Particle Detectors

Lecture 15
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a.a. 2016-2017

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Regime saturato

Regione di amplificazione saturata.

Se si aggiungono piccole quantità di elementi elettronegativi quali freon (CF_3Br) si possono raggiungere guadagni fino a 10^7 prima della scarica.(Salendo un po' con la tensione).

Questo comportamento fu osservato per la prima volta da Charpak e collaboratori utilizzando il cosiddetto gas magico argon-isobutano-freon nelle proporzioni 70:29.6:0.4.

Il vantaggio di operare le camere in regime saturato consiste nella semplificazione dell'elettronica di lettura in quanto abbiamo un segnale più alto ed un range dinamico più basso → ad esempio spesso non serve un amplificatore.

D'altra parte in regime saturato si perde la proporzionalità con la carica rilasciata e quindi la possibilità di una misura di dE/dx.

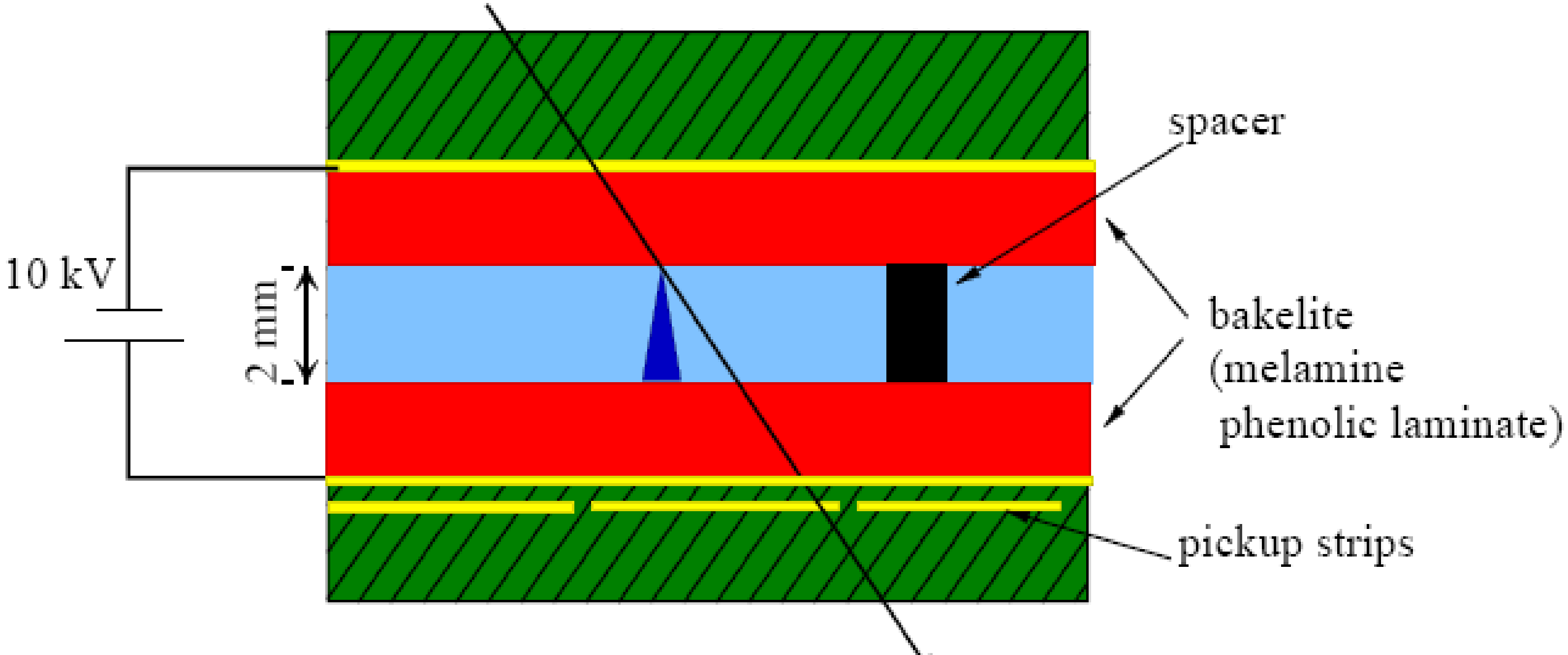
➔

Camere operate in regime saturato sono utilizzate solo per misure di posizione.

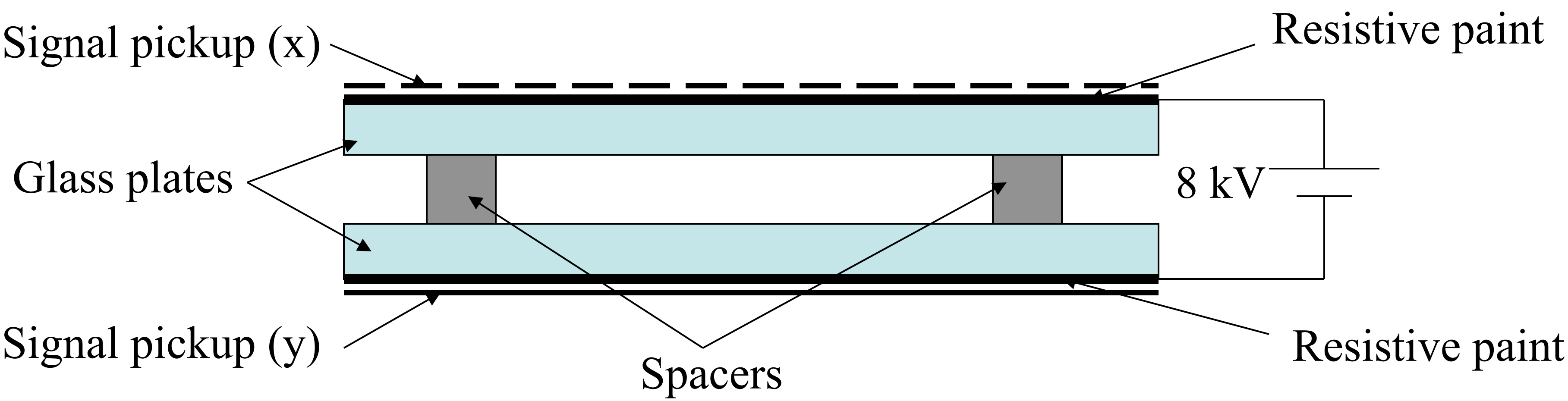
Resistive Plate Chambers (RPC' s)

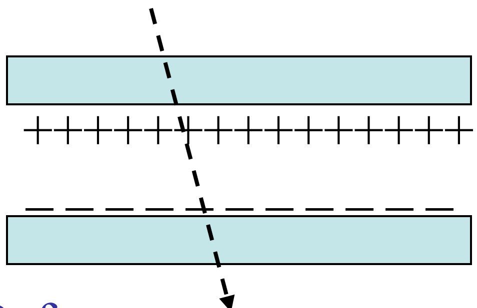
- Principle of operation
  - Very high electric field (few kV/mm) induces avalanches or streamers in the gap
  - High resistivity material localizes the avalanche
  - Signal is induced on the readout electrodes

Typical gas: $C_2F_4H_2$, (C_2F_5H) + few % isobutane



RPC Principles of Operation

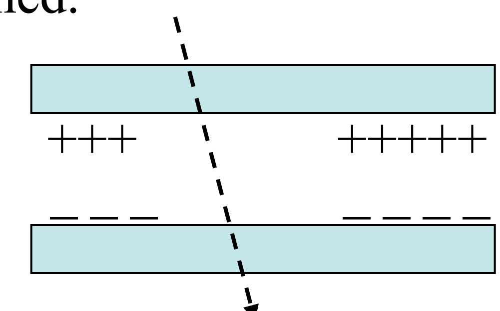




Before

A passing charged particle induces an avalanche, which develops into a spark. The discharge is quenched when all of the locally $(r \approx 0.1\,\mathrm{cm}^2)$ available charge is consumed.

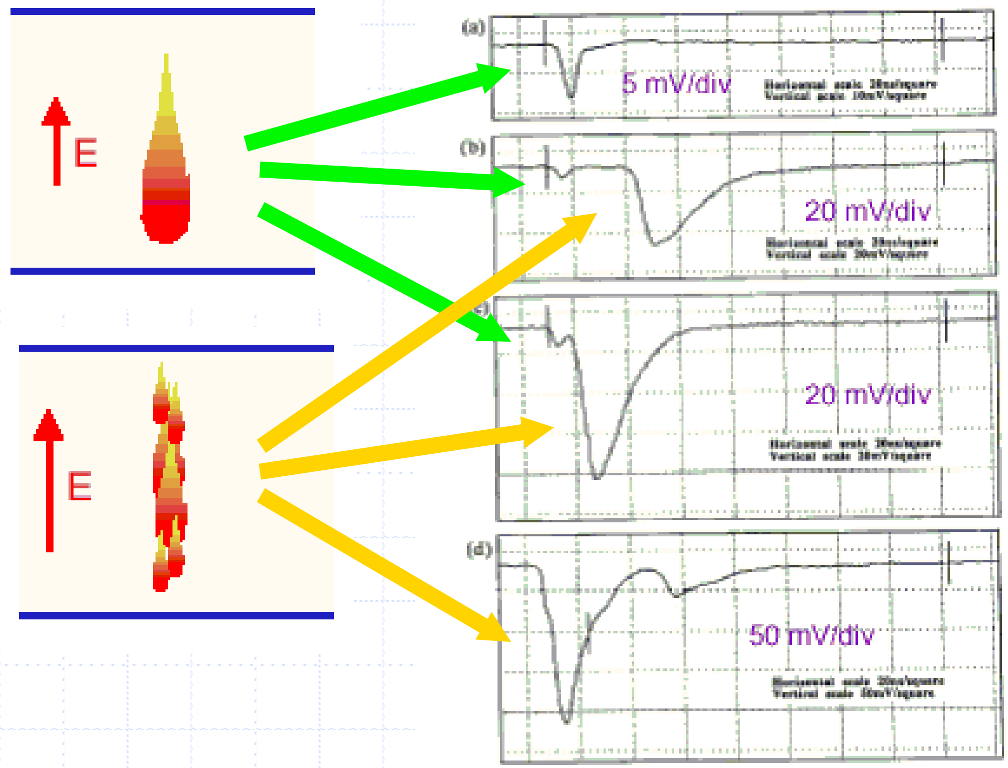
The discharged area recharges slowly through the high-resistivity glass plates.



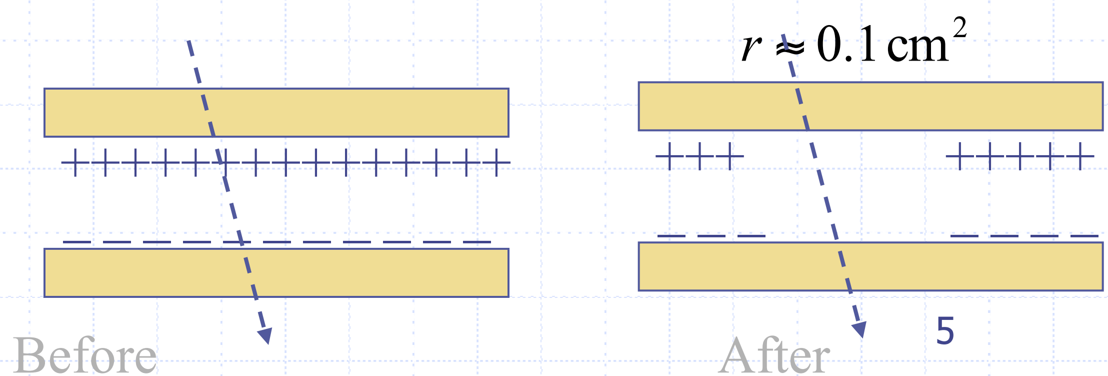
After

RPC's

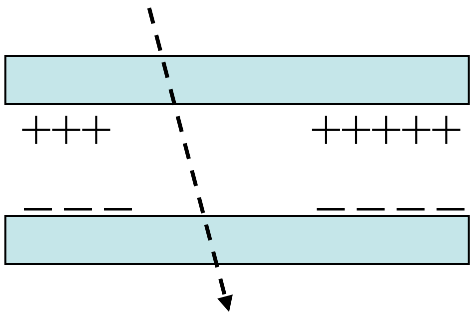
- Avalanche mode
  - Like a proportional chamber
- Streamer mode
  - Small "spark"



- Excellent time resolution
  - 1-2 ns
- In both cases charge must recover to re-establish E field after avalanche or streamer



Principles of Operation: Rate Capability



As noted, each discharge locally deadens the RPC. The recovery time is approximately

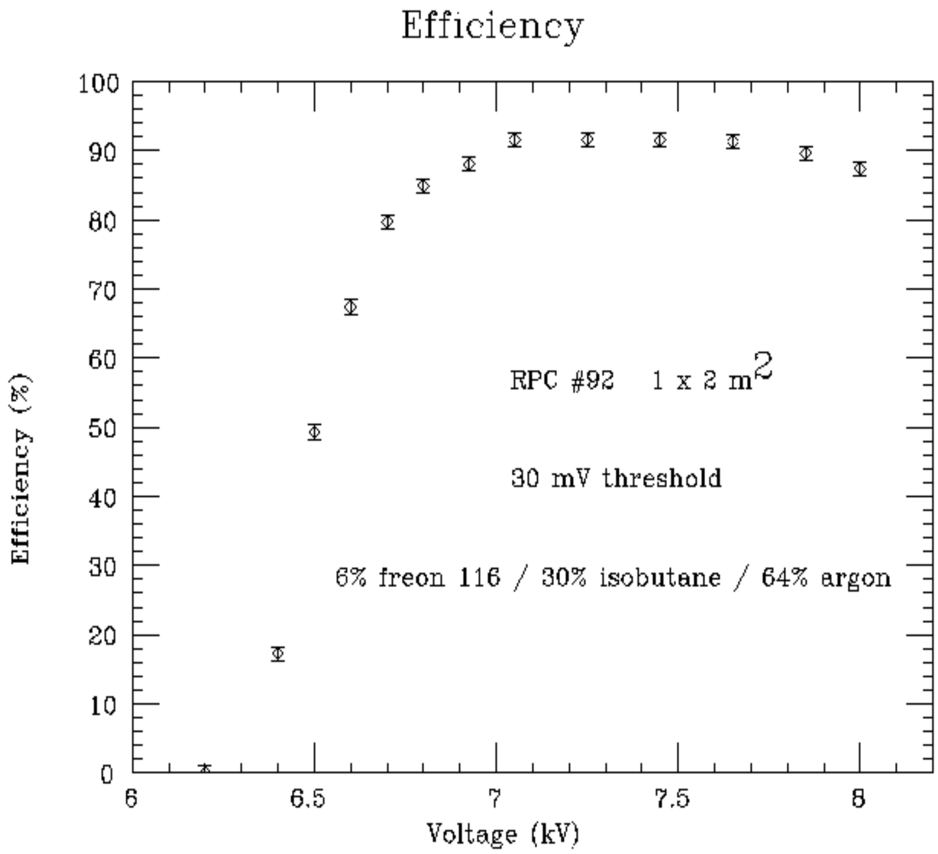
$$\tau = RC \cong \left(\frac{\rho\, l}{A}\right)\left(\frac{\kappa\varepsilon_0 A}{l}\right) = \rho\kappa\varepsilon_0$$

Numerically this is (MKS units)

$$\tau = (5 \text{ x } 10^{10}) \text{ x } 4 \text{ x } (8.85 \text{ x } 10^{-12}) = 2 \text{ s}$$

Assuming each discharge deadens an area of 0.1 cm^2, rates of up To 1 kHz/m^2 can be handled with 1% deadtime or less.

Plateau Curve

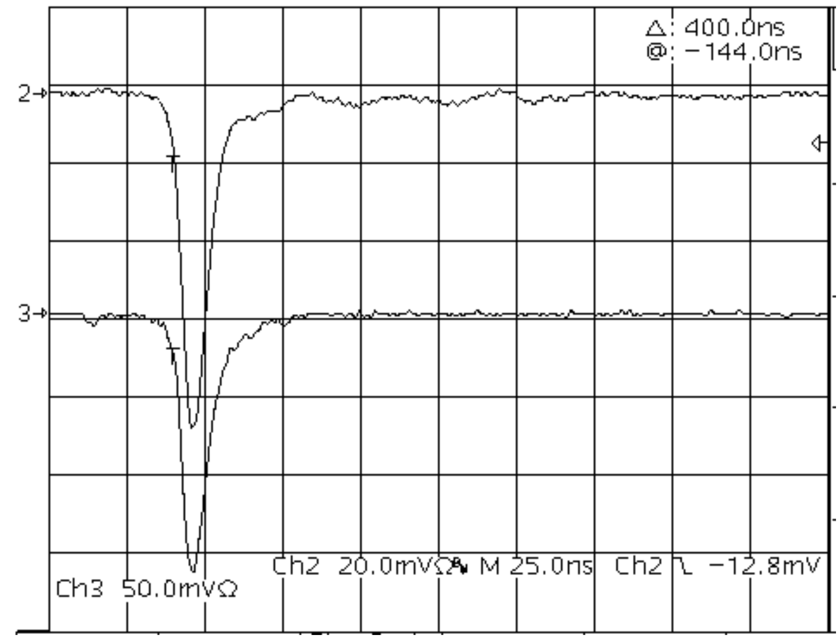


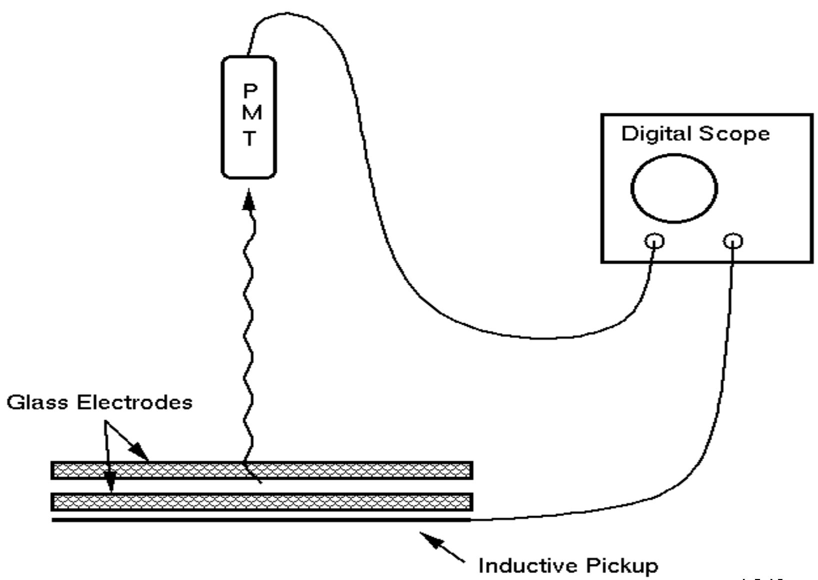
2 mm gap RPCs plateau at a fairly high voltage.

Note the slight falloff in efficiency well above the plateau. This effect is real and typical due to recombination.

Pulse Shape

One interesting feature of RPCs is that the signal can be observed both using a pickup electrode and by viewing the light signal using a PMT.

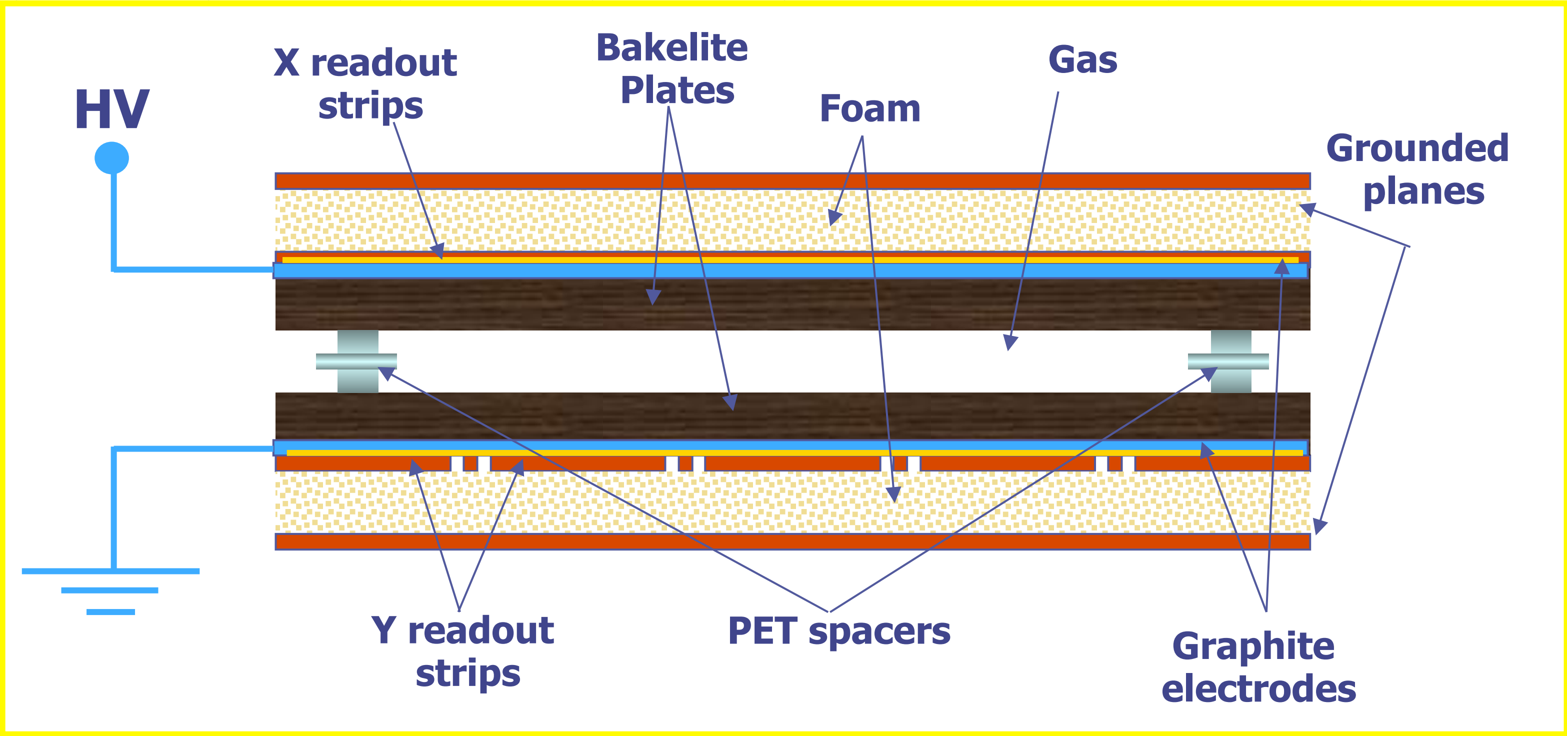




e pulses are large (~100 mV into 50 ns) and fast (FWHM ~ 15ns)→ Good trigger

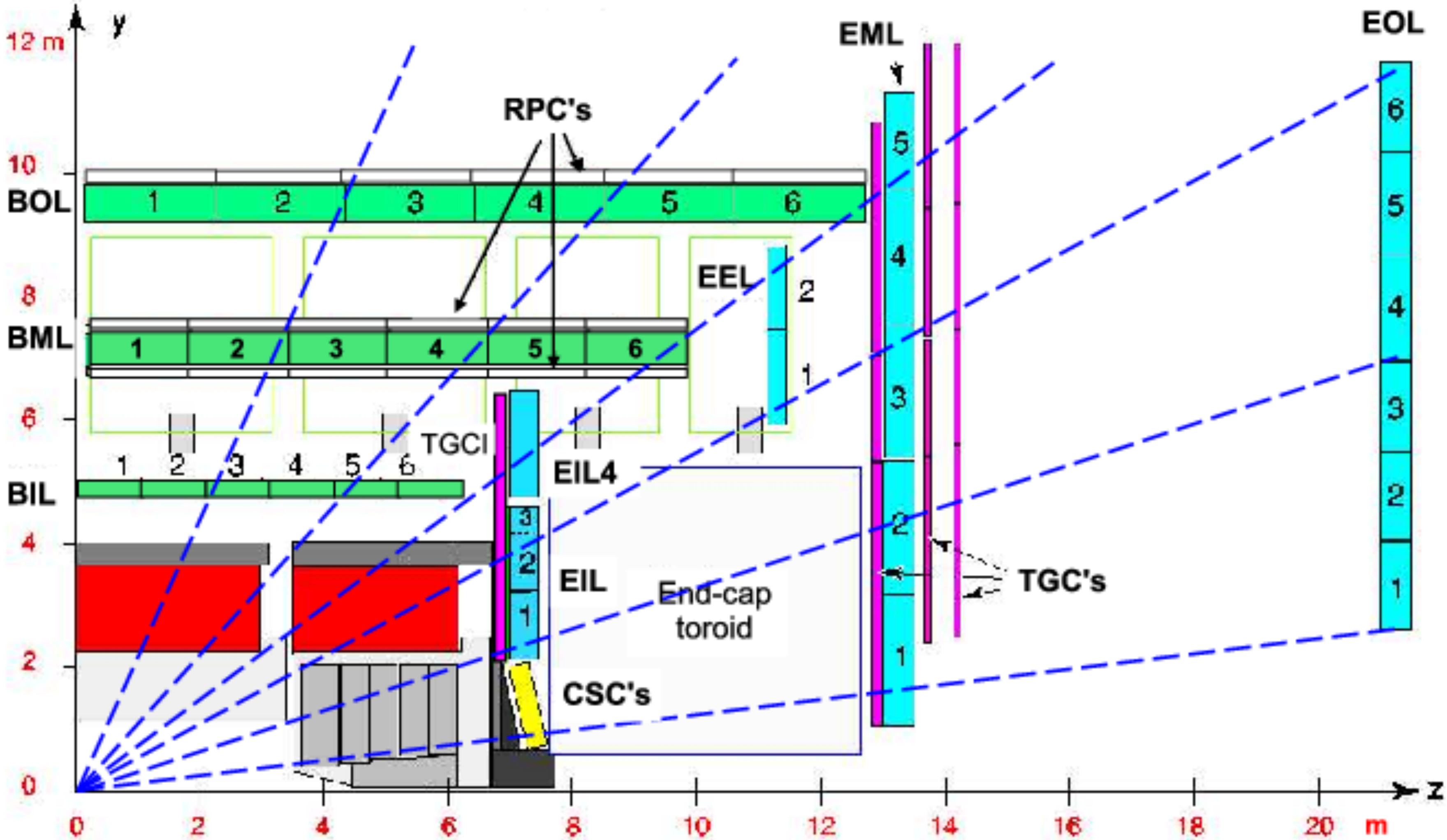
There is a very good correlation between the electronic and the light signal.

ATLAS RPC's

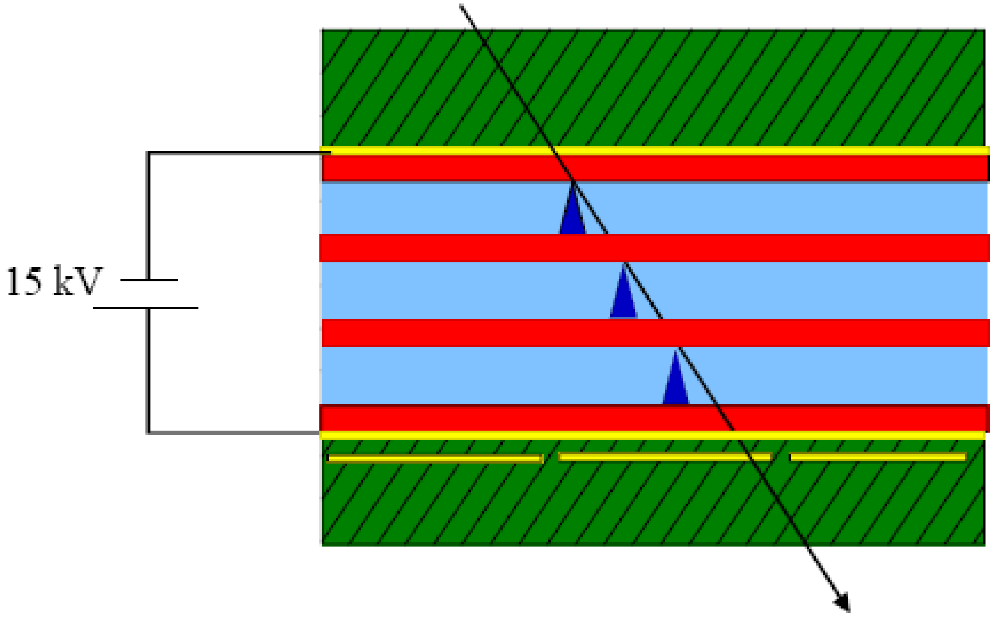


2mm gas gap
8.9kV operating voltage

ATLAS muon spectrometer



RPC's

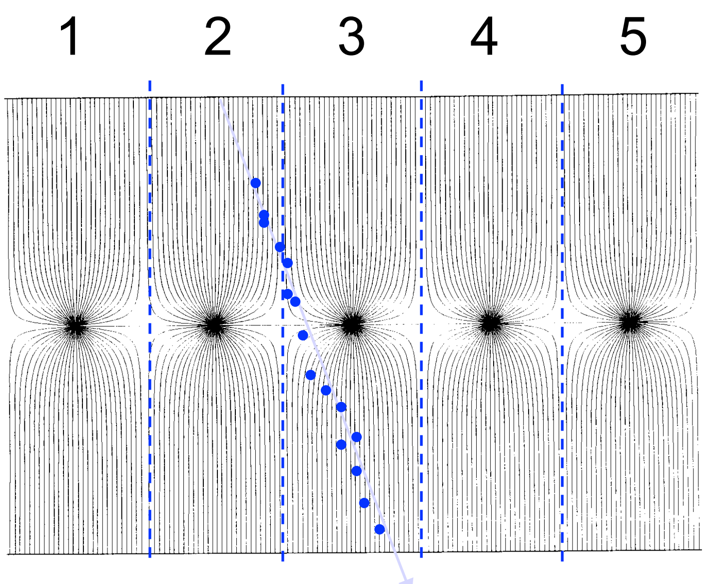


Double and multigap geometries → improve timing and efficiency

Camere proporzionali (MWPC)

Le lineee di campo di ciascun filo si chiudono sul catodo.

Il campo E di ciascun filo e' distinto e separato da quello degli altri fili



Ogni filo crea una "camera" separata.
Le coppie generate in una camera k driftano verso il filo k.
Ciascuna camera raccoglie la frazione di carica generata in essa.

La risoluzione in posizione è digitale ed e' data da: $\sigma = d/(12)^{1/2}$

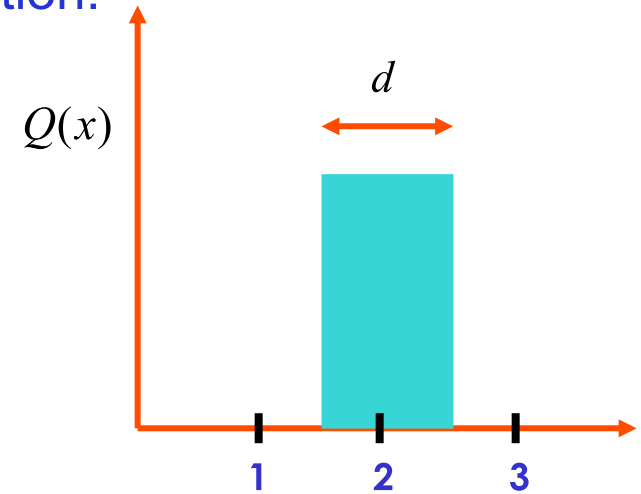
essendo d la distanza fra gli anodi.

Per d di 1÷2 mm la risoluzione è 300÷600 μm quindi piuttosto limitata.

Rivelatori di Particelle

Spatial Resolution: charge sharing

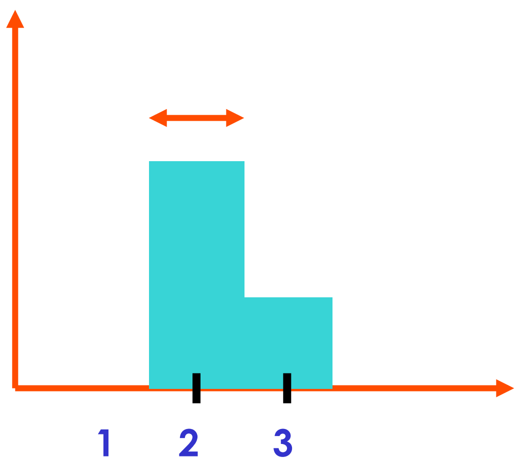
Charge on a single wire/strip is the worst possible situation for the resolution:



$$\sigma^2(x) = \int Q(x)\,(x-\bar{x})^2\,dx = d^2/12$$

where $Q(x)$ is charge readout in position x

(in this case a box with width equal to the pitch)

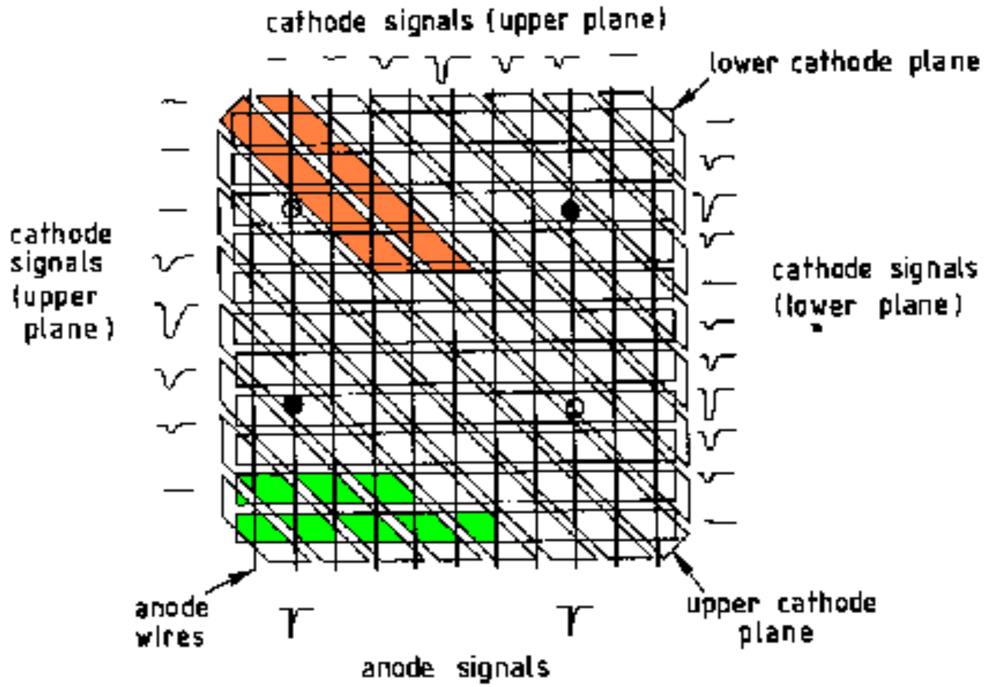


With analogue readout and charge sharing we improve the information content significantly – on the left we know that the hit was between the second and third readout electrode and closest to the 2nd, so we can make a probability function which is much more narrow (some times pitch/10).

Another way of saying it: For every point between wire/strip 2 and 3 there is a unique value of : $(Q_2-Q_3)/(Q_2+Q_3)$, so by measuring this quantity we can reconstruct the position.

Camere proporzionali (MWPC)

- 1 piano di fili
  + 2 piani catodici segmentati



Analog readout of cathode planes.
$\rightarrow \sigma \approx 100\ \mu m$

Le strip catodiche diagonali permettono di eliminare l'ambiguita' degli hit. L'ambiguita' ie' dovuta al fatto che il punto di passaggio P va determinato a partire dai segnali di fili indipendenti che devono essere combinati.

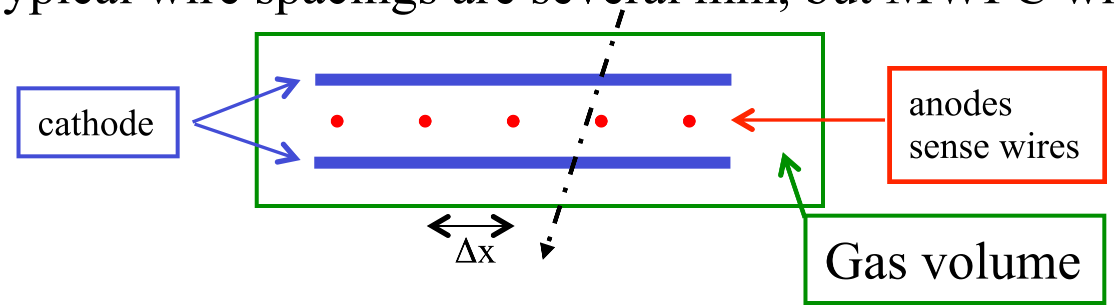
Rivelatori di particelle

Multiwire Proportional Chamber (MWPC)

The spatial resolution (σ) of an MWPC is determined by the sense wire spacing (Δx) if there is charge sharing:

$$\sigma = \frac{\Delta x}{\sqrt{12}}$$

Typical wire spacings are several mm, but MWPC with 1mm spacing have been built.



Advantages of MWPC:

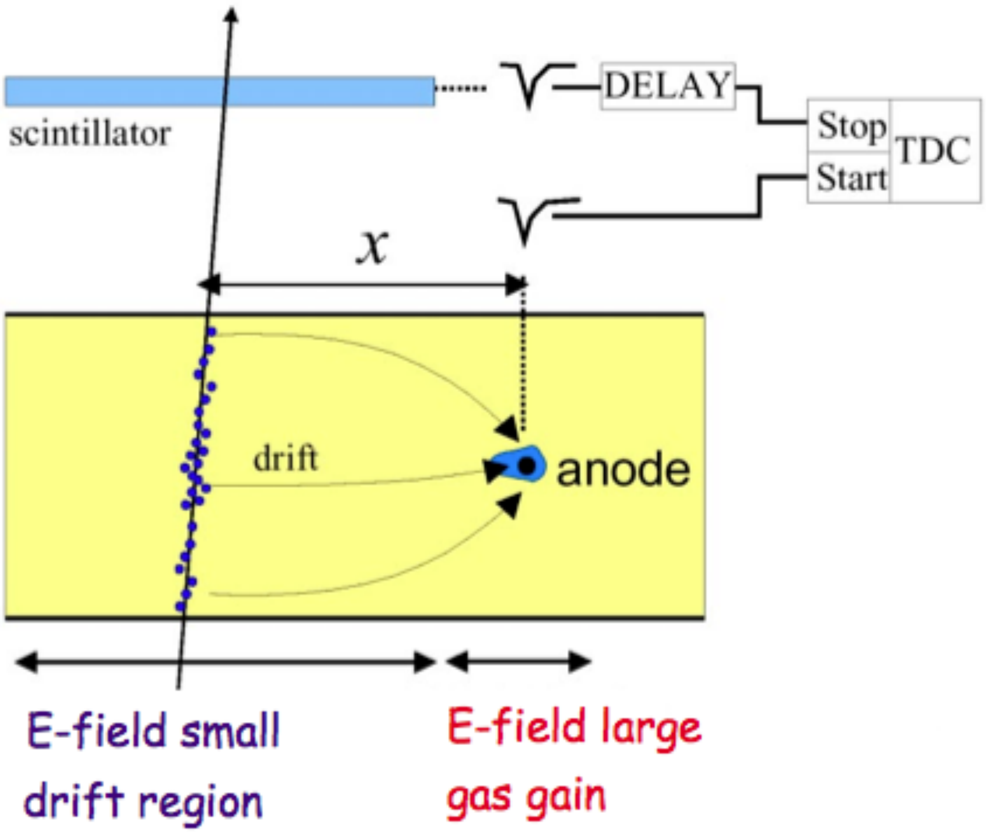
- can cover large area
  - systems with thousands of wires
  - planar or cylindrical geometry
- can get pulse height info
  - dE/dx
  - position info along wire using charge division
- easy to get a position measurement (digital)
- can handle high rates
- works in magnetic field
- ease of construction

Disadvantages of MWPC:

- *poor spatial resolution* — it may be improved by charge sharing down to d/10
- elaborate electronics
  - need low noise premps
  - miniaturization of electronics
- elaborate gas system
- must understand electrostatics
  - forces on wires

Camere a deriva

Possono essere considerate come derivate delle camere proporzionali. In questo caso ricavo la coordinata misurando un tempo.



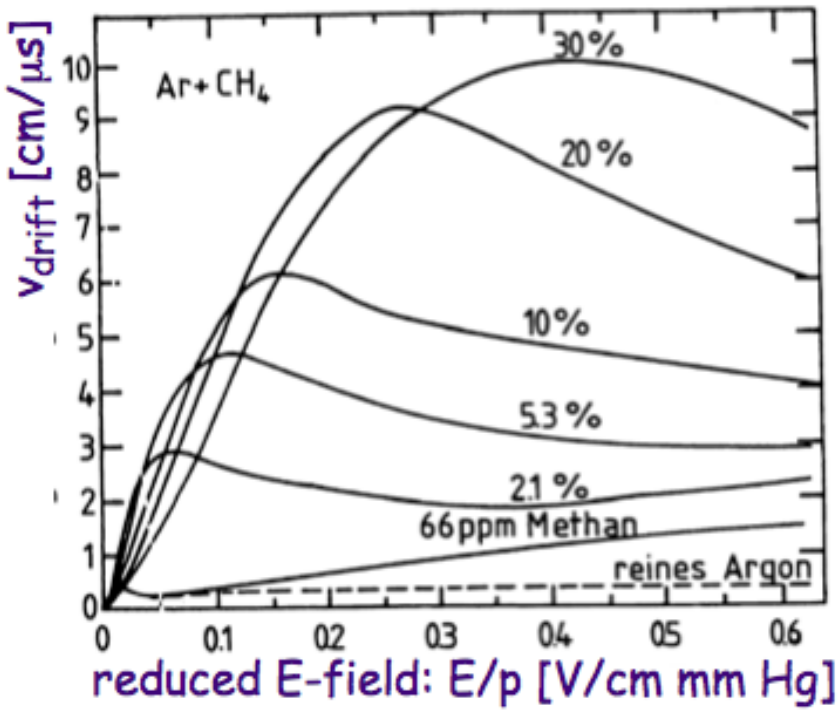
TDC: Time to Digital Converter

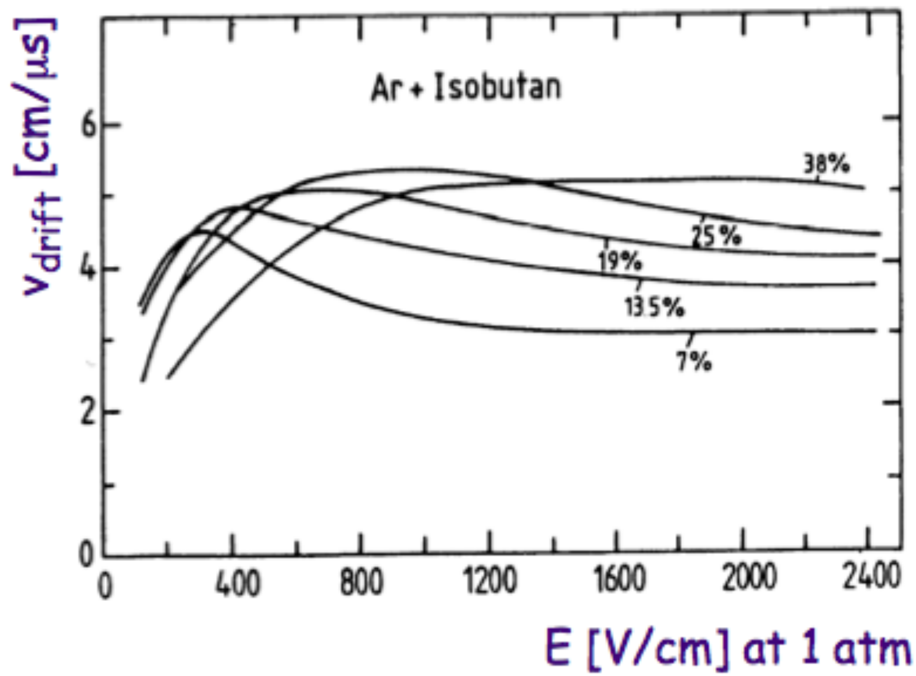
Measure arrival time t_1 of electrons at anode wire relative to reference t_0.

- external definition of time reference t_0 (here by fast scintillator signal)
- x-coordinate given by:

$$x = \int_{t_0}^{t_1} v_D(t)\,dt$$

- if drift velocity v_D constant over full drift distance: $x = v_D(t_1 - t_0) = v_D \Delta t$
- advantage of drift chambers: much larger sensitive volume per read out channel





- strong dependence on the choice of the gas mixture
- details of the energy dependence of the ionisation cross section (Ramsauer minimum) result in a characteristic maximum of the E field dependence.
- for stable operation it is useful to operate in the maximum: $\frac{dv_{drift}}{dE} = 0$
- typical drift velocities : $v_{drift} \approx$ 2-10 cm/μs = 20-100 μm/ns

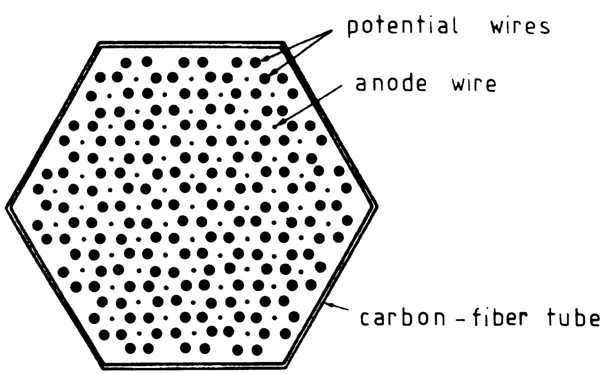
Drift Chambers

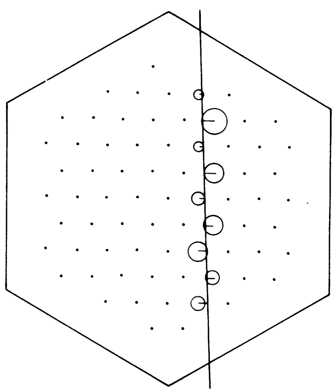
Drift Chambers are MWPCs where the time it takes for the ions to reach the sense wire is recorded. This time info gives position info:

$$x = \int_{t_0}^{t_s} v(t)dt$$ t_0= start time, t_s=stop time=time electrons reach sense wire

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





drift times are circles around the sense wires

The trajectory is given by the straight line tangent to all the circles

Camere a deriva

Vantaggi di una camera a deriva rispetto ad una MWPC:

- più facile da costruire da un punto di vista meccanico (fili più lontani → minori le forze elettrostatiche)
- meno fili → meno elettronica (anche se più costosa)
- migliore precisione (non più limitata alla distanza dei fili $/(12)^{1/2}$.

I parametri fondamentali sono:

- diffusione (buono se piccola)
- velocità di deriva (ottimo se costante). Tipiche velocità di deriva (con argon-isobutano nelle proporzioni 75%-25% e campi elettrici E~700-800V/cm) ~50 mm/μs.

Drift Chamber – Spatial Resolution

Resolution determined by
accuracy of drift time measurement ...

Influenced by:

Diffusion [$\sigma_{Diff.} \sim \sqrt{x}$]

see above: $\sigma^2 \sim 2Dt = 2Dx/v_D \sim x$ ...

δ-electrons [σ_δ = const.]

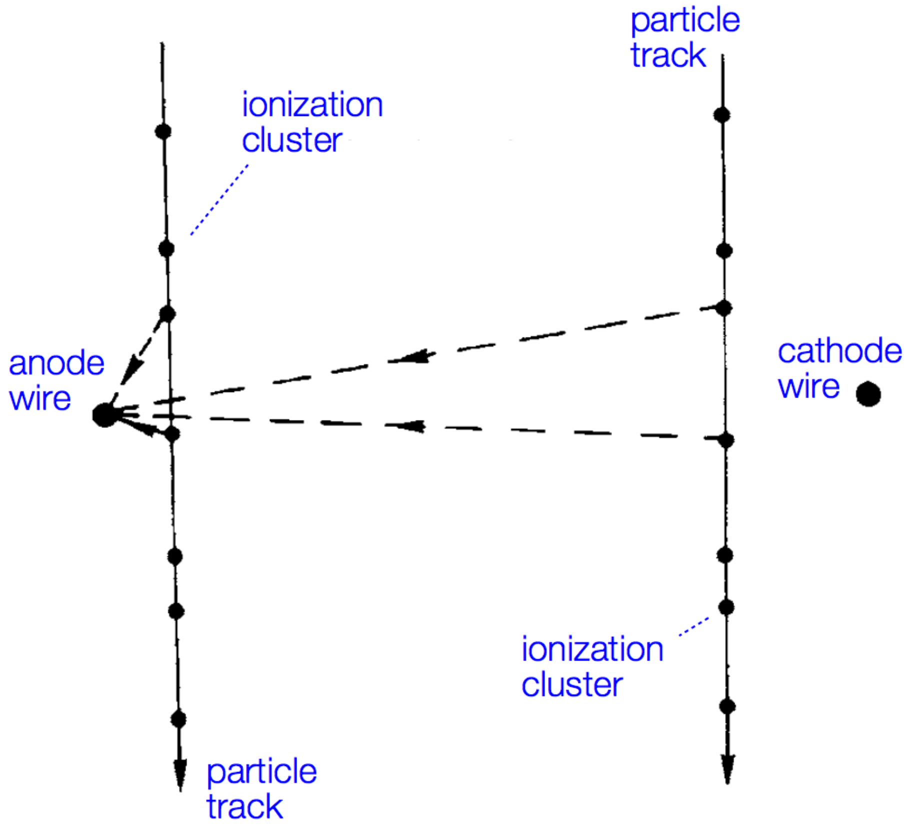
independent of drift length; yields constant
term in spatial resolution ...

Electronics [$\sigma_{electronics}$ = const.]

contribution also independent of drift length ...

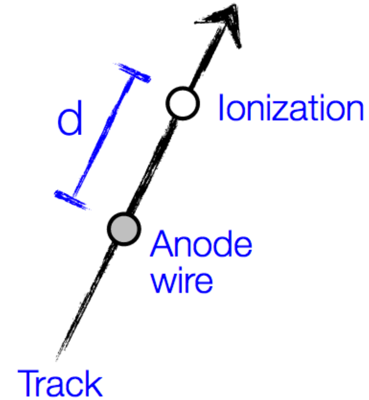
Primary ionization statistics [$\sigma_{prim} = 1/x$]

Spatial fluctuations of charge-carrier production result in
large drift-path differences for particle trajectories close to the anode ...
[minor influence for tracks far away from anode]



Primary ionization statistics:

Step 1: Consider a track passing through an anode wire ...



Probability of no ionization within distance d:

$$P_0(d) = e^{-2Nd}$$

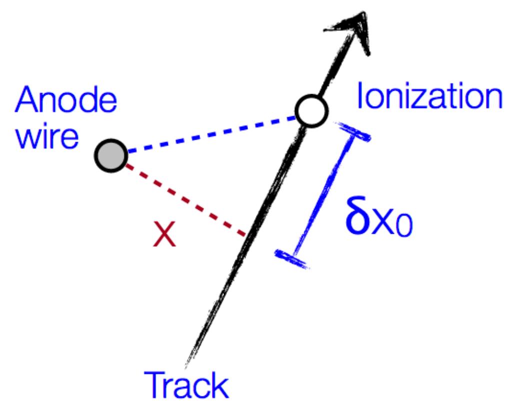
with
N: number of ionizations per unit length

Average minimum distance of closest ionization cluster:

Normalization

$$\delta x_0 = \langle d_{\min} \rangle = \int_0^\infty x e^{-2Nx}\, 2N\, dx = \frac{1}{2N}$$

$$\sigma^2_{\langle d_{\min} \rangle} = \int_0^\infty (x - \frac{1}{2N})^2 e^{-2Nx}\, 2N\, dx = \frac{1}{4N^2}$$



Step 2: Track at distance x ...

$$\delta x = \sqrt{x^2 + (\delta x_0)^2} - x = x\left(\sqrt{1 + \left(\frac{\delta x_0}{x}\right)^2} - 1\right) \approx \frac{x}{2}\left(\frac{\delta x_0}{x}\right)^2 \propto \frac{1}{x}$$

Camere a deriva

Diffusione

In presenza di campo elettrico: $\sigma_x / x \approx \sqrt{\frac{2KT}{eV_0}}$ ➔ limite intrinseco delle camere a deriva.

Il coefficiente di diffusione diminuisce aumentando il campo elettrico (con campi tipici di 1KV/cm ➔ la risoluzione è ~100μm per una distanza di deriva di 1 cm).

Concludendo:

In presenza di campo elettrico, aumentando il campo diminuisce la diffusione ➔ usare gas “freddi” (CO_2) che hanno elettroni termici anche con alti E ➔ bassa moltiplicazione (male) e lungo tempo di deriva (bene).

Gas “caldi” (Argon) hanno elettroni non termici anche per bassi E ➔ diffusione anisotropa ed in genere $D_T > D_L$

In presenza di un campo magnetico la diffusione lungo B non cambia, mentre nella proiezione ortogonale a B gli elettroni fanno archi di cerchio con raggi v_T/ω ➔ la diffusione diminuisce.

$$\sigma_x^2 = \left(\frac{1}{64N^2}\right) \cdot \frac{1}{x^2} + \frac{2D}{v_d} \cdot x + \sigma_{\text{const}}^2$$

1st ionization statistics — diffusion — electronics, δ-electrons

Possible improvements:

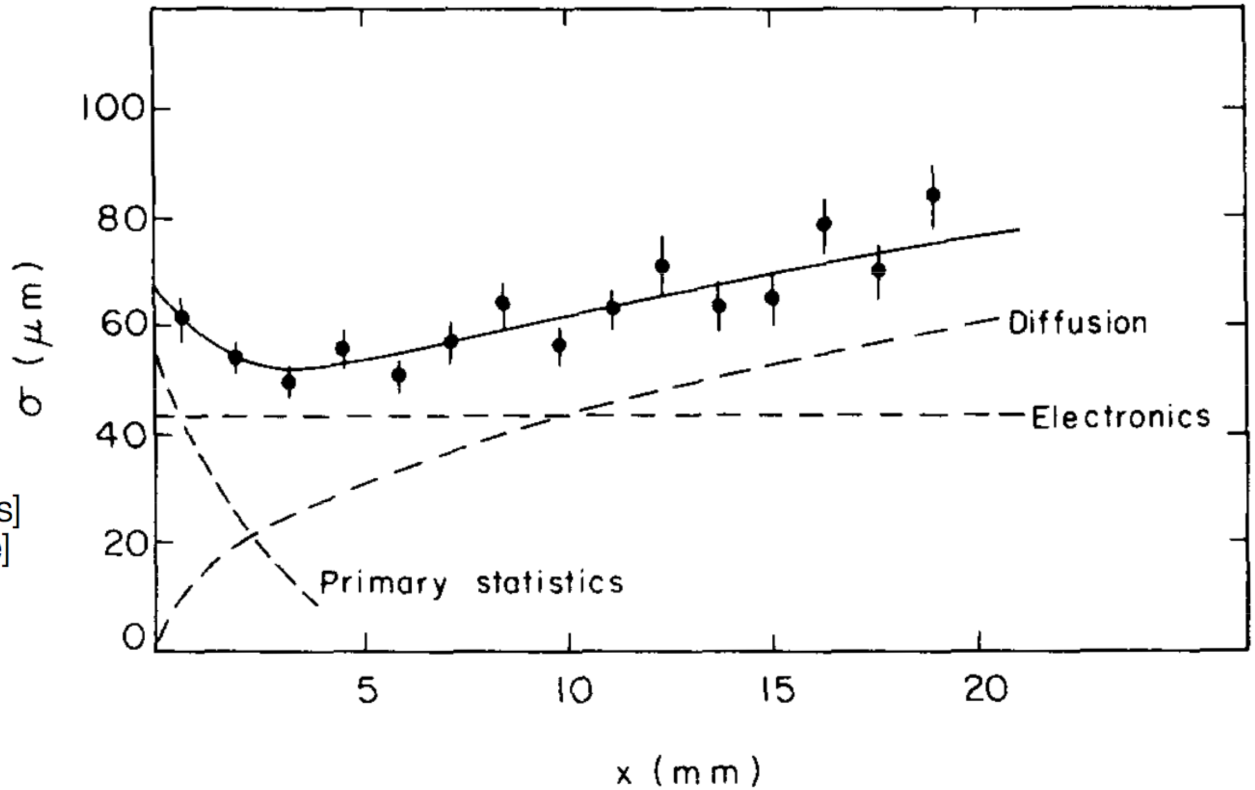
Increase N by increasing pressure ...

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]



La risoluzione non è determinata direttamente dalla spaziatura dei fili ➔ meno fili, meno elettronica, meno strutture di sostegno rispetto alle MWPC.

Drift Chambers

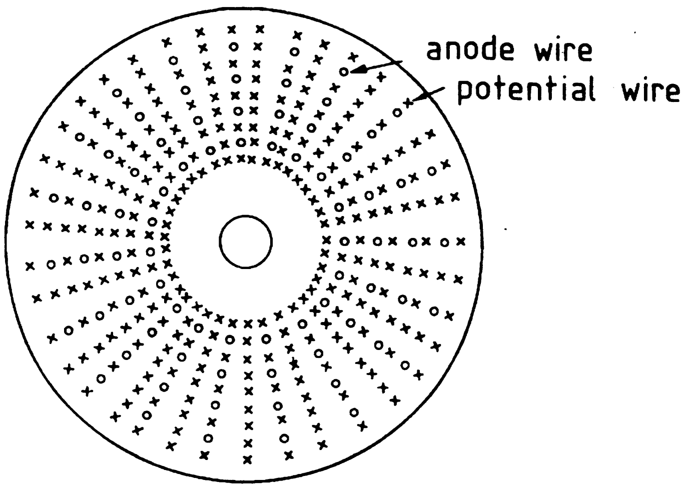
Drift chambers come in all sizes, shapes and geometries:

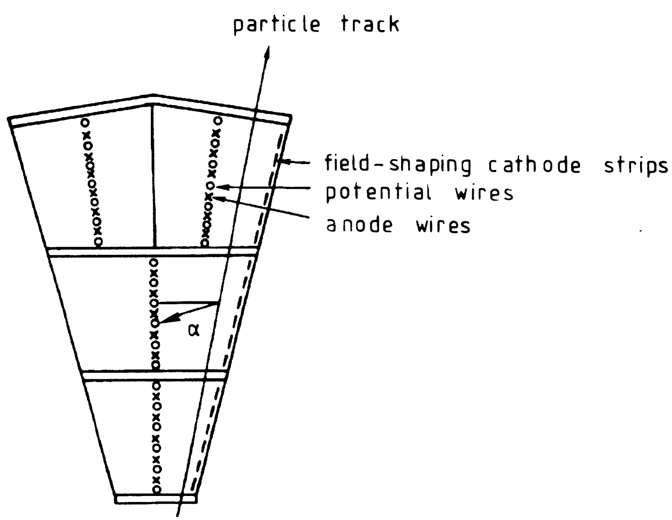
planar ⇒ fixed target **cylindrical ⇒ colliding beam**

Time info gives a "circle" of constant distance around the sense wire (more complicated in B field)

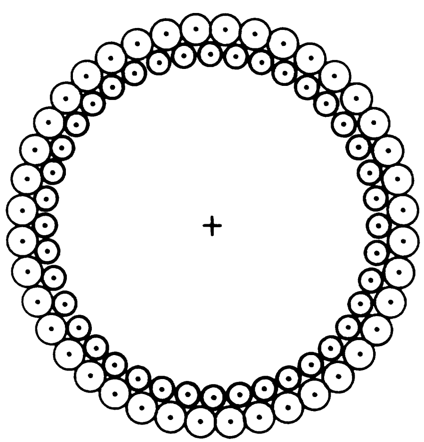
In almost all cases, wires in different layers are staggered to resolve the left-right ambiguity

Typical cylindrical DC:
Many wires in same gas volume.
Use small angle stereo for z.
Usually use single hit electronics.
Sense (anode) and field wires.
CLEO, CDF, BELLE, BABAR



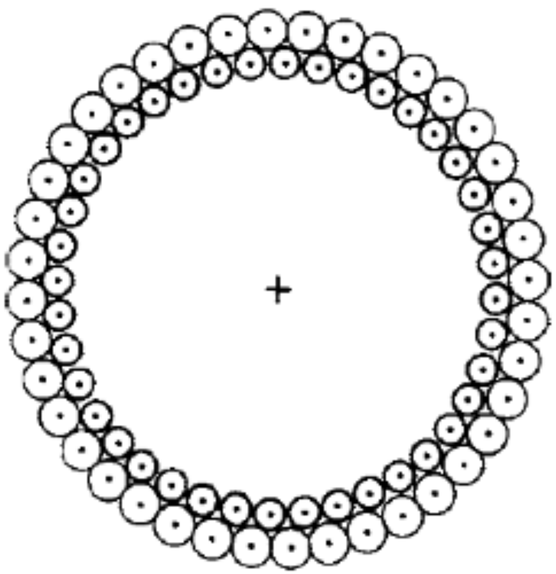


Tube Chamber:
Single sense wire in a cylinder
Can make out of very thin wall tubes.
⇒ very little material
Small drift cell ⇒ single hit electronics
Good cell isolation
⇒ broken wire only affects one tube
CLEO's PTL detector



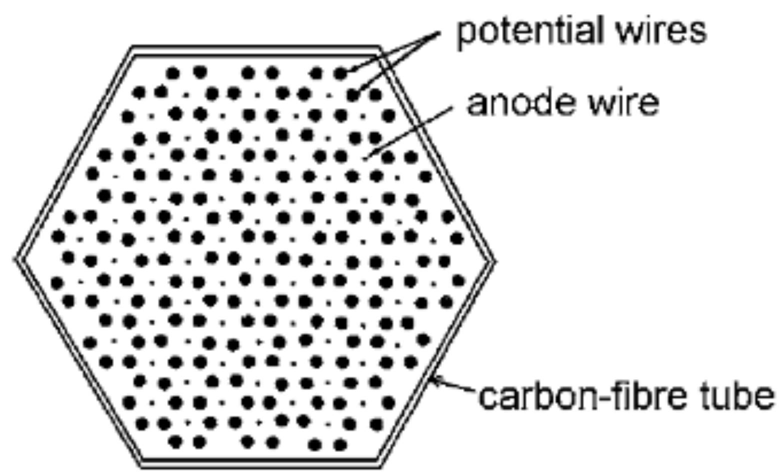
Jet chamber: optimized to resolve two tracks in a "jet".
Drift direction roughly perpendicular to wire plane.
Single track gives multiple hits on several wires.
Use multi-hit electronics so two tracks on a wire can be resolved.
Lorentz angle must taken into account
⇒ wires are "slanted"

Cylindrical configuration of thin-wall straw-tube chambers or multi-wire drift module with 70 drift cells in one carbon-fibre container of 30mm diameter

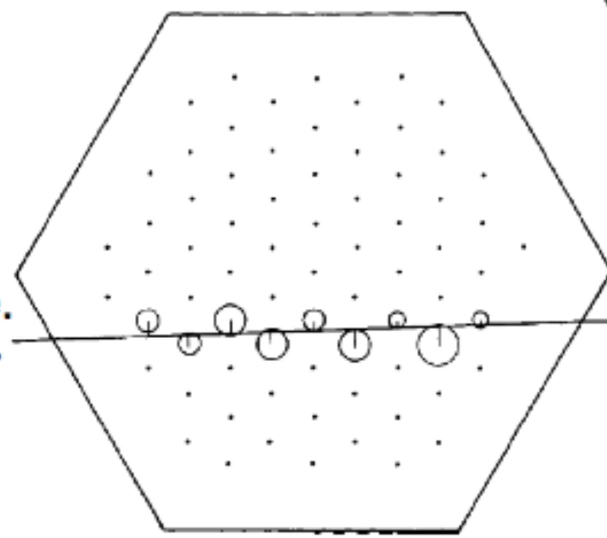


← advantage:
one broken wire =
one channel missing

one broken wire →
can kill a module



The straw tubes have diameters of 5-10mm and are frequently operated at overpressure. These detectors allow for spatial resolutions of 30μm

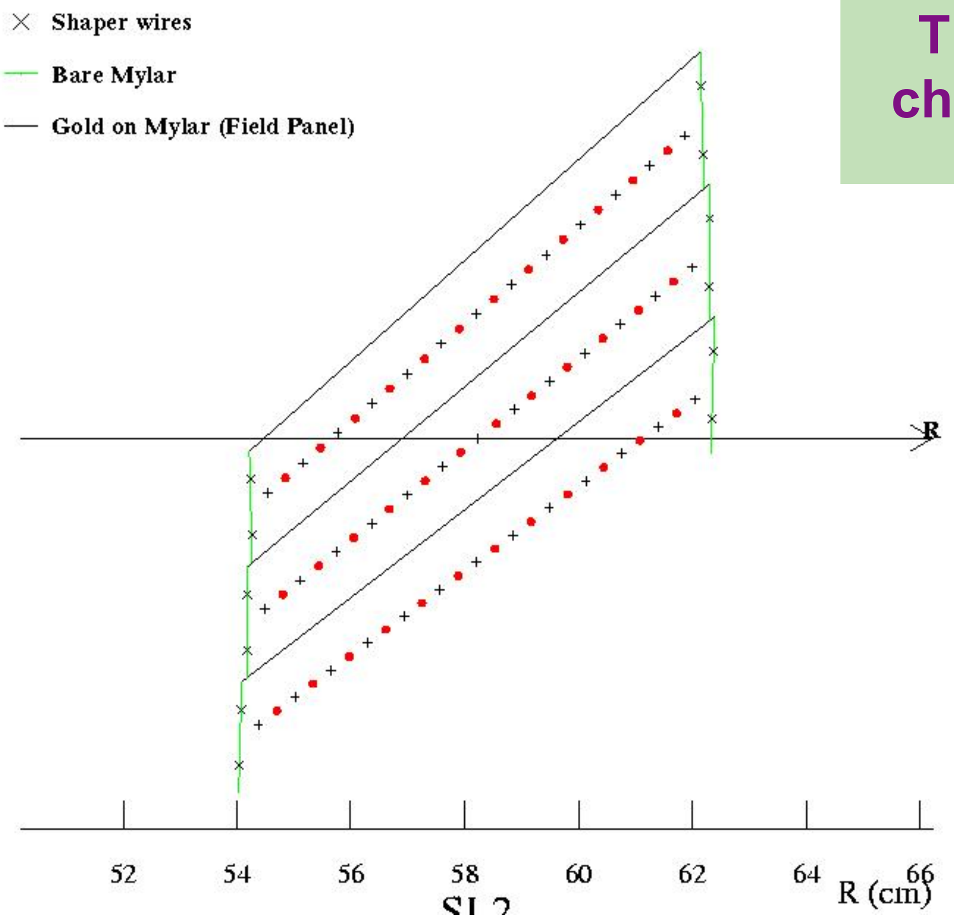


Reconstruction of a particle passage through a multi-wire drift module. The circles indicate the measured drift times of the fired anode wires. The particle track is a tangent to all drift circles

32

Large Area Drift Chambers

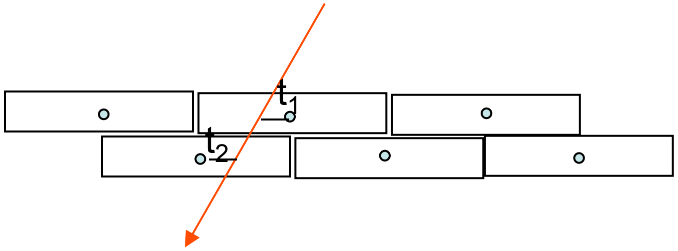
The "open cell" drift chamber uses field and sense wires: field wires create shape of electric field, sense wires detect time of arrival of pulse.



This is the design of the CDF drift chamber - the cells are tilted to take into account ExB drift!

Camere a deriva

Ambiguità destra sinistra: la misura di tempo non può discriminare fra destra e sinistra ➔ staggering



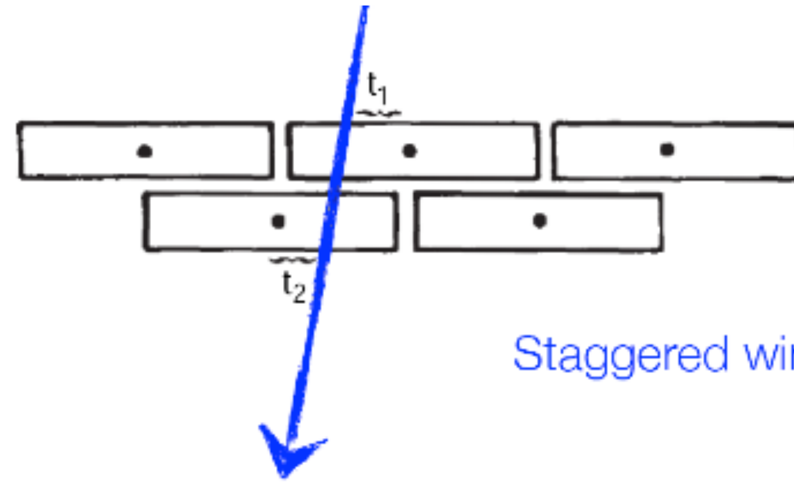
t_1+t_2= tempo per percorrere ½ cella

Se la cella è di ±5 cm (50 mm/μs) ➔ t_1+t_2= 1 μs.

Difficulty:

Time measurement cannot distinguish whether particle has passed right or left from a wire ...

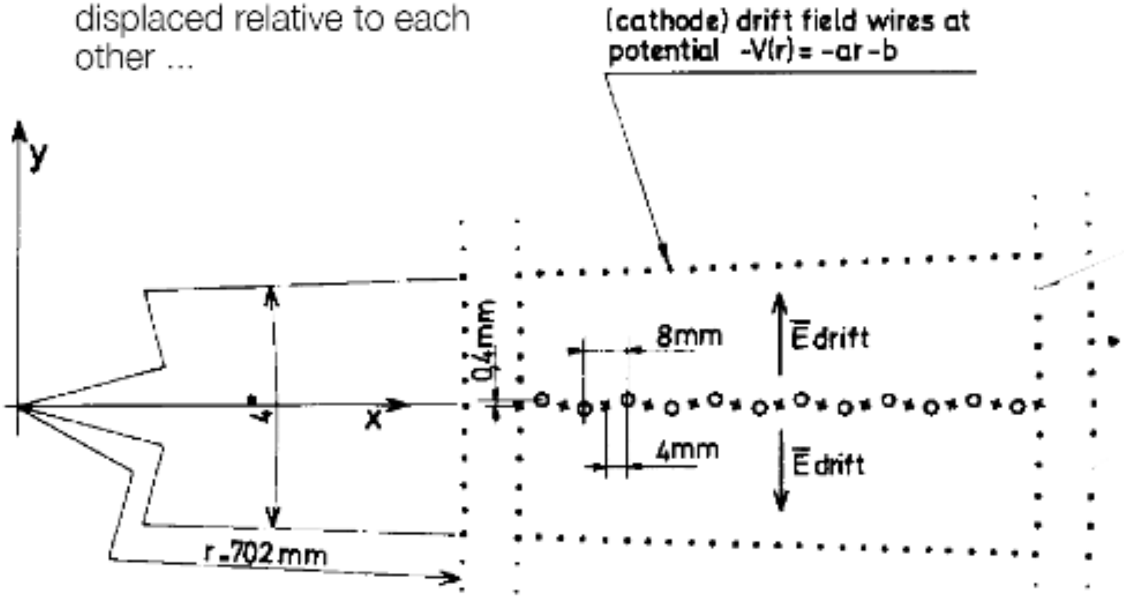
"Left-Right Ambiguity"

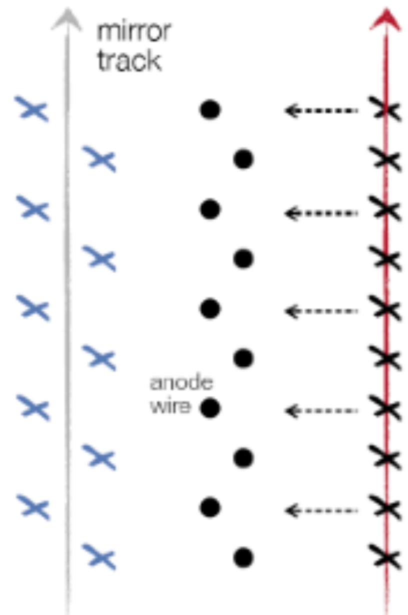


Staggered wires

Solution: "Staggered wires"

Use multiple (two) layers displaced relative to each other ...



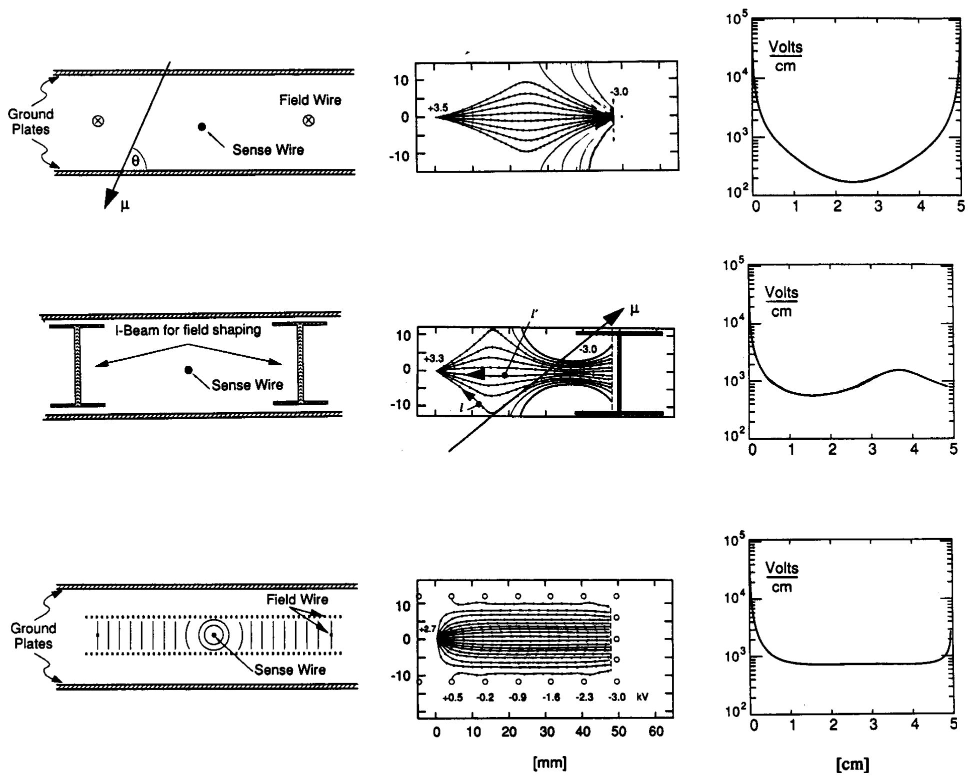


Solution: staggered anode wires

Camere a deriva

Camere a deriva piane.

- Ottimizzare la geometria in modo da avere E costante.
- Scegliere un gas con una velocità di deriva che dipenda poco da E ➔ relazione spazio-tempo lineare.



E(x) non è costante ➔ v_D non è costante.

Un po' meglio della configurazione di sopra

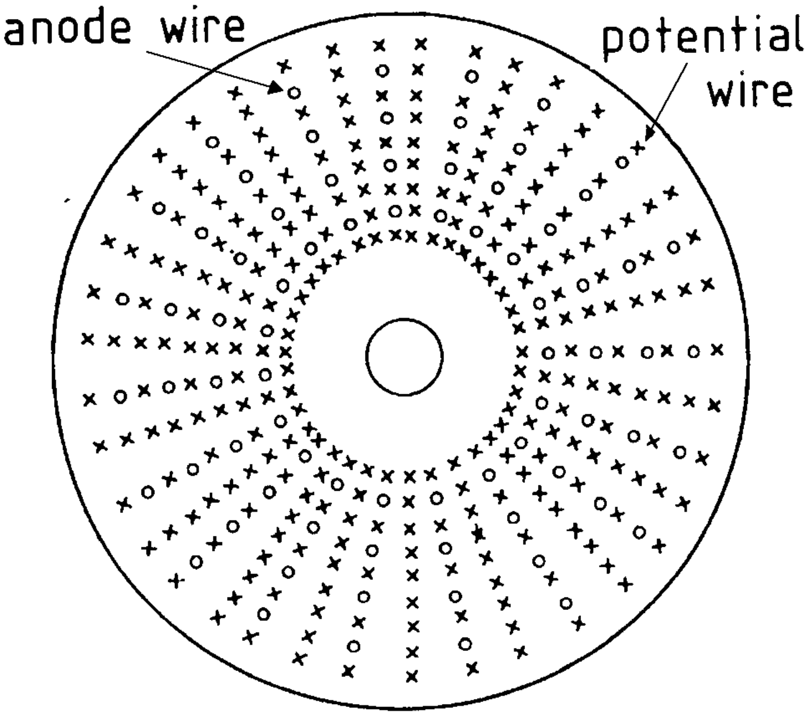
E costante $s=s_o+bt$

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

Camere a deriva

Camere a deriva cilindriche.

In un esperimento ad anelli di collisione conviene usare camere a deriva cilindriche, in quanto ermetiche e facile coprire un grande angolo solido.

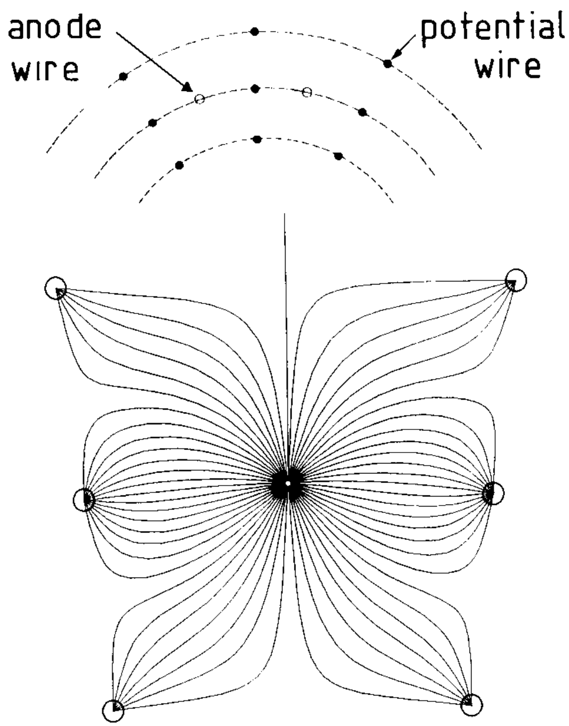


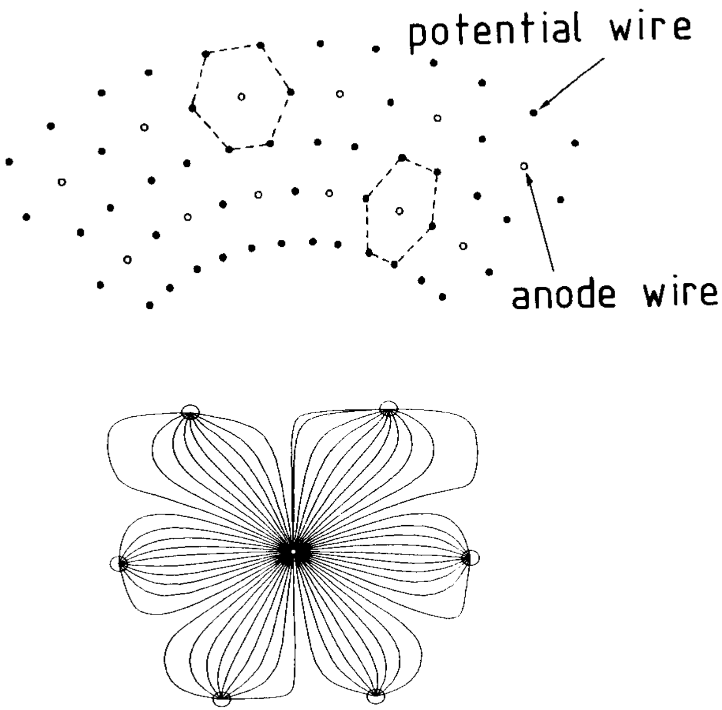
Sezione trasversa di una camera cilindrica.

Strati di fili (anodi, sense) sono separati da fili di potenziale (catodi)

Camere a deriva

Camere a deriva cilindriche.





Configurazione più semplice che fornisce un campo non proprio al meglio

La qualità del campo può essere migliorata con una configurazione a cella chiusa, come indicato .

Camere a deriva

La misura della coordinata z (quella // al filo anodico) è normalmente misurata tramite

- ❖ divisione di carica (filo resistivo)
- ❖ misura di tempo (linee di ritardo)

Le camere a deriva cilindriche tipiche hanno 10÷15 piani di anodi ➔ non sufficienti per identificare le particelle con misure di dE/dx

➔**camere a jet** : ottimizzate per avere il massimo numero di misure nella direzione radiale.

➔**camere a jet :** ottimizzato il campo per avere una velocità di deriva costante

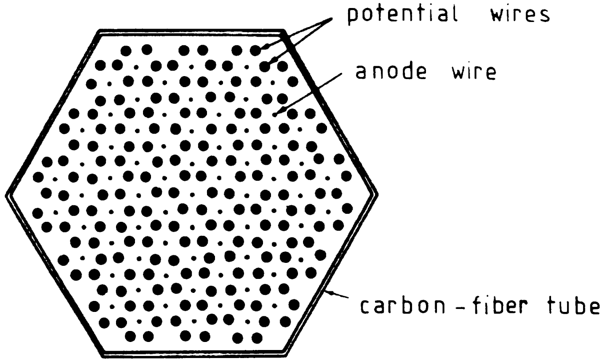
Drift Chambers

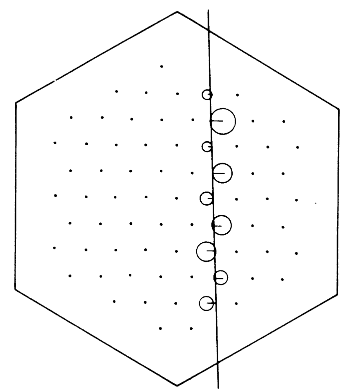
Drift Chambers are MWPCs where the time it takes for the ions to reach the sense wire is recorded. This time info gives position info:

$$x = \int_{t_0}^{t_s} v(t)\,dt$$ t_0= start time, t_s=stop time=time electrons reach sense wire

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





drift times are circles around the sense wires

Camere a deriva

Vantaggi di una camera a deriva rispetto ad una MWPC:

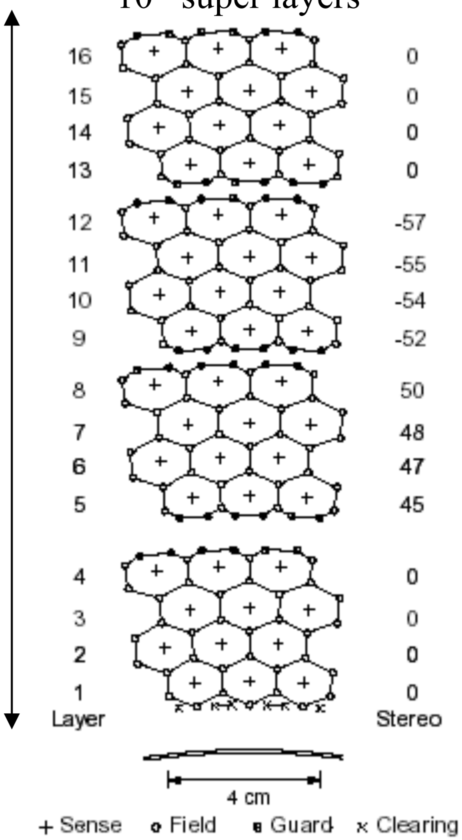
- più facile da costruire da un punto di vista meccanico (fili più lontani → minori le forze elettrostatiche)
- meno fili → meno elettronica (anche se più costosa)
- migliore precisione (non più limitata alla distanza dei fili / $(12)^{1/2}$.

I parametri fondamentali sono:

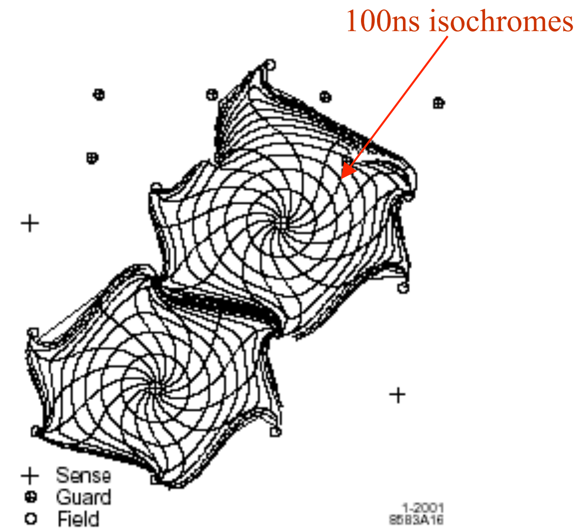
- diffusione (buono se piccola)
- velocità di deriva (ottimo se costante). Tipiche velocità di deriva (con argon-isobutano nelle proporzioni 75%-25% e campi elettrici $E \sim 700$-$800 V/cm$) ~50 mm/μs.

A Real Life Drift Chamber-BaBar

40 layers total
10 “super layers”

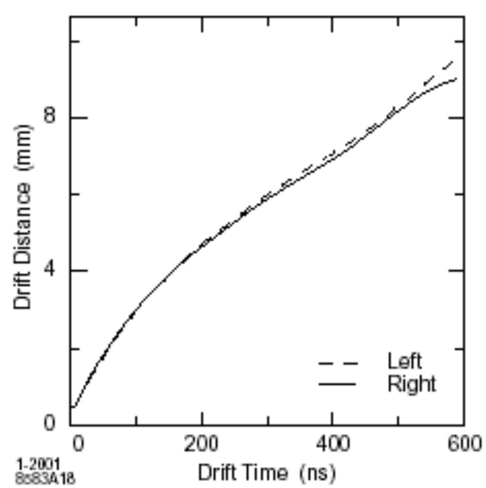


7104 sense wires (20μm diameter)
30gm tension in each wire, sag~200μm
In order to measure “z” (along wire)
some wires are “slanted” at a slight angle
AR/Isobutane gas (80/20%)
HV=~1950V

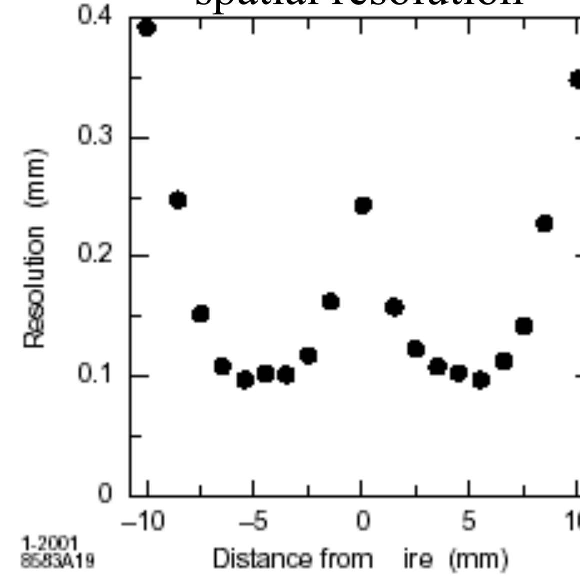


In B=1.5T the ions do not drift straight to the sense wire (anode)

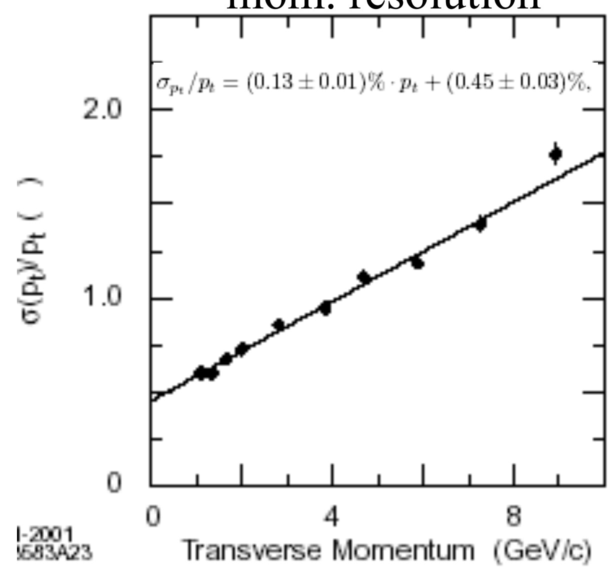
Time to distance relationship complicated!



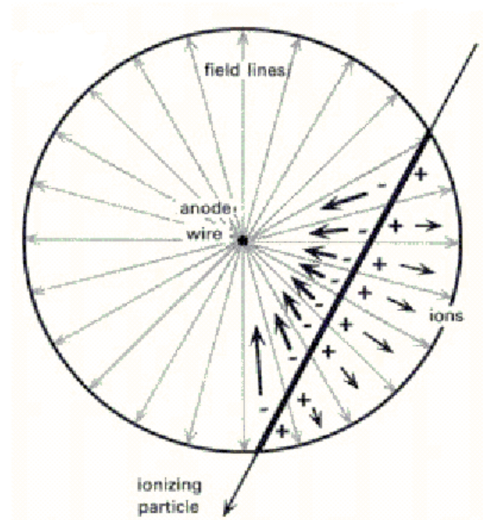
spatial resolution



mom. resolution



Example: ATLAS Muon Drift Tubes



Parameter	Design Value
Gas Mixture	Ar / N_2 / CH_4
	91%/ 4%/ 5%
Gas Pressure	3bar absolute
Track ionisation	330/cm
Gas gain	2×10^4
Wire potential	3270V
Electric Field at the wire	205×10^3V/cm
Electric Field at the wall	340V/cm
Maximum Drift time	500ns
Average drift velocity	30μm/ns
Resolution	80 μm

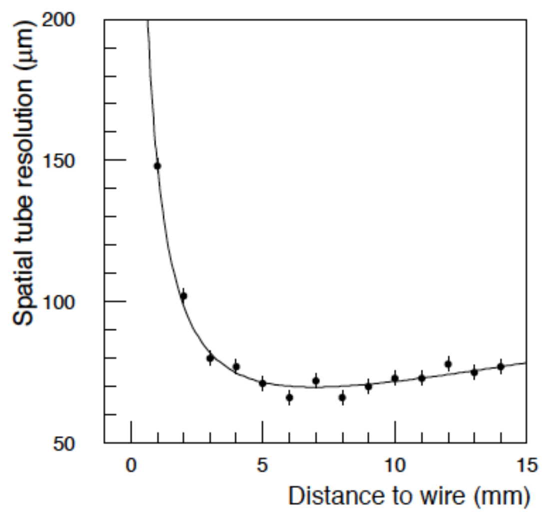


Figure 6-18 Spatial resolution of a single drift tube as a function of the track distance from the wire.

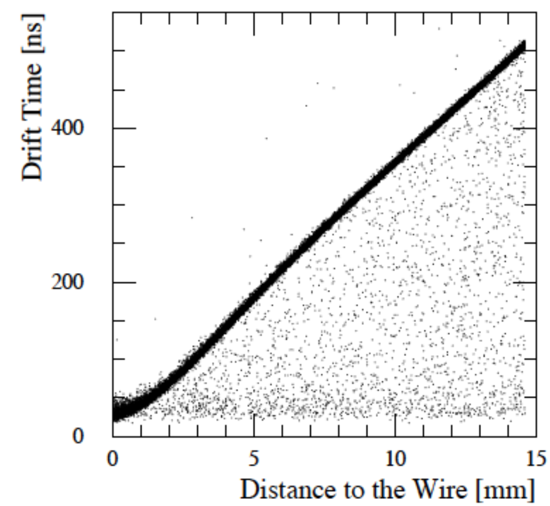
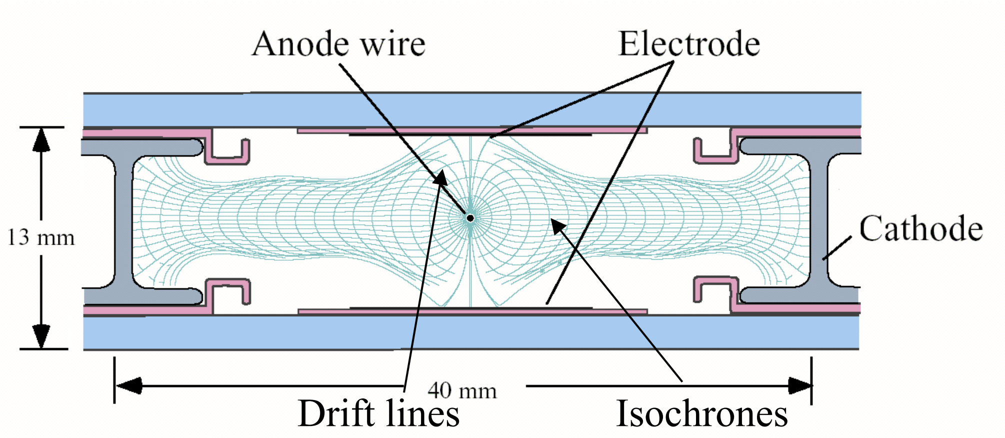


Figure 6-19 r-t relationship for the gas mixture Ar (91)/N_2 (4)/CH_4 (5). The background below the main band is due to Delta rays.

More Complex Geometry: CMS Muon DTs

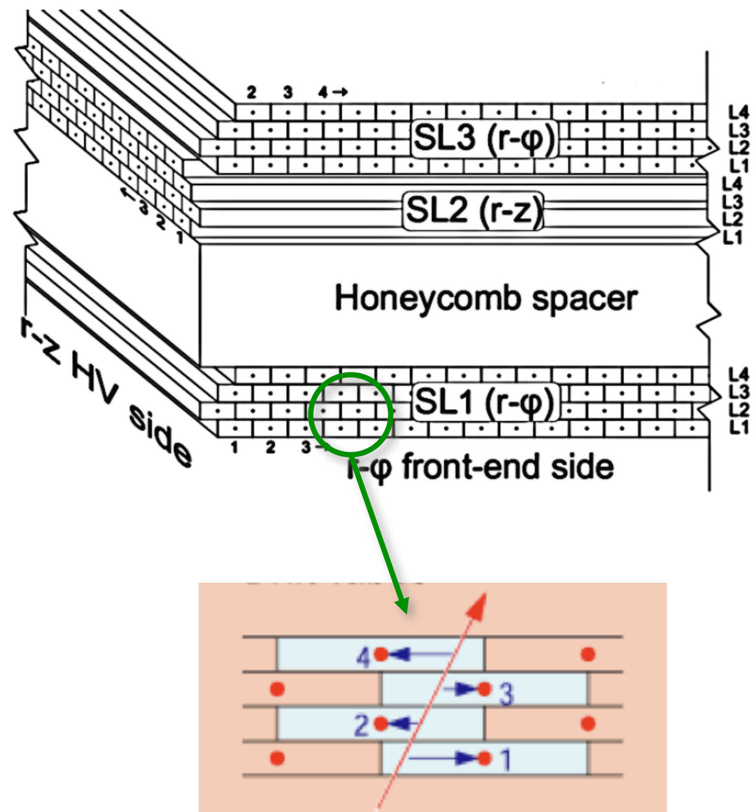
- Additional field shaping electrodes ensure a linear space-time relationship:



- Operating parameters:

Gas Mixture	Ar/CO_2 (85%/15%)
Wire voltage	+3600
Electrode strip voltage	+1800
Cathode strip voltage	-1200
Gain	$9x10^4$

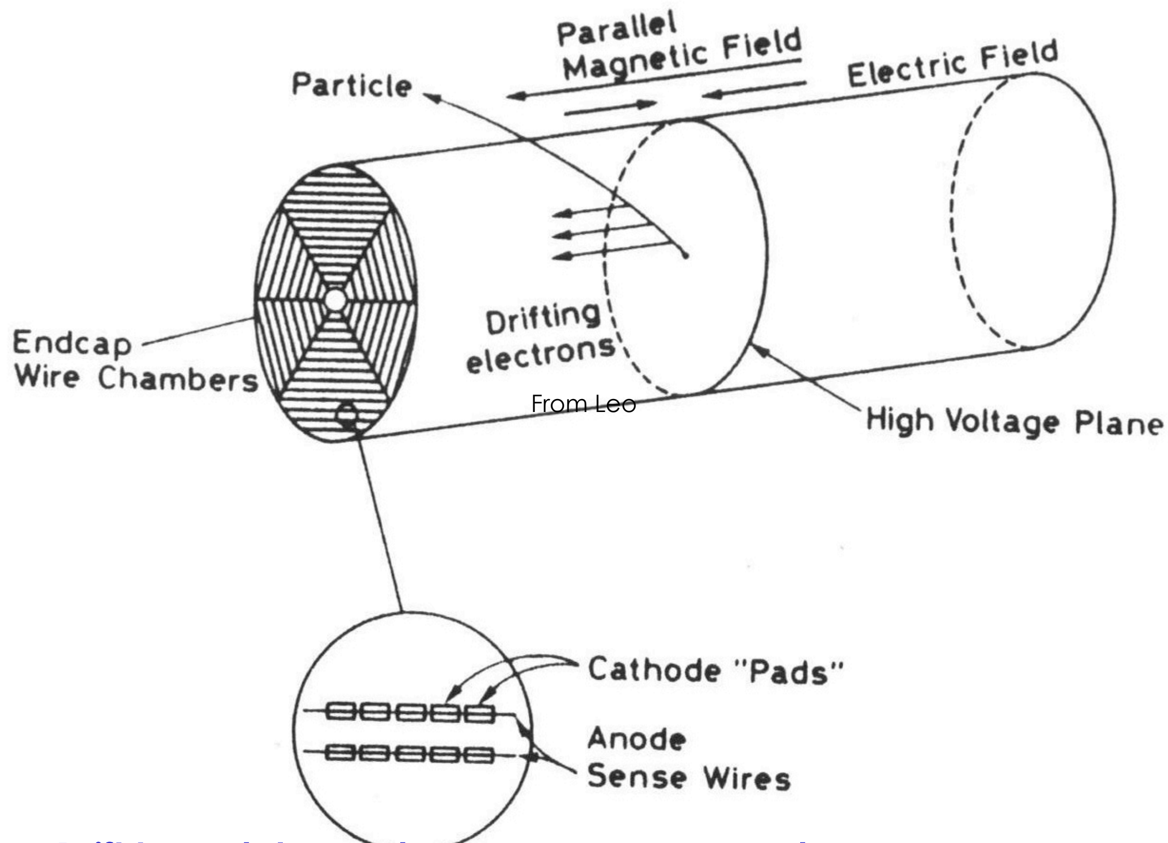
- Alternating layers oriented perpendicular to each other give measurement in 2 dimensions



Time Projection Chamber

- The most sophisticated gas position detector is the Time Projection Chamber or TPC: a 3D tracking detector capable of providing information on many points of a particle track along with information on the specific energy loss, dE/dx, of the particle.

- The TPC makes use of ideas from both the MWPC and drift chamber.
- The detector is a essentially a large gas-filled cylinder with a thin high voltage electrode at the center. (At high energy colliders, the diameter and length of the cylinder can be as large as two meters).
- When voltage is applied, a uniform electric field directed along the axis is created. A parallel magnetic field is also applied.
- The ends of the cylinder are covered by sector arrays of proportional anode wires arranged as shown. Parallel to each wire is a cathode strip cut up into rectangular segments. These segments are also known as cathode pads.



Drift to endplace where x,y are measured

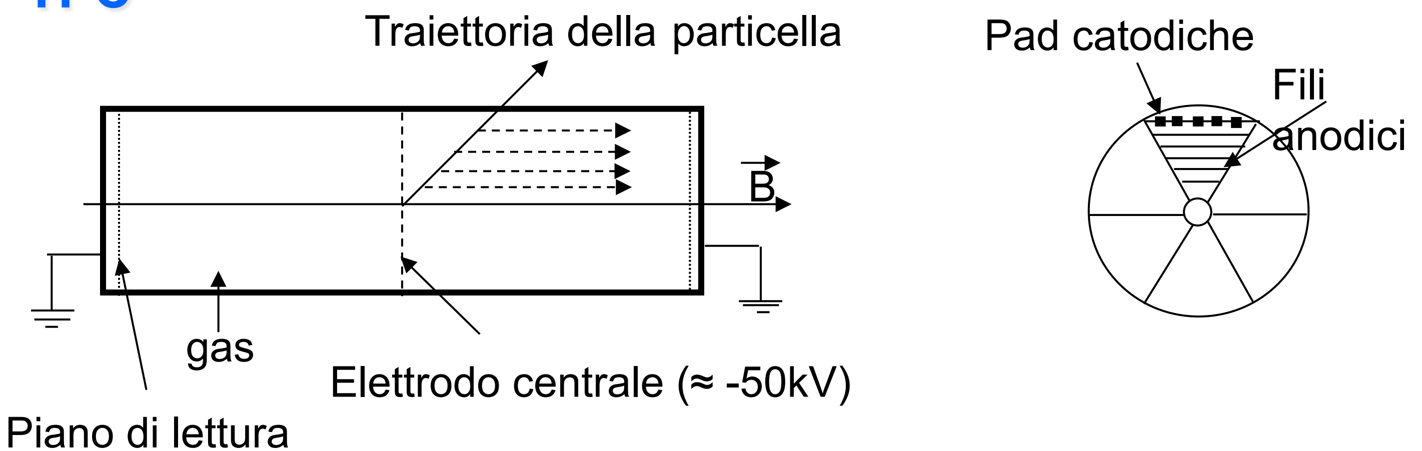
Drift-time provides z

Analogue readout provide dE/dx

Magnetic field provide p (and reduce transverse diffusion during drift)

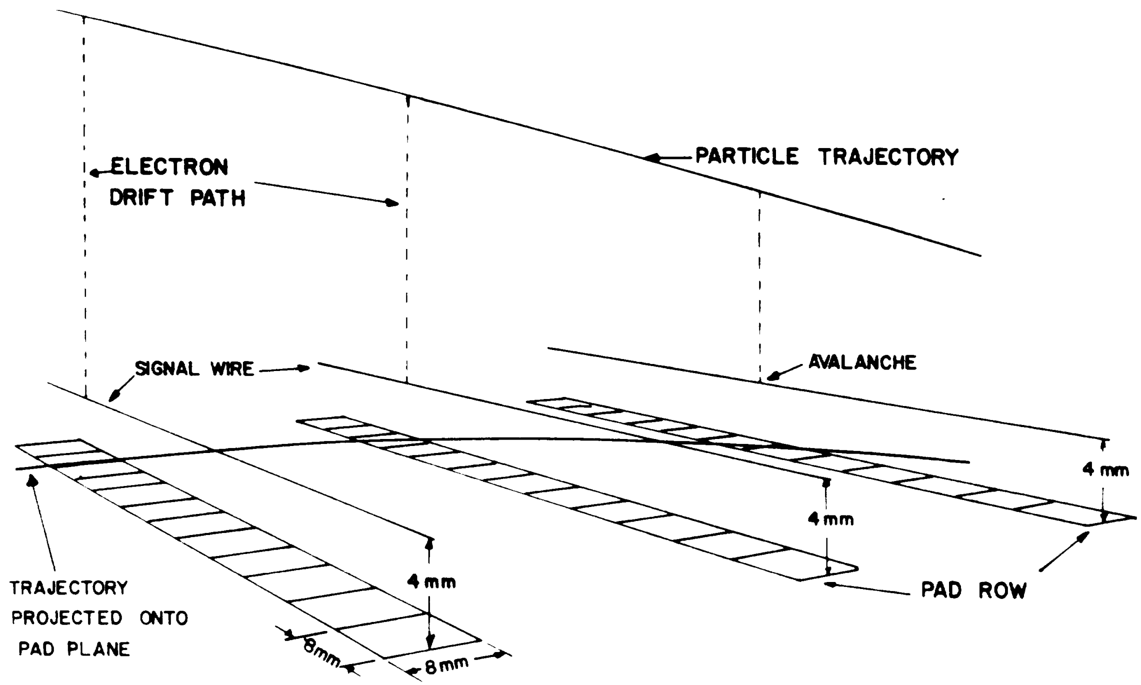
TPC

TPC



- La camera è divisa in 2 metà tramite un elettrodo centrale
- Gli elettroni di ionizzazione primaria si muovono nel campo elettrico verso le placche finali della camera (normalmente delle MWPC). Campo magnetico // al campo elettrico. La diffusione ortogonale al campo è soppressa dal campo B.
- Il tempo di arrivo degli elettroni sulle placche finali fornisce la coordinata lungo l'asse del cilindro (z). La moltiplicazione degli elettroni avviene vicino agli anodi. x e y si ottengono dagli anodi e dal catodo della MWPC suddiviso normalmente in pad.

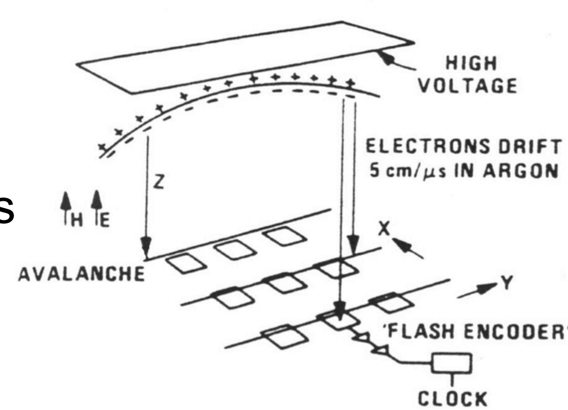
Time Projection Chamber



TPC

- At a colliders, the detector is positioned so that its center is at the interaction point. The TPC thus subtends a solid angle close to 4π. Particles from IP pass through the cylinder volume producing free e- which drift to the endcaps where they are detected by the anode wires as in a MWPC.
- This yields the position of a space point projected onto the endcap plane. One coordinate is given by the position of the firing anode wire while the 2nd is obtained from the signals induced on the row of cathode pads along the anode wire. Using the center-of-gravity method, this locates the position of the avalanche along the firing anode wire.
- The third coordinate, along the cylinder axis, is given by the drift time of the ionization e-. Since all ionization electrons created in the sensitive volume of the TPC will drift towards the endcap, each anode wire over which the particle trajectory crosses will sample that portion of the track. This yields many space points for each track allowing a full reconstruction of the particle trajectory.

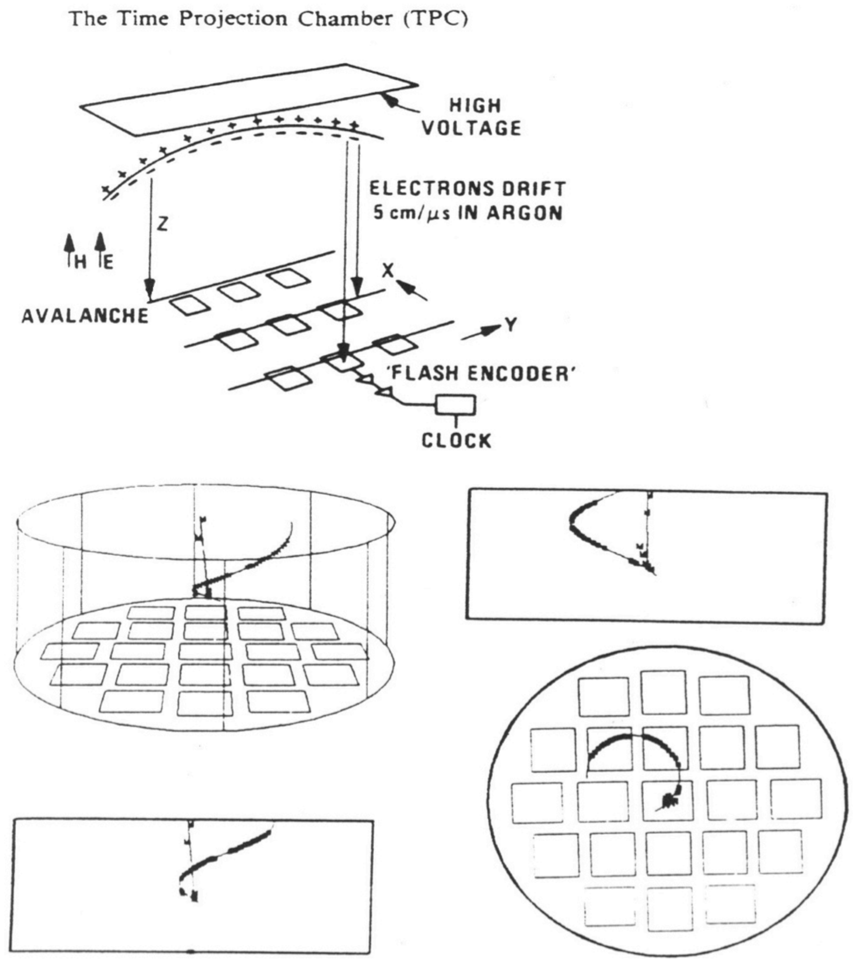
The Time Projection Chamber (TPC)



From Leo

TPC

- Because of the relatively long drift distance, diffusion, particularly in the lateral direction, becomes a problem.
- B field confines the e- to helical trajectories about the drift direction. This reduce diffusion by as much as a factor of 10.
- In order to avoid deviating the trajectories of the drifting e-, the B and E fields must be in perfect alignment and uniform over the volume of the drift zone down to about one part in 10^4.



TPC

La **TPC** permette di determinare un punto nello spazio (x,y,z ovvero r,ϕ,z).
Il segnale analogico sull'anodo fornisce dE/dx.
E//B ➔ angolo di Lorentz = 0 e la velocità di deriva è quindi parallela sia al campo elettrico che magnetico.

Il campo magnetico sopprime la diffusione $\perp$ al campo (Gli elettroni spiralizzano attorno a B.) Per E~ 50KV/m e B ~1.5 T ➔ raggi di Larmor ~1 μm

Richieste:

i. Per misurare bene la coordinata z bisogna conoscere perfettamente la v_D ➔ calibrazione tramite laser e correzioni per la pressione e temperatura.
ii. La deriva avviene su lunghe distanze ➔ gas molto puro e sempre monitorato.
iii. Poco materiale (solo gas) ➔ minimizzo lo scattering multiplo e la conversione dei fotoni.

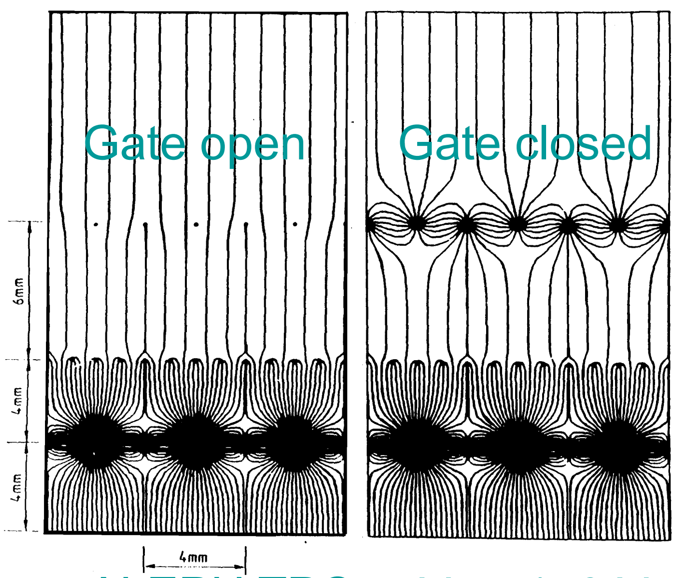
Esempi:

PEP-4 TPC p=8.5 atmosfere, Ar=80%, CH4=20% V_{centr}=-55kV B=1.325T lunga 2m e con raggio 1m.

Aleph TPC lunga 4.4 m e diametro 3.6 m, risoluzione $\sigma_{r\phi}$=173μm, σ_z=740 μm per leptoni isolati.

TPC

Molti ioni positivi creati nella zona di moltiplicazione vicino agli anodi della MWPC che possono andare fino all'elettrodo centrale ➔ carica spaziale che deteriora il campo ➔ si introduce una griglia (gate)

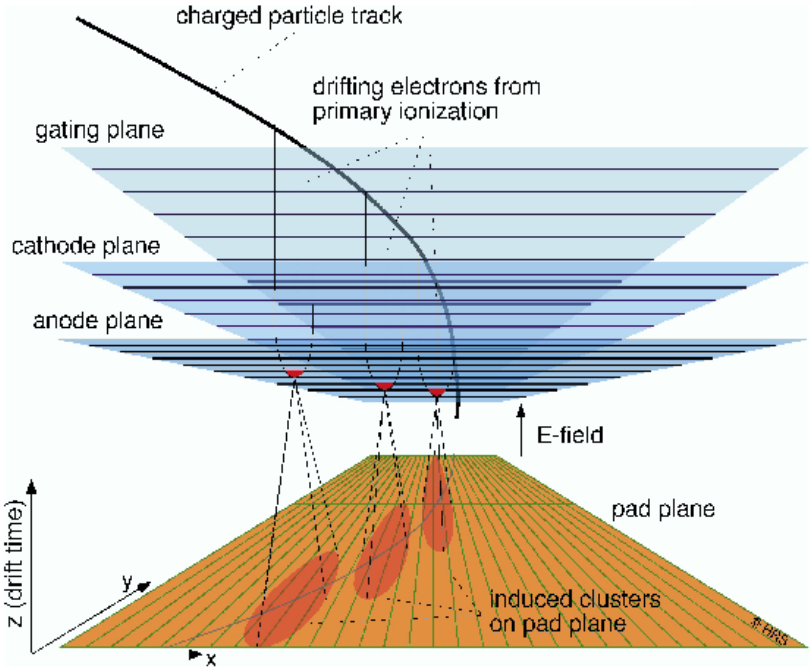


ALEPH TPC $\Delta V_g = 150$ V

(ALEPH coll., NIM A 294 (1990) 121,
W. Atwood et. Al, NIM A 306 (1991) 446)

Il gate è normalmente chiuso, viene aperto solo per un breve tempo quando un trigger esterno segnala un evento interessante → passano gli elettroni. Viene chiuso di nuovo per impedire agli ioni di tornare verso l'elettrodo centrale.

TPC



- A problem which arises during operation is the accumulation of a space charge in the drift volume due to positive ions from avalanches drifting back towards the central cathode. These ions are sufficiently numerous that a distortion of the electric field in the drifting volume occurs.

- This is prevented by placing a grid at ground potential just before the anode wires. Positive Ions are then captured at this grid rather than drifting back into the sensitive volume. The grid also serves to separate the drift region from the avalanche zone and allows an independent control of each.

TPC

- Since the Q collected at the endcaps is $\propto$ the energy loss of the particle, the signal amplitudes from the anode also provide information on the dE/dx of the particle. If p is known from the curvature of its trajectory in the B field, for example, then this information can be used to identify the particle In order for this method to work, however, sufficient resolution in the dE/dx measurement must be obtained. This is much more difficult to realize as many factors must be considered, e.g., electron loss due to attachment, wire gain variations in position and time, calibration of the wires, saturation effects, choice of gas and operating pressure, etc.,. all of which require careful thought!
- Because of the very large amount of data produced for each event, an important consideration is the readout and data acquisition system for a TPC An approach which has been used to use flash ADCs directly coupled to the sense wires. These ADCs are sufficiently fast such that several wires can be multiplexed into one ADC.

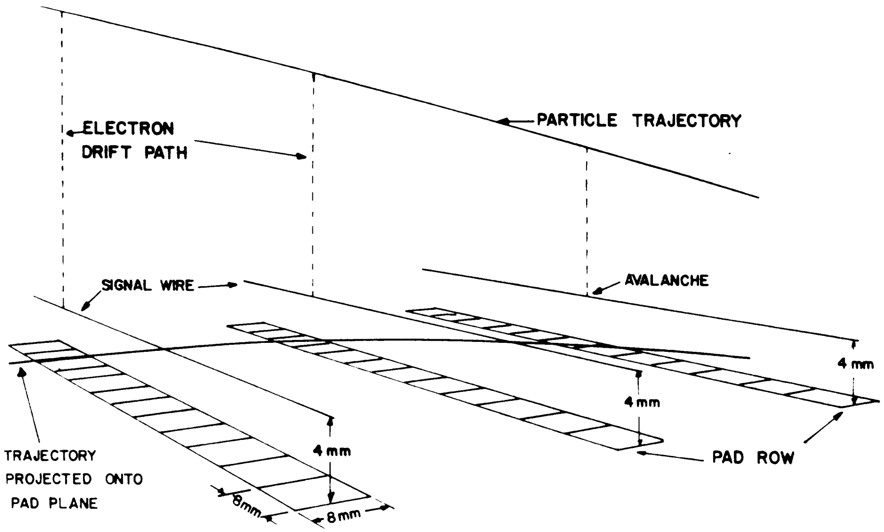
Time Projection Chamber

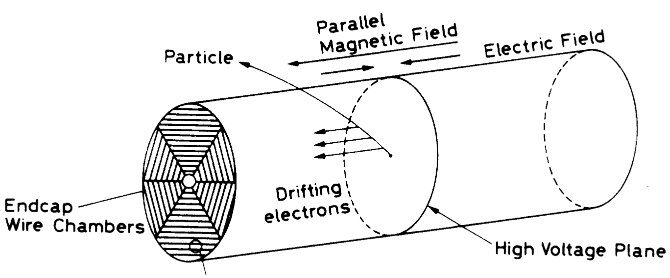
TPC measures all 3 space coordinates

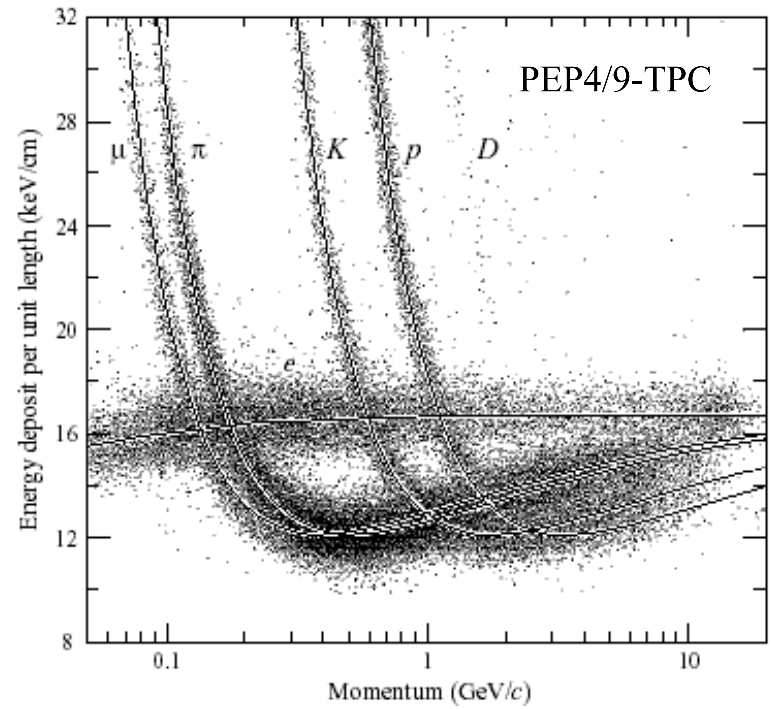
$\sigma_x = \sigma_y \sim 0.1\text{-}0.2$ mm (drift time), $\sigma_z \sim 0.2\text{-}1$mm (readout pad size)

Used at LEP, RHIC

Many hits per track (>100) ⇒ excellent dE/dx measurement







Drawbacks:

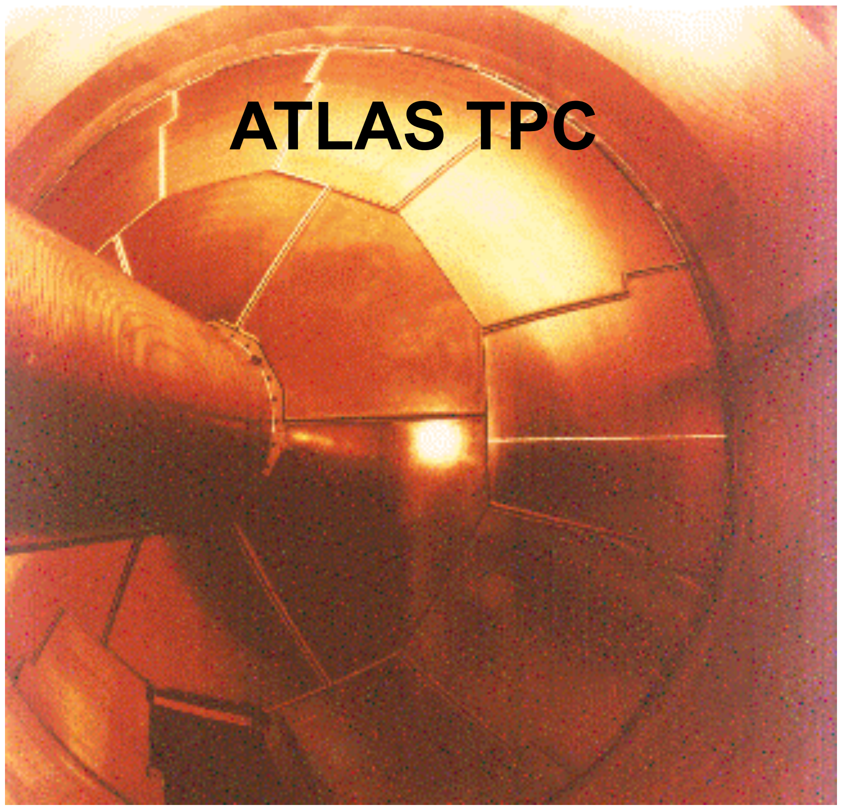
Very complicated electric field shaping: **E**||**B** to reduce effects of diffusion

Long drift times ⇒ complicated gas system

Lots of electronic channels ⇒ complicated electronics

Time Projection Chambers

- Note that the electric and magnetic fields are parallel and must be very homogeneous to permit accurate reconstruction. Laser "tracks" are used for calibration and alignment but extracting good calibration constants is tricky.
- Diffusion of the drifting electrons would normally smear out the measured track but the magnetic field limits this by causing the electrons to spiral in the drift direction



ATLAS TPC