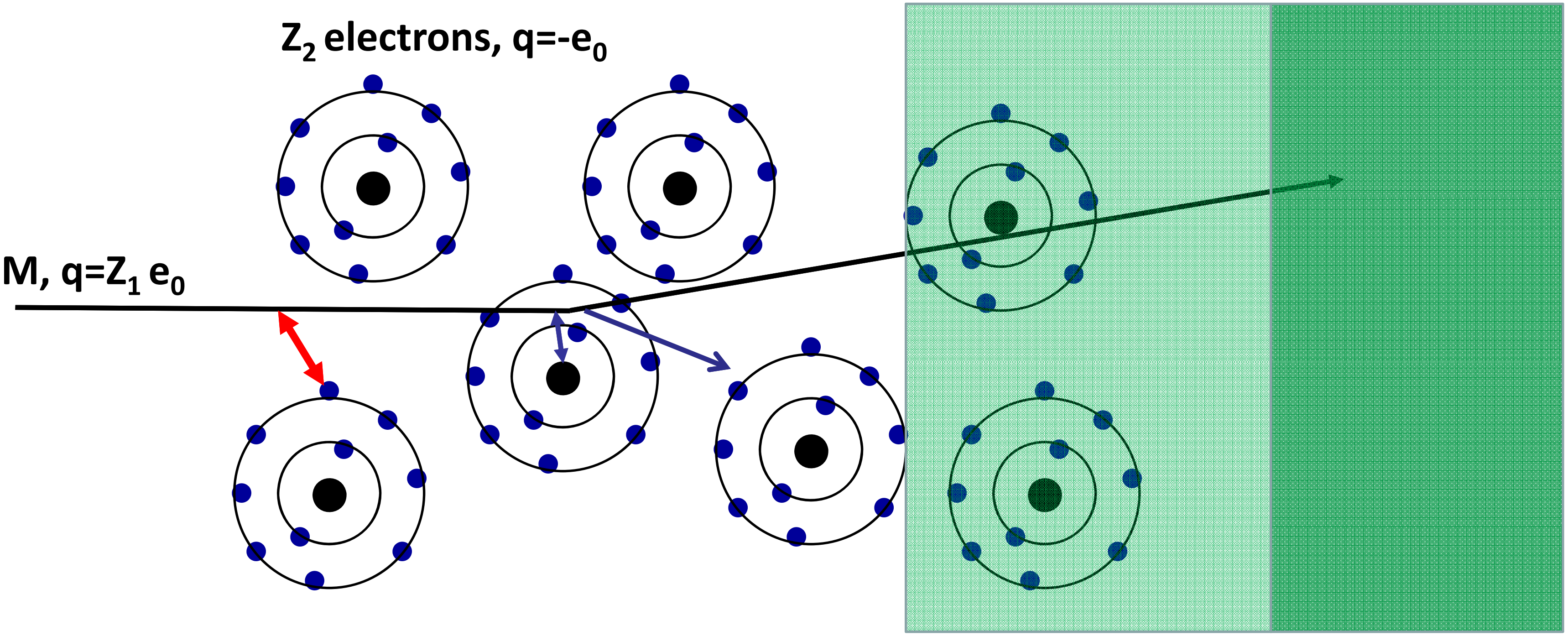
Particle Detectors

Summer Student Lectures 2008

Werner Riegler, CERN, werner.riegler@cern.ch

- **History of Instrumentation ↔ History of Particle Physics**
- **The ‘Real’ World of Particles**
- **Interaction of Particles with Matter**
- **Tracking with Gas and Solid State Detectors**
- **Calorimetry, Particle ID, Detector Systems**

Electromagnetic Interaction of Particles with Matter



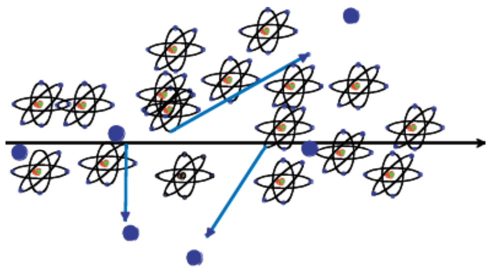
Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called Transition radiation.

Creation of the Signal

Charged particles traversing matter leave excited atoms, electron-ion pairs (gases) or electrons-hole pairs (solids) behind.

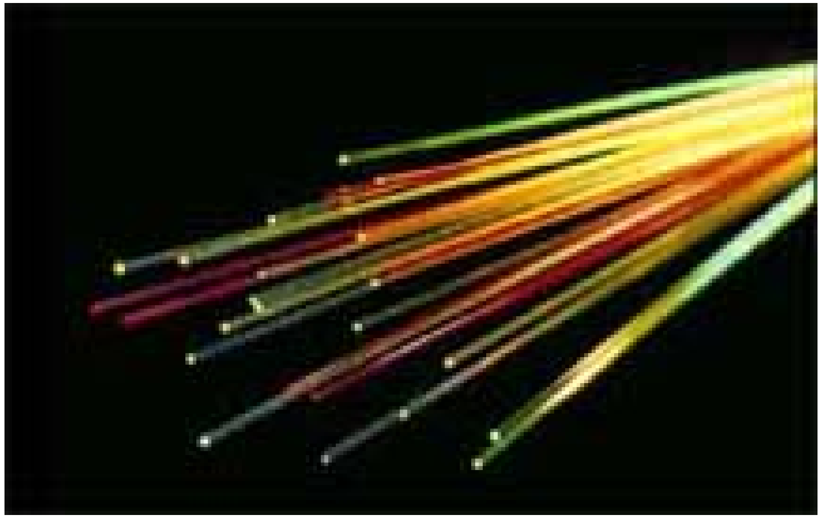


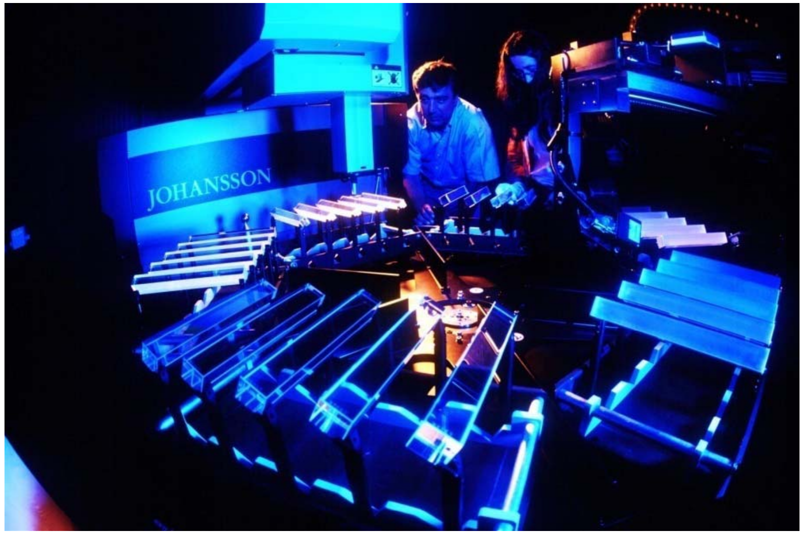
Excitation:

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

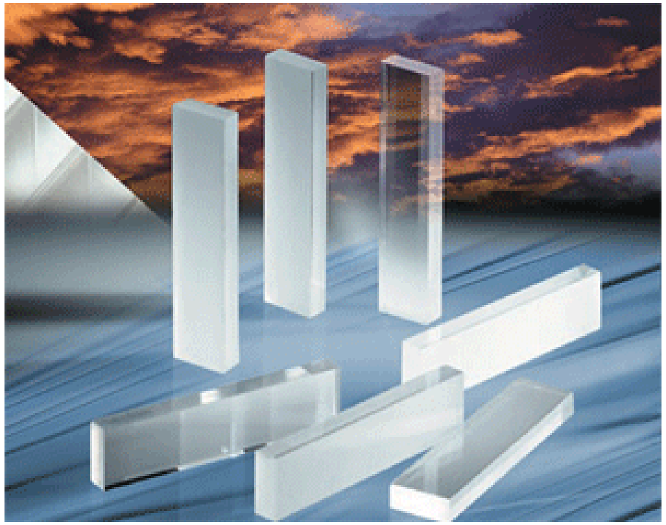
Ionization:

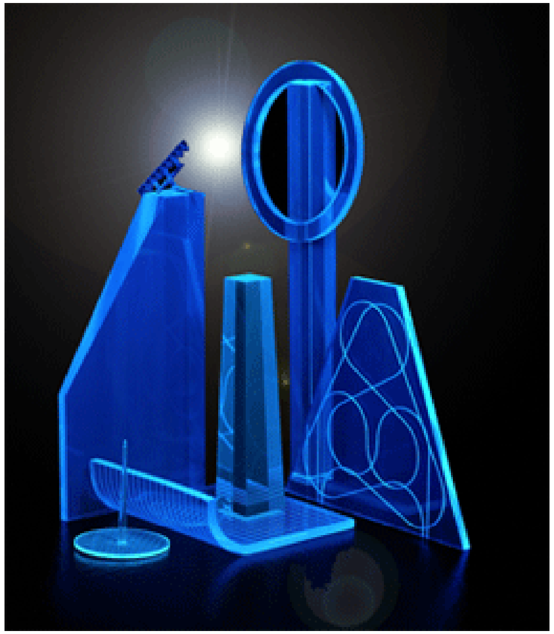
By applying an electric field in the detector volume, the ionization electrons and ions are moving, which induces signals on metal electrodes. These signals are then read out by appropriate readout electronics.



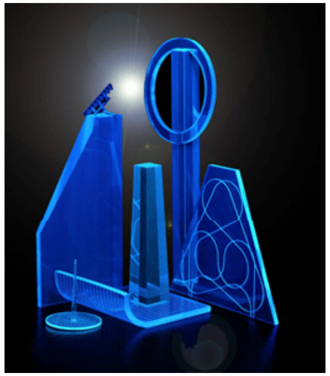


Detectors based on registration of excited Atoms → Scintillators





Detectors based on Registration of excited Atoms → Scintillators



Emission of photons of by excited Atoms, typically UV to visible light.

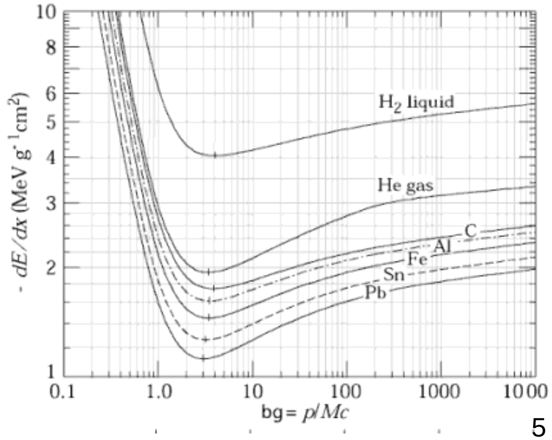
a) **Observed in Noble Gases (even liquid !)**

b) **Inorganic Crystals**
→ **Substances with largest light yield. Used for precision measurement of energetic Photons. Used in Nuclear Medicine.**

c) **Polyzyclic Hydrocarbons (Naphtalen, Anthrazen, organic Scintillators)**
→ **Most important category. Large scale industrial production, mechanically and chemically quite robust. Characteristic are one or two decay times of the light emission.**

Typical light yield of scintillators:

Energy (visible photons) ≈ few % of the total energy Loss.
z.B. 1cm plastic scintillator, $\rho \approx 1$, dE/dx=1.5 MeV, ~15 keV in photons;
i.e. ~ 15 000 photons produced.



Detectors based on Registration of excited Atoms → Scintillators

Organic (‘Plastic’) Scintillators

Low Light Yield **Fast: 1-3ns**

Type	Light[a] output	λ_{max}[b] (nm)	Attenuation[c] length (cm)	Risetime (ns)	Decay[d] 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	~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	~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

LHC bunchcrossing 25ns

Inorganic (Crystal) Scintillators

Large Light Yield **Slow: few 100ns**

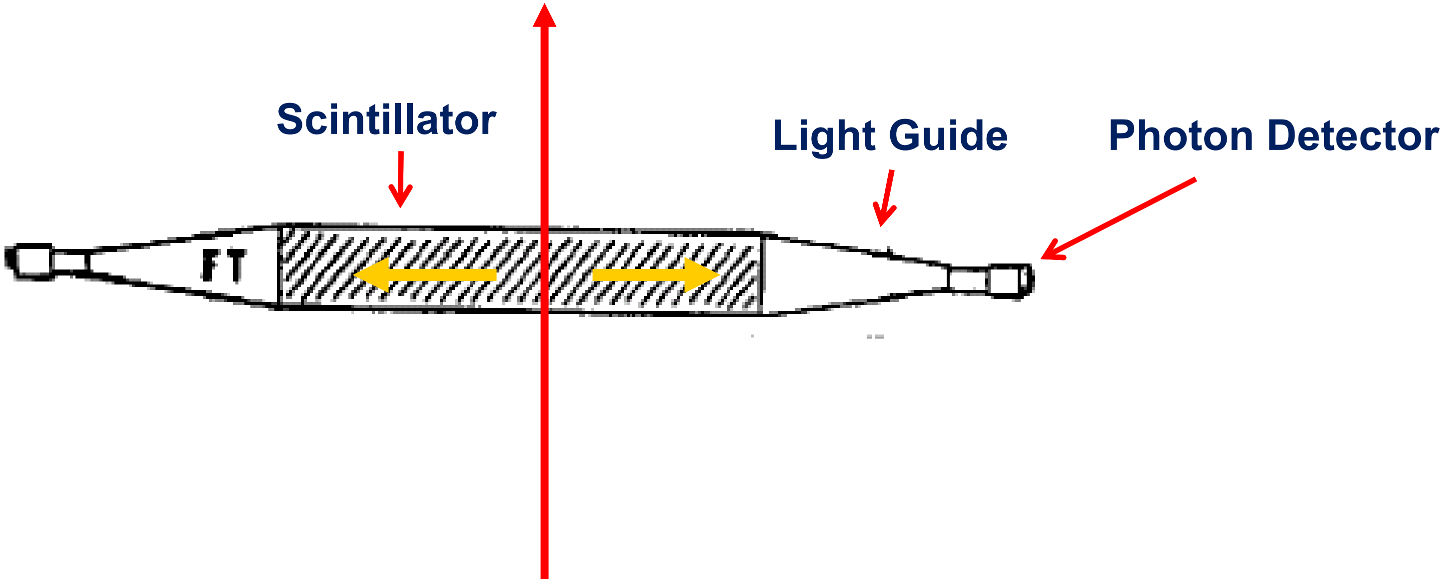
	Relative light output	λ_{max} emission (nm)	Decay time (ns)	Density (g/cm^3)
Inorganic crystals				
NaI(Tl)	230	415	230	3.67
CsI(Tl)	250	560	900	4.51
$Bi_4Ge_3O_{12}$ (BGO)	23–86	480	300	7.13
Organic crystals				
Anthracene	100	448	22	1.25
Trans-stilbene	75	384	4.5	1.16
Naphthalene	32	330–348	76–96	1.03
p,p'-Quarterphenyl	94	437	7.5	1.20
Primary activators				
2,5-Diphenyl-oxazole (PPO)	75	360–416	5[a]	
2-Phenyl-5-(4-biphenylyl)-1,3,4-oxadiazole (PBD)	96	360–5		
4,4''-Bis(2-butyloctyloxy)-*p*-quaterphenyl (BIBUQ)	60	365,393	1.30[a]	

LEP bunchcrossing 25µs

Scintillators

Photons are being reflected towards the ends of the scintillator.

A light guide brings the photons to the Photomultipliers where the photons are converted to an electrical signal.

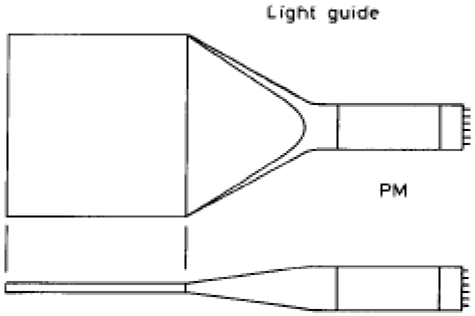


By segmentation one can arrive at spatial resolution.

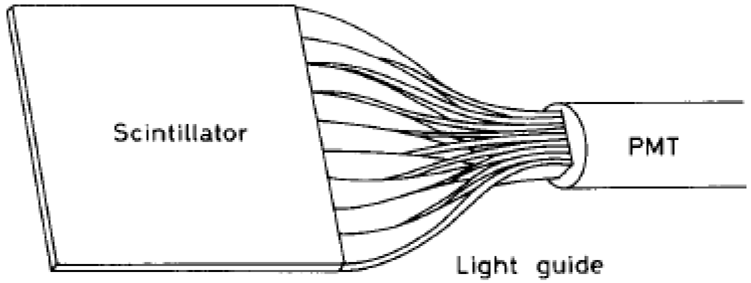
Because of the excellent timing properties (<1ns) the arrival time, or time of flight, can be measured very accurately → Trigger, Time of Flight.

Typical Geometries:

- Light guides: transfer by total internal reflection (+outer reflector)

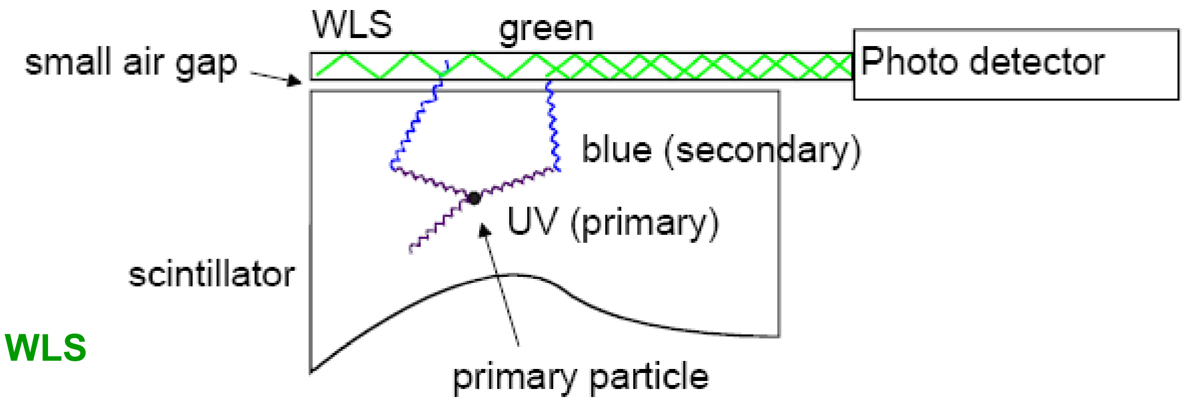


“fish tail”



adiabatic

- wavelength shifter (WLS) bars



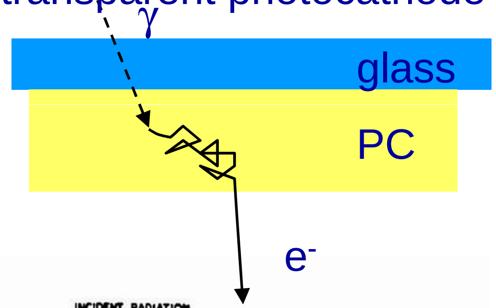
UV light enters the WLS material
Light is transformed into longer wavelength
→Total internal reflection inside the WLS material
→ ‘transport’ of the light to the photo detector

From C. Joram

The frequent use of Scintillators is due to:

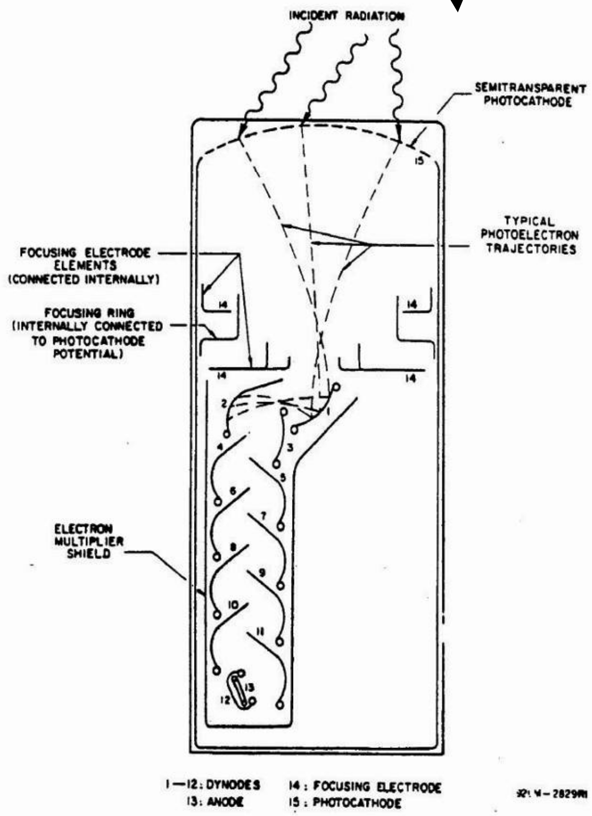
Well established and cheap techniques to register Photons → Photomultipliers and the fast response time → 1 to 100ns

Semitransparent photocathode



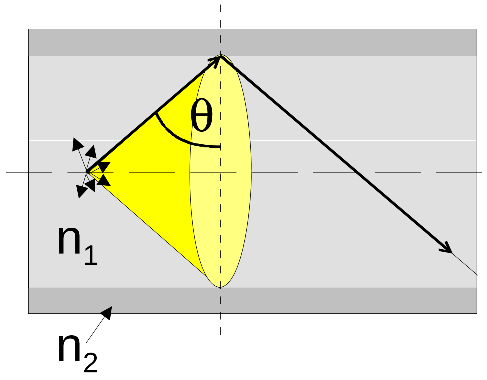
Schematic of a Photomultiplier:

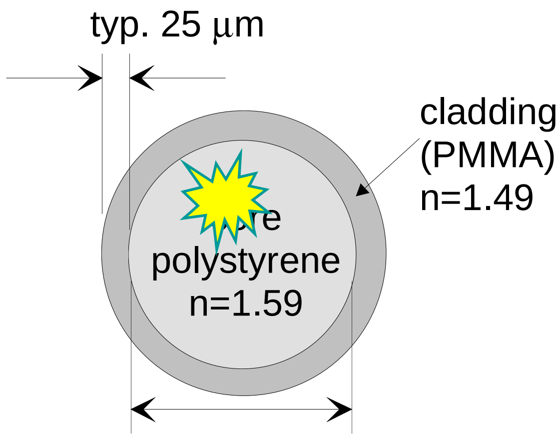
- **Typical Gains (as a function of the applied voltage): 10^8 to 10^{10}**
- **Typical efficiency for photon detection:**
- **< 20%**
- **For very good PMs: registration of single photons possible.**
- **Example: 10 primary Elektrons, Gain 10^7 → 10^8 electrons in the end in T ≈ 10ns. I=Q/T = $10^8 \cdot 1.603 \cdot 10^{-19} / 10 \cdot 10^{-9}$ = 1.6mA.**
- **Across a 50 Ω Resistor → U=R*I= 80mV.**



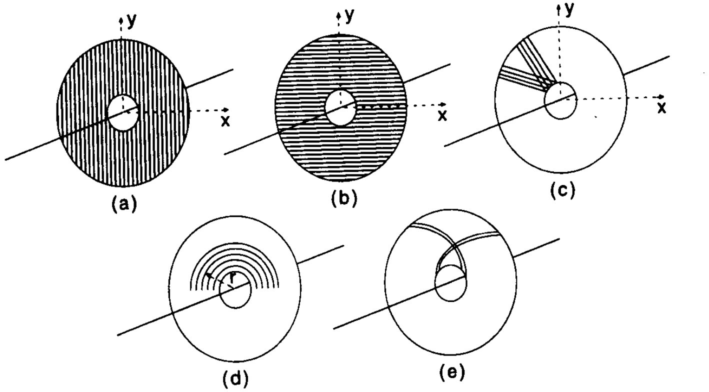
Fiber Tracking

Light transport by total internal reflection

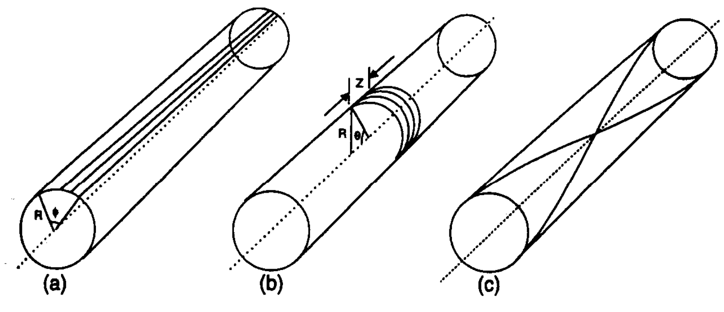




Planar geometries
(end cap)



Circular geometries
(barrel)



High geometrical flexibility

Fine granularity

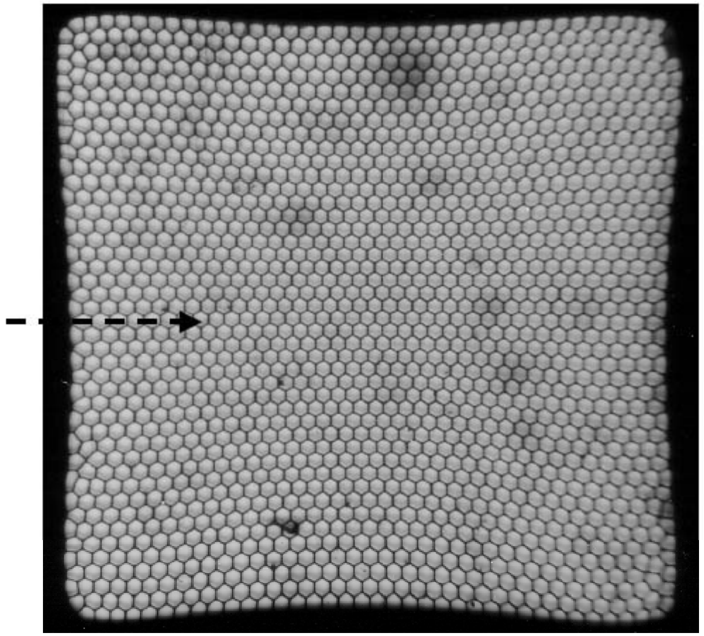
Low mass

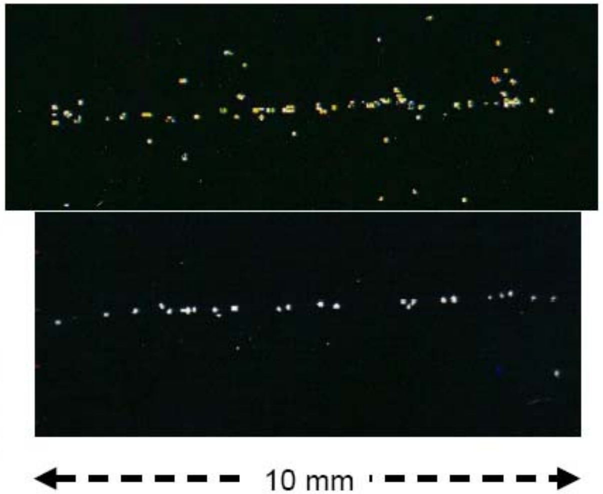
Fast response (ns)

(R.C. Ruchti, Annu. Rev. Nucl. Sci. 1996, 46,281)

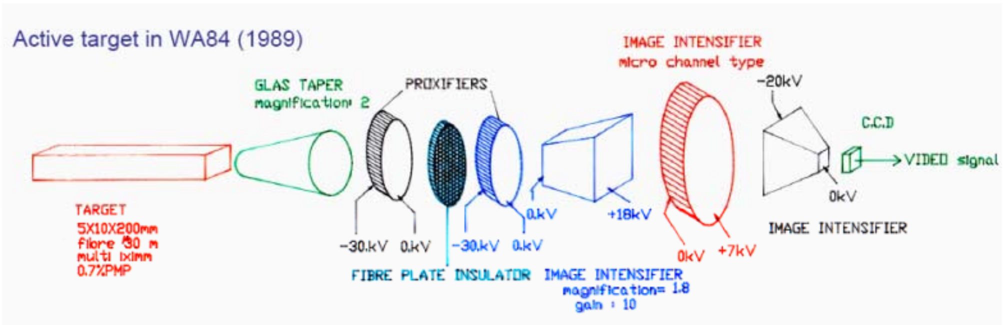
From C. Joram

Fiber Tracking





Images of tracks from 5 GeV/c pions (1989)



Readout of photons in a cost effective way is rather challenging.

From C. Joram

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.

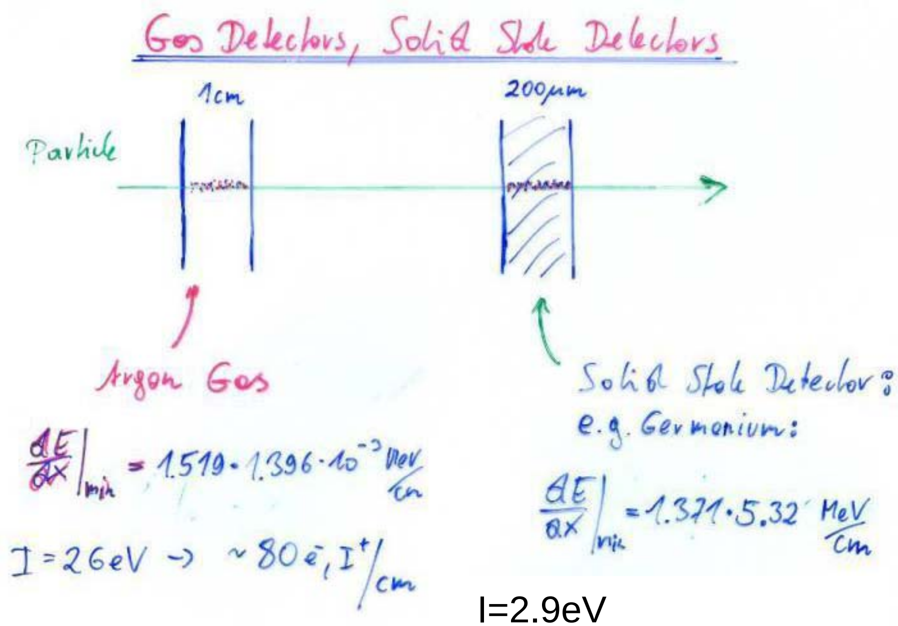
The produced charges can be registered → Position measurement → Tracking Detectors.

Cloud Chamber: Charges create drops → photography.
Bubble Chamber: Charges create bubbles → photography.
Emulsion: Charges 'blacked' the film.

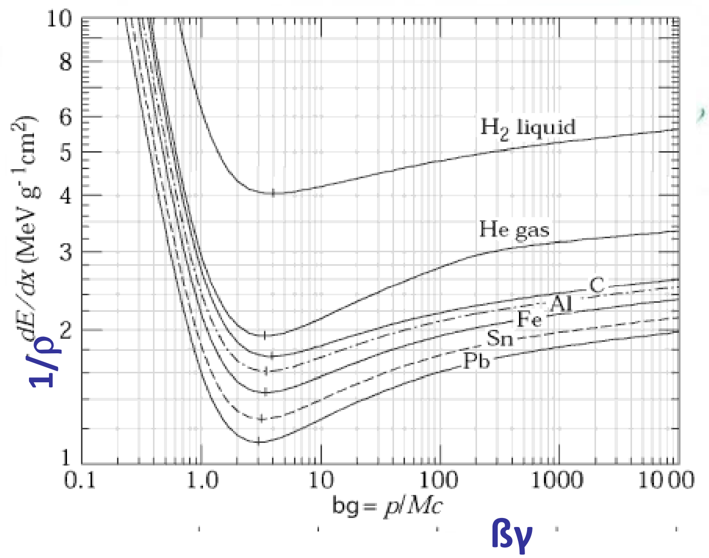
Gas and Solid State Detectors: Moving Charges (electric fields) induce electronic signals on metallic electrons that can be read by dedicated electronics.

→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.



I=2.9eV
2.5 x 10^6 e/h pairs/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 >> ENC i.e. typically q>>1000e-.

Gas Detector: q=80e- /cm → too small.

Solid state detectors have 1000x more density and factor 5-10 less ionization energy.
→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).

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.

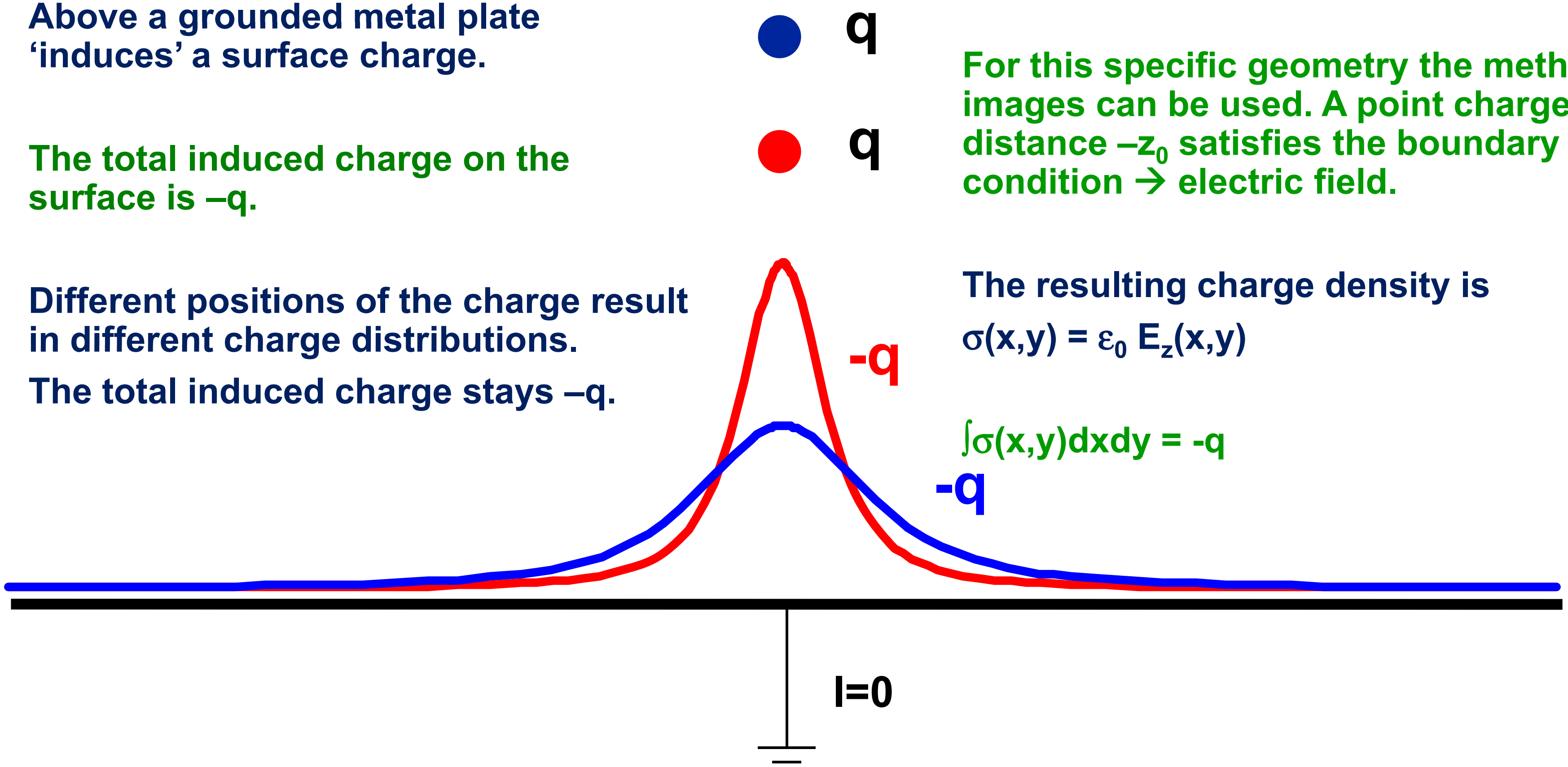
The electric field of the charge must be calculated with the boundary condition that the potential φ=0 at z=0.

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

The resulting charge density is

$\sigma(x,y) = \varepsilon_0 E_z(x,y)$

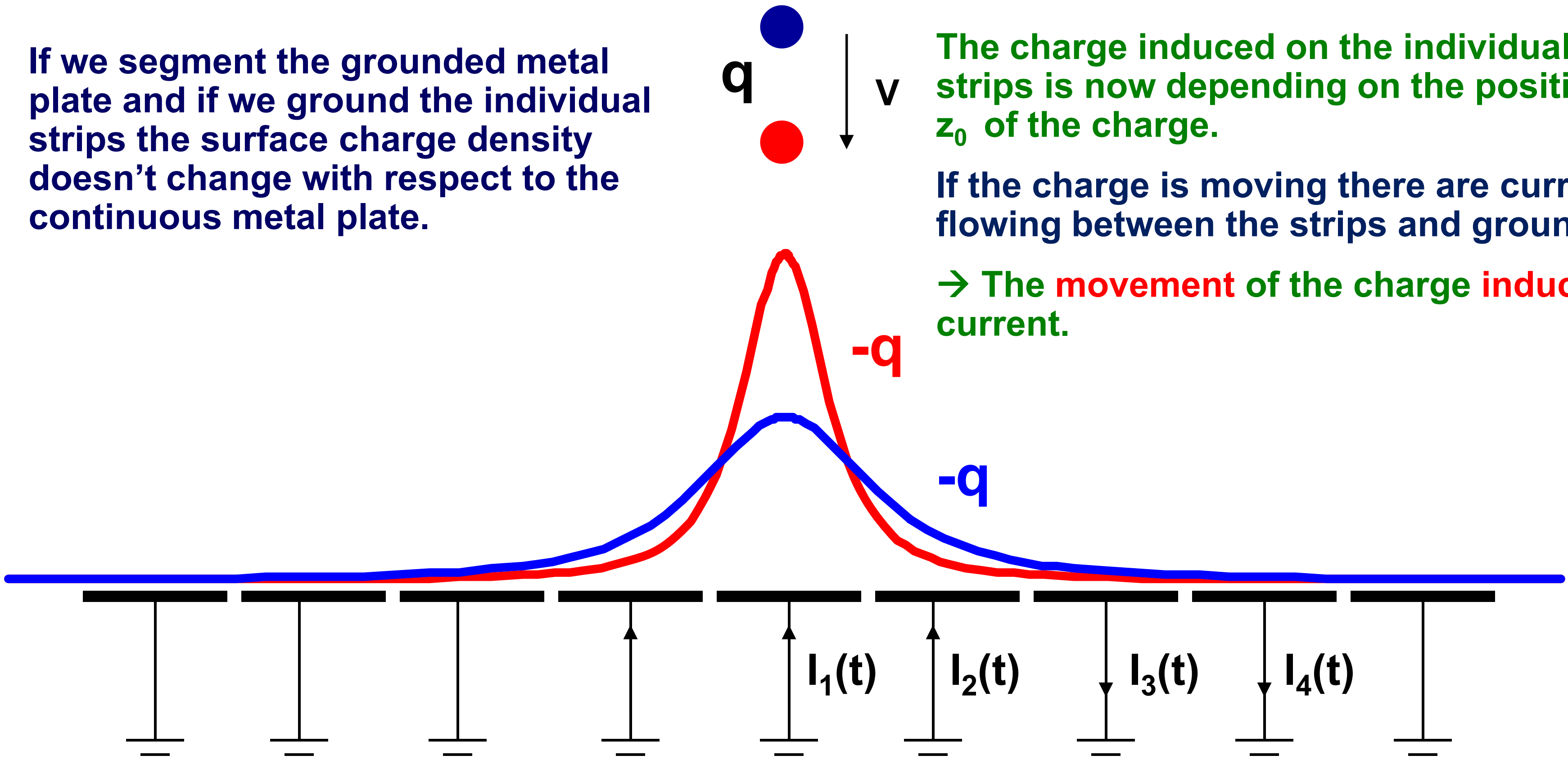
$\int \sigma(x,y)dxdy = -q$



$$E_z(x,y) = -\frac{q z_0}{2\pi\varepsilon_0 (x^2+y^2+z_0^2)^{\frac{3}{2}}} \qquad E_x = E_y = 0 \qquad \sigma(x,y) = \varepsilon_0 E_z(x,y) \qquad Q = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \sigma(x,y)dxdy = -q$$

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.

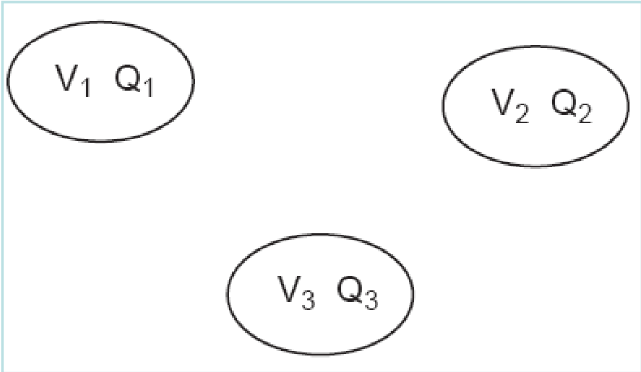
$$Q_1(z_0) = \int_{-\infty}^{\infty}\int_{-w/2}^{w/2} \sigma(x,y)dxdy = -\frac{2q}{\pi}\arctan\left(\frac{w}{2z_0}\right)$$

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

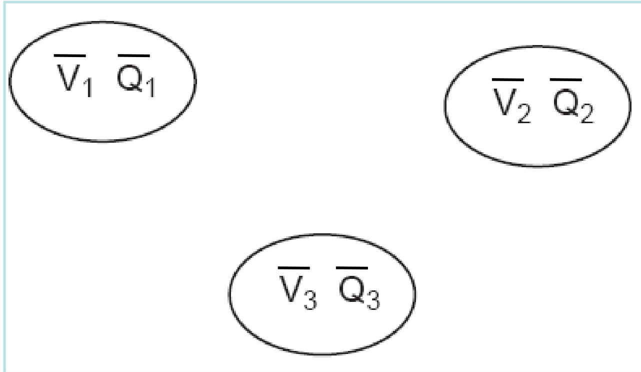
$$I_1^{ind}(t) = -\frac{d}{dt}Q_1[z_0(t)] = -\frac{\partial Q_1[z_0(t)]}{\partial z_0}\frac{dz_0(t)}{dt} = \frac{4qw}{\pi[4z_0(t)^2 + w^2]}v$$

Signal Theorems

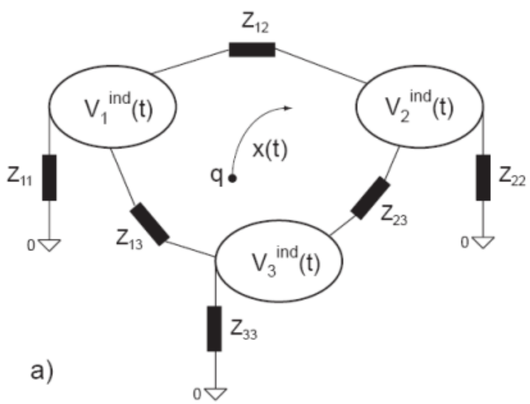
Placing charges on metal electrodes results in certain potentials of these electrodes. A different set of charges results in a different set of potentials. The reciprocity theorem states that



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



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.

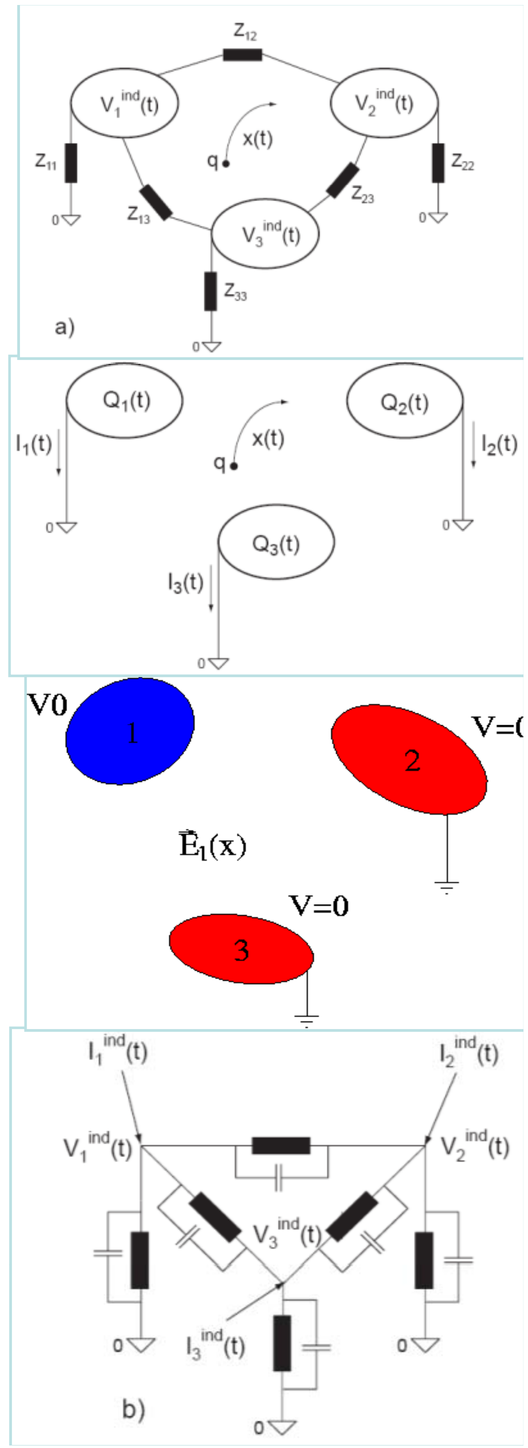
The current induced on a grounded electrode by a charge q moving along a trajectory x(t) is calculated the following way (Ramo Theorem):

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

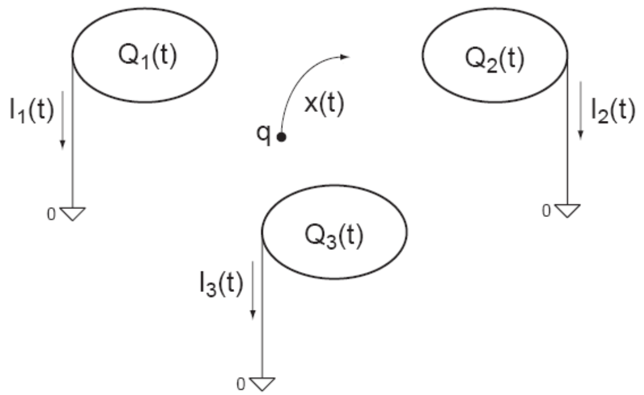
$$I_n(t) = -\frac{q}{V_0}\vec{E_n}[\vec{x}(t)]\frac{d\vec{x}(t)}{dt} = -\frac{q}{V_0}\vec{E_n}[\vec{x}(t)]\vec{v}(t)$$

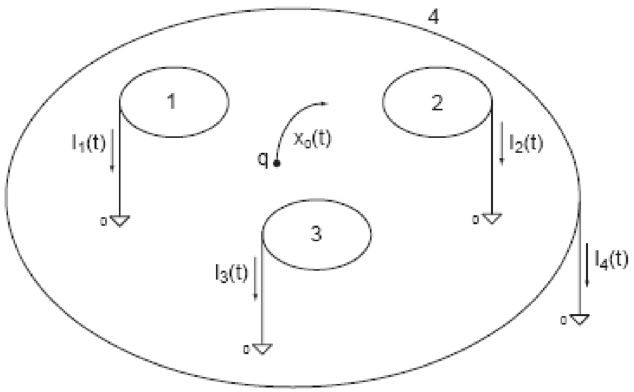
These currents are then placed as ideal current sources on a circuit where the electrodes are 'shrunk' to simple nodes and the mutual electrode capacitances are added between the nodes. These capacitances are calculated from the weighting fields by

$$c_{nm} = \frac{\varepsilon_0}{V_w}\oint_{\boldsymbol{A}_n} \boldsymbol{E}_m(\boldsymbol{x})d\boldsymbol{A} \qquad C_{nn} = \sum_m c_{nm} \qquad C_{nm} = -c_{nm} \quad n \neq m$$



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 x_0 to a point x_1 is**

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

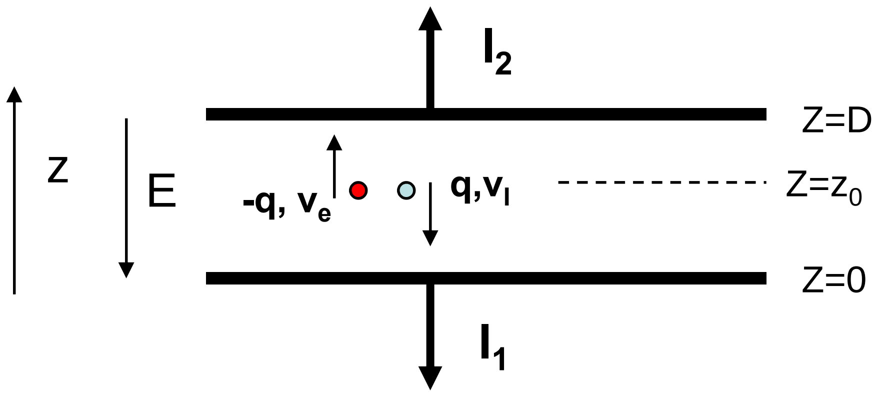
and is independent on the actual path.

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.

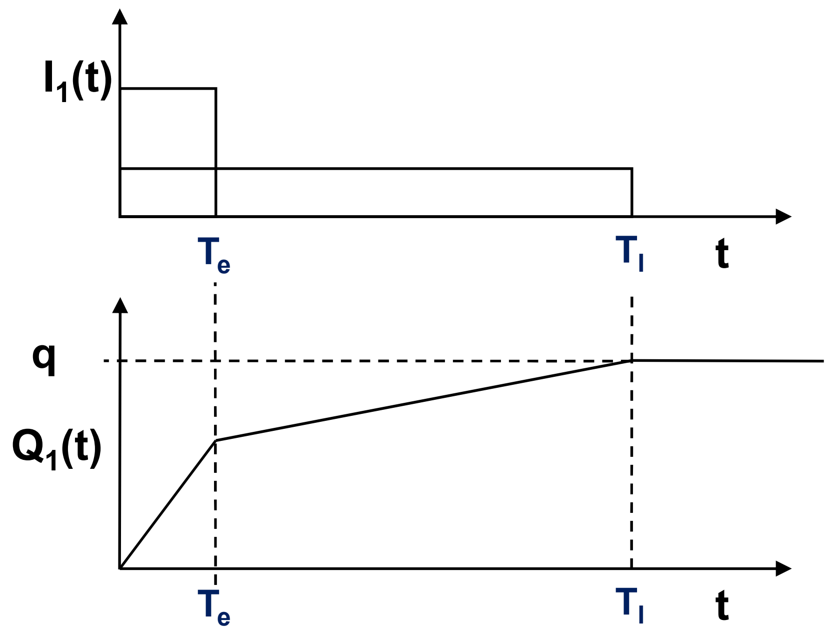
Signals in a Parallel Plate Geometry

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



$E_1=V_0/D$
$E_2=-V_0/D$

$I_1= -(-q)/V_0*(V_0/D)*v_e - q/V_0\ (V_0/D)\ (-v_I)$
$= q/D*v_e+q/D*v_I$
$I_2=-I_1$



$Q^{tot}_1= \int I_1 dt = q/D*v_e\ T_e + q/D*v_I*T_I$
$= q/D*v_e*(D-z_0)/v_e + q/D*v_I*z_0/v_I$
$= q(D-z_0)/D + qz_0/D =$
$q_e+q_I=q$

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.

Detectors based on Ionization

→ Gas detectors:

- Wire Chambers
- Drift Chambers
- Time Projection Chambers
- Transport of Electrons and Ions in Gases

Solid State Detectors

- Transport of Electrons and Holes in Solids
- Si- Detectors
- Diamond Detectors

Gas Detectors with internal Electron Multiplication

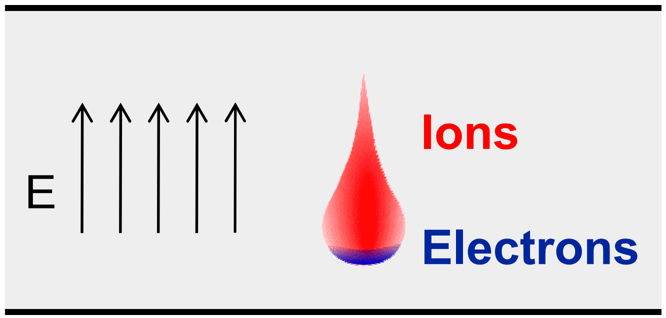
Principle: At sufficiently high electric fields (100kV/cm) the electrons gain energy in excess of the ionization energy → secondary ionzation etc. etc.

$dN = N \alpha dx$ α…Townsend Coefficient

$N(x) = N_0 \exp(\alpha x)$ $N/N_0 = A$ (Amplification, Gas Gain)

Avalanche in a homogeneous field:

Problem: High field on electrode surface → breakdown



In an inhomogeneous Field: α(E) → $N(x) = N_0$ exp [⇩α(E(x'))dx']

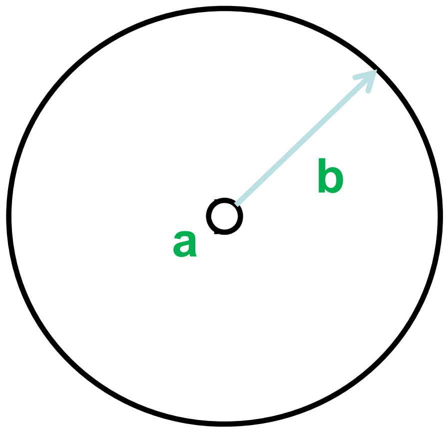
Wire Chamber: Electron Avalanche

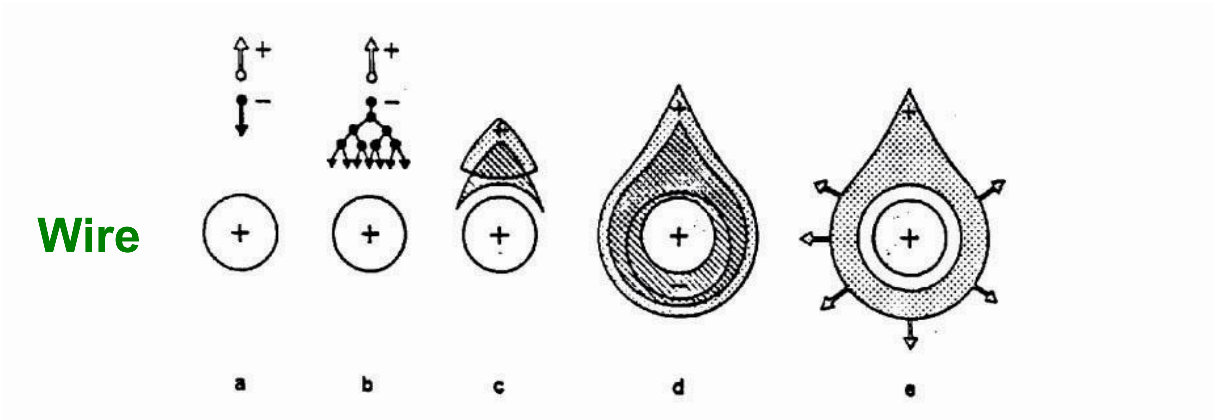
Wire with radius (10-25μm) in a tube of radius b (1-3cm):

$$E(r) = \frac{\lambda}{2\pi\varepsilon_0}\frac{1}{r} = \frac{V_0}{\ln\frac{b}{a}}\frac{1}{r}, \qquad V(r) = \frac{V_0}{\ln\frac{b}{a}}\ln\frac{r}{a},$$

Electric field close to a thin wire (100-300kV/cm). E.g. V_0=1000V, a=10μm, b=10mm, E(a)=150kV/cm

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





Wire Chamber: Electron Avalanches on the Wire

Proportional region: A≈10^3-10^4 **LHC**

Semi proportional region: A≈10^4-10^5
(space charge effect)

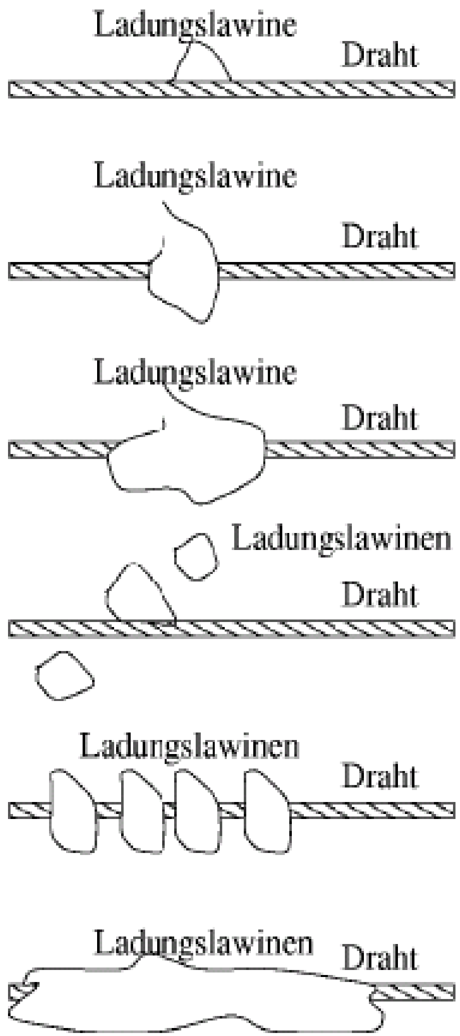
Saturation region: A >10^6
Independent the number of primary electrons.

1970ies

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

Limited Geiger region:
Avalanche propagated by UV photons.

Geiger region: A≈10^9 **1950ies**
Avalanche along the entire wire.

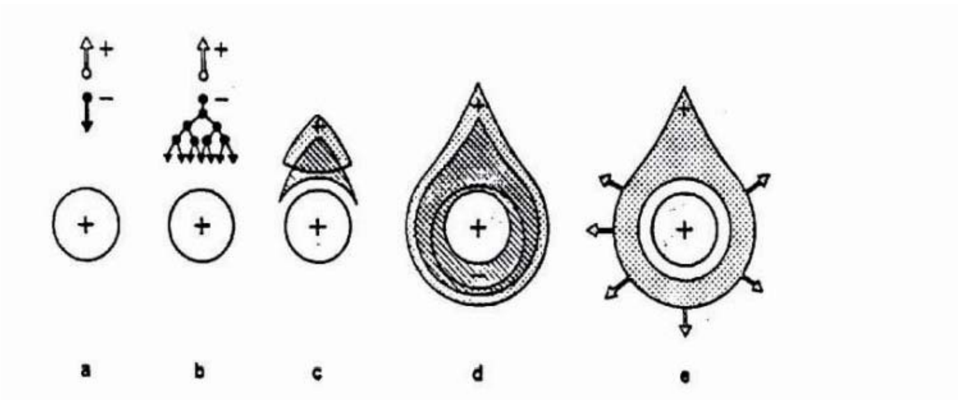


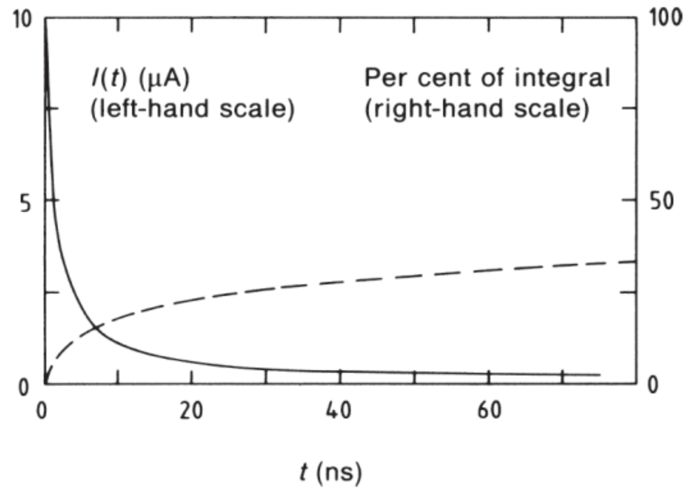
Wire Chamber: Signals from Electron Avalanches

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 (<<1ns). Ions are difting towards the tube wall (typically several 100μs.)

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

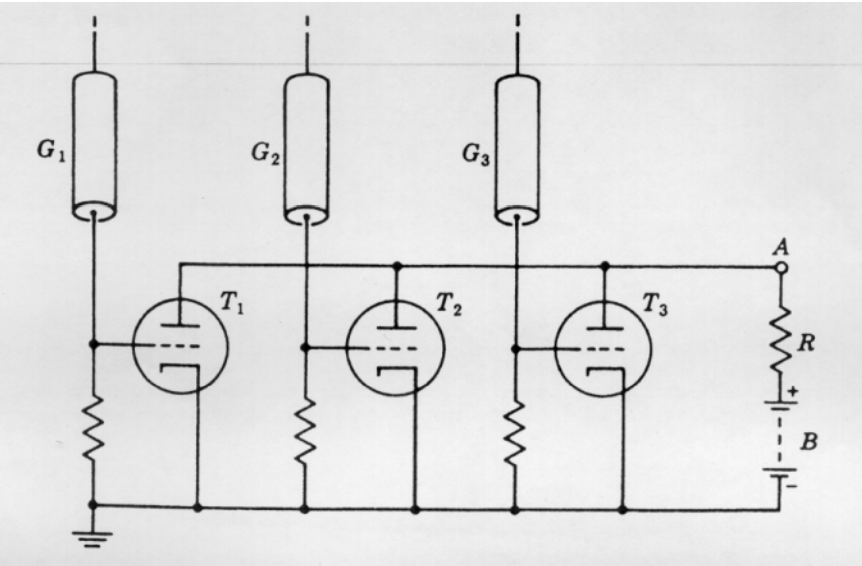
The total charge induced by the electrons, i.e. the charge of the current spike due to the short electron movement amounts to 1-2% of the total induced charge.



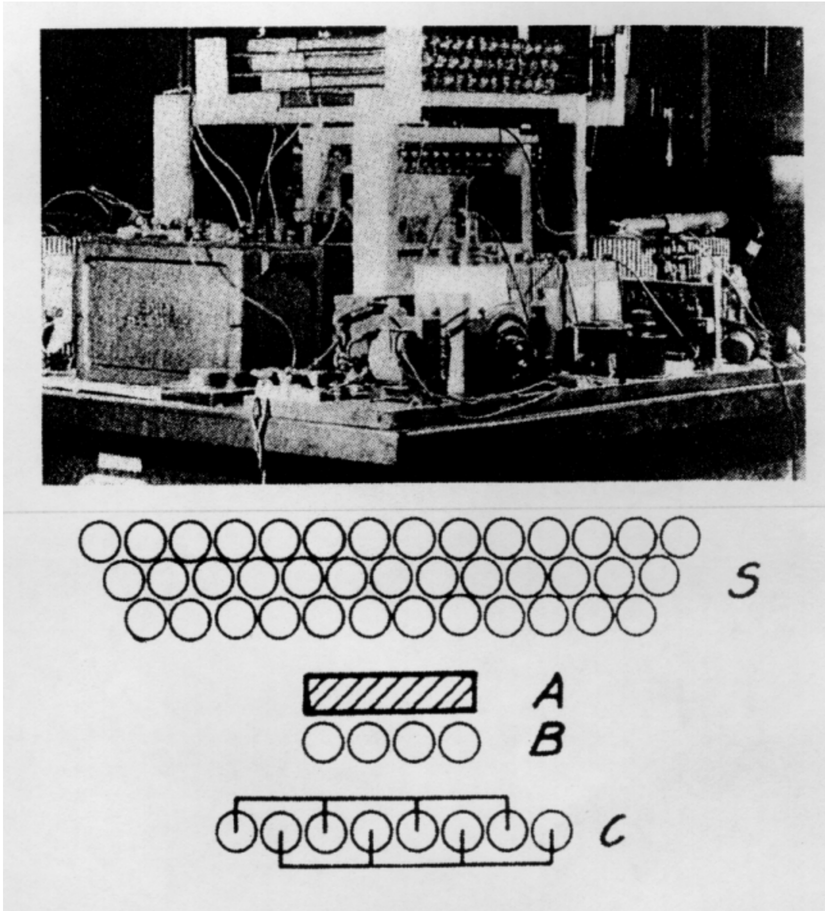


Detectors with Electron Multiplication

Rossi 1930: Coincidence circuit for n tubes



Cosmic ray telescope 1934



Geiger mode, large deadtime

Position resolution is determined by the size of the tubes.

Signal was directly fed into an electronic tube.

Multi Wire Proportional Chamber

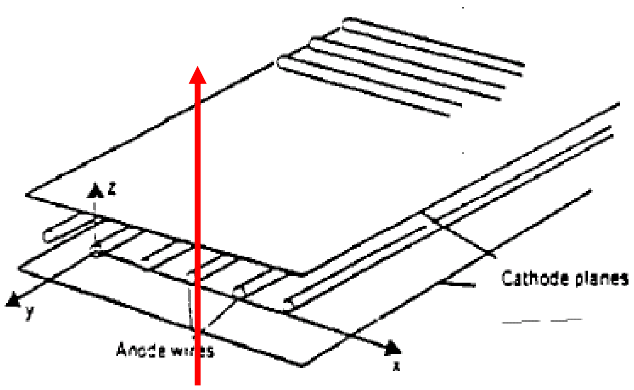
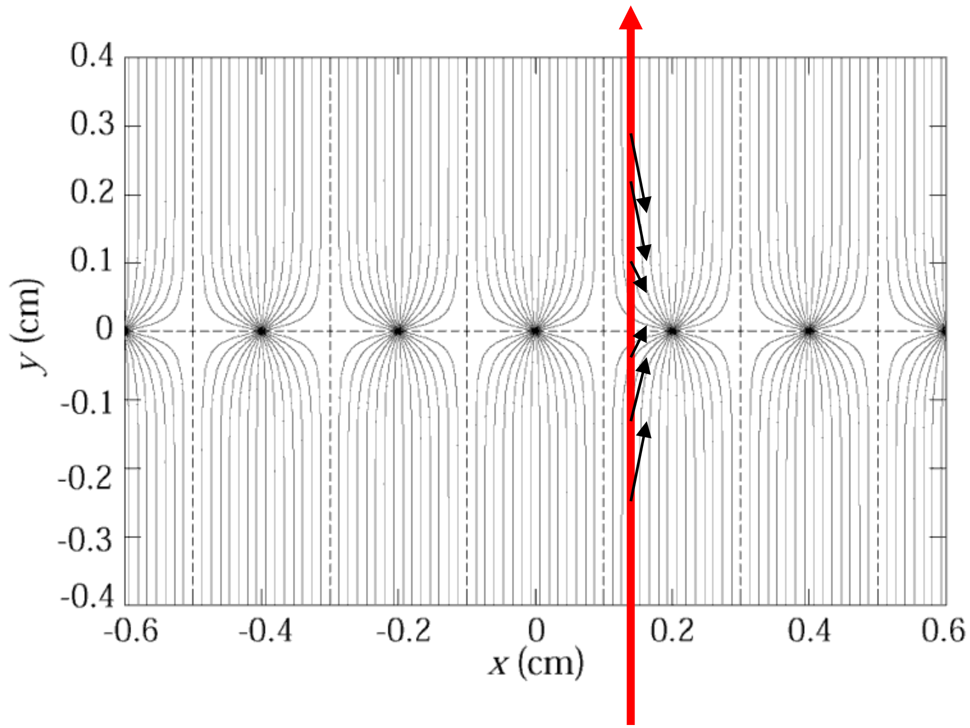


Abbildung 2.27: *Vieldrahtproportionalkammer.*



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

For 10% occupancy → every μs one pulse

→ 1MHz/wire rate capabiliy !

→ Compare to Bubble Chamber with 10 Hz !

Multi Wire Proportional Chamber

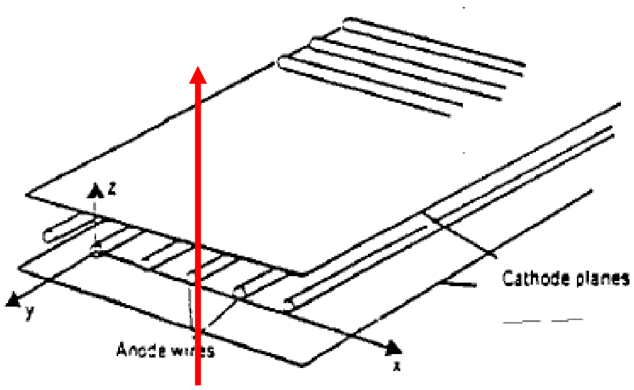
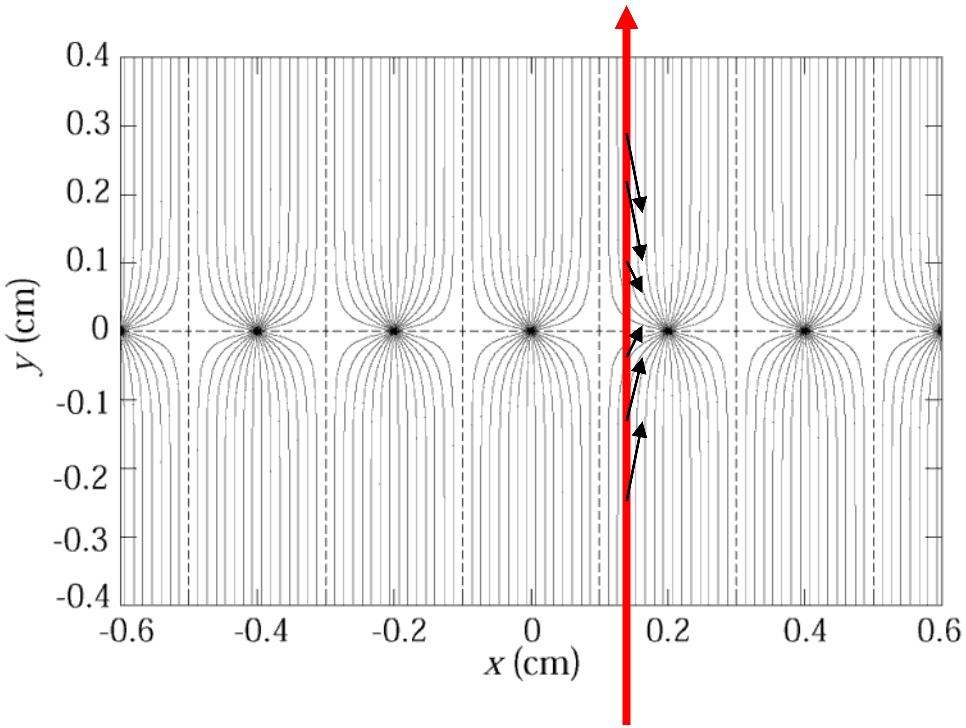


Abbildung 2.27: *Vieldrahtproportionalkammer.*



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

For second coordinate:

→Another chamber at 90^0 relative rotation

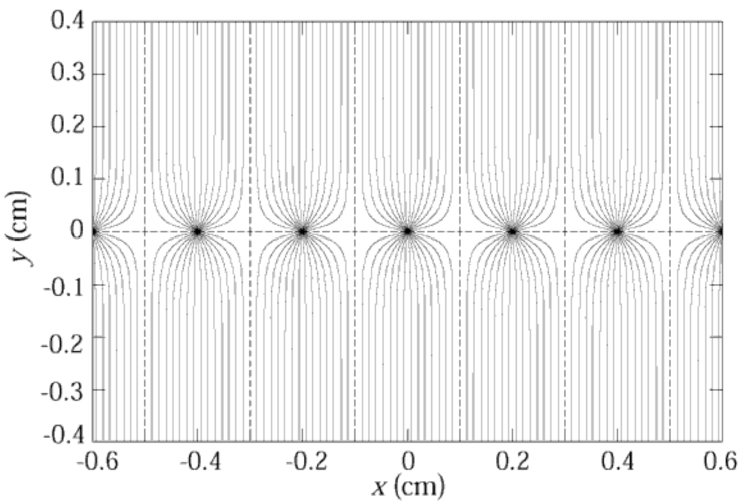
→Signal propagation to the two ends of the wire.

→Pulse height measurement on both ends of the wire. Because of resisitvity 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 50µm can be achieved.

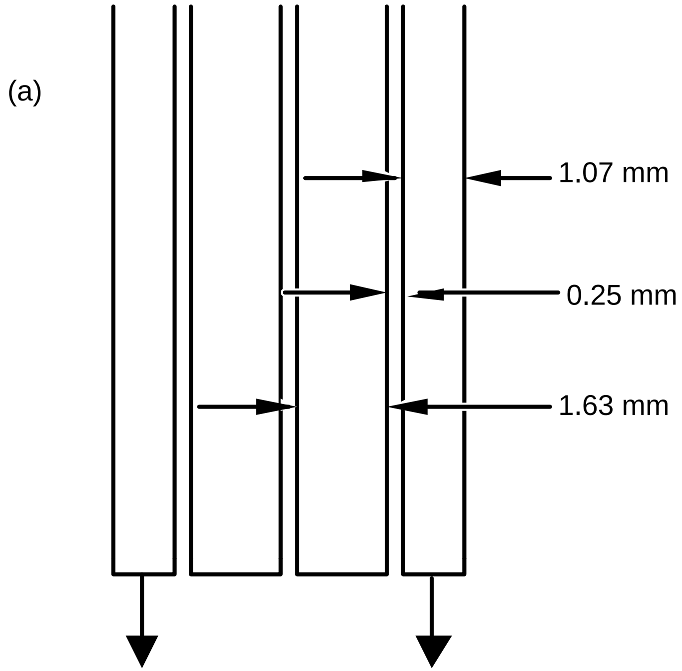
Multi Wire Proportional Chamber

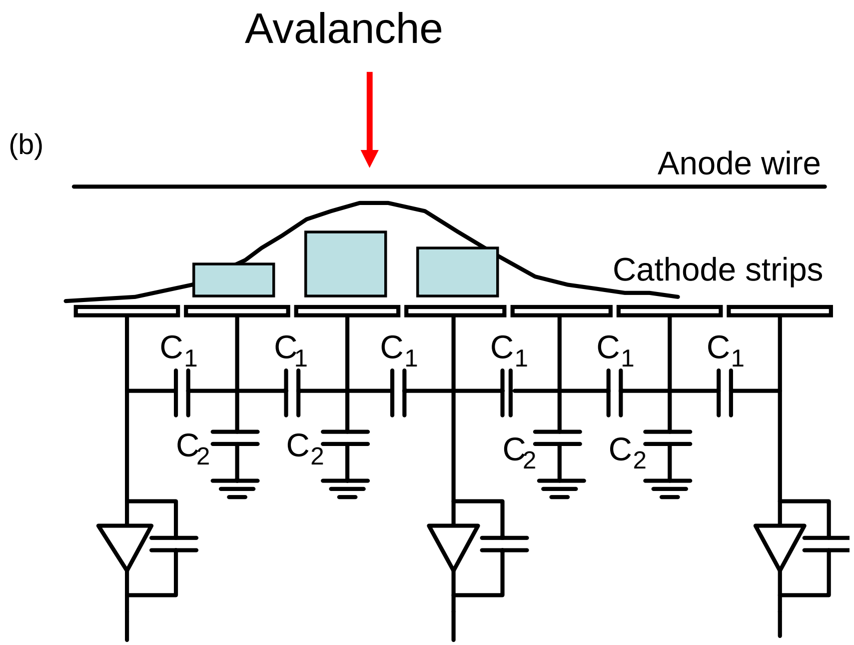


Cathode strip:

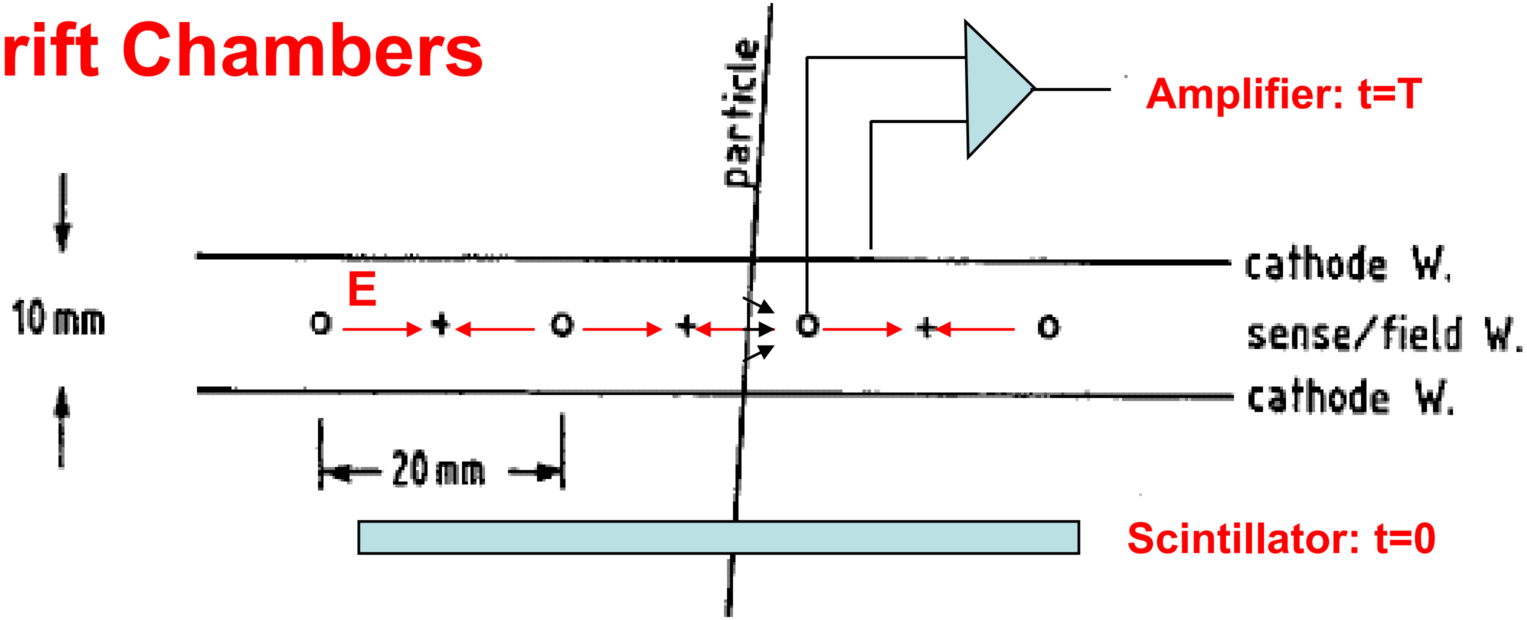
Width (1σ) of the charge distribution ≈ distance between Wires and cathode plane.

'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.

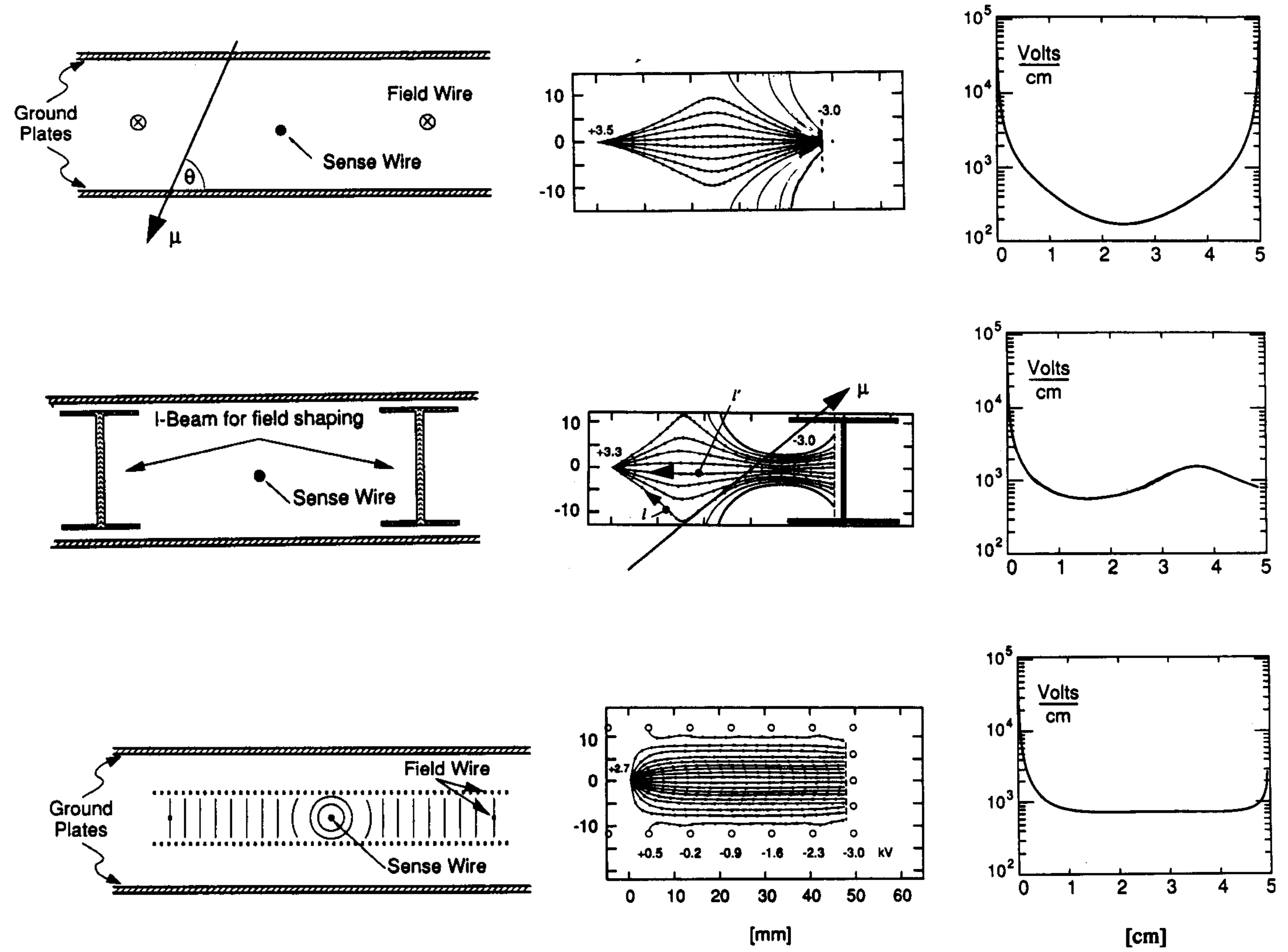
The time between the passage of the particle and the arrival of the electrons at the wire is measured.

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

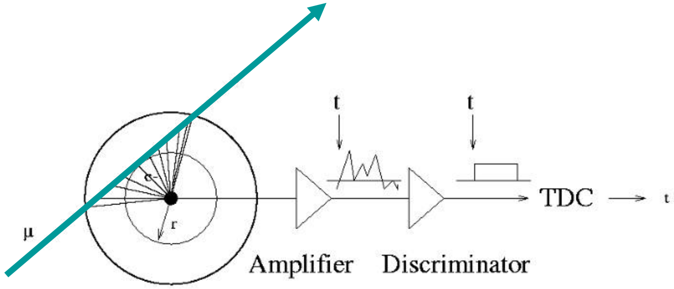
Electric Field ≈ 1kV/cm



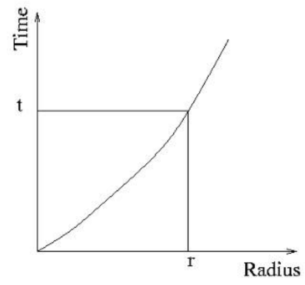
W. Klempt, Detection of Particles with Wire Chambers, Bari 04

The Geiger Counter reloaded: Drift Tube

ATLAS MDT R(tube) =15mm



Calibrated Radius-Time correlation



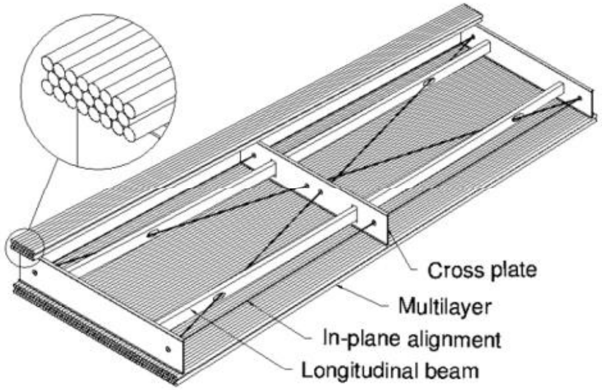
Primary electrons are drifting to the wire.

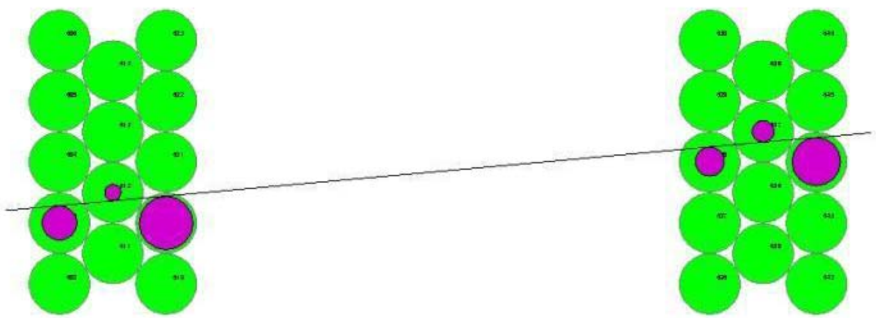
Electron avalanche at the wire.

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, 80µm per tube

The Geiger counter reloaded: Drift Tube

Atlas Muon Spectrometer, 44m long, from r=5 to11m.

1200 Chambers

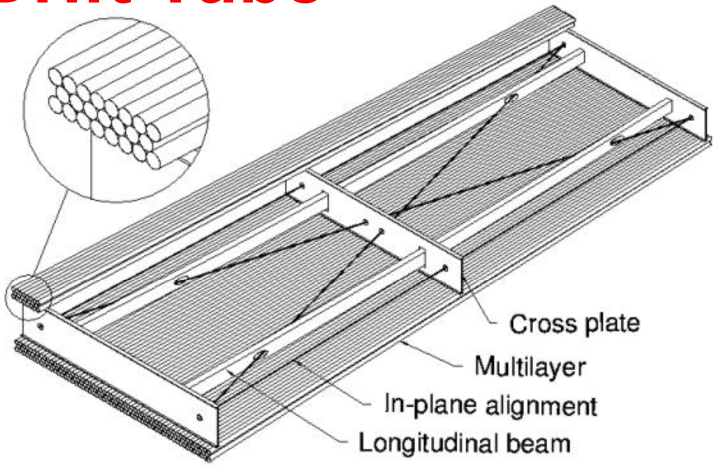
6 layers of 3cm tubes per chamber.

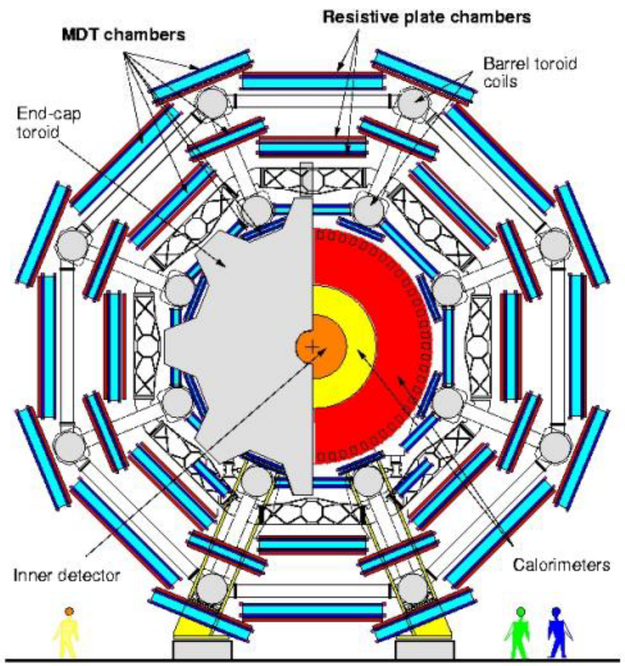
Length of the chambers 1-6m !

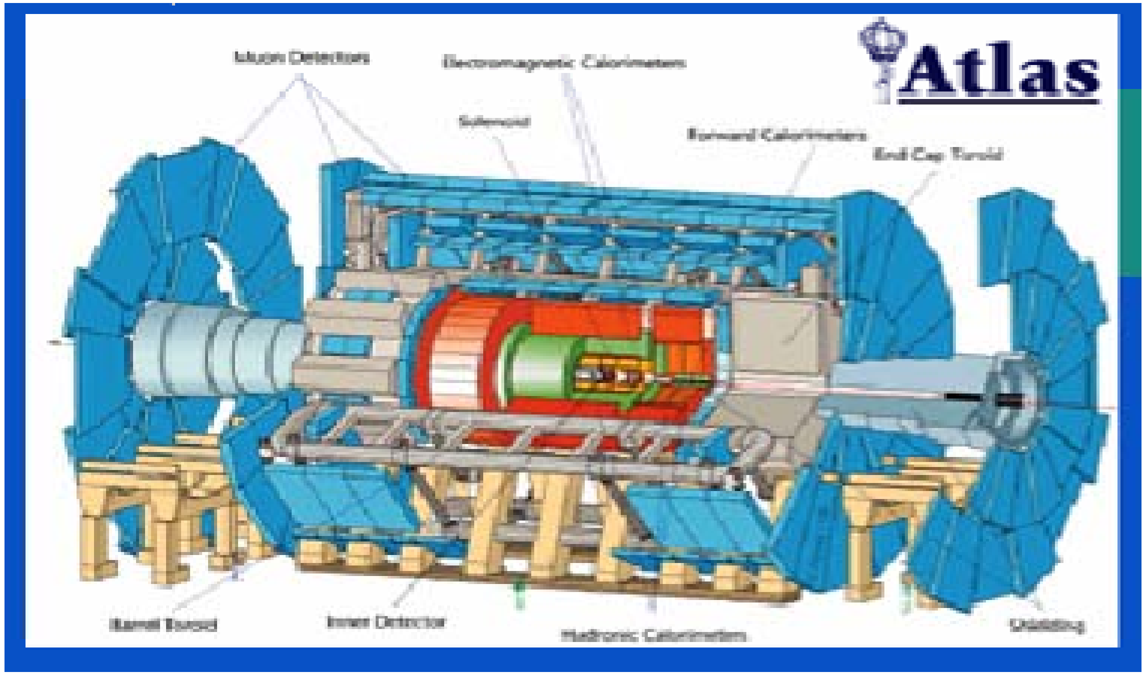
Position resolution: 80μm/tube, <50μm/chamber (3 bar)

Maximum drift time ≈700ns

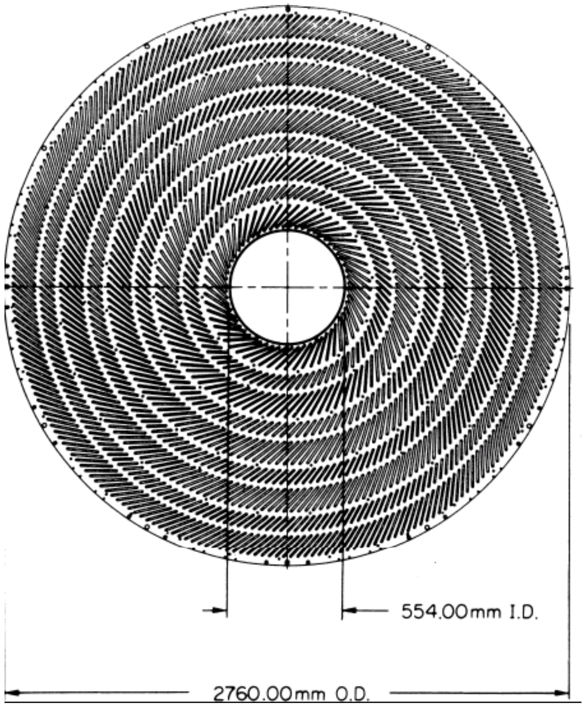
Gas Ar/CO_2 93/7





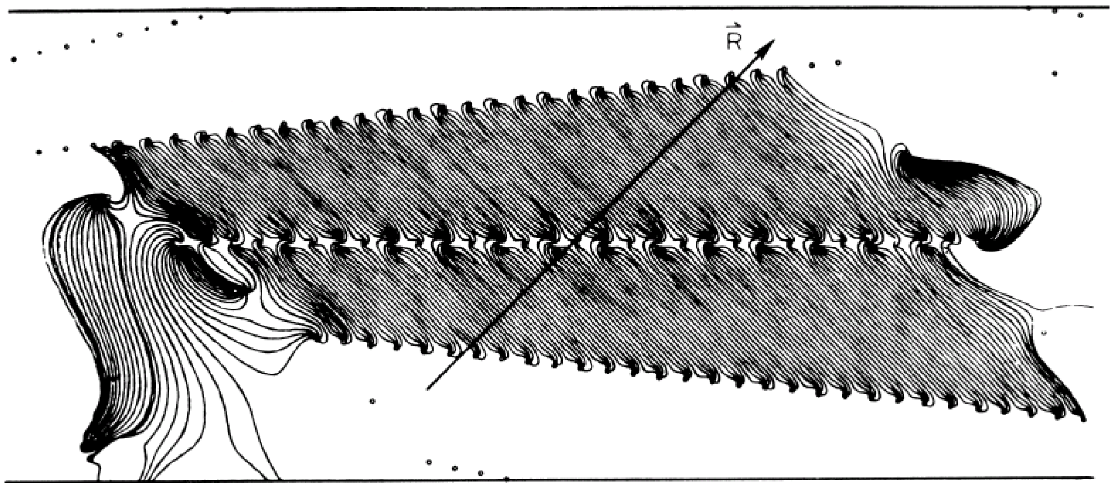


Large Drift Chambers



Central Tracking Chamber CDF Experiment.

660 drift cells tilted 45^0 with respect to the particle track.



Drift cell

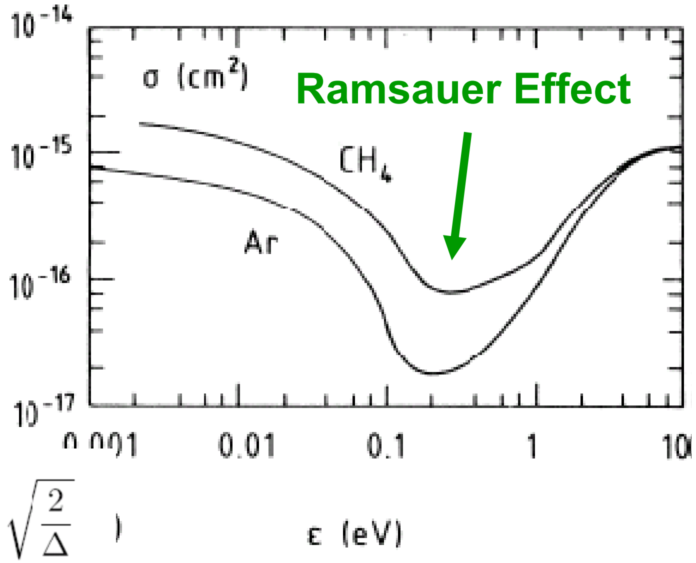
Transport of Electrons in Gases: Drift-velocity

Electrons are completely ‘randomized’ in each collision. The actual drift velocity v along the electric field is quite different from the average velocity u of the electrons i.e. →about 100 times smaller.

The velocities v and u are determined by the atomic crossection σ(ε) and the fractional energy loss Δ(ε) per collision (N is the gas density i.e. number of gas atoms/m^3, m is the electron mass.):

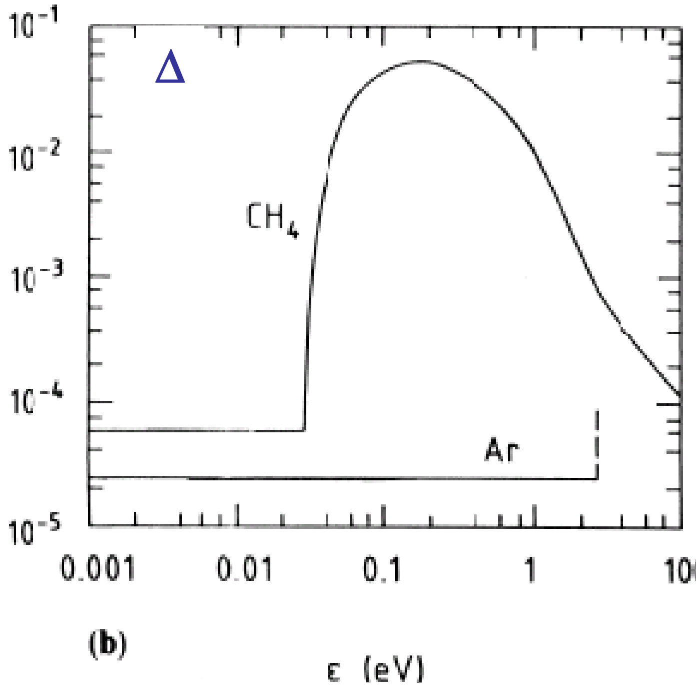
$$v = \sqrt{\frac{eE}{mN\sigma}\sqrt{\frac{\Delta}{2}}} \qquad u = \sqrt{\frac{eE}{mN\sigma}\sqrt{\frac{2}{\Delta}}}$$

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

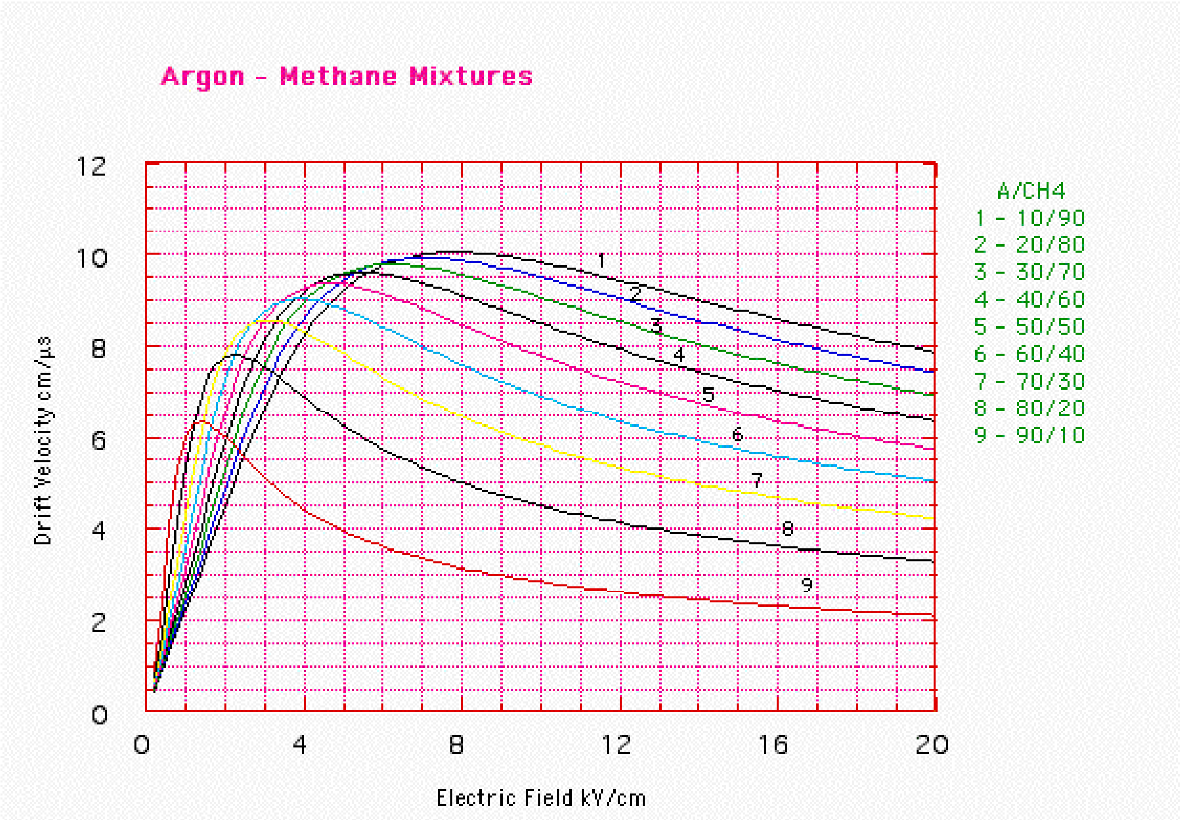


Because σ(ε) und Δ(ε) show a strong dependence on the electron energy in the typical electric fields, the electron drift velocity v shows a strong and complex variation with the applied electric field.

v is depending on E/N: doubling the electric field and doubling the gas pressure at the same time results in the same electric field.



Transport of Electrons in Gases: Drift-velocity

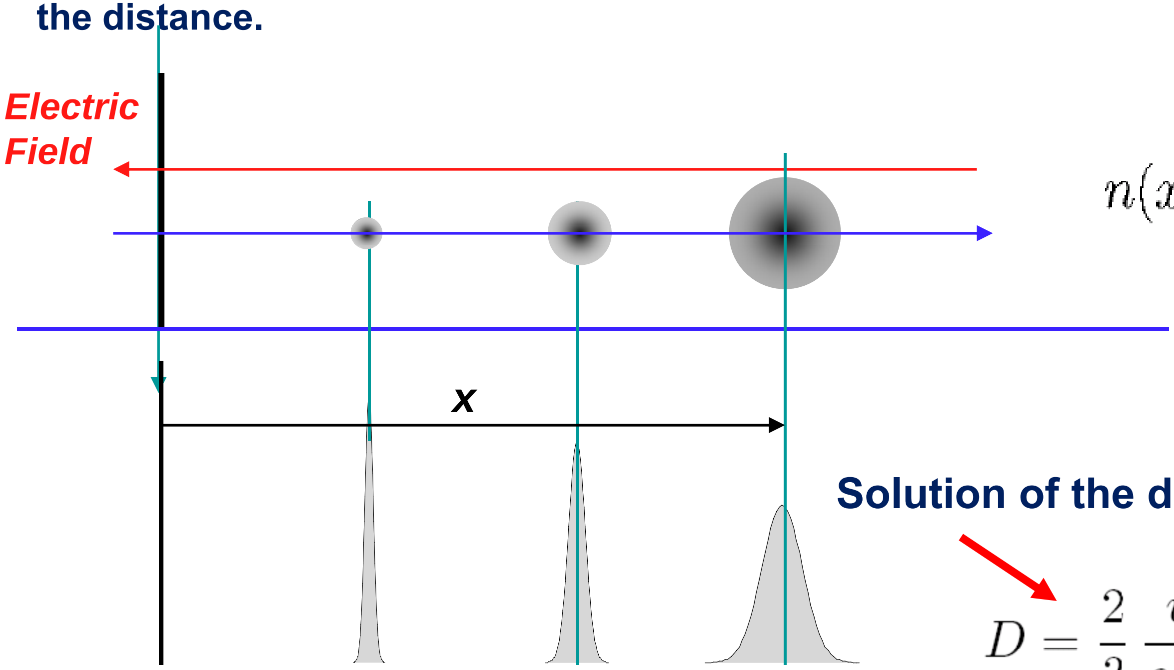


Typical Drift velocities are v=5-10cm/µs (50 000-100 000m/s).
The microscopic velocity u is about ca. 100mal larger.

Only gases with very small electro negativity are useful (electron attachment)
→Noble Gases (Ar/Ne) are most of the time the main component of the gas.
→Admixture of CO_2, CH_4, Isobutane etc. for 'quenching' is necessary (avalanche multiplication – see later).

Transport of Electrons in Gases: Diffusion

An initially point like cloud of electrons will 'diffuse' because of multiple collisions and assume a Gaussian shape. The diffusion depends on the average energy of the electrons. The variance σ^2 of the distribution grows linearly with time. In case of an applied electric field it grows linearly with the distance.



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

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

Solution of the diffusion equation (l=drift distance)

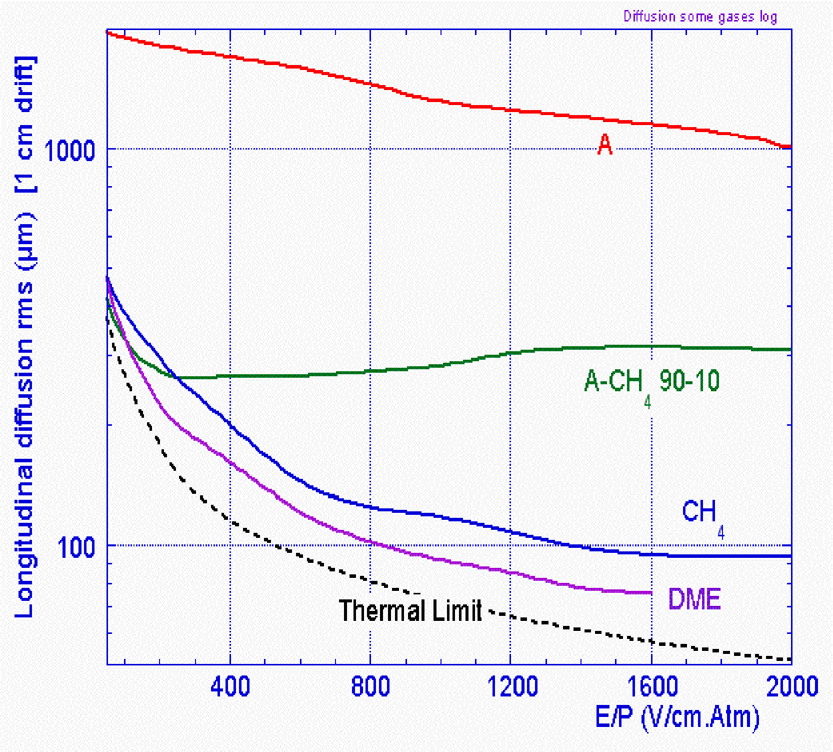
$$D = \frac{2}{3}\frac{v}{eE}\epsilon \quad \longrightarrow \quad \sigma_x = \sqrt{\frac{4}{3}\frac{l}{eE}\epsilon}$$

Thermodynamic limit:

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

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

Transport of Electrons in Gases: Diffusion



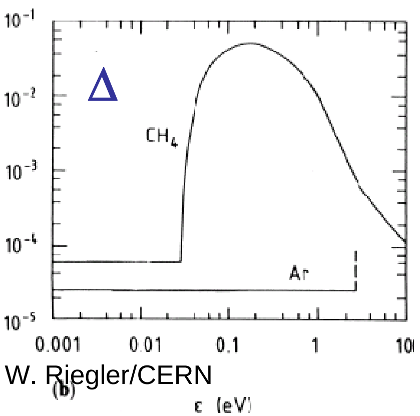
The electron diffusion depends on E/P and scales in addition with $1/\sqrt{P}$.

At 1kV/cm and 1 Atm Pressure the thermodynamic limit is σ=70μm for 1cm Drift.

'Cold' gases are close to the thermodynamic limit i.e. gases where the average microscopic energy $\varepsilon=1/2mu^2$ is close to the thermal energy 3/2kT.

CH_4 has very large fractional energy loss → low ε → low diffusion.

Argon has small fractional energy loss/collision → large ε → large diffusion.



Drift of Ions in Gases

Because of the larger mass of the Ions compared to electrons they are not randomized in each collision.

The crossections are ≈ constant in the energy range of interest.

Below the thermal energy the velocity is proportional to the electric field $v = \mu E$ (typical). Ion mobility $\mu \approx 1\text{-}10\ cm^2/Vs$.

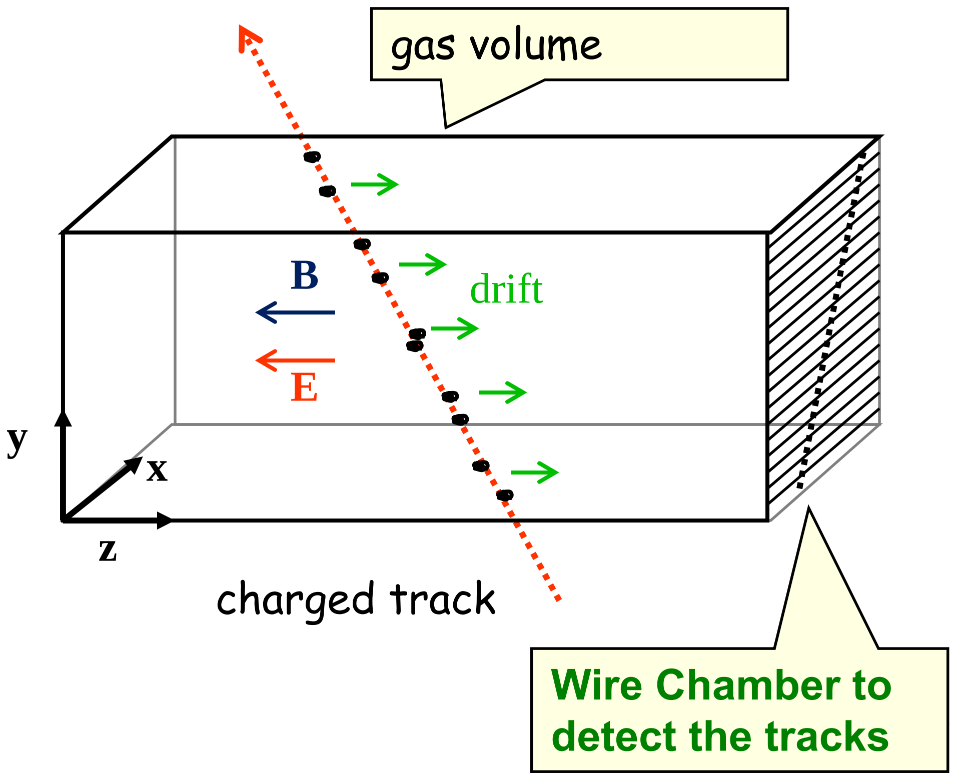
Above the thermal energy the velocity increases with $\sqrt{E}$.

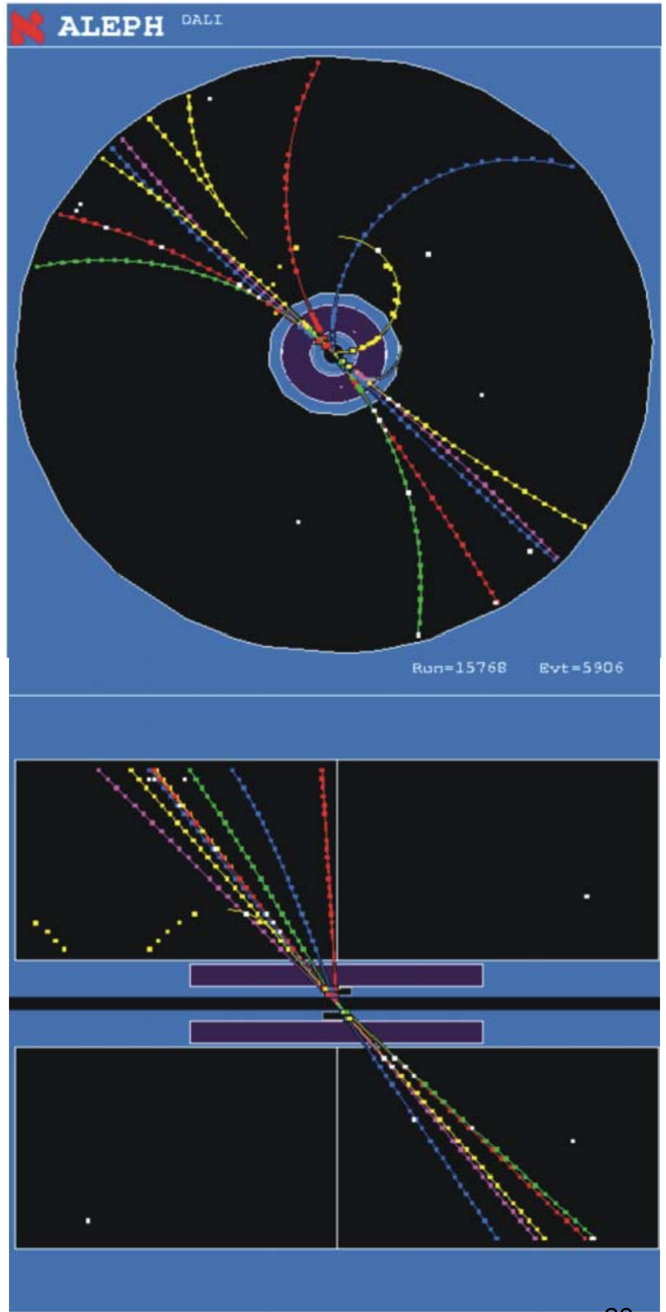
$V = \mu E$, $\mu(Ar) = 1.5 cm^2/Vs$ → 1000V/cm → v=1500cm/s=15m/s → 3000-6000 times slower than electrons !

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 µs.
Distance up to 2.5m !





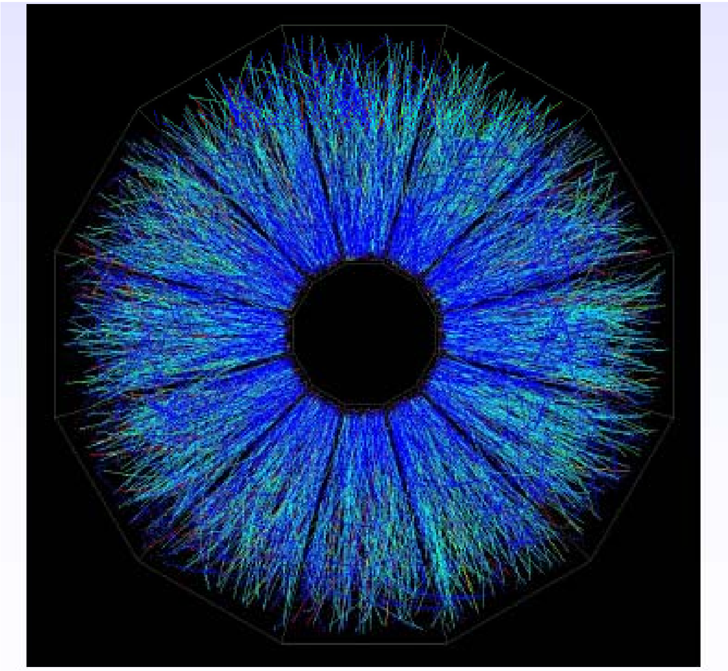
D.Vilaland CERN 2005

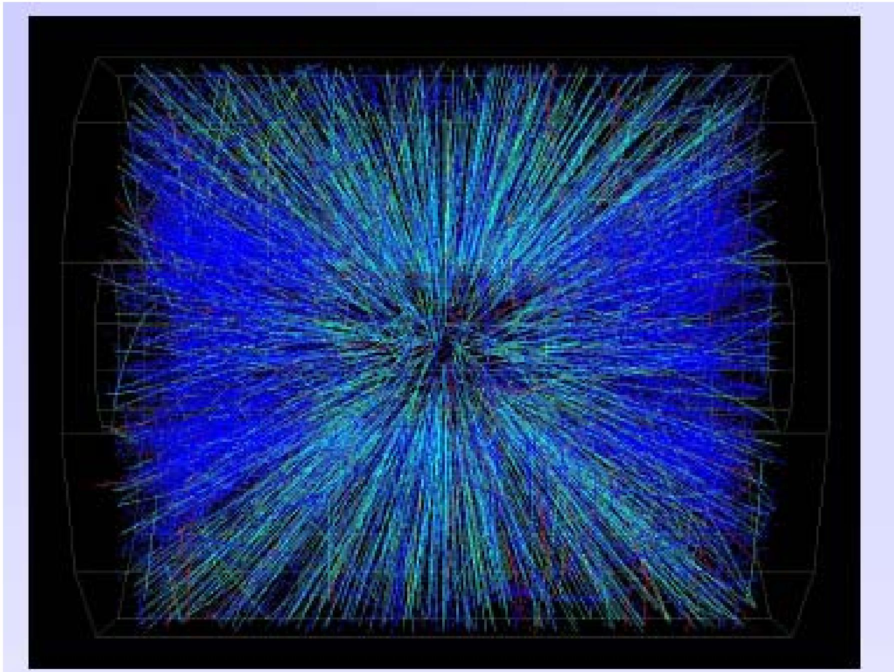
STAR TPC (BNL)

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

Typically around 200 tracks per event.

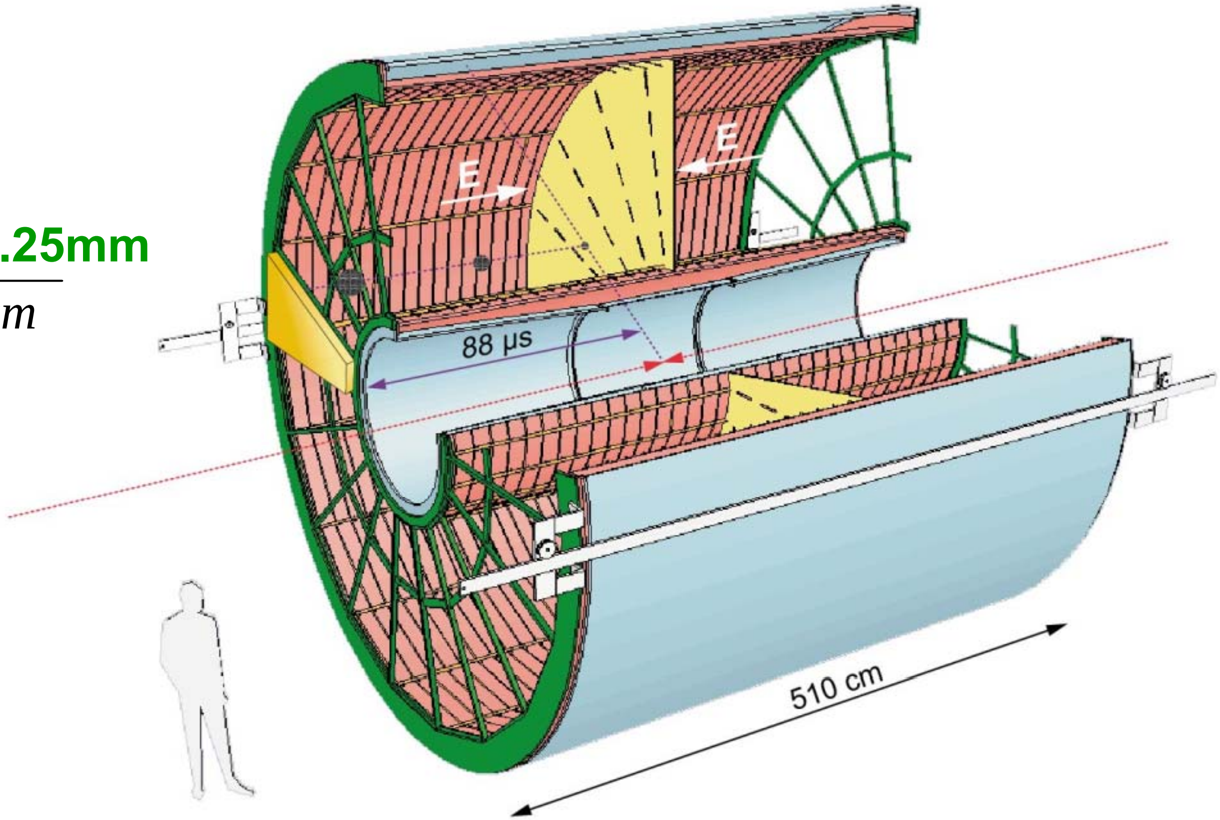
Great advantage of a TPC: The only material that is in the way of the particles is gas → very low multiple scattering → very good momentum resolution down to low momenta !





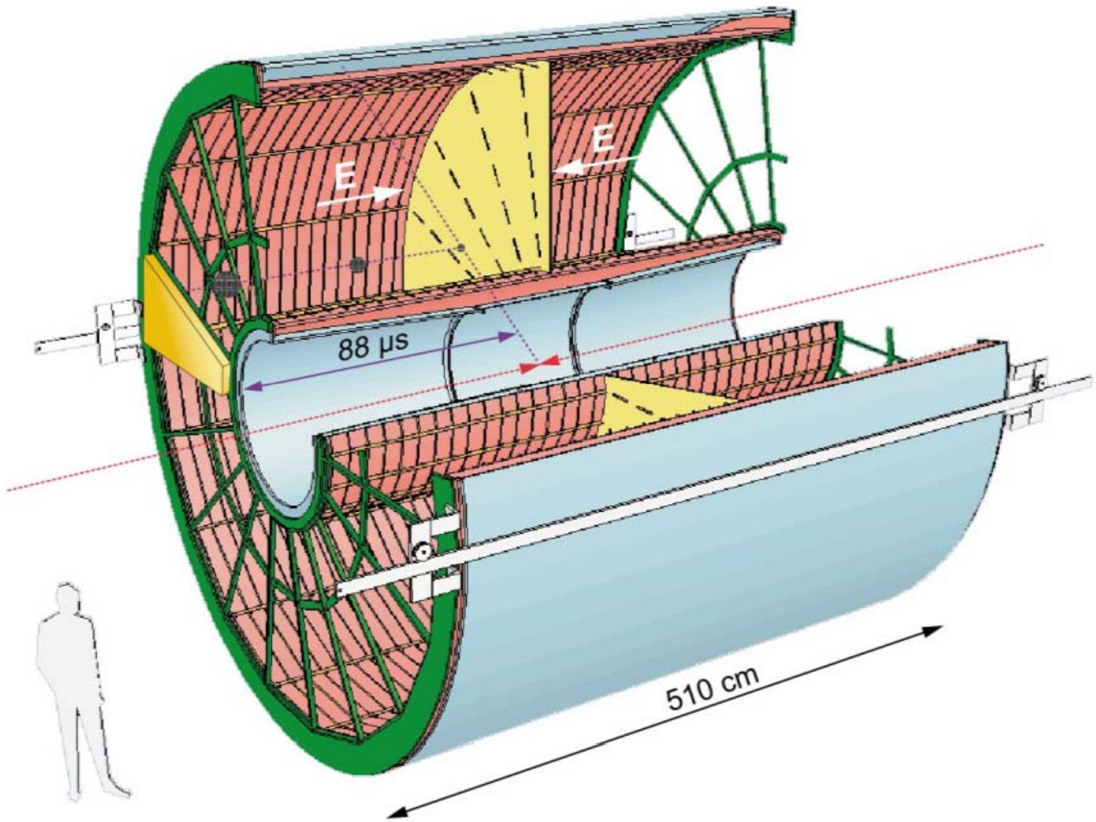
ALICE TPC: Detector Parameters

- Gas Ne/ CO_2 90/10%
- Field 400V/cm
- Gas gain >10^4
- Position resolution σ= 0.25mm
- Diffusion: σ_t= 250μm $\sqrt{cm}$
- Pads inside: 4x7.5mm
- Pads outside: 6x15mm
- B-field: 0.5T



ALICE TPC: Construction Parameters

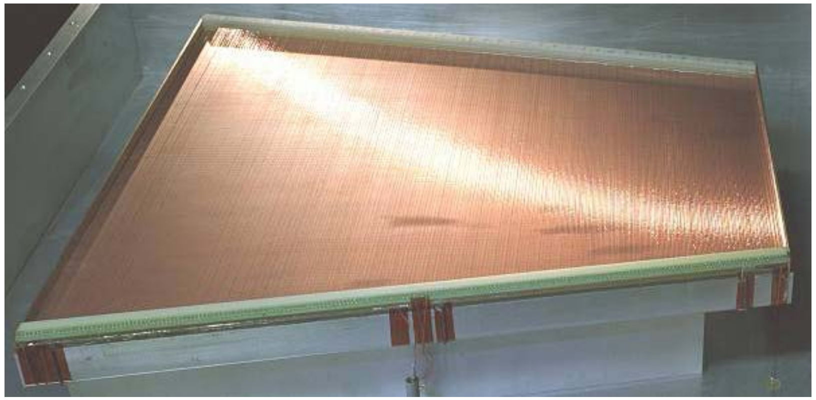
- **Largest TPC:**
  - Length 5m
  - Diameter 5m
  - Volume $88m^3$
  - Detector area $32m^2$
  - Channels ~570 000
- **High Voltage:**
  - Cathode -100kV
- **Material X_0**
  - Cylinder from composite materials from airplane industry (X_0= ~3%)



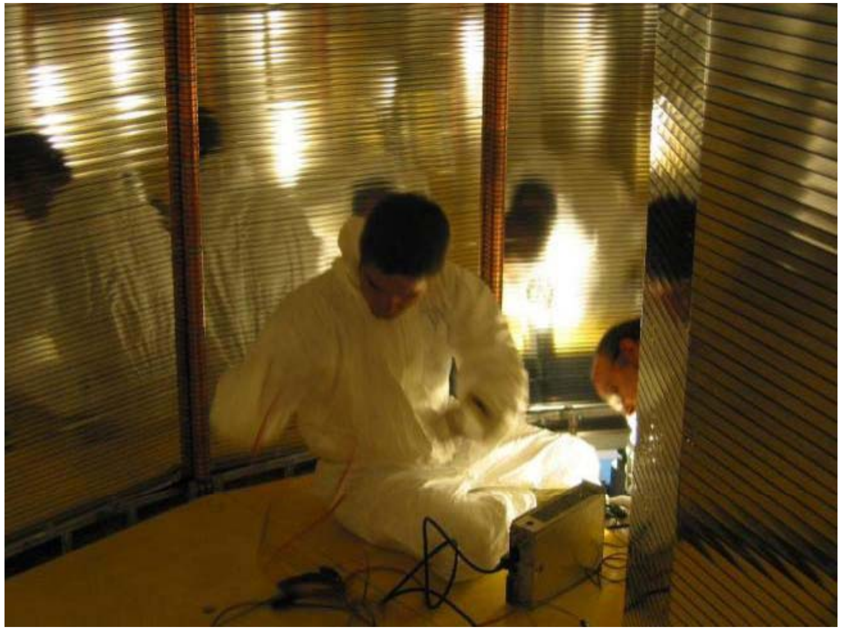
ALICE TPC: Pictures of the Construction

Precision in z: 250μm

End plates 250μm



Wire chamber: 40μm

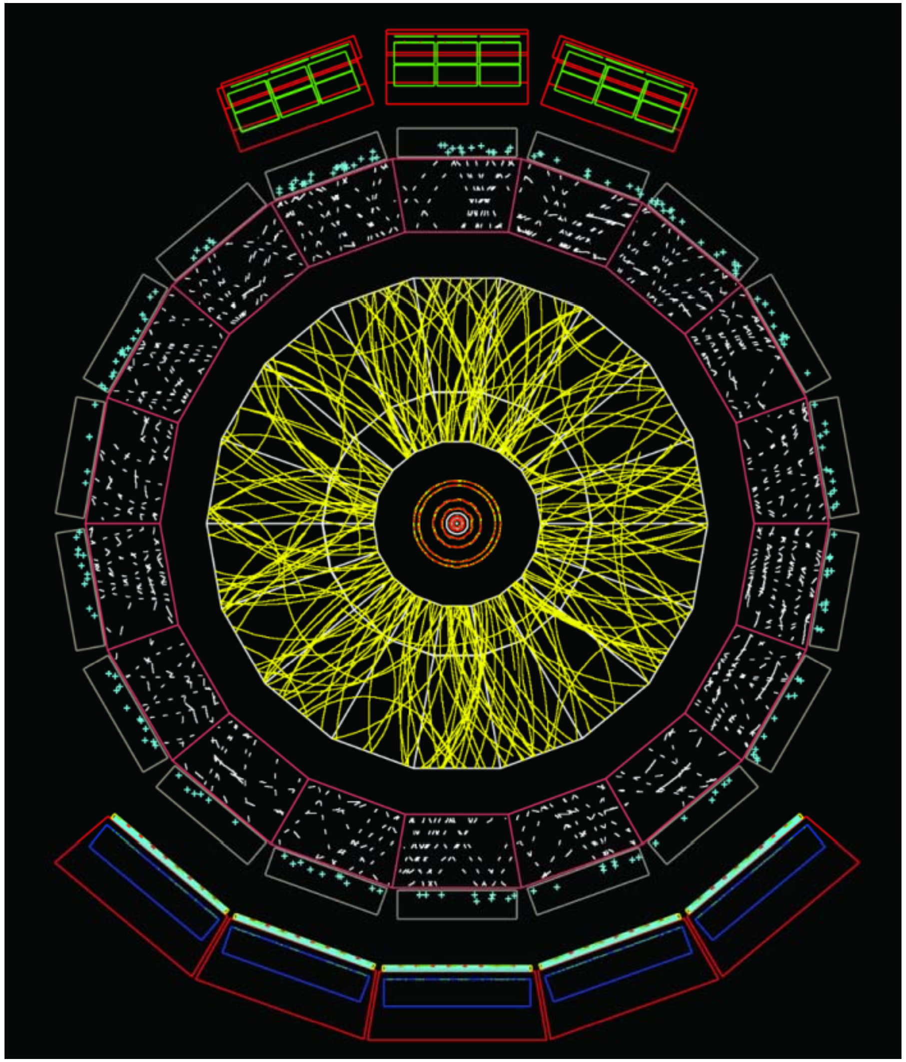


ALICE TPC Construction

My personal contribution:

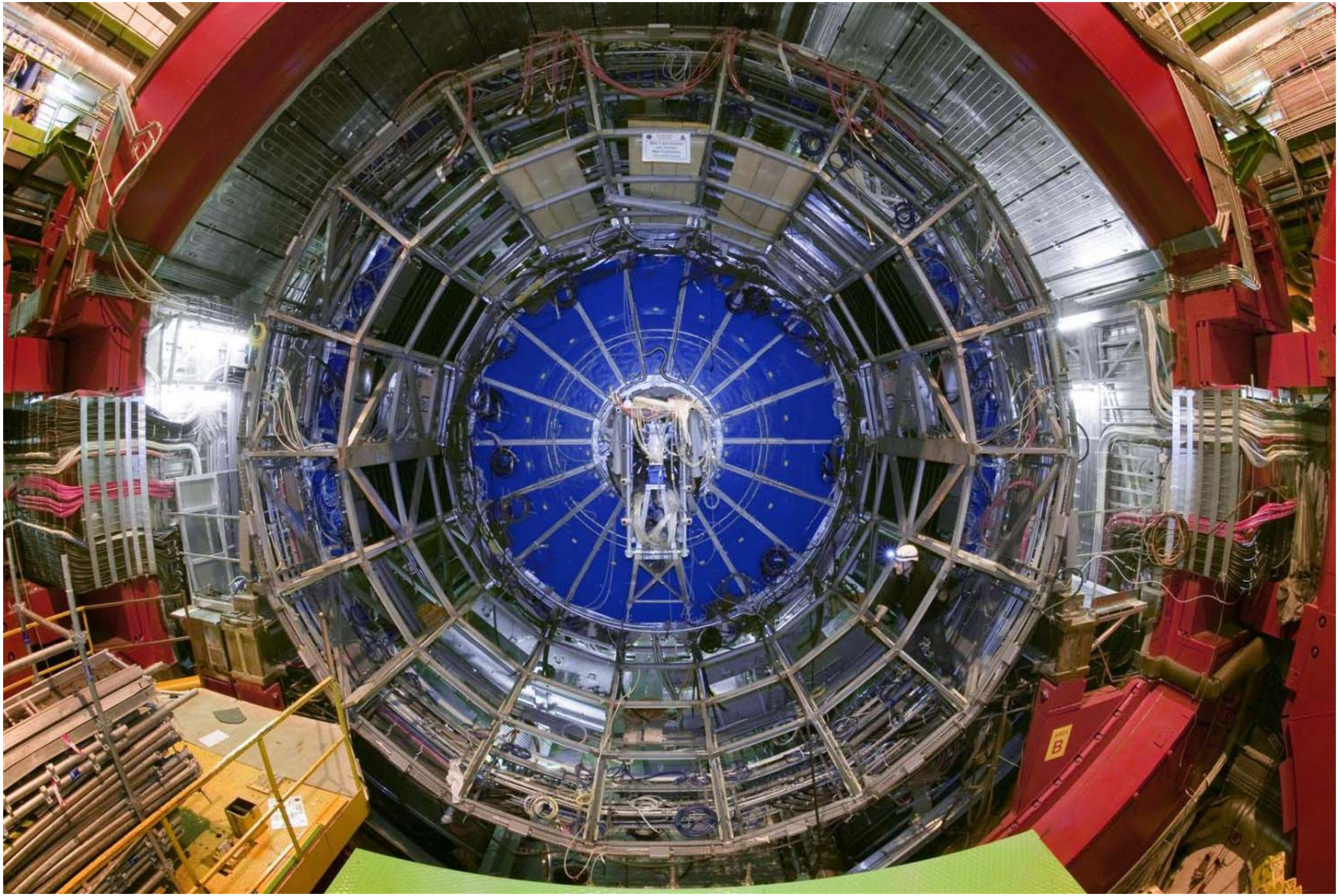
A visit inside the TPC.

ALICE : Simulation of Particle Tracks

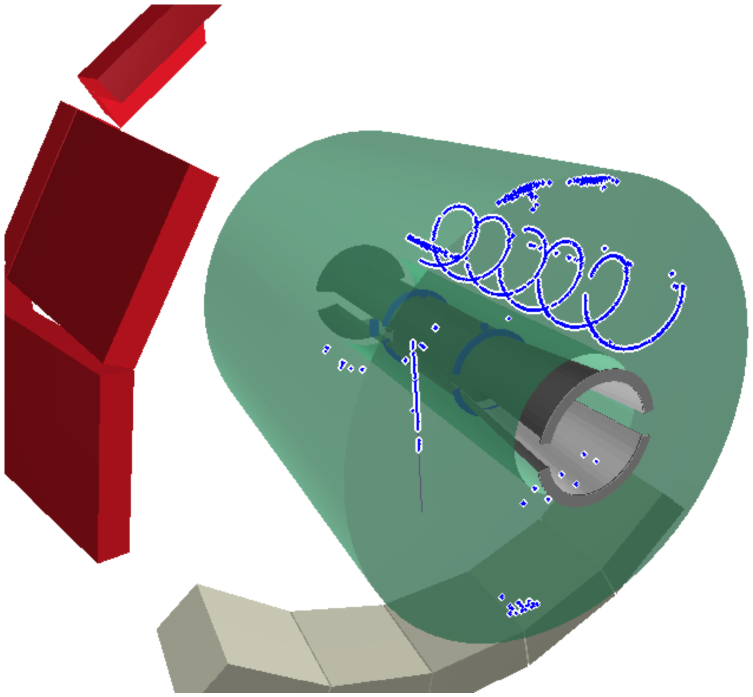


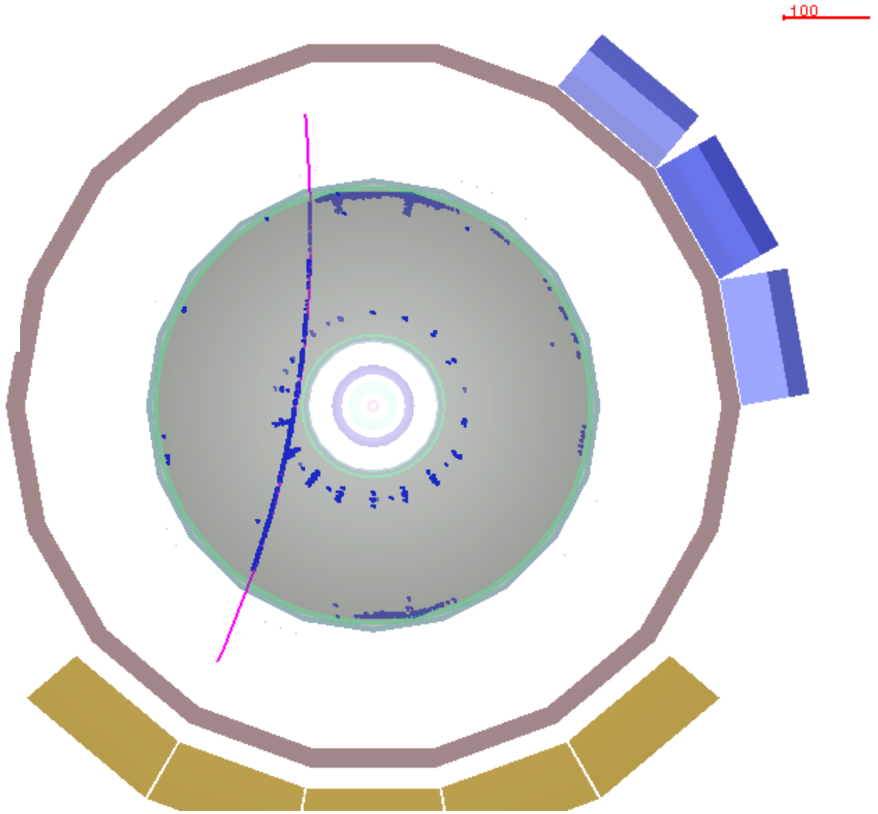
- Simulation of particle tracks for a Pb Pb collision (dN/dy ~8000)
- Angle: Θ=60 to 62º
- If all tracks would be shown the picture would be entirely yellow !
- Up to 40 000 tracks per event !
- TPC is currently under commissioning

TPC installed in the ALICE Experiment



First Cosmic Muon Event Displays from the ALICE TPC June 2008 !





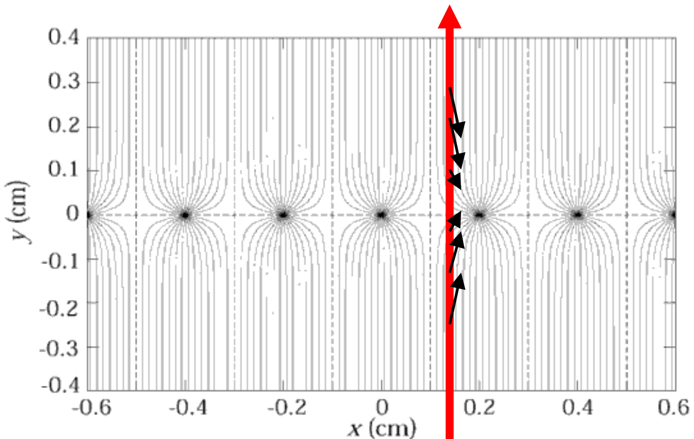
Position Resolution/Time resolution

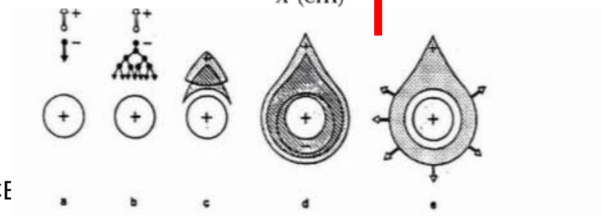
Up to now we discussed gas detectors for tracking applications. Wire chambers can reach tracking precisions down to 50 micrometers at rates up to <1MHz/cm^2.

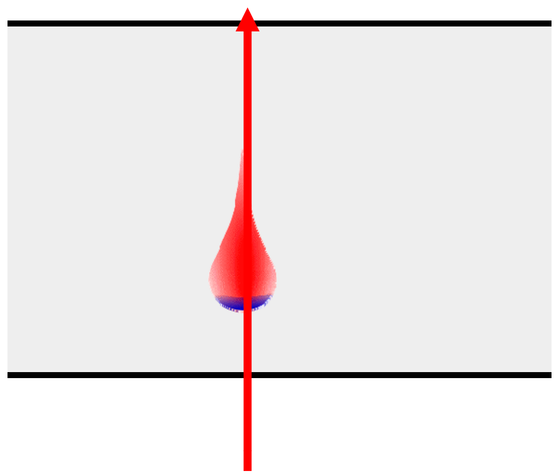
What about time resolution of wire chambers ?

It takes the electrons some time to move from thir 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).

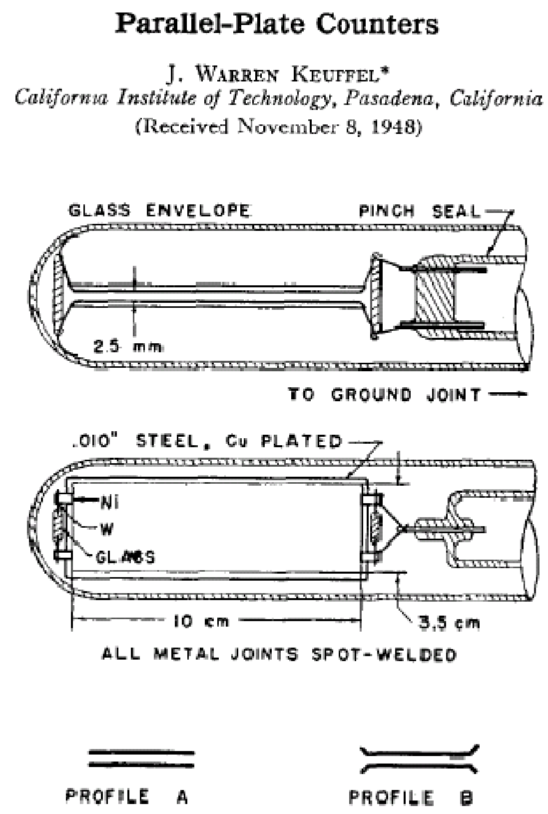
Discharged electrodes must be recharged → Dead time of several ms.

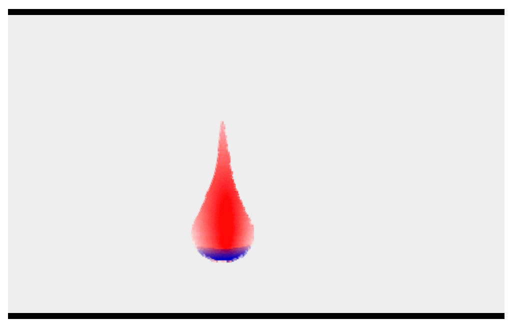
Parallel Plate Avalanche Chambers (PPAC):

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^2) 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 area rather small 1-5kV/cm.





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 ~ $\varepsilon * \rho$) will only allow a very localized 'discharge'. The rest of the entire surface stays completely unaffected.

→ **Large area detectors are possible !**

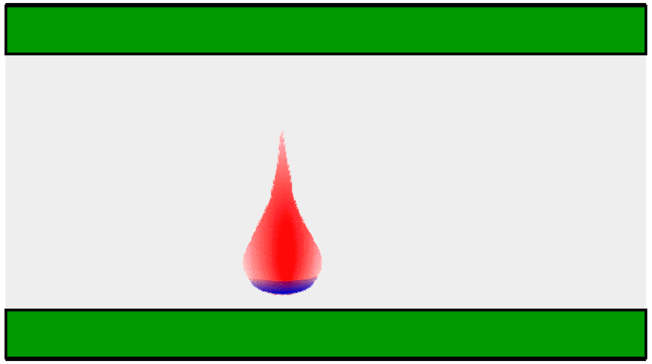
Resistive plates from Bakelite ($\rho = 10^{10}$-10^{12} Ωcm) or window glass ($\rho = 10^{12}$-10^{13} Ωcm).

Gas gap: 0.25-2mm.
Electric Fields 50-100kV/cm.
Time resolutions: 50ps (100kV/cm), 1ns(50kV/cm)

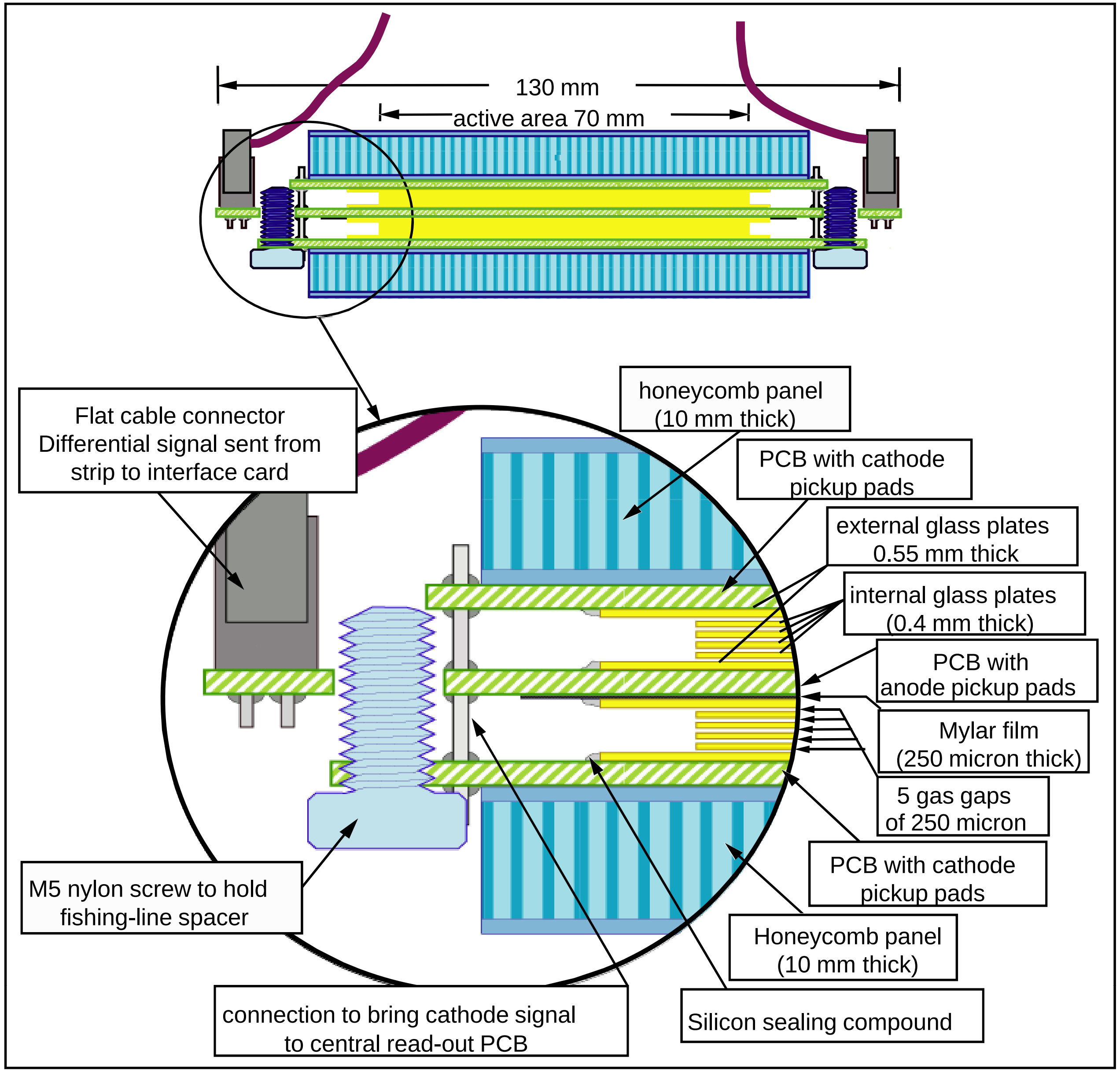
Application: Trigger Detectors, Time of Flight (TOF)

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

Rate limit of kHz/cm^2 for 10^{10} Ωcm.



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 !

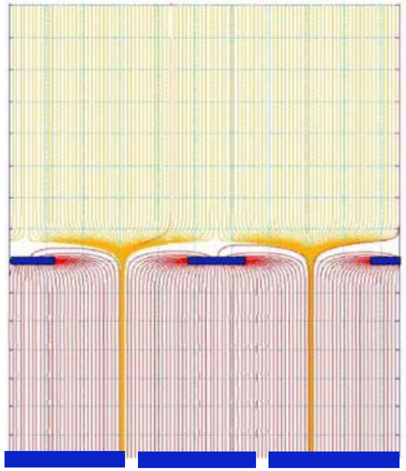
Large TOF systems with 50ps time resolution made from window glass and fishing lines !

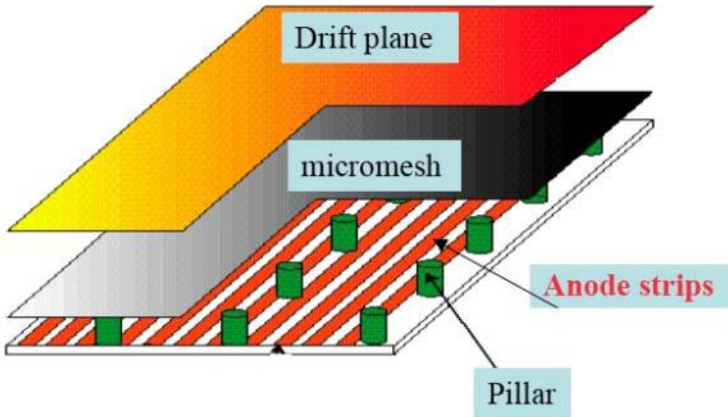
Before RPCs → Scintillators with very special photomultipliers – very expensive. Very large systems are unaffordable.

GEMs & MICROMEGAS

MICROMEGAS

Narrow gap (50-100 µm) PPC with thin cathode mesh
Insulating gap-restoring wires or pillars

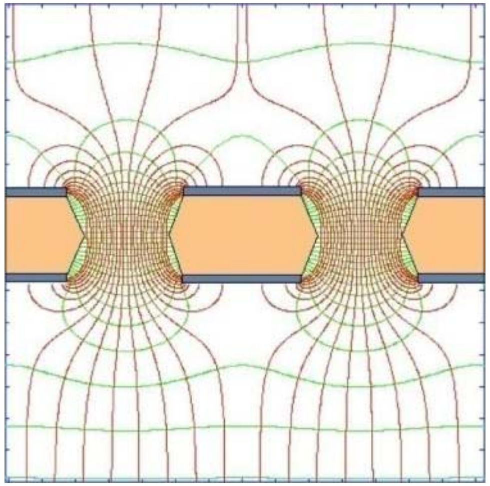


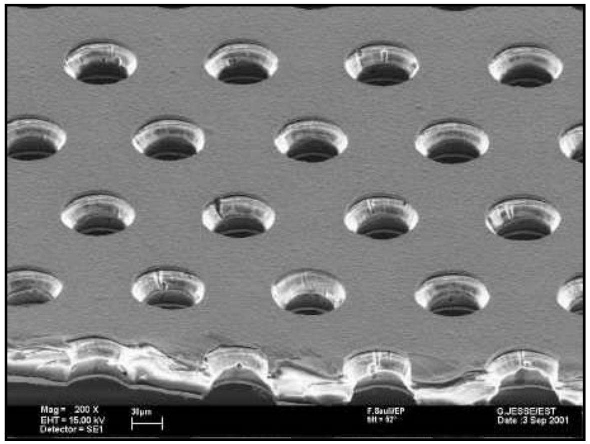


Y. Giomataris et al, Nucl. Instr. and Meth. A376(1996)239

GEM

Thin metal-coated polymer foils
70 µm holes at 140 mm pitch

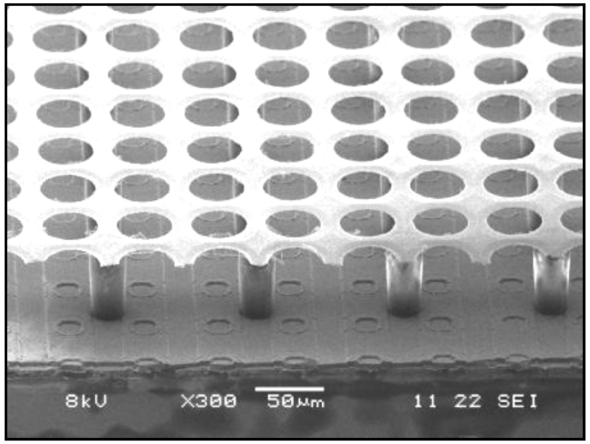




F. Sauli, Nucl. Instr. and Methods A386(1997)531

MPGDs with Integrate Micromesh, INGRID

Going even another step further, by wafer post-processing techniques, MPGD structure scan be put on top of a pixelized readout chip, making the entire detector a monolithic unit !
→ IntegratedGrid (INGRID) . In addition a TDC was put on each pixel measuring drift times →

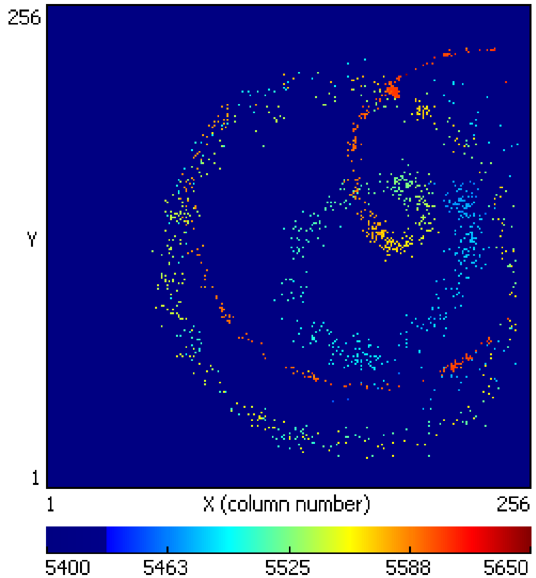


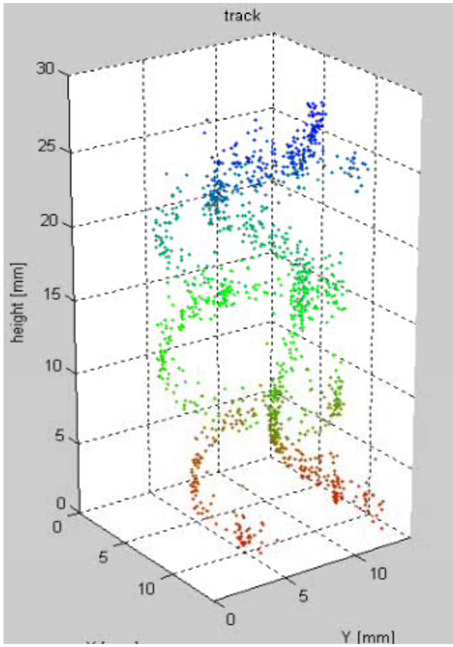
Micromesh on a pixelized readout chip produced by Opto-Chemical Wafer Post-Processing Techniques.

With 3cm Drift gap: 5 cm^3 Mini TPC ! Tracks from Sr90 source in 0.2T Magnetic Field !

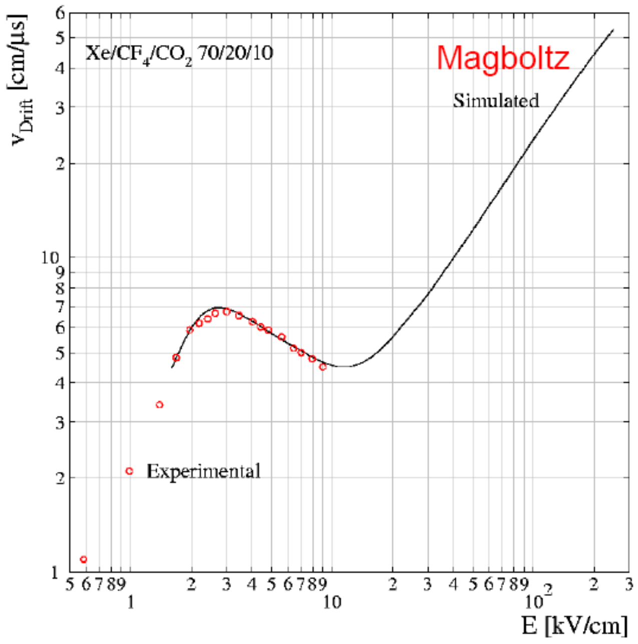
Single ionization electrons are seen.

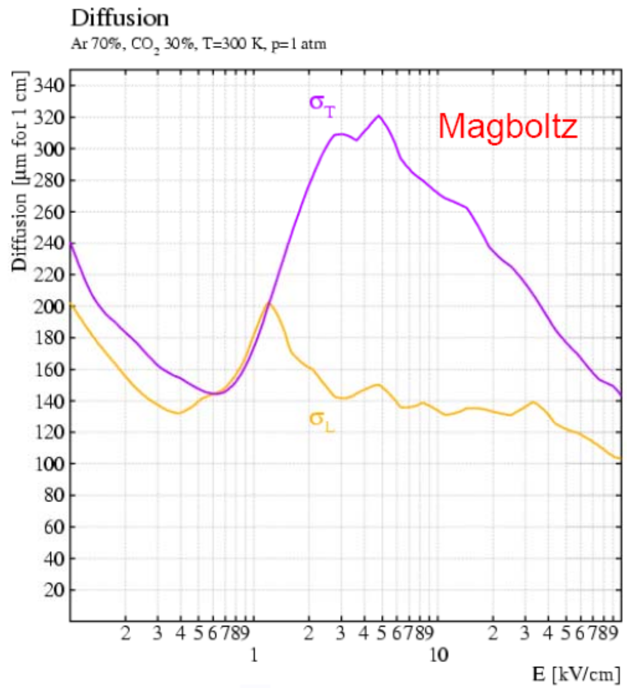
Fantastic position resolution …

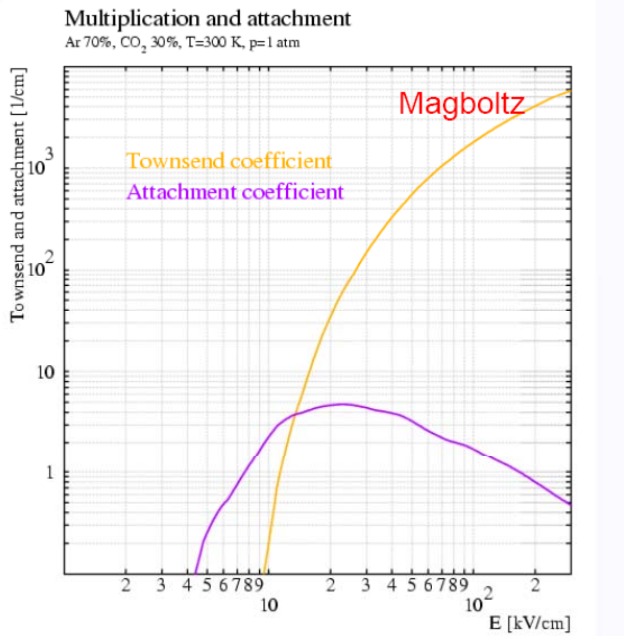




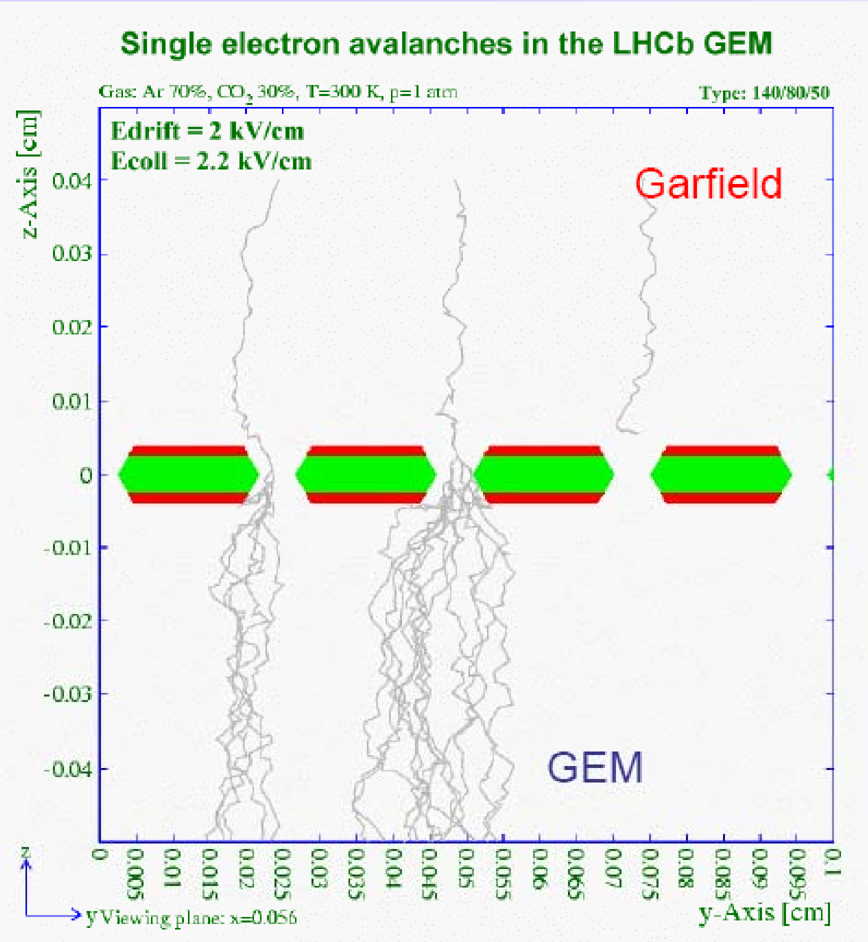
Detector Simulation



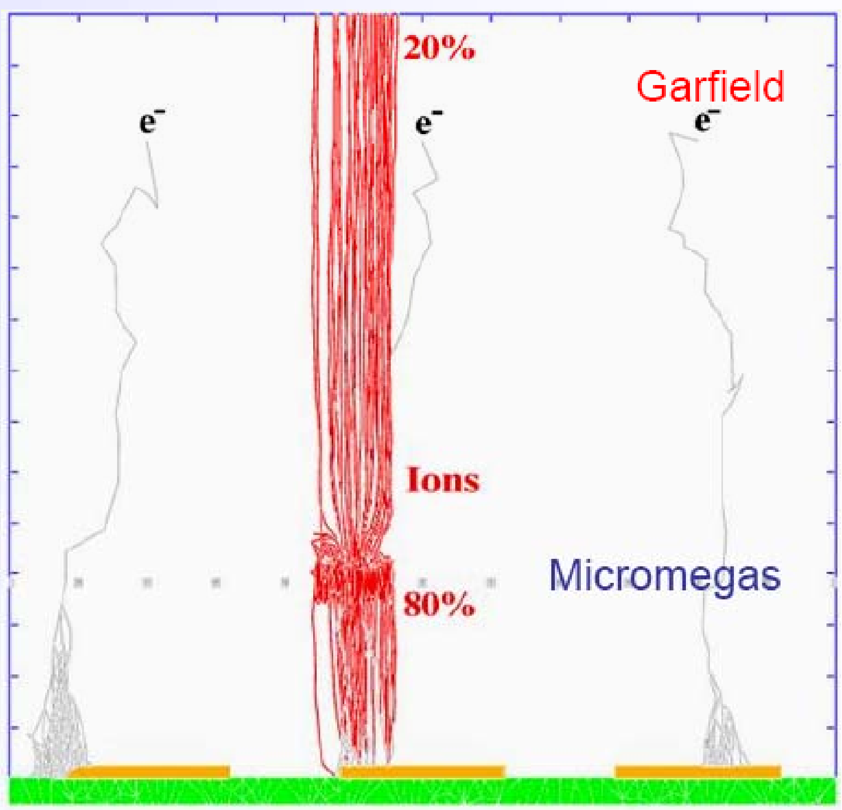




Detector Simulation



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 lead to wire chambers that can track up to MHz/cm^2 of particles, accumulate up to 1-2C/cm of wire and 1-2 C/cm^2 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 it's 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.

Novel gas detectors, the Micro Pattern Gas Detectors, have proven to work efficiently as high rate, low material budget trackers in the 'regime' between silicon trackers and large wire chambers.

'VERTEX' – Detectors

By direct measurement of the 'decay-position' of the particle one can measure the lifetime and therefore identify the particle.

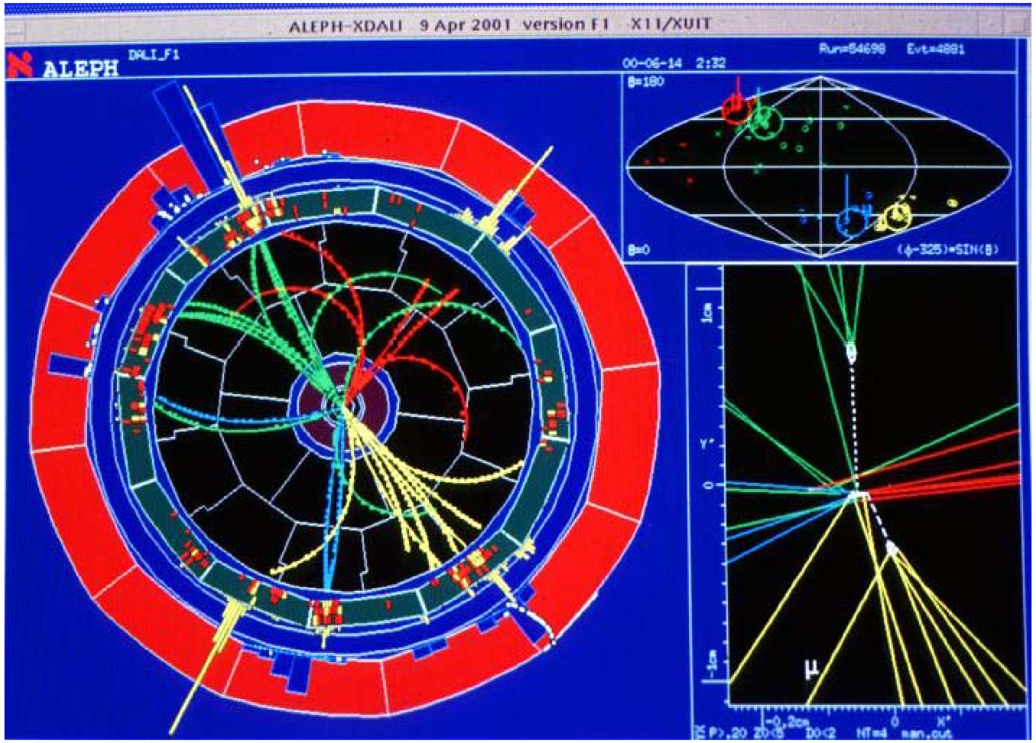
Mainly for Charm, Beauty Hadron and Tau-Lepton Physics.

Typical Lifetimes: 10^{-12} to 10^{-13} s

Typical decay distances: 20-500 µm

Typical required Resolution: ~10 µm

Silicon Strip or Pixel Detectors.



Detectors based on Ionization

Gas detectors:

- Wire Chambers
- Drift Chambers
- Time Projection Chambers
- Transport of Electrons and Ions in Gases

→ Solid State Detectors

- Transport of Electrons and Holes in Solids
- Si- Detectors
- Diamond Detectors

Solid State Detectors

In gaseous detectors, a charged particle is liberating electrons from the atoms, which are freely bouncing between the gas atoms.

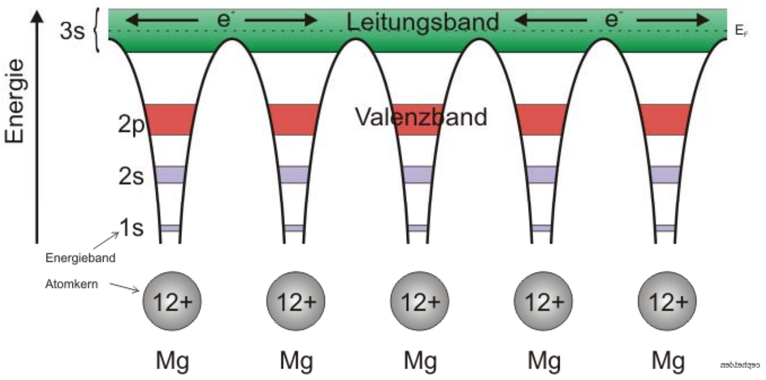
An applied electric field makes the electrons and ions move, which induces signals on the metal readout electrodes.

For individual gas atoms, the electron energy levels are discrete.

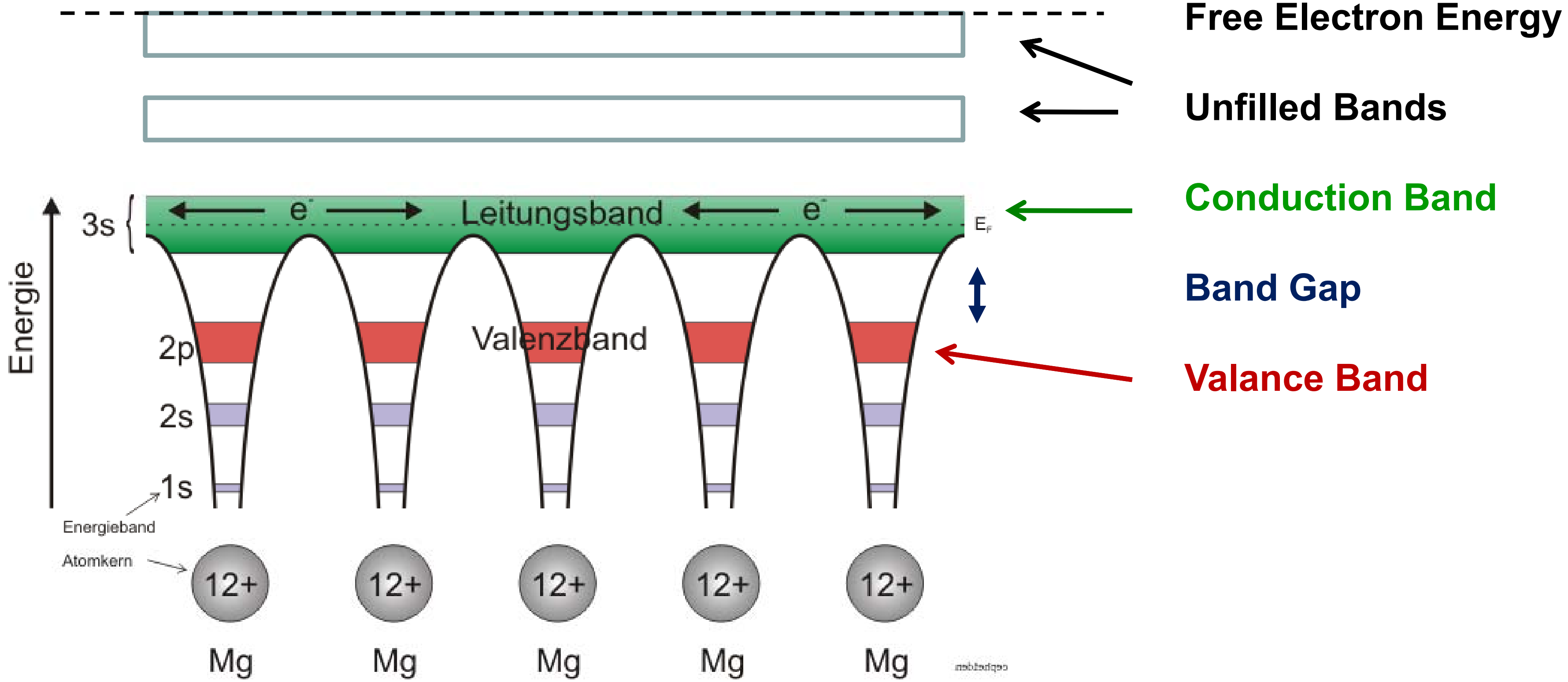
In solids (crystals), the electron energy levels are in 'bands'.

Inner shell electrons, in the lower energy bands, are closely bound to the individual atoms and always stay with 'their' atoms.

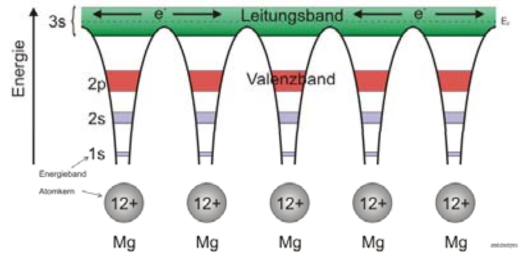
In a crystal there are however energy bands that are still bound states of the crystal, but they belong to the entire crystal. Electrons in this bands and the holes in the lower band can freely move around the crystal, if an electric field is applied.



Solid State Detectors



Solid State Detectors



In case the conduction band is filled the crystal is a conductor.

In case the conduction band is empty and 'far away' from the valence band, the crystal is an insulator.

In case the conduction band is empty but the distance to the valence band is small, the crystal is a semiconductor.

The energy gap between the last filled band – the valence band – and the conduction band is called band gap E_g.

The band gap of Diamond/Silicon/Germanium is 5.5, 1.12, 0.66 eV.

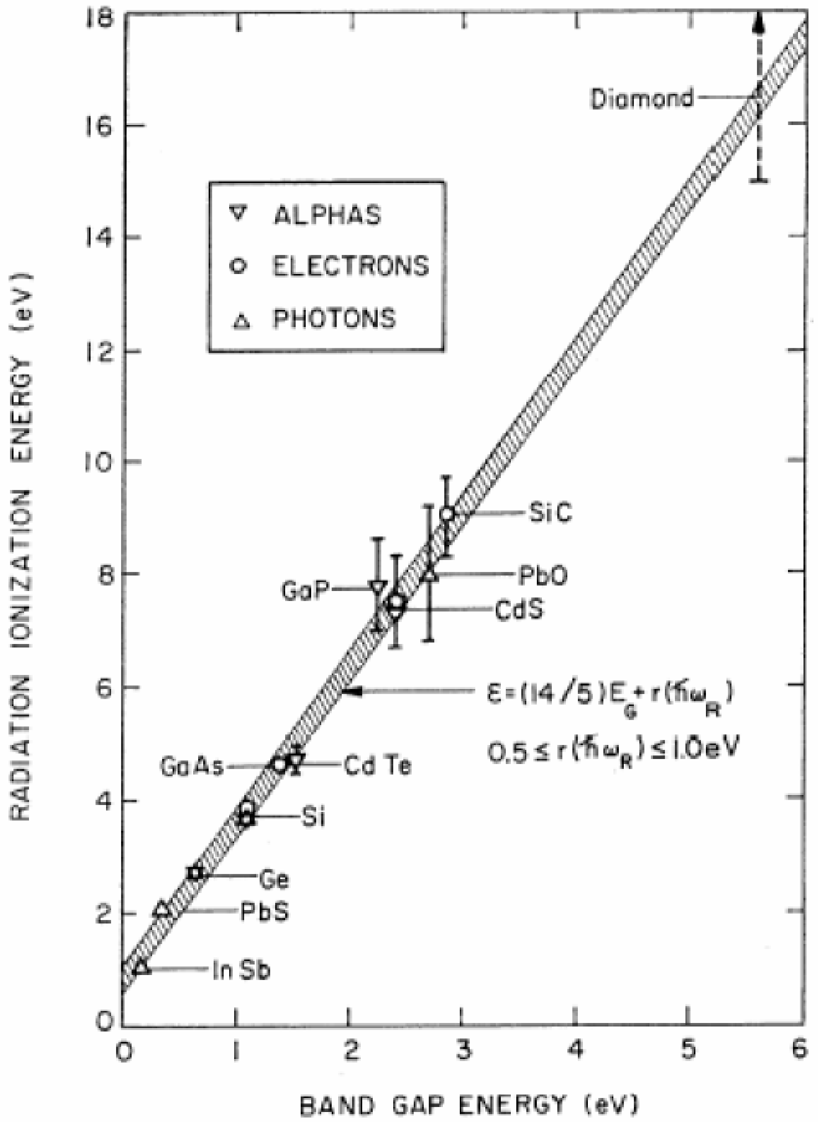
The average energy to produce an electron/hole pair for Diamond/Silicon/Germanium is 13, 3.6, 2.9eV.

In case an electron in the valence band gains energy by some process, it can be excited into the conduction band and a hole in the valence band is left behind.

Such a process can be the passage of a charged particle, but also thermal excitation → probability is proportional Exp($-E_g/kT$).

The number of electrons in the conduction band is therefore increasing with temperature i.e. the conductivity of a semiconductor increases with temperature.

Solid State Detectors



	Diamond	SiC (4H)	GaAs	Si	Ge
Atomic number Z	6	14/6	31/33	14	32
Bandgap E_g [eV]	5.5	3.3	1.42	1.12	0.66
E(e-h pair) [eV]	13	7.6-8.4	4.3	3.6	2.9
density [g/cm^3]	3.515	3.22	5.32	2.33	5.32
e-mobility μ_e [cm^2/Vs]	1800	800	8500	1450	3900
h-mobility μ_h [cm^2/Vs]	1200	115	400	450	1900

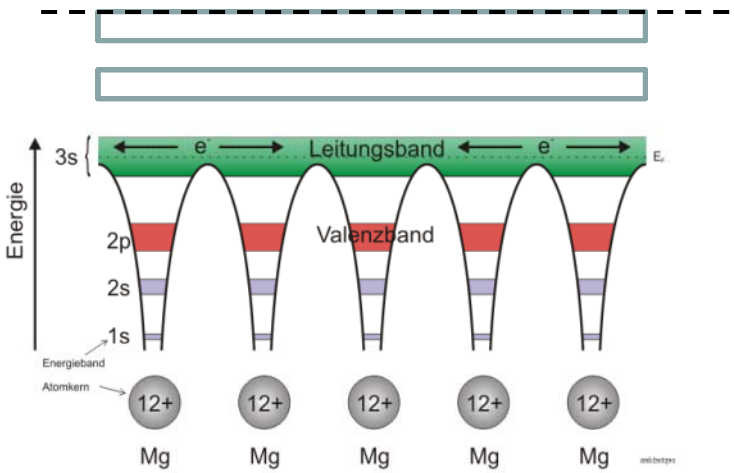
Solid State Detectors

It is possible to treat electrons in the conduction band and holes in the valence band similar to free particles, but with and effective mass different from elementary electrons not embedded in the lattice.

This mass is furthermore dependent on other parameters such as the direction of movement with respect to the crystal axis. All this follows from the QM treatment of the crystal.

If we want to use a semiconductor as a detector for charged particles, the number of charge carriers in the conduction band due to thermal excitation must be smaller than the number of charge carriers in the conduction band produced by the passage of a charged particle.

Diamond (E_g=5.5eV) can be used for particle detection at room temperature, Silicon (E_g=1.12 eV) and Germanium (E_g=0.66eV) must be cooled, or the free charge carriers must be eliminated by other tricks → doping → see later.



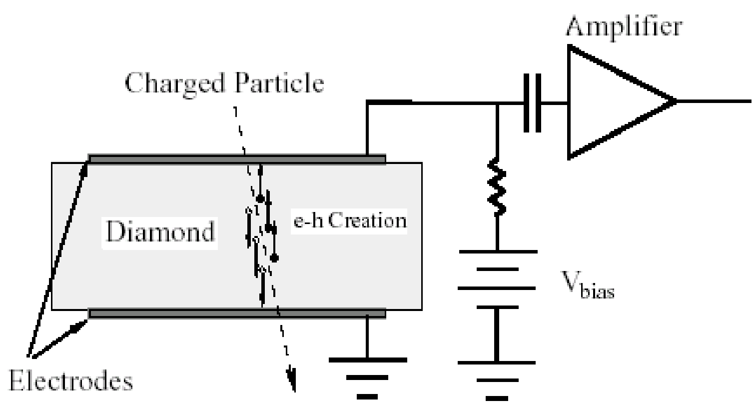
Solid State Detectors

The average energy to produce an electron/hole pair for Diamond/Silicon/Germanium is 13, 3.6, 2.9eV.

Comparing to gas detectors, the density of a solid is about a factor 1000 larger than that of a gas and the energy to produce and electron/hole pair e.g. for Si is a factor 7 smaller than the energy to produce an electron-ion pair in Argon.

The number of primary charges in a Si detector is therefore about 10^4 times larger than the one in gas → while gas detectors need internal charge amplification, solid state detectors don't need internal amplification.

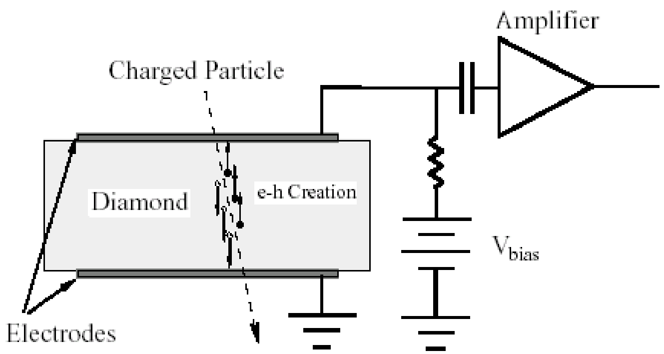
While in gaseous detectors, the velocity of electrons and ions differs by a factor 1000, the velocity of electrons and holes in many semiconductor detectors is quite similar.



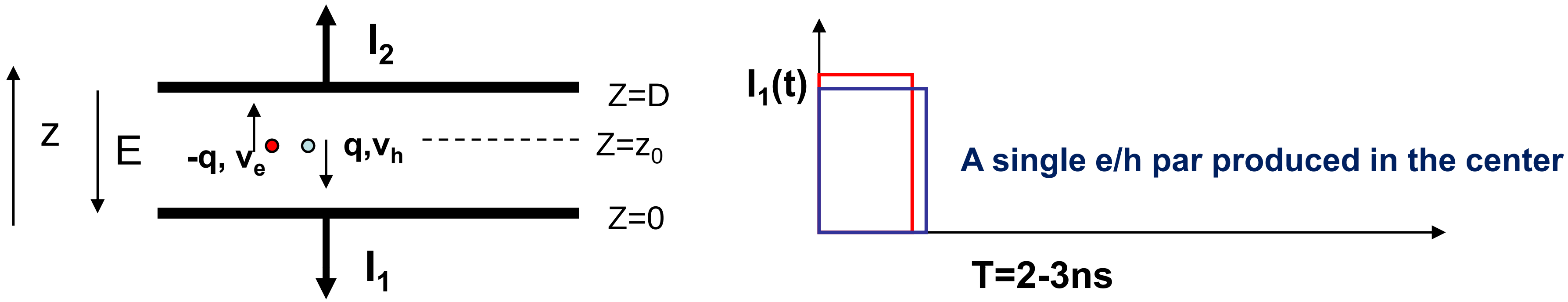
Diamond → A solid state ionization chamber

Diamond Detector

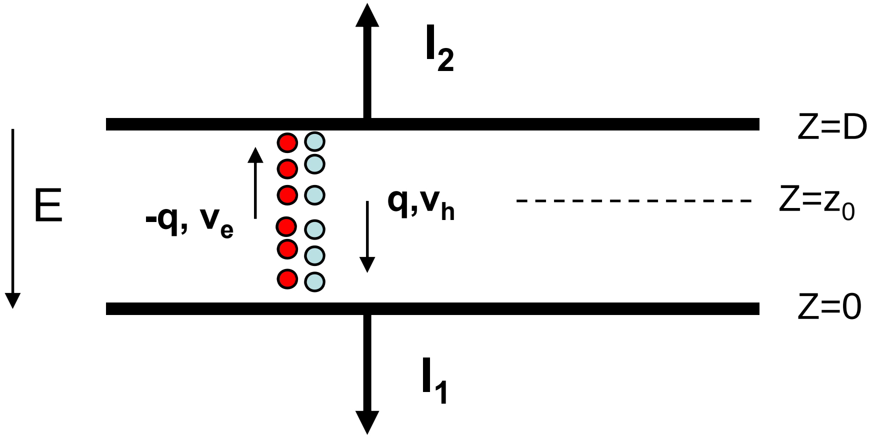
Typical thickness – a few 100μm.
<1000 charge carriers/cm³ at room temperature due to large band gap.

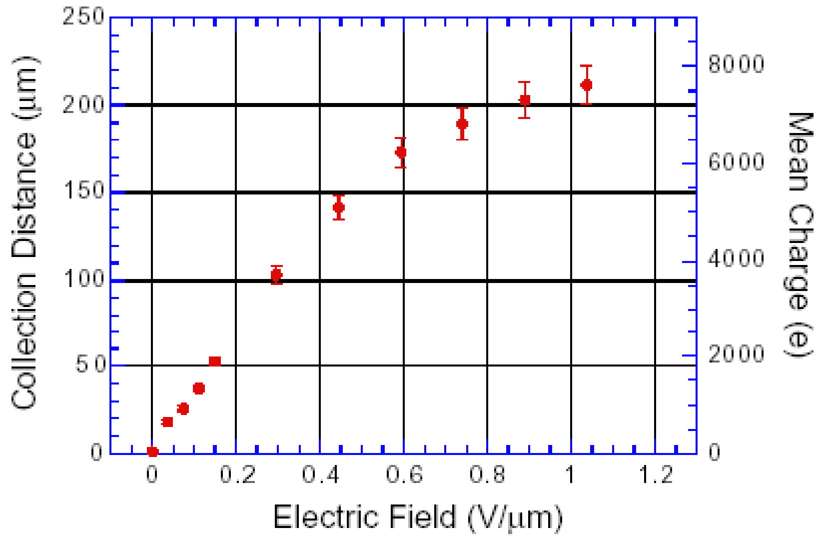


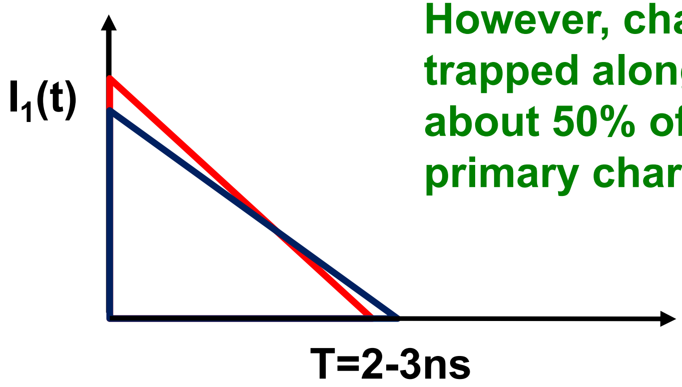
Velocity:
μ_e=1800 cm²/Vs, μ_h=1600 cm²/Vs
Velocity = μE, 10kV/cm → v=180 μm/ns → Very fast signals of only a few ns length !



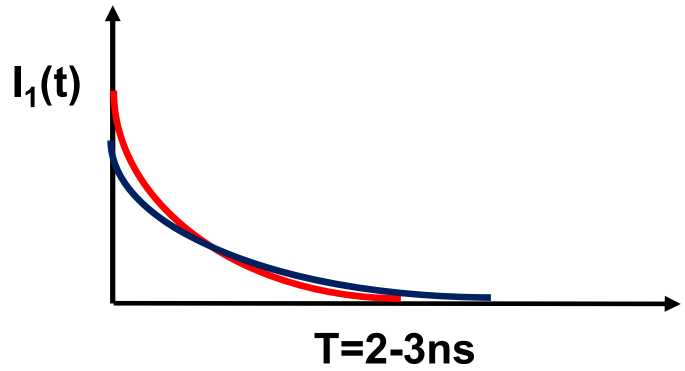
Diamond Detector







However, charges are trapped along the track, only about 50% of *produced* primary charge is *induced* →



Silicon Detector

Velocity:

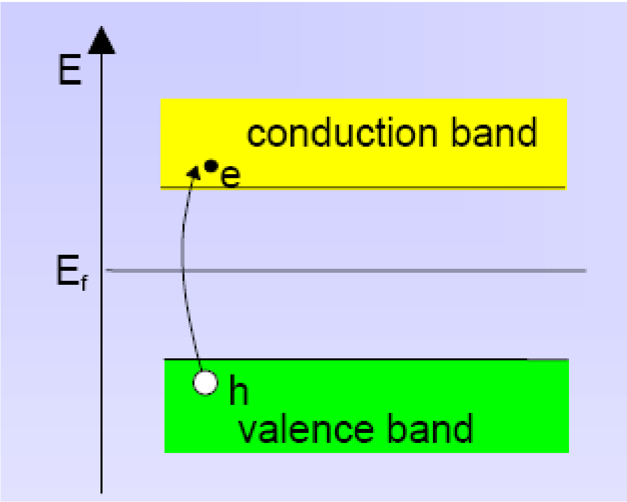
μ_e=1450 cm²/Vs, μ_h=505 cm²/Vs, 3.63eV per e-h pair.

~11000 e/h pairs in 100µm of silicon.

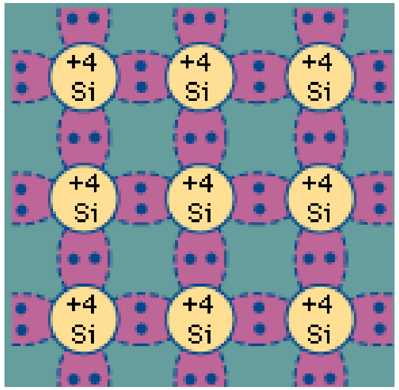
However: Free charge carriers in Si:

T=300 K: n/h = 1.45 x 10^{10} / cm^3 but only 33000e-/h in 300µm produced by a high energy particle.

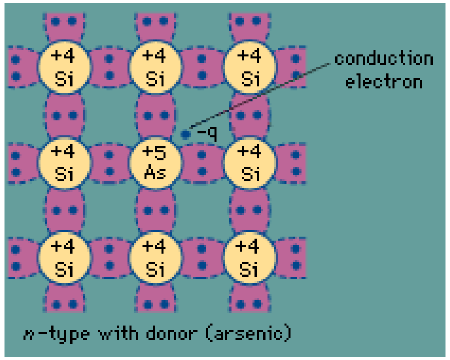
Why can we use Si as a solid state detector ???

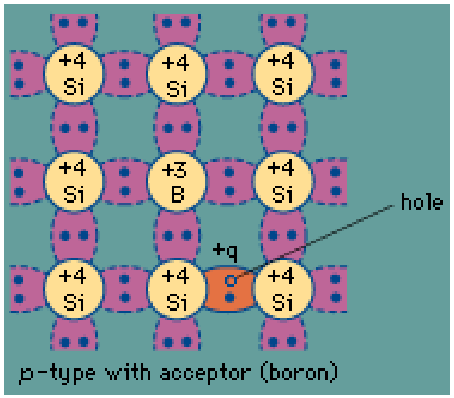


Doping of Silicon



doping



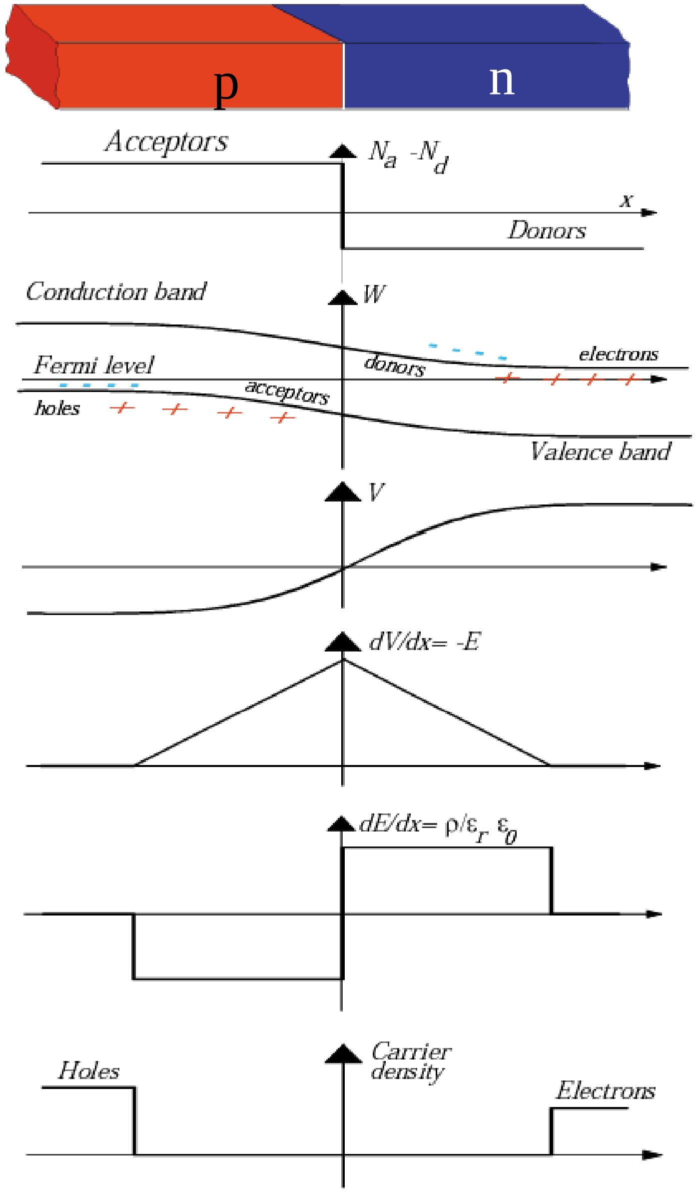


In a silicon crystal at a given temperature the number of electrons in the conduction band is equal to the number of holes in the valence band.

Doping Silicon with Arsen (+5) it becomes and n-type conductor (more electrons than holes).

Doping Silicon with Boron (+3) it becomes a p-type conductor (more holes than electrons).

Bringing p and n in contact makes a diode.



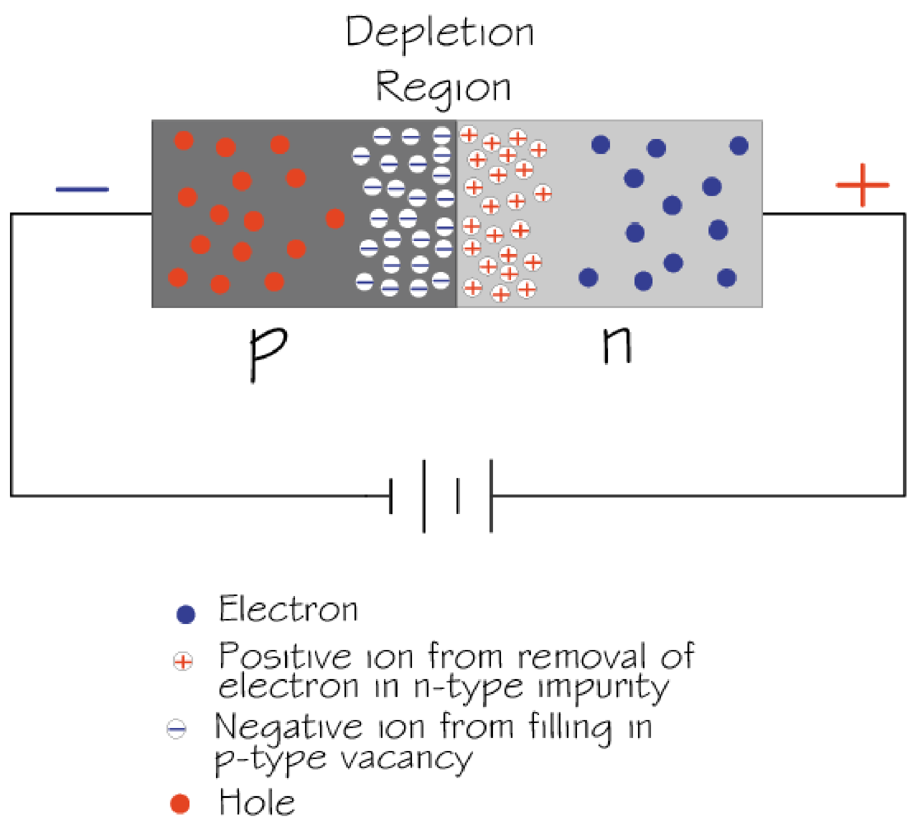
Si-Diode used as a Particle Detector !

At the p-n junction the charges are depleted and a zone free of charge carriers is established.

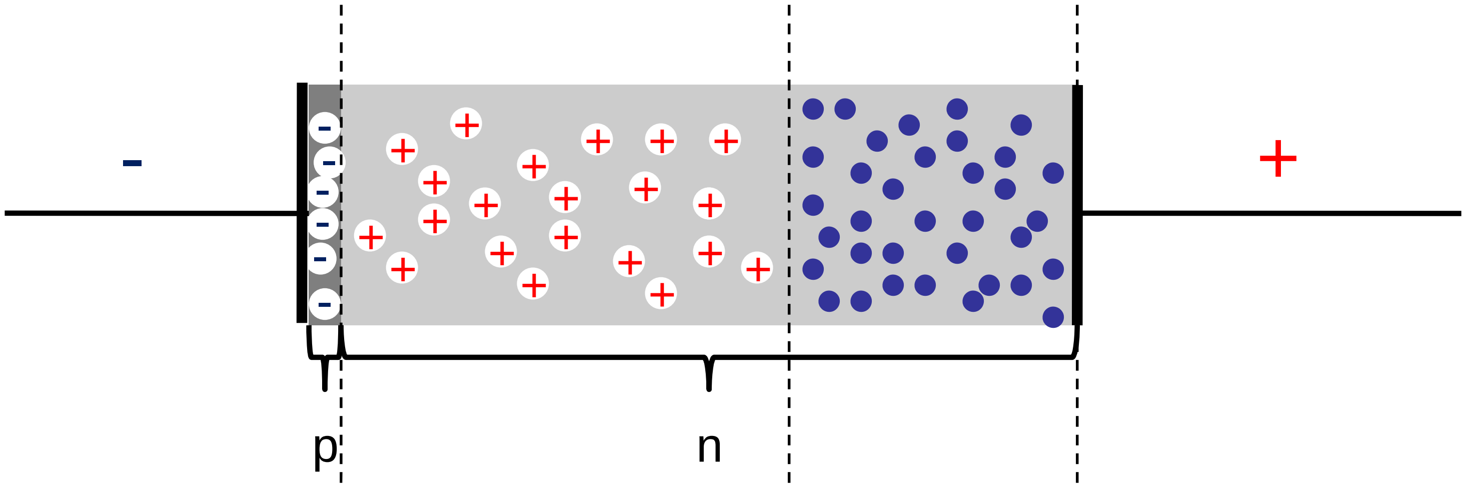
By applying a voltage, the depletion zone can be extended to the entire diode → highly insulating layer.

An ionizing particle produces free charge carriers in the diode, which drift in the electric field and induce an electrical signal on the metal electrodes.

As silicon is the most commonly used material in the electronics industry, it has one big advantage with respect to other materials, namely highly developed technology.

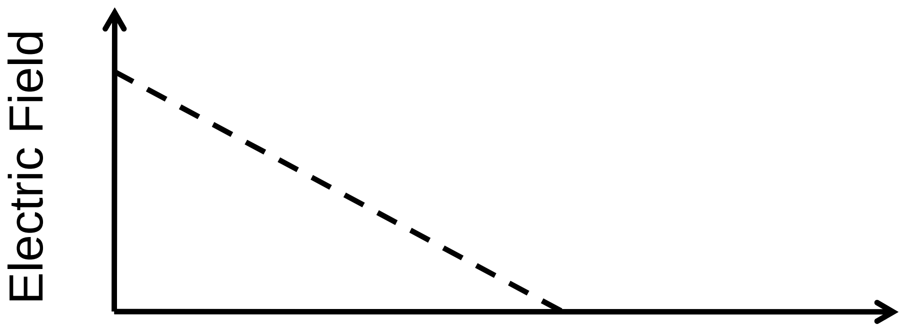


Under-Depleted Silicon Detector

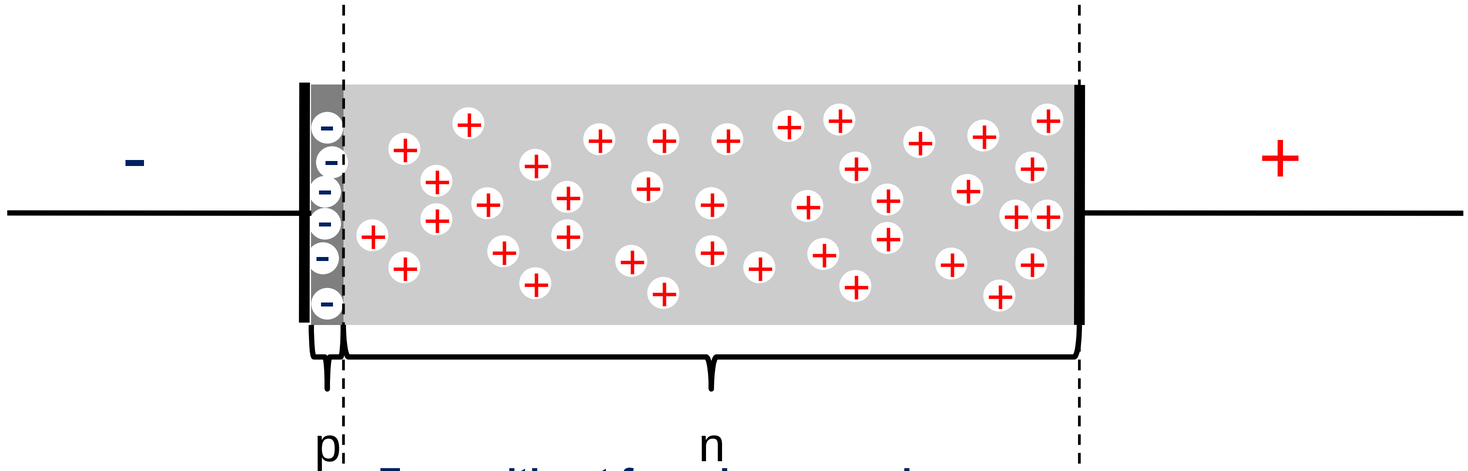


Zone without free charge carriers positively charged. Sensitive Detector Volume.

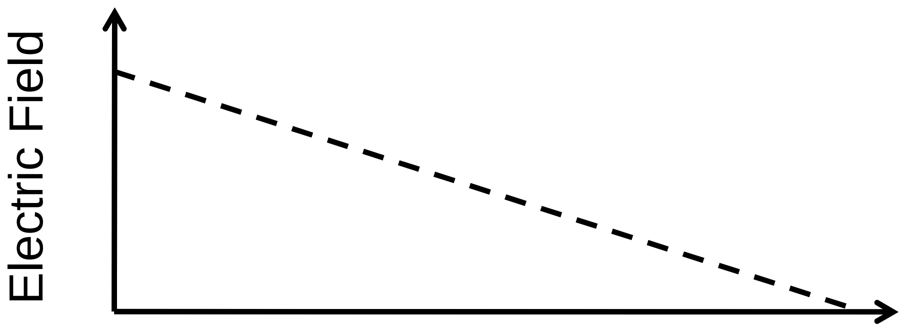
Zone with free electrons. Conductive. Insensitive to particles.



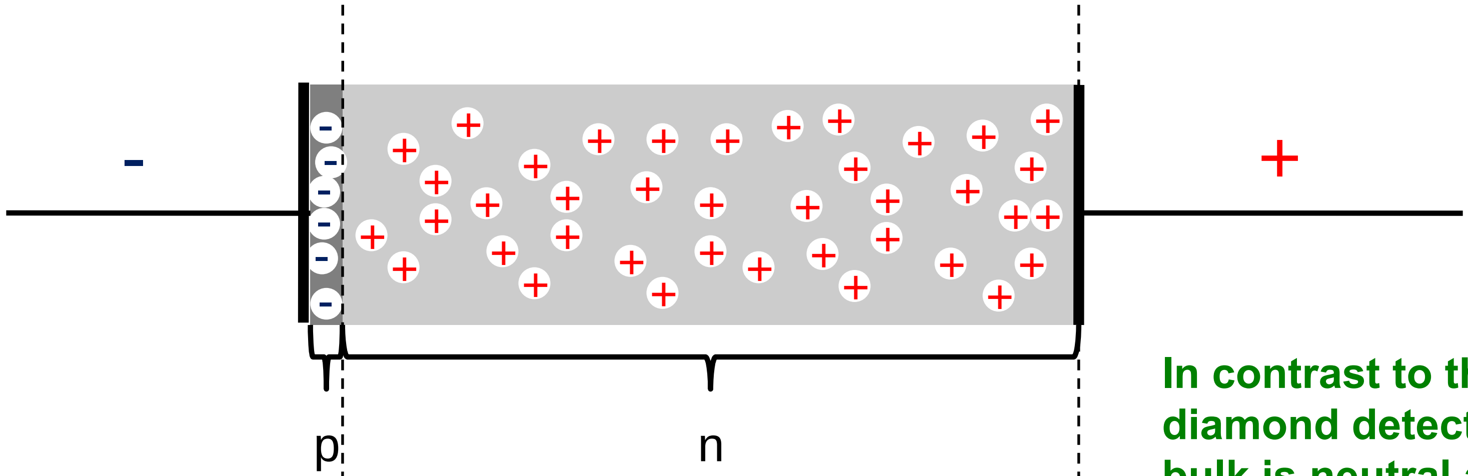
Fully-Depleted Silicon Detector



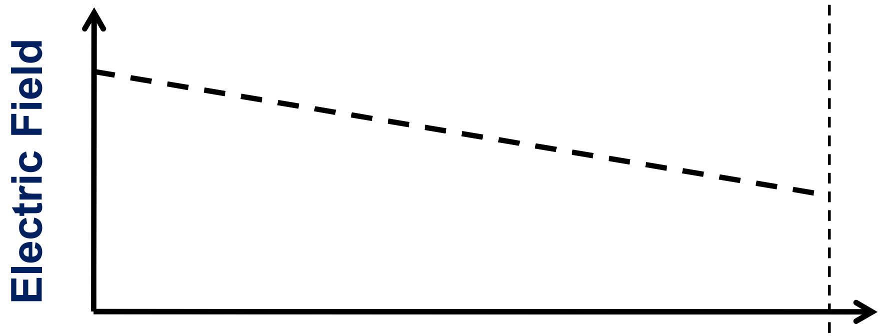
Zone without free charge carriers positively charged.
Sensitive Detector Volume.



Over-Depleted Silicon Detector



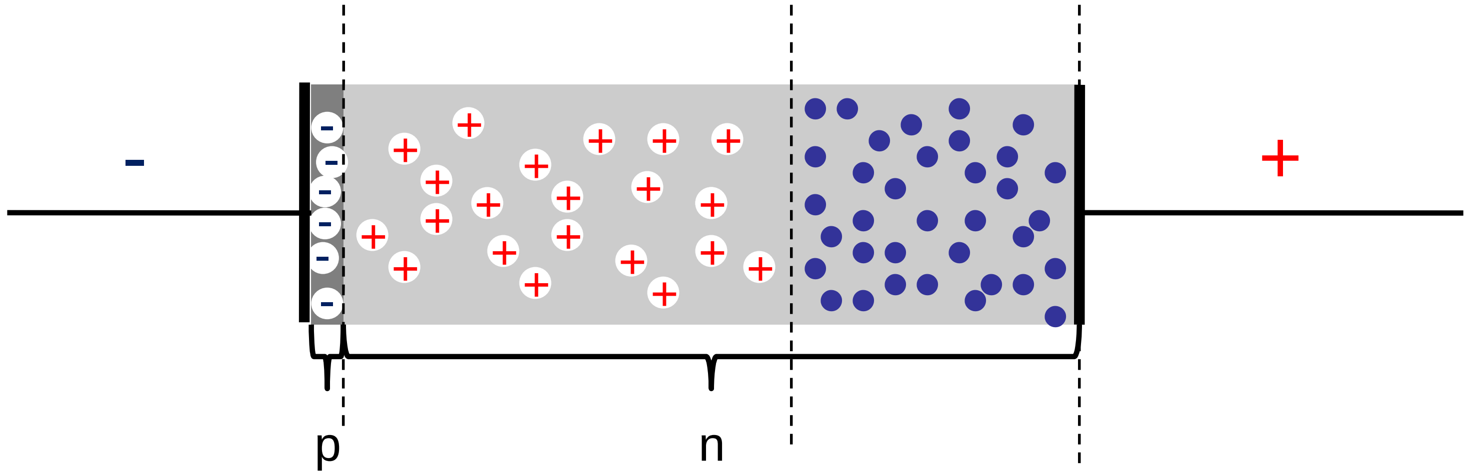
Zone without free charge carriers positively charged. Sensitive Detector Volume.



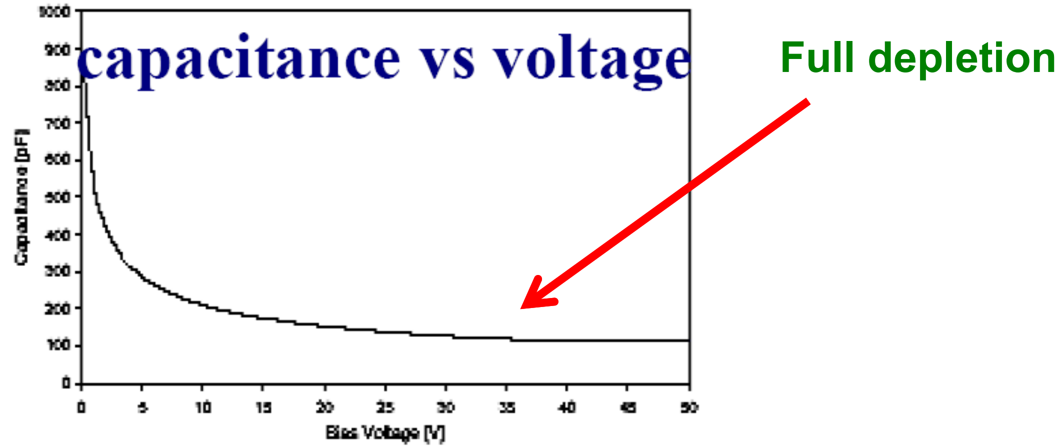
In contrast to the (un-doped) diamond detector where the bulk is neutral and the electric field is therefore constant, the sensitive volume of a doped silicon detector is charged (space charge region) and the field is therefore changing along the detector.

→ Velocity of electrons and holes is not constant along the detector.

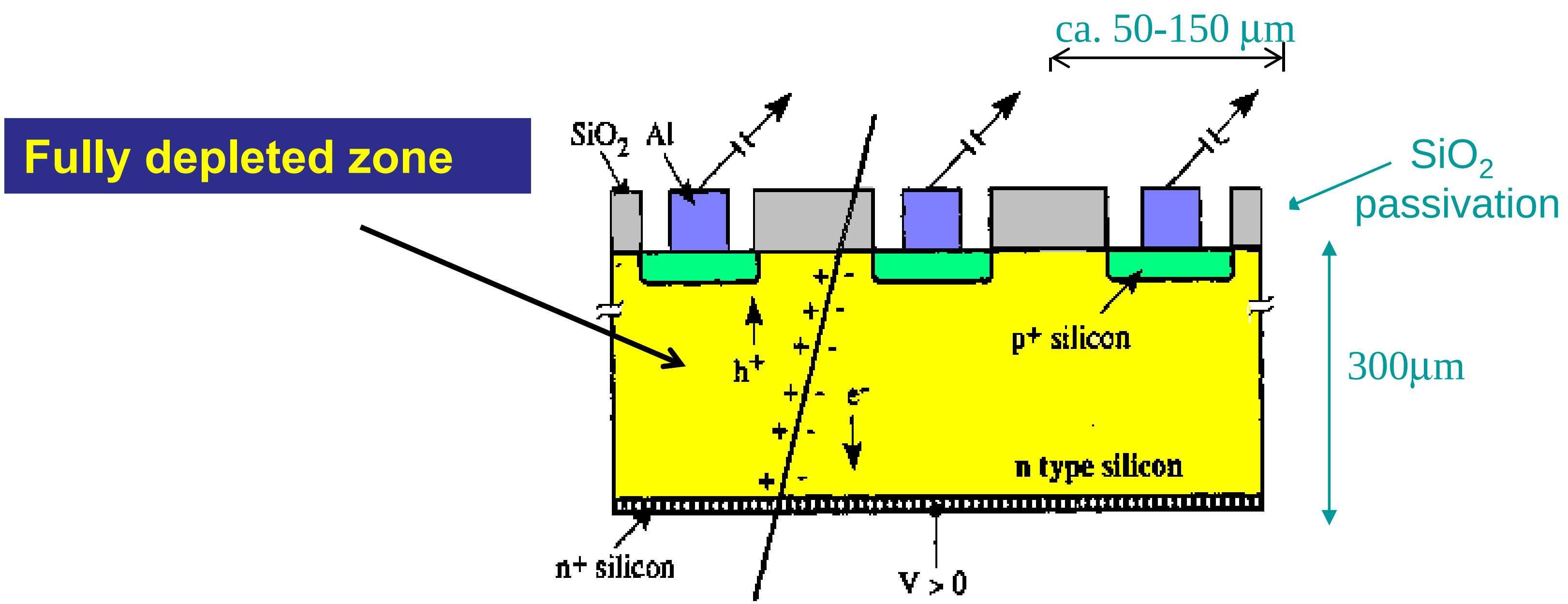
Depletion Voltage



The capacitance of the detector decreases as the depletion zone increases.



Silicon Detector



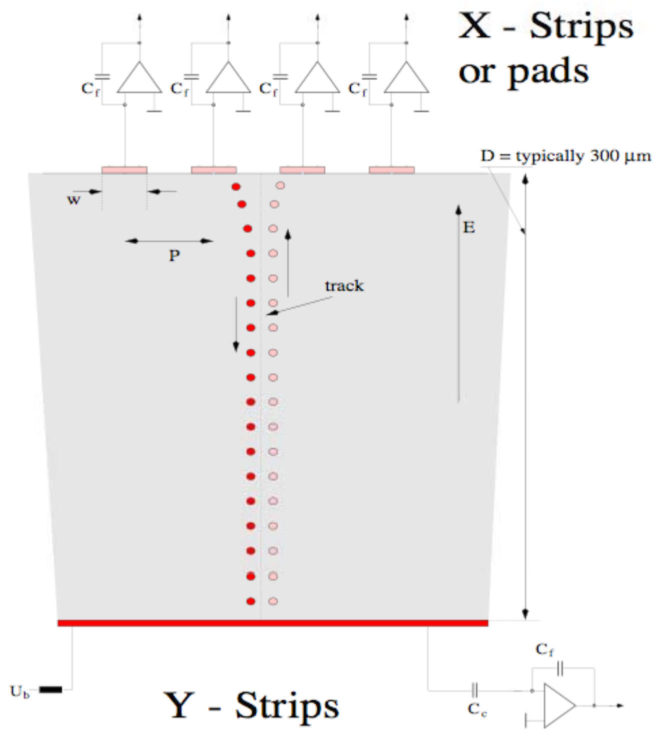
N (e-h) = 11 000/100µm

Position Resolution down to ~ 5µm !

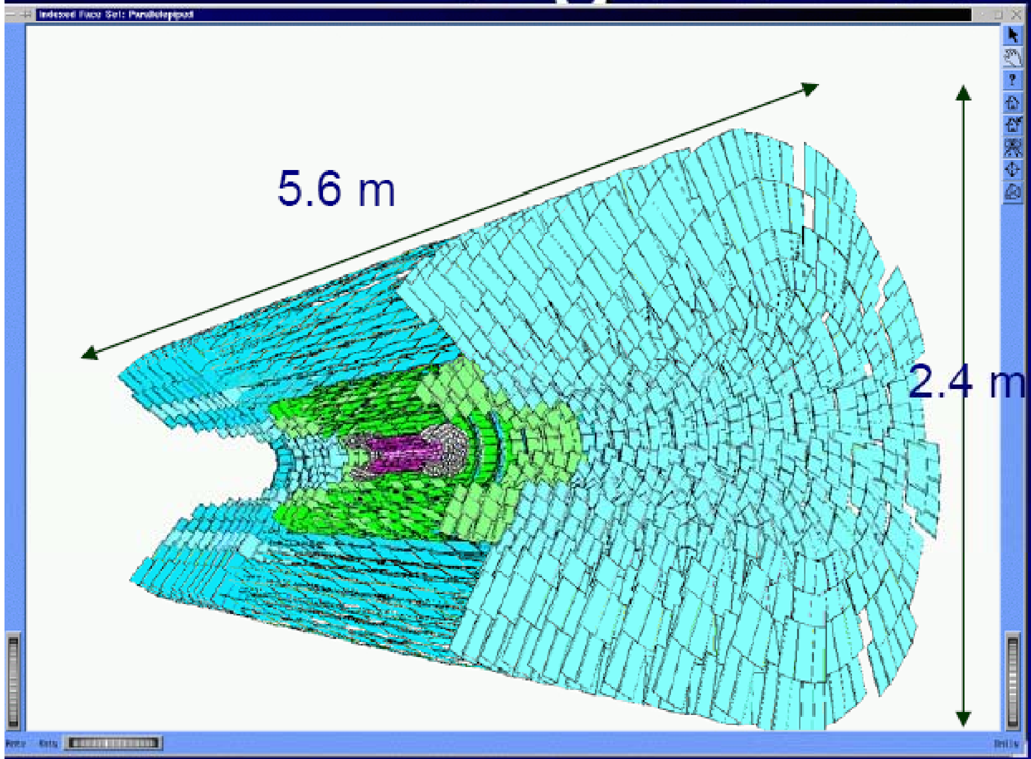
Silicon Detector

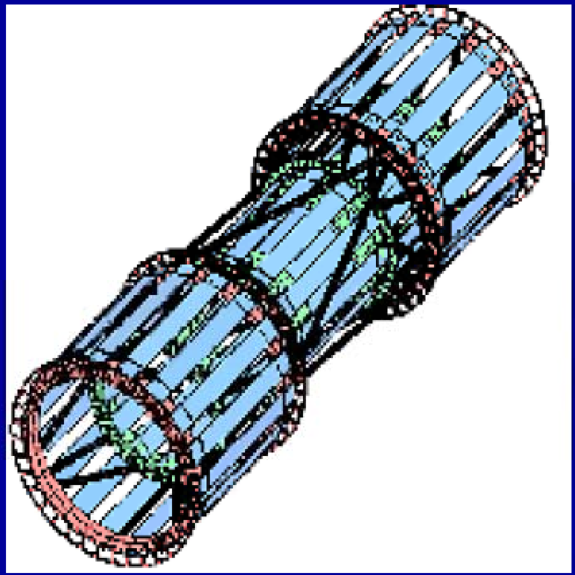
Every electrode is connected to an amplifier →
Highly integrated readout electronics.

Two dimensional readout is possible.



Large Silicon Systems





CMS tracker (~2007)

12000 modules

~ 445 m^2 silicon area

~ 24,328 silicon wafers

~ 60 M readout channels

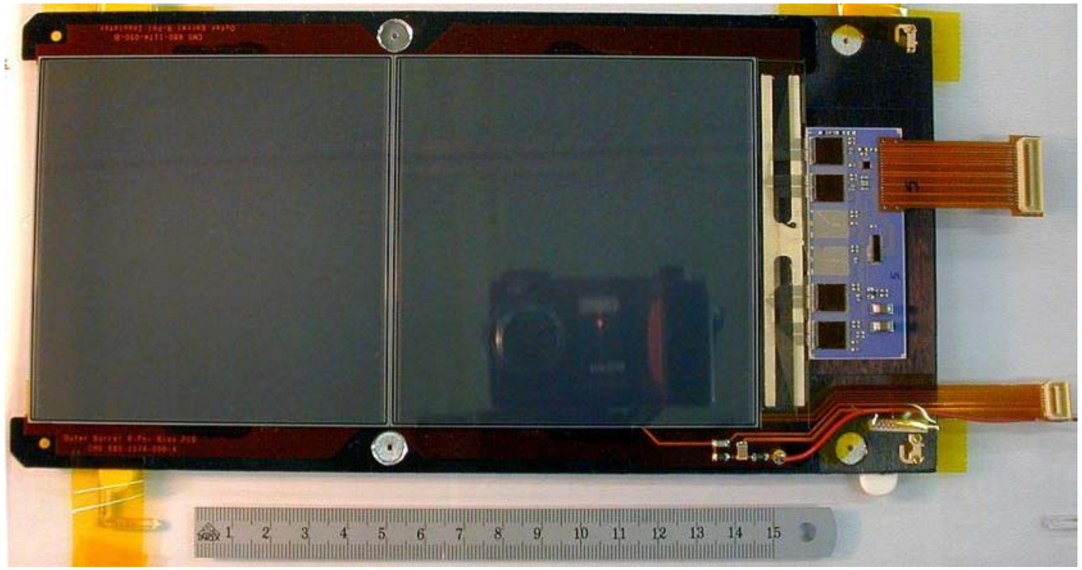
CDF SVX IIa (2001-)

~ 11m^2 silicon area

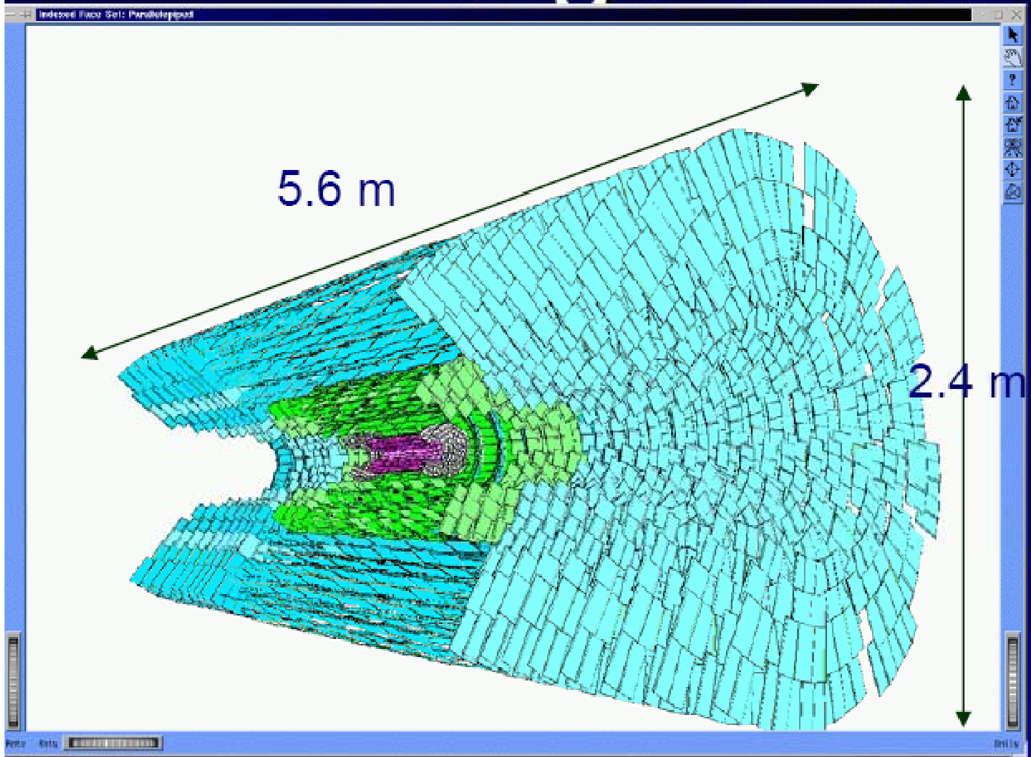
~ 750 000 readout channels

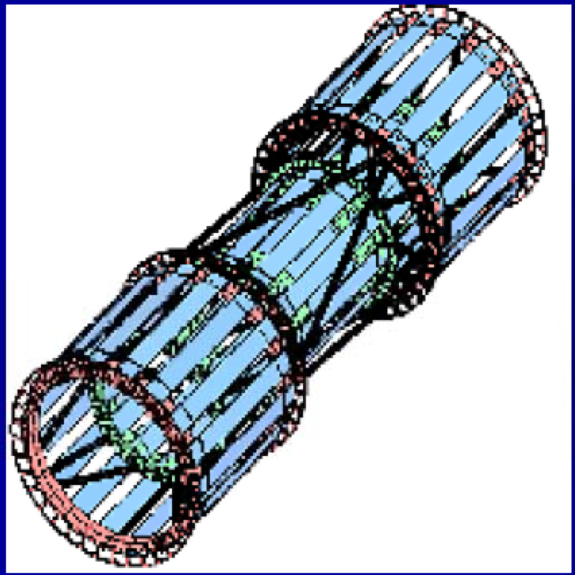
Picture of an CMS Si-Tracker Module

Outer Barrel Module



Large Silicon Systems





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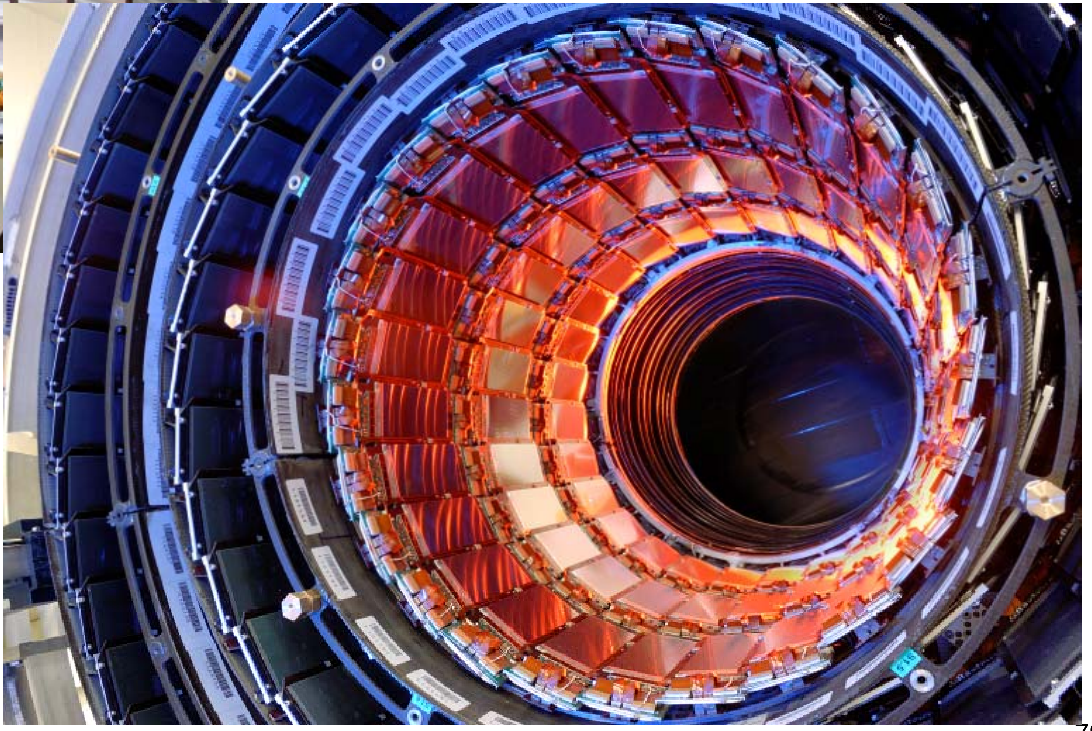
CMS Tracker



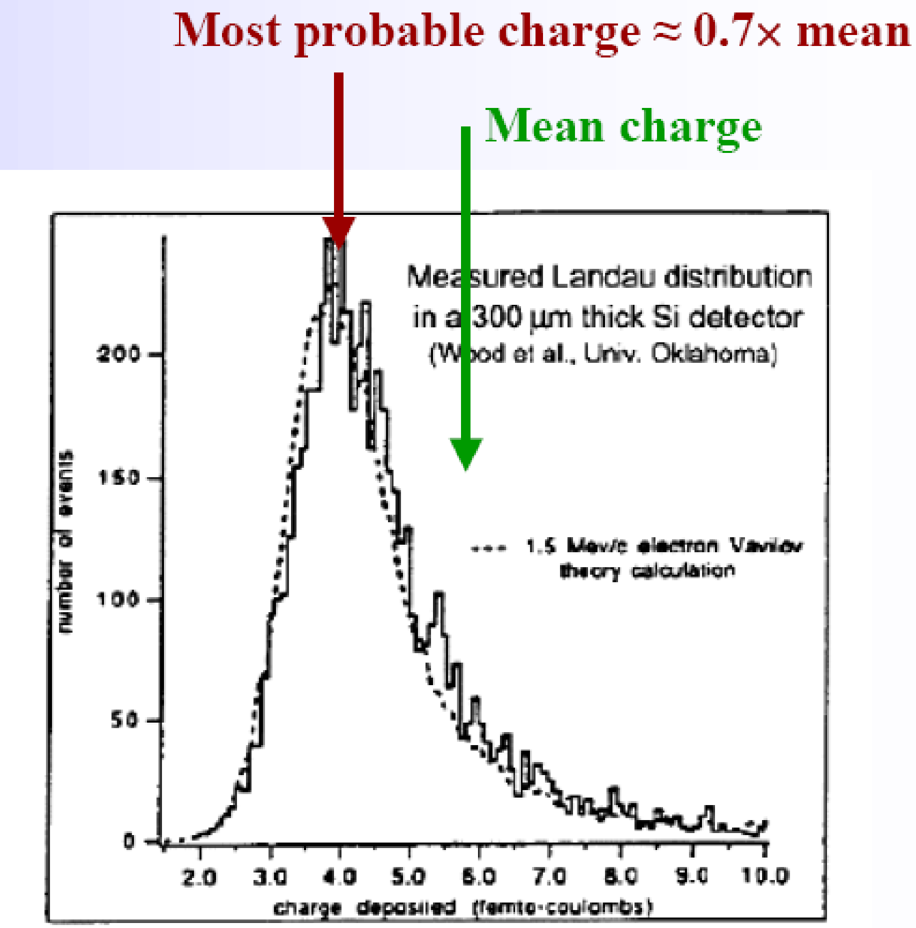
The Charge Signal

extra slide not shown

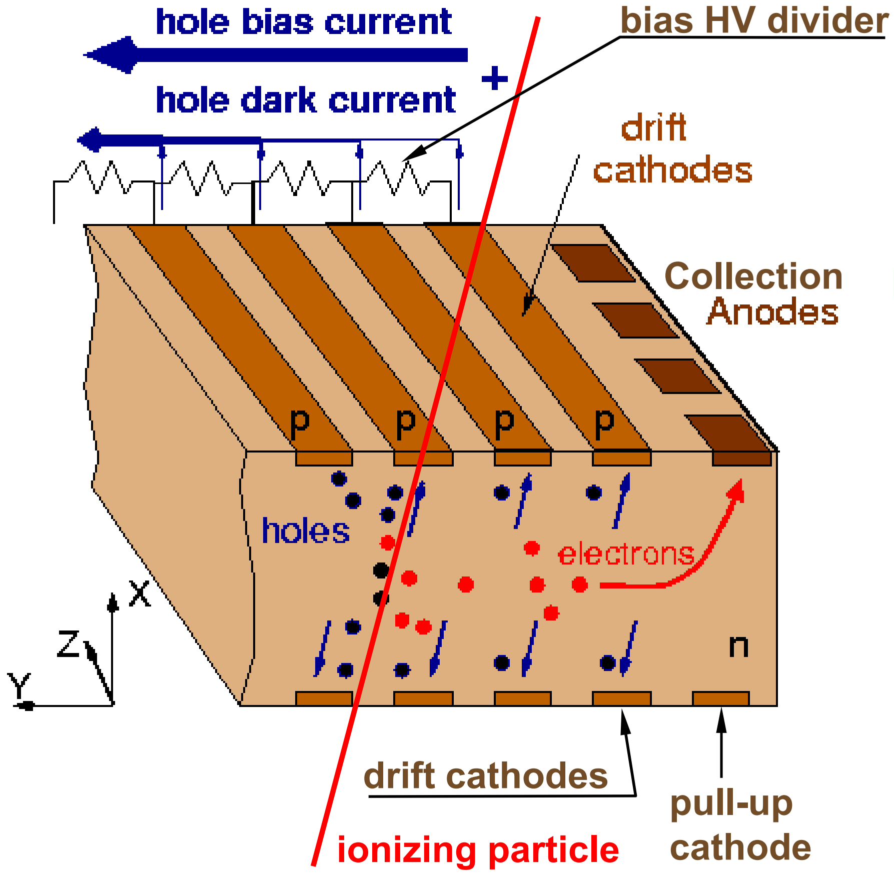
Collected Charge for a Minimum Ionizing Particle (MIP)

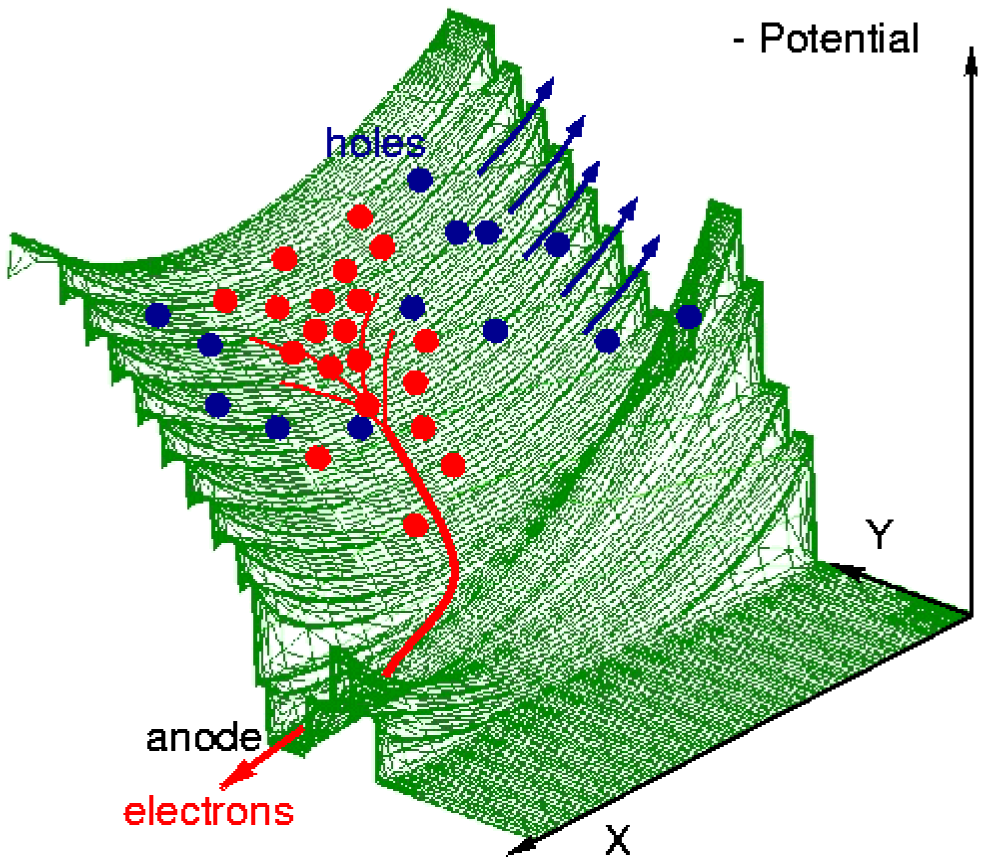
- **Mean energy loss**
  dE/dx (Si) = 3.88 MeV/cm
  ⇒ 116 keV for 300μm thickness
- **Most probable energy loss**
  ≈ 0.7 ×mean
  ⇒ 81 keV
- **3.6 eV to create an e-h pair**
  ⇒ 72 e-h / μm (mean)
  ⇒ 108 e-h / μm (most probable)
- **Most probable charge** (300 μm)

  ≈ 22500 e ≈ 3.6 fC

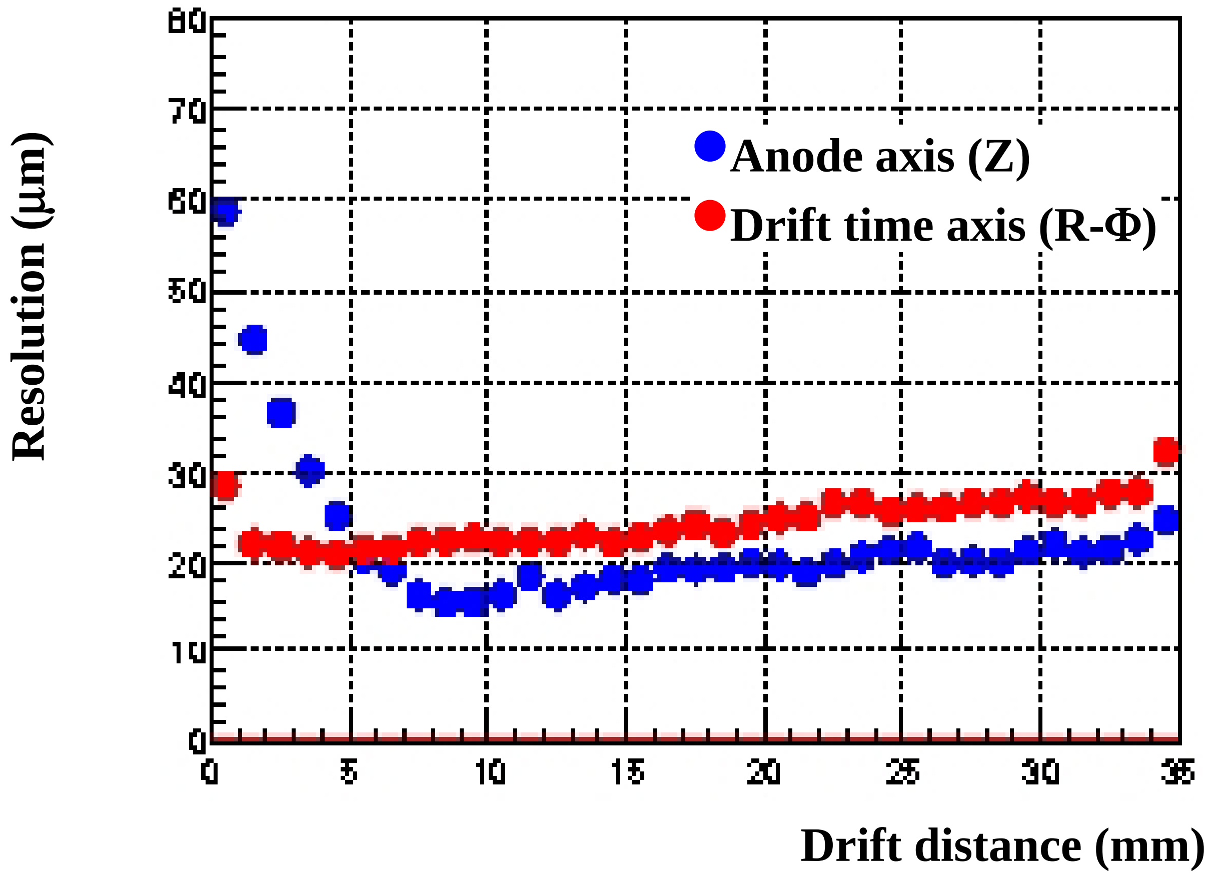


Silicon Drift Detector (like gas TPC !)

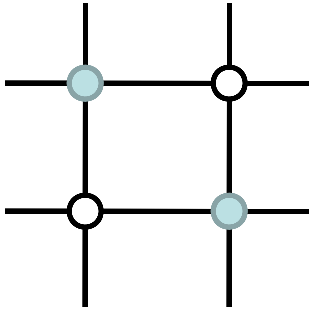




Silicon Drift Detector (like gas TPC !)



Pixel-Detectors



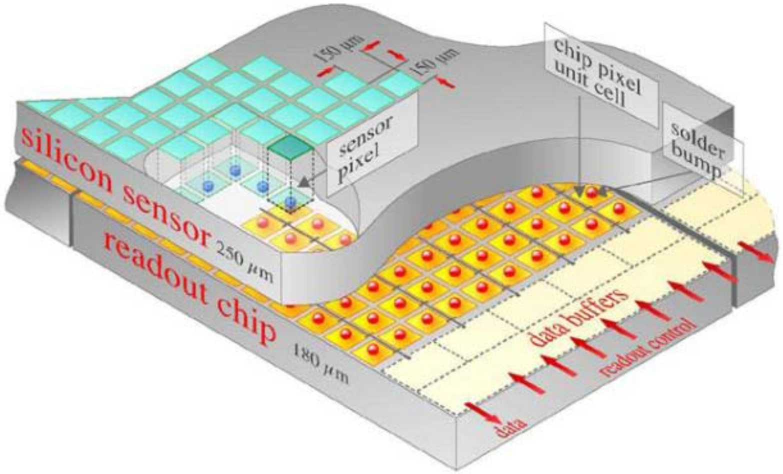
Problem:
2-dimensional readout of strip detectors results in 'Ghost Tracks' at high particle multiplicities i.e. many particles at the same time.

Solution:
Si detectors with 2 dimensional 'chessboard' readout. Typical size 50 x 200 μm.

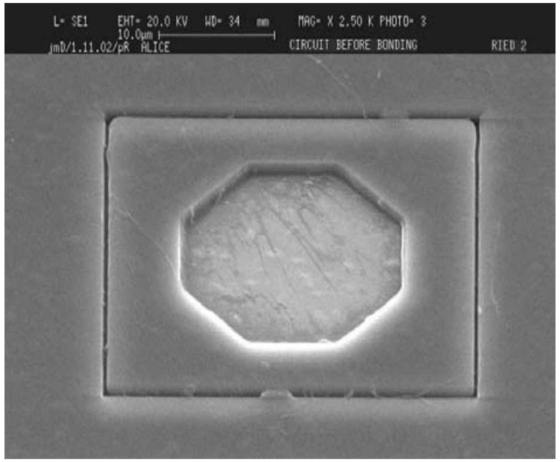
Problem:
Coupling of readout electronics to the detector.

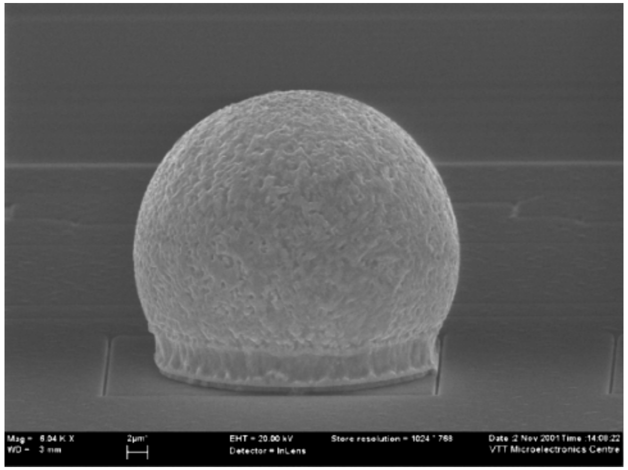
Solution:
Bump bonding.

Bump Bonding of each Pixel Sensor to the Readout Electronics



ATLAS: 1.4x10^8 pixels



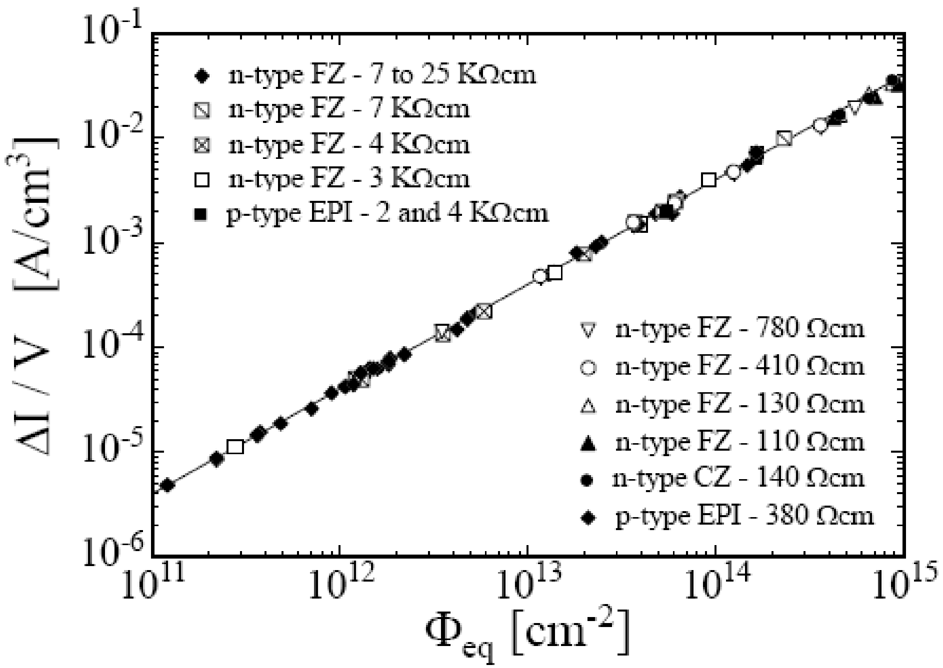


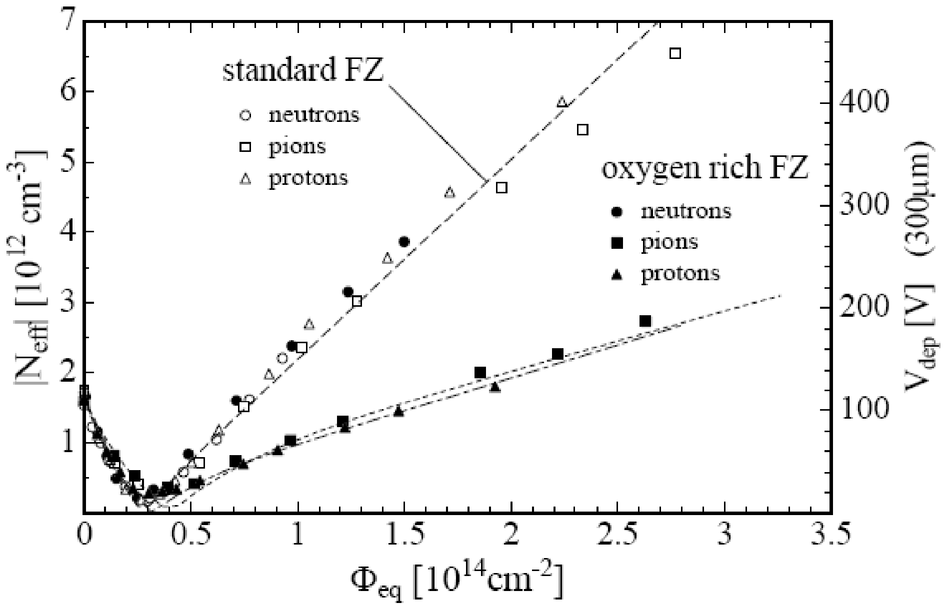
Radiation Effects 'Aging'

Increase in leakage current

Increase in depletion voltage

Decrease in charge collection efficiency due to underdepletion and charge trapping.





Silicon Detectors: towards higher Radiation Resistance

Typical limits of Si Detectors are at 10^{14}-10^{15} Hadrons/cm^2

LHC

- We can identify 3 different regions to match radiation damage and occupancy in the current LHC detector

R	Φ	Technology
>50 cm	10^{13}	p-on-n strip 500 µm thick, high resistivity (≈5 KΩ·cm), pitch ~ 200 µm
20-50 cm	10^{14}	p-on-n strips 320 µm thick, low resistivity (≈2 KΩ·cm), pitch ~80 µm
<20 cm	10^{15}	n-on-n pixels 270 µm thick sensors low resistivity (≈2 KΩ·cm) oxygenated

SLHC

- Radiation fluence increases by about a factor of 10 from one region to the other and by a factor of 10 between LHC and SLHC.

R	Φ	CCE	Technology
>50 cm	10^{14}	20ke	Present rad-hard technology (or n-on-p)
20-50 cm	10^{15}	10ke	Present n+-n LHC pixel (or n-on-p)
<20 cm	10^{16}	>5Ke	RD needed

R&D Strategy:

Defect Engineering
- Oxygen enriched Si

New Materials
- Diamonds
- Czochralski Si
- …

New Geometries

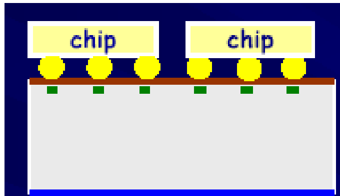
Low Temperature Operation

High Resolution Low Mass
Silicon Trackers, Monolithic Detectors

Linear Collider Physics requirement:

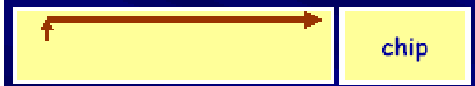
δ (IP) < 5 μm $\oplus$ 10 μm/(p $\sin^{3/2}\theta$)

(best SLD 8 μm $\oplus$ 33 μm/(p $\sin^{3/2}\theta$))



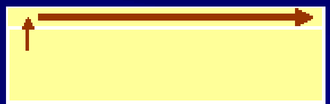
Hybrid Active Pixel: Chip bump bonded to sensor

RD: make it thinner (LHC sensors 2% X_0/layer), improve space point resolution with interleaved pixels



CCD: charge collected in thin layer and transferred through silicon

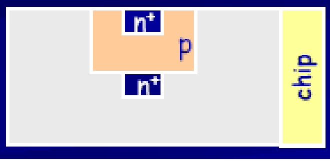
RD: readout speed, radiation hardness, material support



CMOS sensors (MAPS, FAPS): standard CMOS wafer integrates all functions.

RD: fast readout, non-standard technologies

Poster by Deptuch on Mimosa



DEPFET, CMOS on SOI (talk by Kucewiz) :

Fully depleted sensor with integrated preamp

RD:pixel size, power, thinning, speed

Large variety of monolithic pixel Detectors explored, mostly adapted to low collision rates of LC.

Summary on Solid State Detectors

Solid state detectors provide very high precision tracking in particle physics experiments (down to 5um) for vertex measurement but also for momentum spectroscopy over large areas (CMS).

Technology is improving rapidly due to rapis Silicon development for electronics industry.

Typical number where detectors start to strongly degrade are 10^{14}-10^{15} hadron/cm^2.

Diamond, engineered Silicon and novel geometries provide higher radiation resistance.

Clearly, monolithic solid state detectors are the ultimate goal. Current developments along these lines are useful for low rate applications.