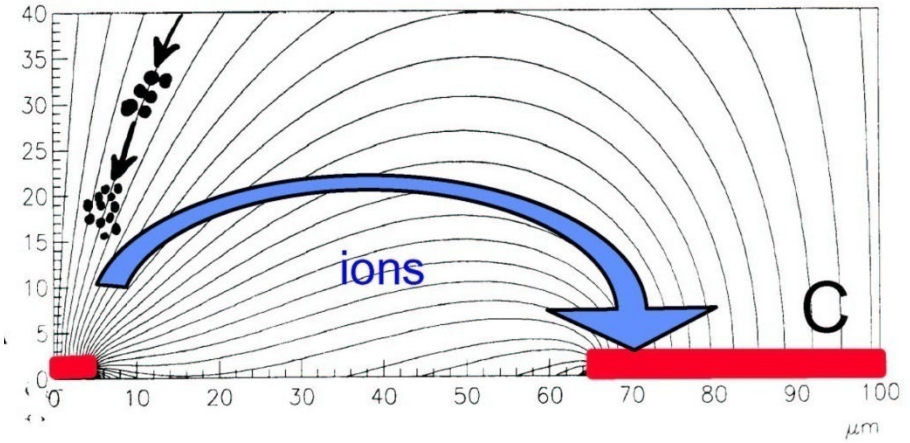


Cathodes: deposited layer is typically poorly conductive → charge accumulation on both sides of the layer → high electric fields → high breakdown probability → random high pulses

Microstrip gas chamber (MSGC)

Operation with high track density: multiple hits per cell → need smaller cell size. Fix electrodes to a substrate (e.g. glass), typical distance 100μm.





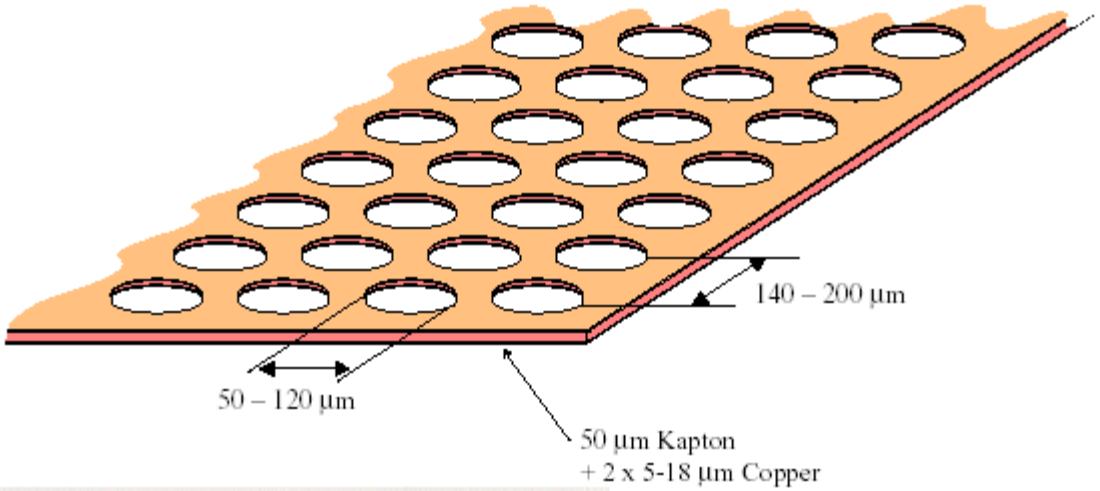
nisation counters

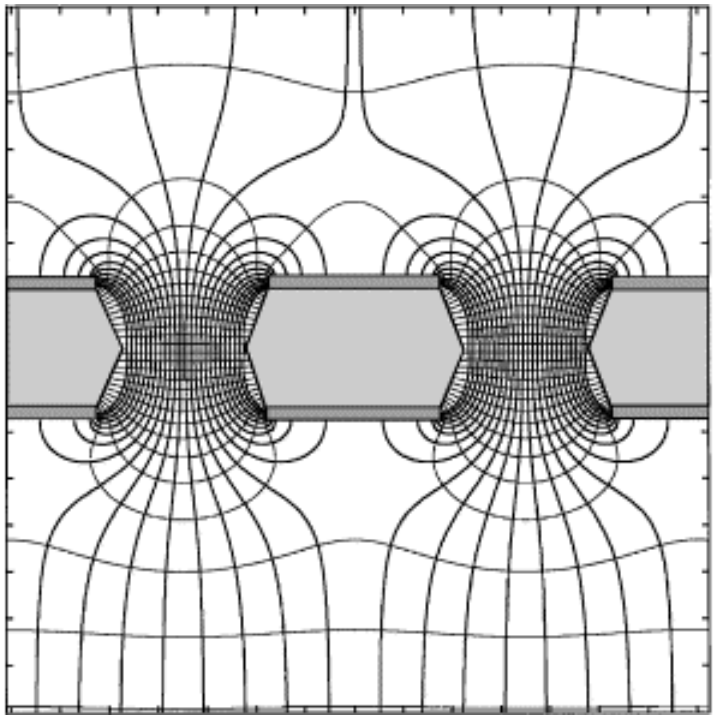
Microstrip gas chamber (MSGC) 2

Turned out to be very delicate instruments, very sensitive to large local deposition of energy in form of ionizination (e.g. low energy α particles, recoil nuclei or nuclear fragments).

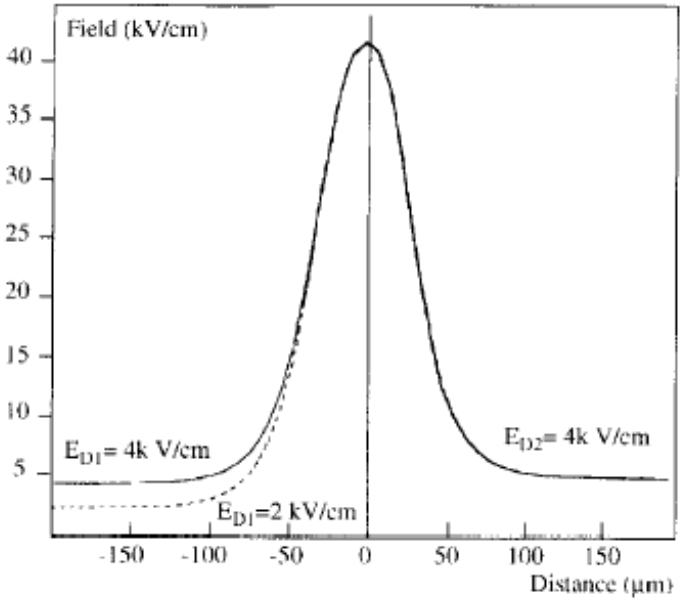
Way out: divide gas amplification in two or more steps.

GEM (gas electron multiplier) preamplification





The E field in the holes is non-uniform – large enough to get gas amplification of about 100: useful as a preamplification stage for MSGCs.



MSGC+GEM

Two amplificatin stages in gas: GEM and MSGC.

Considerably improves the operation stability of the MSGC chamber.

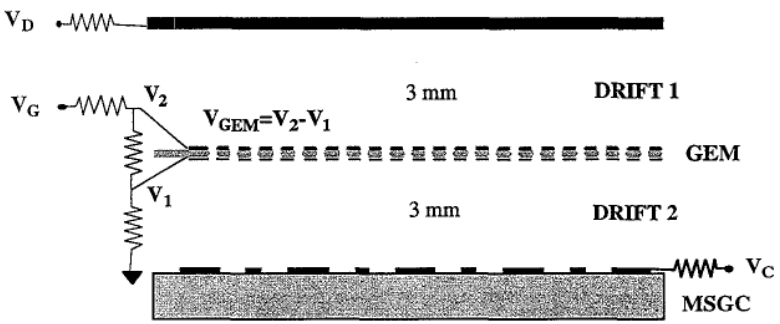


Fig. 12

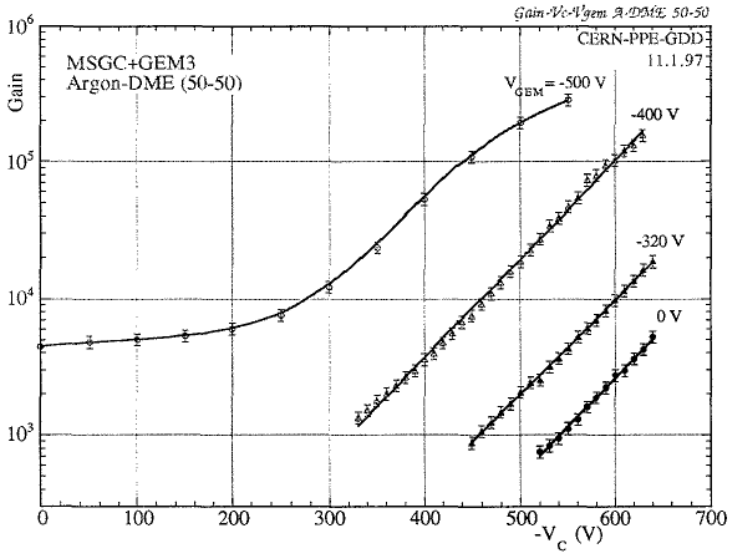
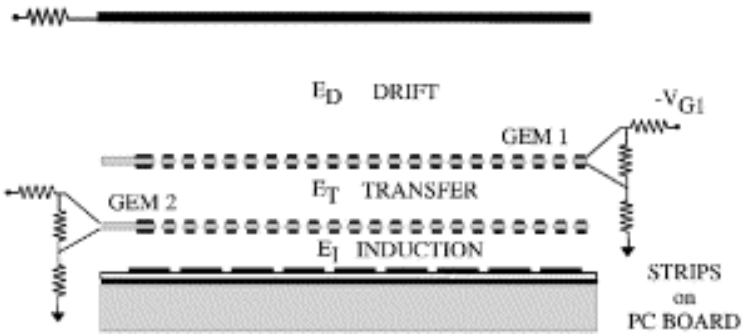


Fig. 13

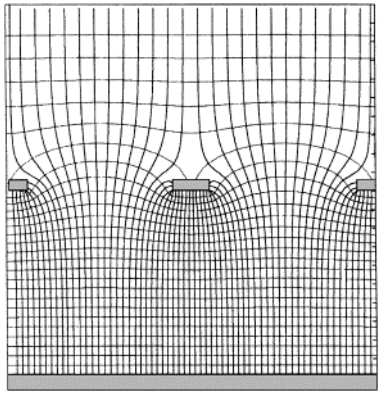
2x GEM + cathode pads



Two amplificatin stages in gas: 2xGEM, cathode with pads for read-out.

Very simle production!

MICROMEGAS

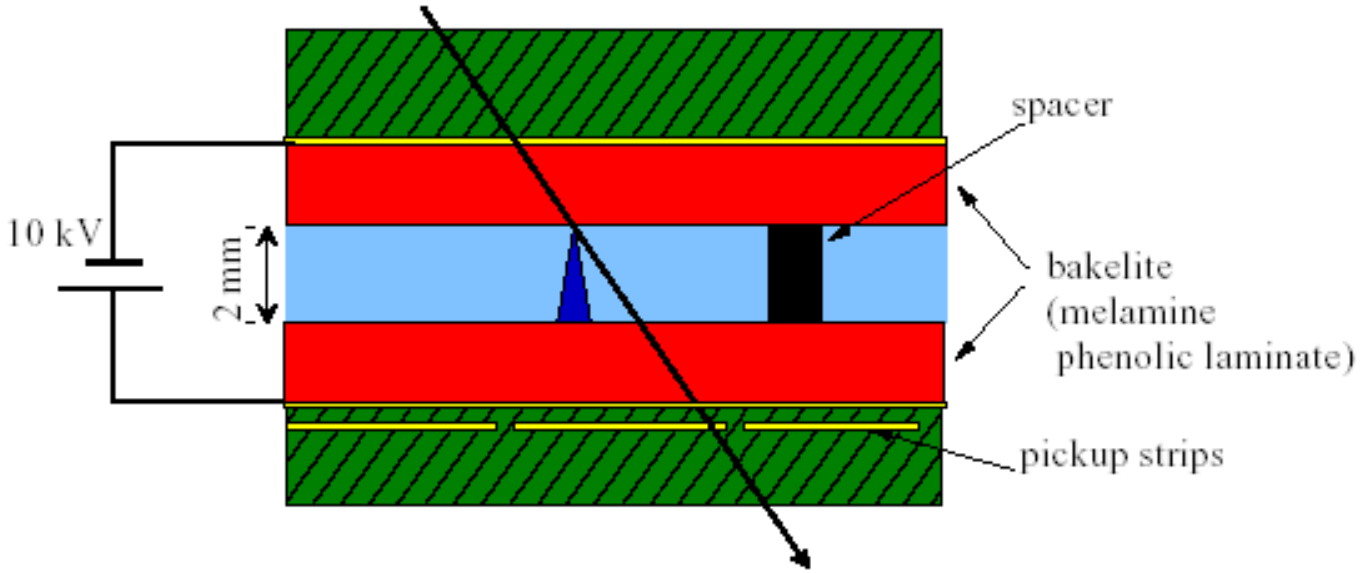


Instead of the GEM foil use a mesh of thin wires. The effect is similar.

2x GEM + MICROMEGAS

Probably the most popular combination at present.

Resistive plate chambers (RPC)



Gas amplification in a uniform electric filed.

Gas: $C_2F_4H_2$, (C_2F_5H) + few % isobutane

Bakelite: covered by the linse seed oil...

Time dispersion $\approx$ 1..2 ns $\rightarrow$ suited as trigger chamber

Problem: Operation close to streamer mode and ageing (BaBar)

High rate operation of wire chambers

With increased rate the gas chamber amplification decreases. As a consequence the detection efficiency is reduced.

Flux R of incoming particles, each produces charge nMe; ions drift towards the cathode (total time t_0) → uniform charge distribution in the chamber volume -> screening of the E field. The anode potential is reduced by:

$\Delta U = nMe_0 R\, t_0/(4\pi^2\varepsilon_0)$,

and small ΔU_o, the amplification is

$M = M_0 \exp(-\Delta U/U_1)$

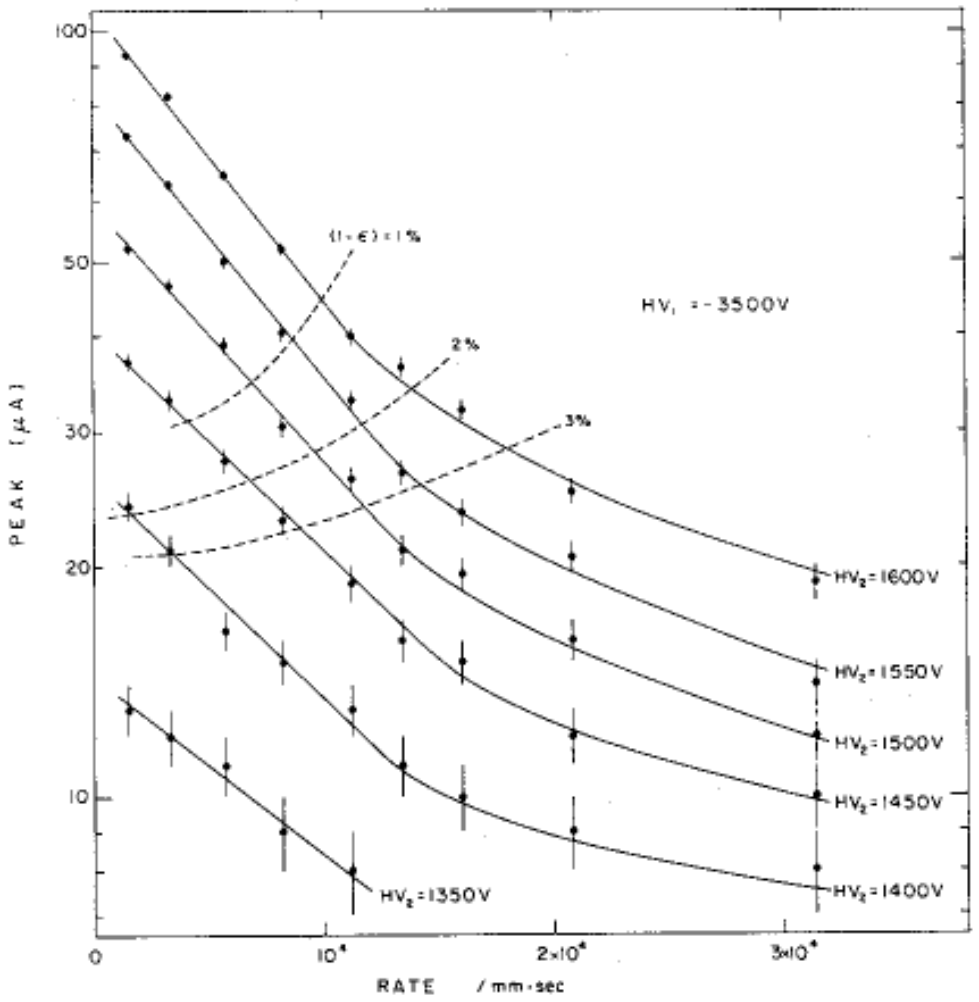


Fig. 54 Rate dependence of the peak current for minimum ionizing particles, in a drift chamber. The dashed curves show the equal inefficiency intercept, for a fixed detection threshold (5 μA) [9].

Distribution of charges in the chamber volume, cylindrical counter

Needed: dq/dS, charge density as a function of radius, for constant particle impact rate R.

Use expressions from the signal time evolution derivation.

$$E = \frac{U_0 C}{2\pi\varepsilon_0}\frac{1}{r}$$

$$Q = nMe_0$$

$$t_0 = \frac{\pi\varepsilon_0 p}{\mu^+ U_0 C}(b^2 - a^2)$$

$$\frac{dr}{dt} = v = \mu^+ \frac{E}{p} = \frac{\mu^+}{p}\frac{U_0 C}{2\pi\varepsilon_0}\frac{1}{r}$$

$$\frac{dN}{dS} = \frac{dN}{2\pi r dr} = \frac{dN}{dt}\frac{dt}{2\pi r dr} = R\frac{1}{2\pi}\left(\frac{\mu^+}{p}\frac{U_0 C}{2\pi\varepsilon_0}\right)^{-1}$$

Bottomline: charge density is constant in the gas volume!

$$\frac{dq}{dS} = \frac{dN}{dS}Q = \frac{dN}{dS}nMe_0 = \frac{Rp\varepsilon_0}{\mu^+ U_0 C}nMe_0$$

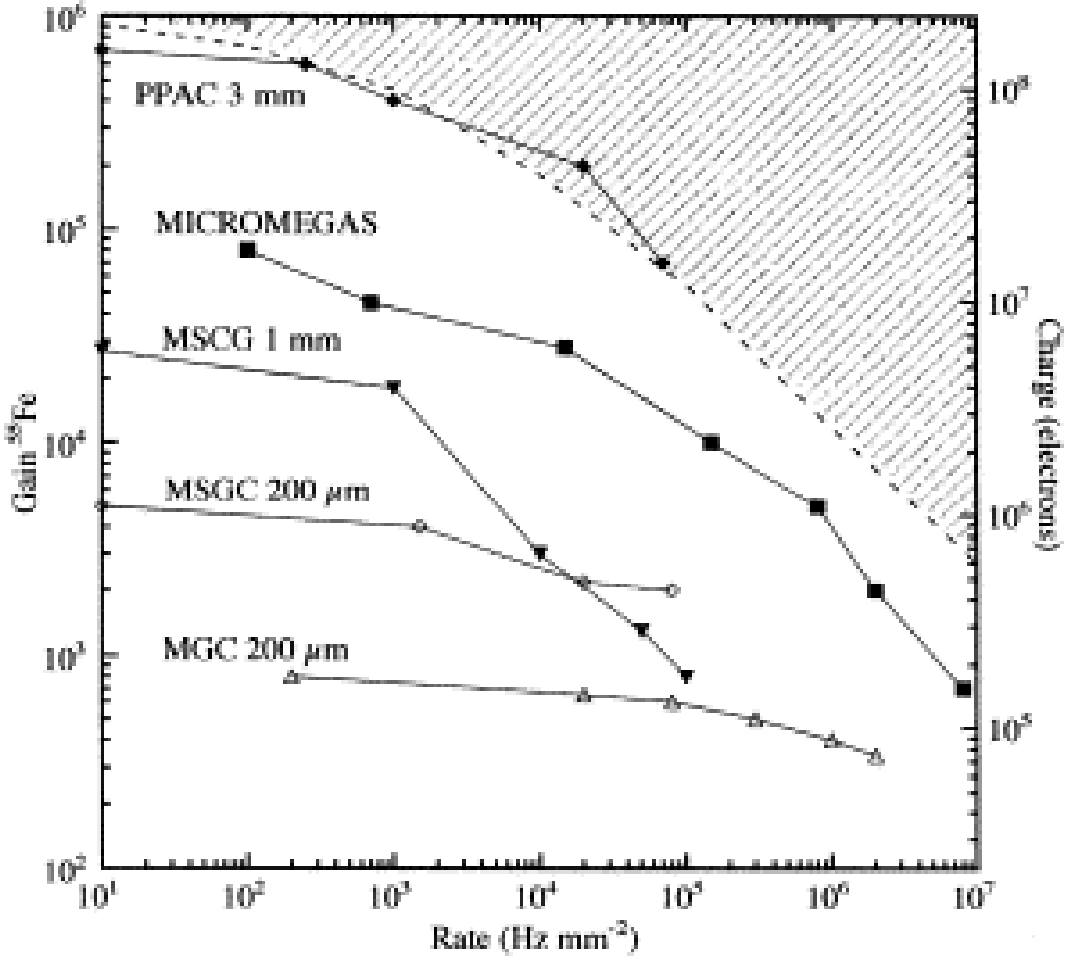
Total charge between the anode and cathode:

$$q = \frac{Rp\varepsilon_0}{\mu^+ U_0 C}nMe_0\pi(b^2 - a^2) = RnMe_0 t_0$$

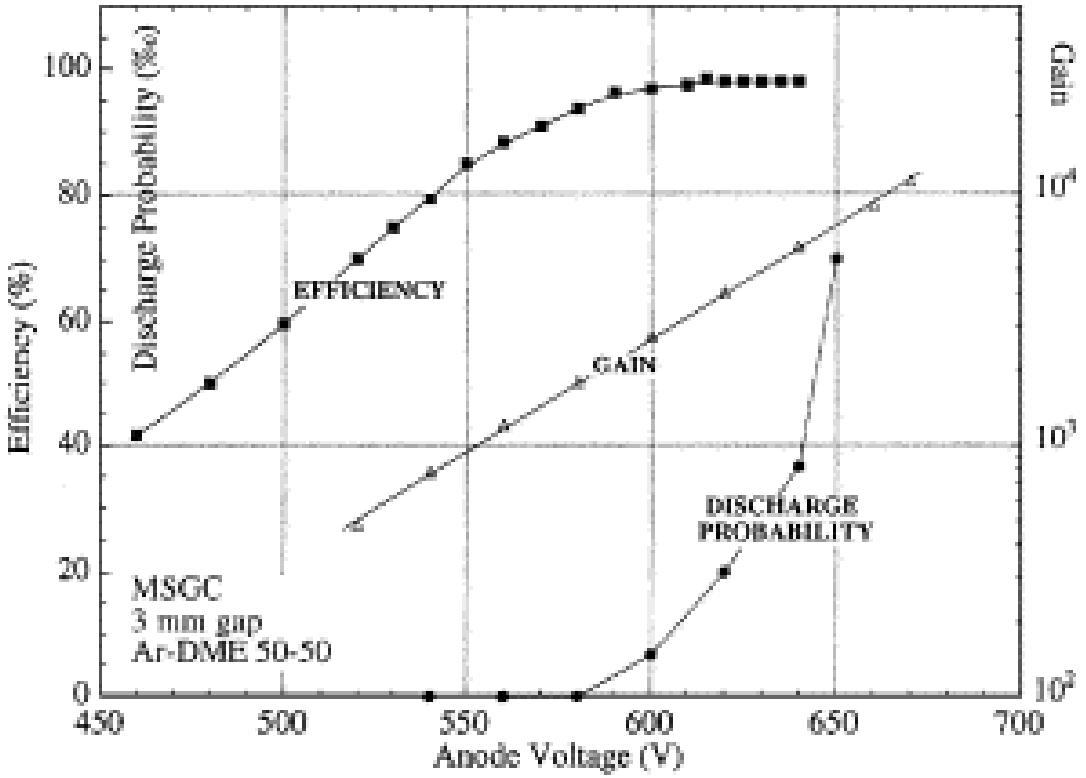
High rate operation of wire chambers

Gain decrease vs rate for various micro-pattern detector types.

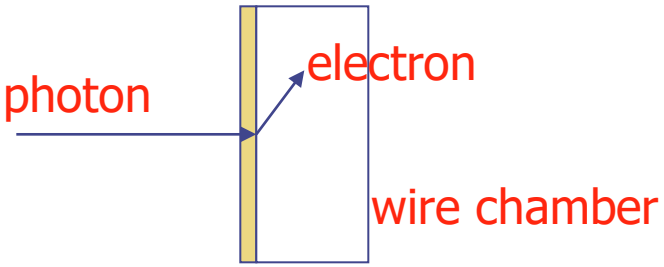
Shaded: instabilities → forbidden region.



High rate operation of wire chambers:discharge probability



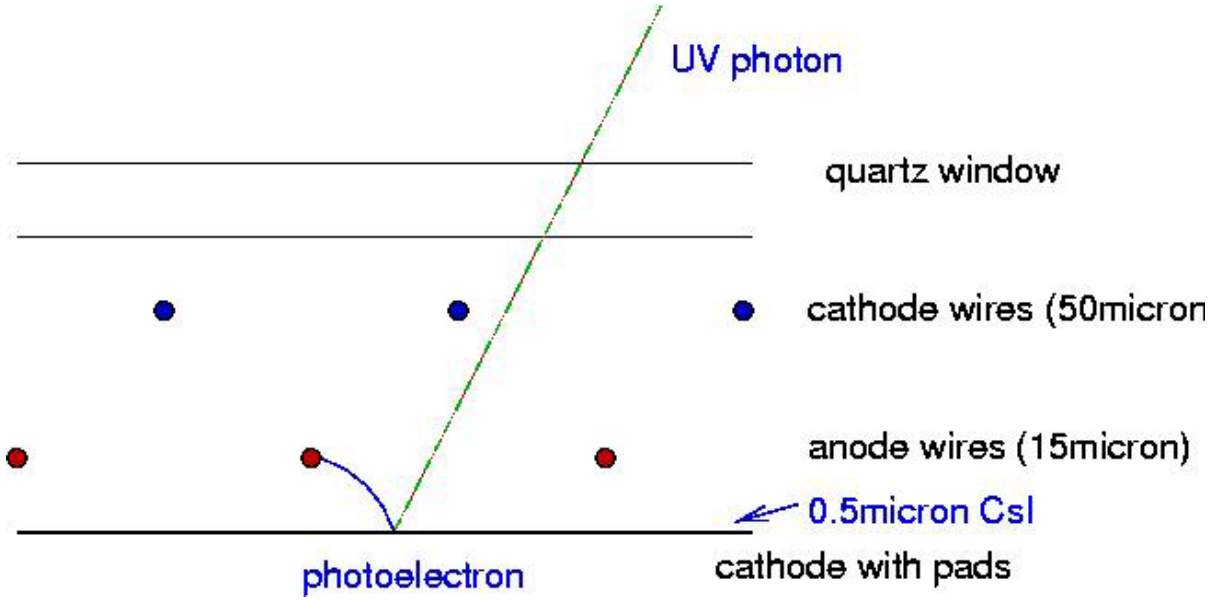
UV, X and γ photon detection in wire chambers



A multiwire proportional chamber can be used as a detector of electromagnetic radiation as well: if the photon hits an electron out of the material in the chamber (photo-effect), this electron can then be treated as a charged particle. In such a way a position sensitive detection of X, γ and UV rays becomes possible.

- 511 keV γ rays from the annihilation of positrons and electrons (PET - positron emission tomography): a γ ray is "converted" into an electron in a layer of a high Z material
- X rays: a high Z gas (e.g. Xenon) is added to the gas mixture to increase the probability for photo-effect
- UV photons: one of the cathodes of a multiwire chamber is covered by a material with low work function

UV photon detection in wire chambers

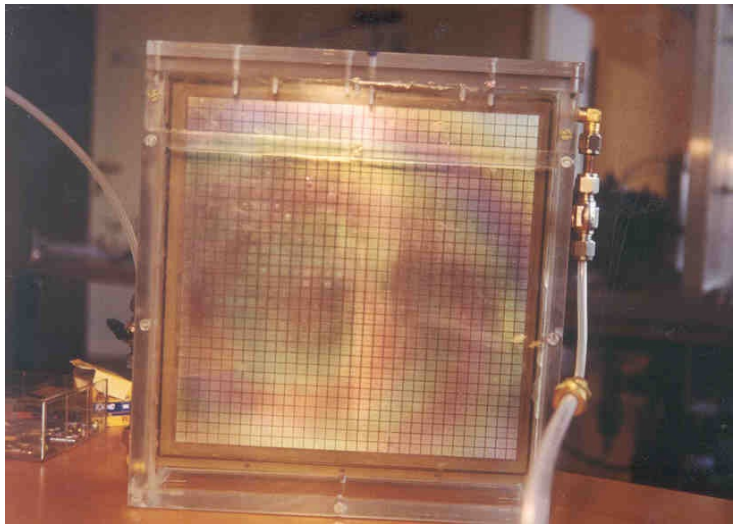


One of the cathodes of a multiwire chamber is segmented with pads (e.g. 8mmx8mm) and covered by a material which

- has a low work function
- is able to survive in gas
- does not interact with the substrate

-> about a micron of CsI on a Sn-Pb substrate

The other cathode: wires



UV photon detection in wire chambers: photosensitive materials

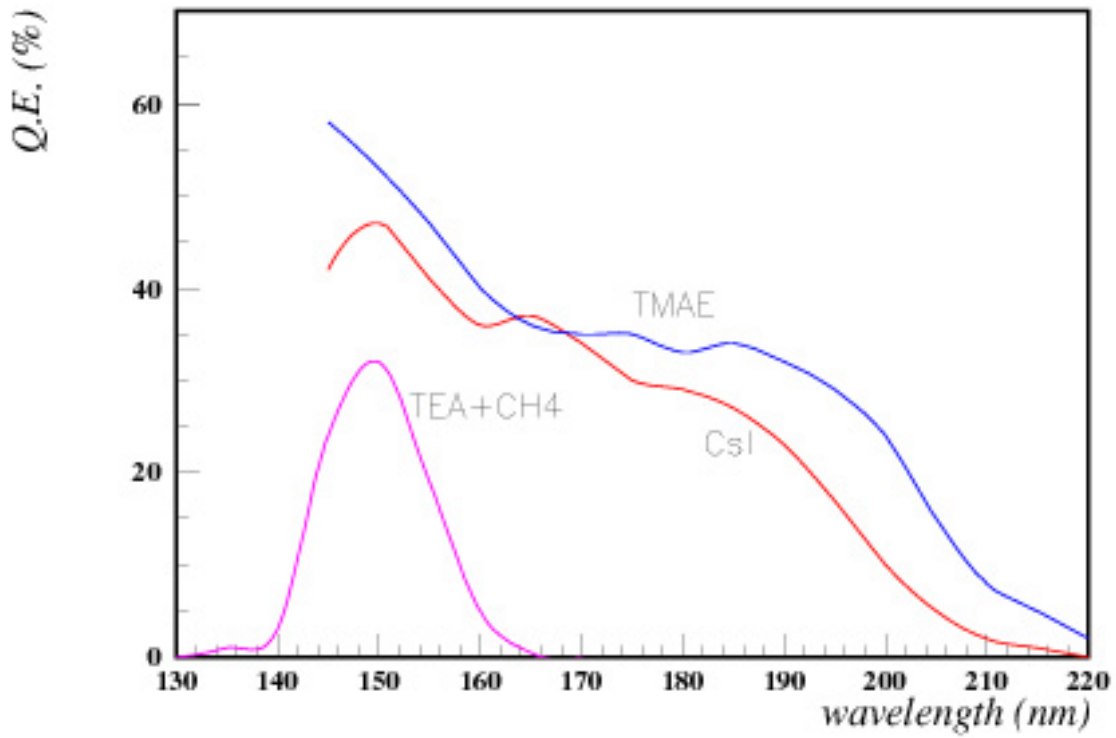
Either added to the gas mixture

- TMAE
- TEA

or a layer on one of the cathodes

- CsI on a Sn-Pb substrate

quantum efficiency vs λ



UV photon detection in wire chambers: single photon pulse height distribution

Starting with one electron we ask what is the probability P(n,x) that n electrons will result at a distance x?

The probabilities have to satisfy a set of differential equations

$$\frac{d}{dx}P(1,x) = -\alpha P(1,x)$$

$$\frac{d}{dx}P(2,x) = -2\alpha P(2,x) + \alpha P(1,x)$$

$$\frac{d}{dx}P(n,x) = -n\alpha P(n,x) + (n-1)\alpha P(n-1,x)$$

with initial conditions P(1,0) = 1; P(n,0) = 0, n>1.

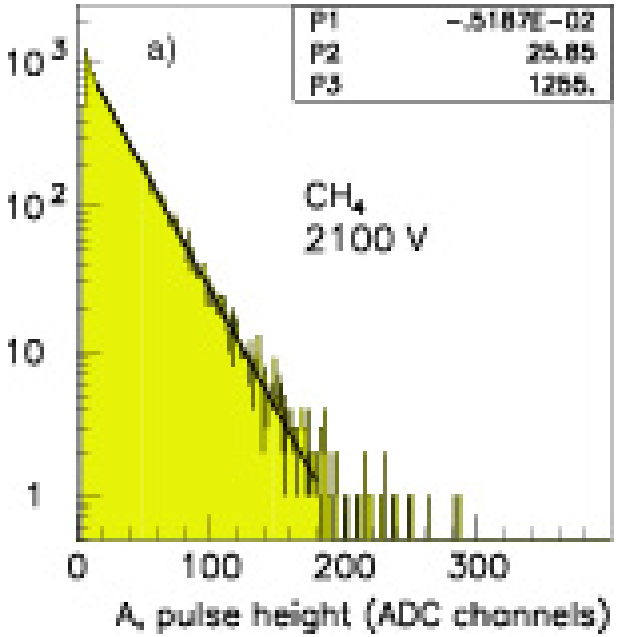
UV photon detection in wire chambers: single photon pulse height distribution

By successive integration we get

$$P(1,x) = e^{-\alpha x}$$

$$P(2,x) = e^{-\alpha x}(1-e^{-\alpha x})$$

$$P(n,x) = e^{-\alpha x}(1-e^{-\alpha x})^{n-1}$$



Taking into account that $e^{\alpha x}$ is the mean value of n, we arrive at

$$P(n,x) = \frac{1}{n}(1-\frac{1}{n})^{n-1}$$

which is for n>>1 and with U=pulse height

$$P(U) = \frac{1}{U}e^{-\frac{U}{U}}$$

UV photon detection in wire chambers: photo-electron detection

Distribution of pulse heights due to individual photoelectrons is exponential!

Dramatic consequence for photo-electron detection probability (=efficiency). For a given electronics threshold U_{th} the efficiency is

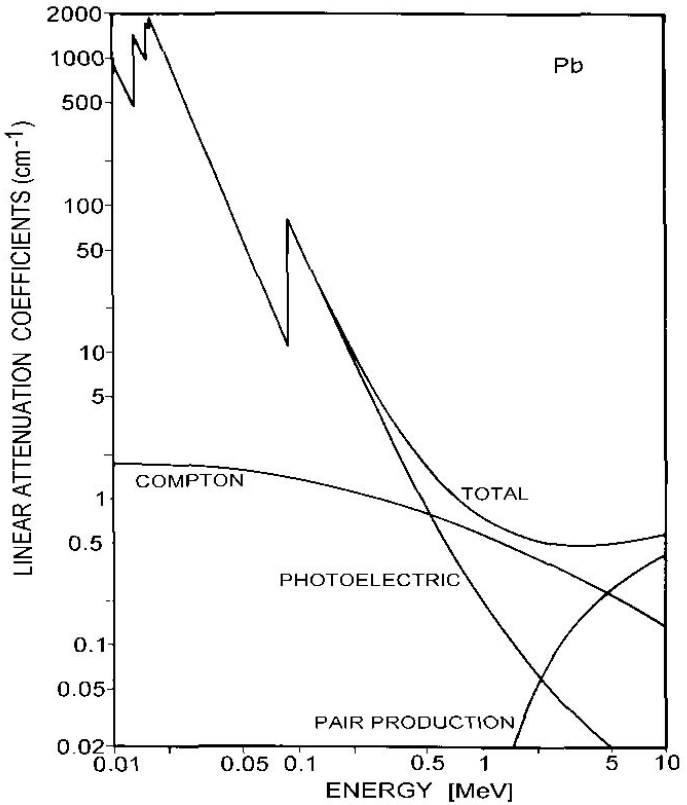
$$\varepsilon = \int_{U_{th}}^{\infty} \frac{1}{\overline{U}} e^{-\frac{U}{\overline{U}}} dU = e^{-\frac{U_{th}}{\overline{U}}}$$

→ efficient detection of single photons is only possible with a low noise electronics!

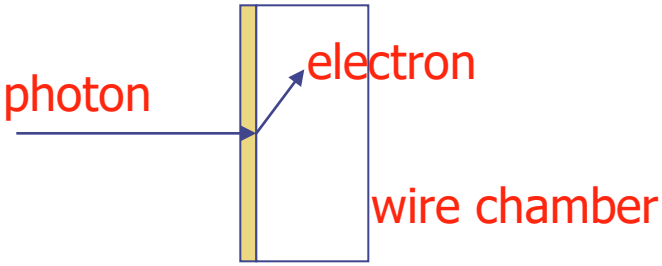
How low is low? The visual charge is about 20% (for integration times of order τ=20ns) of the avalanche charge, i.e. at a gas amplification of 2 10^5 the average detected signal corresponds to 4 10^4 electrons.

If we want to cut noise at 4σ, and keep a 90% efficiency (U_{th} = 0.1 $\overline{U}$), the electronics noise has to be kept at 4x10^4x0.1/4 = 1000 e- ENC

Detection of γ rays in ionisation counters



Attenuation coefficient for lead

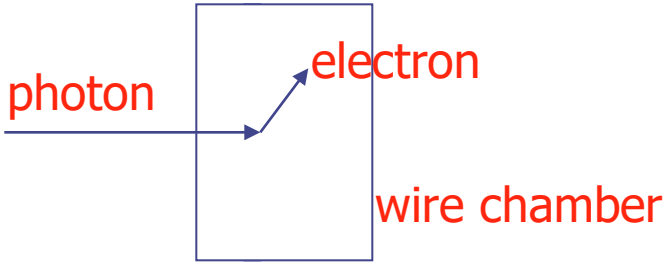


Need a high Z material (large photon absorption cross section) at the entrance of the wire chamber.

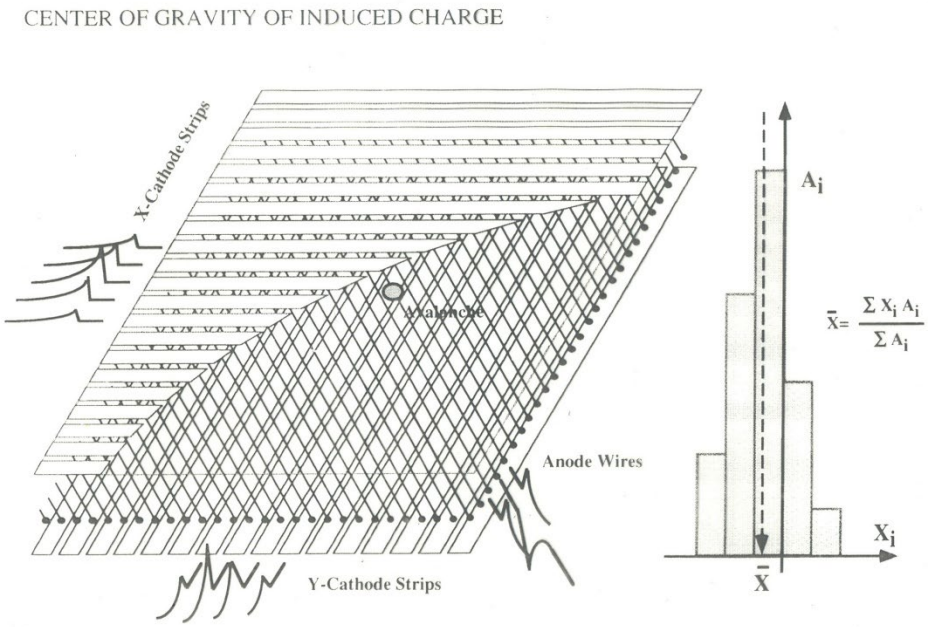
Thin layer→ electrons have to be able to get out of it

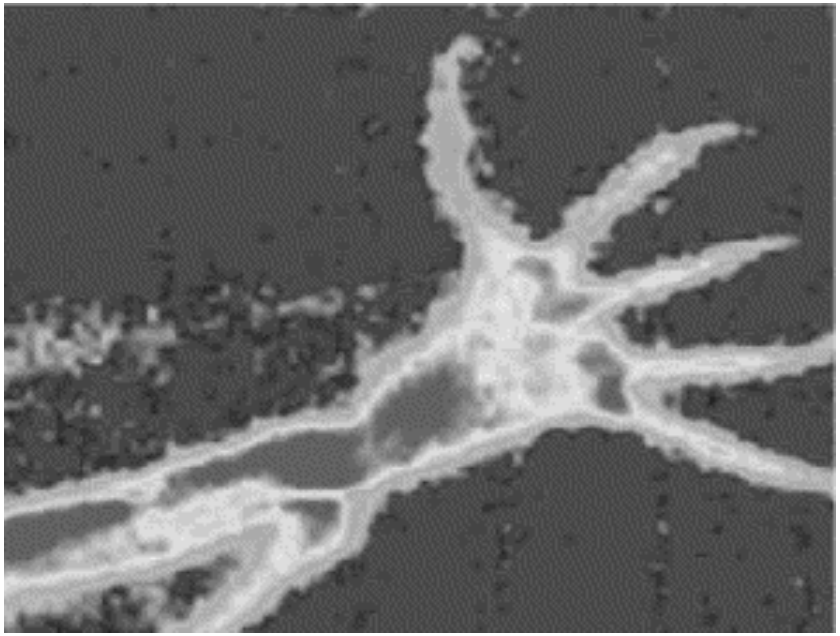
→ low efficiency

Detection of X rays in ionisation counters



Need a high Z gas (large photon absorption cross section): the best is Xe, Ar is OK as well.





X ray picture of a small mammal foot, recorded with a 2xGEM+pad chamber.