Particle Detection Techniques in HEP

Lecture 2: Gaseous Tracking Detectors

Post-Graduate Lecture Series

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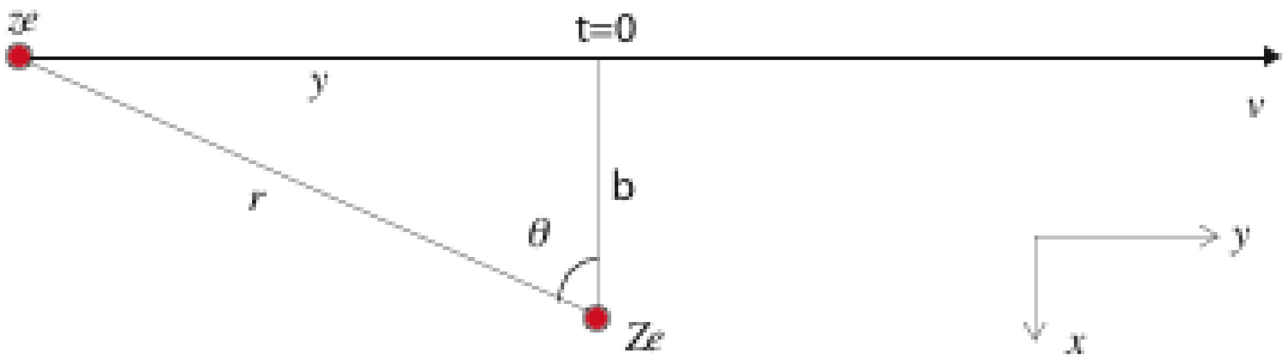
Lecture 2 “Gaseous Tracking Detectors”

- Charged particles in matter (ionisation)
- Charge collection
- Operational modes of gas amplification
- Gas mixtures
- Electron and ion drift in a gas
- Multi wire proportional chambers
- Drift chambers
- MSGC, TGEMs, Micromegas
- The T2K time projection chamber

Charged Particle Interaction with Matter (a)

When a charged particle traverses a layer of material, three processes could occur**: ionisation** of atoms, **Cherenkov radiation** or the emission of **transition radiation** (i.e. scintillation light). Consider the electromagnetic interaction of a particle, of charge *ze, passing a stationary charge Ze (the "target" particle) with impact parameter b and velocity v.*



Assuming that the moving particle passes the target so rapidly that the latter remains stationary during the "collision", *b will remain constant. In this case, the longitudinal electrostatic force exerted on the target before and after the moment of closest approach will cancel. The effective transverse force is then:*

$$F_x = \frac{Zze^2}{4\pi\varepsilon_0 r^2}\cos\theta = \frac{Zze^2}{4\pi\varepsilon_0 b^2}\cos^3\theta \qquad \boxed{r = \frac{b}{\cos\theta}}$$

Charged Particle Interaction with Matter (b)

Therefore the impulse delivered to the target is

$$\Delta p = \int_{-\infty}^{\infty} F_x \, \mathrm{d}t = \frac{Zze^2}{4\pi\varepsilon_0 b^2} \int_{-\pi/2}^{\pi/2} \cos^3\theta \, \frac{b}{v\cos^2\theta} \, \mathrm{d}\theta$$

$$\boxed{\begin{aligned} \mathrm{d}t &= \frac{\mathrm{d}y}{v} \\ y &= b\tan\theta \\ \mathrm{d}y &= b\sec^2\theta \, \mathrm{d}\theta \end{aligned}}$$

i.e. $$\Delta p = \frac{Zze^2}{2\pi\varepsilon_0 b v}$$

The above calculation has been performed for a non-relativistic approach. If the projectile particle is moving relativistically, then:

E_x is increased by a factor γ and dy *is decreased by a factor γ*

So, *Δp remains unchanged as:* $$\frac{Zze^2}{2\pi\varepsilon_0 b \beta c}$$

It is useful to consider for some purposes this momentum transfer as the product of the maximum force exerted and a characteristic time.

$$\Delta p = F_x^{\max} . \tau$$

Where, Fx and the "collision time" τ are:

$$F_x^{\max} = \frac{Zze^2}{4\pi\varepsilon_0 b^2}\gamma$$

$$\tau = \frac{2b}{\gamma\beta c} \qquad \text{(eq.1)}$$

Charged Particle Interaction with Matter (c)

Two assumptions have been made:

1) Impulse approximation – the target does not move (significantly) during the collision

2) The target remains non-relativistic.

If the assumptions hold, then the target gains kinetic energy given by:

$$E_T = \frac{(\Delta p)^2}{2m_T} = \frac{Z^2 z^2 e^4}{2(2\pi\varepsilon_0)^2 b^2 \beta^2 c^2 m_T} \propto \frac{Z^2}{m_T}$$

The matter the particle travels through consists of nuclei, of charge *Ze and an approximate mass* Am_p*, each surrounded by Z electrons each of charge e and mass* m_e.

Thus $$\frac{\text{Energy transfer to nuclei}}{\text{Energy transfer to electrons}} = \frac{Z^2 / Am_p}{Z \, 1/m_e} \approx \frac{Z / 2m_p}{Z / m_e} = \frac{m_e}{2m_p}$$

Given the ratio between the electron and proton masses, it is therefore reasonable to consider only the energy lost to electrons. For a single electron, we have:

$$E_e = \frac{2z^2 e^4}{(4\pi\varepsilon_0)^2 b^2 \beta^2 m_e c^2} \qquad \text{(eq. 2)}$$

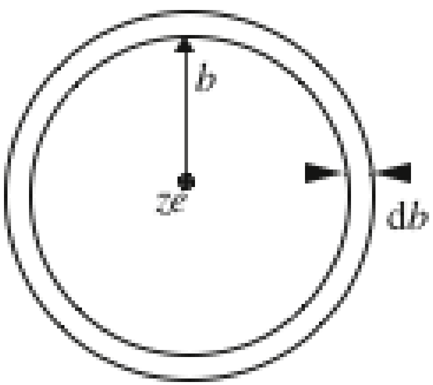
Charged Particle Interaction with Matter (d)

Since E_e is determined by the impact parameter b, the probability of an energy loss between E and E+dE is given by the probability of an impact parameter between b and b+db, where b corresponds to E and b+db corresponds to E+dE.

So, $P(E_e)dE = -P'(b)db$ -the minus sign arising as an increase in b results in a decrease in E.

The energy loss is not due to an interaction with a single target electron.

However, consider a thin slice of material, of density ρ and thickness Δ*x.*



Then $$P'(b)\mathrm{d}b = 2\pi b\mathrm{d}b \times \text{no. of electrons per unit area}$$
$$= 2\pi b\, Z \frac{N_A}{A} \rho\, \Delta x\, \mathrm{d}b \qquad \text{(eq. 2b)}$$

$$\text{(eq. 2)} \Rightarrow \quad b^2 = \frac{2z^2e^4}{(4\pi\varepsilon_0)^2 \beta^2 m_e c^2 E_e} \overset{\text{(diff.)}}{\Longrightarrow} 2b\,\mathrm{d}b = -\frac{2z^2e^4}{(4\pi\varepsilon_0)^2 \beta^2 m_e c^2} \frac{\mathrm{d}E}{E_e^2}$$

Charged Particle Interaction with Matter (e)

$$\text{(sub eq. 2b)} \Longrightarrow \quad P(E_e)\,\mathrm{d}E = \frac{\pi Z N_A \rho \Delta x}{A} \frac{2z^2 e^4}{(4\pi\varepsilon_0)^2 \beta^2 m_e c^2} \frac{dE}{E_e^{\,2}} \qquad \text{(eq. 3)}$$

So the most probable energy loss in traversing this slice is:

$$\overline{\Delta E} = \int_{E_{min}}^{E_{max}} E\, P(E)\,\mathrm{d}E = \frac{2\pi Z N_A \rho \Delta x\, z^2 e^4}{(4\pi\varepsilon_0)^2 \beta^2 m_e c^2 A} \left[\ln E\right]_{E_{min}}^{E_{max}} \qquad \text{(eq. 4)}$$

This can be simplified by grouping together a number of physical constants, which depend on the properties of neither the projectile particle nor the target material. Lets define:

$$C = 2\pi N_A \left(\frac{e^2}{4\pi\varepsilon_0 m_e c^2} \right)^2 \quad \text{i.e. } C = 0.03006\ (\text{kg m}^{-2})^{-1} = 0.3006\ (\text{g cm}^{-2})^{-1} \qquad \text{(eq. 5)}$$

Hence

$$\overline{\Delta E} = C \frac{m_e c^2}{\beta^2} \frac{Zz^2}{A} \rho \Delta x \left[\ln E\right]_{E_{min}}^{E_{max}} \qquad \text{(eq. 6)}$$

$$= 2C \frac{m_e c^2}{\beta^2} \frac{Zz^2}{A} \rho \Delta x \left[\ln b\right]_{b_{min}}^{b_{max}} \qquad \text{(eq. 6b)}$$

Charged Particle Interaction with Matter (f)

Obviously there must be some limits on E_{min} *and* E_{max} *(or* b_{min} *and* b_{max}*) to prevent the value of the integral being infinite, which is of course unphysical. For* E_{min} *, this is where the collision becomes very "soft", and the electric field of the passing particle simply perturbs the atomic electron adiabatically, with no energy being absorbed. This occurs when the collision time is long compared with the period of the electron in its atomic orbit.*

$$\text{(i.e.)} \quad \tau > \frac{1}{f_{rot}} \quad \text{From eq. 1} \Rightarrow \frac{2b}{\gamma\beta c} > \frac{1}{f_{rot}}$$

Now, $hf_{rot} \approx I_0$,

where I_0 *is the mean ionisation potential of the atom, thus:*

$$b_{max} = \frac{\gamma\beta c}{2 f_{rot}} \approx \frac{\gamma\beta c h}{2 I_0}$$

For E_{max}, *there are a number of possible limits. The above calculation becomes invalid when the electron receives enough energy for it to become relativistic. There are also absolute limits on the maximum transferable energy. For example, it clearly cannot be greater than the energy of the incoming particle. A proper quantum mechanical, relativistic calculation is needed for the full result. However, it can be determined approximately by relatively simple quantum mechanical arguments. It can be shown that for any incoming particle significantly heavier than an electron (i.e. muon, pion, proton or nuclear fragment), then the most important limit comes from the fact that the uncertainty principle does not allow b to be specified too precisely, and so limits* b_{min}.

Charged Particle Interaction with Matter (g)

For a projectile particle which is not extremely relativistic ($\gamma < 100$), then the limit on b_{min} is:

$$b_{\min} = \frac{\hbar}{m_e \gamma \beta c}$$

Substituting these limits in to eq. 6 gives the following approximate expression for the **mean energy loss**:

$$\overline{\Delta E} = 2C\frac{m_e c^2}{\beta^2}\frac{Zz^2}{A}\rho\Delta x \ln\left(\frac{\gamma\beta c h}{2I_0}\frac{m_e\gamma\beta c}{\hbar}\right) = 2C\frac{m_e c^2}{\beta^2}\frac{Zz^2}{A}\rho\Delta x \ln\left(\frac{\pi\gamma^2\beta^2 m_e c}{I_0}\right)$$

The full quantum mechanical treatment (by Bethe and Bloch) for "heavy" particles (not electrons) gives the result:

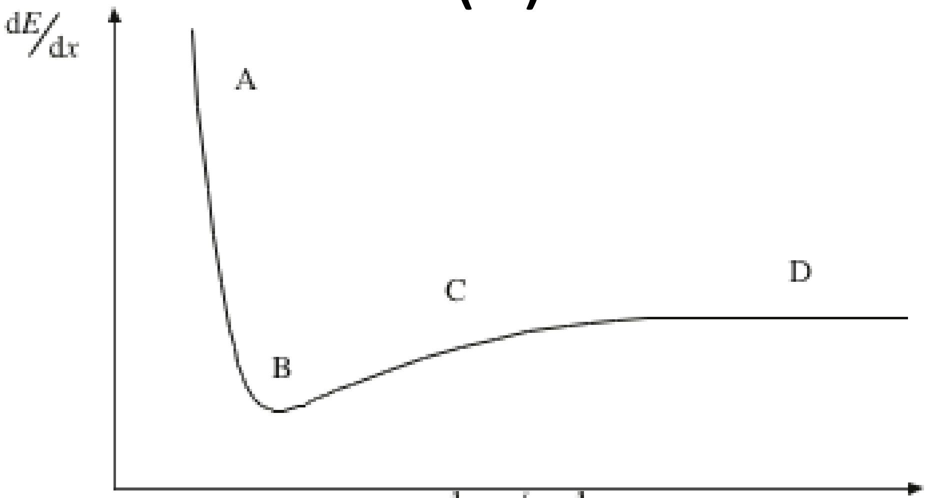
$$\boxed{\overline{\Delta E} = 2C\frac{m_e c^2}{\beta^2}\frac{Zz^2}{A}\rho\Delta x\left[\ln\left(\frac{2\gamma^2\beta^2 m_e c}{I_0}\right) - \beta^2 - \frac{\varepsilon}{2} - \frac{\delta(\beta)}{2}\right]}$$

The two additional terms are:

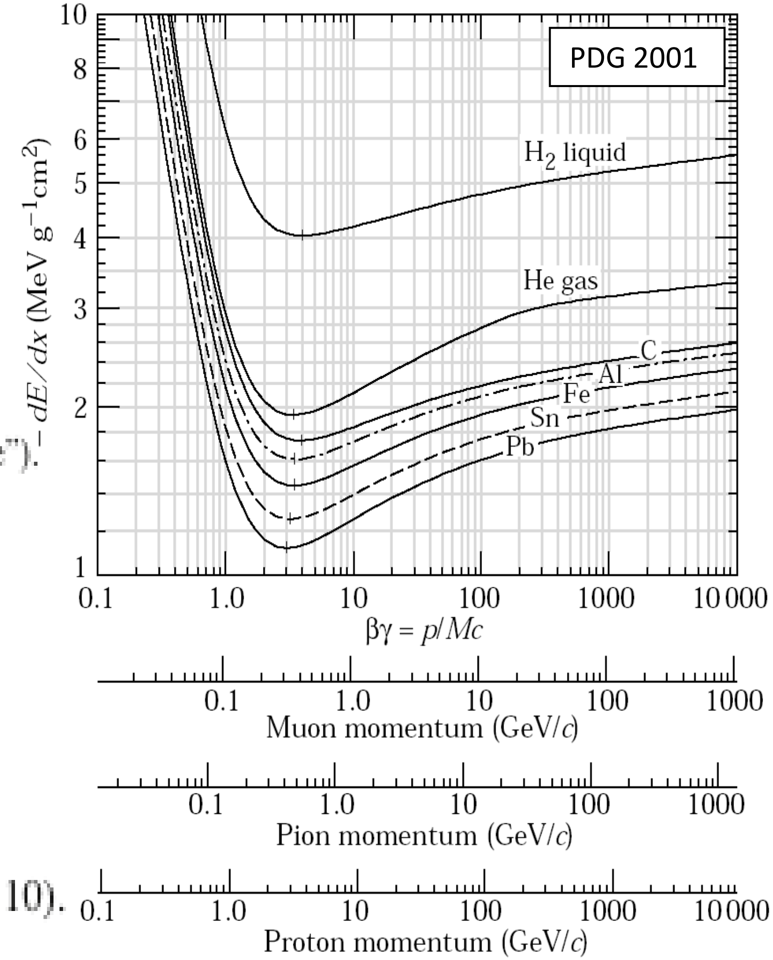
ε, a small correction due to screening of the inner atomic electrons (the "shell correction"). It is often ignored.

δ, a function of β and the dielectric constant of the medium, and is known as the "density effect". Polarisation of the material at large values of *b (which are only important for large γ) screens the effect of the traversing charge. It is much more important for dense media, such as solids, than it is for gases.*

Charged Particle Interaction with Matter (h)



Schematically, the variation of mean energy loss per unit thickness, dE/dx , *has the following behaviour as a function of β or γ:*



A – rapid decrease $\propto \dfrac{1}{\beta^2}$ $\left(\approx \dfrac{1}{v^2}\right)$ at non-relativistic velocities.

B – minimum at $E \approx 3\,Mc^2$ i.e. $\gamma \approx 3$ ("Minimum Ionisation Particle").

$\left.\dfrac{dE}{dx}\right)_{min} \approx 1 - 1.5$ MeV (g cm^{-2})$^{-1}$ for most materials.

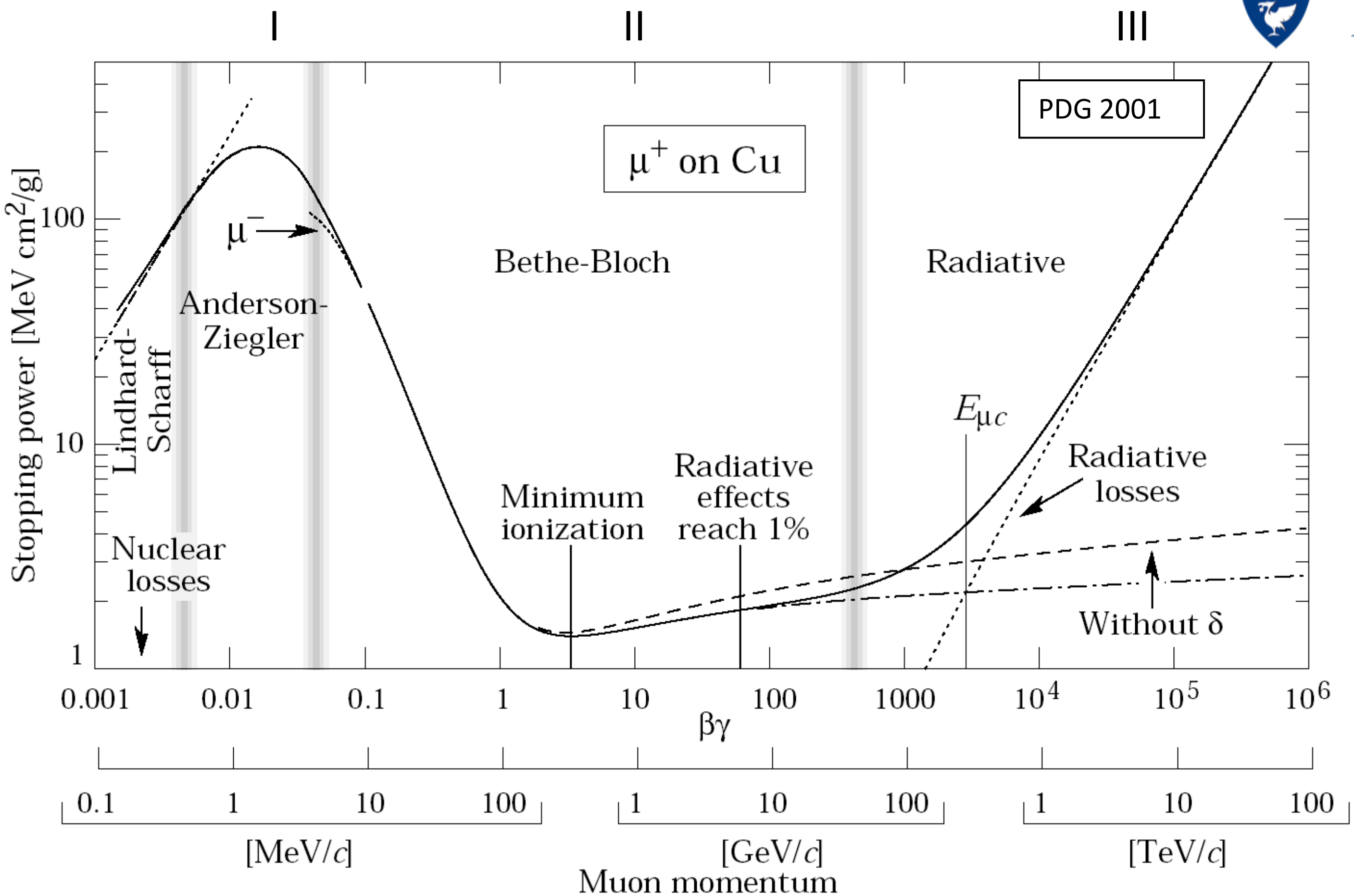
C – slow logarithmic "relativistic rise" $\propto \ln(\gamma)$

for $\gamma \approx 1000 \Rightarrow 1.5 \times \left.\dfrac{dE}{dx}\right)_{min}$ in very low density materials.

D – plateau as ionisation is limited by the *density effect*.

In solids, limited to only $\sim 1.1 \left.\dfrac{dE}{dx}\right)_{min}$ (reached at γ as low as 10).

Other Mechanisms



I   At very low energy ionisation is impossible. Only have interactions with nucleus.

II   For most particles ionisation dominates from a few MeV up to TeV-scale.

III   Above that Bremsstrahlung due to nuclear electric field dominates.

Electrons (low mass) are an exception! Bremsstrahlung dominates from 5-20 MeV!

Where does the lost energy go?

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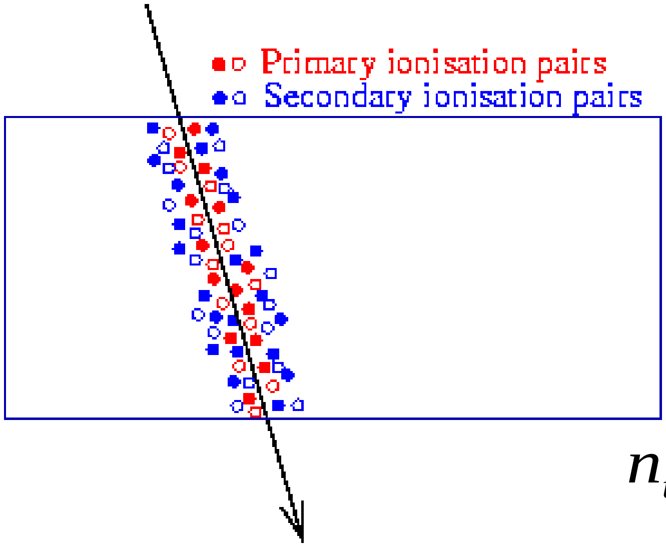


Ionisation produces electron/ion pairs (in general ~100 pairs/cm)

Primary electrons have enough energy to cause secondary ionisation.

$$n_{total} = \frac{\Delta E}{W_i} \left(= \frac{\text{total energy loss}}{\text{effective energy loss per pair}} \right)$$

Gas	Z	A	δ (g/cm^3)	E_{ex}	E_i (eV)	I_0	W_i	dE/dx (MeV/g cm^{-2})	dE/dx (keV/cm)	n_p (i.p./cm) a)	n_T (i.p./cm) a)
H_2	2	2	8.38×10^{-5}	10.8	15.9	15.4	37	4.03	0.34	5.2	9.2
He	2	4	1.66×10^{-4}	19.8	24.5	24.6	41	1.94	0.32	5.9	7.8
N_2	14	28	1.17×10^{-3}	8.1	16.7	15.5	35	1.68	1.96	(10)	56
O_2	16	32	1.33×10^{-3}	7.9	12.8	12.2	31	1.69	2.26	22	73
Ne	10	20.2	8.39×10^{-4}	16.6	21.5	21.6	36	1.68	1.41	12	39
Ar	18	39.9	1.66×10^{-3}	11.6	15.7	15.8	26	1.47	2.44	29.4	94
Kr	36	83.8	3.49×10^{-3}	10.0	13.9	14.0	24	1.32	4.60	(22)	192
Xe	54	131.3	5.49×10^{-3}	8.4	12.1	12.1	22	1.23	6.76	44	307
CO_2	22	44	1.86×10^{-3}	5.2	13.7	13.7	33	1.62	3.01	(34)	91
CH_4	10	16	6.70×10^{-4}		15.2	13.1	28	2.21	1.48	16	53
C_4H_{10}	34	58	2.42×10^{-3}		10.6	10.8	23	1.86	4.50	(46)	195

F. Sauli, CERN 77-09

ΔE (for a mip)

Electron Drift:

The drift velocity for electrons in an *E*-field, *w,* has a more complex dependence on *E.*

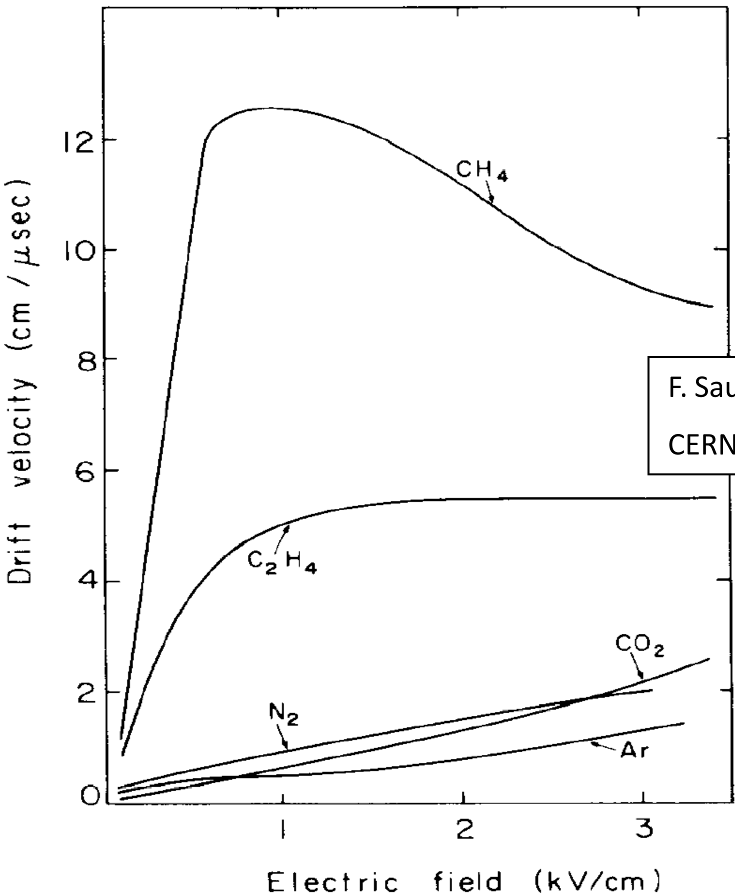
Electrons (very light) accelerate quickly between interactions and have a longer mean free path length.

$$w = \frac{e}{2m} E\tau$$

τ: average time between collisions ($\propto 1/\sigma$)

Strong dependence on gas-mixture, *E* and p.

If your detector should measure drift times, choose voltage/gas where drift velocity is (almost) constant!



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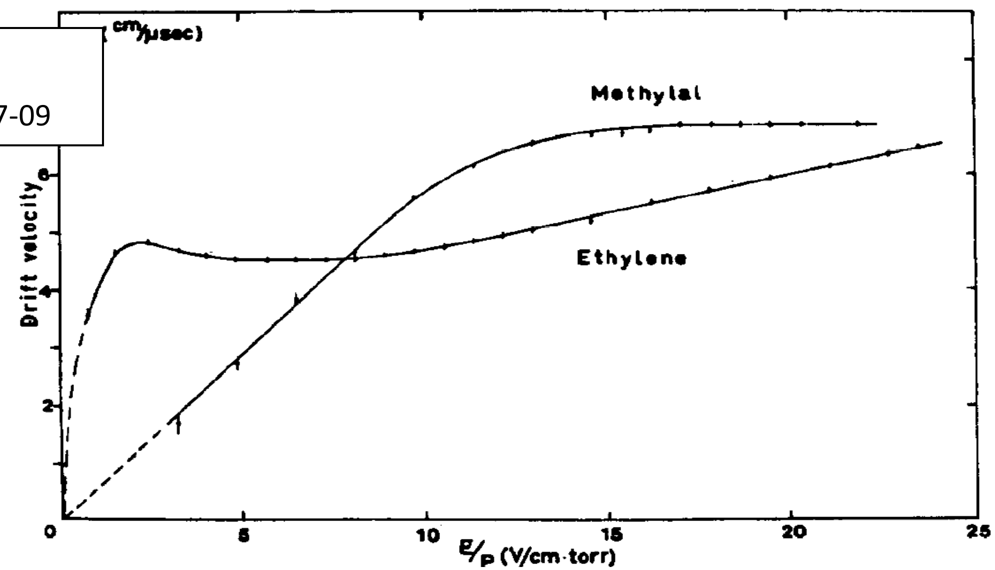


Drift and Diffusion in a Magnetic Field

Often detectors have magnetic fields as well. How does this affect the drift?

Two common cases:

$E \perp B$

Added component to the drift in direction of the Lorentz angle: $\vec{E} \times \vec{B}$

$\Rightarrow$ Curved trajectory towards anode

Charge collection becomes a bit slower

$E \parallel B$

Drift towards anode unaffected

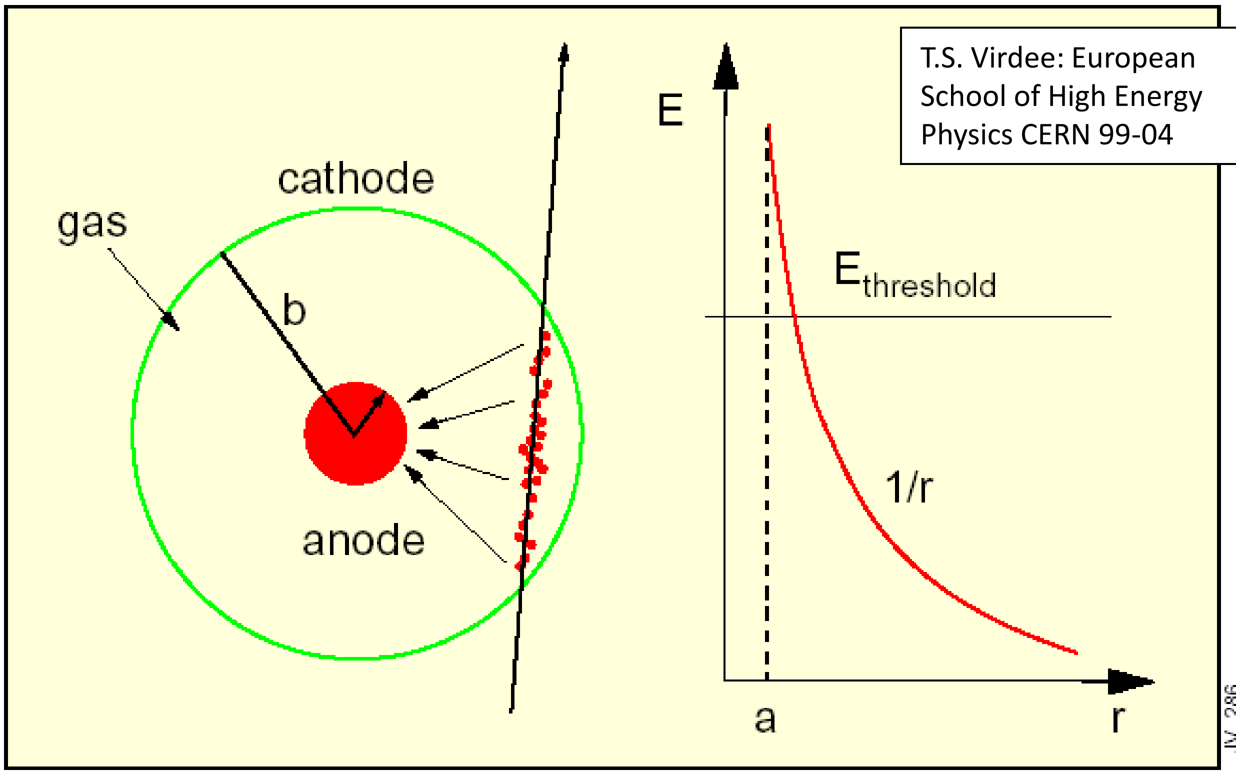
Diffusion transverse to drift direction is forced in circles!
Transverse diffusion remains small over large drift distance!

Exploited in time-projection-chambers (TPC) (discussed later)

Detecting e/ion Pairs Produced by a Charged Particle

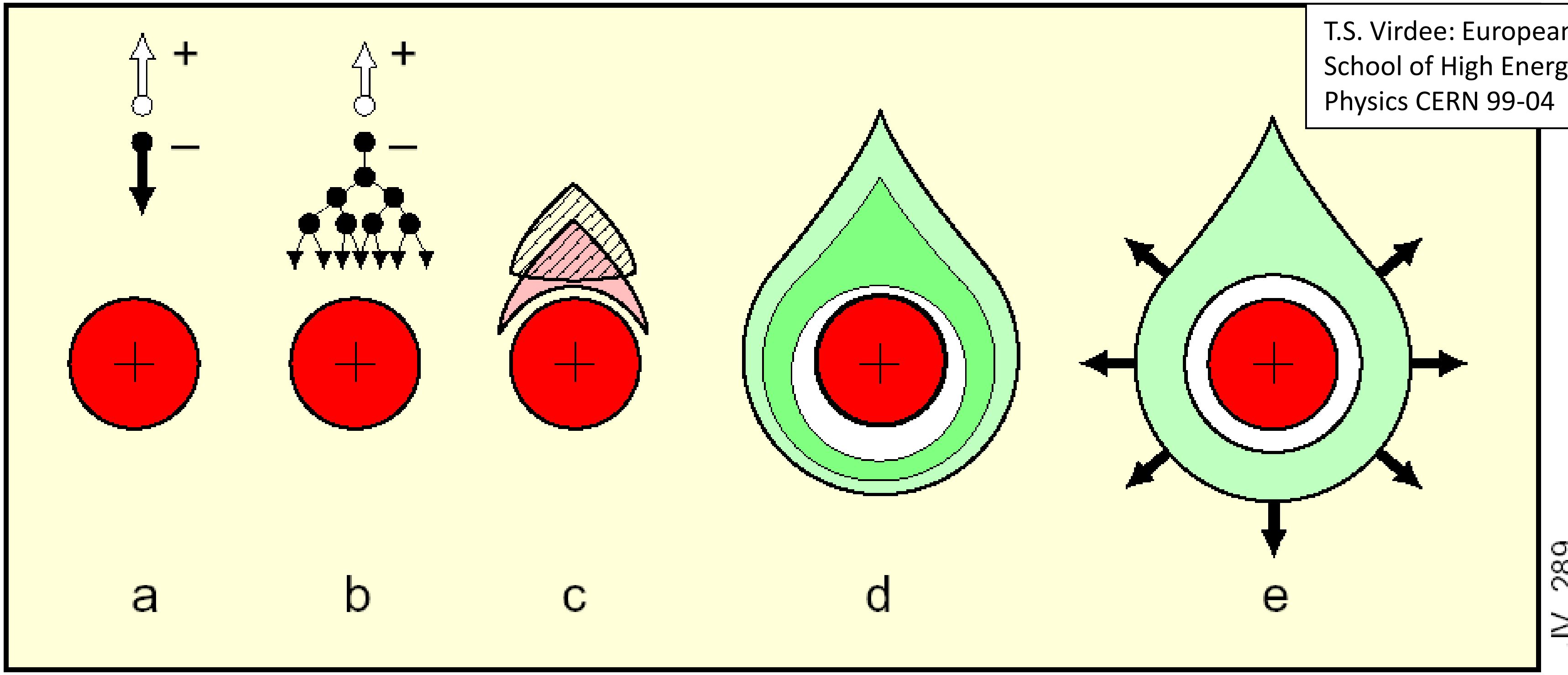
In *E*-field electrons (ions) drift to anode (cathode)
But, 100 e/ion pairs do not constitute a measurable signal
(noise from electronic amplifier typically ~1000 electrons or more).
In a strong *E*- field ($E > E_{threshold}$) electrons can obtain enough energy to cause further ionisation, thus producing an avalanche of e/ion pairs (***gas amplification***).

Simple particle detector: Gas filled tube with anode wire in the centre. (Using a very thin anode wire is an easy way to achieve a high field.)



T.S. Virdee: European School of High Energy Physics CERN 99-04

Gas Amplification



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a) Electrons (ions) drift towards anode (cathode)

b) Gas avalanche produces more e/ion pairs

c) Ion cloud reduces field and stops avalanche

d,e) Electrons collected on anode, ions drift to cathode

Operational Modes of Gas Amplification

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Behaviour of gaseous detectors depends strongly on the field strength.

I) very low field: partial (or no) charge collection

II) *__Ionisation mode__*: charge collection but no amplification

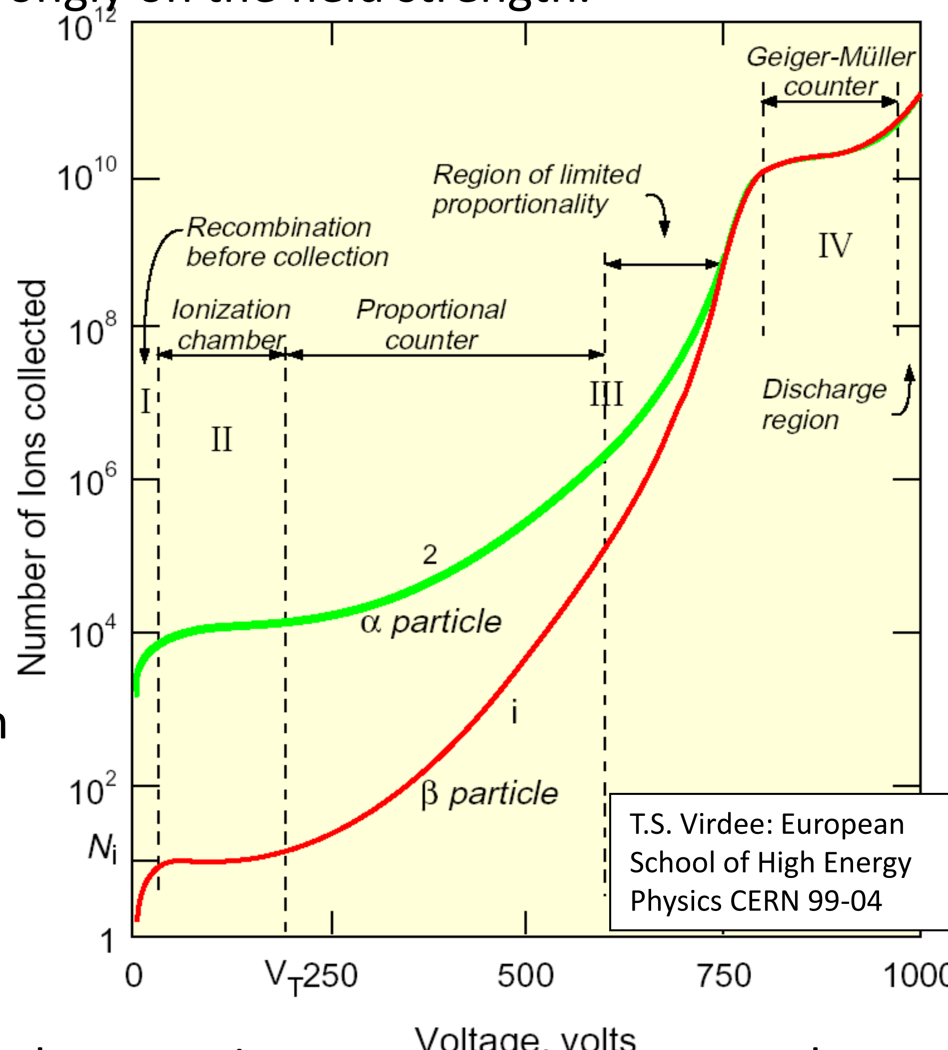
III) *__Proportional mode__*:

proportional charge amplification.

Gain highly dependent on V!

__Streamer mode__: proportionality lost by distortion of *E*-field by space-charge

IV) *__Geiger or saturated mode__*: full ionisation of the gas volume (photo-emission). Only stopped by interruption of HV



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In HEP: chambers mostly in proportional mode, sometimes streamer or saturated mode (can be read out without an electronic amplifier!)

The Choice of Gas(-Mixture)

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The requirements:

- High specific ionisation
- Gas amplification at low working voltage and good proportionality
- High voltage before saturation (high gain achievable)
- High rate capability (fast charge drift & fast recovery) and long lifetime (of detector)

Noble gases:

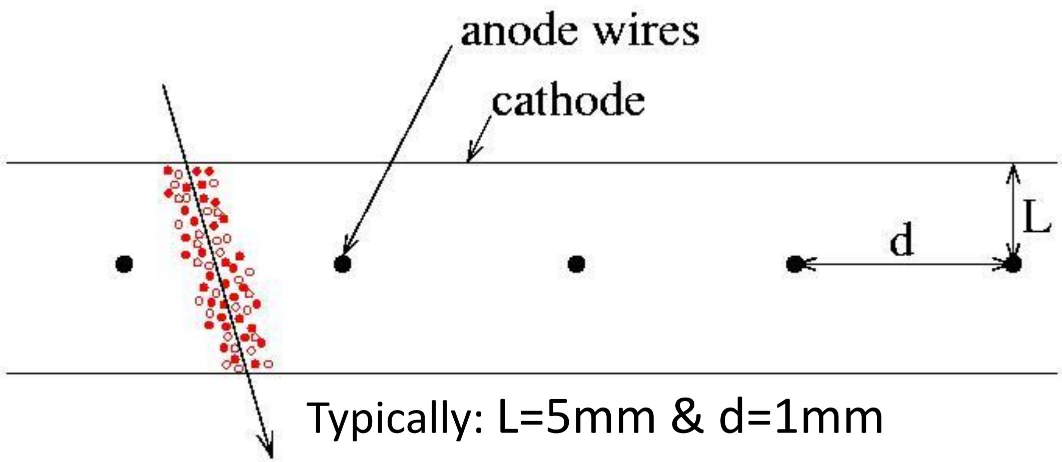
- Few non-ionising energy loss modes $\Rightarrow$ avalanche multiplication at low V
- Heavy gases (Ar, Xe, Kr) $\Rightarrow$ high specific ionisation
- Excited Ar emits 11.6eV photons $\Rightarrow$ free electrons at cathode $\Rightarrow$ new showers $\Rightarrow$ permanent discharge

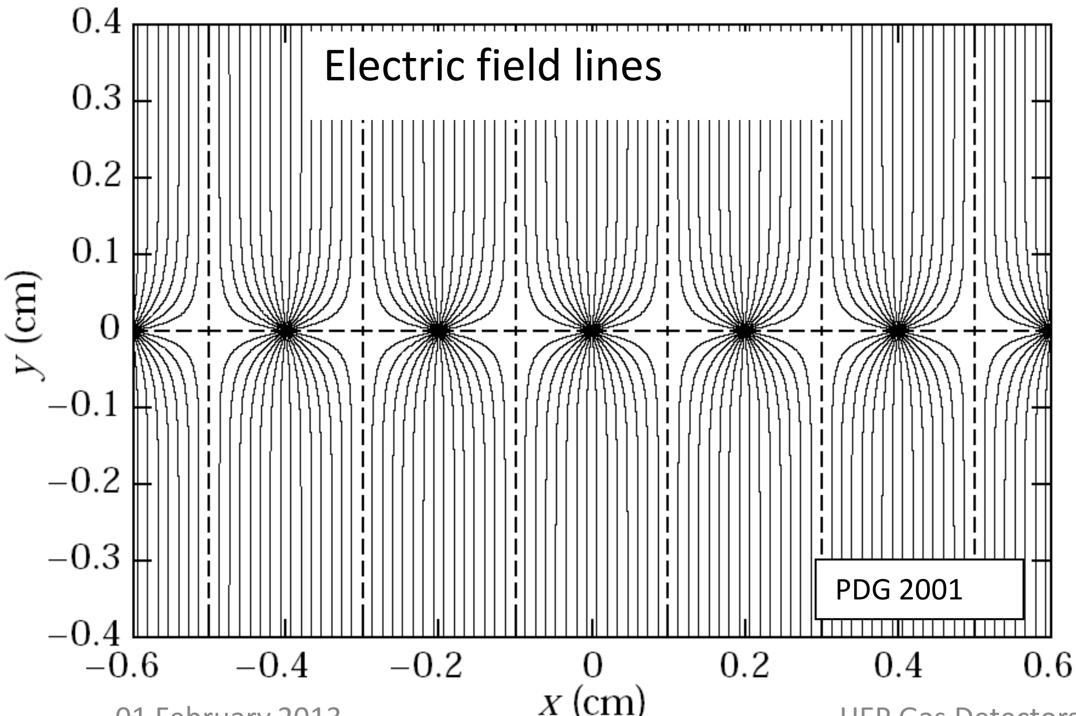
Poly-atomic gases:

- Many non-ionising states $\Rightarrow$ effective absorption of γ's. (photon-quenching)
  e.g. Methane effectively absorbs γ's 7.9-14.5 eV
  Organic gases: Methane, CO^2, BF^3, freons, isobutane (C^4H^{10})
- Small admixture of photon-quencher prevents permanent discharge in eg. Ar!
- Absorbed energy is released in break-up/inelastic collisions $\Rightarrow$ formation of radicals $\Rightarrow$ damage detector materials or leave solid or liquid organic deposits on anode or cathode
- In a high rate environment gas may get fully quenched $\Rightarrow$ Gas must be circulated!
  Needed anyway to control gas mixture and because most detectors leak!

Multi Wire Proportional Chamber (MWPC)

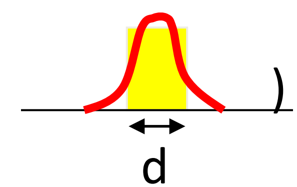
Charpak et al. (1968) $\Rightarrow$ Nobel prize 1992





Electrons/ions drift along field lines
Ions $\Rightarrow$ cathode
Electrons $\Rightarrow$ nearest anode wire!

If all charge collected on 1 wire, resolution along x determined by wire spacing (pitch): $\sigma_x = \frac{d}{\sqrt{12}}$

(Gaussian width: )

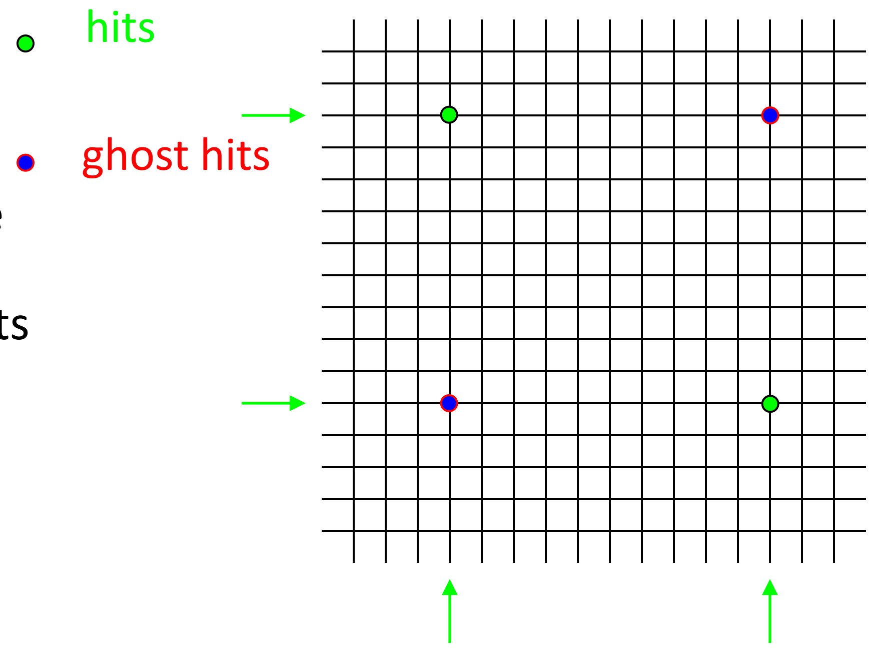
Charge sharing $\Rightarrow$ better resolution

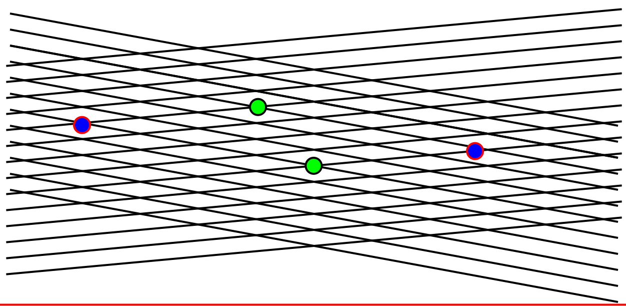
Original worry: Capacitive coupling between wires is largely compensated for by positive charge in avalanches

Only sensitive to *x*-coordinate.

The y-Coordinate

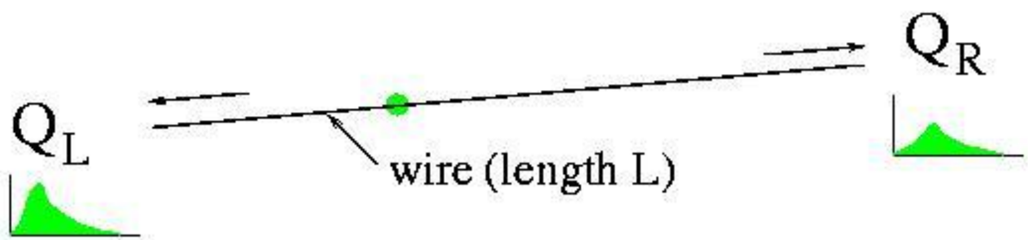
- Crossed wire planes:
  - Perpendicular (ghost hits when more than 1 particle!)
  - Stereo-angle (few degrees) only ghosts from hits near to each other





- Two-sided readout
  - Charge division (resistive wire)

$$y/L = Q_R/(Q_R + Q_L)$$

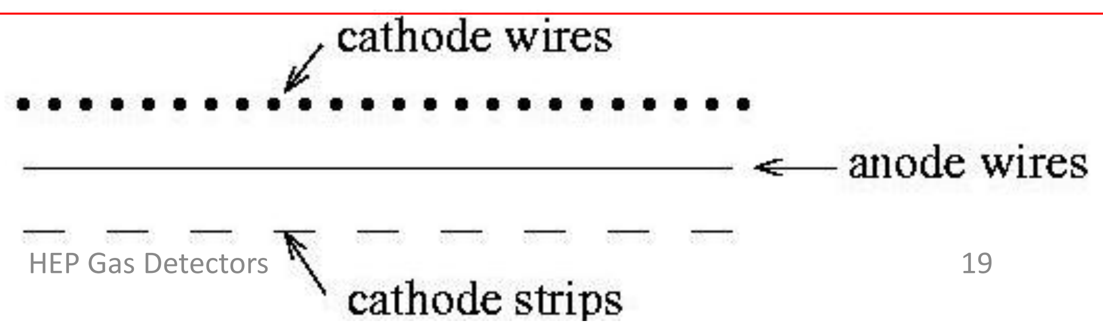


  - Time difference

  Note: velocity along wire 30 cm/ns so at best $\sigma(x)$ ~ several cm

- Segmented cathode planes
  - Strips/wires/pads

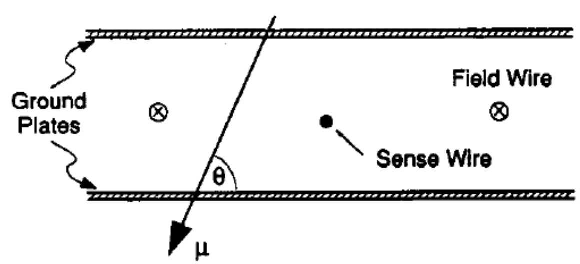
  (Slow!)

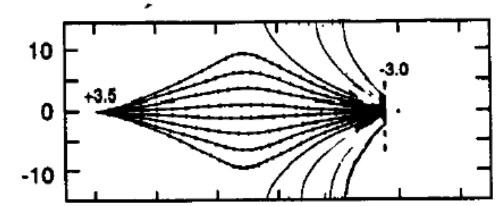


Drift Chambers

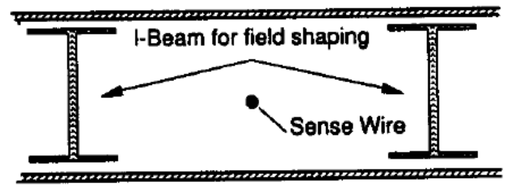
(examples of planar drift chambers)

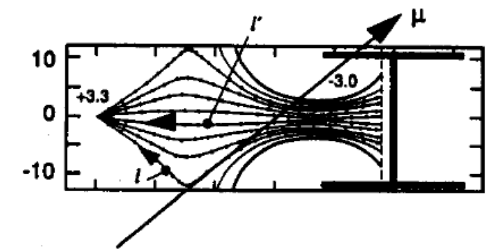
Field lines aligned with *x*-direction via use of field and sense wires (cathode and anode wires)





Then *x* can be measured from the arrival time



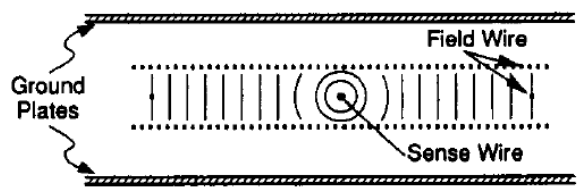


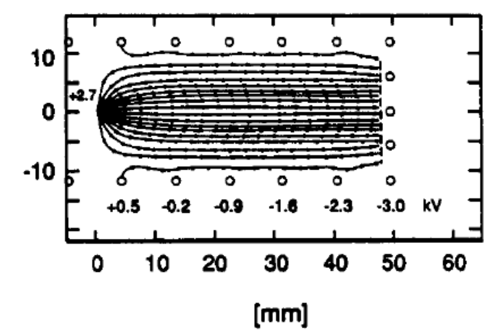
Better *x*-resolution while using larger wire pitch than in MWPC's

Fewer wires → less electronics, less mechanical support

As field is generated between wires various geometries possible:

- Planar
- Cylindrical
- …

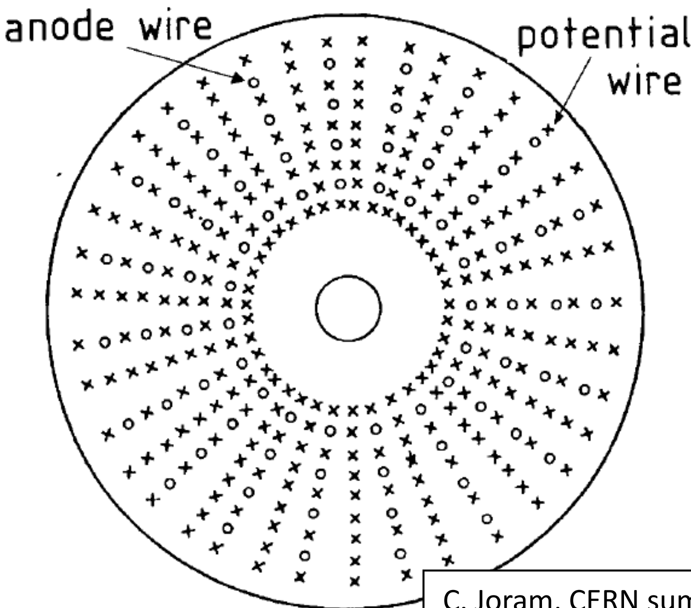


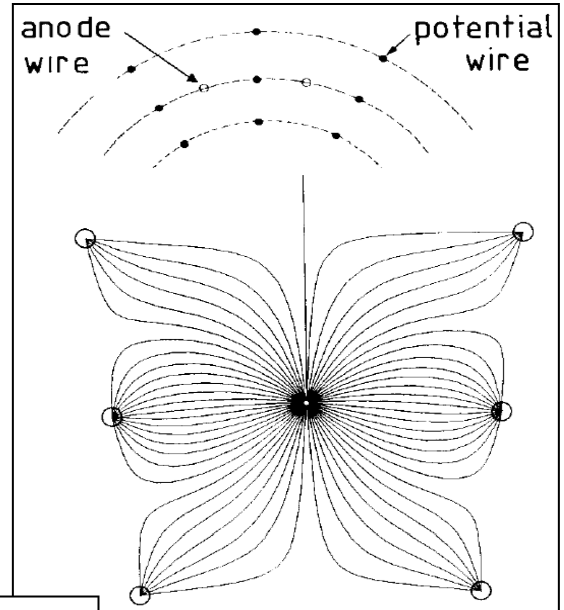


Aim to get linear relation between position and arrival time!

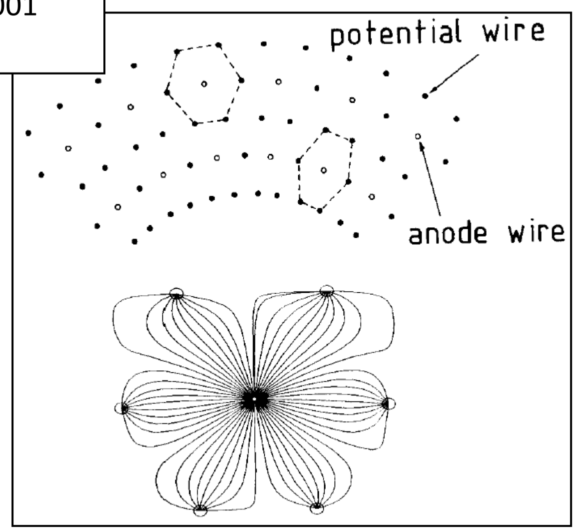
U. Becker, in: Instrumentation in High Energy Physics, World Scientific

Other Drift Chamber Geometries





C. Joram, CERN summer student lectures 2001



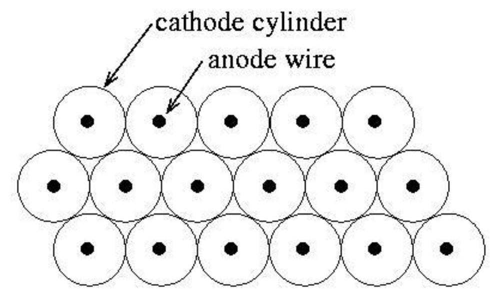
Cylindrical:

- barrel shape
- wires supported from end plates
- very little material (centrally)

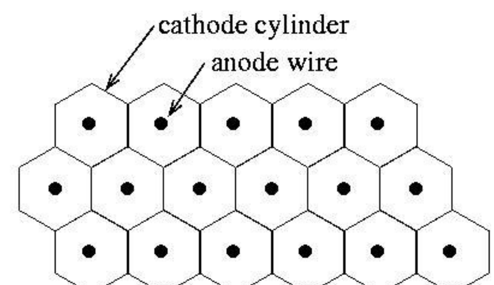
One broken wire can destroy large section!

Tubes or cells:

- self supporting
- less material at end-support
- “easier” to build

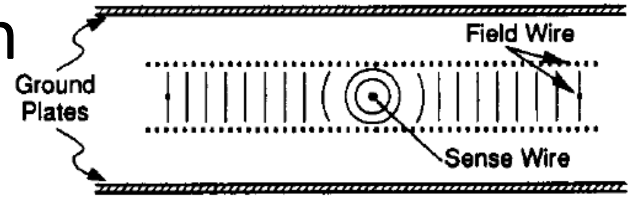


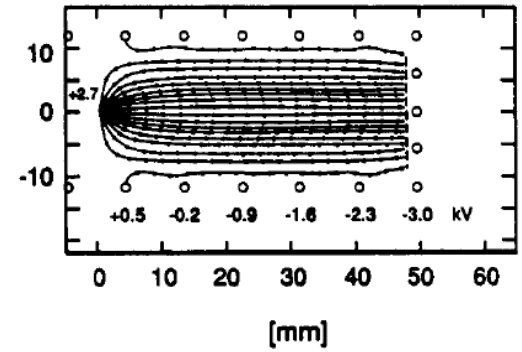
Straw tubes



Honeycomb cells

Position Resolution in Drift Chambers

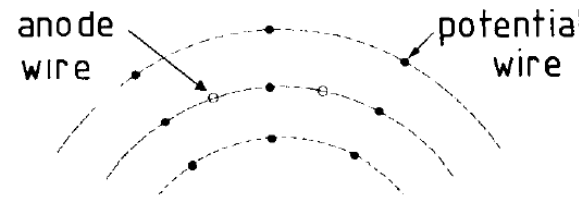


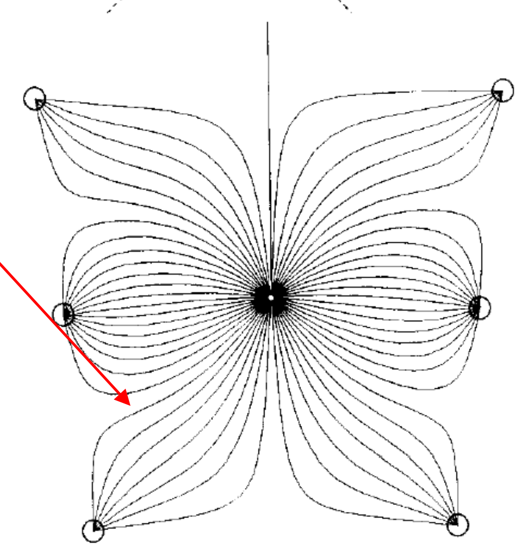


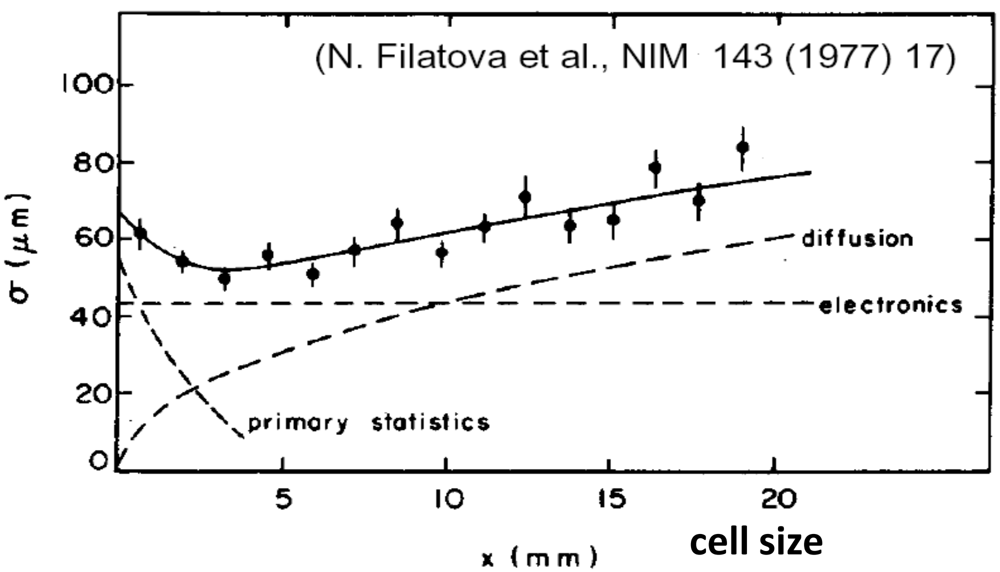
Remember electron drift velocity ~ few cm/μs:

With timing precision of a few ns $\Rightarrow$ $\sigma(x)$ ~100 μm

- Measurement precision:
  - Statistics primary ionisation (for small “cell”-sizes)
  - Electronics
- Spread in arrival time:
  - Diffusion (especially for long drift paths)
  - Path length fluctuation complex in E-fields







Moving Towards Small Gaseous Tracking Detectors

Future (high rate) experiments need small scale detectors to prevent having too many hit wires/strips per event.
(occupancy = fractional hit rate per channel per event)

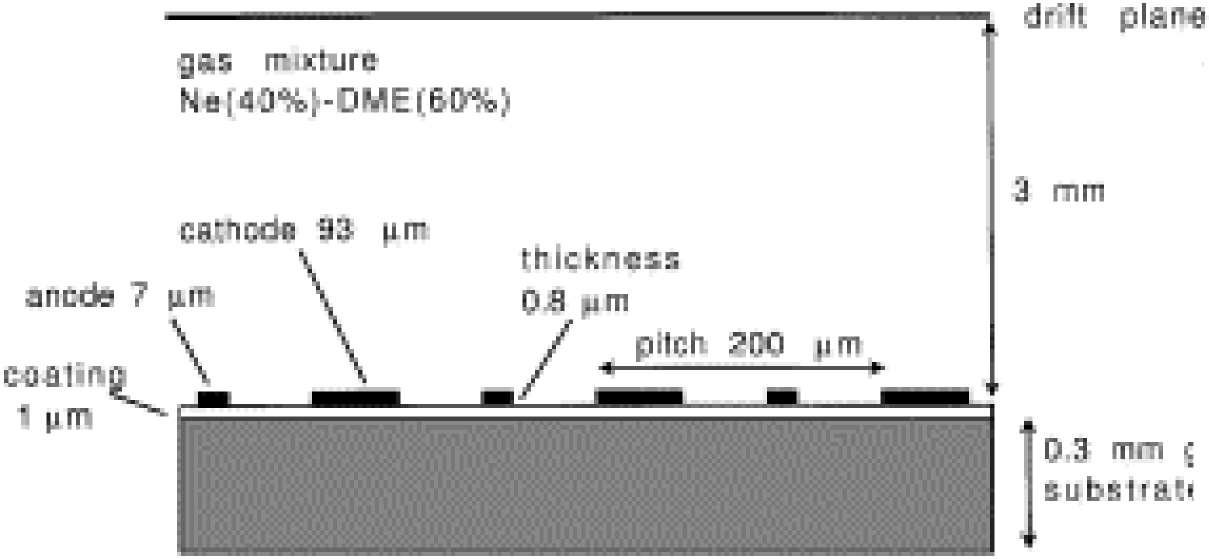
Challenges for small & fast gaseous detectors:

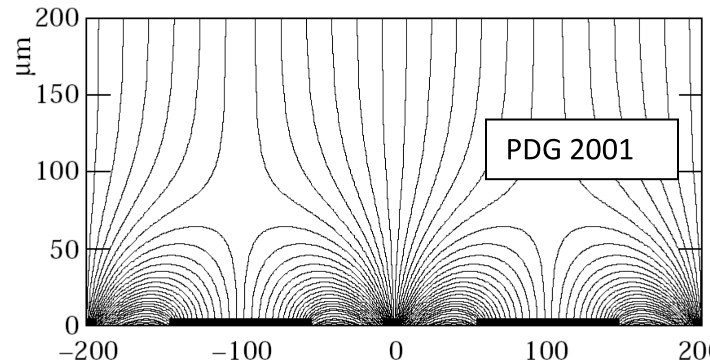
- small structures (detection elements)
- high voltage to get enough charge
- prevent (slow) ions from drifting back to cathode

There are several technologies for small scale gaseous tracking detectors:

- Micro-strip gas chambers (MSGC)
- Gas electron multipliers (GEM)
- Micromegas
- Micro-gap chambers
- Micro-gap wire chambers
- GEMs combined with pixel detectors

Micro-Strip Gas Chambers (MSGC)



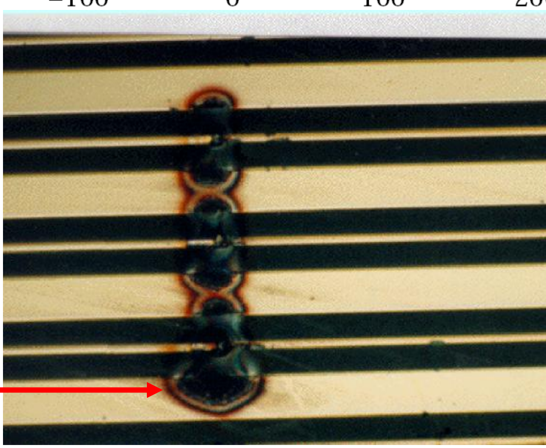


Example: CMS MCGC's (abandoned)

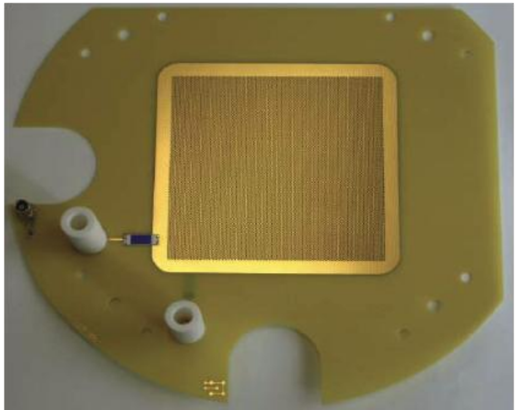
MSGC's:

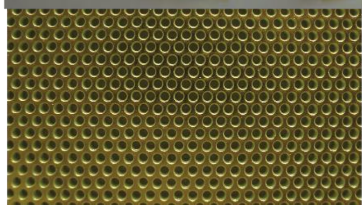
- anode and cathode strips etched on glass substrate
- cathode strips provide fast "drain" for ions from avalanche

High sensitivity to discharges, damaging strips



Thick Gas Electron Multipliers (TGEMs)





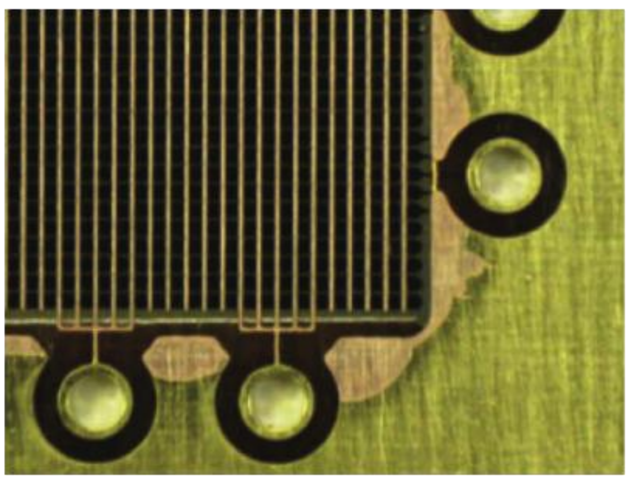
500 μm diameter

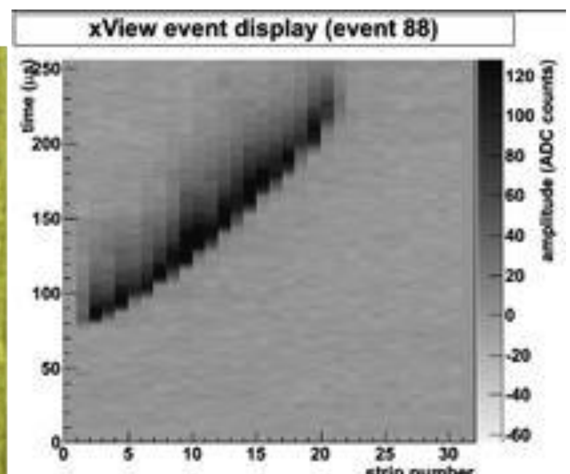
holes

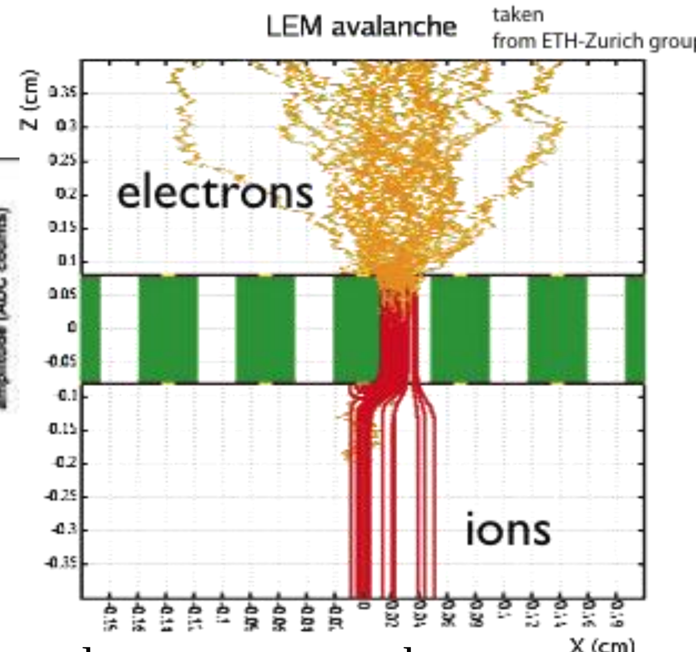
The TGEM is a double sided metallised PCB plate with holes drilled in a regular pattern.
By applying a potential difference to the TGEM electrodes, an electric field is attained in the holes.

Charge amplification (Townsend avalanche):

Gain: $G = \exp(\alpha x)$ where, x is effective multiplication length; $\alpha \sim Ap \exp(-Bp/E)$: first Townsend coefficient.

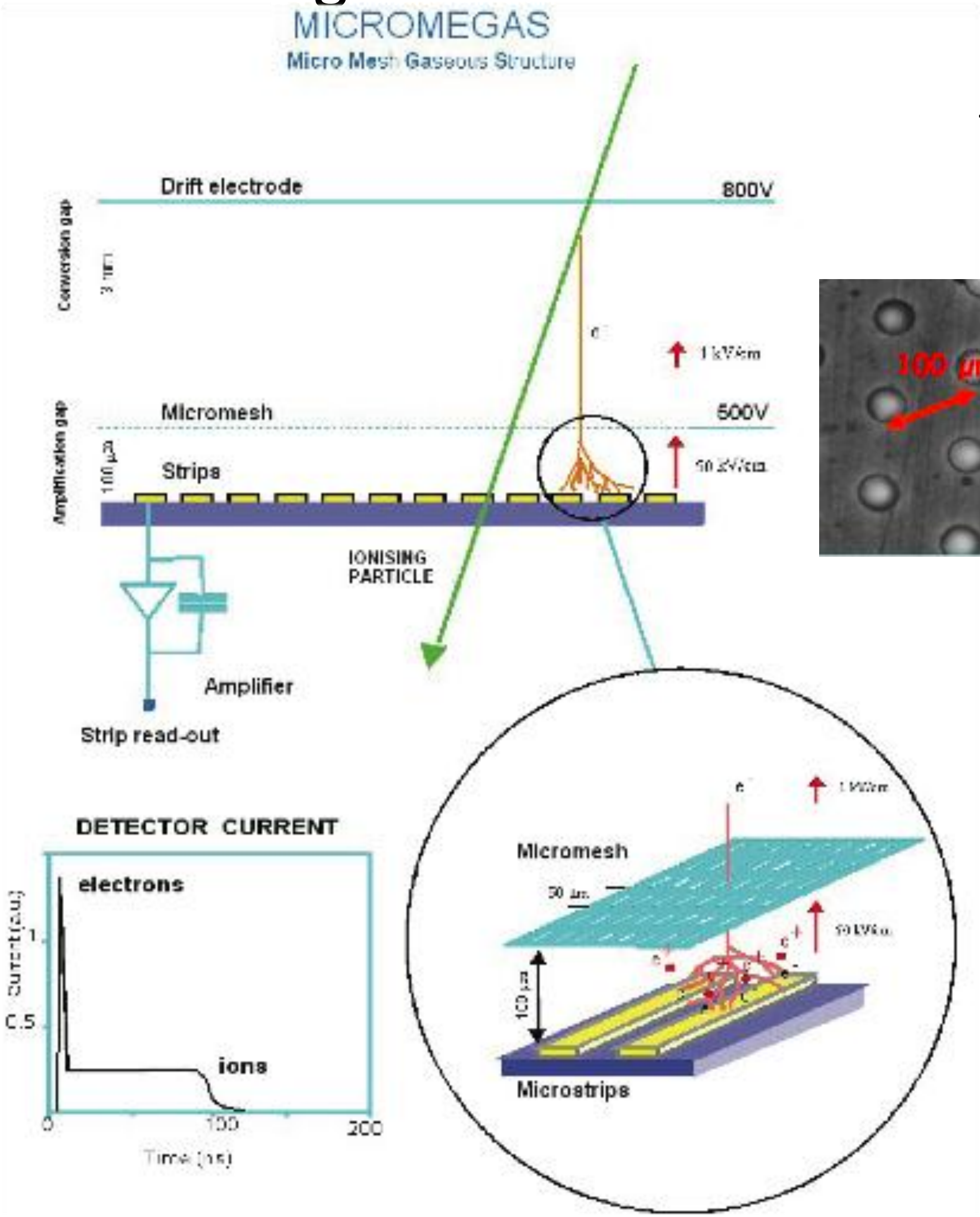




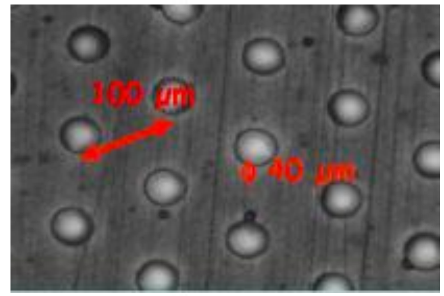


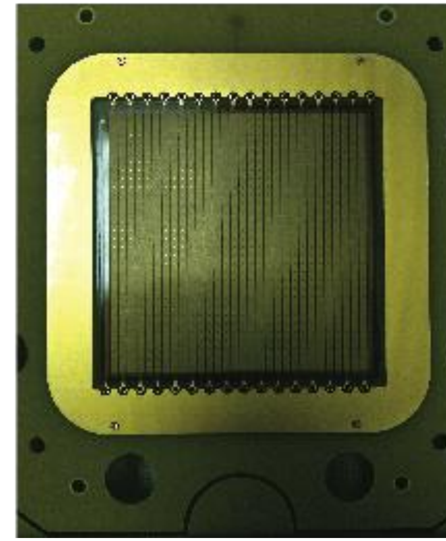
Read the segmented charge and reconstruct tracks

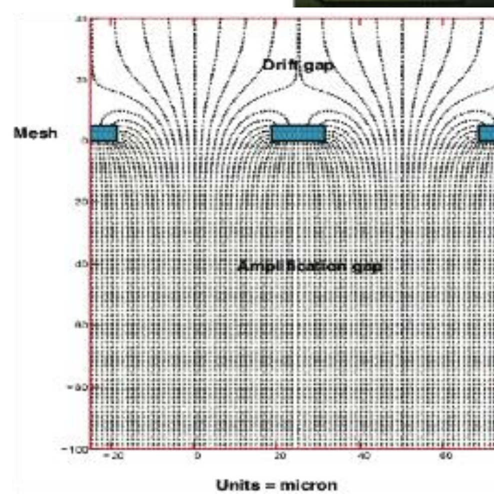
Micromegas



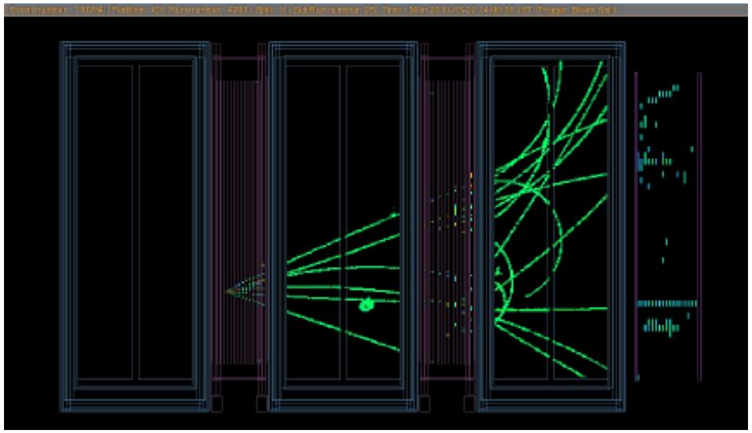
Thin (~100µm) amplification gap between a micromesh and the anode (strips, pads)







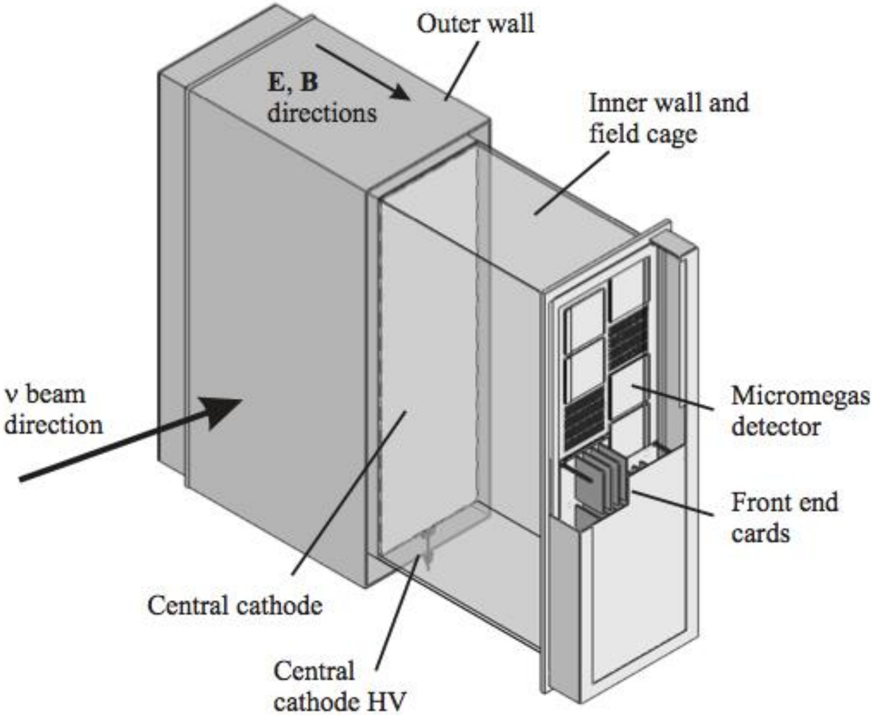
The T2K Time Projection Chamber (TPC)



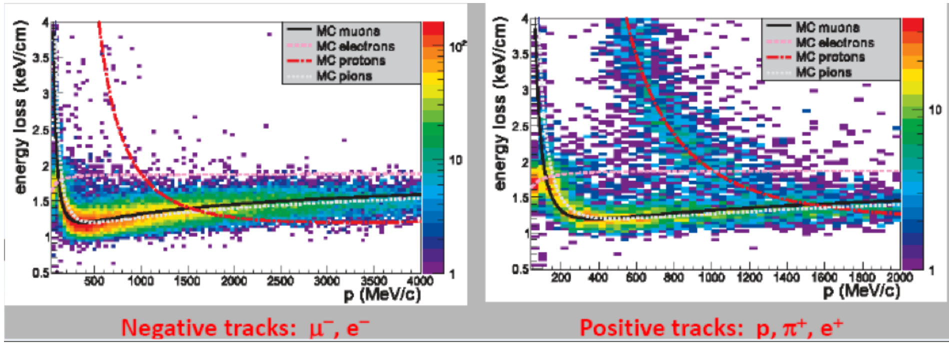
T2K event display

The 12 Micromegas modules

T2K TPC drift gas: 95% Ar, 3% CF4, 2% iC4H10



Particle identification based on energy loss(dE/dx) of charged particles in the gas.



Difficulties With Gaseous Tracking Detectors

Difficult to build (and transport):

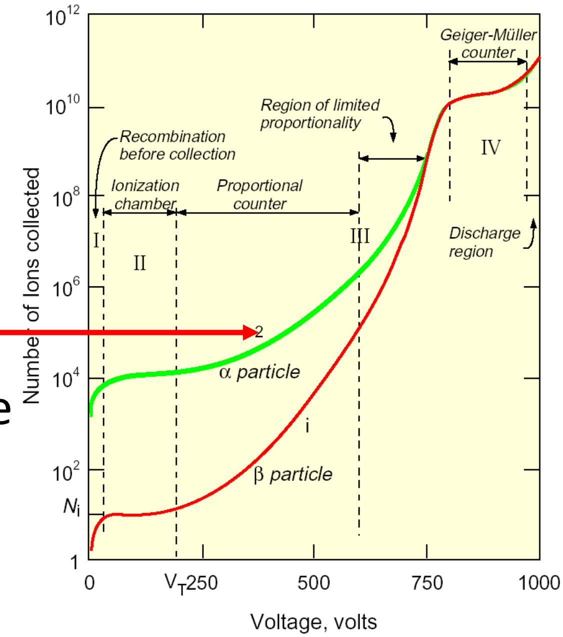
• very thin wires need to be strung under tension (fragile) (one broken wire can destroy large section of chamber)

• larger drift chambers need bulky end plates

Complicated to operate:

• gain highly sensitive to voltage/field strength

-in some layouts small mechanical distortions can change detector behaviour (discharges)



• behaviour is sensitive to (complex) gas mixture

• combination of (often) organic gases with high voltage gives complicated ageing effects due to the effects of radicals/organic deposits

Nevertheless, gaseous tracking detectors are widely used very successfully