

# Grundlagen der Teilchendetektoren

Werner Riegler, Sommersemester 2008

- ◆ **Geschichte der Instrumentierung – Teilchenphysik**
- ◆ **Grundlagen - ‘die Welt der Elementarteilchen’**
- ◆ **ElektroMagnetische Wechselwirkung geladener Teilchen mit Materie**
- ◆ **Detektoren basierend auf Nachweis angeregter Zustände**
- ◆ **Detektoren basierend auf Nachweis von Ionisationsladung, Spurdetektoren (Gasdetektoren, Festkörperdetektoren)**

# Creation of the Signal

The charged particles traversing matter leave excited atoms, ionization electrons/holes and ions behind.

## Excitation:

The photons emitted by the excited atoms can be detected with photon detectors like photomultipliers or semiconductor photon detectors.

## Ionization:

By applying an electric field in the detector volume, the ionization electrons and ions are moving, which induces signals on metal electrodes. These signals are then read out by appropriate readout electronics.

## Detektoren basierend auf Nachweis angeregter Zustände → Szintillatoren:

- Prompte Photonenemission von Zuständen, welche durch Wechselwirkung mit geladenen Teilchen (Energieverlust) angeregt wurden, typischerweise UV bis sichtbares Licht.
  - a) Beobachtet in Edelgasen (auch verflüssigt !)
  - b) Inorganischen Kristallen, mit oder ohne Aktivierungsstörstellen
  - c) Polyzyklischen Kohlenwasserstoffen (Naphtalen, Anthrazen, organische Szintillatoren)
- ad b) Substanzen mit grösster Lichtausbeute, verwendet zur Präzisionsmessung energetischer Photonen. Anwendung auch z. B. in Nuklearmedizin
- ad c) Bedeutendste Kategorie. industriell tonnenweise hergestellt, mechanisch und chemisch relativ widerstandsfähig. Charakteristisch sind zwei oder mehrere Abklingkonstanten der Lichtemission.

Charakteristisch ist für (fast) alle Szintillatoren, daß die Lichtausbeute von der Energieverlustdichte abhängig ist: Sättigung der Lichtausbeute (Birk'sches Gesetz)

$$\frac{d\text{Licht}}{dx} \left( \text{oder } \frac{dQ}{dx} \right) \propto \frac{dE/dx}{1 + \beta \cdot dE/dx} \quad \begin{array}{l} \beta = 0 \quad \text{keine Sättigung} \\ \beta = 10^{-2} \dots 10^{-4} \propto (\text{Dichte } \rho)^3 \end{array}$$

## Typische Lichtausbeute von Szintillatoren

Energie (sichtbare Photonen)  $\approx$  einige % des totalen Energieverlustes.  
 z.B. 1cm Plastikszintillator,  $\rho \approx 1$ ,  $dE/dx=1.5$  MeV,  $\sim 15$  keV in Photonen; i.e.  $\sim 15$  000 Photonen erzeugt.

### Organisch

Type	Light <sup>a</sup> output	$\lambda_{\text{max}}^b$ (nm)	Attenuation <sup>c</sup> length (cm)	Risetime (ns)	Decay <sup>d</sup> time (ns)	Pulse FWHM (ns)
NE 102A	58-70	423	250	0.9	2.2-2.5	2.7-3.2
NE 104	68	406	120	0.6-0.7	1.7-2.0	2.2-2.5
NE 104B	59	406	120	1	3.0	3
NE 110	60	434	400	1.0	2.9-3.3	4.2
NE 111	40-55	375	8	0.13-0.4	1.3-1.7	1.2-1.6
NE 114	42-50	434	350-400	$\sim 1.0$	4.0	5.3
Pilot B	60-68	408	125	0.7	1.6-1.9	2.4-2.7
Pilot F	64	425	300	0.9	2.1	3.0-3.3
Pilot U	58-67	391	100-140	0.5	1.4-1.5	1.2-1.9
BC 404	68	408	—	0.7	1.8	2.2
BC 408	64	425	—	0.9	2.1	$\sim 2.5$
BC 420	64	391	—	0.5	1.5	1.3
ND 100	60	434	400	—	3.3	3.3
ND 120	65	423	250	—	2.4	2.7
ND 160	68	408	125	—	1.8	2.7

### Anorganisch

	Relative light output	$\lambda_{\text{max}}$ emission (nm)	Decay time (ns)	Density (g/cm <sup>3</sup> )
<i>Inorganic crystals</i>				
NaI(Tl)	230	415	230	3.67
CsI(Tl)	250	560	900	4.51
Bi <sub>4</sub> Ge <sub>3</sub> O <sub>12</sub> (BGO)	23-86	480	300	7.13
<i>Organic crystals</i>				
Anthracene	100	448	22	1.25
Trans-stilbene	75	384	4.5	1.16
Naphthalene	32	330-348	76-96	1.03
<i>p,p'</i> -Quaraterphenyl	94	437	7.5	1.20
<i>Primary activators</i>				
2,5-Diphenyl-oxazole (PPO)	75	360-416	5*	
2-Phenyl-5-(4-biphenyl)-1,3,4-oxadiazole (PBD)	96	360-5		
4,4"-Bis(2-butyl-octyloxy)- <i>p</i> -quaterphenyl (BIBUQ)	60	365,393	1.30*	

LEP bunchcrossing 25 $\mu$ s, LHC bunchcrossing 25ns

Die experimentelle, vielseitige Anwendung von Szintillatoren beruht zum Teil auf:  
 guten und relativ billigen Möglichkeiten des Lichtnachweises  
 ("Photovervielfacher,, oder ,englisch, Photomultipliers) dem schnellen  
 Zeitverhalten (1 bis 100 ns) der Szintillatoren.

### Schematischer Aufbau eines Photomultipliers:

- Typische Ladungsverstärkung (als Funktion der Hochspannung) :  $10^8$  bis  $10^{10}$
- Typische Effizienz für Photonennachweis: < 20%
- Bei sehr guten PMs : Nachweis einzelner Photonen möglich
- Signal Beispiel: 10 primäre Elektronen, Verstärkung  $10^7 \rightarrow 10^8$  Elektronen am Ausgang, in  $T \approx 10\text{ns}$ .  $I=Q/T = 10^8 \cdot 1.603 \cdot 10^{-19} / 10 \cdot 10^{-9} = 1.6\text{mA}$ .
- Durch  $50 \Omega \rightarrow U=R \cdot I = 80\text{mV}$ .

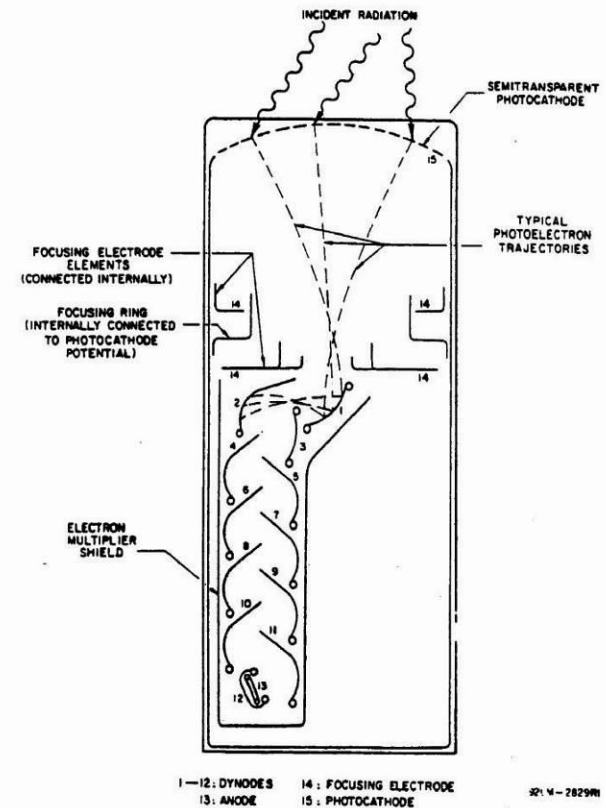
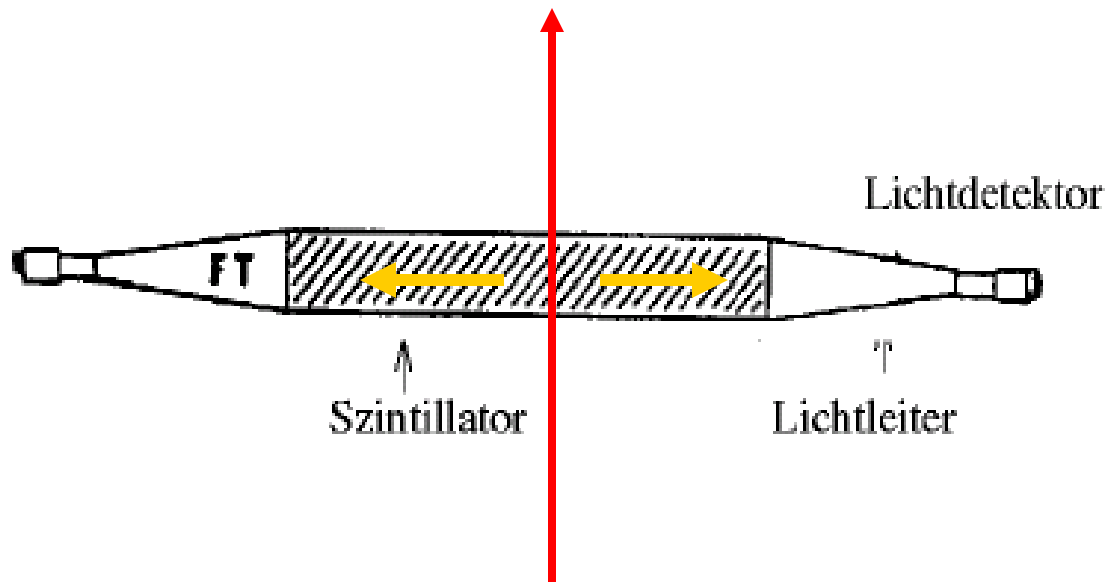


Abbildung 2.13: Schematische Zeichnung eines Photovervielfachers (RCA 8575). Zwischen den Dynoden wird eine Potentialdifferenz angelegt (typisch  $\sim 200\text{V}$ ), wodurch die Elektronen beschleunigt und beim Aufprall auf die Dynode mehrere Elektronen pro einfallendem Elektron erzeugt werden. Typische Verstärkungsfaktoren sind  $\sim 10^8$ , typische Nachweeffizienz von Photonen ist  $\sim 20\%$ . Quelle: Courtesy of RCA, New Products Division, Lancaster, PA.

## Klassischer Aufbau:

Photonen werden innerhalb des Szintillators zu den Enden reflektiert.

Durch Lichtleiter wird das Licht zu Photomultipliern geleitet und dort in ein Elektronisches Signal umgewandelt.



Durch Segmentierung kann Ortsauflösung erreicht werden.

Durch gutes Zeitverhalten kann die Ankunftszeit oder 'Flugzeit von Teilchen sehr genau gemessen werden ( $<1\text{ns}$ )  $\rightarrow$  Trigger.

# Detectors based on Registration of Ionization: Tracking in Gas and Solid State Detectors

Charged particles leave a trail of ions (and excited atoms) along their path:  
Electron-Ion pairs in gases and liquids, electron hole pairs in solids.

The produced charges can be registered → Position measurement → Tracking Detectors.

Cloud Chamber: Charges create drops → photography.

Bubble Chamber: Charges create bubbles → photography.

Emulsion: Charges 'blackened' the film.

Gas and Solid State Detectors: Moving Charges (electric fields) induce electronic signals on metallic electrodes that can be read by dedicated electronics.

→ In solid state detectors the charge created by the incoming particle is sufficient.

→ In gas detectors (e.g. wire chamber) the charges are internally multiplied in order to provide a measurable signal.

# The Principle of Signal Induction by Moving Charges

A point charge  $q$  at a distance  $z_0$  above a grounded metal plate 'induces' a surface charge.

The total induced charge on the surface is  $-q$ .

Different positions of the charge result in different charge distributions.

The total induced charge stays  $-q$ .

The electric field of the charge must be calculated with the boundary condition that the potential  $\phi=0$  at  $z=0$ .

For this specific geometry the method of images can be used. A point charge  $-q$  at distance  $-z_0$  satisfies the boundary condition  $\rightarrow$  electric field.

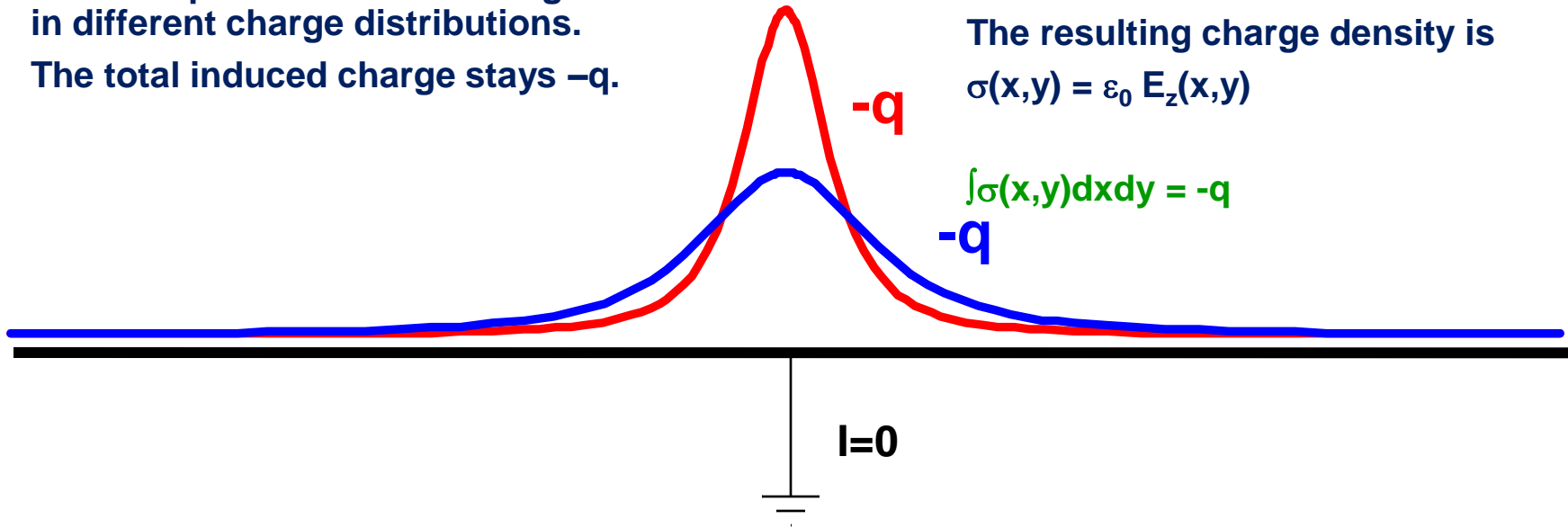
●  $q$

●  $q$

The resulting charge density is

$$\sigma(x,y) = \epsilon_0 E_z(x,y)$$

$$\int \sigma(x,y) dx dy = -q$$



$$E_z(x,y) = -\frac{qz_0}{2\pi\epsilon_0(x^2 + y^2 + z_0^2)^{\frac{3}{2}}}$$

$$E_x = E_y = 0$$

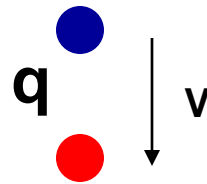
$$\sigma(x,y) = \epsilon_0 E_z(x,y)$$

$$Q = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \sigma(x,y) dx dy = -q$$



# Principle of Signal Induction by Moving Charges

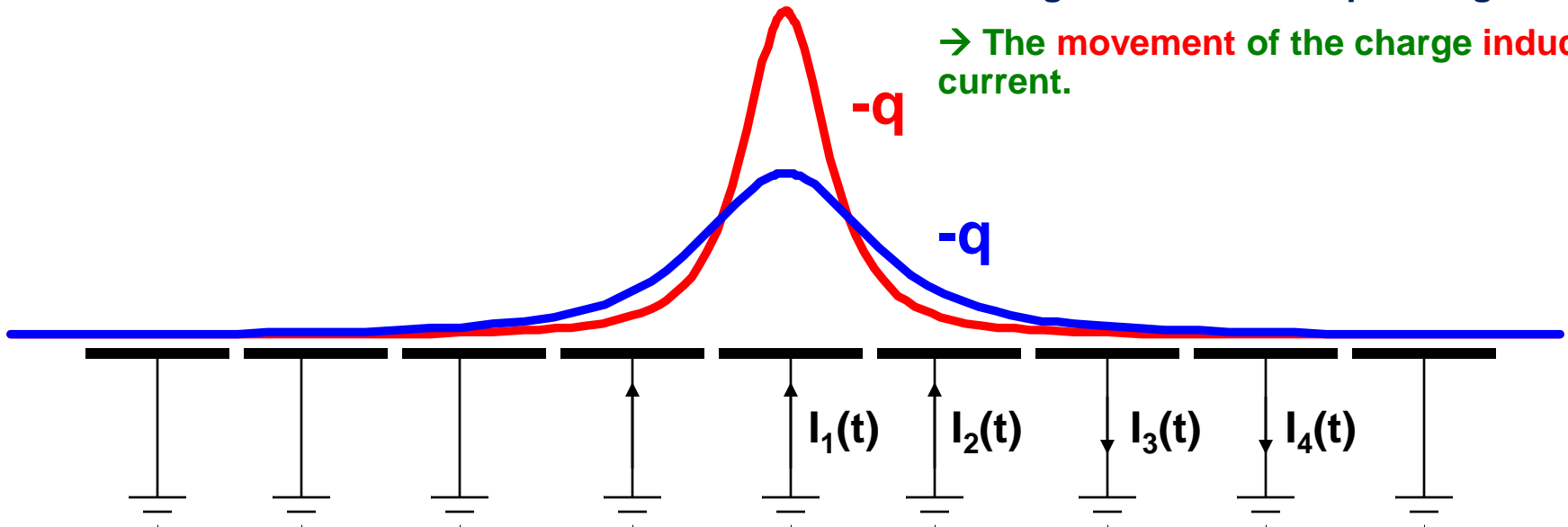
If we segment the grounded metal plate and if we ground the individual strips the surface charge density doesn't change with respect to the continuous metal plate.



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

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

→ The movement of the charge induces a current.



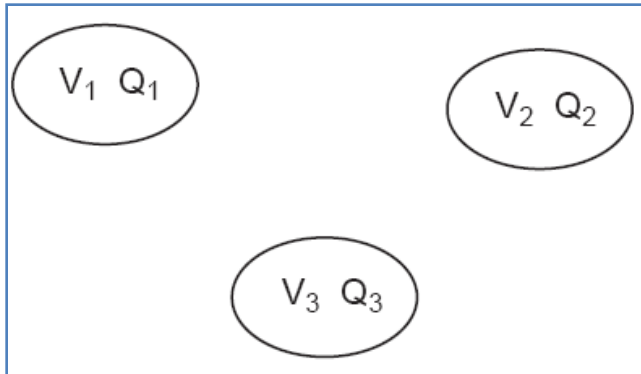
$$Q_1(z_0) = \int_{-\infty}^{\infty} \int_{-w/2}^{w/2} \sigma(x, y) dx dy = -\frac{2q}{\pi} \arctan\left(\frac{w}{2z_0}\right)$$

$$z_0(t) = z_0 - vt$$

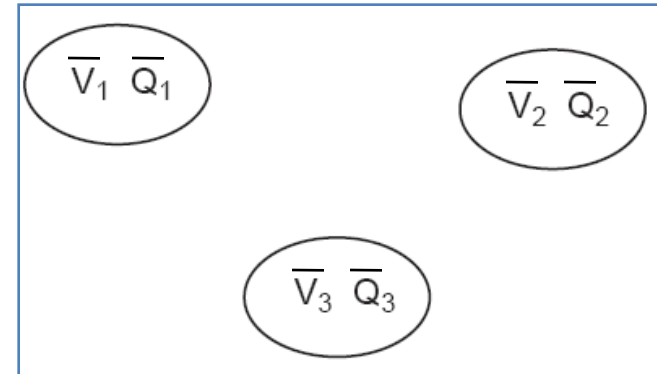
$$I_1^{ind}(t) = -\frac{d}{dt} Q_1[z_0(t)] = -\frac{\partial Q_1[z_0(t)]}{\partial z_0} \frac{dz_0(t)}{dt} = \frac{4qw}{\pi[4z_0(t)^2 + w^2]} v$$

# Signal Theorems

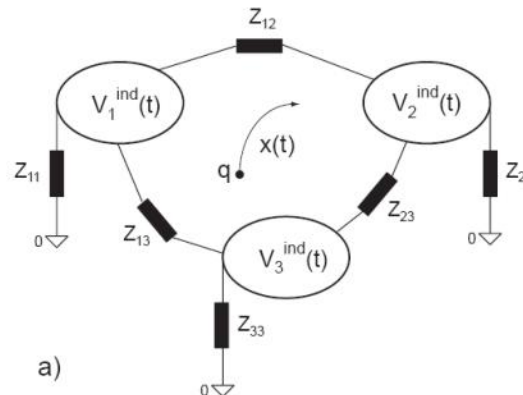
Placing charges on metal electrodes results in certain potentials of these electrodes. A different set of charges results in a different set of potentials. The reciprocity theorem states that



$$\sum_{n=1}^N Q_n \bar{V}_n = \sum_{n=1}^N \bar{Q}_n V_n$$



Using this theorem we can answer the following general question: What are the signals created by a moving charge on metal electrodes that are connected with arbitrary discrete (linear) components ?



# Signal Theorems

What are the charges induced by a moving charge on electrodes that are connected with arbitrary linear impedance elements ?

One first removes all the impedance elements, connects the electrodes to ground and calculates the currents induced by the moving charge on the grounded electrodes.

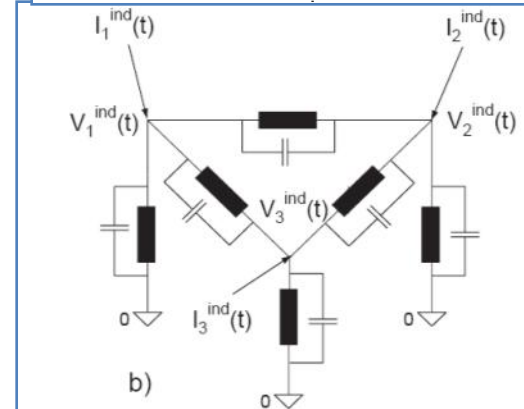
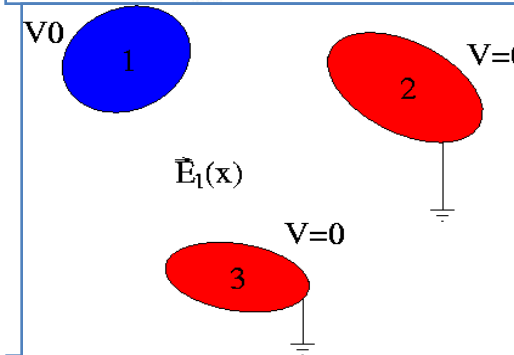
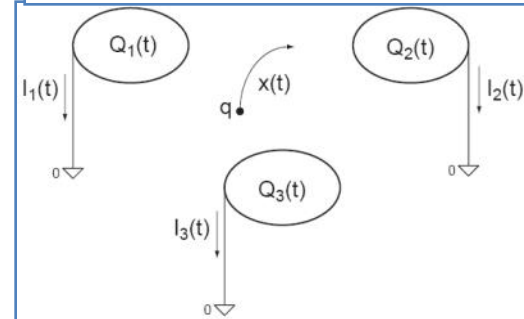
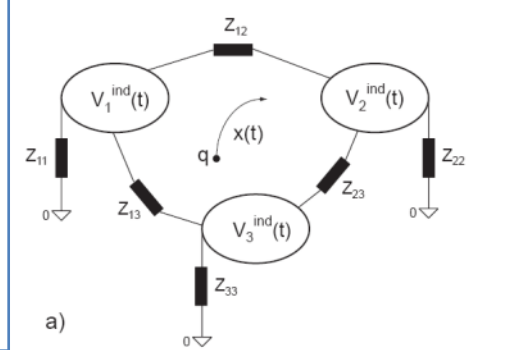
The current induced on a grounded electrode by a charge  $q$  moving along a trajectory  $x(t)$  is calculated the following way (Ramo Theorem):

One removes the charge  $q$  from the setup, puts the electrode to voltage  $V_0$  while keeping all other electrodes grounded. This results in an electric field  $E_n(x)$ , the Weighting Field, in the volume between the electrodes, from which the current is calculated by

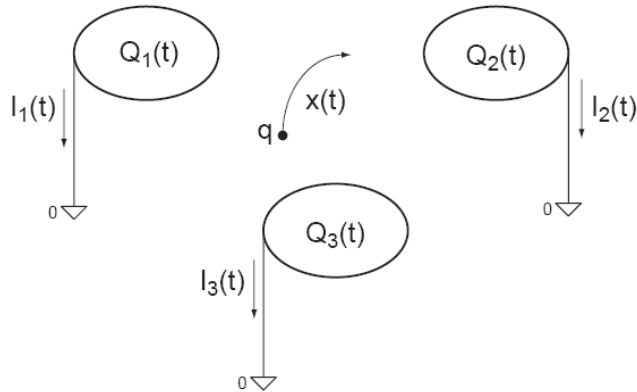
$$I_n(t) = -\frac{q}{V_0} \vec{E}_n[\vec{x}(t)] \frac{d\vec{x}(t)}{dt} = -\frac{q}{V_0} \vec{E}_n[\vec{x}(t)] \vec{v}(t)$$

These currents are then placed as ideal current sources on a circuit where the electrodes are 'shrunk' to simple nodes and the mutual electrode capacitances are added between the nodes. These capacitances are calculated from the weighting fields by

$$c_{nm} = \frac{\epsilon_0}{V_w} \oint_{A_n} \vec{E}_m(x) dA \quad C_{nn} = \sum_m c_{nm} \quad C_{nm} = -c_{nm} \quad n \neq m$$



# Signal Theorems

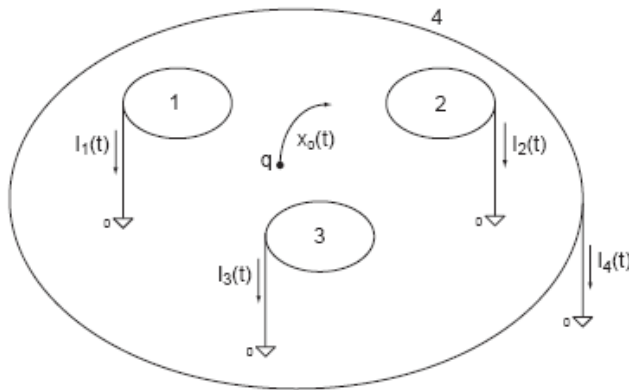


The following relations hold for the induced currents:

1) The charge induced on an electrode in case a charge in between the electrode has moved from a point  $\mathbf{x}_0$  to a point  $\mathbf{x}_1$  is

$$Q_n^{ind} = \int_{t_0}^{t_1} I_n^{ind}(t) dt = -\frac{q}{V_w} \int_{t_0}^{t_1} \mathbf{E}_n[\mathbf{x}(t)] \dot{\mathbf{x}}(t) dt = \frac{q}{V_w} [\psi_n(\mathbf{x}_1) - \psi_n(\mathbf{x}_0)]$$

and is independent on the actual path.



2) Once ALL charges have arrived at the electrodes, the total induced charge in the electrodes is equal to the charge that has ARRIVED at this electrode.

3) In case there is one electrode enclosing all the others, the sum of all induced currents is zero at any time.

# Signals in a Parallel Plate Geometry

E.g.: Elektron-ion pair in gas  
 or Electron-ion pair in a liquid  
 or Electron-hole pair in a solid

$$E_1 = V_0/D$$

$$E_2 = -V_0/D$$

$$I_1 = -(-q)/V_0 * (V_0/D) * v_e - q/V_0 (V_0/D) (-v_i)$$

$$= q/D * v_e + q/D * v_i$$

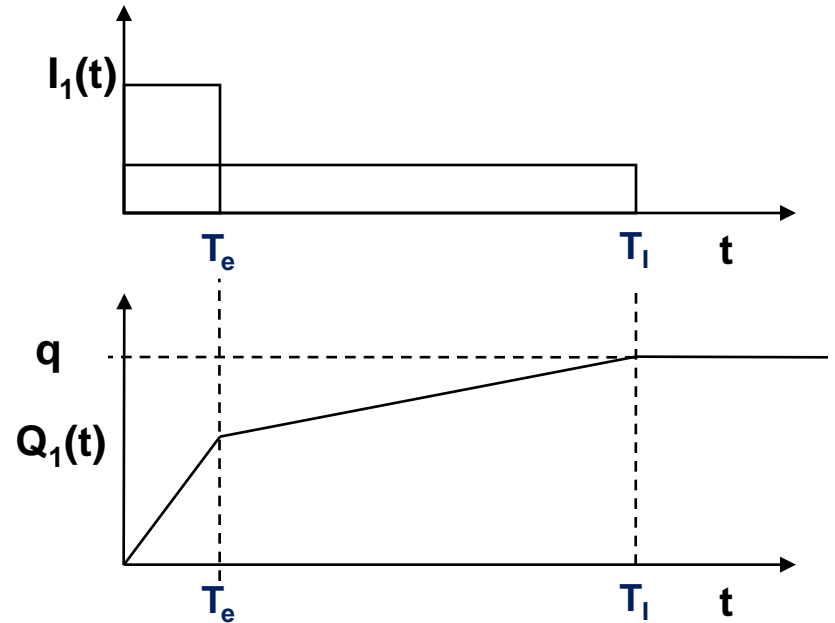
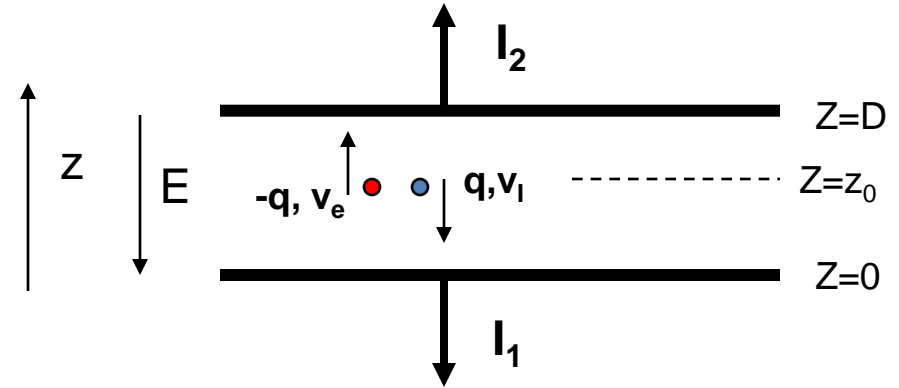
$$I_2 = -I_1$$

$$Q_1^{\text{tot}} = \int I_1 dt = q/D * v_e T_e + q/D * v_i T_i$$

$$= q/D * v_e * (D - z_0)/v_e + q/D * v_i * z_0/v_i$$

$$= q(D - z_0)/D + qz_0/D =$$

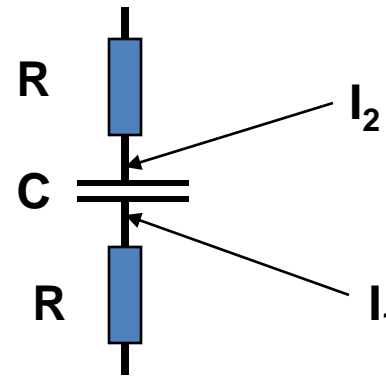
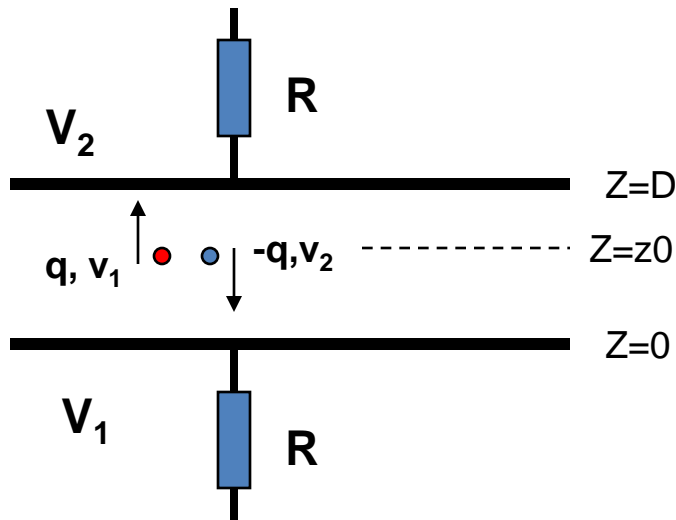
$$q_e + q_i = q$$



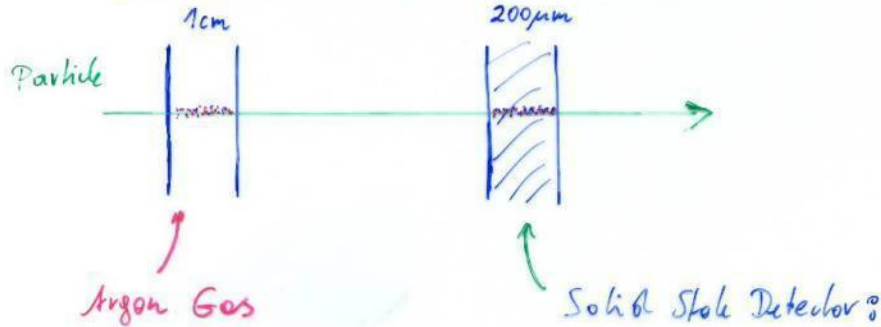
The total induced charge on a specific electrode, once all the charges have arrived at the electrodes, is equal to the charge that has arrived at this specific electrode.

# Signals in a Parallel Plate Geometry

In case the electrodes are not grounded but connected by arbitrary active or passive elements one first calculates the currents induced on the grounded electrodes and places them as ideal current sources on the equivalent circuit of the electrodes.



## Gas Detectors, Solid State Detectors



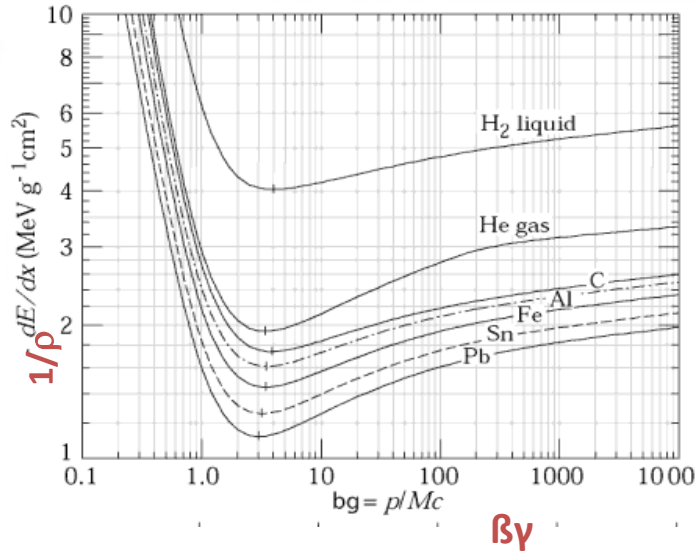
$$\left. \frac{dE}{dx} \right|_{\text{min}} = 1.519 \cdot 1.396 \cdot 10^{-2} \frac{\text{MeV}}{\text{cm}}$$

$$I = 26 \text{ eV} \rightarrow \sim 80 e^- / \text{cm}$$

$$I = 2.9 \text{ eV}$$

$$2.5 \times 10^6 \text{ e/h pairs/cm}$$

$$\left. \frac{dE}{dx} \right|_{\text{min}} = 1.371 \cdot 5.32 \frac{\text{MeV}}{\text{cm}}$$



The induced signals are readout out by dedicated electronics.

The noise of an amplifier determines whether the signal can be registered. **Signal/Noise >>1**

The noise is characterized by the 'Equivalent Noise Charge (ENC)' = Charge signal at the input that produced an output signal equal to the noise.

ENC of very good amplifiers can be as low as 50e-, typical numbers are ~ 1000e-.

In order to register a signal, the registered charge must be  $q \gg \text{ENC}$  i.e. typically  $q \gg 1000e^-$ .

**Gas Detector:  $q=80e^- / \text{cm} \rightarrow$  too small.**

Solid state detectors have 1000x more density and factor 5-10 less ionization energy.  
 $\rightarrow$  Primary charge is  $10^4$ - $10^5$  times larger than is gases.

**Gas detectors need internal amplification in order to be sensitive to single particle tracks.**

Without internal amplification they can only be used for a large number of particles that arrive at the same time (ionization chamber).

# Gas Detectors with internal Electron Multiplication

**Principle:** At sufficiently high electric fields (100kV/cm) the electrons gain energy in excess of the ionization energy → secondary ionization etc. etc.

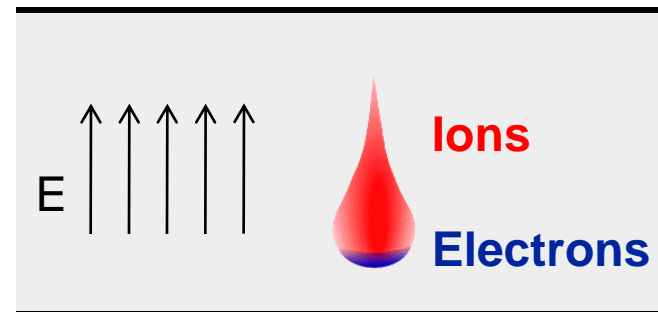
$$dN = N \alpha dx$$

$\alpha$ ...Townsend Coefficient

$$N(x) = N_0 \exp(\alpha x)$$

$N/N_0 = A$  (Amplification, Gas Gain)

**Avalanche in a homogeneous field:**



**In an inhomogeneous Field:**  $\alpha(E) \rightarrow N(x) = N_0 \exp [\int \alpha(E(x')) dx']$



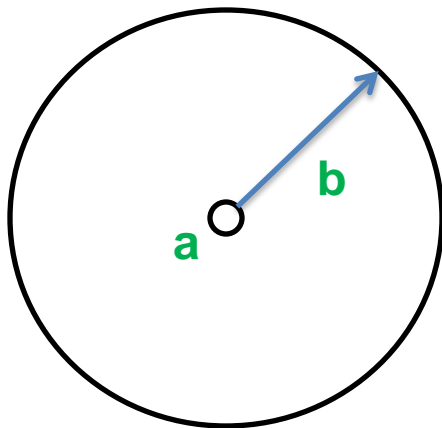
# Wire Chamber: Electron Avalanche

Wire with radius (10-25 $\mu\text{m}$ ) in a tube of radius  $b$  (1-3cm):

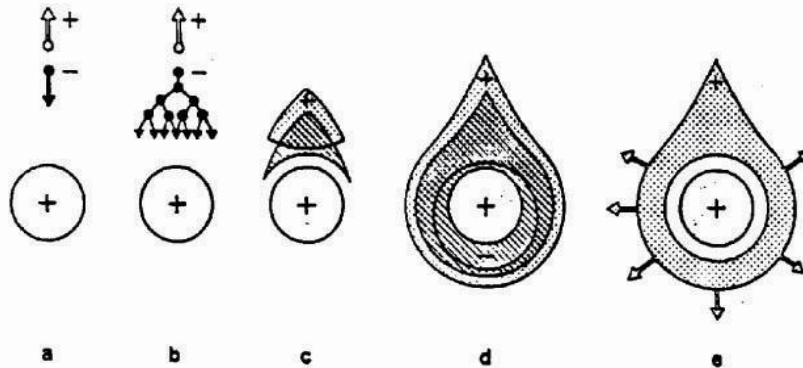
$$E(r) = \frac{\lambda}{2\pi\epsilon_0 r} = \frac{V_0}{\ln \frac{b}{a}} \frac{1}{r}, \quad V(r) = \frac{V_0}{\ln \frac{b}{a}} \ln \frac{r}{a}$$

Electric field close to a thin wire (100-300kV/cm). E.g.  $V_0=1000\text{V}$ ,  $a=10\mu\text{m}$ ,  $b=10\text{mm}$ ,  $E(a)=150\text{kV/cm}$

Electric field is sufficient to accelerate electrons to energies which are sufficient to produce secondary ionization  $\rightarrow$  electron avalanche  $\rightarrow$  signal.



Wire



# Wire Chamber: Electron Avalanches on the Wire

Proportional region:  $A \approx 10^3 - 10^4$

LHC

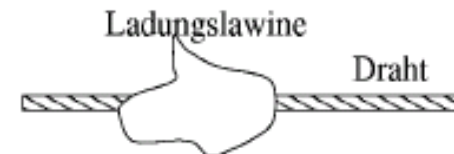


Semi proportional region:  $A \approx 10^4 - 10^5$   
(space charge effect)

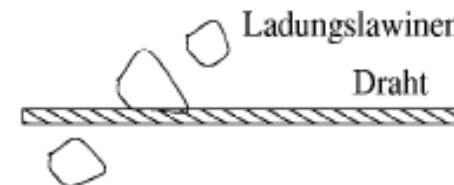


Saturation region:  $A > 10^6$   
Independent the number of primary electrons.

1970ies



Streamer region:  $A > 10^7$   
Avalanche along the particle track.

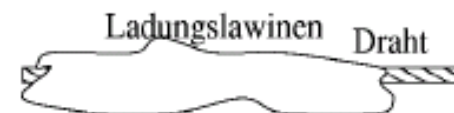


Limited Geiger region:  
Avalanche propagated by UV photons.



Geiger region:  $A \approx 10^9$   
Avalanche along the entire wire.

1950ies

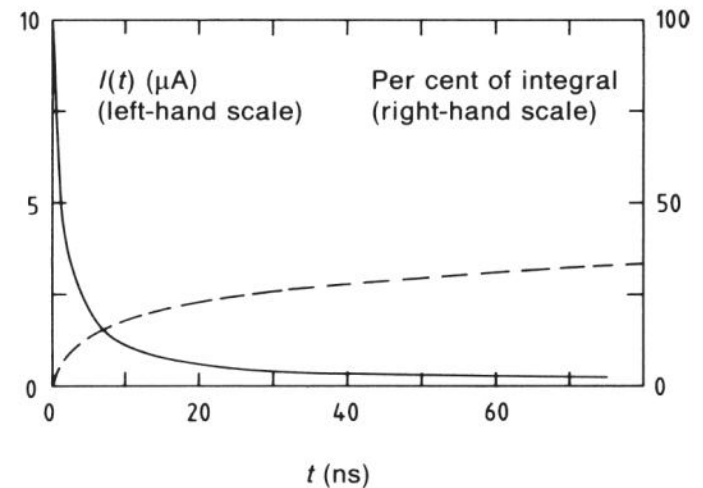
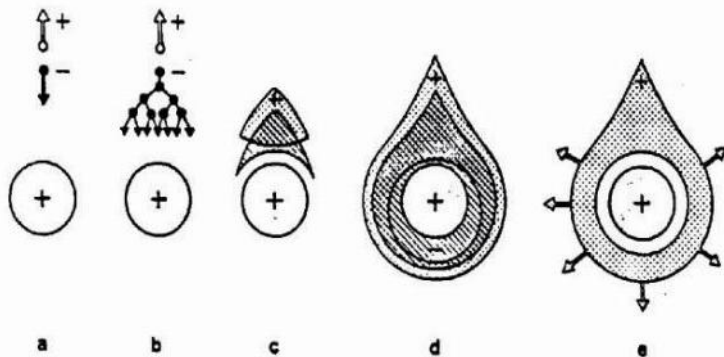


# Wire Chamber: Signals from Electron Avalanches

The electron avalanche happens very close to the wire. First multiplication only around  $R = 2x$  wire radius. Electrons are moving to the wire surface very quickly ( $\ll 1\text{ns}$ ). Ions are drifting towards the tube wall (typically several  $100\mu\text{s}$ .)

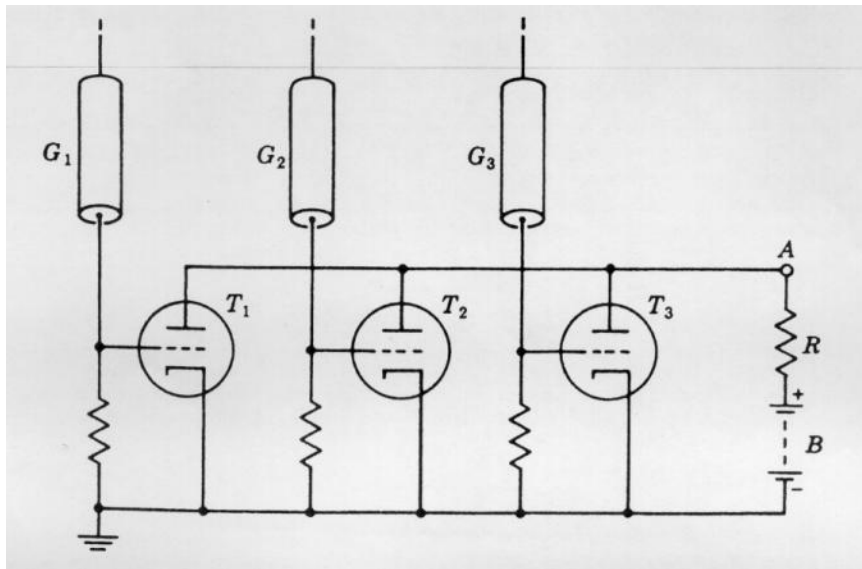
The signal is characterized by a very fast 'spike' from the electrons and a long Ion tail.

The total charge induced by the electrons, i.e. the charge of the current spike due to the short electron movement amounts to 1-2% of the total induced charge.



# Detectors with Electron Multiplication

Rossi 1930: Coincidence circuit for n tubes

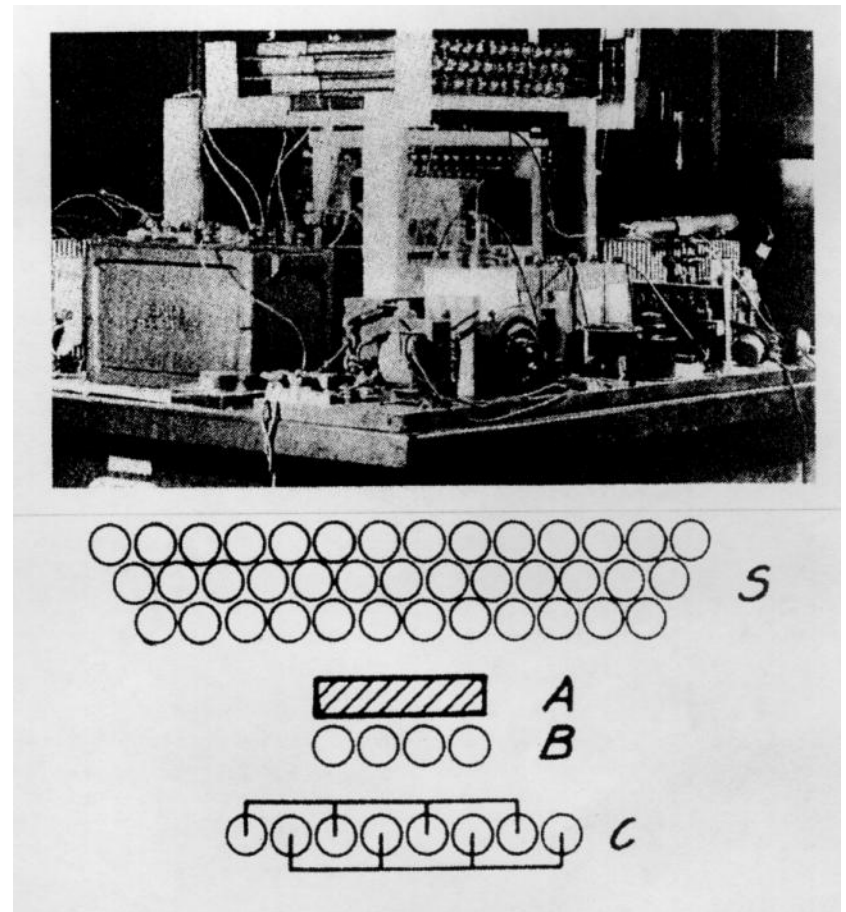


Geiger mode, large deadtime

Position resolution is determined by the size of the tubes.

Signal was directly fed into an electronic tube.

Cosmic ray telescope 1934



# Multi Wire Proportional Chamber

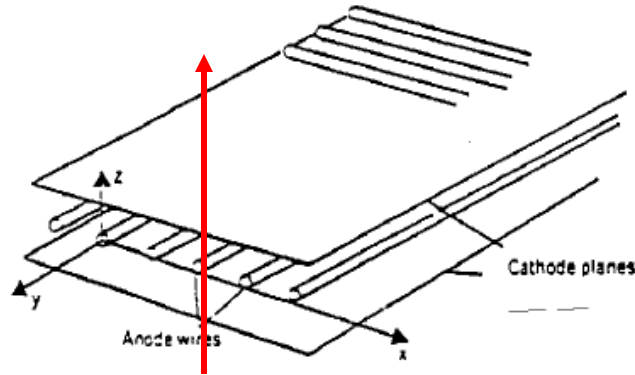
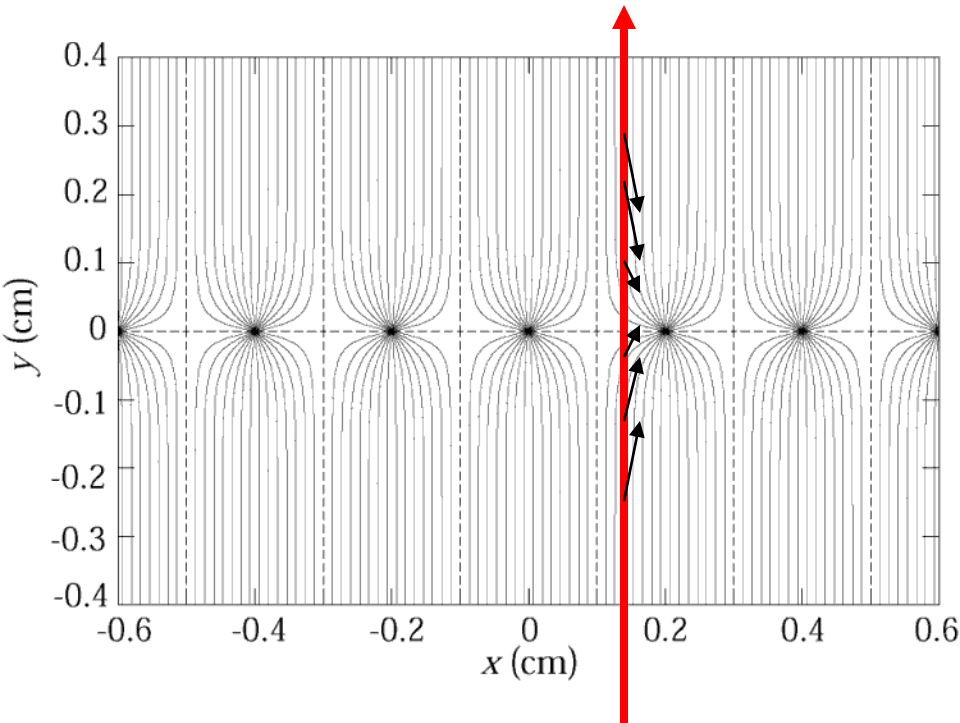


Abbildung 2.27: Vieldrahtproportionalkammer.



**Classic geometry (Crosssection), Charpak 1968 :**

**One plane of thin sense wires is placed between two parallel plates.**

**Typical dimensions:**

**Wire distance 2-5mm, distance between cathode planes ~10mm.**

**Electrons ( $v \approx 5 \text{ cm}/\mu\text{s}$ ) are collected within  $\approx 100 \text{ ns}$ . The ion tail can be eliminated by electronics filters  $\rightarrow$  pulses of  $< 100 \text{ ns}$  length.**

**For 10% occupancy  $\rightarrow$  every  $\mu\text{s}$  one pulse**

**$\rightarrow$  1MHz/wire rate capability !**

**$\rightarrow$  Compare to Bubble Chamber with 10 Hz !**

# Multi Wire Proportional Chamber

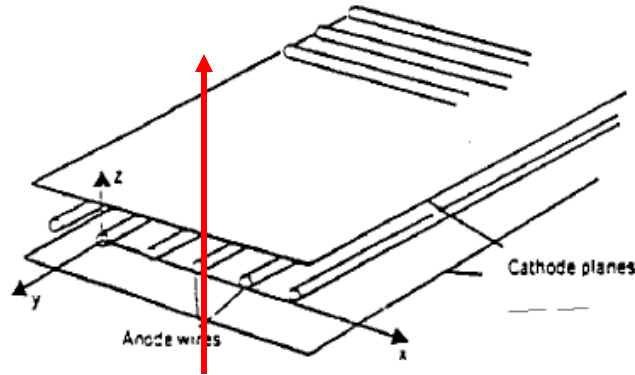
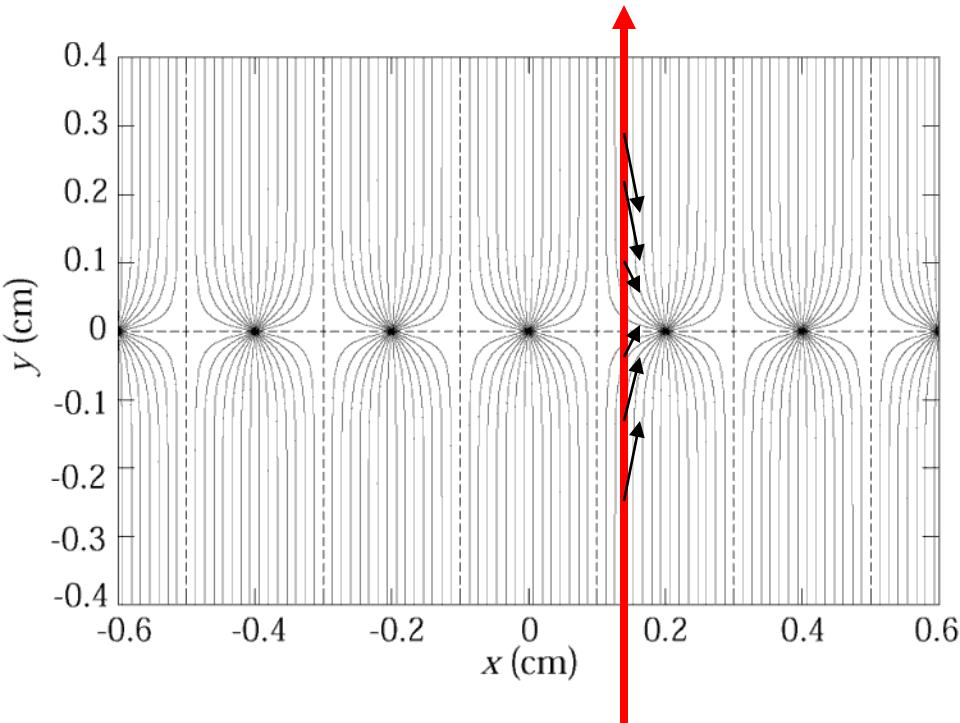


Abbildung 2.27: Vieldrahtproportionalkammer.



In order to eliminate the left/right ambiguities: Shift two wire chambers by half the wire pitch.

For second coordinate:

→ Another chamber at 90° relative rotation

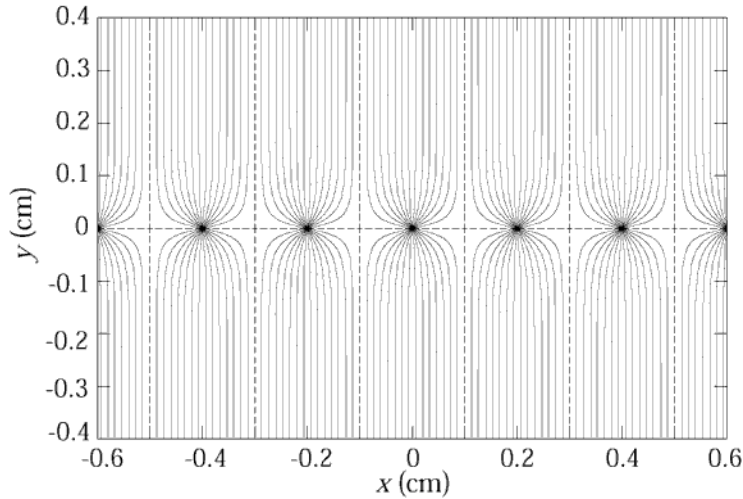
→ Signal propagation to the two ends of the wire.

→ Pulse height measurement on both ends of the wire. Because of resistivity of the wire, both ends see different charge.

Segmenting of the cathode into strips or pads:

The movement of the charges induces a signal on the wire AND on the cathode. By segmentation of the cathode plane and charge interpolation, resolutions of 50 $\mu$ m can be achieved.

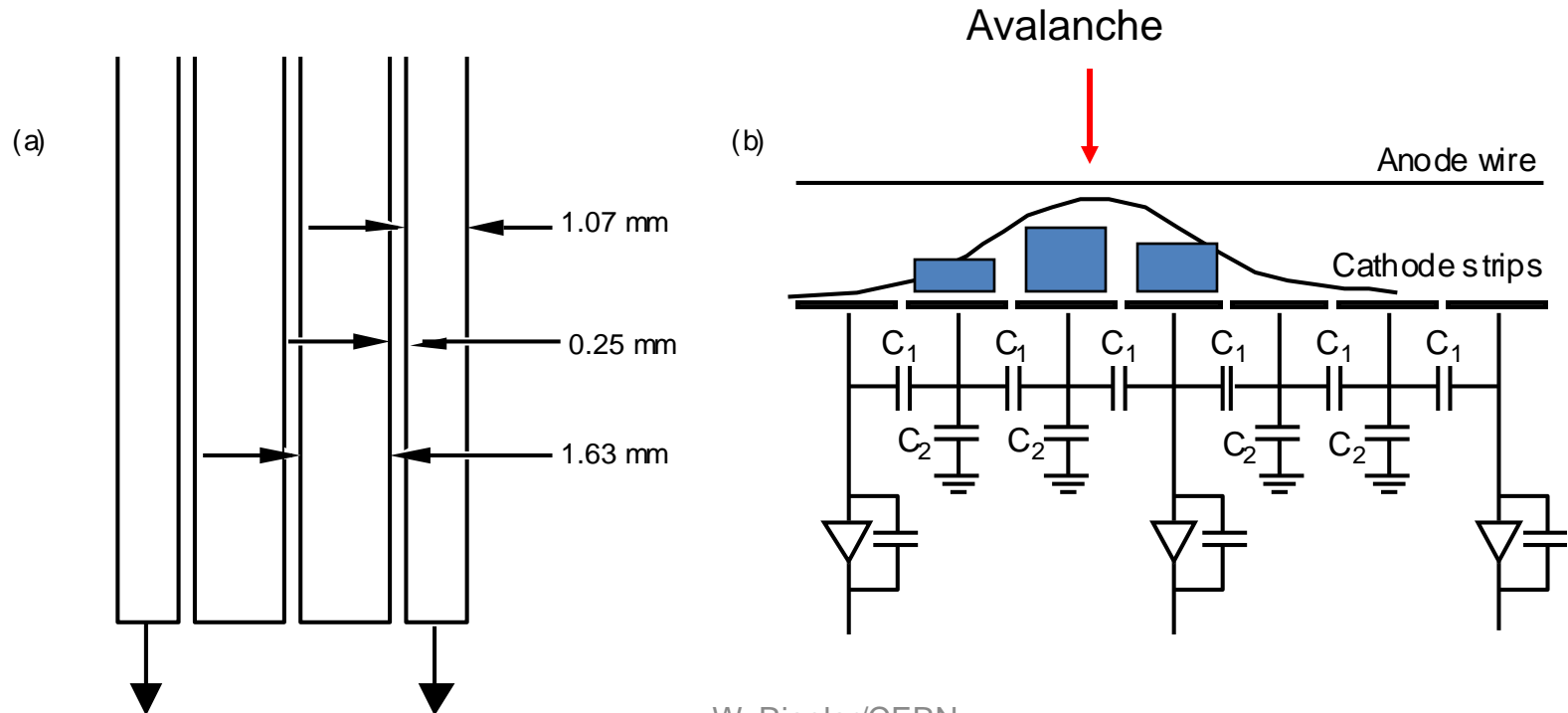
# Multi Wire Proportional Chamber



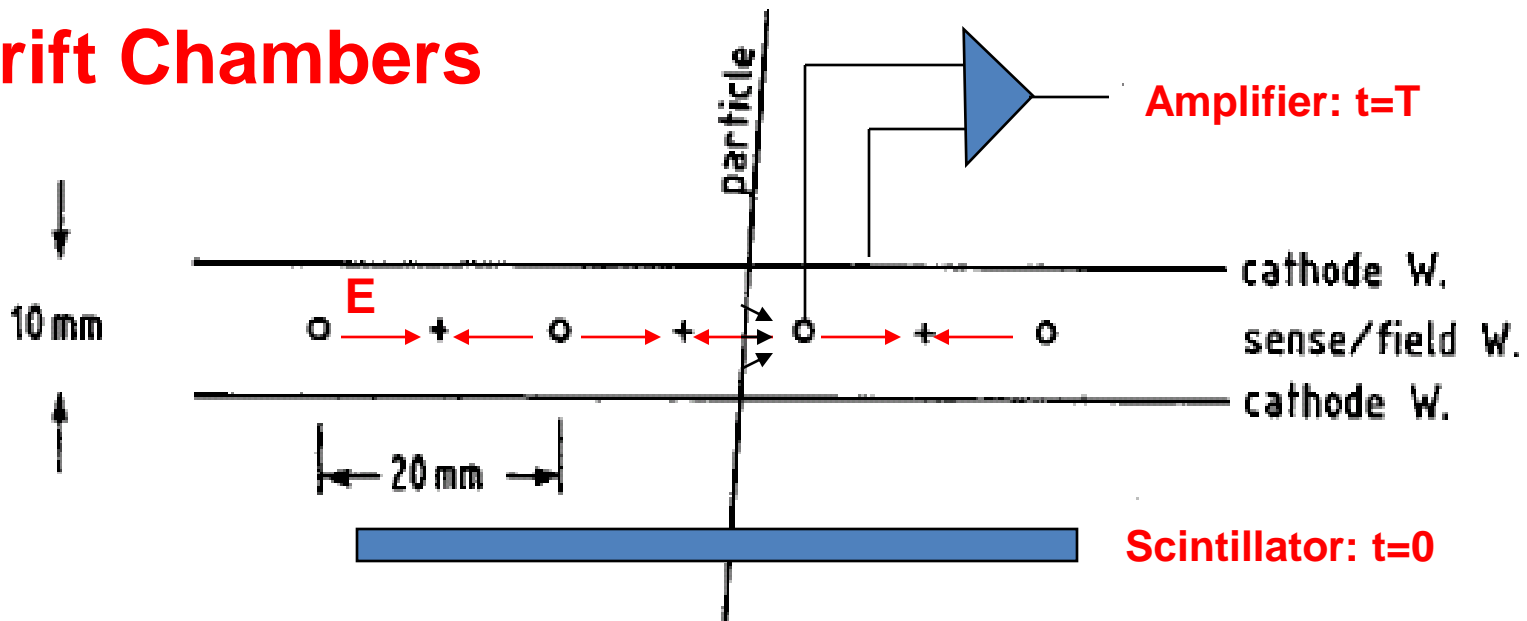
**Cathode strip:**

**Width ( $1\sigma$ ) of the charge distribution  $\approx$  distance between wires and cathode plane.**

**'Center of gravity' defines the particle trajectory.**



# Drift Chambers



In an alternating sequence of wires with different potentials one finds an electric field between the 'sense wires' and 'field wires'.

The electrons are moving to the sense wires and produce an avalanche which induces a signal that is read out by electronics.

The time between the passage of the particle and the arrival of the electrons at the wire is measured.

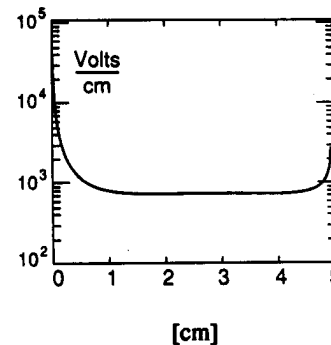
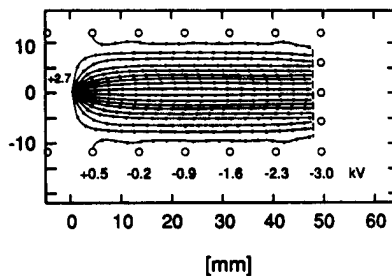
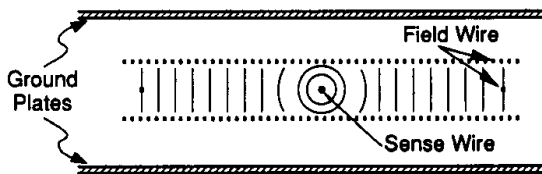
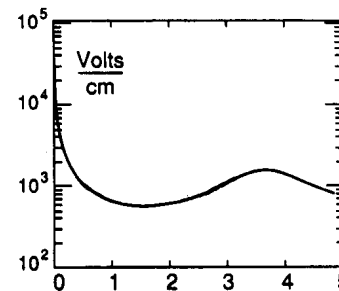
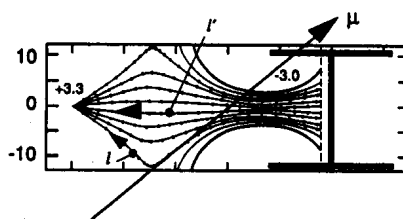
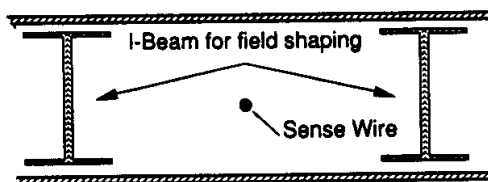
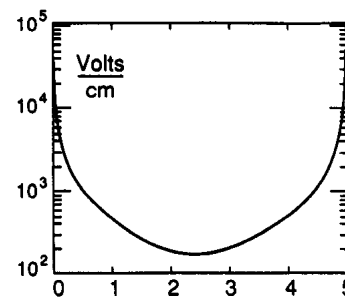
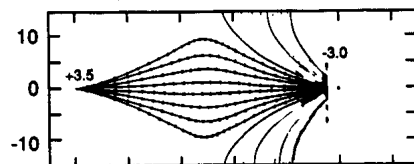
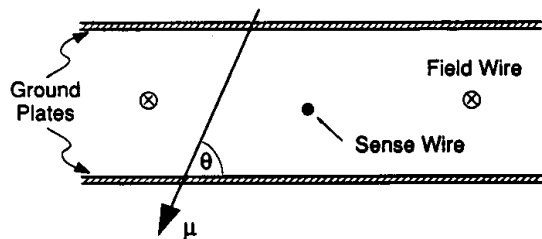
The drift time  $T$  is a measure of the position of the particle !

By measuring the drift time, the wire distance can be increased (compared to the Multi Wire Proportional Chamber) → save electronics channels !



# Drift Chambers, typical Geometries

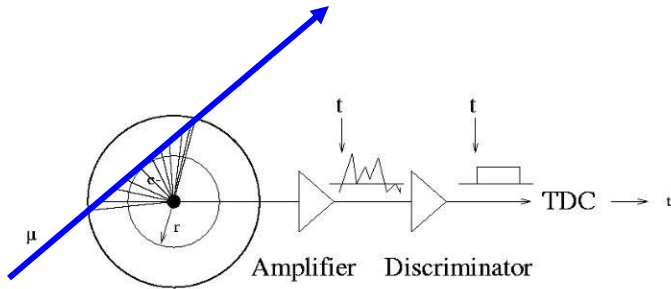
Electric Field  $\approx 1\text{kV/cm}$



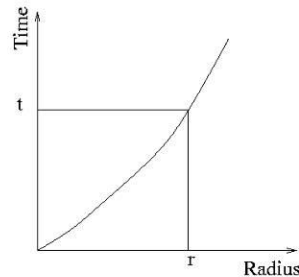
# The Geiger Counter reloaded: Drift Tube

Primary electrons are drifting to the wire.

ATLAS MDT R(tube) = 15mm



Calibrated Radius-Time correlation

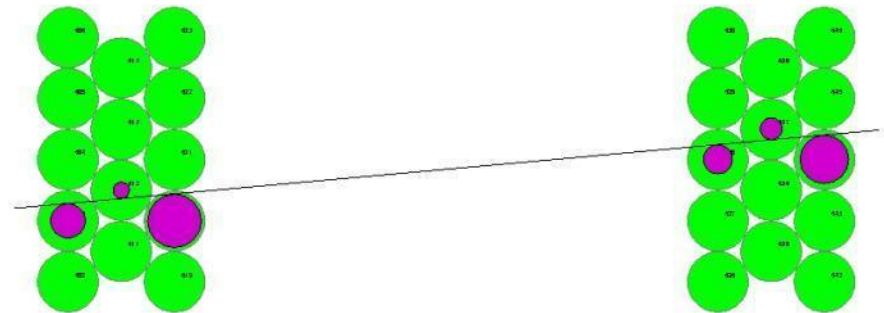
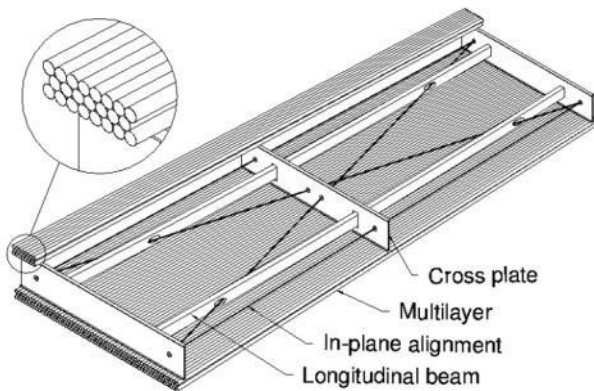


Electron avalanche at the wire.

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

Many of these circles define the particle track.

ATLAS Muon Chambers



ATLAS MDTs, 80 $\mu$ m per tube

# The Geiger counter reloaded: Drift Tube

Atlas Muon Spectrometer, 44m long, from  $r=5$  to 11m.

1200 Chambers

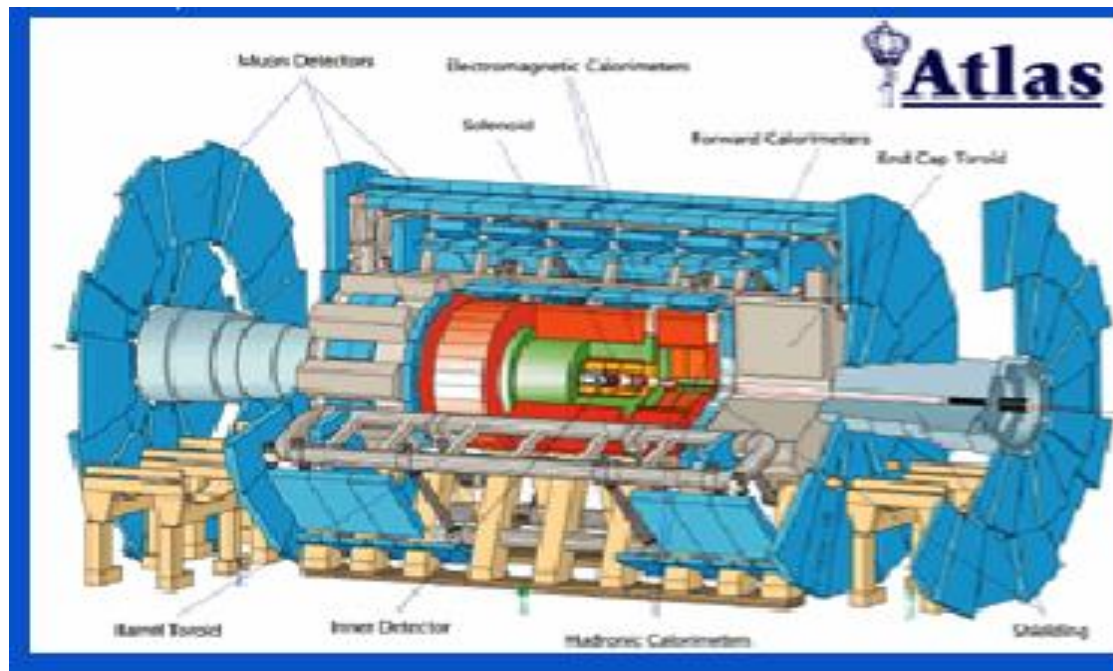
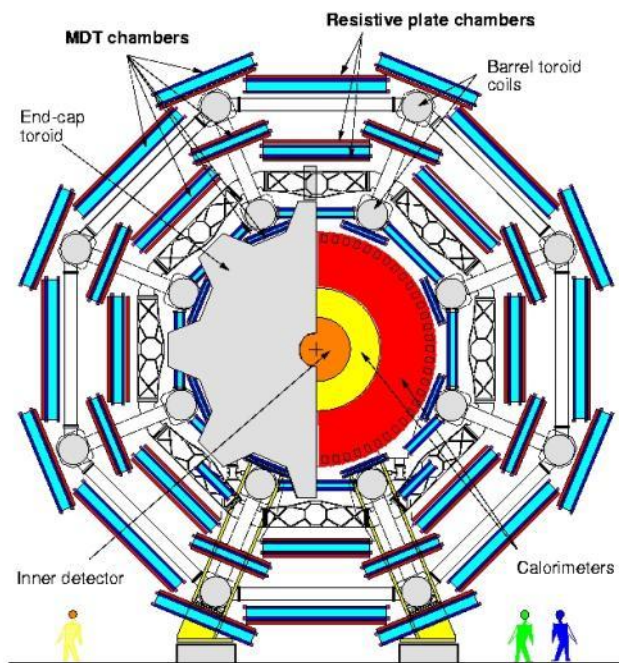
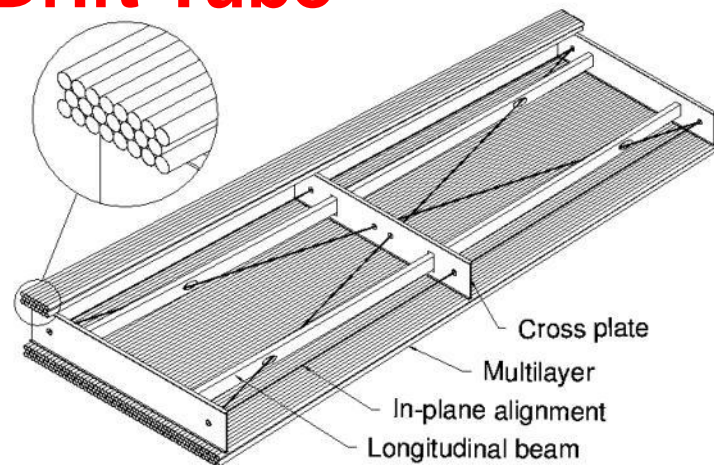
6 layers of 3cm tubes per chamber.

Length of the chambers 1-6m !

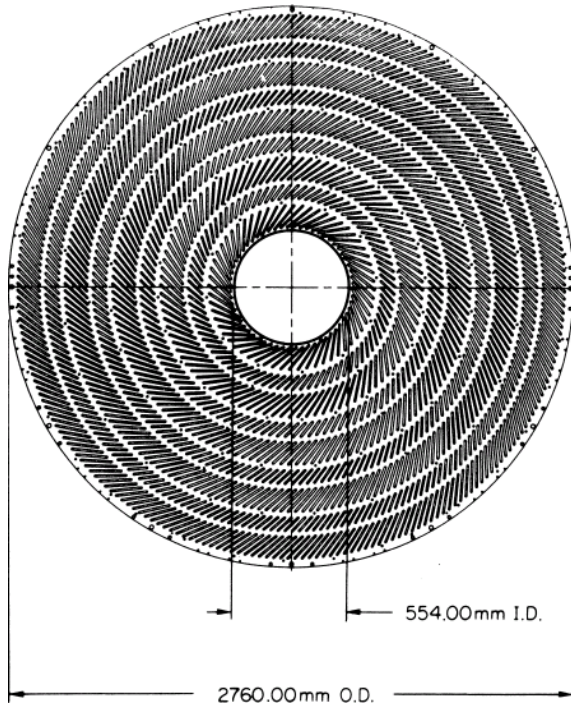
Position resolution:  $80\mu\text{m}/\text{tube}$ ,  $<50\mu\text{m}/\text{chamber}$  (3 bar)

Maximum drift time  $\approx 700\text{ns}$

Gas Ar/CO<sub>2</sub> 93/7

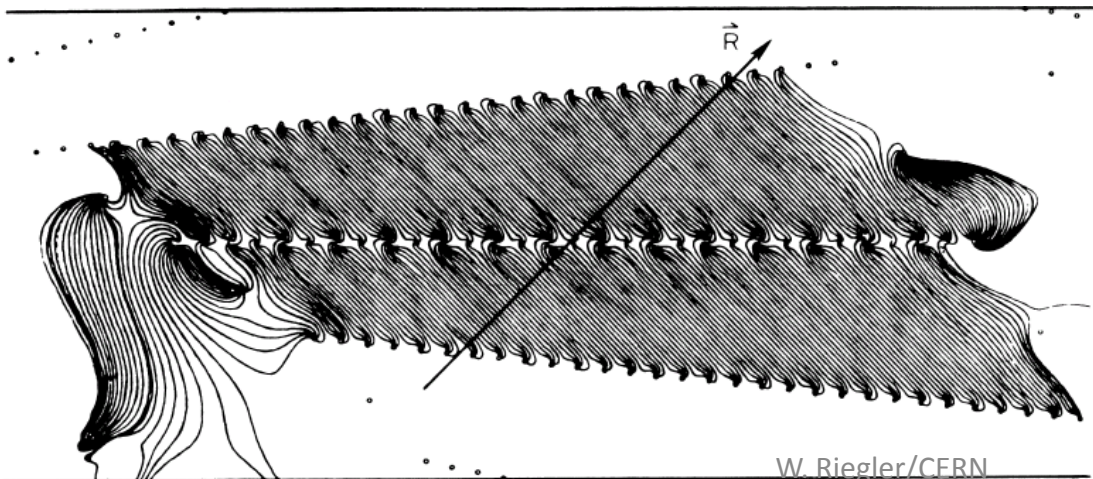


# Large Drift Chambers



Central Tracking Chamber CDF  
Experiment.

660 drift cells tilted  $45^\circ$  with respect to  
the particle track.



Drift cell

# Time Projection Chamber (TPC):

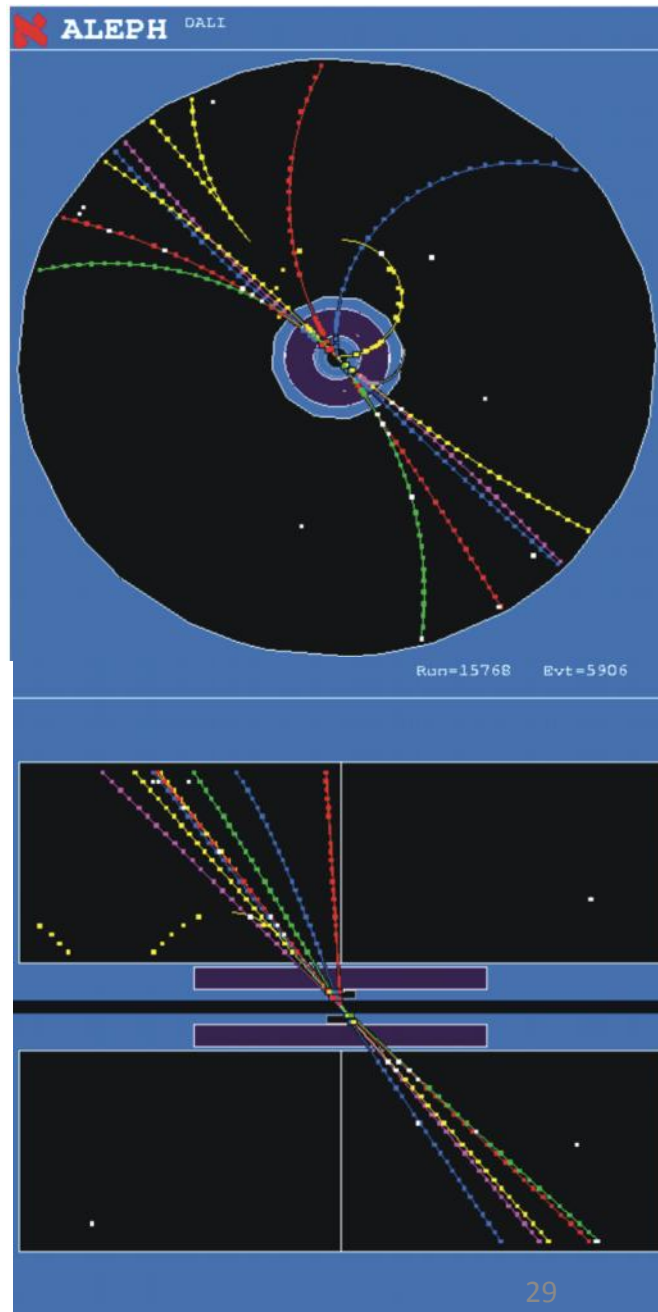
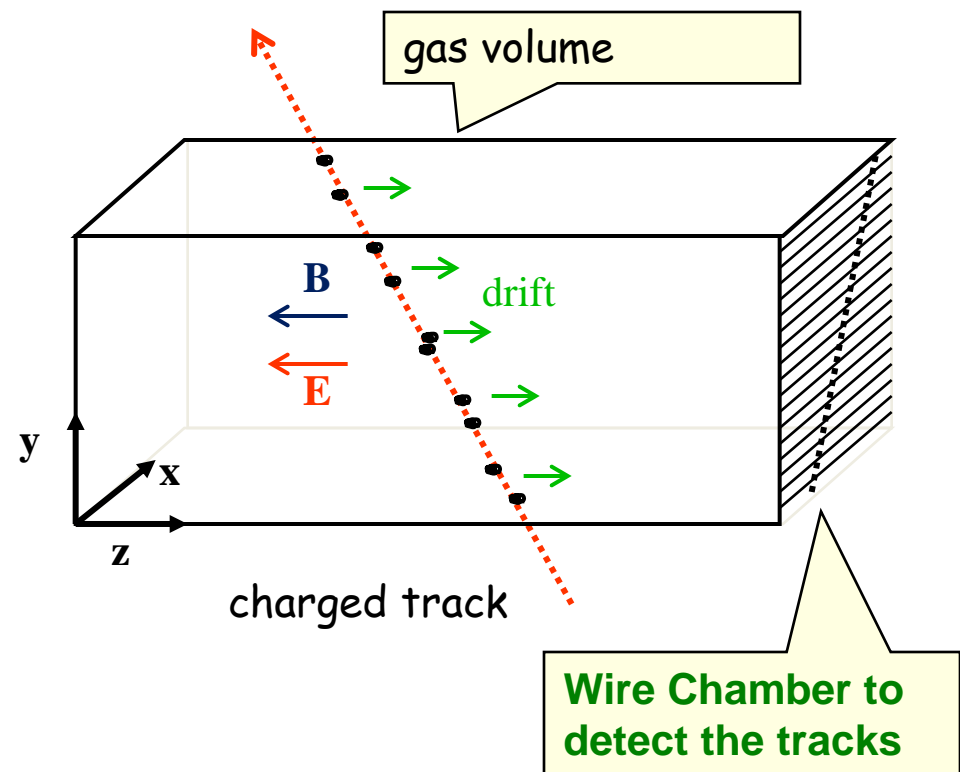
Gas volume with parallel E and B Field.

B for momentum measurement. Positive effect:

Diffusion is strongly reduced by E/B (up to a factor 5).

Drift Fields 100-400V/cm. Drift times 10-100  $\mu$ s.

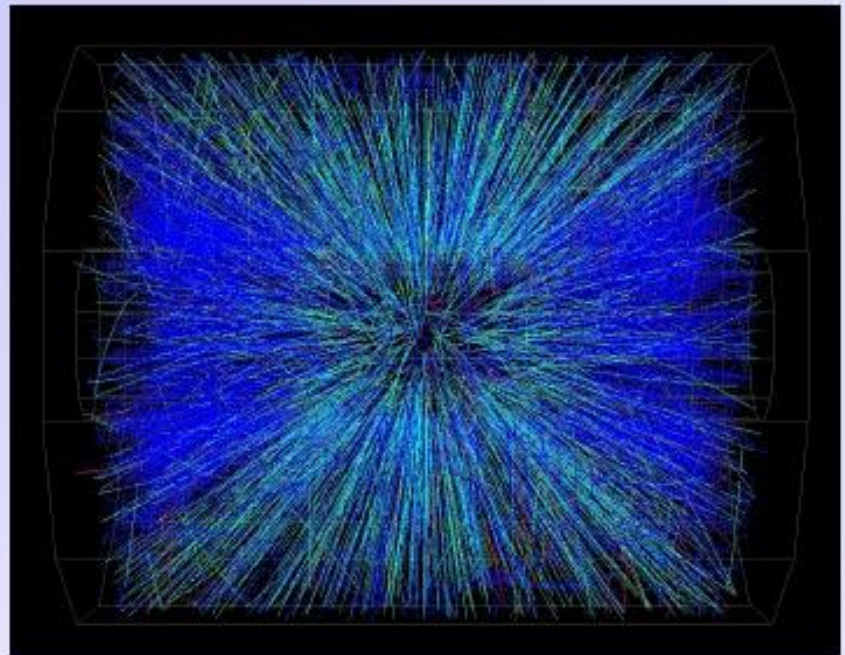
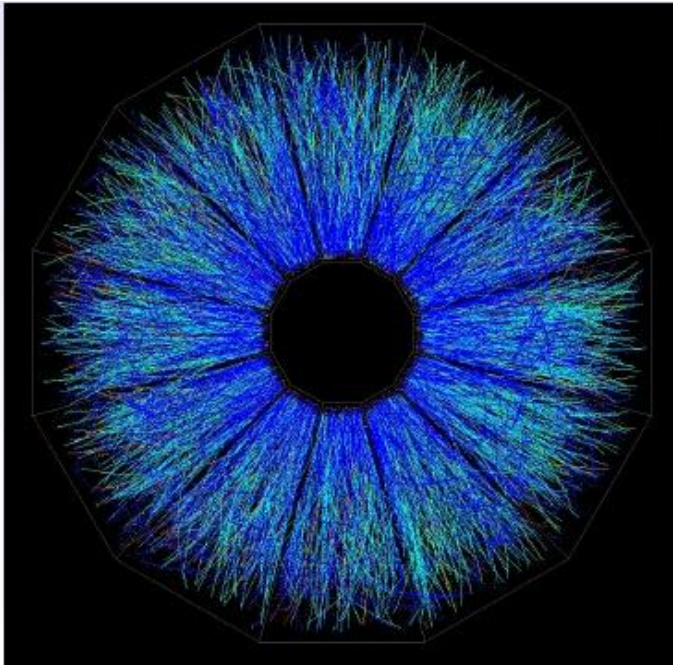
Distance up to 2.5m !



# STAR TPC (BNL)

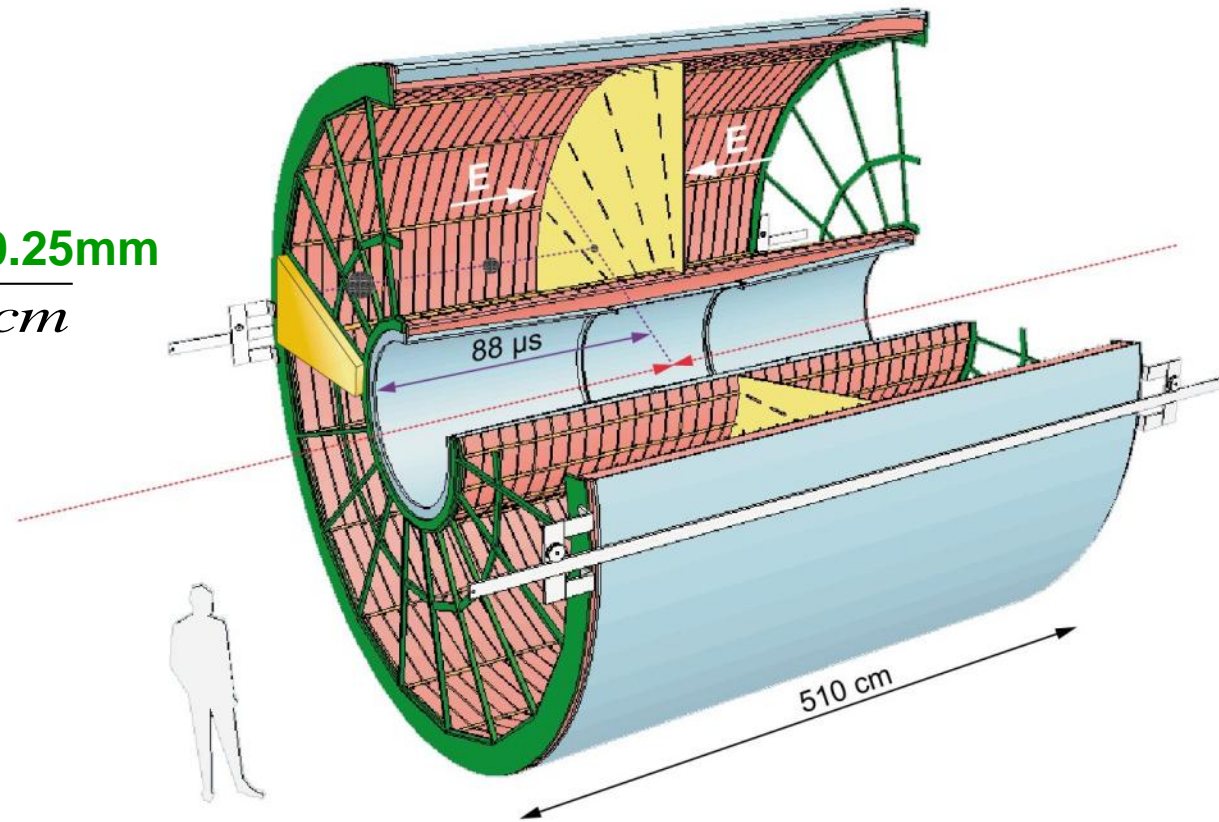
Event display of a Au Au collision at CM energy of 130 GeV/n.

Typically around 2000 tracks per event.



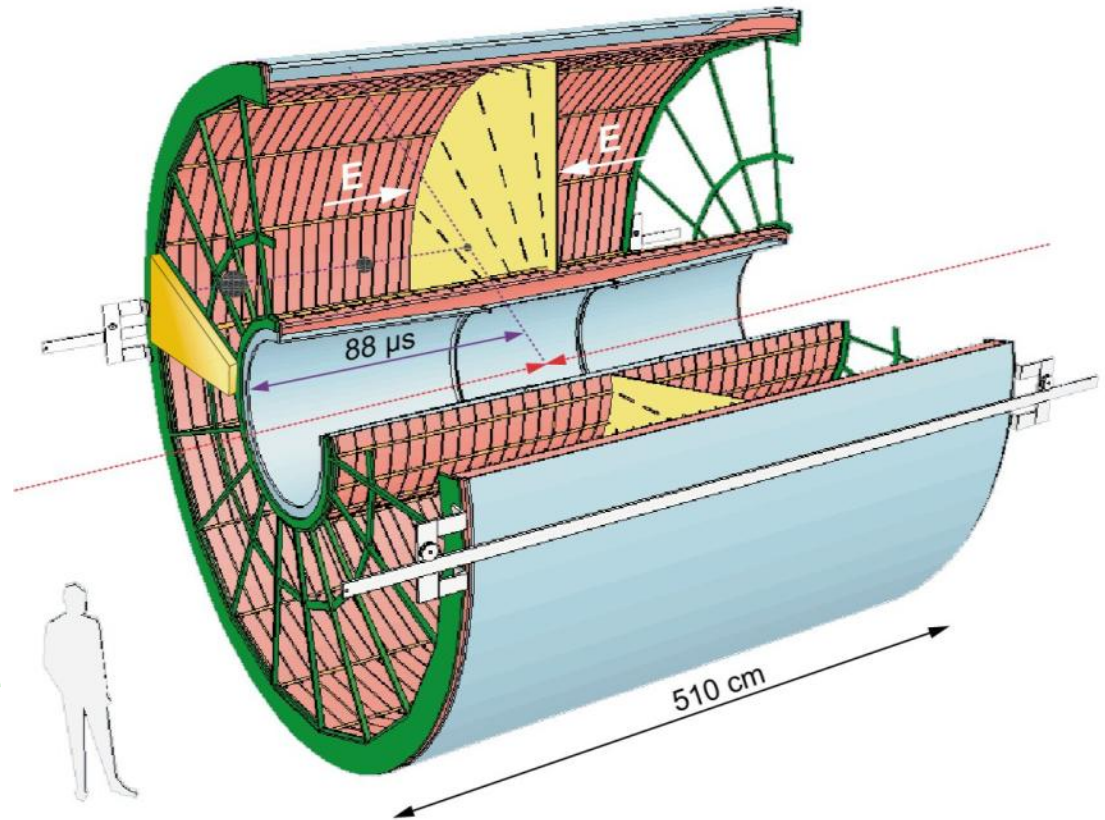
# ALICE TPC: Detector Parameters

- Gas Ne/ CO<sub>2</sub> 90/10%
- Field 400V/cm
- Gas gain >10<sup>4</sup>
- Position resolution  $\sigma = 0.25\text{mm}$
- Diffusion:  $\sigma_t = 250\mu\text{m} \sqrt{cm}$
- Pads inside: 4x7.5mm
- Pads outside: 6x15mm
- B-field: 0.5T



# ALICE TPC: Construction Parameters

- **Largest TPC:**
  - Length 5m
  - Diameter 5m
  - Volume 88m<sup>3</sup>
  - Detector area 32m<sup>2</sup>
  - Channels ~570 000
- **High Voltage:**
  - Cathode -100kV
- **Material X<sub>0</sub>**
  - Cylinder from composite materials from airplane industry (X<sub>0</sub>= ~3%)





# ALICE TPC: Pictures of the Construction

Precision in z:  $250\mu\text{m}$

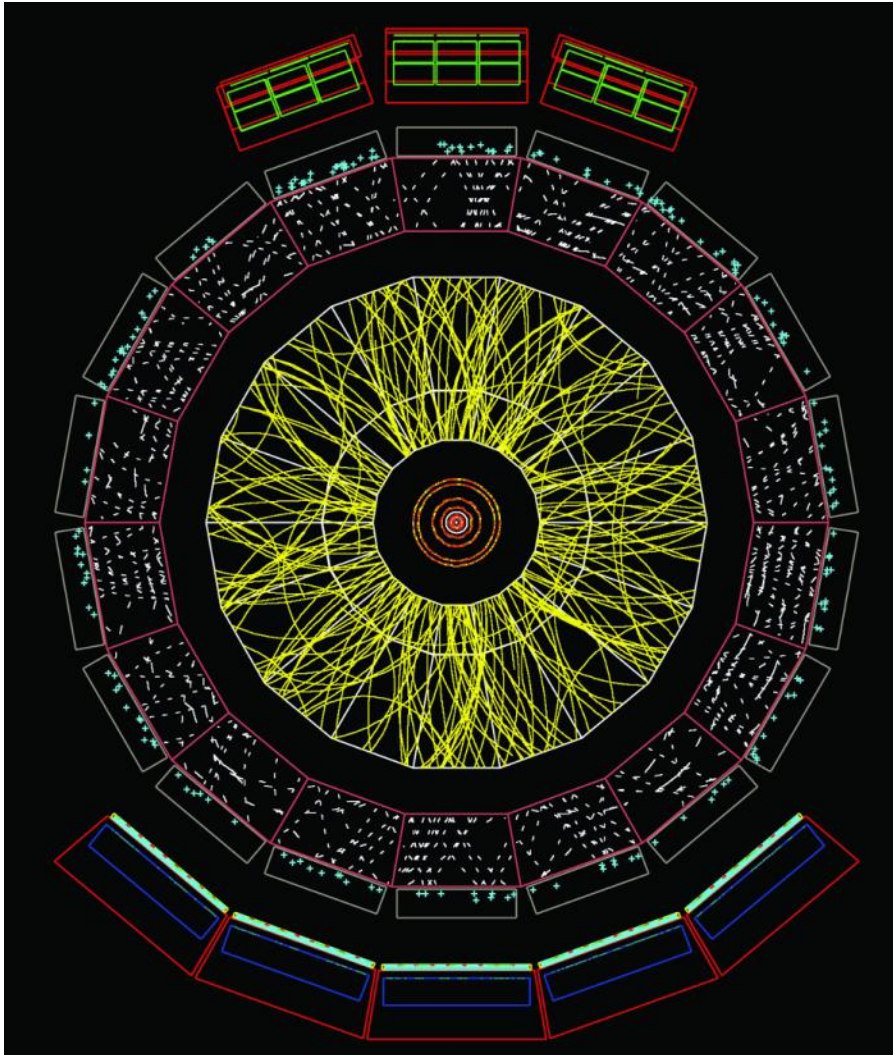


End plates  $250\mu\text{m}$

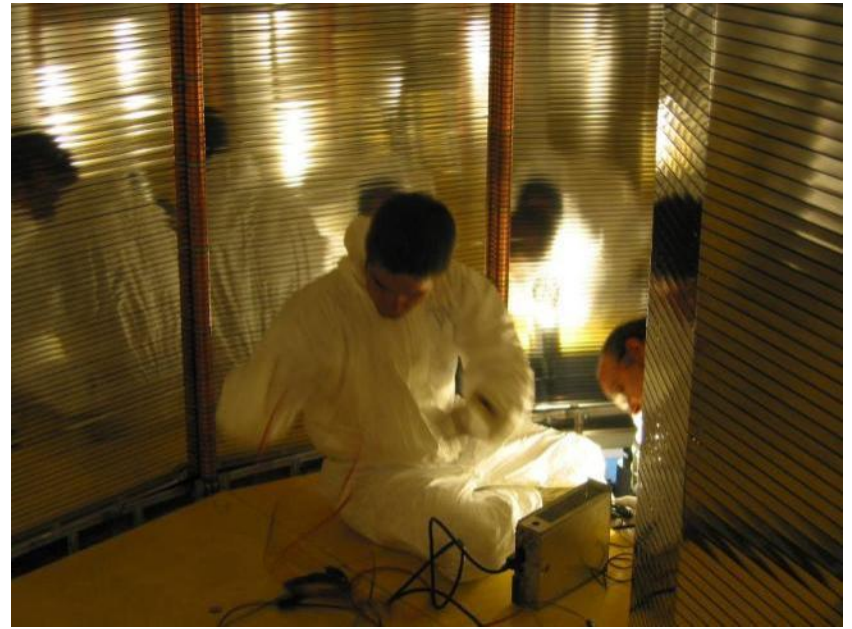


Wire chamber:  $40\mu\text{m}$

# ALICE : Simulation of Particle Tracks



- Simulation of particle tracks for a Pb Pb collision ( $dN/dy \sim 8000$ )
- Angle:  $\Theta = 60$  to  $62^\circ$
- If all tracks would be shown the picture would be entirely yellow !
- Up to 40 000 tracks per event !
- TPC is currently under commissioning



## ALICE TPC Construction

My personal  
contribution:

A visit inside the TPC.



W. Riegler/CERN

## Drift von Elektronen in Elektrischen Feldern:

In Abwesenheit elektrischer Felder haben die Elektronen die thermische Energie  $\varepsilon=3/2 kT$ . Für  $T=300K \rightarrow 3/2kT=40meV \rightarrow v=120\ 000m/s$ . Da die Elektronen sehr kleine Massen im Vergleich zu den Stossatomen haben wird die Bewegungsrichtung bei jedem Stoss völlig 'randomisiert'.

In Anwesenheit elektrischer Felder überlagert sich eine Geschwindigkeit in Richtung des elektrischen Feldes. Es ergibt sich eine mittlere makroskopische Geschwindigkeit  $v$  und eine mittlere mikroskopische Geschwindigkeit  $u$  (eine mittlere Energie  $\varepsilon=1/2mu^2$ ).

Wir vernachlässigen die thermische Bewegung und bringen zum Zeitpunkt  $t=0$  ein Elektron in ein Gas mit angelegtem elektrischen Feld  $E$ . Das Elektron wird in Richtung des Feldes beschleunigt bis es einen Stoss erfährt und in eine zufällige Richtung abgelenkt wird.

Danach wird es wiederum in Richtung des Feldes beschleunigt bis zum nächste Stoss etc. Das Elektron wird so lange an Energie gewinnen bis der mittlere Energieverlust pro Stoss gleich der gewonnen Energie ist.

Ist  $v$  die makroskopische Driftgeschwindigkeit so gewinnt ein Elektron auf der Strecke  $x$  die Energie  $eEx$  und benötigt dazu die Zeit  $T=x/v$ . Ist  $\tau$  die mittlere Zeit zwischen zwei Stößen, so ergeben sich  $n=T/\tau$  Stöße.

Bezeichnen wir den relativen Energieverlust pro Stoss mit  $\Delta$  so ergibt sich dass  $n \cdot 1/2mu^2 \Delta = eEx \rightarrow mu^2 \Delta = 2eEv \tau$  (1)

Die mittlere freie Weglänge zwischen zwei Stößen ist durch  $\lambda=1/N\sigma$  (2) gegeben ( $N=Atome/cm^3$ ).

Die makroskopische Driftgeschwindigkeit ist durch  $v=qE/m \tau$  gegeben (3).

## Drift von Elektronen in Elektrischen Feldern:

Aus (1)(2)(3) folgt

$$v = \sqrt{\frac{eE}{mN\sigma}} \sqrt{\frac{\Delta}{2}} \quad u = \sqrt{\frac{eE}{mN\sigma}} \sqrt{\frac{2}{\Delta}}$$

$$\frac{u}{v} = \sqrt{\frac{2}{\Delta}}$$

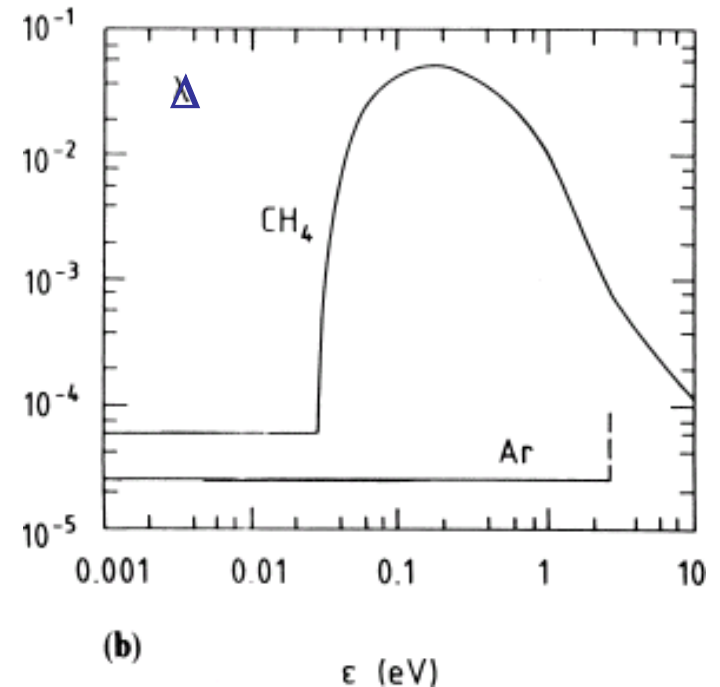
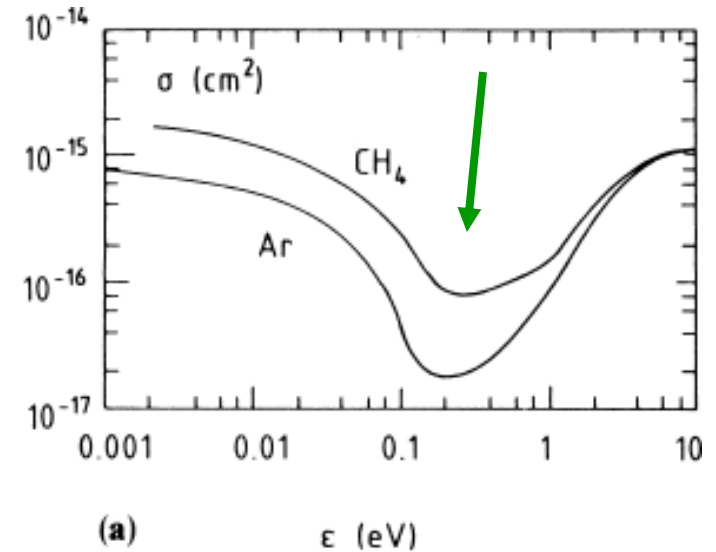
Da der relative Energieverlust  $\approx$  dem Massenverhältnis von Elektron und Atomen entspricht ist  $\Delta$  typischerweise  $10^{-4} \rightarrow u/v \approx 150$ .

$\sigma(\epsilon)$  und  $\Delta(\epsilon)$  sind stark von der Elektronenenergie  $\epsilon$  abhängig.

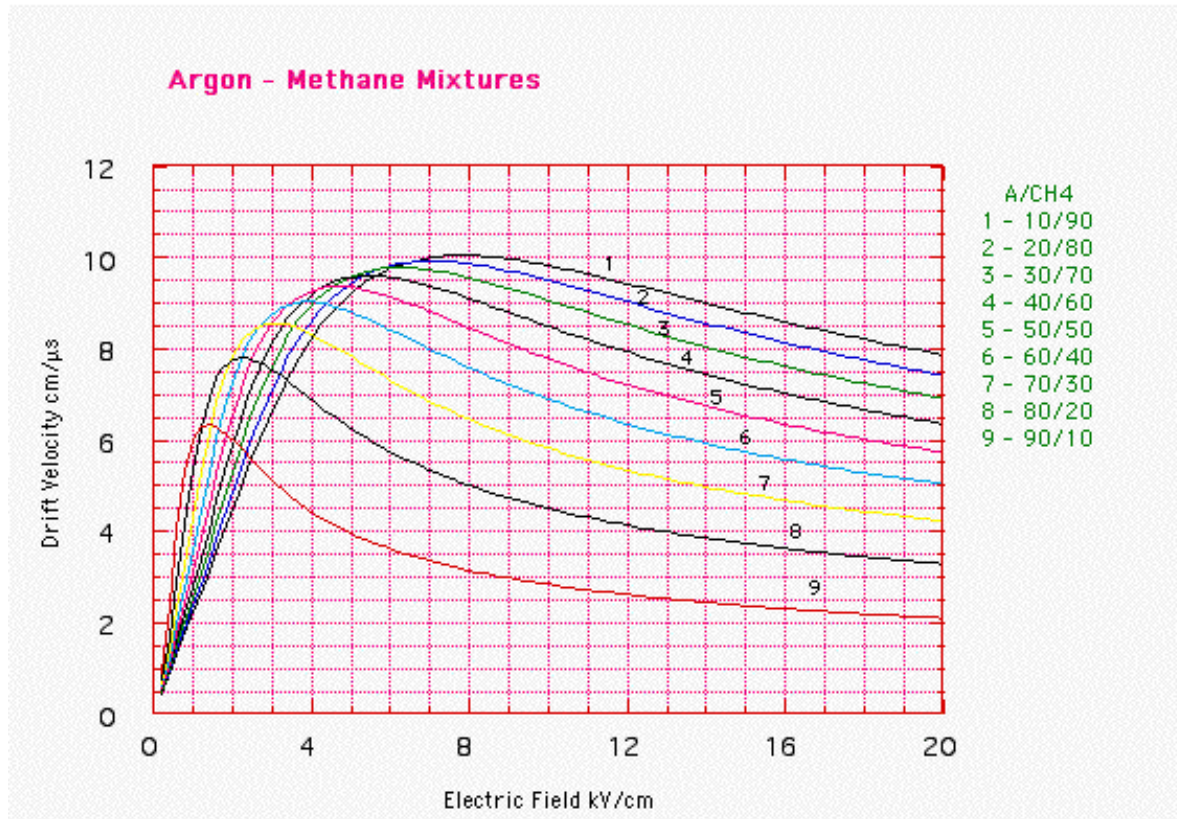
Die Driftgeschwindigkeit  $v$  ist deshalb sehr stark von kleinen Beimengungen anderer Gase abhängig.

$v$  ist vom Verhältnis  $E/N$  abhängig.

## Ramsauer Effekt



## Drift von Elektronen in Elektrischen Feldern:

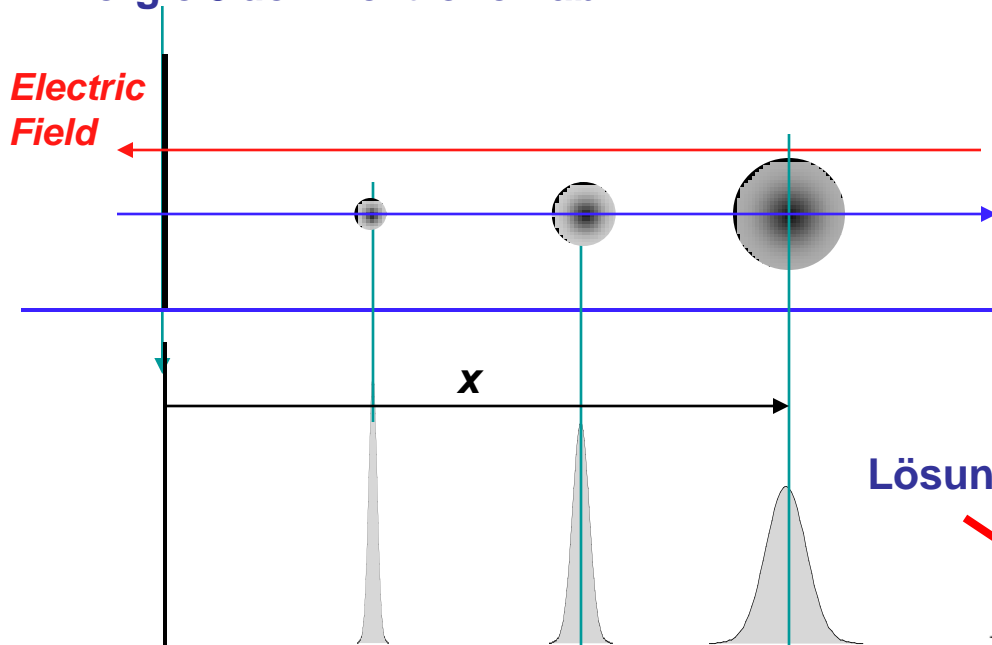


Typische Driftgeschwindigkeiten sind  $v=5-10\text{cm}/\mu\text{s}$  (50 000-100 000m/s).  
Die mikroskopische Geschwindigkeit  $u$  ist ca. 100mal grösser.

Nur Gase mit sehr kleiner Elektronegativität sind brauchbar (Elektronenanlagerung)  
→Edelgase stellen meist die Hauptkomponente des Gases dar.  
→Beimischung von  $\text{CO}_2$ ,  $\text{CH}_4$ , Isobutane etc. zum 'Quenching' (siehe Ladungsmultiplikation)

## Drift von Elektronen in Elektrischen Feldern, Diffusion:

Eine anfangs punktförmig Ladungswolke von Elektronen wird sich durch die zahlreichen mikroskopischen Stöße vergrößern. Die Diffusion hängt von der Energie  $\epsilon$  der Elektronen ab.



$$n(x) = \left( \frac{1}{\sqrt{4\pi Dt}} \right)^3 e^{-\frac{(x-v_D t)^2}{4Dt}}$$

$$\sigma_x = \sqrt{2Dt}$$

Lösung der Diffusionsgleichung ( $l$ =Driftdistanz)

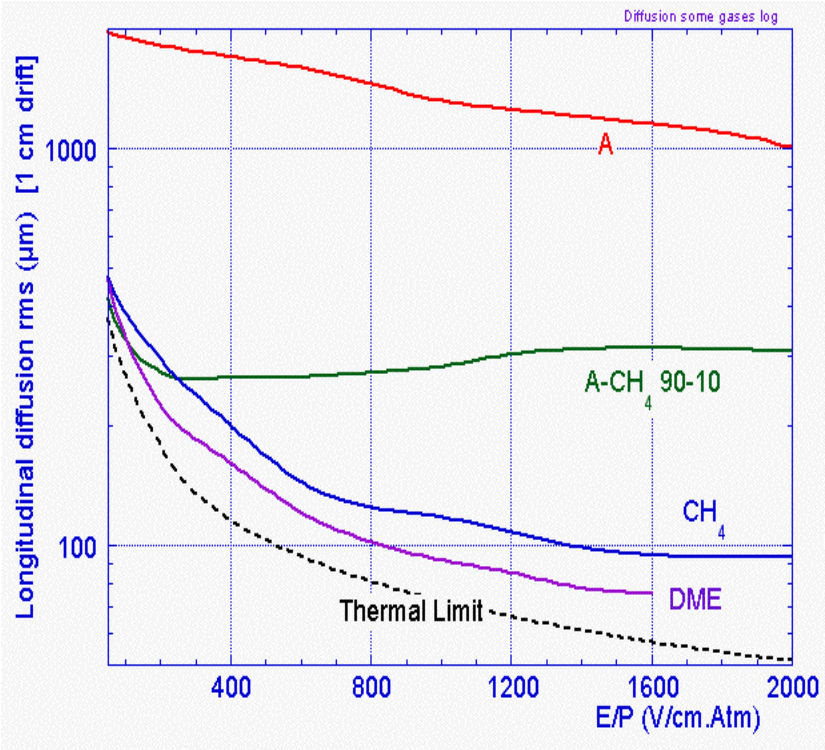
$$D = \frac{2}{3} \frac{v}{eE} \epsilon \quad \rightarrow \quad \sigma_x = \sqrt{\frac{4}{3} \frac{l}{eE} \epsilon}$$

Thermischer Grenzwert:

$$\epsilon = \frac{3}{2} kT \quad \rightarrow \quad \sigma_x = \sqrt{\frac{2kTl}{eE}}$$

Da  $\epsilon = \epsilon(E/P)$   $\sigma = \frac{1}{\sqrt{P}} F\left(\frac{E}{P}\right)$

# Drift von Elektronen in Elektrischen Feldern: Diffusion



Der Diffusion ist wie Driftgeschwindigkeit von  $E/N$  oder  $E/P$  abhängig und skaliert zusätzlich mit  $1/\sqrt{P}$ .

Bei 1kV/cm und 1 Atm Druck ist das thermische limit  $\sigma=70\mu\text{m}$  für 1cm Drift.

‘Kalte’ Gase sind nahe dem Thermische limit i.e. Gase bei welchen sich eine niedrige mittlere mikroskopische Energie  $\varepsilon=1/2mu^2$  einstellt sodass  $\varepsilon$  vergleichbar mit der thermischen Energie  $3/2kT$  ist.

CH<sub>4</sub> zeigt grossen relativen Energieverlust/Stoss  $\rightarrow$  kleines  $\varepsilon$ .  $\rightarrow$  kleine Diffusion

Argon zeigt kleinen relativen Energieverlust/Stoss  $\rightarrow$  hohes  $\varepsilon$ ,  $\rightarrow$  hohe Diffusion.



## Der Einfluss Magnetischer Felder:

Ist ein Elektron zusätzlich zum Elektrischen Feld E einem Magnetfeld B ausgesetzt so ändern sich Driftgeschwindigkeit, Diffusion und Driftrichtung.

Die Zyklotronfrequenz des Elektrons ist  $\omega = e/m \cdot B$ . Von vorhin wissen wir dass  $v = e/m \cdot E \cdot \tau \rightarrow \omega \tau = v \cdot B/E$

Für  $v = 10 \text{ cm}/\mu\text{s}$  und  $E = 1000 \text{ V}/\text{cm} \rightarrow \omega \tau = 1$ .

Zwischen zwei Stößen wird das Elektron im Mittel um 1 Rad ( $60^\circ$ ) abgelenkt.

Die detaillierte Rechnung ergibt:

$$v = v(B=0) \cdot \text{Sqrt}[(1 + \omega^2 \tau^2 \cos^2 \Phi) / (1 + \omega^2 \tau^2)]$$

$\Phi$  = Winkel zwischen E und B

$\rightarrow v(B) \leq v(B=0)$

$\rightarrow$  E parallel B:  $v(B) = v(B=0)$

$\rightarrow$  E normal B:  $v = v(B=0) / \sqrt{1 + \omega^2 \tau^2}$

Driftrichtung der Elektronen  $\neq$  Richtung des Elektrischen Feldes.  $\alpha$  = Winkel zwischen E und v

$\rightarrow$  Lorentzwinkel. Es gilt:  $\text{Tan} \alpha = \omega \tau$

Diffusion in Richtung des Magnetfeldes wird verringert:

$D = D / (1 + \omega^2 \tau^2)$  in Richtung des Magnetfeldes.

In TPCs mit E parallel B e.g.  $\omega \tau = 5$ ,  $\sigma(B) = \sigma(B=0) / 5$

## Drift von Ionen in Elektrischen Feldern

Auf Grund der hohen Masse der Ionen wird die Bewegungsrichtung beim Stoss nicht völlig randomisiert.

Die Stossquerschnitte sind im betreffenden Energiebereich  $\approx$  constant.

Unterhalb der thermischen Energie ist die Geschwindigkeit proportional dem Elektrischen Feld (typisch).

Über der Thermischen Energie steigt die Geschwindigkeit mit  $\sqrt{E}$  an.

$V = \mu E$ ,  $\mu(\text{Ar}) = 1.5 \text{ cm}^2/\text{Vs} \rightarrow 1000 \text{ V/cm} \rightarrow v = 1500 \text{ cm/s} = 15 \text{ m/s} \rightarrow 3000\text{-}6000$  mal langsamer als Elektronen !

$\omega\tau \approx 10^{-4} \rightarrow$  Für Ionen spielt das Magnetfeld keine Rolle.

## Zusammenfassung von Transport von Elektronen und Ionen:

Typische Driftgeschwindigkeiten von Elektronen:  $5-10\text{cm}/\mu\text{s}$  in Feldern von einigen  $\text{kV}/\text{cm}$ .  
Die Driftgeschwindigkeit ist eine Funktion von  $E/P$ .

Das Transportverhalten ist durch die energieabhängigen atomaren Stossprozesse definiert und kann typischerweise mit 10% Genauigkeit berechnet werden.

Die Diffusion hat ein thermisches Limit und beträgt ca.  $70\mu\text{m}$  für  $1\text{cm}$  Drift bei  $1\text{kV}/\text{cm}$  und  $300\text{K}$ .  
Interessant sind Gase welche eine Diffusion aufzeigen die nahe an diesem Limit liegt.  
Die Diffusion  $\sigma$  ist von Gasdruck  $P$  und Feld  $E$  über  $\sigma=1/\sqrt{P} \cdot f(E/P)$  abhängig.

Durch Magnetfelder stellt sich ein Winkel  $\alpha$  zwischen Richtung des Elektrischen Feldes und Driftrichtung der Elektronen ein (Lorentzwinkel).

Die Diffusion wird in Richtung des Magnetfeldes verringert.

Ionen haben Driftgeschwindigkeiten von  $v=\mu E$ , (e.g.  $\mu=1.5\text{cm}^2/\text{Vs}$  für Argon  $\rightarrow 1500\text{cm}/\text{s}$  für  $1\text{kV}/\text{cm}$ ).  $\rightarrow$  Ionen sind  $10^3-10^4$  mal langsamer als Elektronen.

Ionen sind durch Magnetfelder nicht beeinflusst.

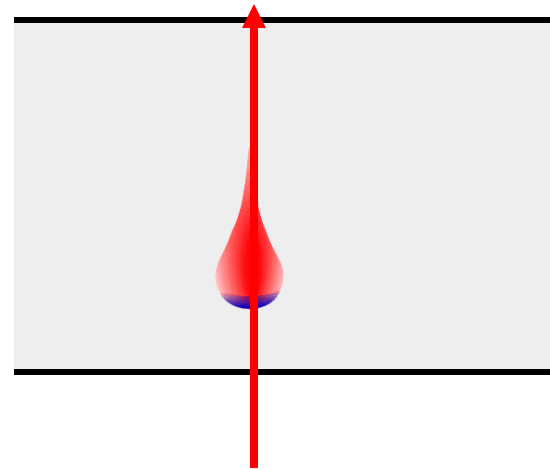
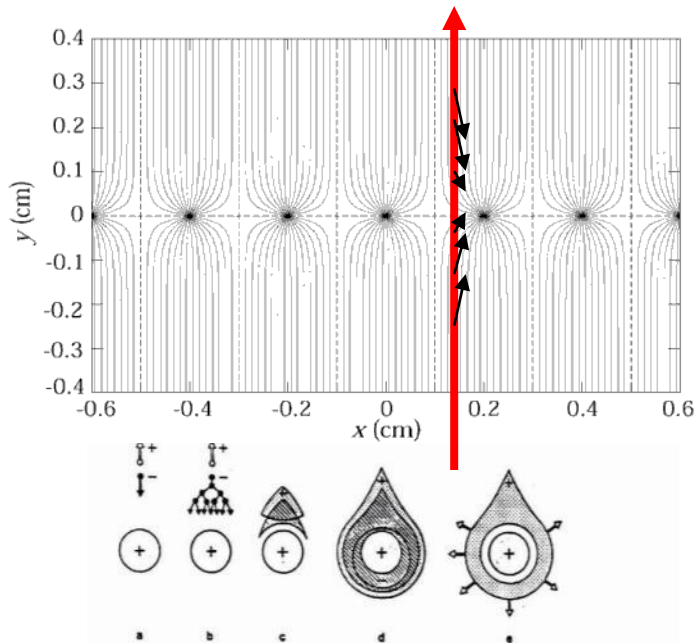
# Position Resolution/Time resolution

Up to now we discussed gas detectors for tracking applications. Wire chambers can reach tracking precisions down to 50 micrometers at rates up to  $<1\text{MHz/cm}^2$ .

What about time resolution of wire chambers ?

It takes the electrons some time to move from their point of creation to the wire. The fluctuation in this primary charge deposit together with diffusion limits the time resolution of wire chambers to about 5ns (3ns for the LHCb trigger chambers).

By using a parallel plate geometry with high field, where the avalanche is starting immediately after the charge deposit, the timing fluctuation of the arriving electrons can be eliminated and time resolutions down to 50ps can be achieved !



# Resistive Plate Chambers (RPCs)

## Keuffel 'Spark' Counter:

High voltage between two metal plates. Charged particle leaves a trail of electrons and ions in the gap and causes a discharge (Spark).

→ Excellent Time Resolution (<100ps).

Discharged electrodes must be recharged → Dead time of several ms.

## Parallel Plate Avalanche Chambers (PPAC):

At more moderate electric fields the primary charges produce avalanches without forming a conducting channel between the electrodes. No Spark → induced signal on the electrodes. Higher rate capability.

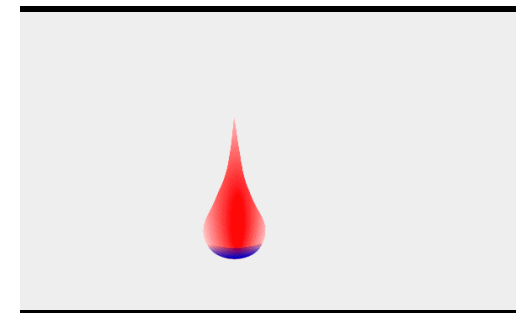
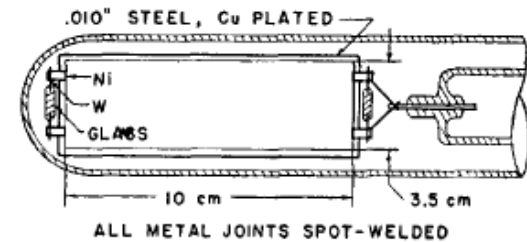
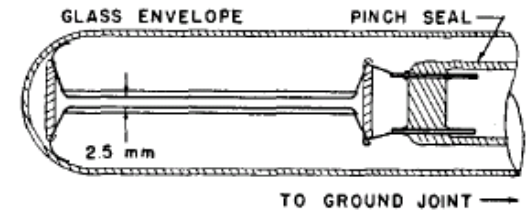
However, the smallest imperfections on the metal surface cause sparks and breakdown.

→ Very small (few cm<sup>2</sup>) and unstable devices.

In a wire chamber, the high electric field (100-300kV/cm) that produces the avalanche exists only close to the wire. The fields on the cathode planes are rather small 1-5kV/cm.

## Parallel-Plate Counters

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(Received November 8, 1948)



# Resistive Plate Chambers (RPCs)

→ Place resistive plates in front of the metal electrodes.

No spark can develop because the resistivity together with the capacitance ( $\tau \sim \epsilon * \rho$ ) will only allow a very localized 'discharge'. The rest of the entire surface stays completely unaffected.

→ Large area detectors are possible !

Resistive plates from Bakelite ( $\rho = 10^{10}$ - $10^{12} \Omega\text{cm}$ ) or window glass ( $\rho = 10^{12}$ - $10^{13} \Omega\text{cm}$ ).

Gas gap: 0.25-2mm.

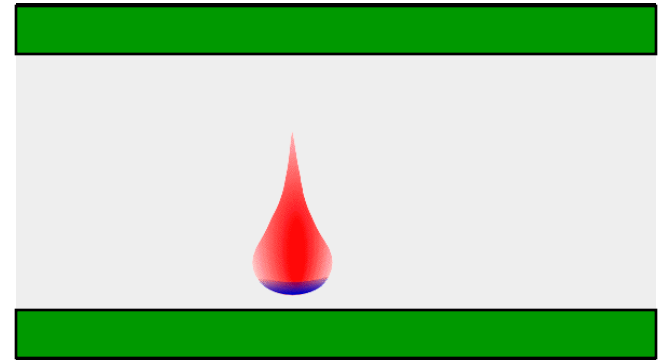
Electric Fields 50-100kV/cm.

Time resolutions: 50ps (100kV/cm), 1ns(50kV/cm)

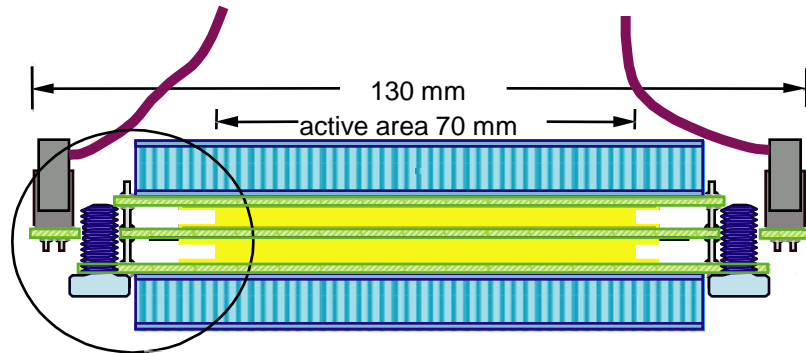
Application: Trigger Detectors, Time of Flight (TOF)

Resistivity limits the rate capability: Time to remove avalanche charge from the surface of the resistive plate is ( $\tau \sim \epsilon * \rho$ ) = ms to s.

Rate limit of kHz/cm<sup>2</sup> for  $10^{10} \Omega\text{cm}$ .



# ALICE TOF RPCs



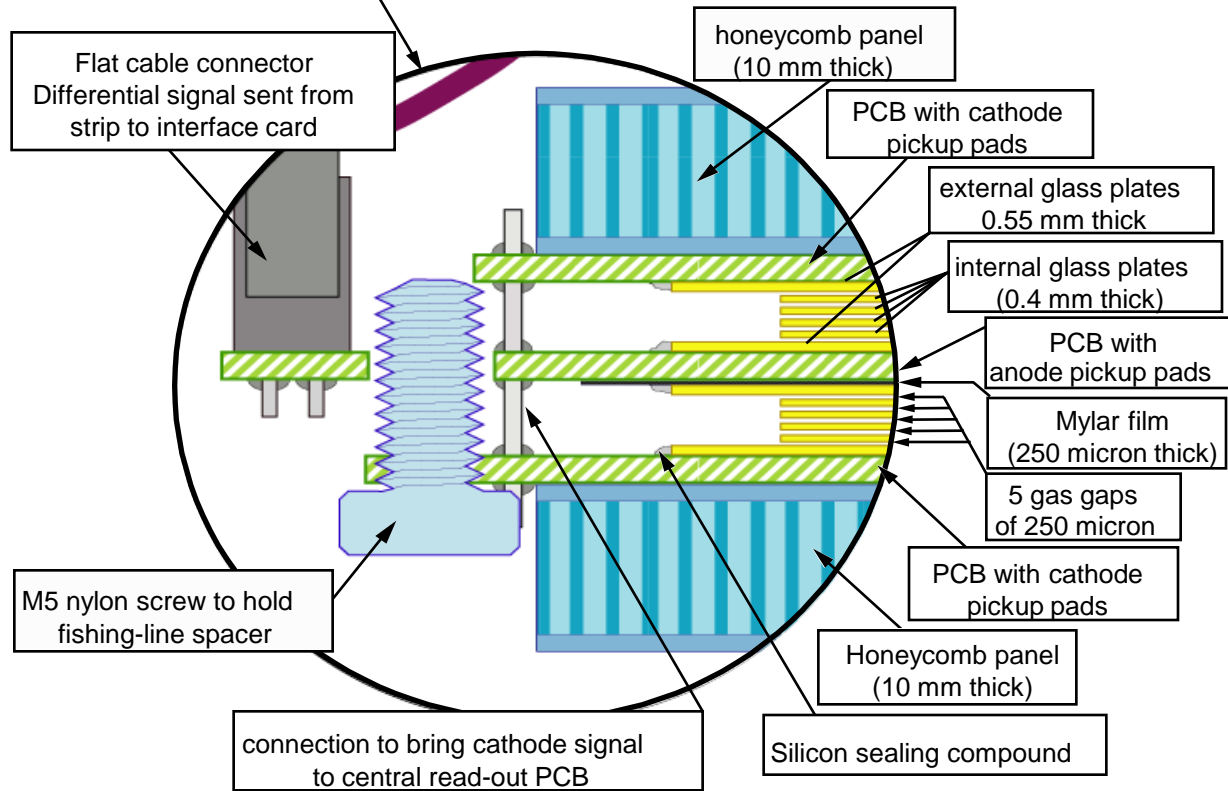
Several gaps to increase efficiency.  
Stack of glass plates.

Small gap for good time resolution:  
0.25mm.

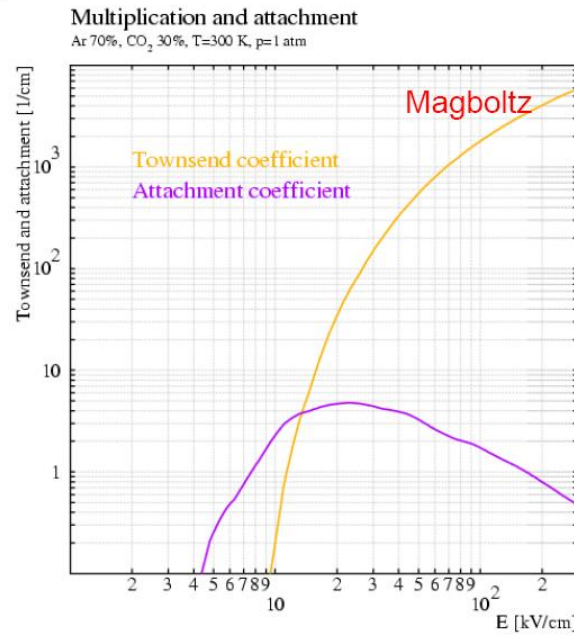
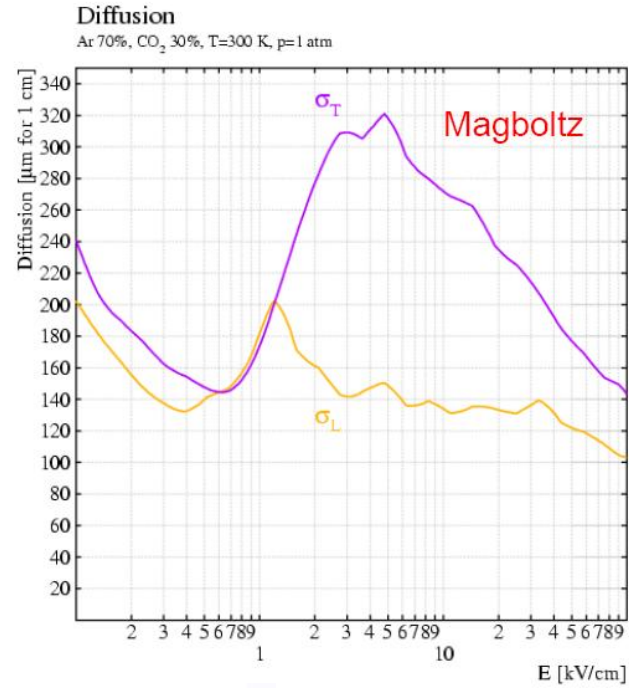
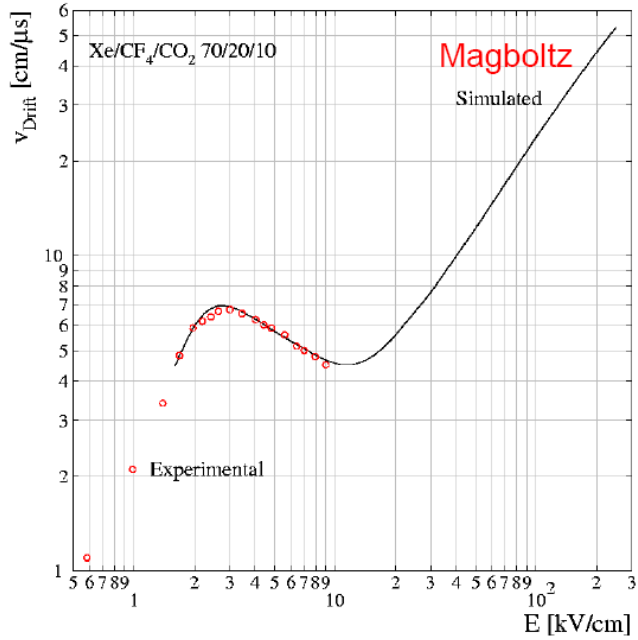
Fishing lines as high precision  
spacers !

Large TOF systems with 50ps time  
resolution made from window glass  
and fishing lines !

Before RPCs → Scintillators with very  
special photomultipliers – very  
expensive. Very large systems are  
unaffordable.

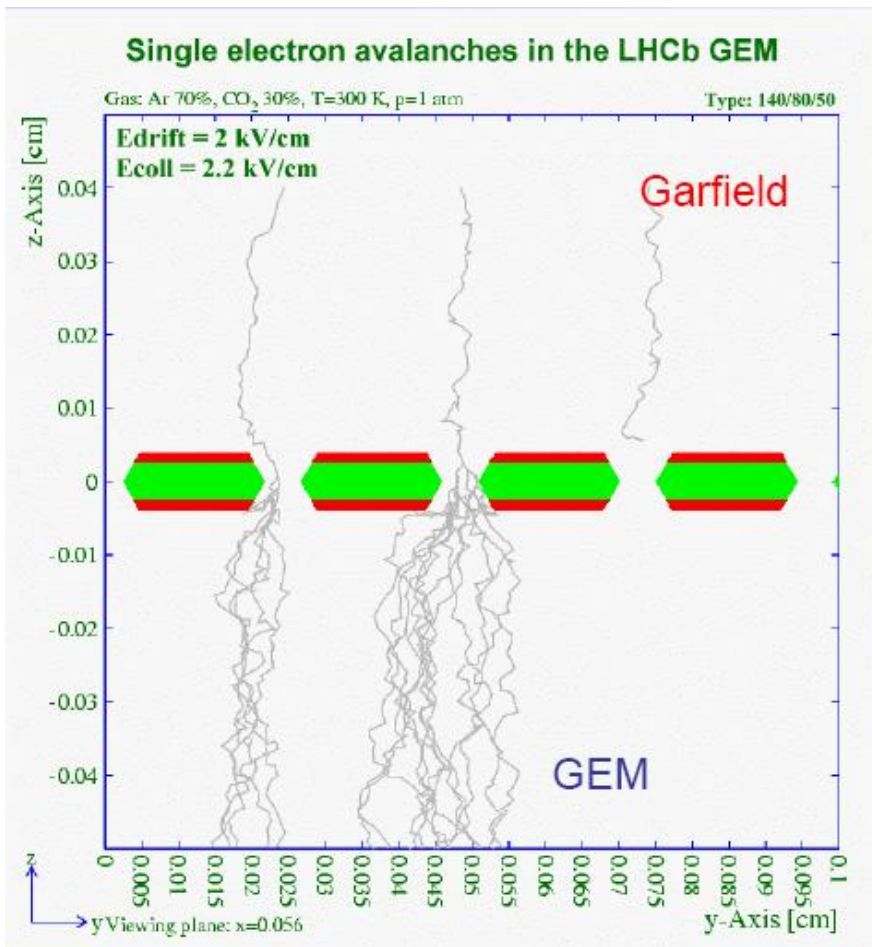


# Detector Simulation

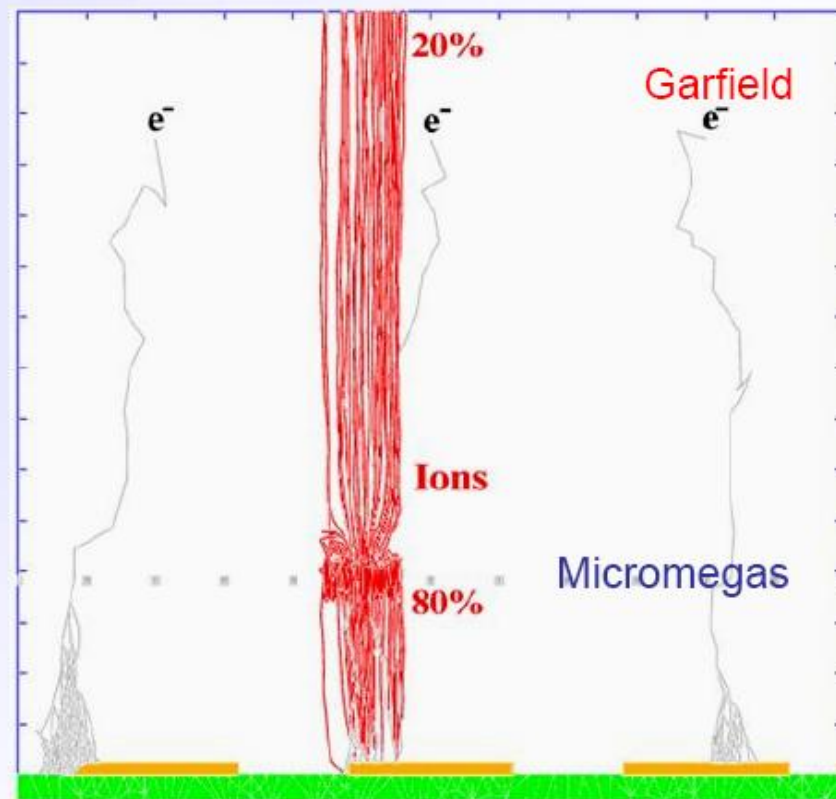




# Detector Simulation



Electrons paths and multiplication



Positive ion backflow

# Summary on Gas Detectors

Wire chambers feature prominently at LHC. A decade of very extensive studies on gases and construction materials has led to wire chambers that can track up to MHz/cm<sup>2</sup> of particles, accumulate up to 1-2C/cm of wire and 1-2 C/cm<sup>2</sup> of cathode area.

While silicon trackers currently outperform wire chambers close to the interaction regions, wire chambers are perfectly suited for the large detector areas at outer radii.

Large scale next generation experiments foresee wire chambers as large area tracking devices.

The Time Projection Chamber – if the rate allows its use – is unbeatable in terms of low material budget and channel economy. There is no reason for replacing a TPC with a silicon tracker.

Gas detectors can be simulated very accurately due to excellent simulation programs.