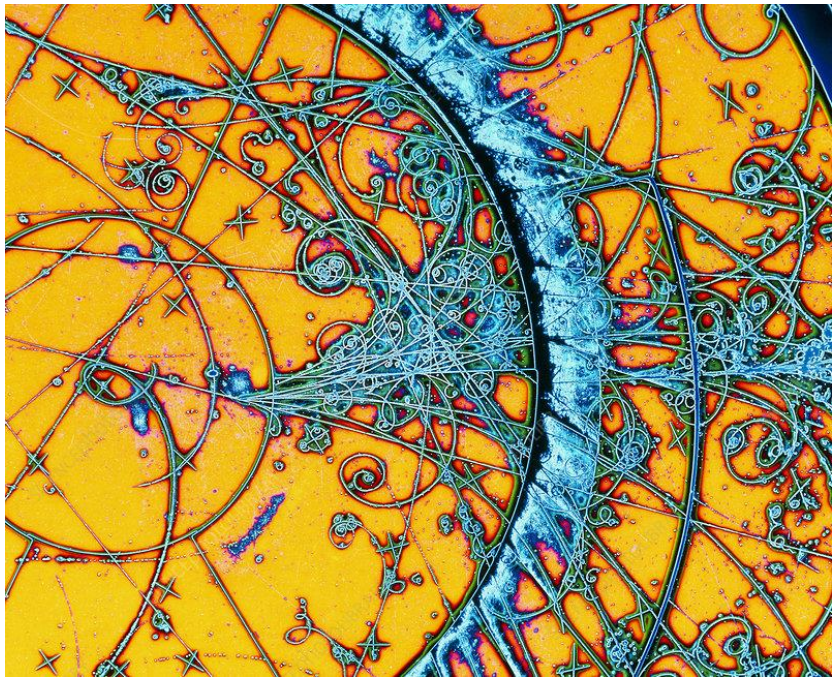
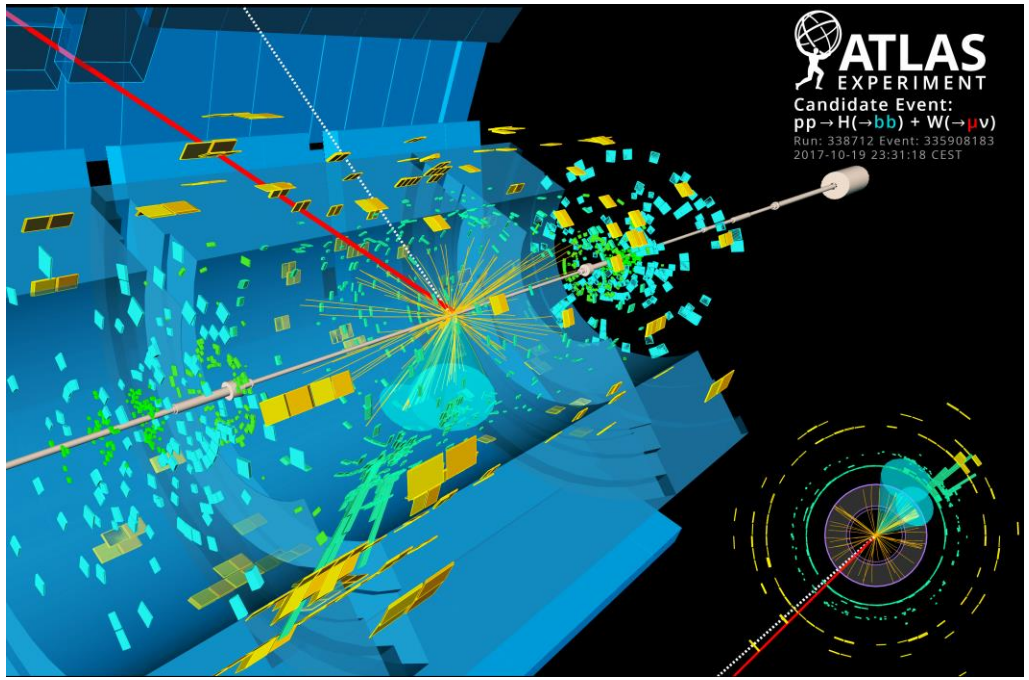
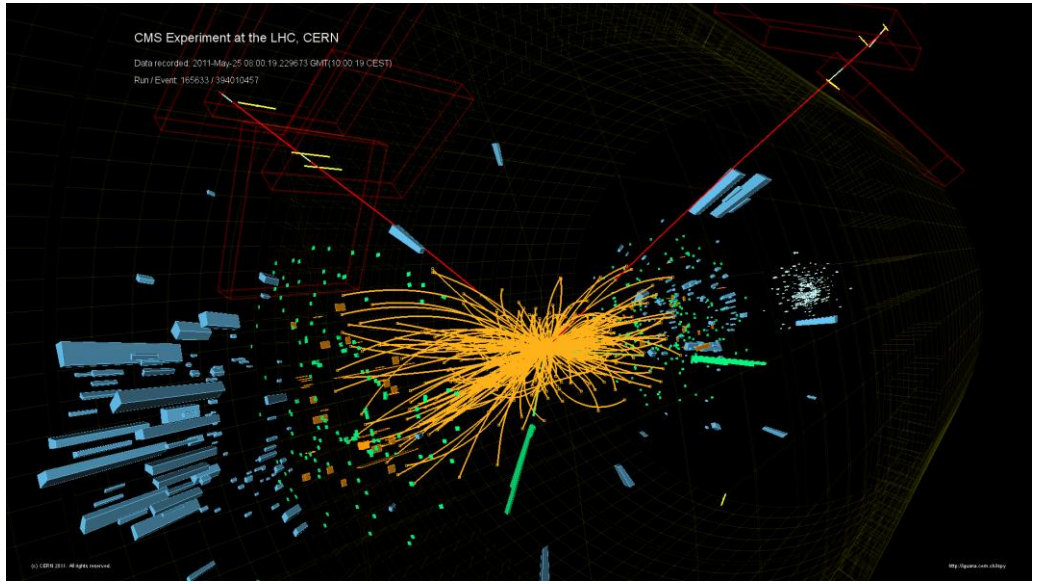



ATLAS
EXPERIMENT
Candidate Event:
pp→H(→bb) + W(→μν)
Run: 338712 Event: 335908183
2017-10-19 23:31:18 CEST


CMS Experiment at the LHC, CERN

Particle Detectors

Summer Student Lectures 2023

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

History of Instrumentation ↔ History of Particle Physics

The ‘Real’ World of Particles

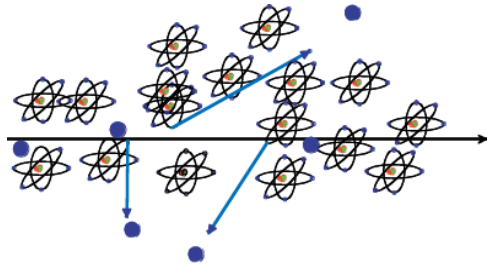
Interaction of Particles with Matter

Tracking Detectors, Calorimeters, Particle Identification

Detector Systems

Creation of the Signal

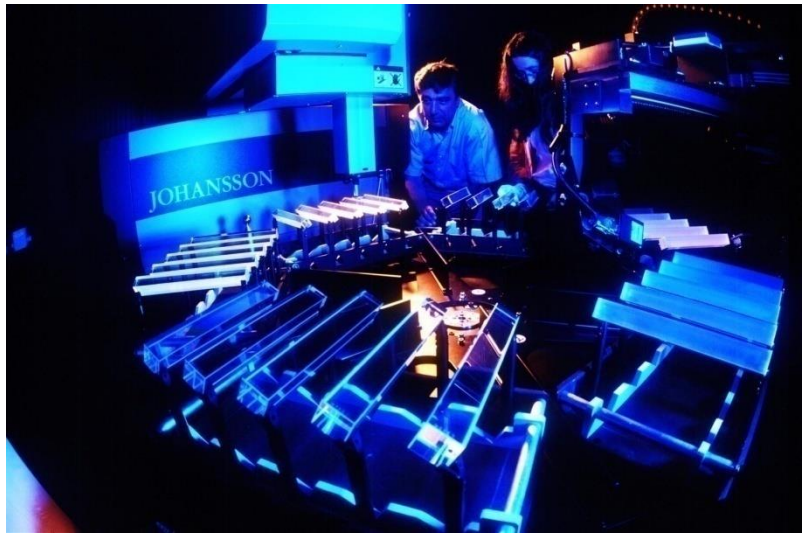
Charged particles traversing matter leave excited atoms, electron-ion pairs (gases) or electrons-hole pairs (solids) behind.

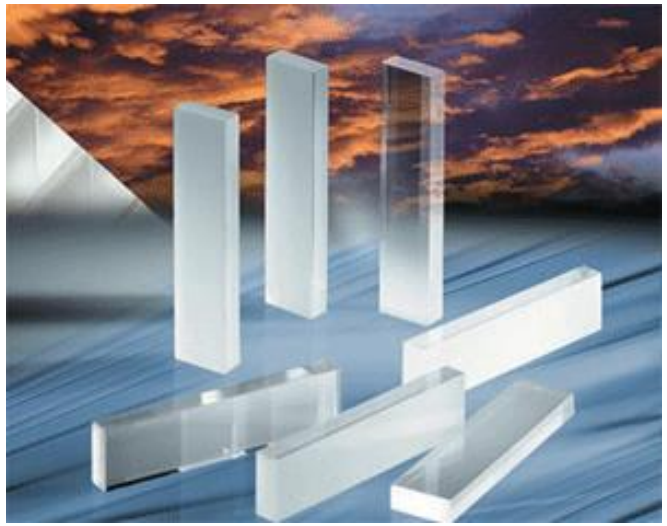


Excitation:
The photons emitted by the excited atoms in transparent materials can be detected with photon detectors like photomultipliers or semiconductor photon detectors.

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





Scintillators

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

a) Observed in Noble Gases (even liquid !)

b) Inorganic Crystals

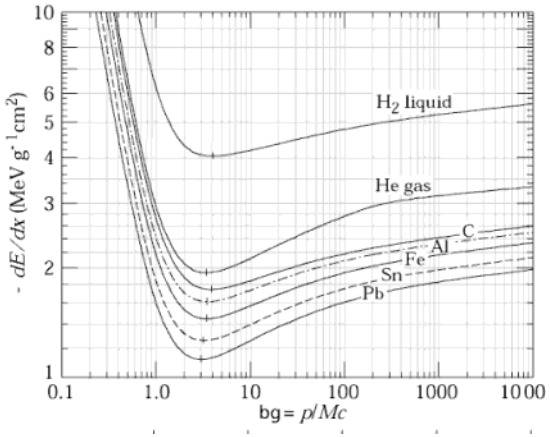
→ Substances with largest light yield. Used for precision measurement of energetic Photons. Used in Nuclear Medicine.

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.



Scintillators

Organic ('Plastic') Scintillators

Low Light Yield

Fast: 1-3ns

Type	Light output	λ_{max} (nm)	Attenuation length (cm)	Risetime (ns)	Decay 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 bunch-crossing 25ns

Inorganic (Crystal) Scintillators

Large Light Yield

Slow: few 100ns

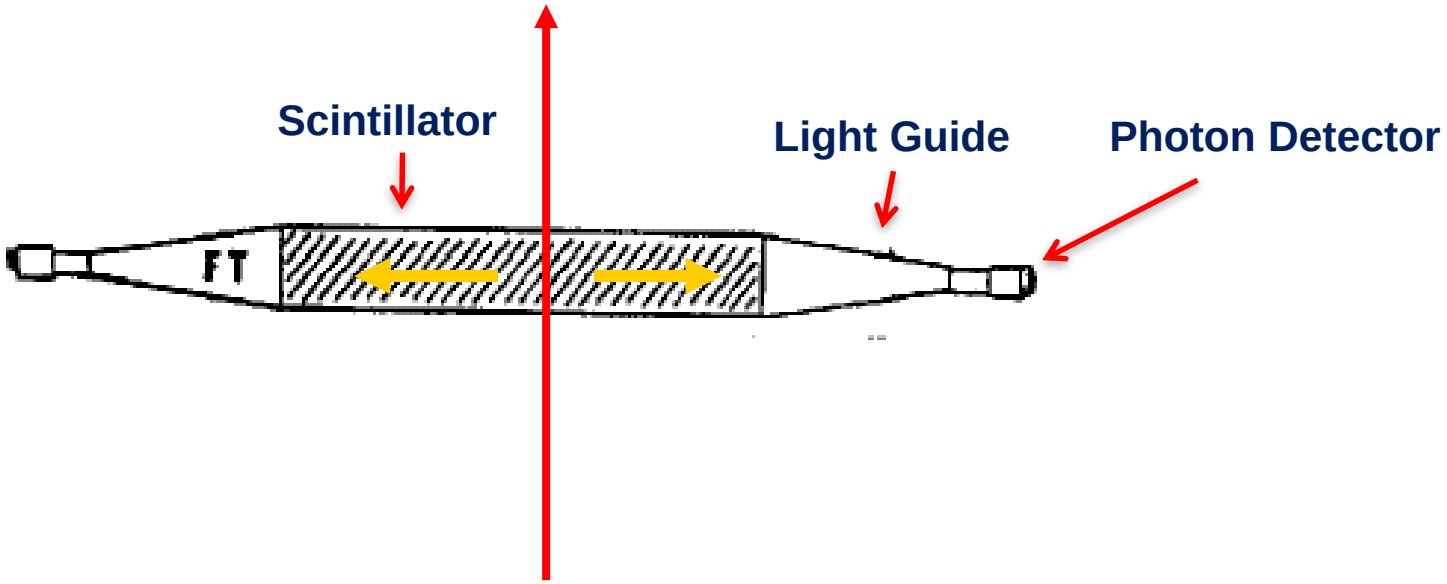
	Relative light output	λ_{max} emission (nm)	Decay time (ns)	Density (g/cm³)
Inorganic crystals				
NaI(Tl)	230	415	230	3.67
CsI(Tl)	250	560	900	4.51
$Bi_4Ge_3O_{12}$ (BGO)	23–86	480	300	7.13
Organic crystals				
Anthracene	100	448	22	1.25
Trans-stilbene	75	384	4.5	1.16
Naphthalene	32	330–348	76–96	1.03
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[b]	

LEP bunch-crossing 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.



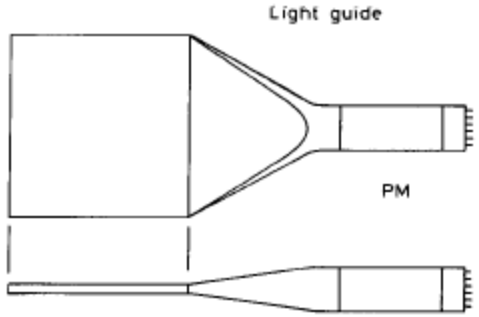
By segmentation one can arrive at spatial resolution.

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

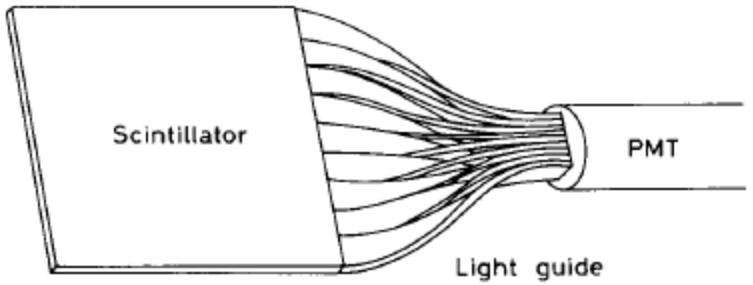
Scintillators

Typical Geometries:

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

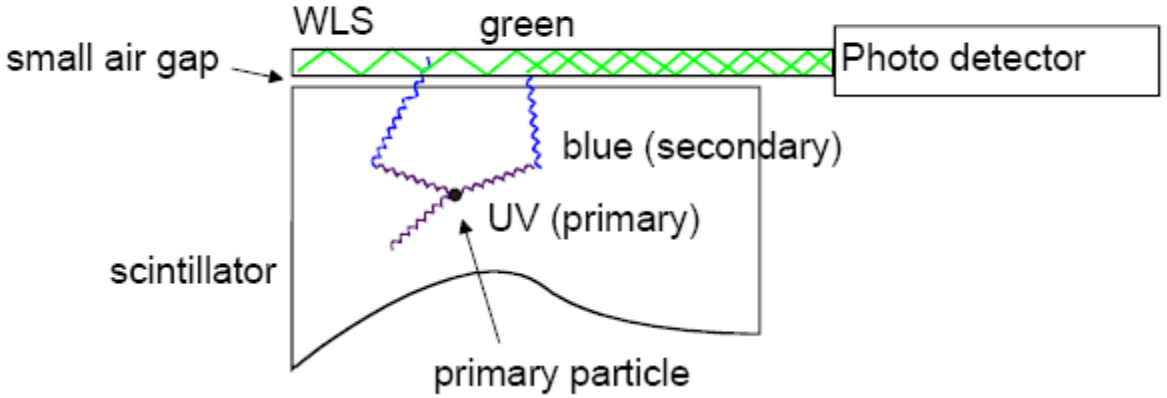


"fish tail"



adiabatic

- wavelength shifter (WLS) bars

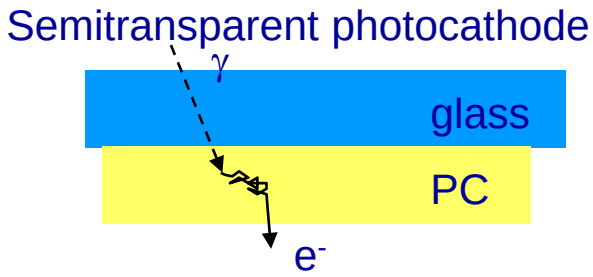


UV light enters the WLS material
Light is transformed into longer wavelength
→Total internal reflection inside the WLS material
→ 'transport' of the light to the photo detector

Photomultipliers

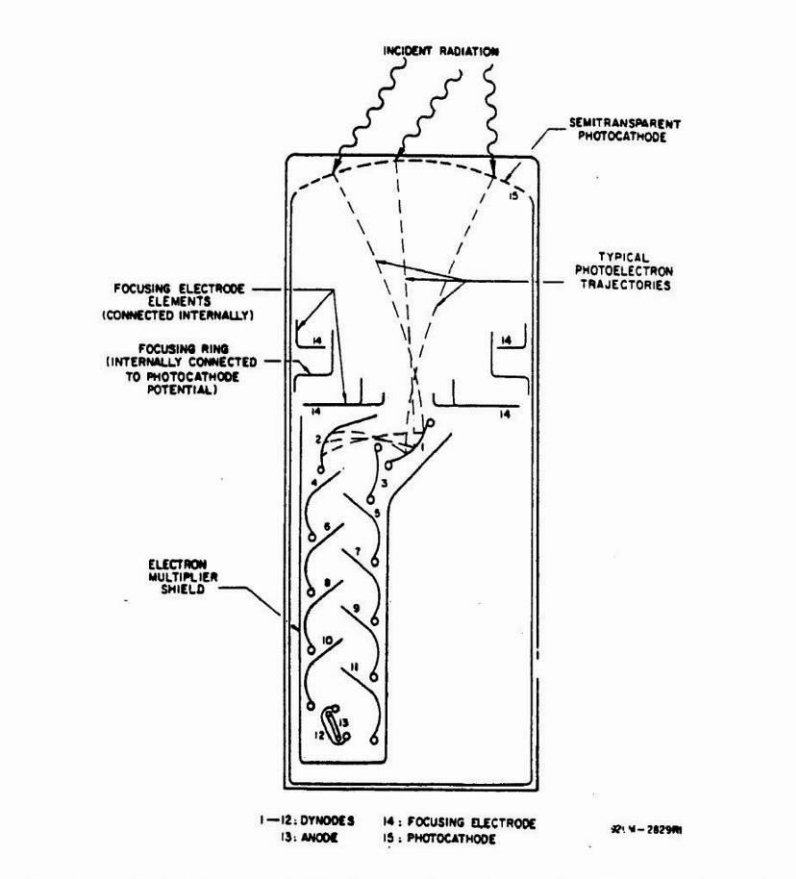
The frequent use of Scintillators is due to:

Well established, fast response time → 1 to 100ns



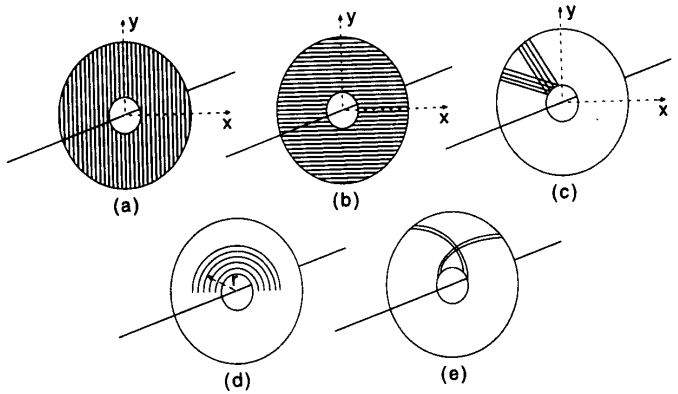
Schematic of a Photomultiplier:

- 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. $I=Q/T = 10^8*1.603*10^{-19}/10*10^{-9}= 1.6mA$.
- Across a 50 Ω Resistor → U=R*I= 80mV.

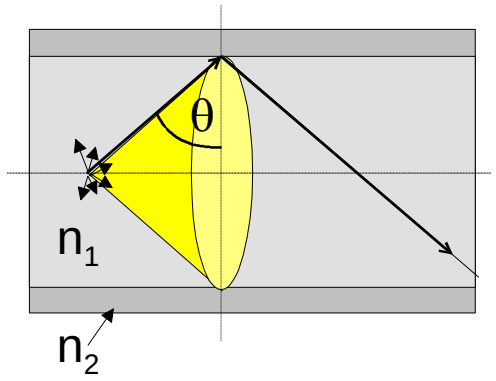


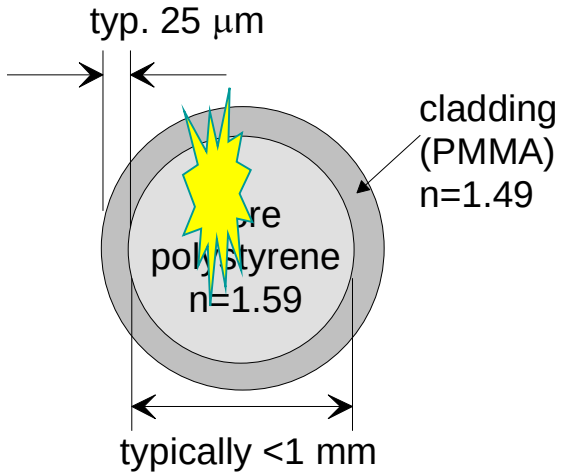
Scintillating fibers

Planar geometries
(end cap)

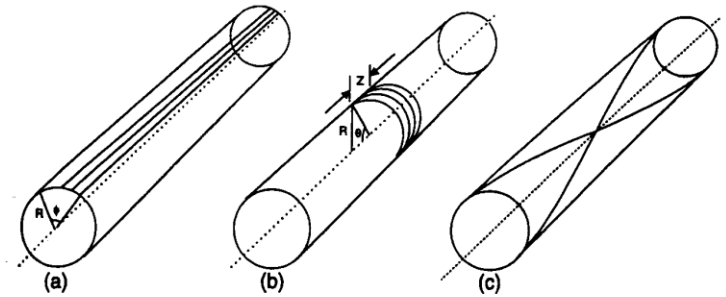


Light transport by total internal reflection



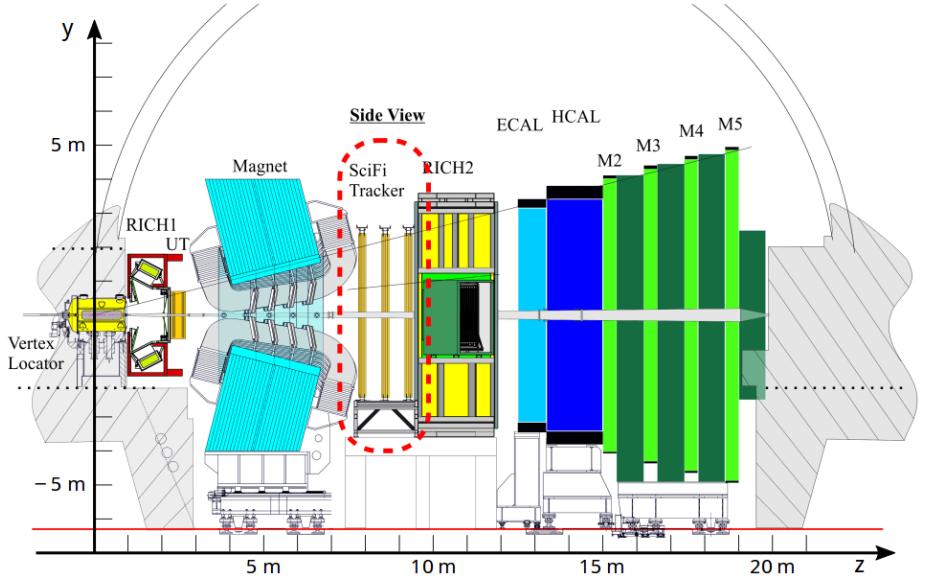


Circular geometries
(barrel)



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

- High geometrical flexibility
- Fine granularity
- Low mass
- Fast response (ns)



Photon Detectors at LHC

Photomultipliers (PMT):
- ATLAS Barrel Hadron Calorimer scintillator readout
- ALICE T0 cherenkov detector and V0 scintillator trigger detector
- LHCb ECAL and HCAL scintillator readout
- CMS Hadron Forward Calorimeter quartz fiber readout

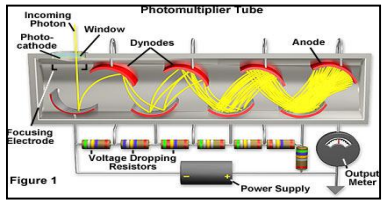
Multi Anode Photomultipliers (MA PMT):
- LHCb RICH upgrade
- CMS Hadron Forward Calorimeter upgrade

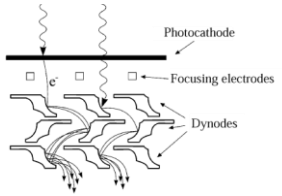
Micro Channel Plate Photomultipliers (MCP PMT):
- ALICE T0 cherenkov detector upgrade

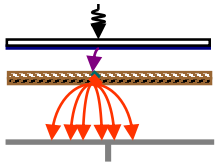
Hybrid Photon Detectors (HPD):
- CMS Hadron Barrel and Hadron Endcap Calorimeter Scinitillator readout
- LHCb RICH detector

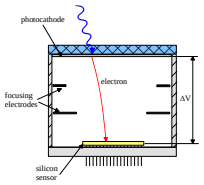
Avalanche Photo Diodes (APD):
- CMS ECAL
- ALICE PHOS and ECAL Calorimeters

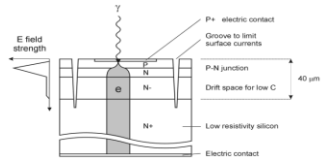
Geigermode APDs (GAPD) = Multi Pixel Photon Counters (MPPC) = Silicon Photo Multiplier (SiPM):
- CMS Hadron Barrel and Hadron Endcap Calorimeter to replace HPDs
- LHCb Fiber Tracker (operation around -40 degrees)

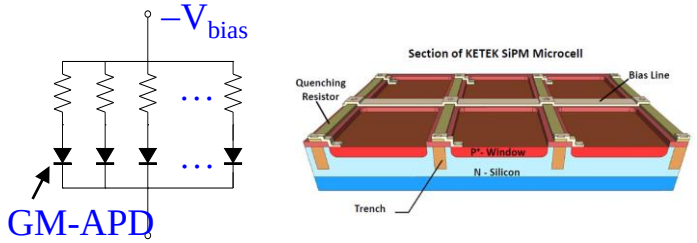












Detectors based registration of ionization: Gas and solid state detectors

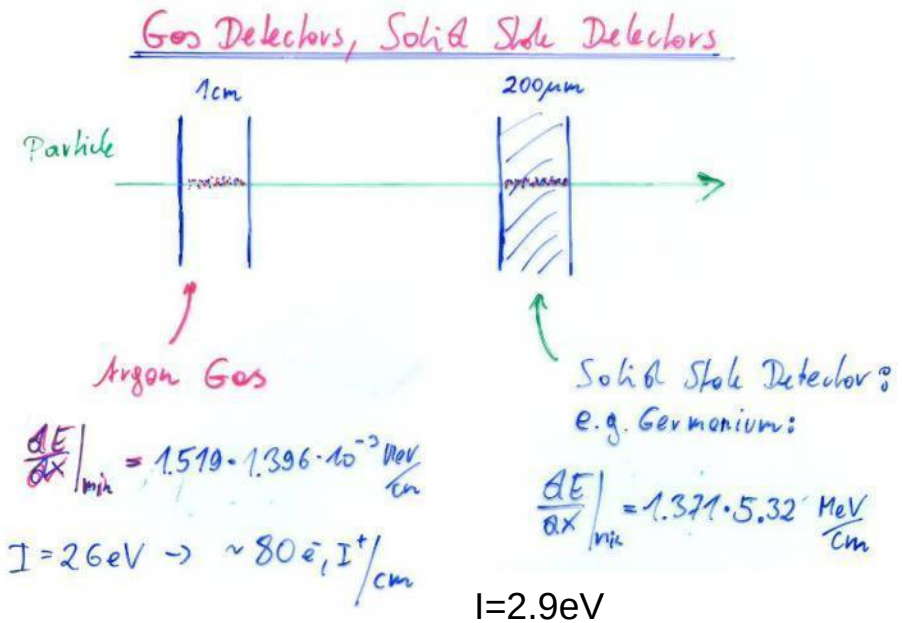
Cloud Chamber: Charges create drops → photography.
Bubble Chamber: Charges create bubbles → photography.
Emulsion: Charges 'blacked' the film.

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

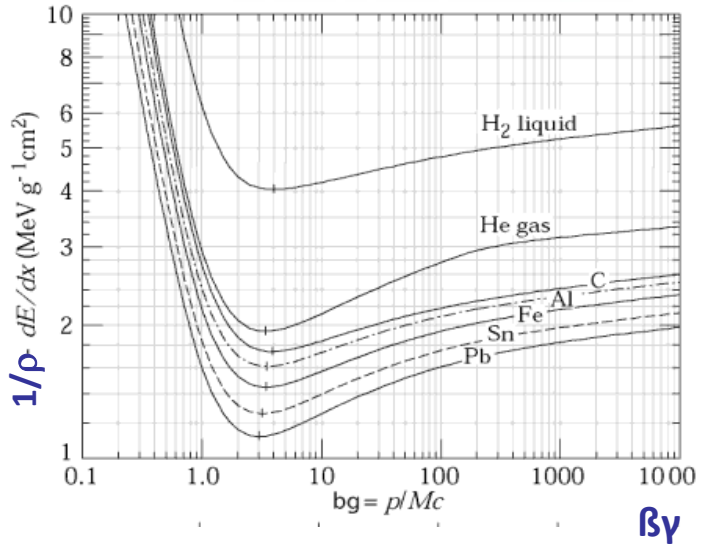
In gas detectors (e.g. wire chamber) the charges are internally multiplied in order to provide a measurable signal.

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

For solid state photon detectors or for very thin silicon detectors for high precision timing, internal avalanche multiplication is used.



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 go below 50e- (even down to a few electrons for small pixels), typical numbers are ~ 1000e-. Typically linear dependence on detector capacitance.

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

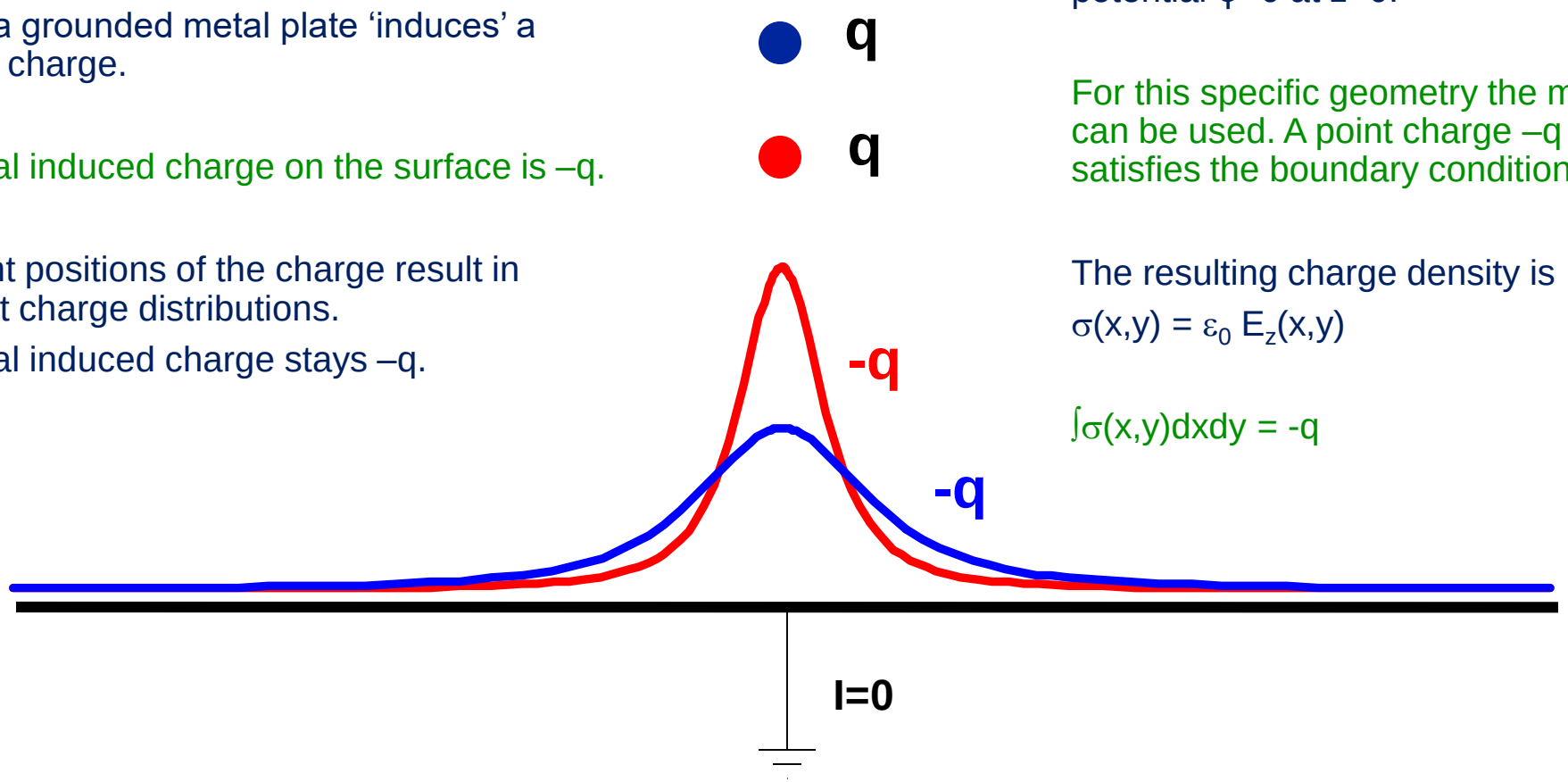
A point charge q at a distance z_0

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

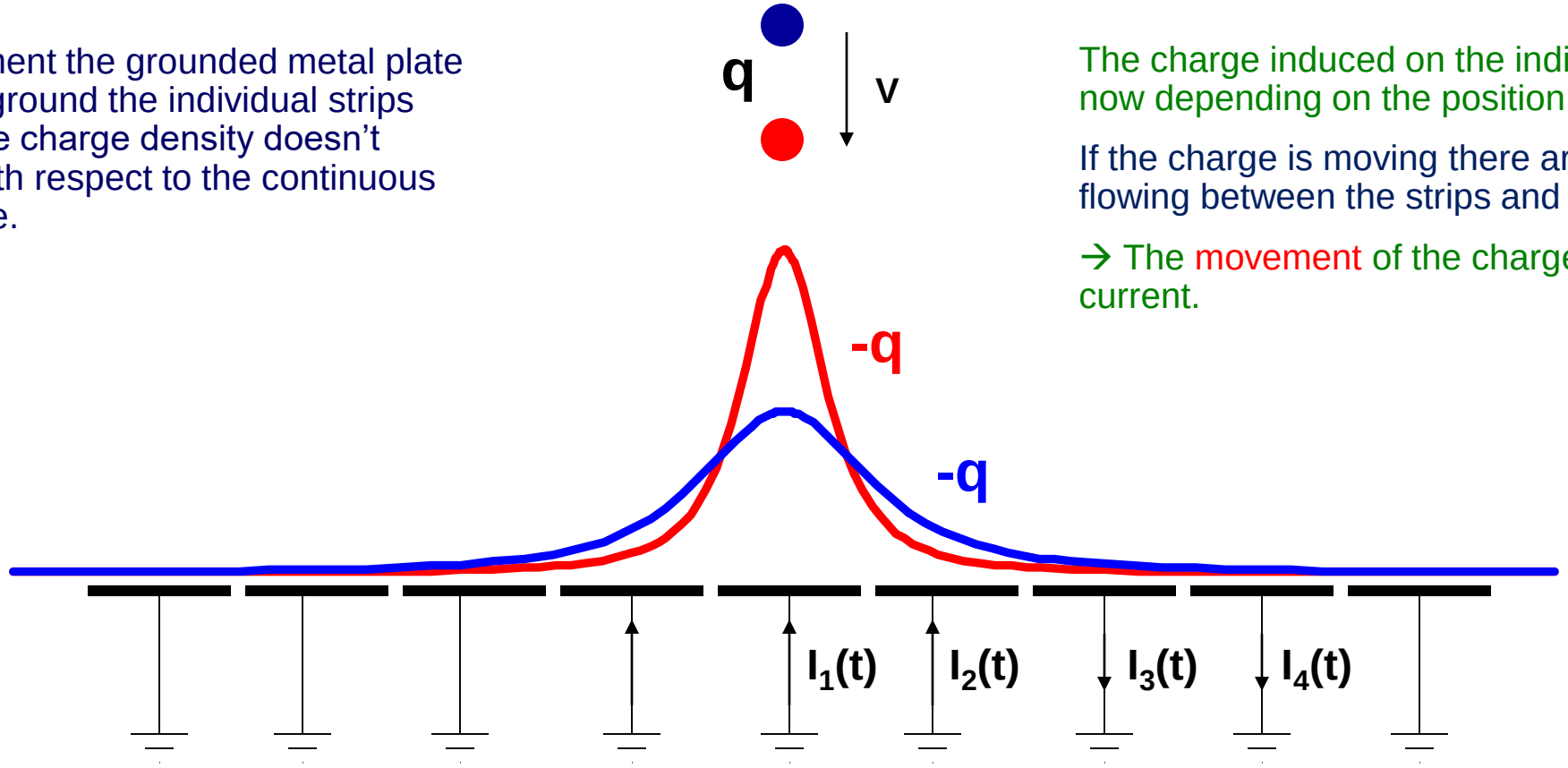
$\sigma(x,y) = \varepsilon_0 E_z(x,y)$

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

$$E_z(x,y) = -\frac{qz_0}{2\pi\varepsilon_0(x^2+y^2+z_0^2)^{\frac{3}{2}}} \qquad E_x = E_y = 0 \qquad \sigma(x,y) = \varepsilon_0 E_z(x,y) \qquad Q = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\sigma(x,y)dxdy = -q$$

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

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.

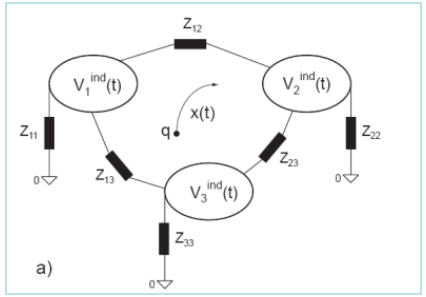
The current induced on a grounded electrode by a charge q moving along a trajectory x(t) is calculated the following way (Ramo-Shockley Theorem):

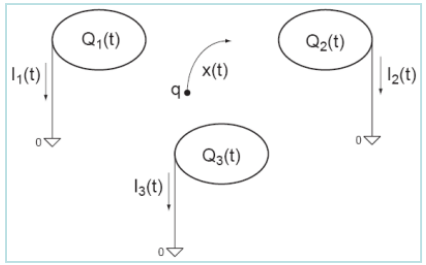
One removes the charge q from the setup, puts the electrode to voltage V_0 while keeping all other electrodes grounded. This results in an electric field $E_n(x)$, the Weighting Field, in the volume between the electrodes, from which the current is calculated by

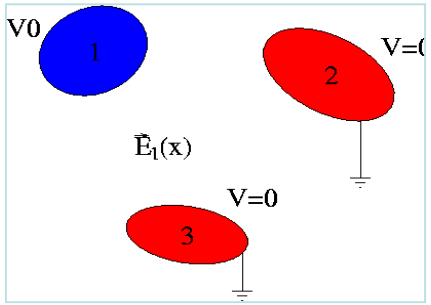
$$I_n(t) = -\frac{q}{V_0}\vec{E_n}[\vec{x}(t)]\frac{d\vec{x}(t)}{dt} = -\frac{q}{V_0}\vec{E_n}[\vec{x}(t)]\vec{v}(t)$$

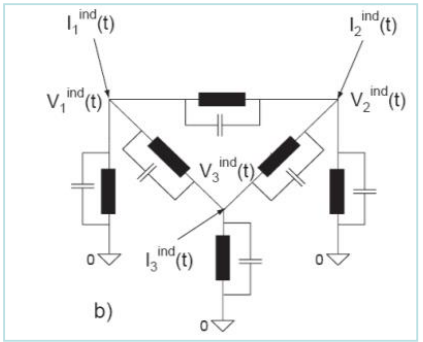
These currents are then placed as ideal current sources on a circuit where the electrodes are 'shrunk' to simple nodes and the mutual electrode capacitances are added between the nodes. These capacitances are calculated from the weighting fields by

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

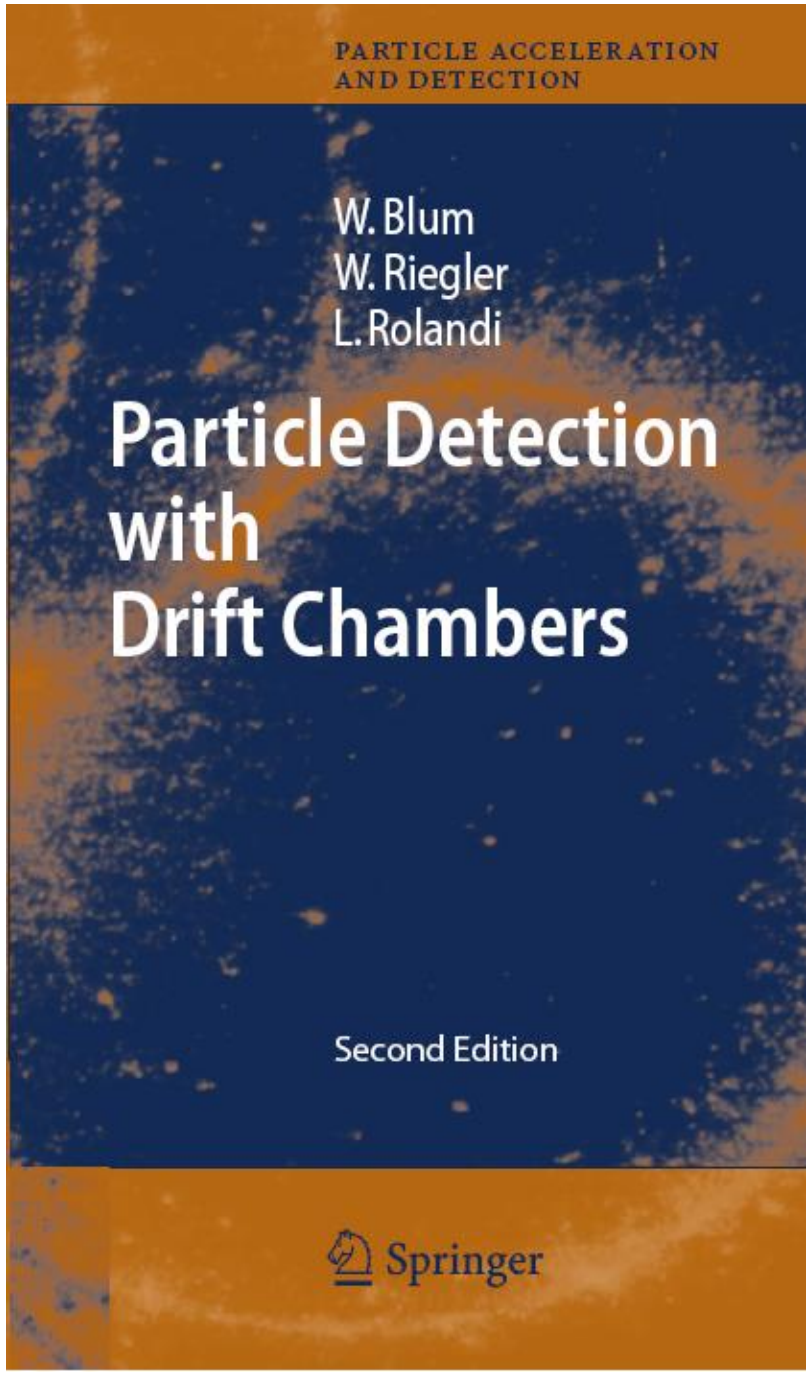








More on signal theorems, readout electronics etc. can be found in this book →



Detectors based on Ionization

→ Gas detectors:

- Wire Chambers
- Drift Chambers
- Time Projection Chambers

Solid State Detectors

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

Gas Detectors with internal Electron Multiplication

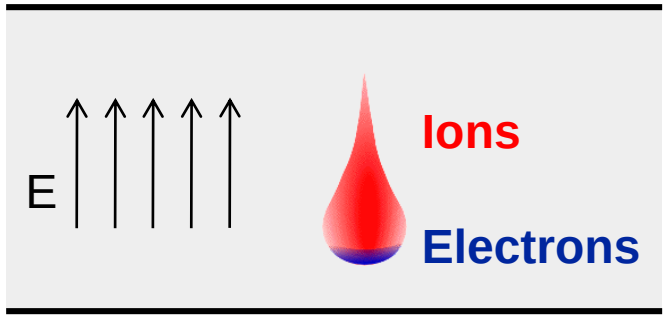
Principle: At sufficiently high electric fields (100kV/cm) the electrons gain energy in excess of the ionization energy → secondary ionzation etc. etc.

$dN = N \alpha dx$ 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: $\alpha(E)$ → $N(x) = N_0 \exp[\int \alpha(E(x'))dx']$

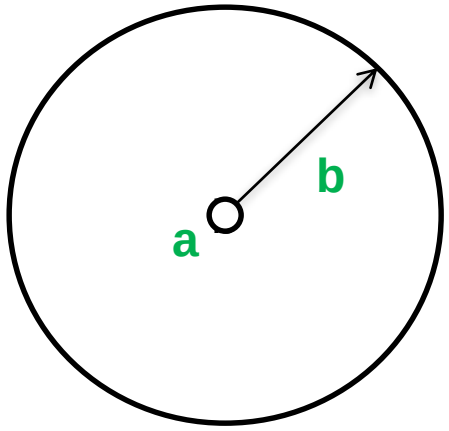
Wire Chamber: Electron Avalanche

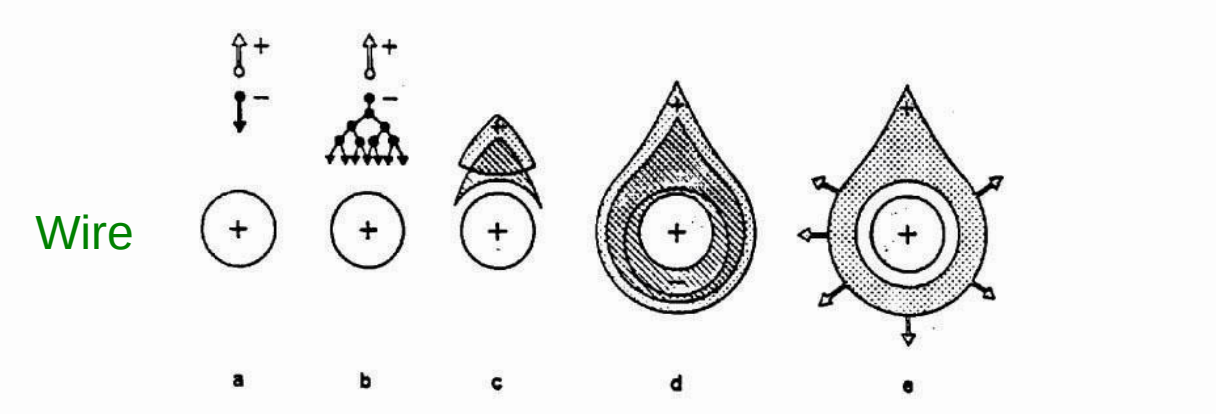
Wire with radius (10-25μm) in a tube of radius b (1-3cm):

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

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

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

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

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

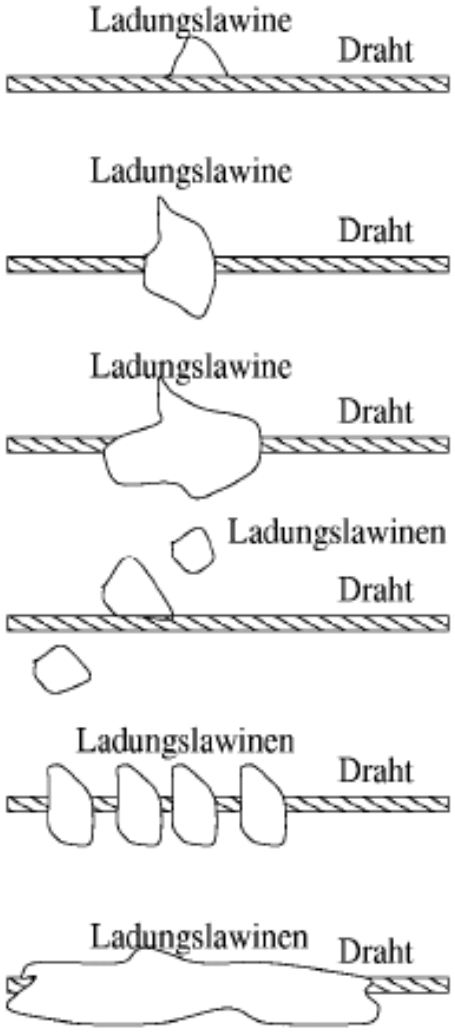
Limited Geiger region:
Avalanche propagated by UV photons.

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

LHC

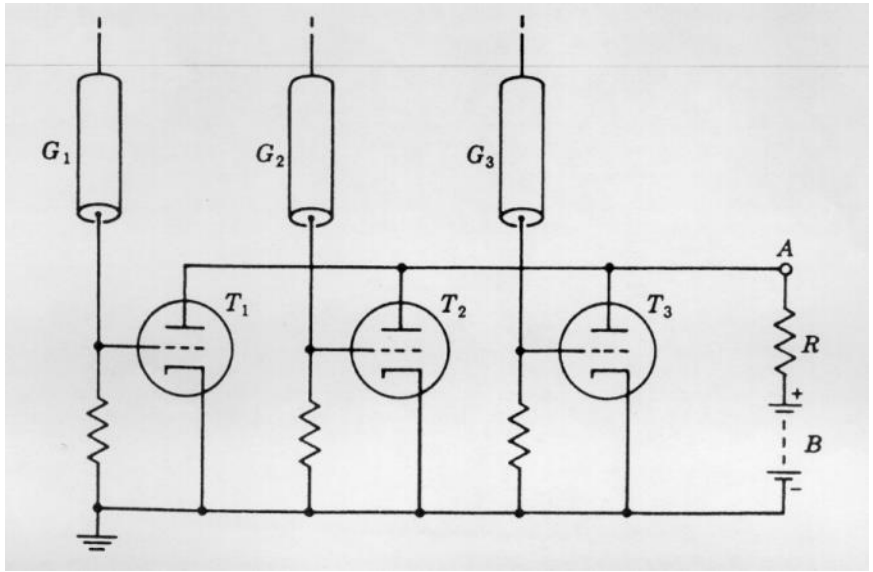
1970ies

1950ies



Detectors with Electron Multiplication

Rossi 1930: Coincidence circuit for n tubes

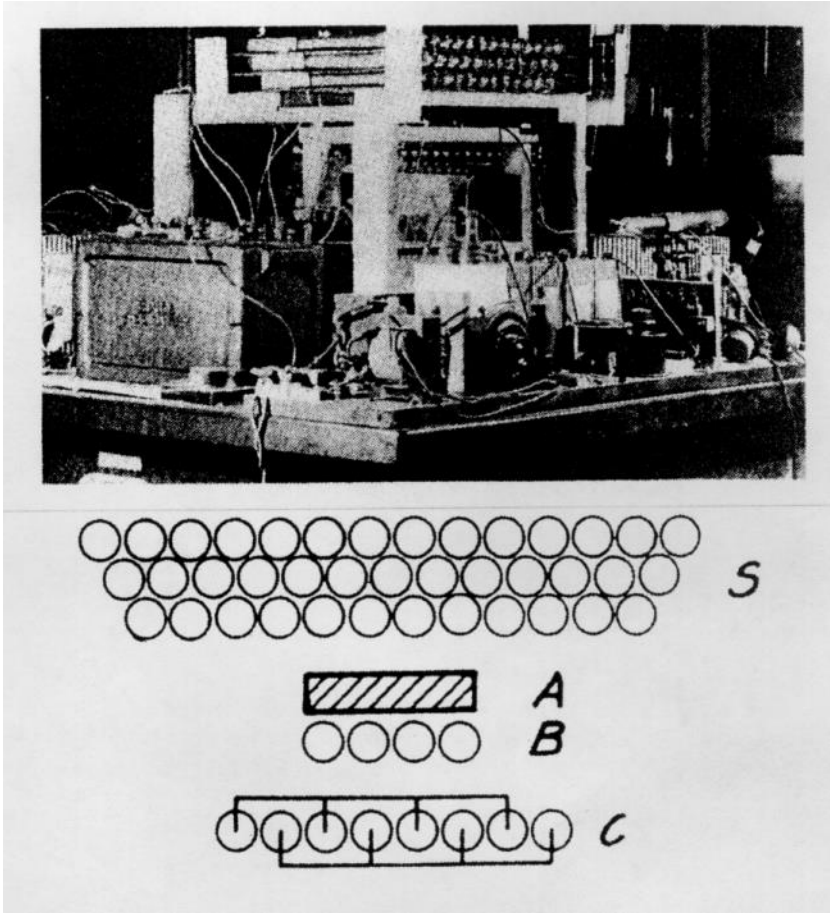


Geiger mode, large deadtime

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

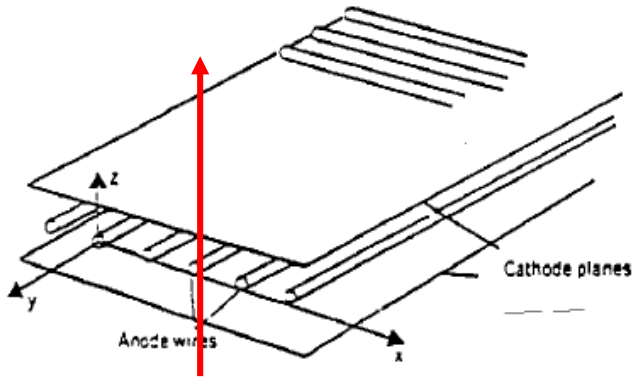
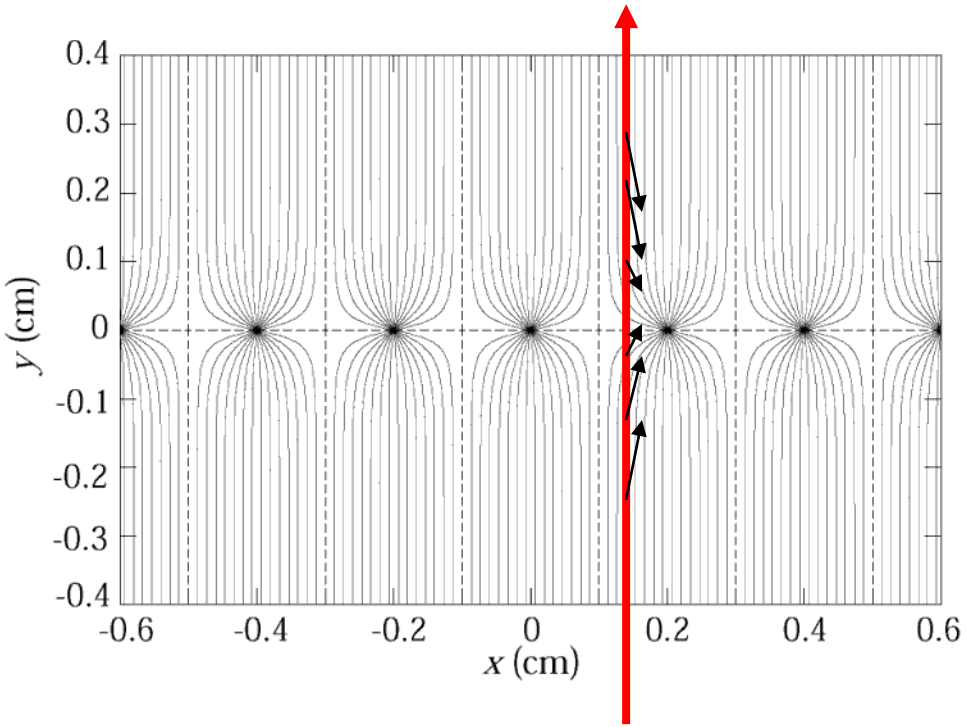


Abbildung 2.27: *Vieldrahtproportionalkammer.*



Classic geometry (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

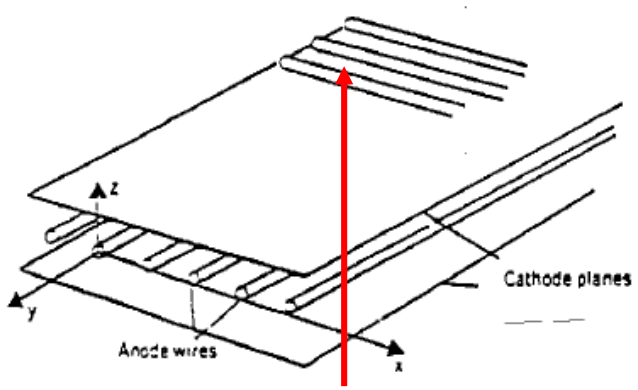
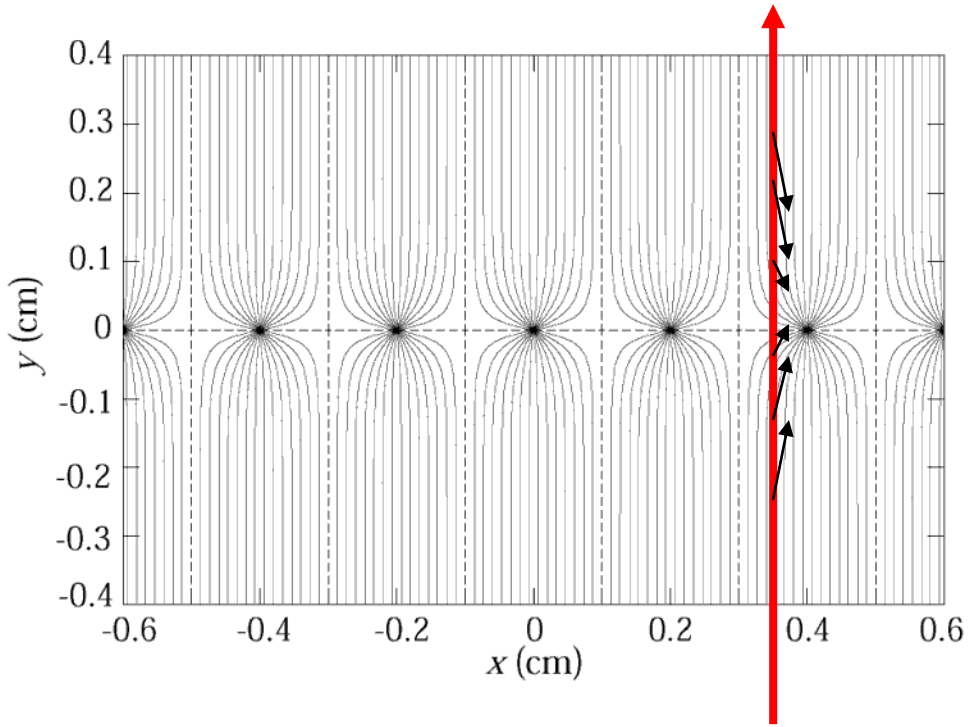


Abbildung 2.27: *Vieldrahtproportionalkammer.*



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

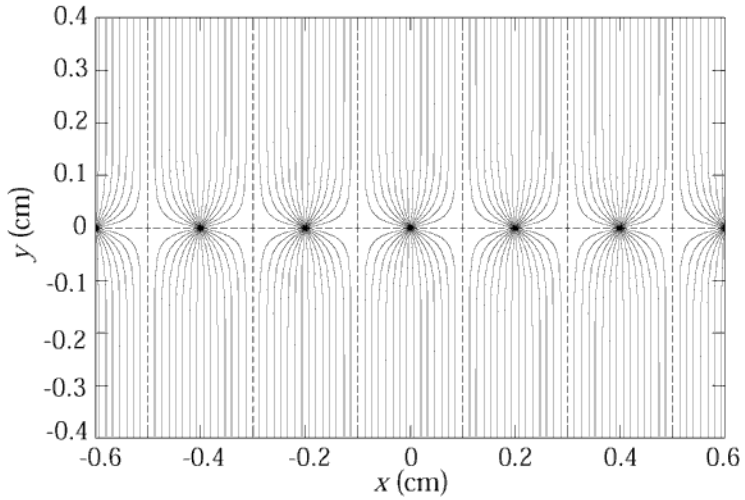
→Signal propagation to the two ends of the wire.

→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.

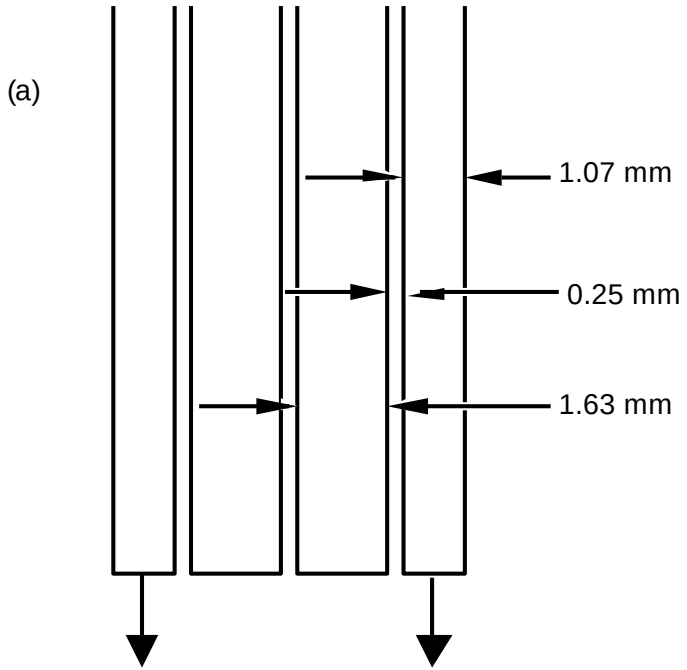
Multi Wire Proportional Chamber

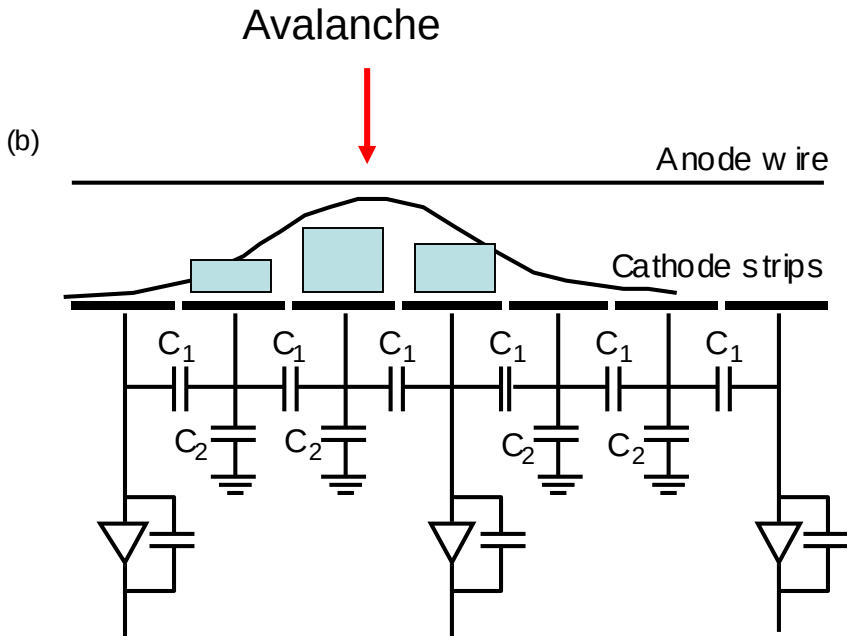


Cathode strip:

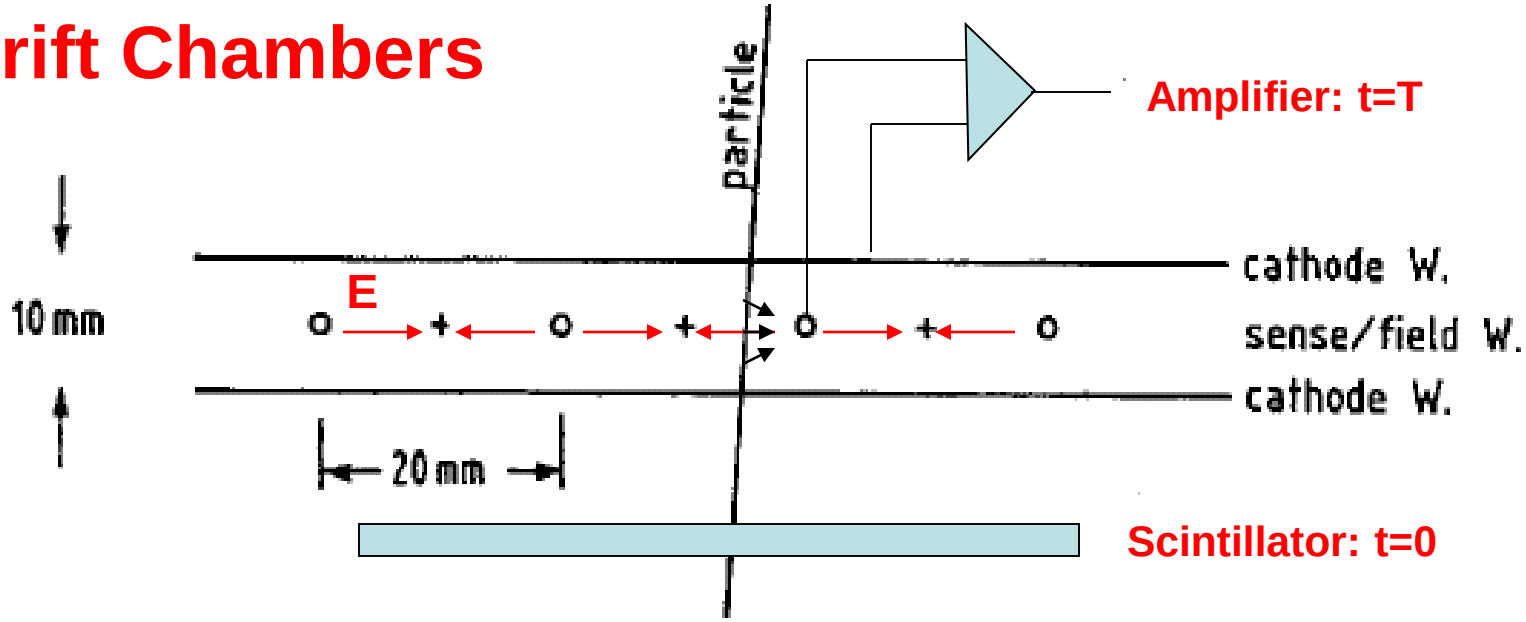
Width (1σ) of the charge distribution ≈ distance between Wires and cathode plane.

'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.

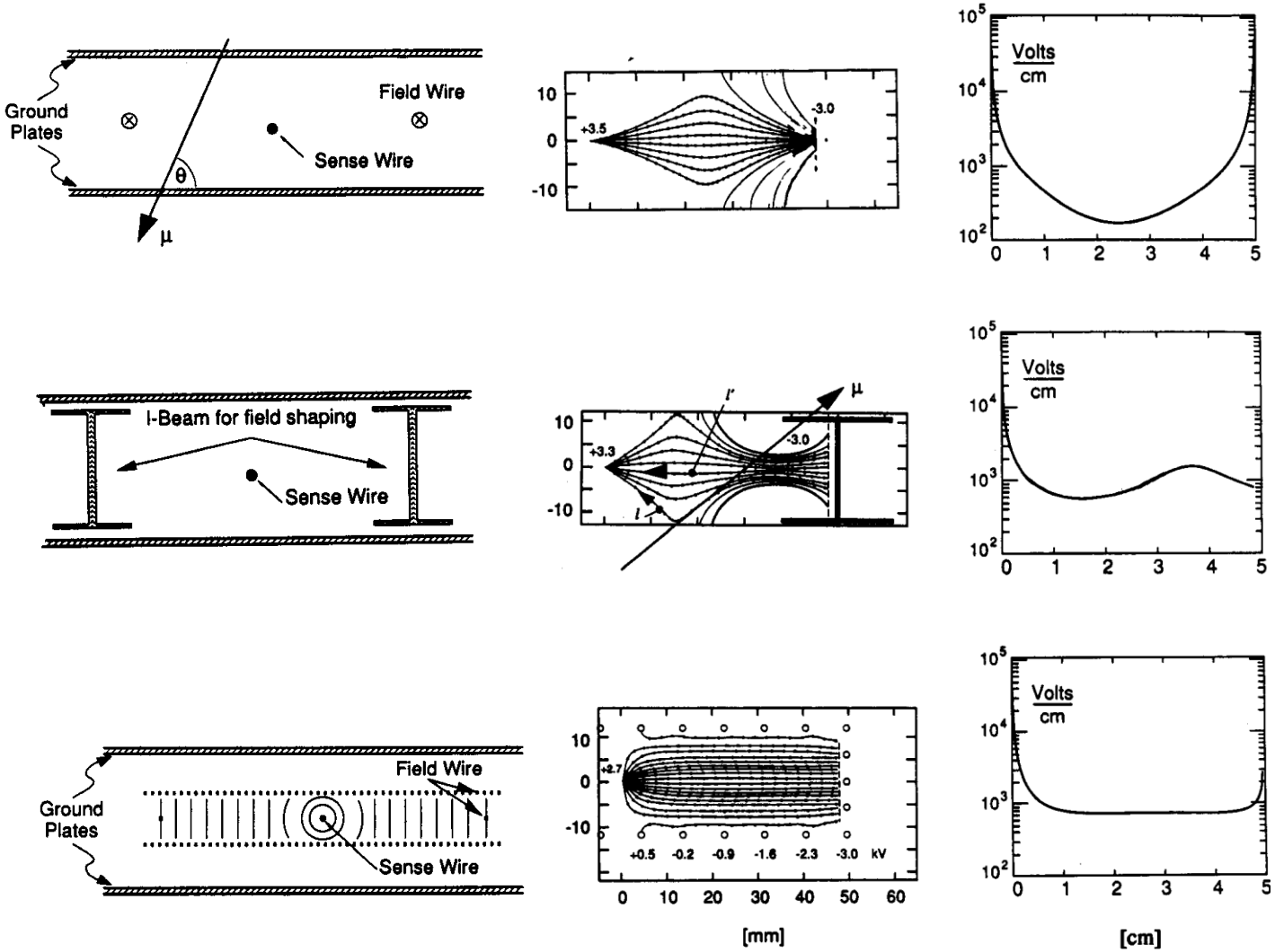
The time between the passage of the particle and the arrival of the electrons at the wire is measured.

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

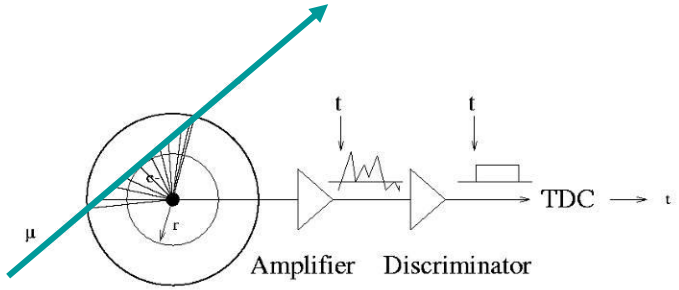
Electric Field ≈ 1kV/cm



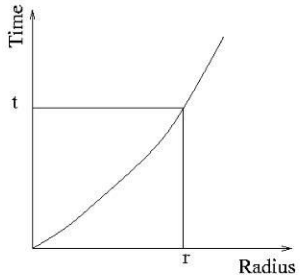
U.Becker Instr. of HEP, Vol#9, p516 World Scientific (1992) ed F.Sauli

The Geiger Counter reloaded: Drift Tube

ATLAS MDT R(tube) =15mm



Calibrated Radius-Time correlation



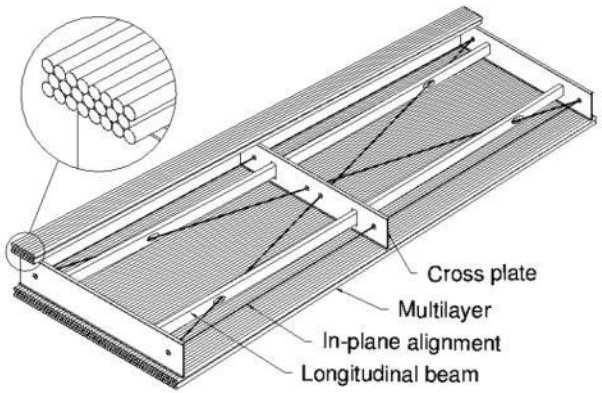
Primary electrons are drifting to the wire.

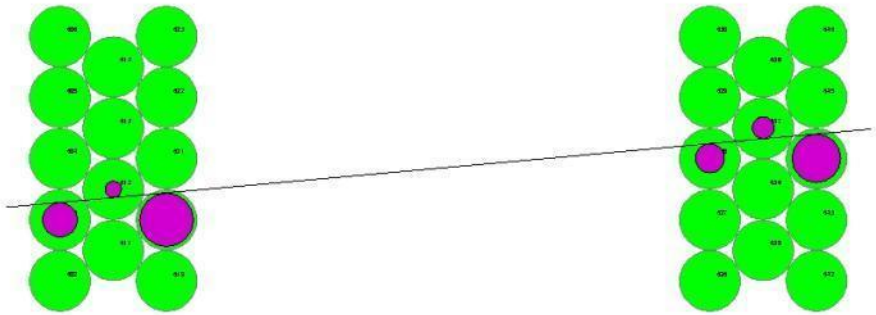
Electron avalanche at the wire.

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

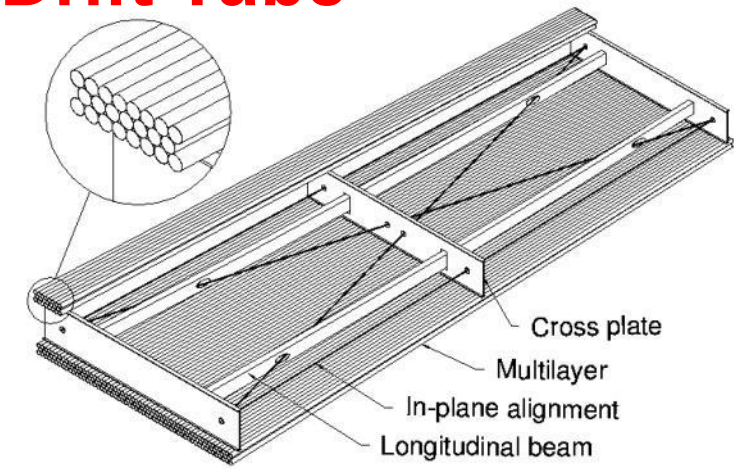
6 layers of 3cm tubes per chamber.

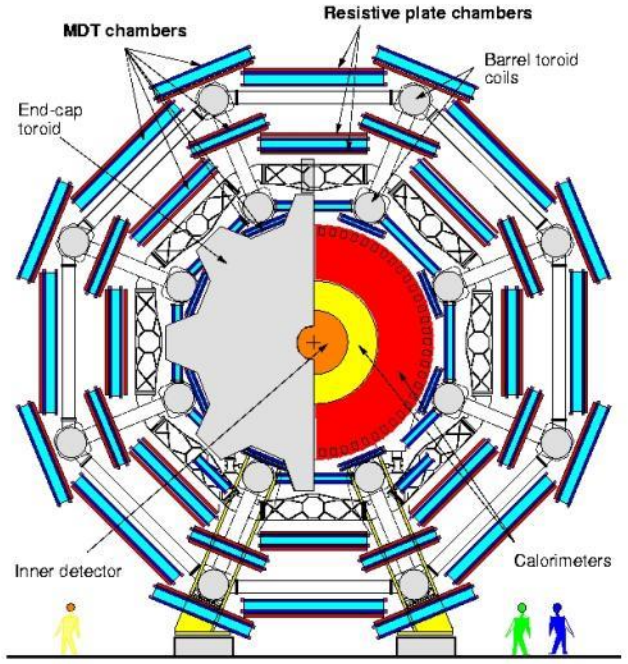
Length of the chambers 1-6m !

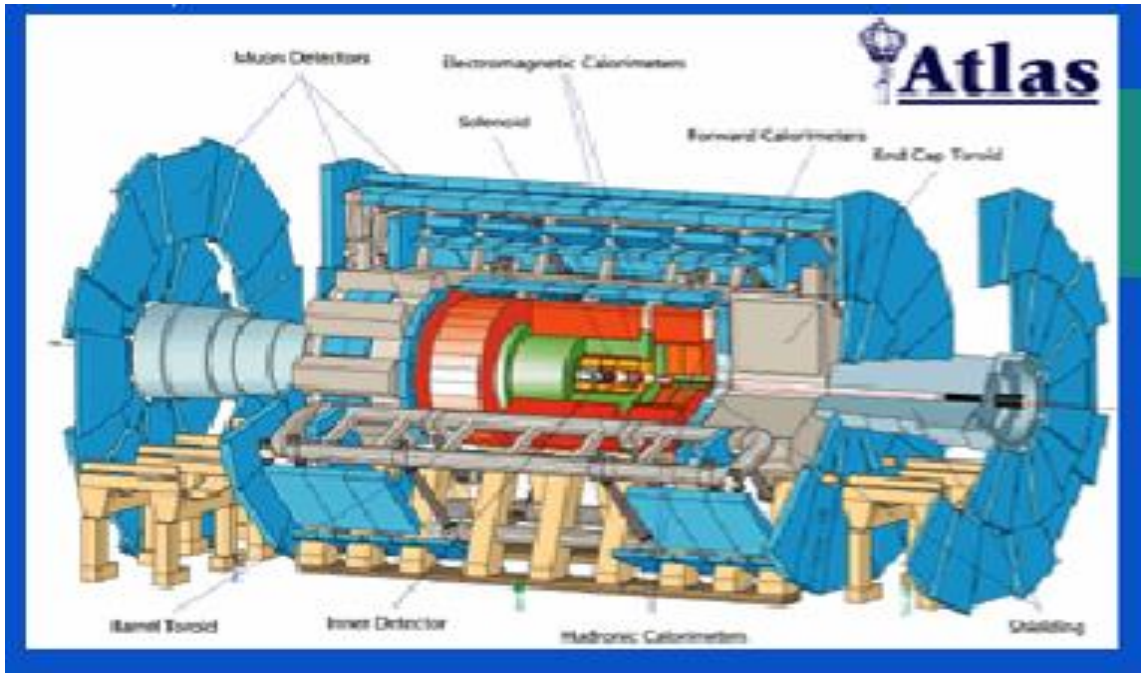
Position resolution: 80μm/tube, <50μm/chamber (3 bar)

Maximum drift time ≈700ns

Gas Ar/CO_2 93/7



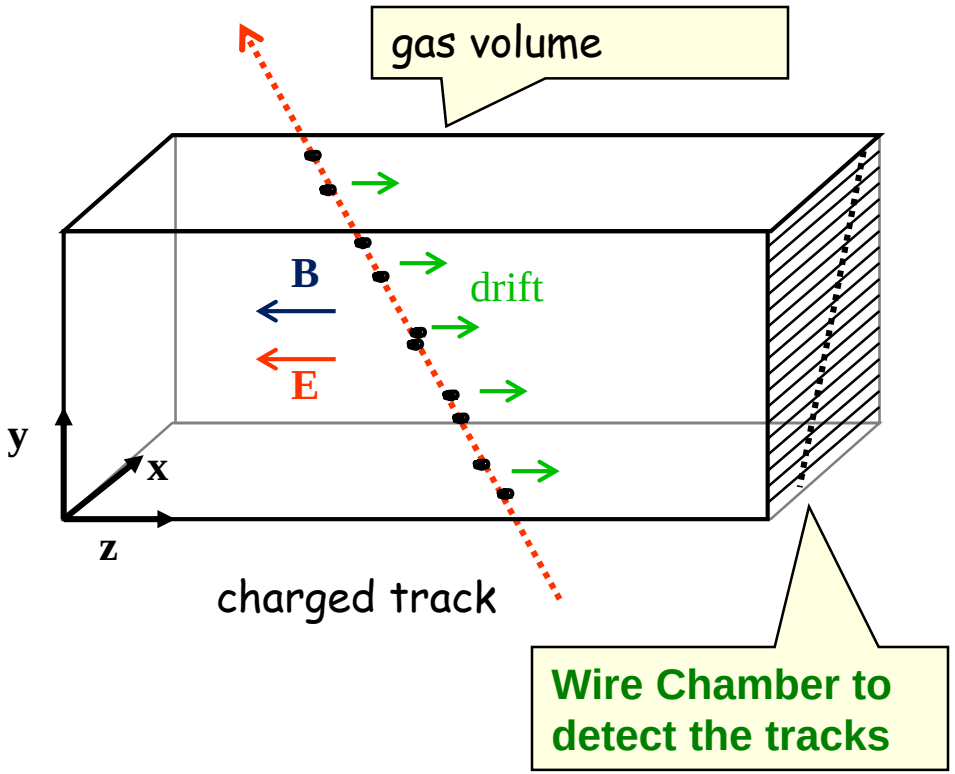


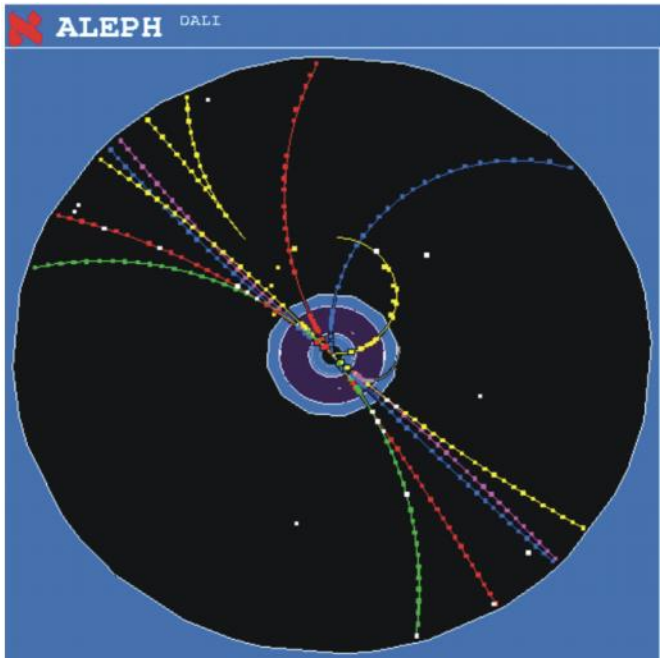


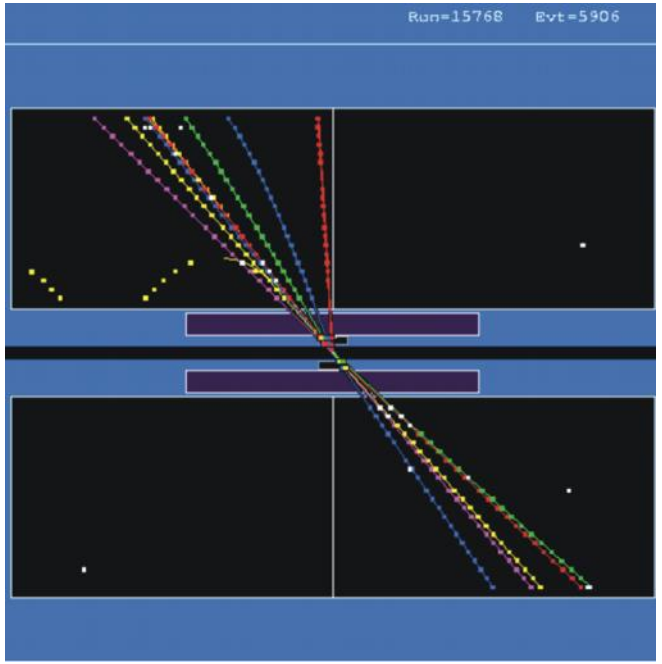
Time Projection Chamber (TPC):

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 !





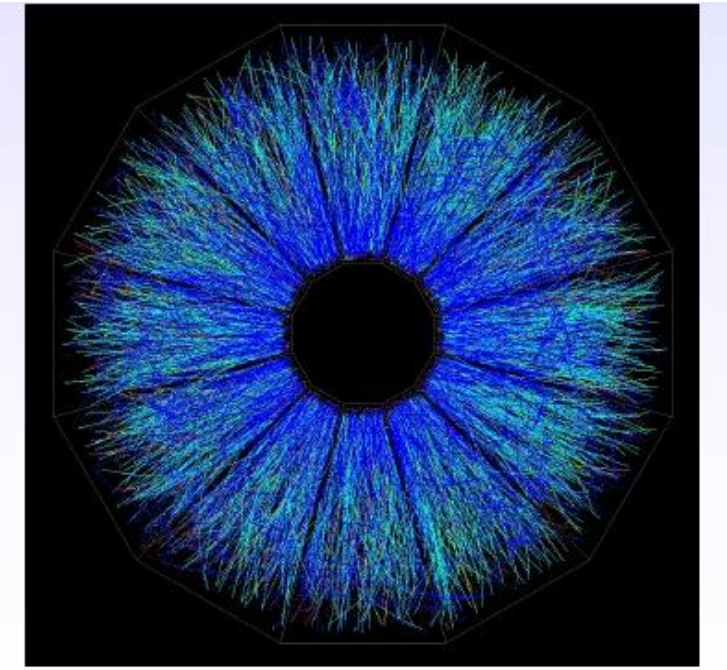


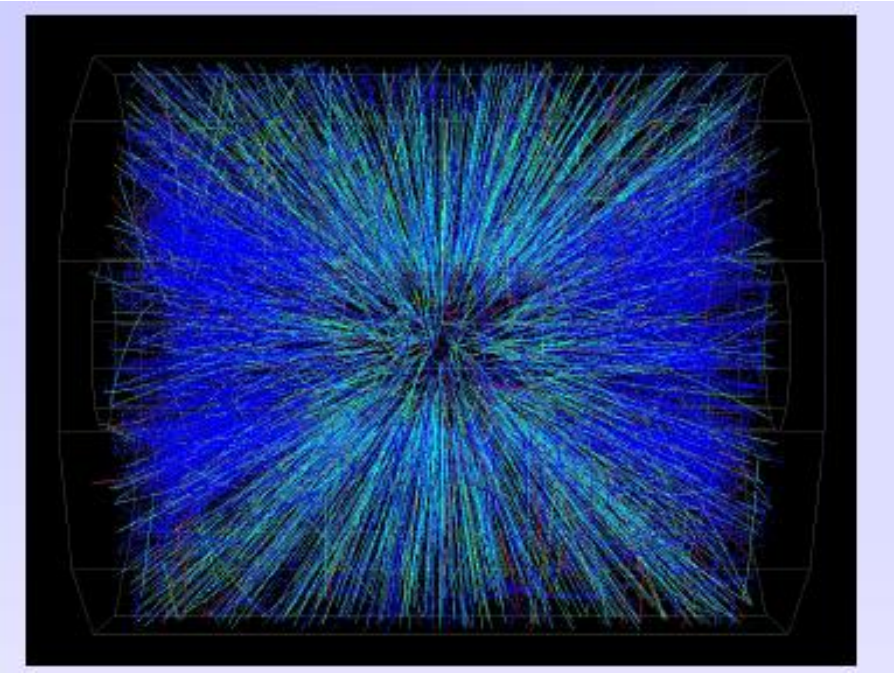
STAR TPC (BNL)

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

Typically around 200 tracks per event.

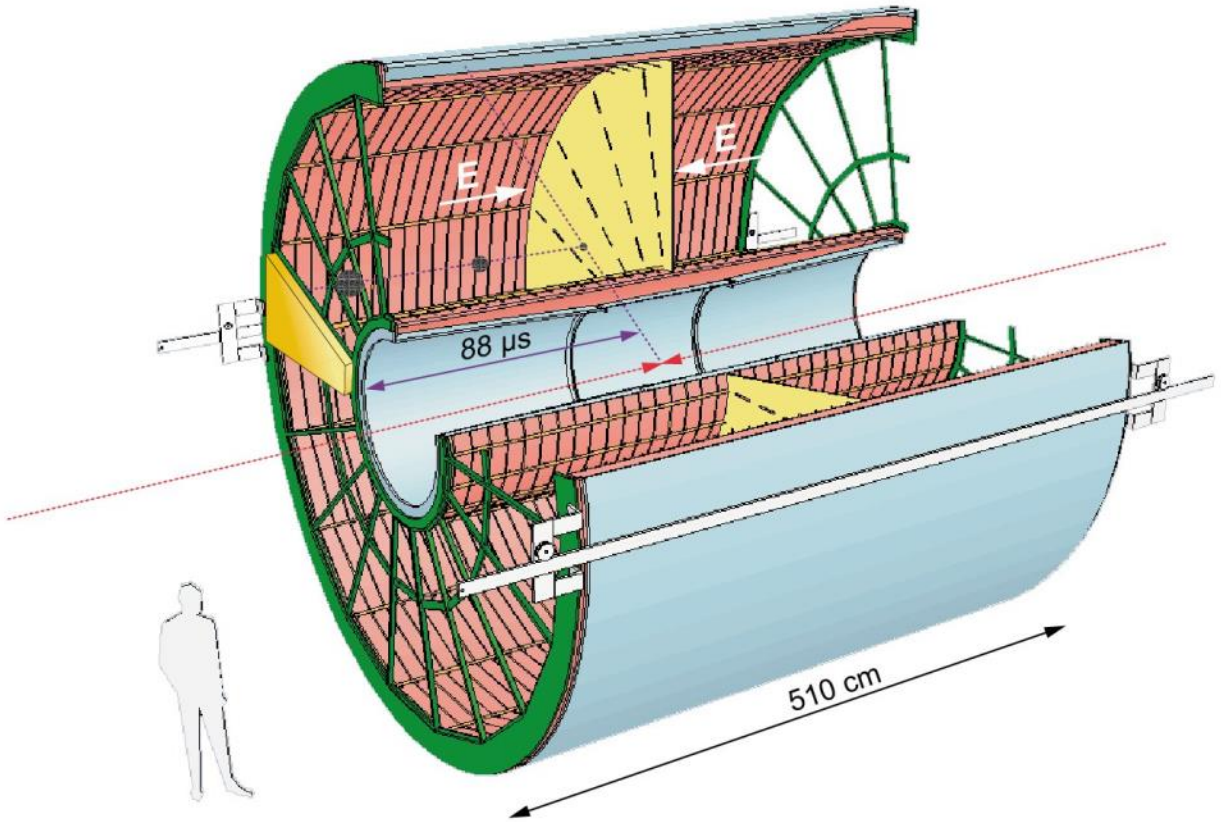
Great advantage of a TPC: The only material that is in the way of the particles is gas → very low multiple scattering → very good momentum resolution down to low momenta !





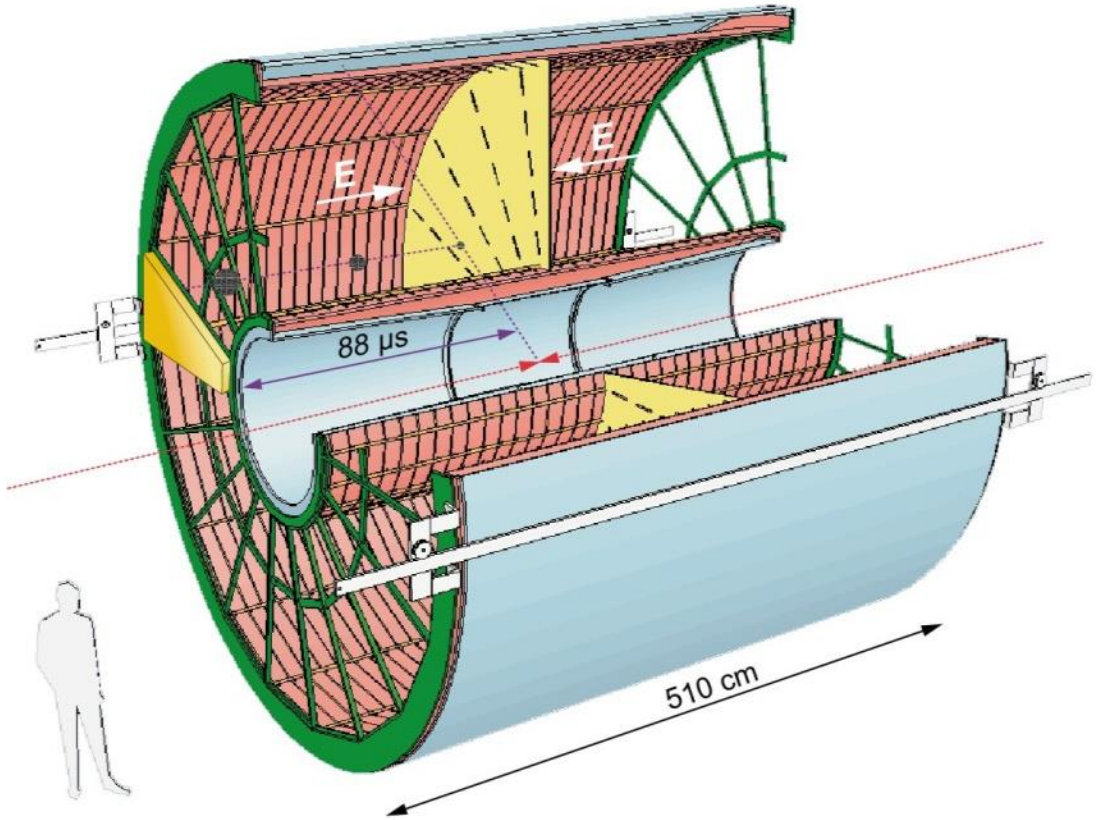
ALICE TPC: Detector Parameters

- 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

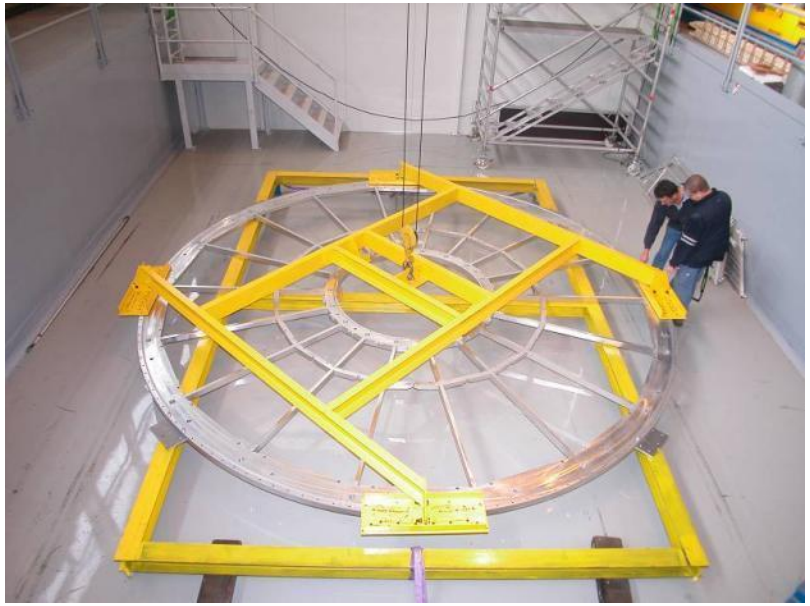
- Largest TPC:
  - Length 5m
  - Diameter 5m
  - Volume 88m^3
  - Detector area 32m^2
  - Channels ~570 000
- High Voltage:
  - Cathode -100kV
- Material X_0
  - Cylinder from composite materials from airplane industry (X_0= ~3%)

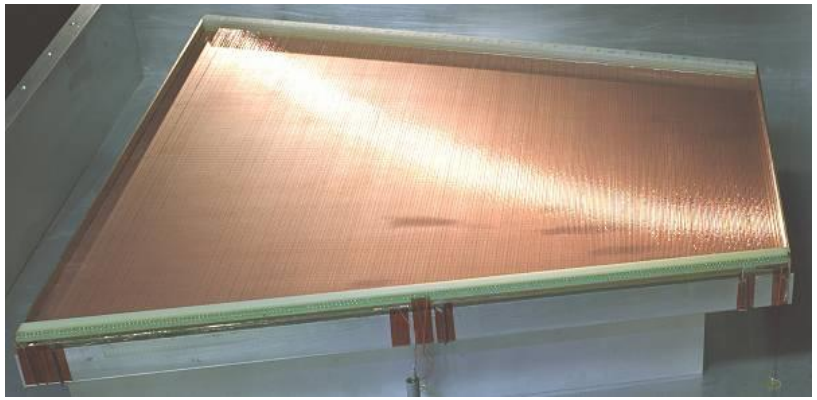


ALICE TPC: Pictures of the Construction

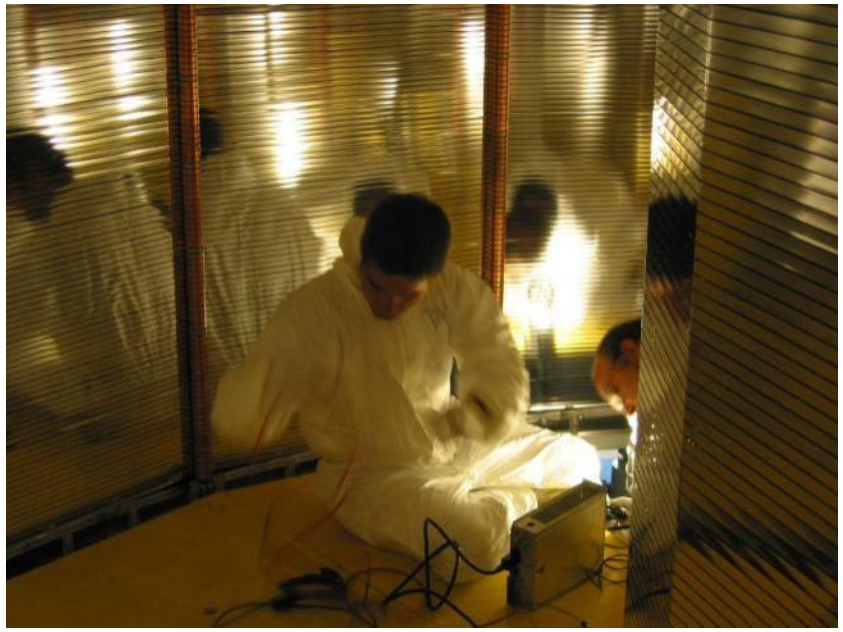
Precision in z: 250μm

End plates 250μm





Wire chamber: 40μm

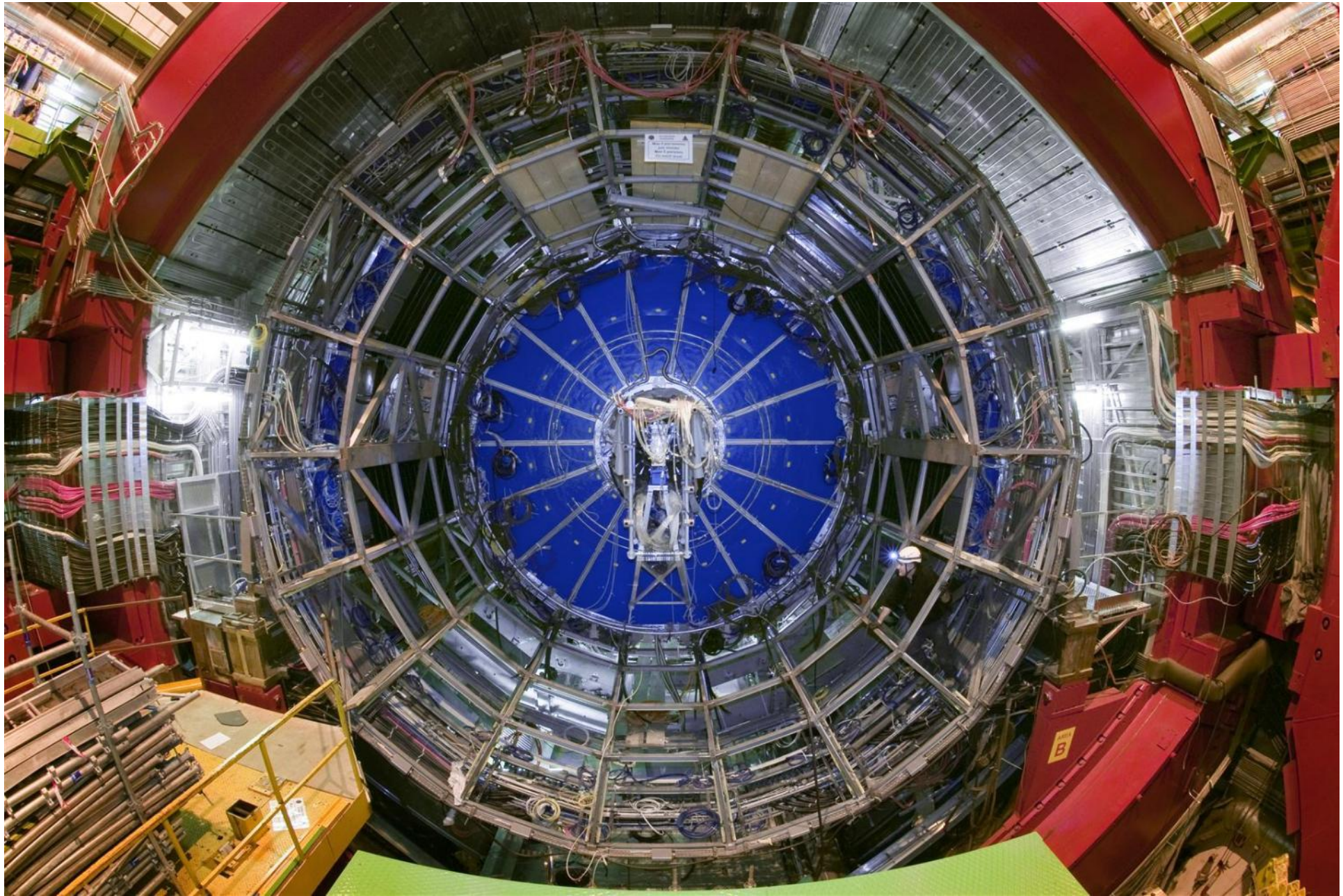


ALICE TPC Construction

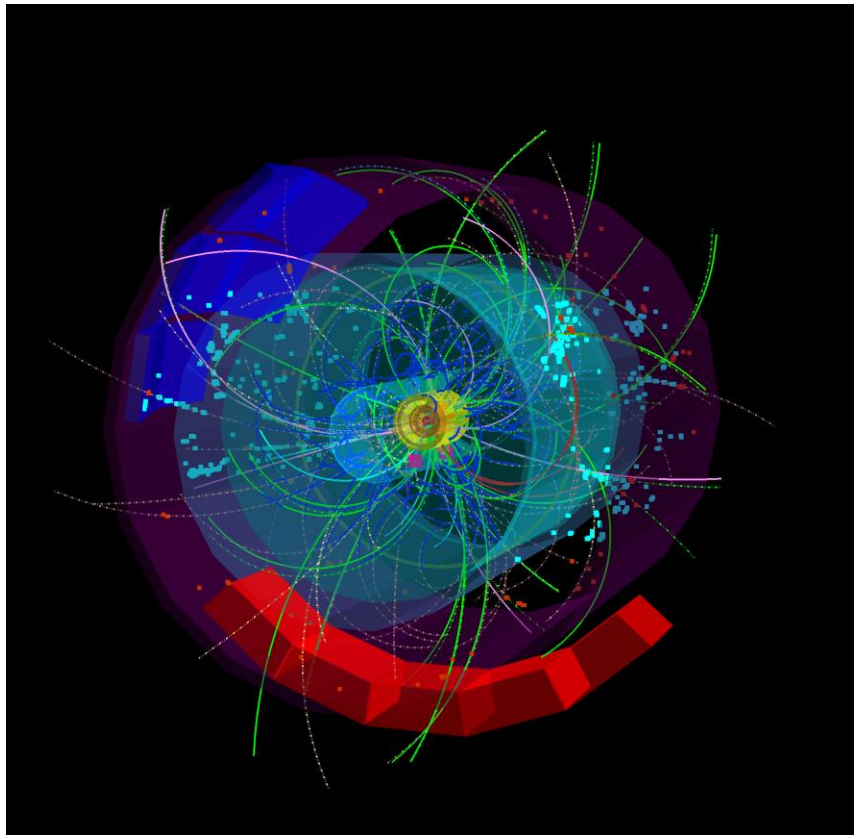
My personal contribution:

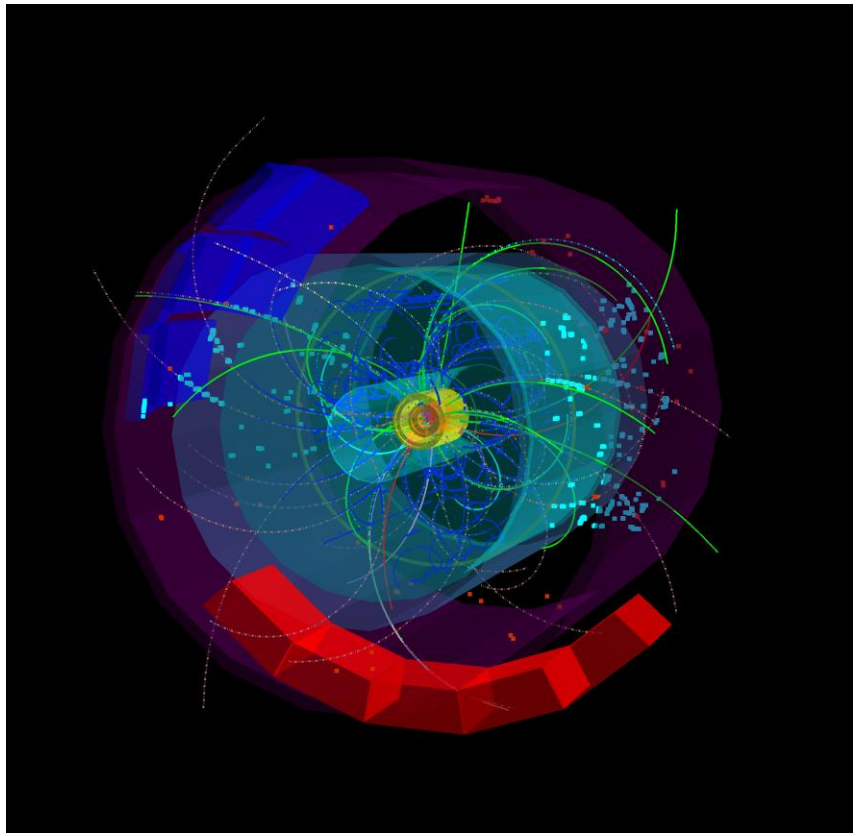
A visit inside the TPC.

TPC installed in the ALICE Experiment

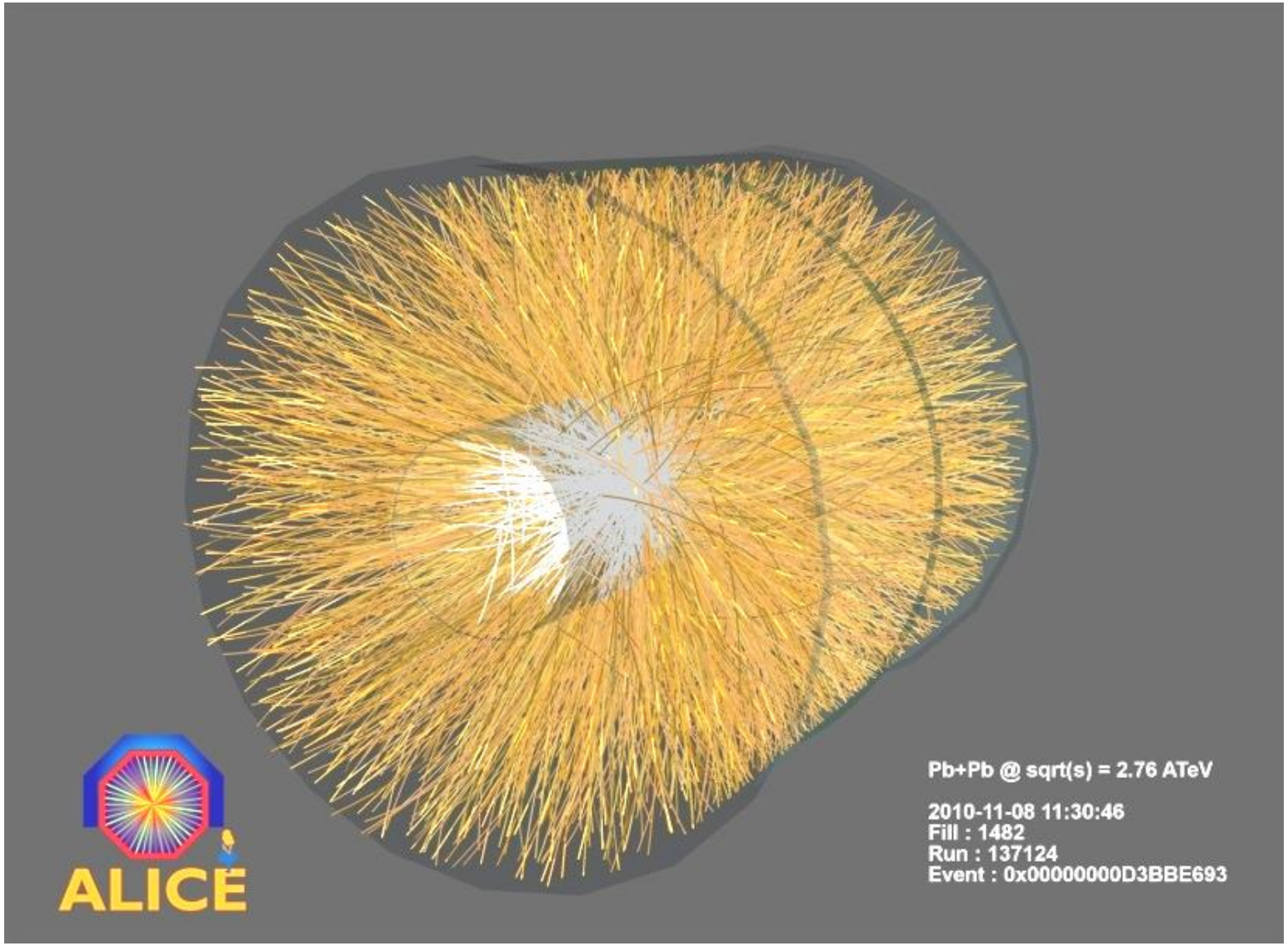


First 7 TeV p-p Collisions in the ALICE TPC in March 2010 !





First Pb Pb Collisions in the ALICE TPC in Nov 2010 !

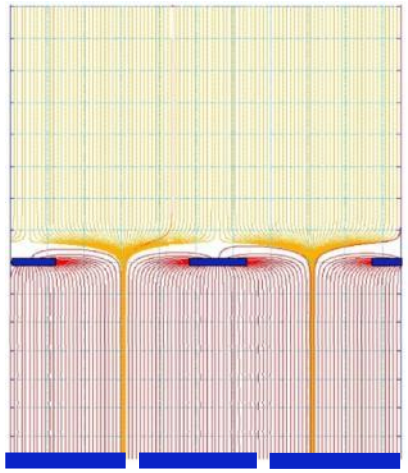


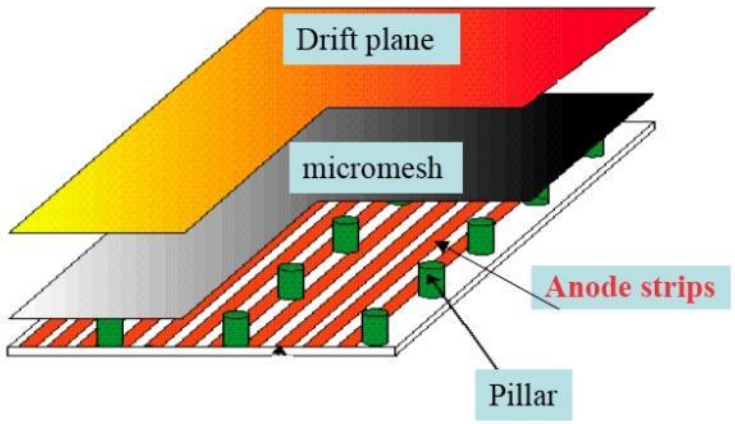
GEMs & MICROMEGAS

MICROMEGAS

Narrow gap (50-100 µm) PPC with thin cathode mesh

Insulating gap-restoring wires or pillars



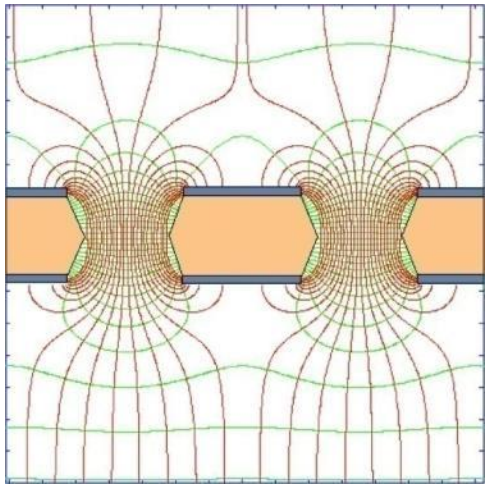


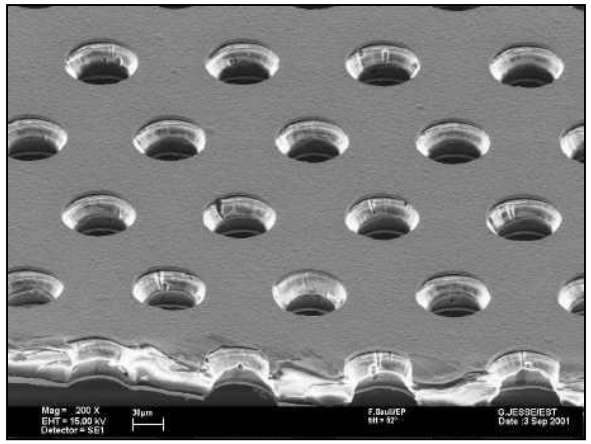
Y. Giomataris et al, Nucl. Instr. and Meth. A376(1996)239

GEM

Thin metal-coated polymer foils

70 µm holes at 140 mm pitch





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

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.

Detectors based on Ionization

Gas detectors:

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

Solid State Detectors

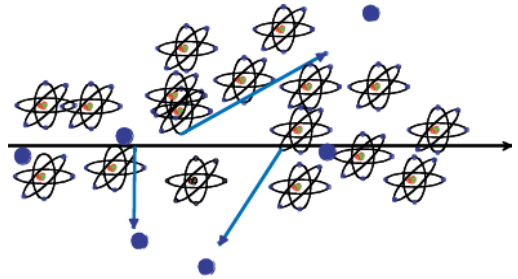
- Transport of Electrons and Holes in Solids
- Si- Detectors
- Diamond Detectors

Solid State Detectors

Gas 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.



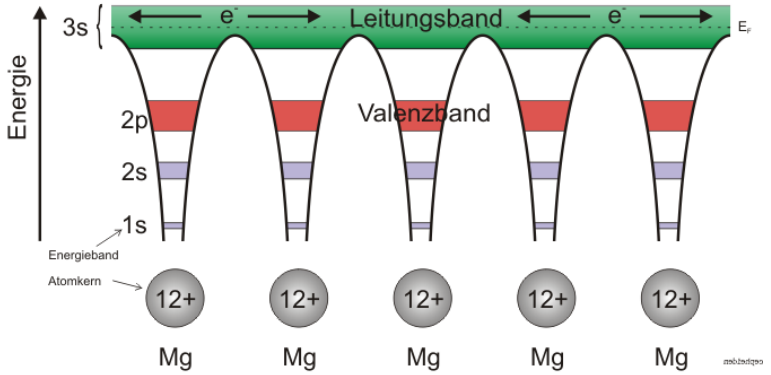
For individual gas atoms, the electron energy levels are discrete.

Solid State Detectors

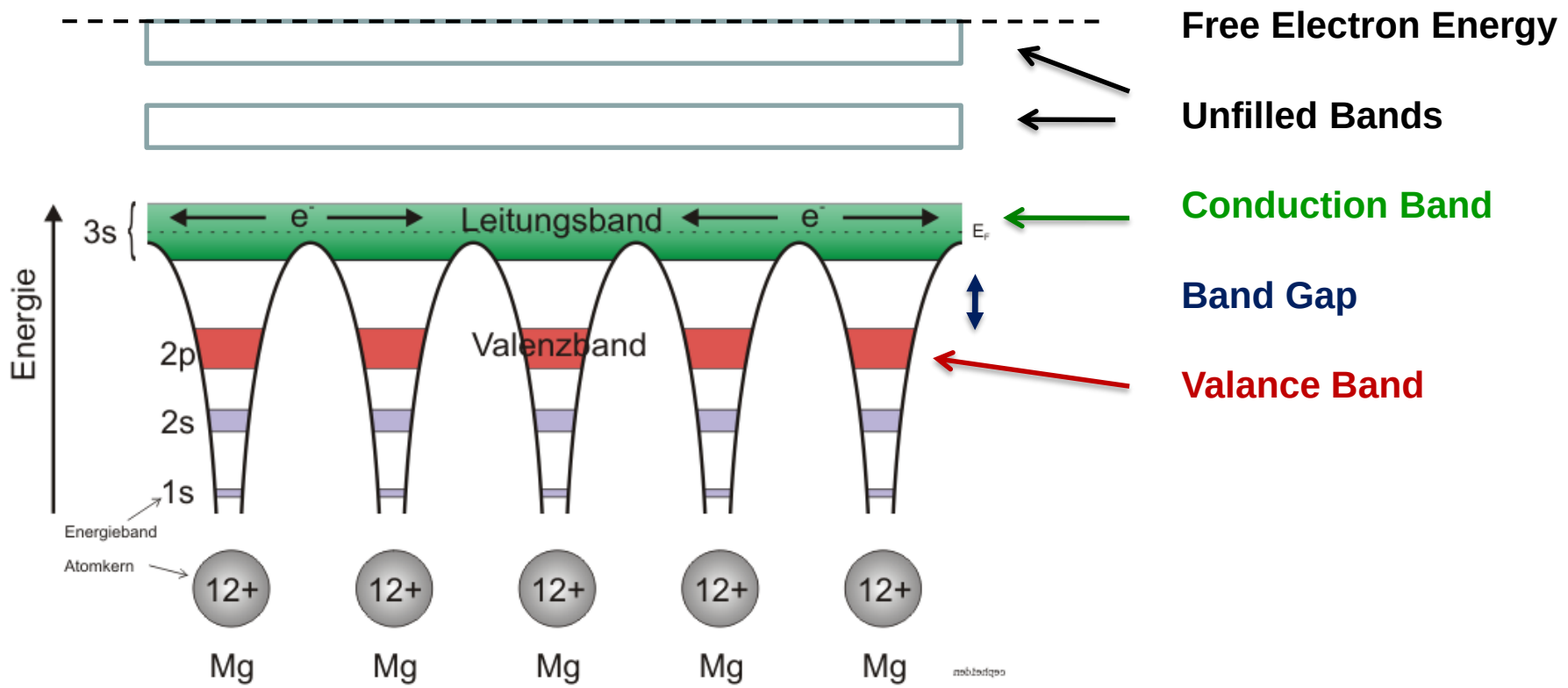
In solids (crystals), the electron energy levels are in ‘bands’.

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 these bands and the holes in the lower band can freely move around the crystal, if an electric field is applied.



Solid State Detectors



Conductor, Insulator, Semiconductor

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.

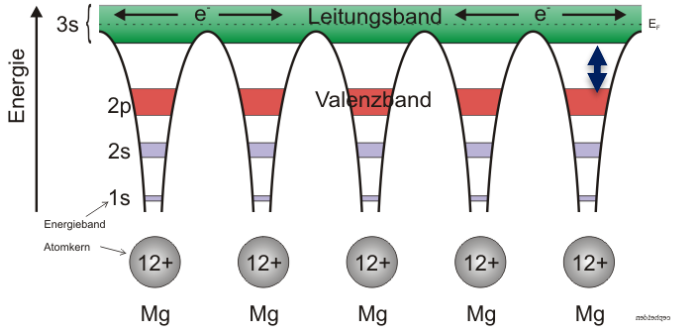
Solid State Detectors

Band Gap, e-h pair Energy

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.



Band Gap

Temperature, Charged Particle Detection

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

Electron, Hole Movement:

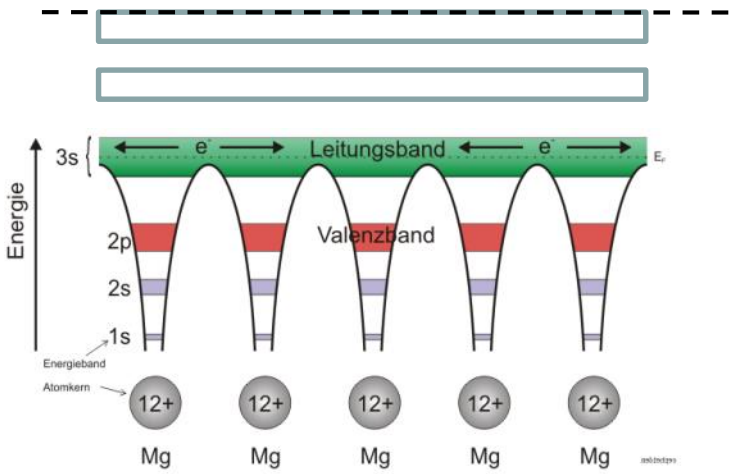
It is possible to treat electrons in the conduction band and holes in the valence band similar to free particles, but with an effective mass different from elementary electrons not embedded in the lattice.

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 (solid state physics).

Cooling:

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

Primary ‘ionization’:

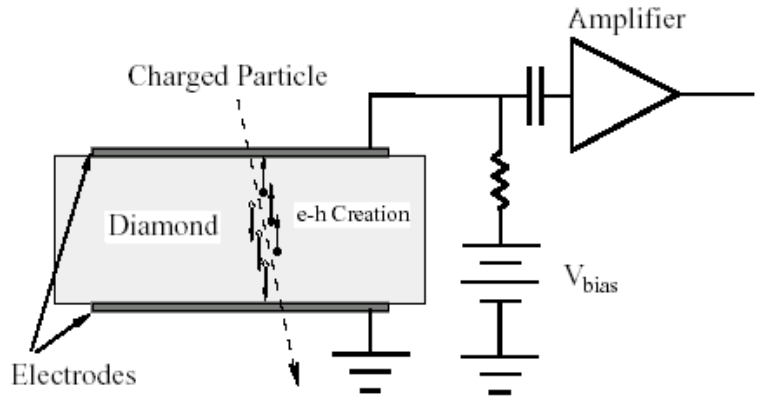
The average energy to produce an electron/hole pair is: Diamond (13eV), Silicon (3.6eV), Germanium (2.9eV)

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.

Solid State vs. Gas Detector:

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.

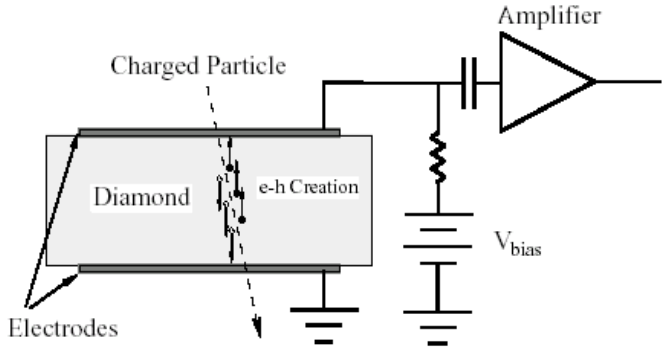
While in gaseous detectors, the velocity of electrons and ions differs by a factor 1000, the velocity of electrons and holes in many semiconductor detectors is quite similar → very short signals.



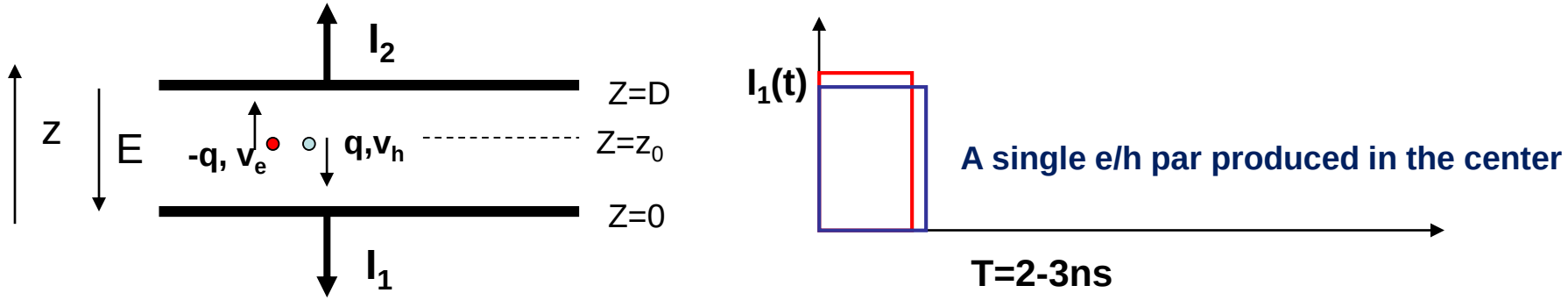
Diamond → A solid state ionization chamber

Diamond Detector

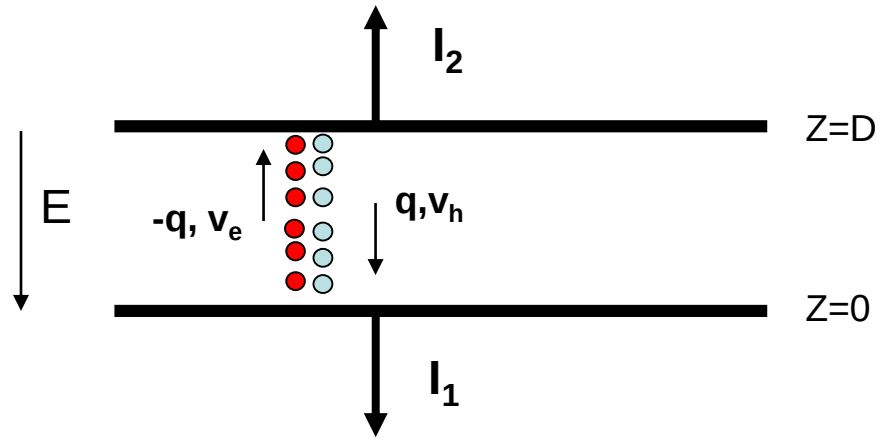
Typical thickness – a few 100μm.
<1000 charge carriers/cm^3 at room temperature due to large band gap.

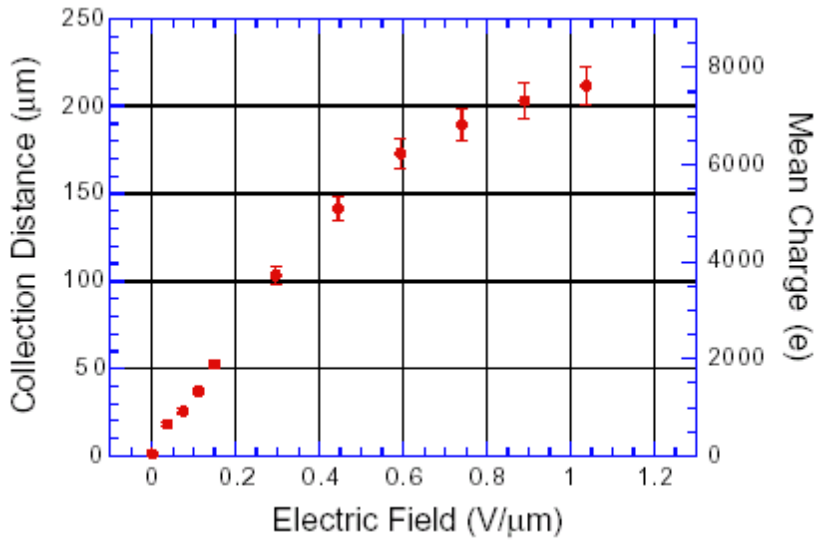


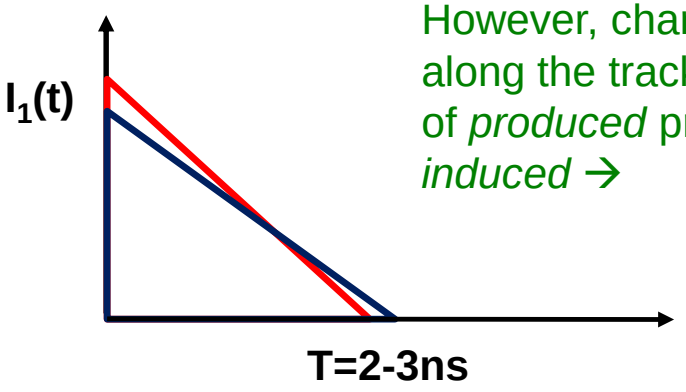
Velocity:
μ_e=1800 cm^2/Vs, μ_h=1600 cm^2/Vs
Velocity = μE, 10kV/cm → v=180 μm/ns → Very fast signals of only a few ns length !



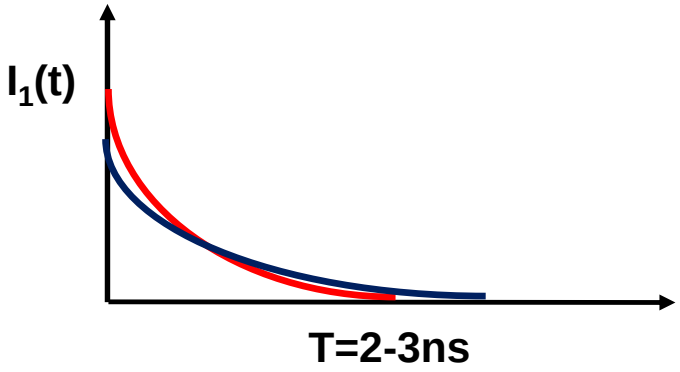
Diamond Detector







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

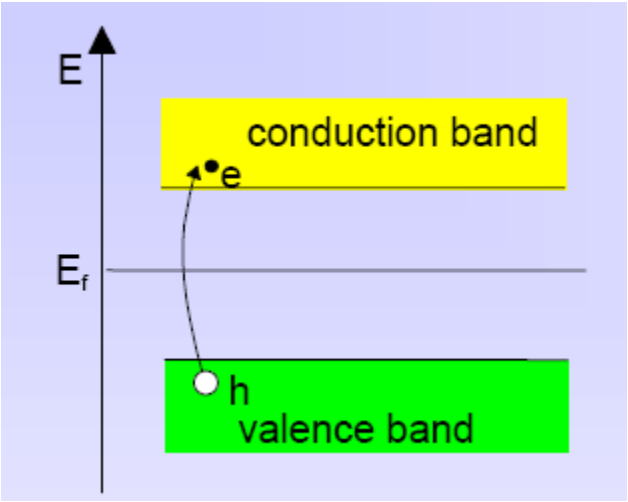


Silicon Detector

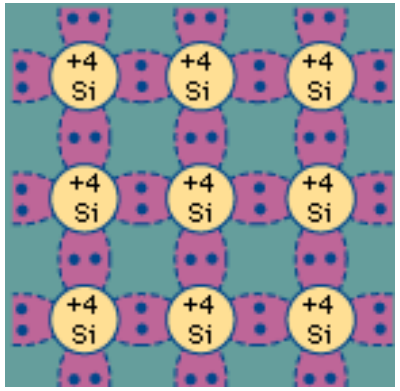
Velocity:
μ_e=1450 cm^2/Vs, μ_h=505 cm^2/Vs, 3.63eV per e-h pair.
~33000 e/h pairs in 300µm of silicon.

However: Free charge carriers in Si:
T=300 K: e,h = 1.45 x 10^{10} / cm^3 but only 33000 e/h pairs in 300µm produced by a high energy particle.

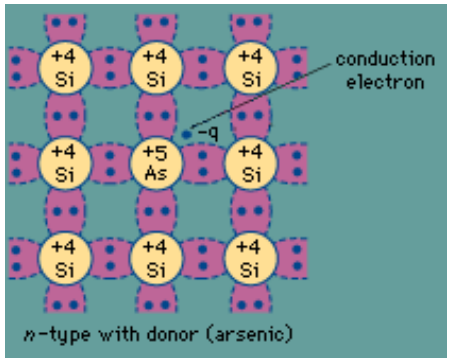
Why can we use Si as a solid state detector ???

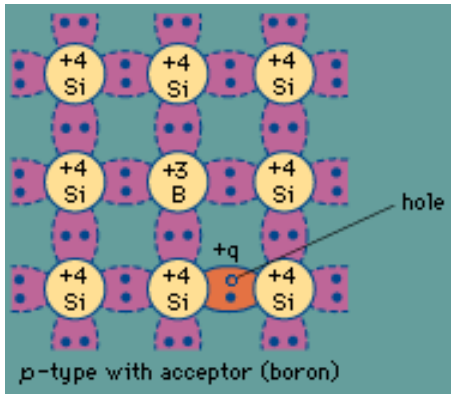


Doping of Silicon



doping



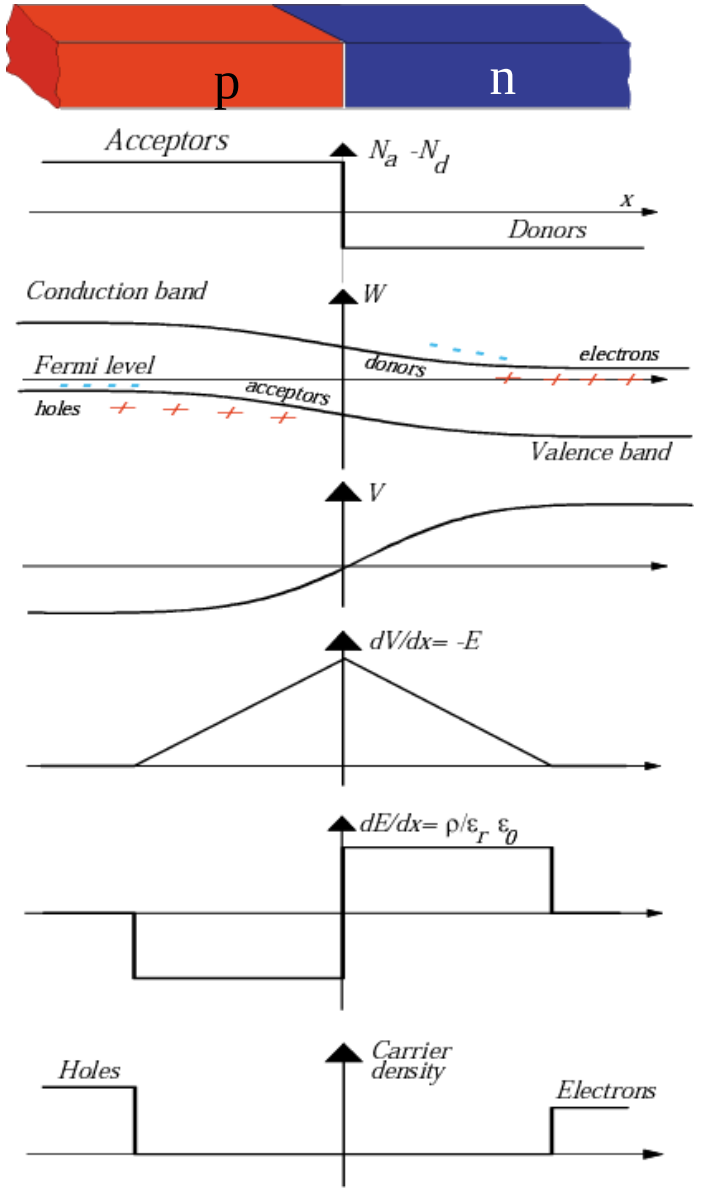


In a silicon crystal at a given temperature the number of electrons in the conduction band is equal to the number of holes in the valence band.

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.



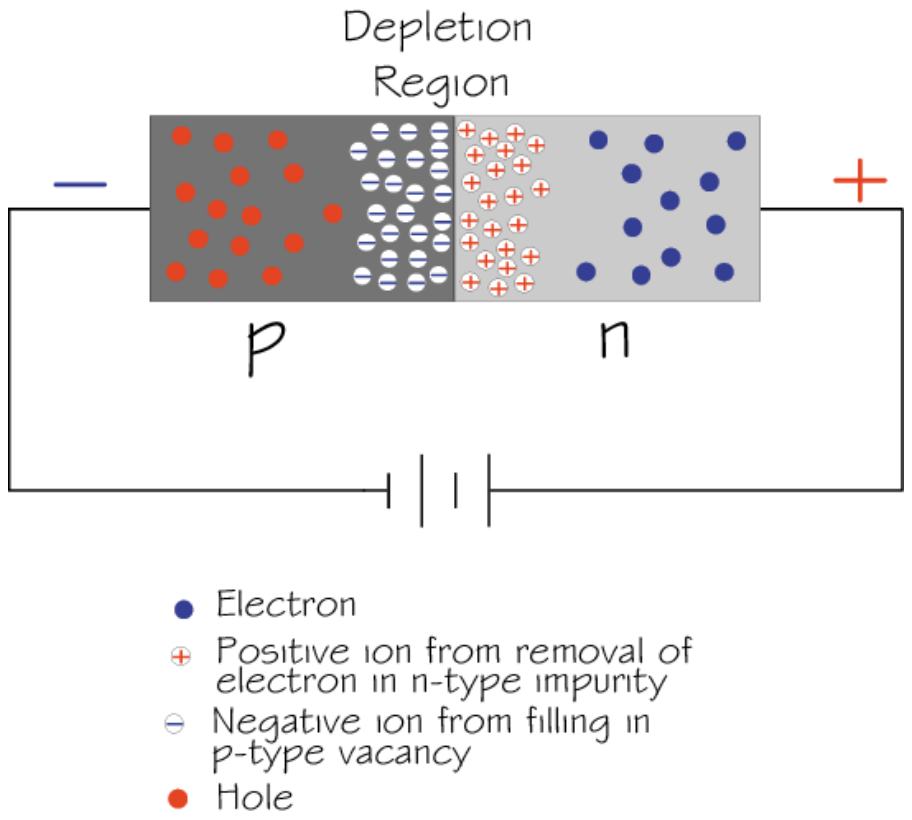
Si-Diode used as a Particle Detector !

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

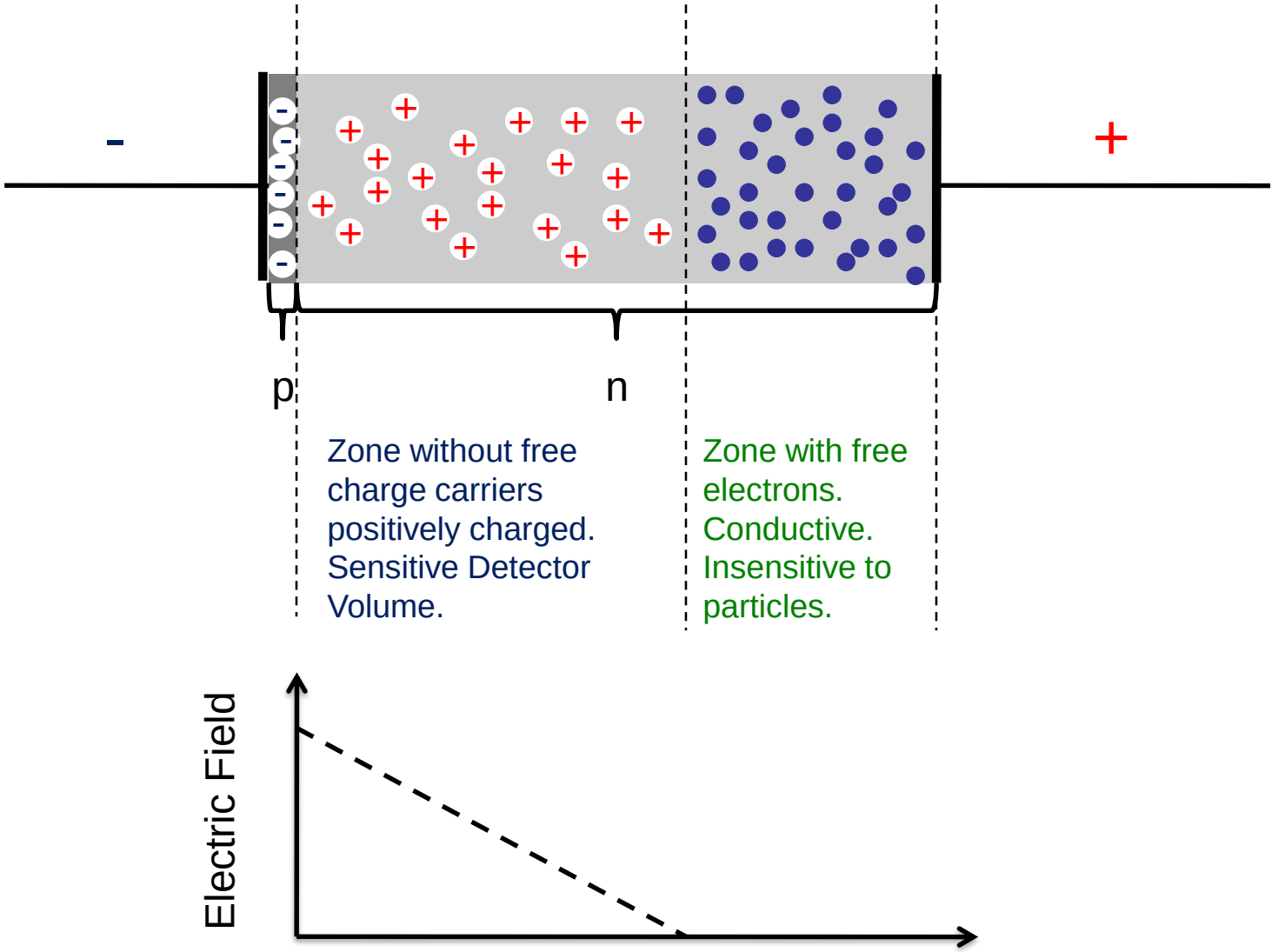
By applying a voltage, the depletion zone can be extended to the entire diode → highly insulating layer.

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.

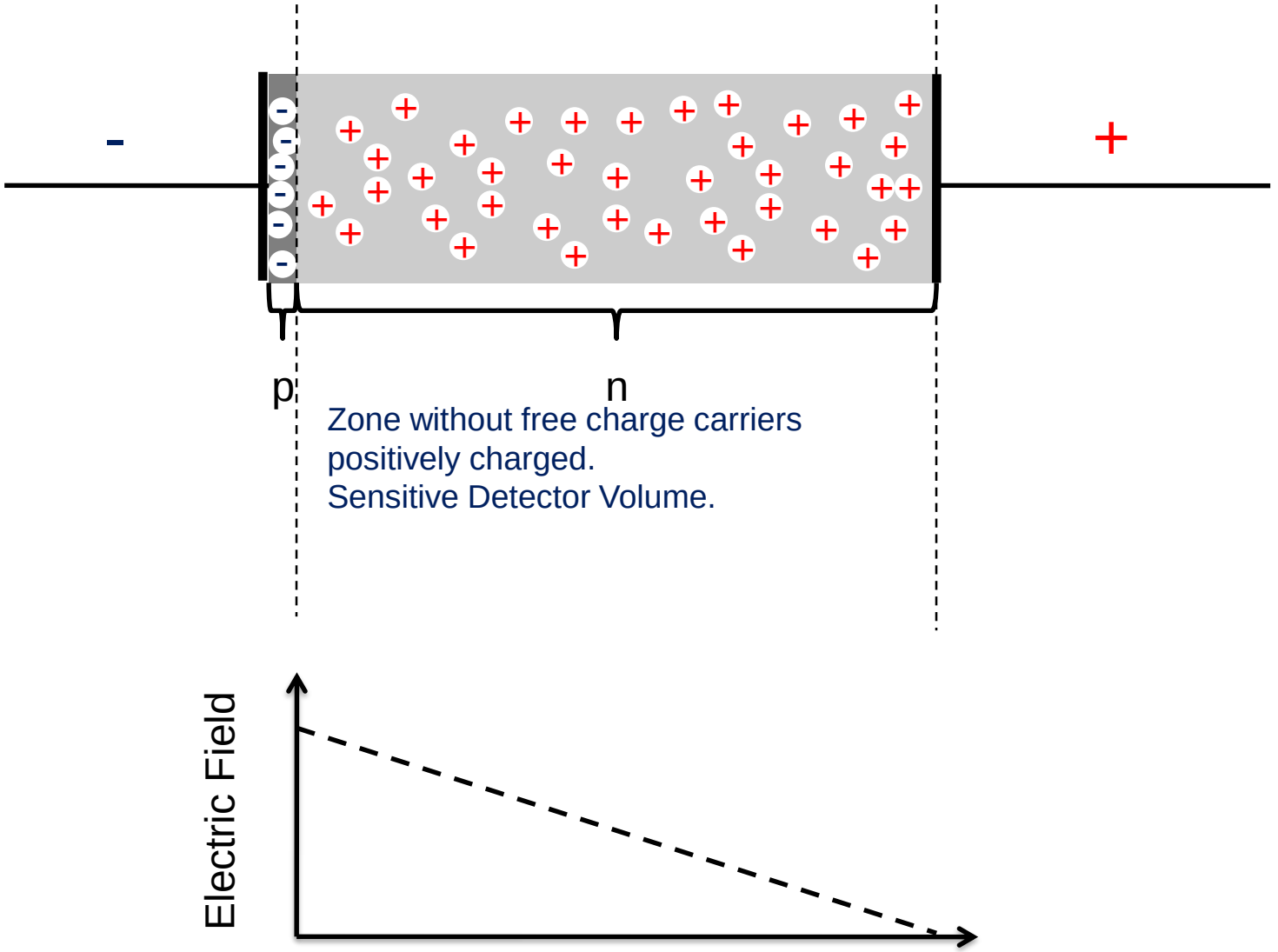
As silicon is the most commonly used material in the electronics industry, it has one big advantage with respect to other materials, namely highly developed technology.



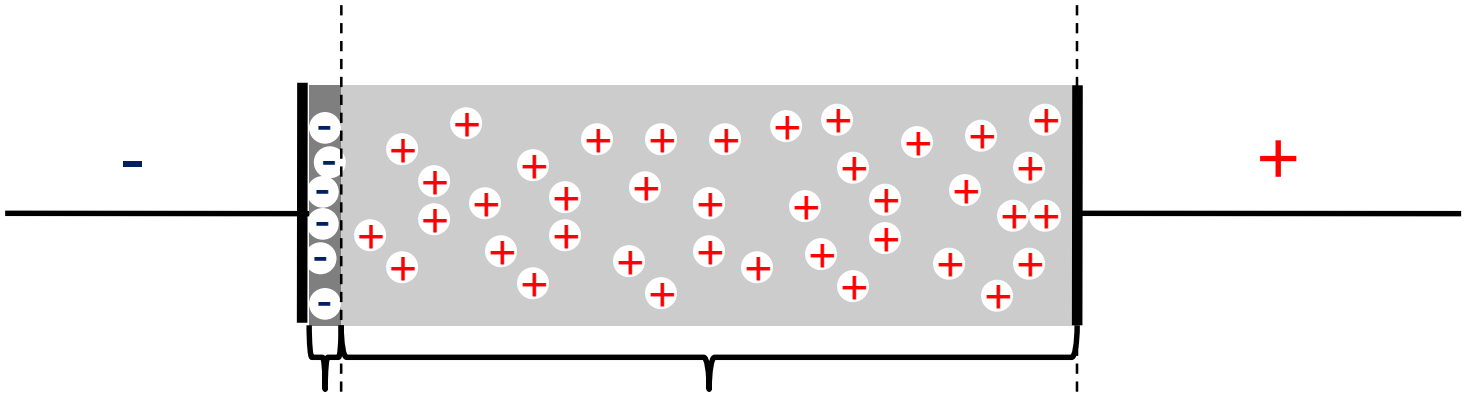
Under-Depleted Silicon Detector



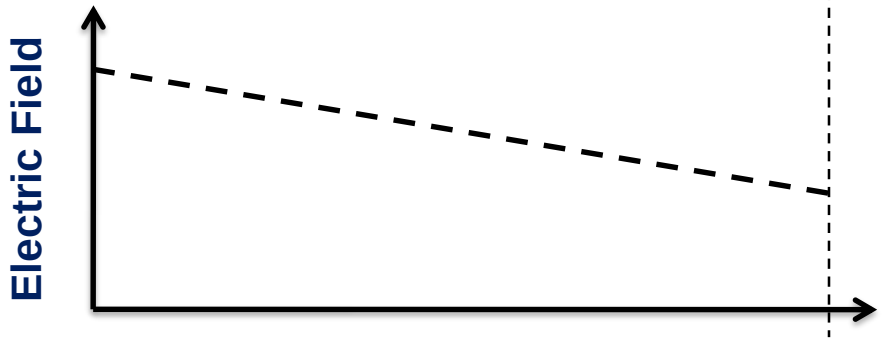
Fully-Depleted Silicon Detector



Over-Depleted Silicon Detector



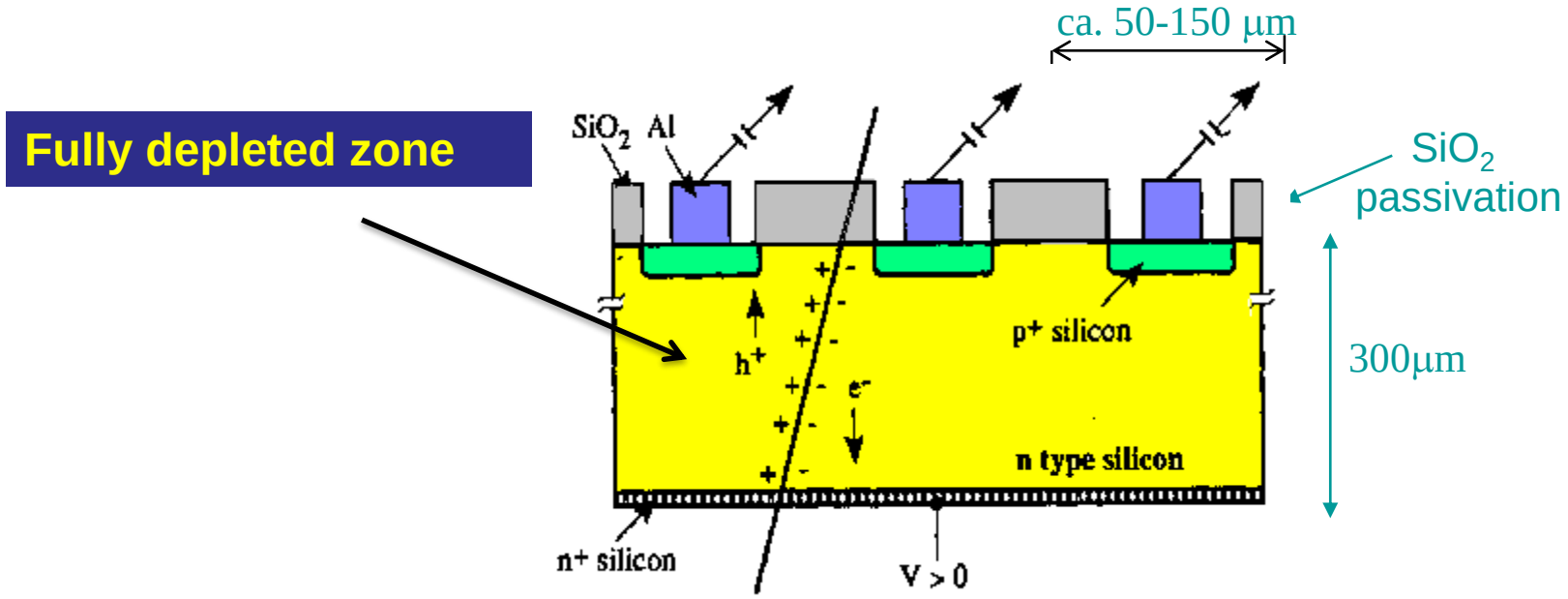
Zone without free charge carriers positively charged. Sensitive Detector Volume.



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.

Silicon Detector



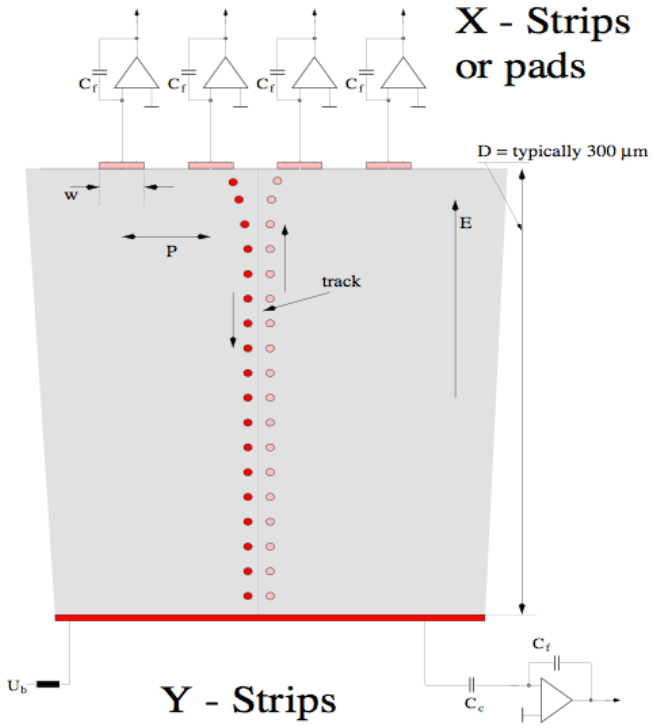
N (e-h) = 11 000/100μm

Position Resolution down to ~ 5μm !

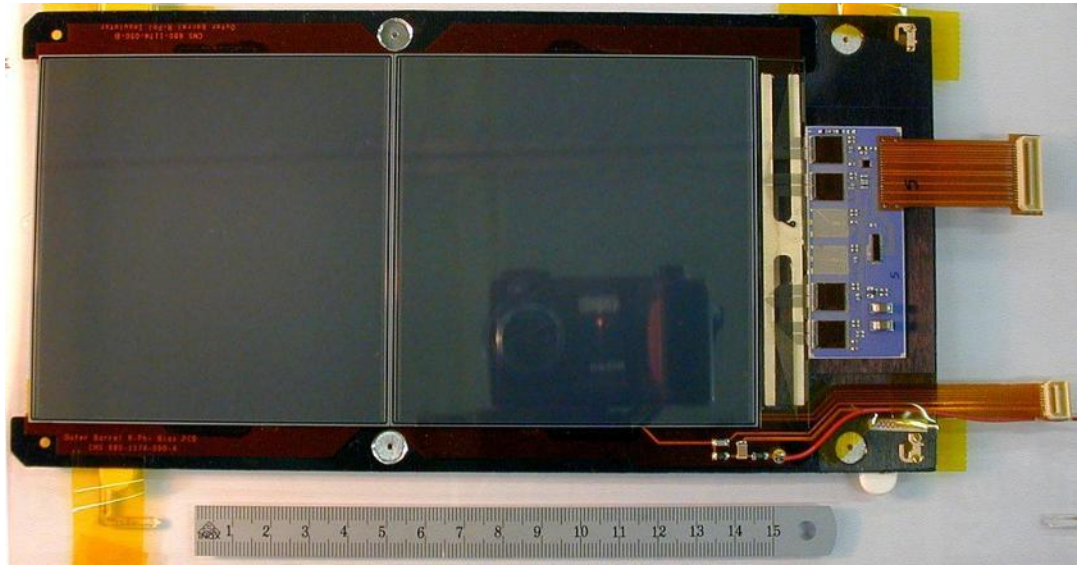
Silicon Detector

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

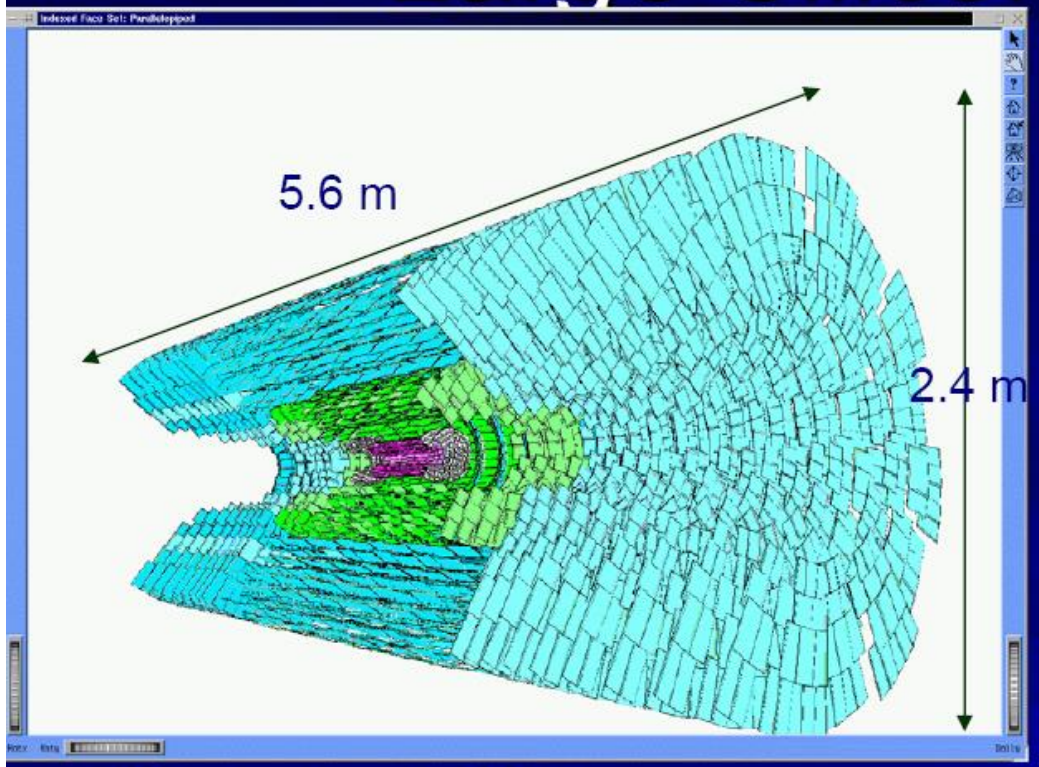
Two dimensional readout is possible.



CMS Outer Barrel Module



Large Silicon Systems



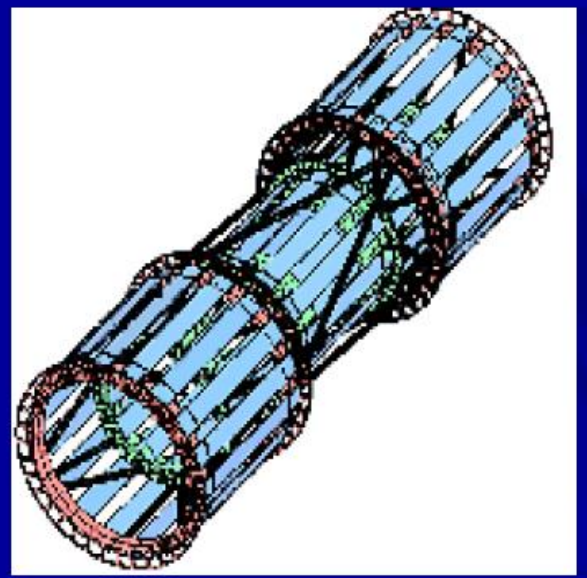
CMS tracker (~2007)

12000 modules

~ 445 m^2 silicon area

~ 24,328 silicon wafers

~ 60 M readout channels

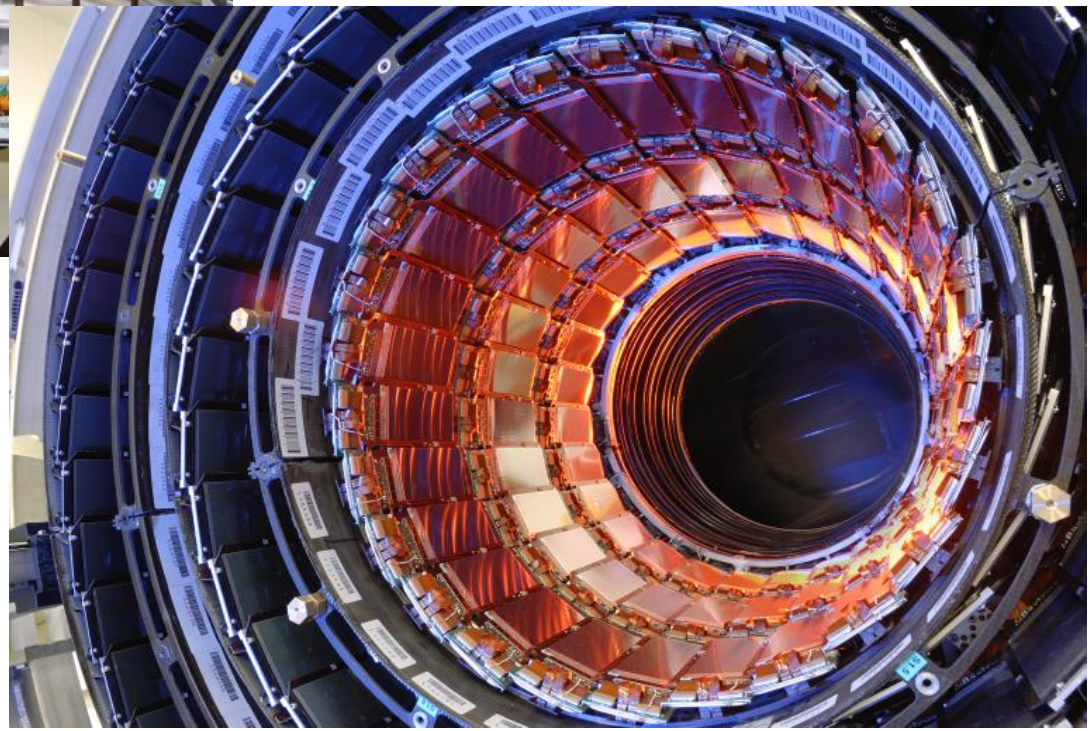


CDF SVX IIa (2001-)

~ 11m^2 silicon area

~ 750 000 readout channels

CMS Tracker



Pixel-Detectors

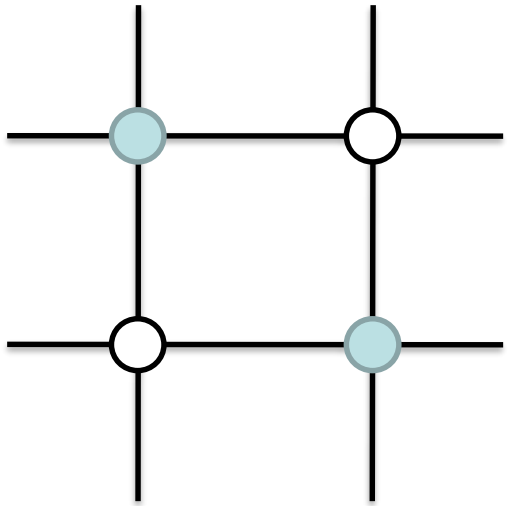
Problem:
2-dimensional readout of strip detectors results in ‘Ghost Tracks’ at high particle multiplicities i.e. many particles at the same time.

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

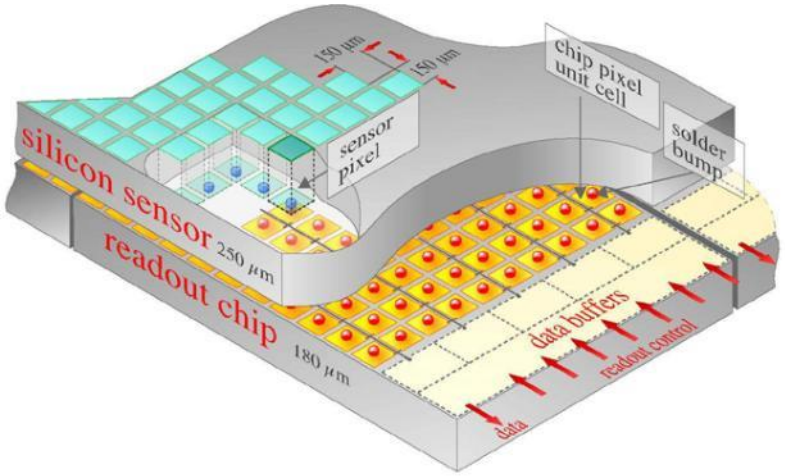
Problem:
Coupling of readout electronics to the detector

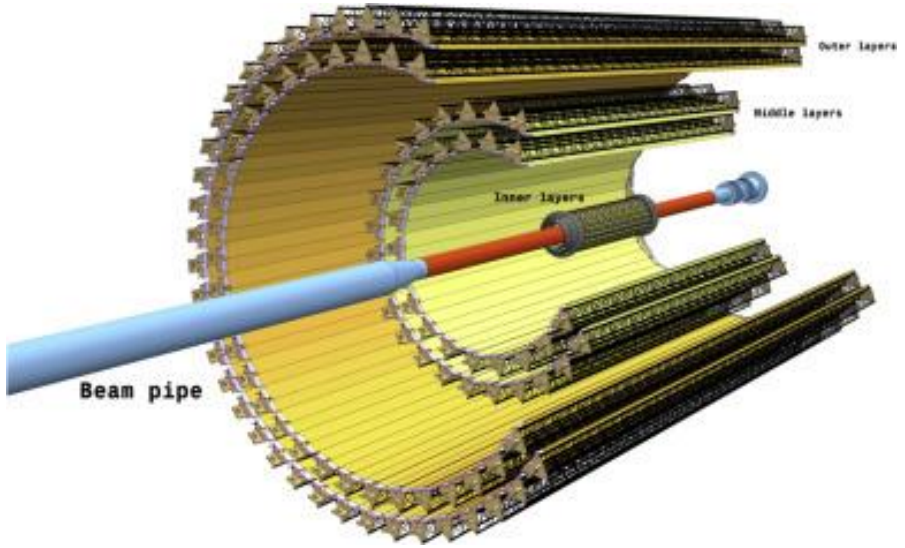
Solution:
Bump bonding for correcting a sensor to the readout electronics chip

Monolithic silicon sensors that incorporate the sensor and the electronics inside one substrate

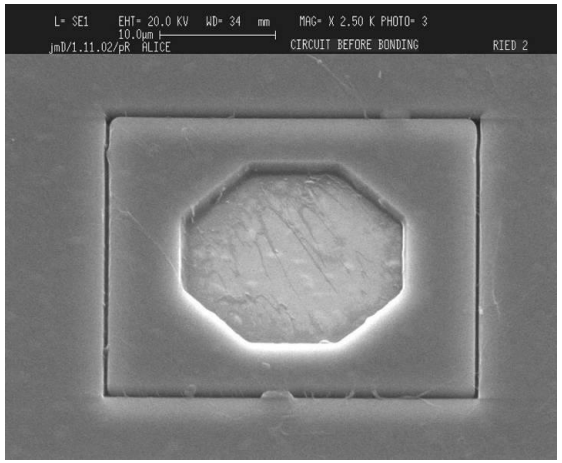


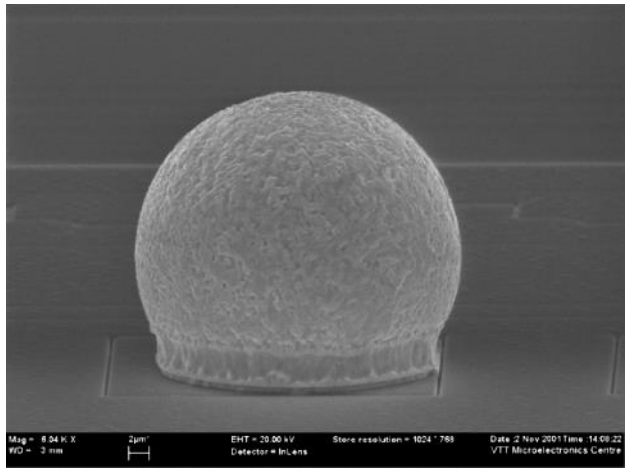
Pixel-Detectors





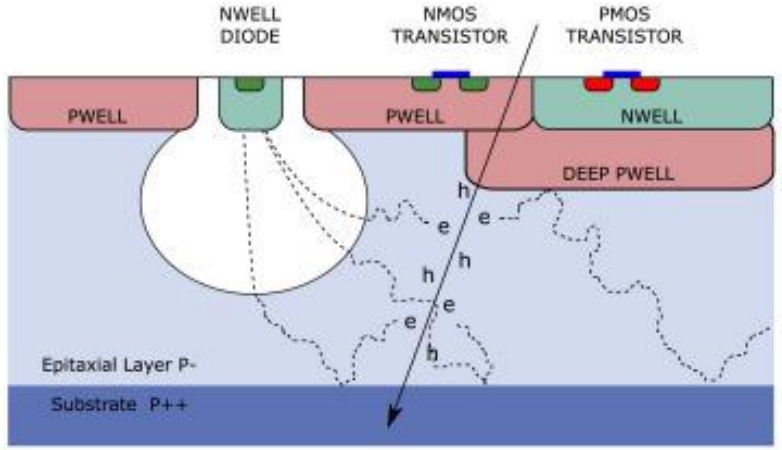
ATLAS: 10^8 pixels





Bump bonding of pixels to readout electronics.
'Hybrid Pixel Deterctors'

ALICE: 10^{10} pixels



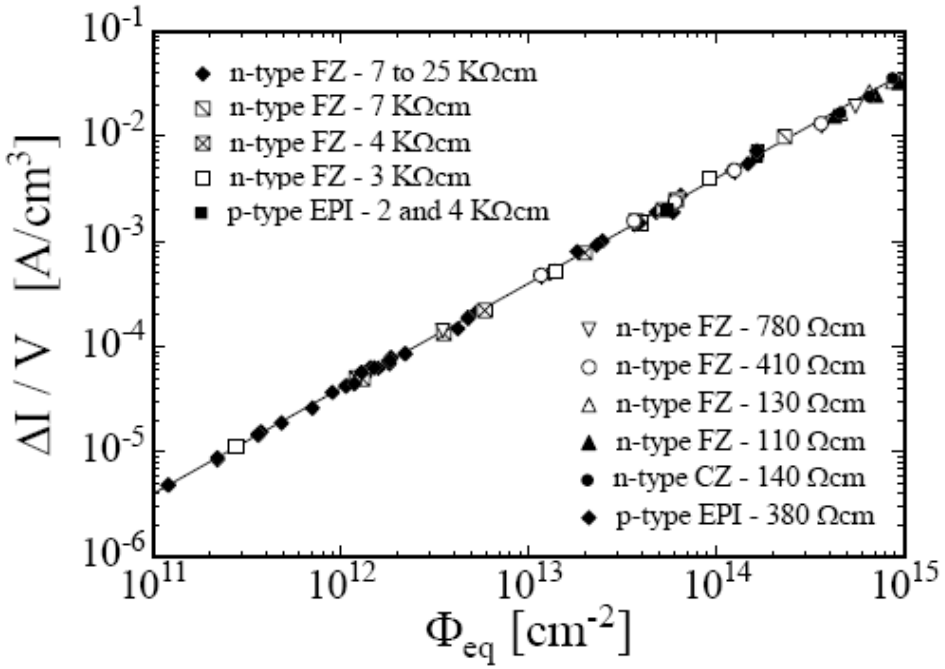
Sensitive element and electronics on the same silicon wafer produced with 'standard' electronics fabrication process. 'Monolithic Pixel Deterctors'

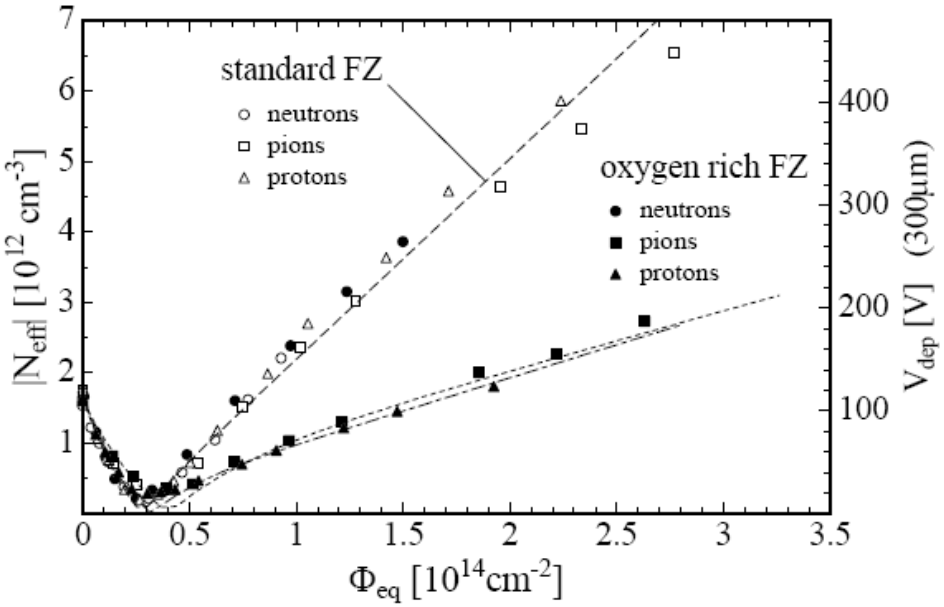
Radiation Effects 'Aging'

Increase in leakage current

Increase in depletion voltage

Decrease in charge collection efficiency due to under-depletion and charge trapping.





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).

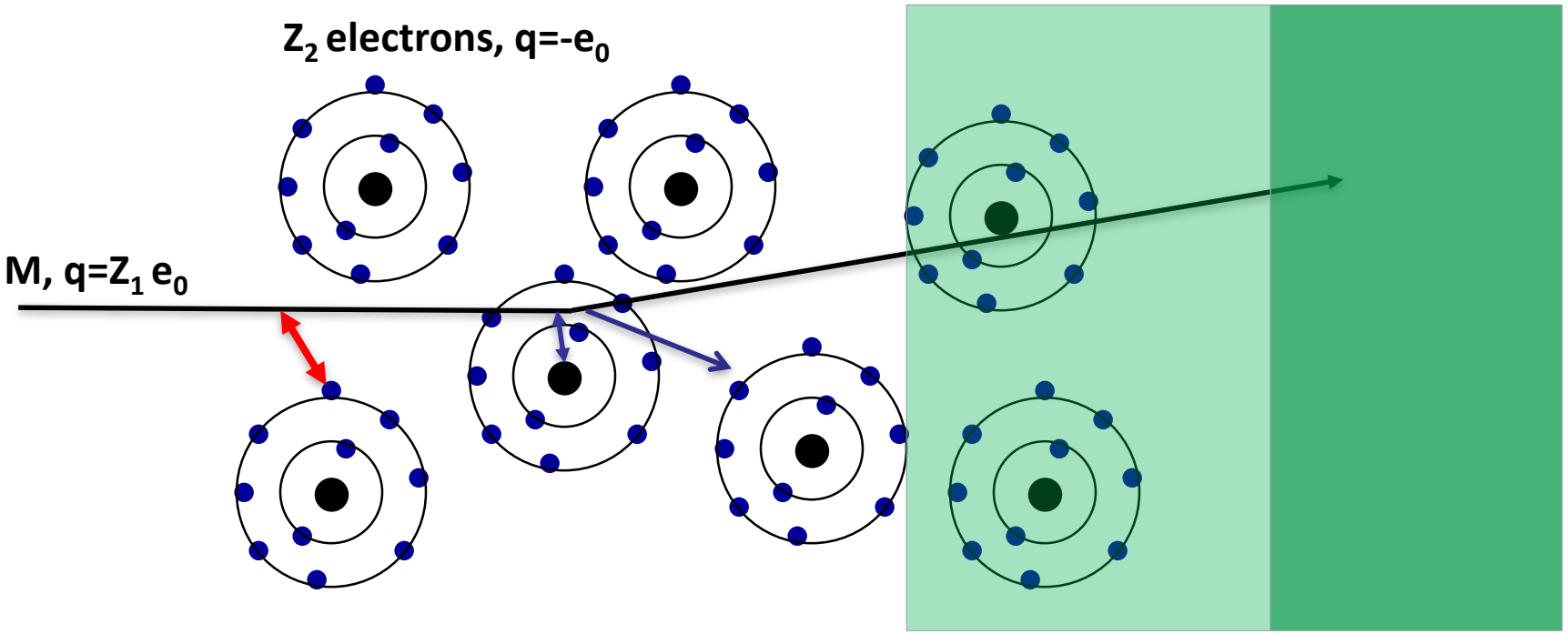
Technology is improving rapidly due to rapid Silicon development for electronics industry.

Typical numbers where detectors start to strongly degrade are 10^{15}-10^{16} hadron/cm^2.

‘Engineered silicon’, ‘diamonds’ and novel geometries provide higher radiation resistance.

Clearly, monolithic solid state detectors are an ultimate goal.

Electromagnetic Interaction of Particles with Matter



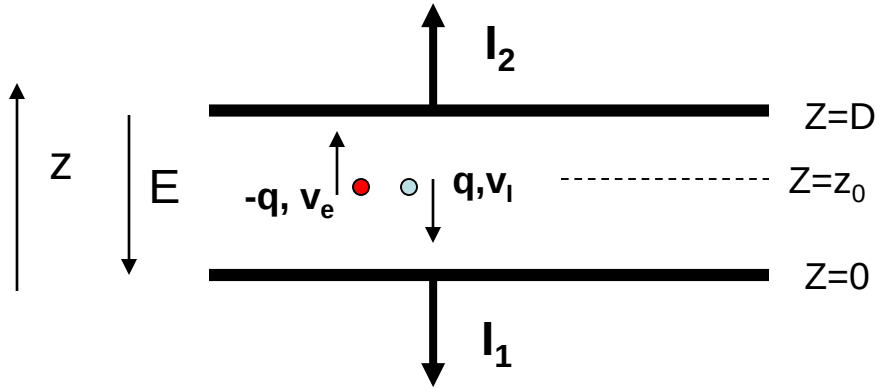
Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

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.

Signals in a Parallel Plate Geometry

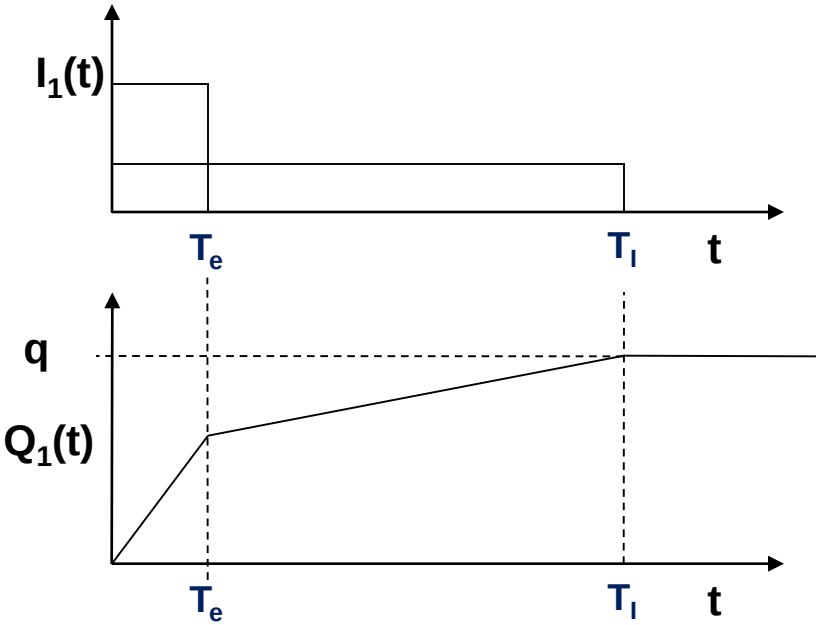
E.g.: Elektron-ion pair in gas
or Electron-ion pair in a liquid
or Electron-hole pair in a solid



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

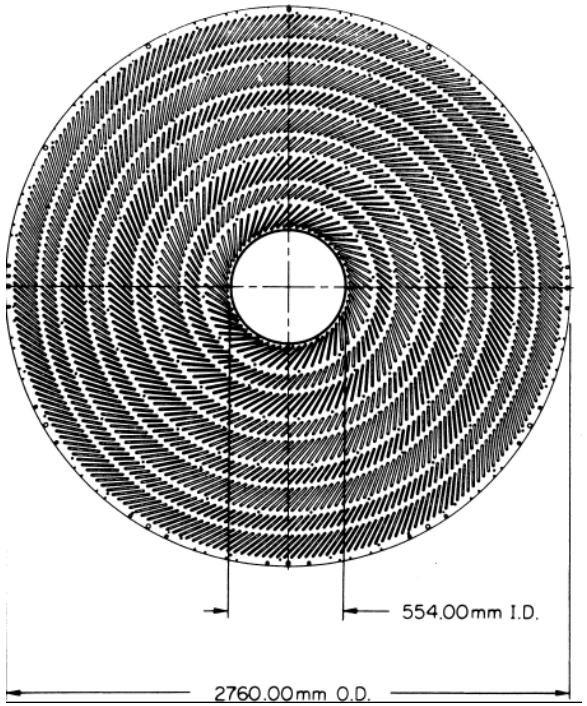
$I_1= -(-q)/V_0*(V_0/D)*v_e - q/V_0\ (V_0/D)\ (-v_l)$
$= q/D*v_e+q/D*v_l$
$I_2=-I_1$

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



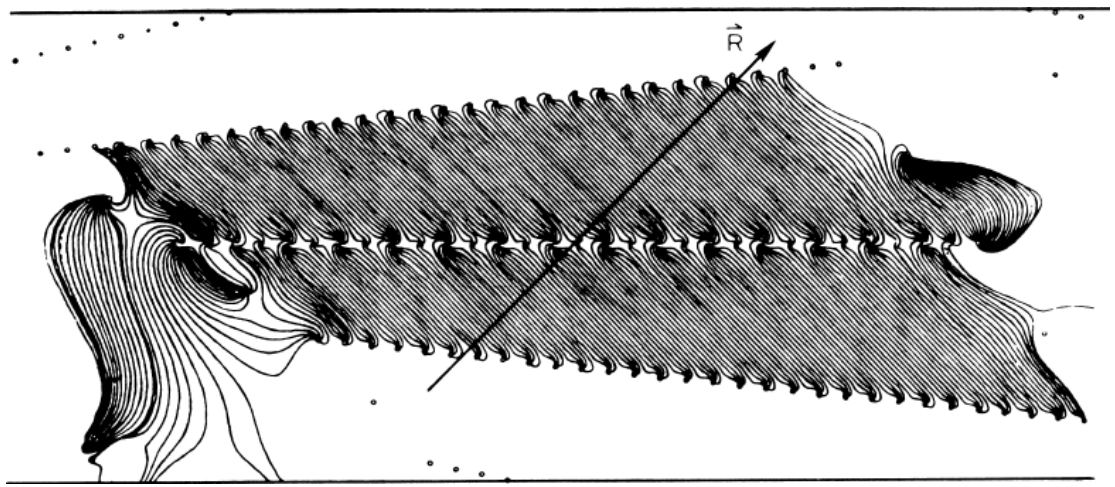
The total induced charge on a specific electrode, once all the charges have arrived at the electrodes, is equal to the charge that has arrived at this specific electrode.

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.

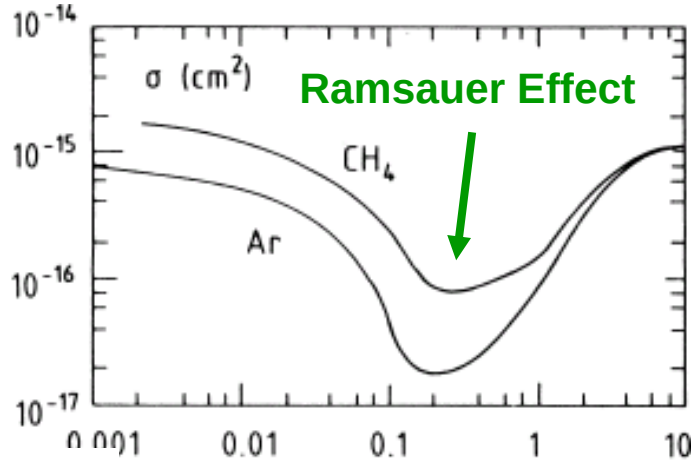
The velocities v and u are determined by the atomic crossection σ(ε) and the fractional energy loss Δ(ε) per collision (N is the gas density i.e. number of gas atoms/m³, m is the electron mass.):

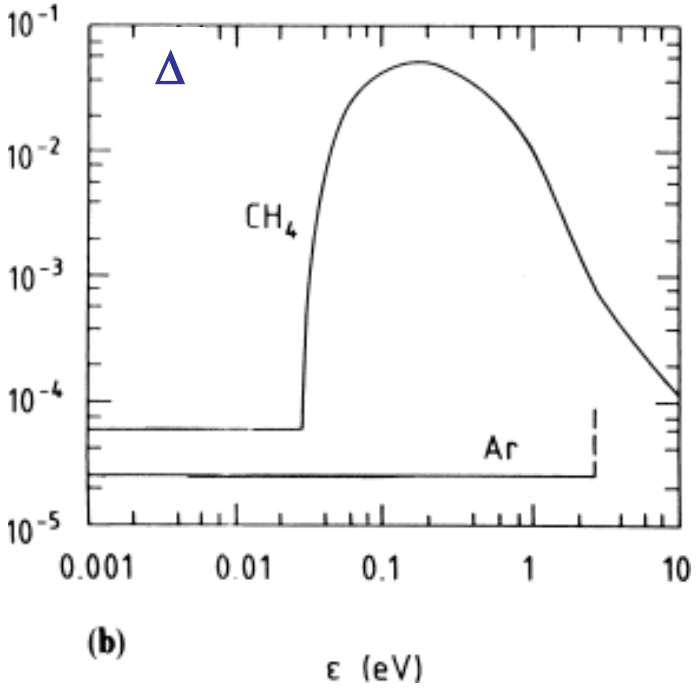
$$v = \sqrt{\frac{eE}{mN\sigma}\sqrt{\frac{\Delta}{2}}} \qquad u = \sqrt{\frac{eE}{mN\sigma}\sqrt{\frac{2}{\Delta}}}$$

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

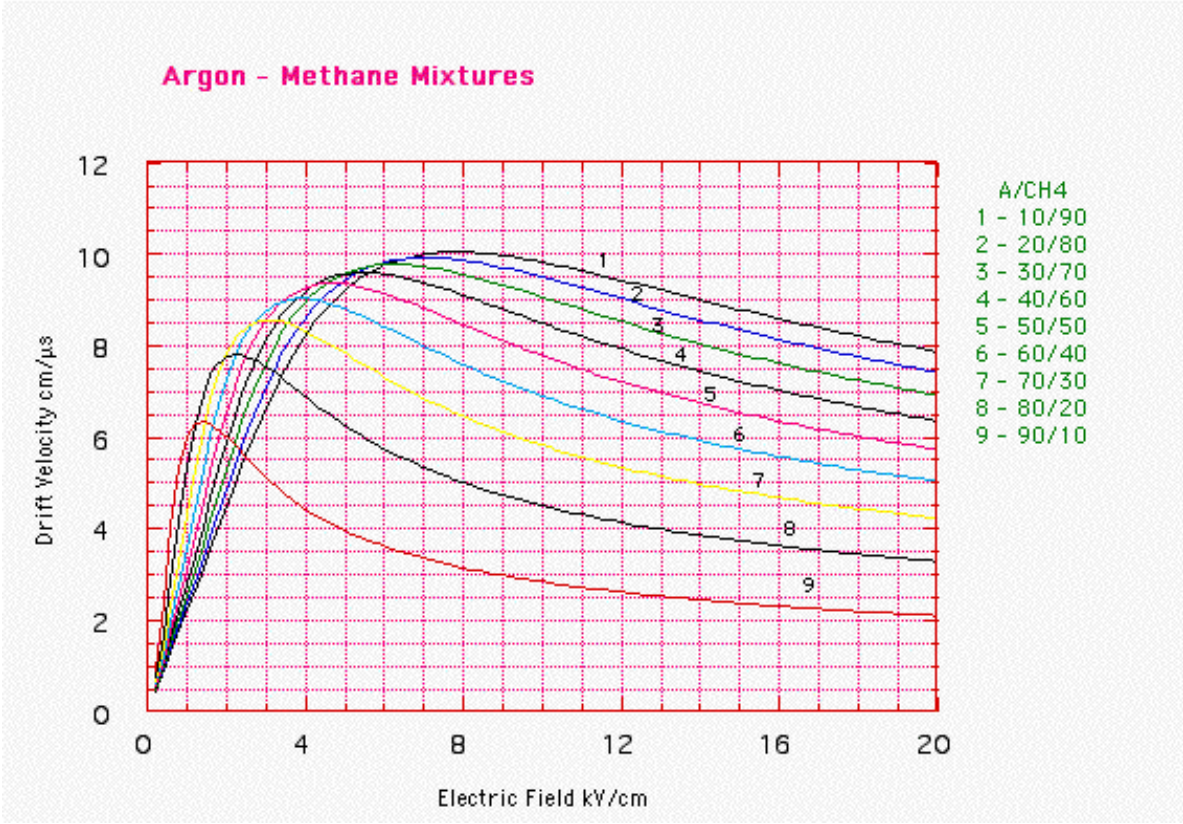
Because σ(ε)und Δ(ε) show a strong dependence on the electron energy in the typical electric fields, the electron drift velocity v shows a strong and complex variation with the applied electric field.

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

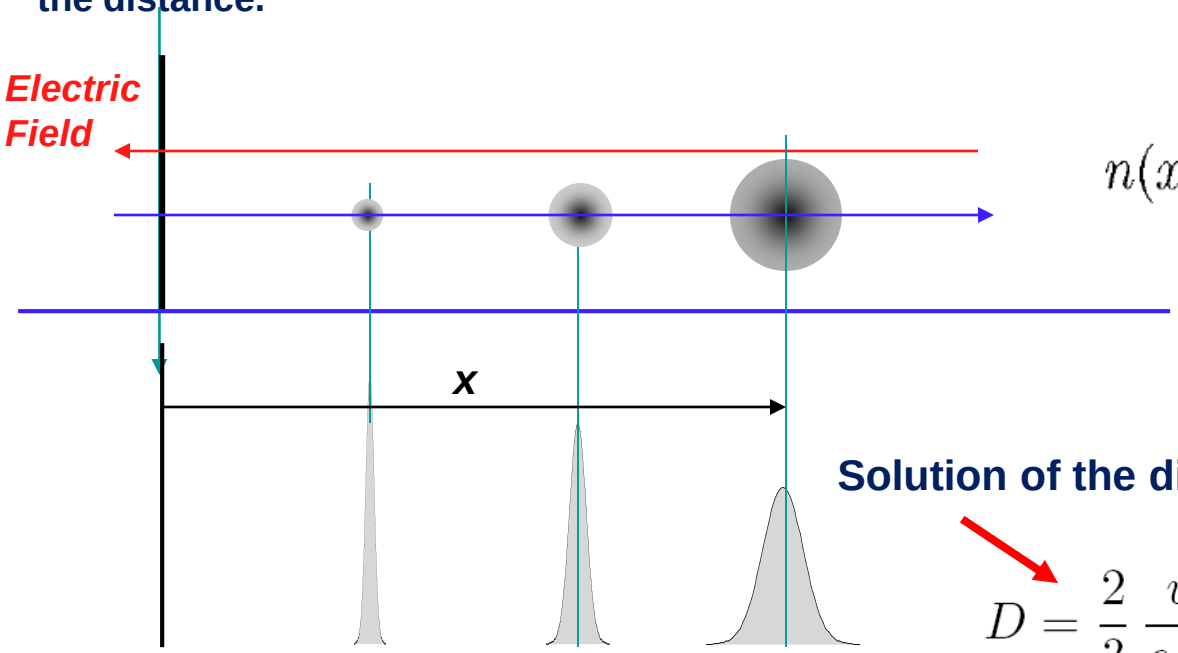


Typical Drift velocities are v=5-10cm/μs (50 000-100 000m/s).
The microscopic velocity u is about ca. 100mal larger.

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.



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

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

Solution of the diffusion equation (l=drift distance)

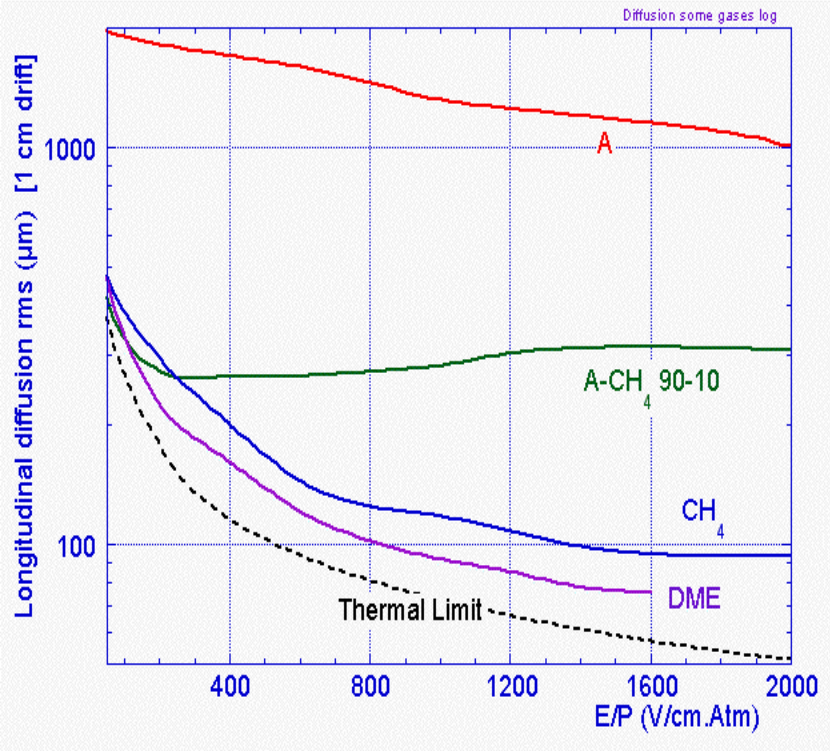
$$D = \frac{2}{3}\frac{v}{eE}\epsilon \quad \rightarrow \quad \sigma_x = \sqrt{\frac{4}{3}\frac{l}{eE}\epsilon}$$

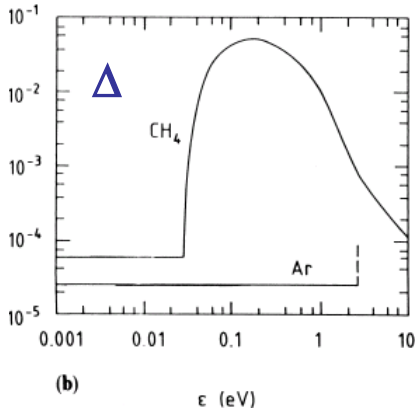
Thermodynamic limit:

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

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.

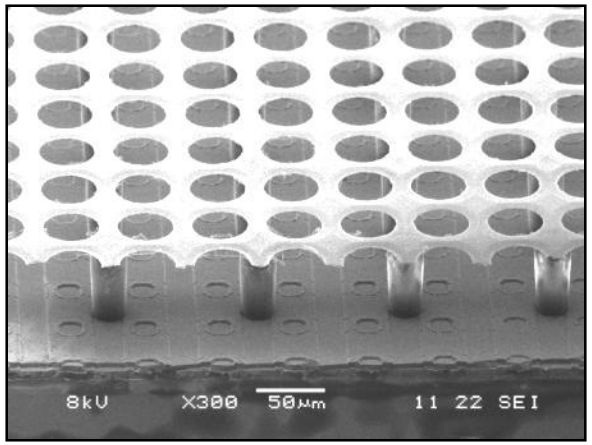
Below the thermal energy the velocity is proportional to the electric field
$v = \mu E$ (typical). Ion mobility $\mu \approx 1\text{-}10\ cm^2/Vs$.

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 !

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 cm³ Mini TPC !
Tracks from Sr90 source in 0.2T Magnetic Field !

Single ionization electrons are seen.

Fantastic position resolution …