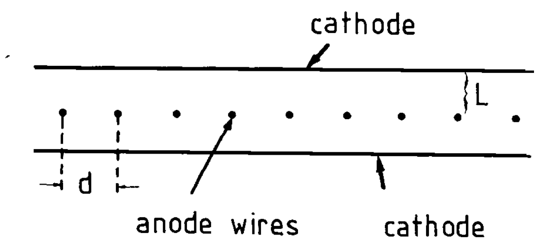
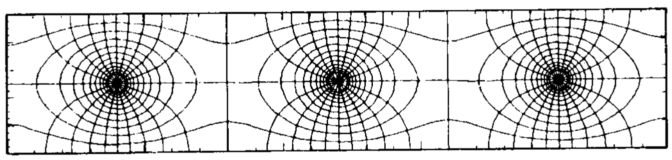
Multi wire proportional chamber (MWPC)

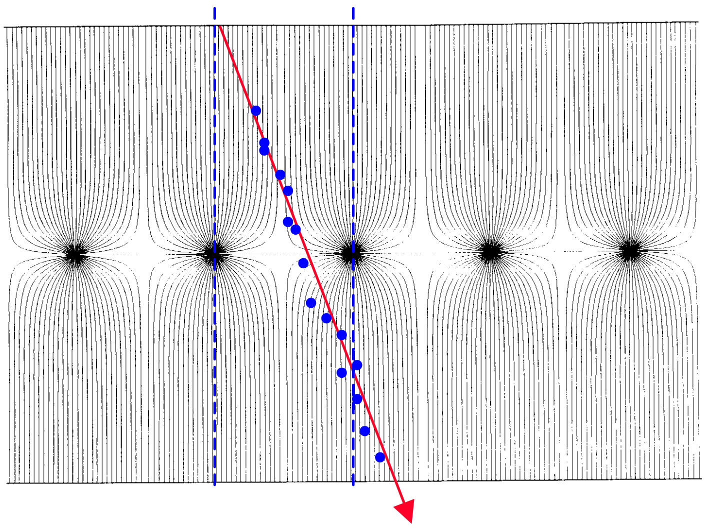
(G. Charpak et al. 1968, Nobel prize 1992)





field lines and equipotentials around anode wires

Capacitive coupling of non-screened parallel wires? Negative signals on all wires? Compensated by positive signal induction from ion avalanche.



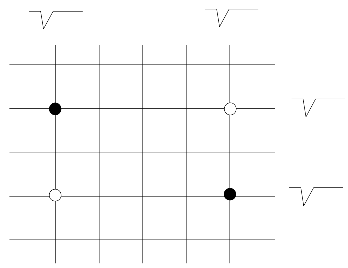
Typical parameters:
L=5mm, d=1mm,
a_{wire}=20mm.

Normally digital readout:
spatial resolution limited to $s_x \approx \frac{d}{\sqrt{12}}$ (d=1mm, σ_x=300 mm)

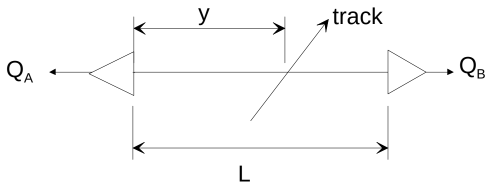
Address of fired wire(s) give only 1-dimensional information. Secondary coordinate ….

Secondary coordinate

- Crossed wire planes. Ghost hits. Restricted to low multiplicities. Also stereo planes (crossing under small angle).

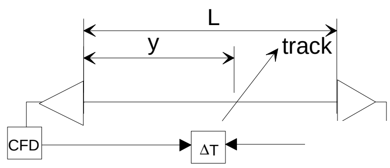


- Charge division. Resistive wires (Carbon,2kΩ/m).



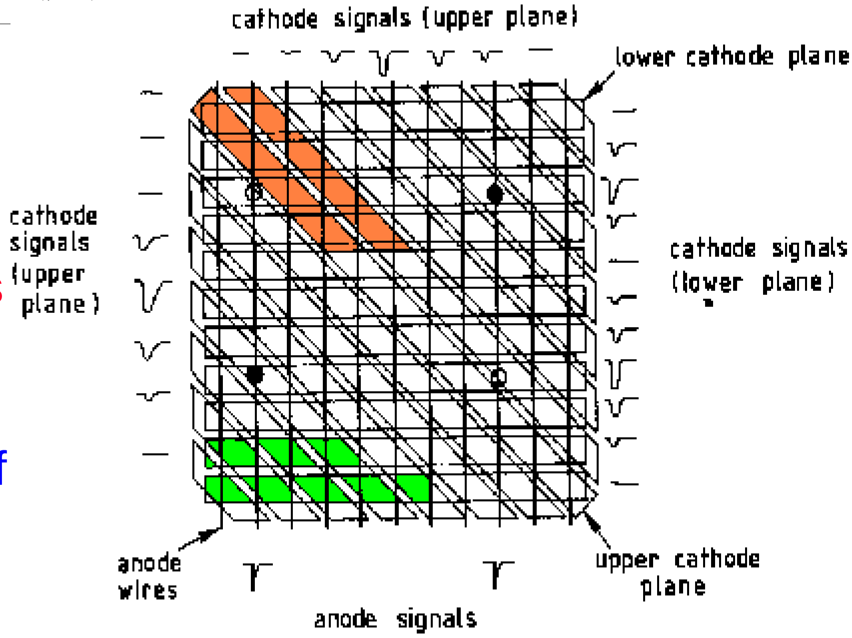
$$\frac{y}{L}=\frac{Q_B}{Q_A+Q_B} \qquad s\left(\frac{y}{L}\right) \text{ up to } 0.4\%$$

- Timing difference (DELPHI Outer detector, OPAL vertex detector)



$$s(\Delta T) = 100\,ps$$
$$\rightarrow\ s(y) \approx 4cm \quad \text{(OPAL)}$$

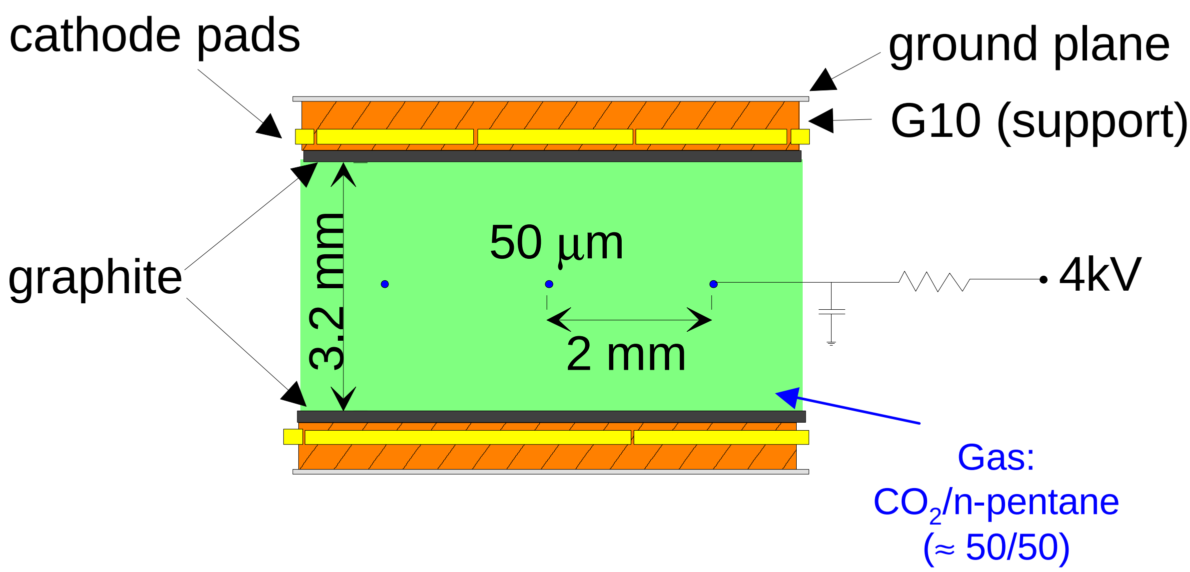
- 1 wire plane
  + 2 segmented cathode planes



Analog readout of cathode planes.
→ σ ≈ 100 µm

Some 'derivatives'

- Thin gap chambers (TGC)

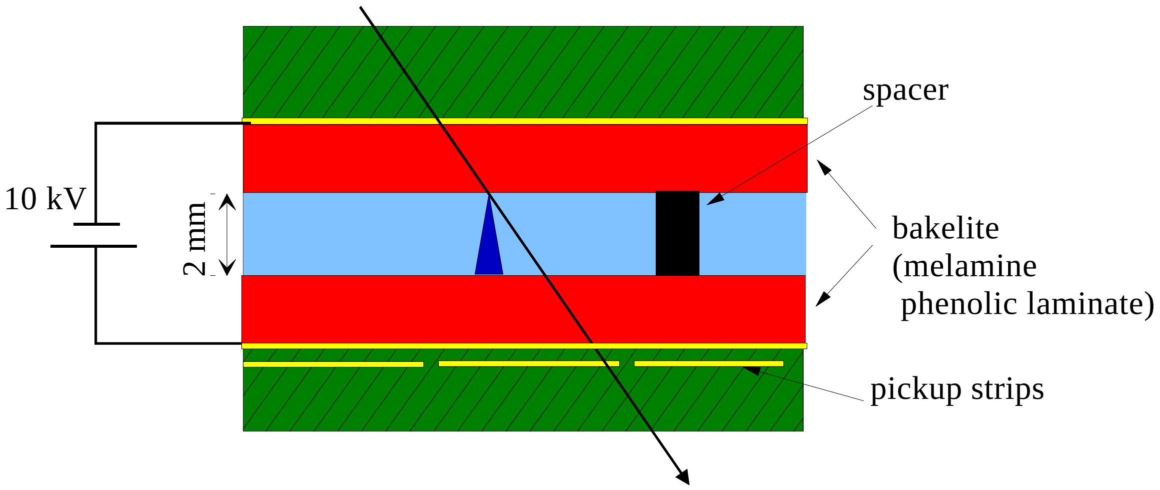


Operation in saturated mode. Signal amplitude limited by by the resistivity of the graphite layer (≈ 40kΩ/☐).

Fast (2 ns risetime), large signals (gain 10^6), robust

Application: OPAL pole tip hadron calorimeter.
G. Mikenberg, NIM A 265 (1988) 223
ATLAS muon endcap trigger, Y.Arai et al. NIM A 367 (1995) 398

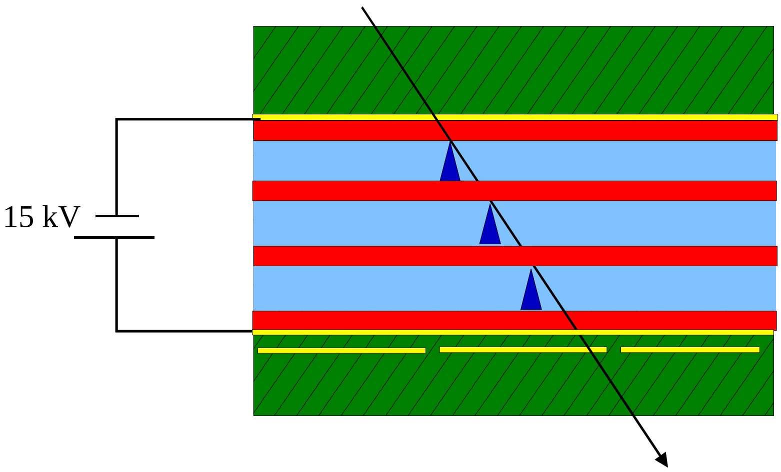
- Resistive plate chambers (RPC) No wires !



Gas: $C_2F_4H_2$, (C_2F_5H) + few % isobutane

(ATLAS, A. Di Ciaccio, NIM A 384 (1996) 222)

Time dispersion ≈ 1..2 ns → suited as trigger chamber
Rate capability ≈ 1 kHz / cm^2

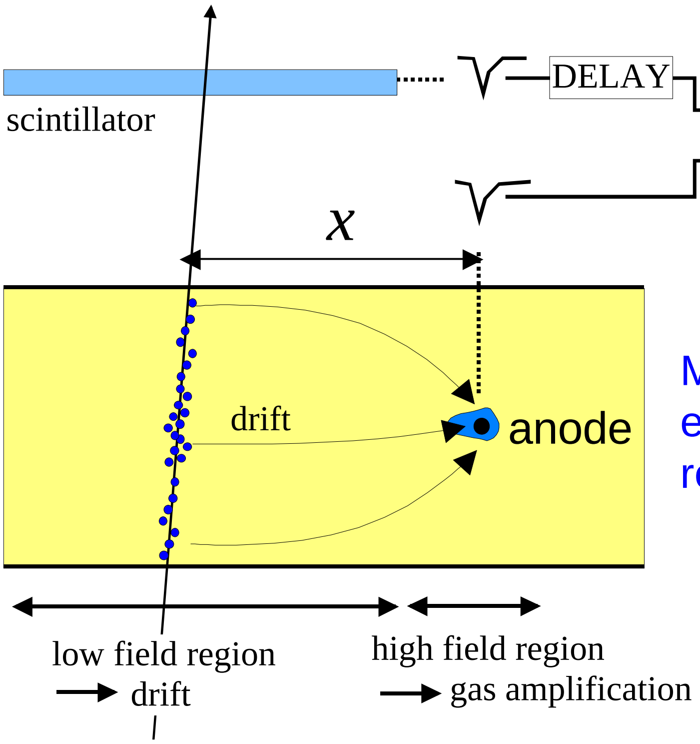


Double and multigap geometries → improve timing and efficiency

Problem: Operation close to streamer mode.

Drift chambers

(First studies: T. Bressani, G. Charpak, D. Rahm, C. Zupancic, 1969
First operation drift chamber: A.H. Walenta, J. Heintze, B. Schürlein, NIM 92 (1971) 373)



Measure arrival time of electrons at sense wire relative to a time t_0.

$$x = \int v_D(t)dt$$

What happens during the drift towards the anode wire ?

- ☞ Diffusion ?
- ☞ Drift velocity ?

Drift and diffusion in gases

No external fields:

Electrons and ions will lose their energy due to collisions with the gas atoms → thermalization

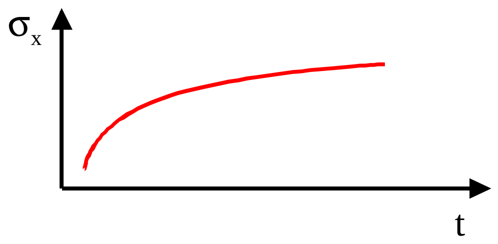
$$\varepsilon = \frac{3}{2}kT \approx 40 \text{ meV}$$

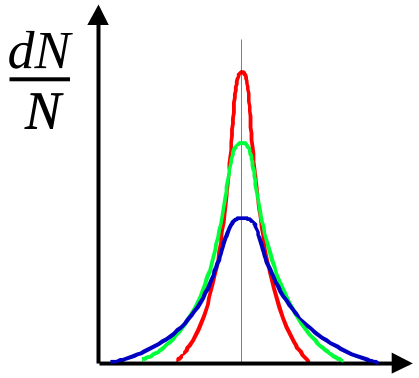
Undergoing multiple collisions, an originally localized ensemble of charges will diffuse

$$\frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}} e^{-(x^2/4Dt)}\, dx$$

D: diffusion coefficient

$$\sigma_x(t) = \sqrt{2Dt} \qquad or \quad D = \frac{\sigma_x^2(t)}{2t}$$



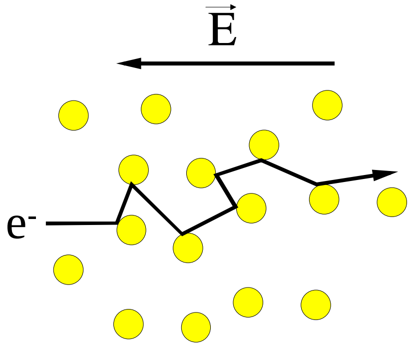


External electric field:

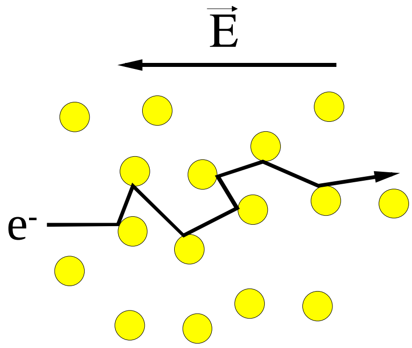
“stop and go” traffic due to scattering from gas atoms

$\rightarrow$ drift

$$\vec{v}_D = \mu \vec{E} \qquad \mu = \frac{e\tau}{m} \text{ (mobility)}$$



in the equilibrium ... $\frac{x}{v_D t} l_e e = eEx$

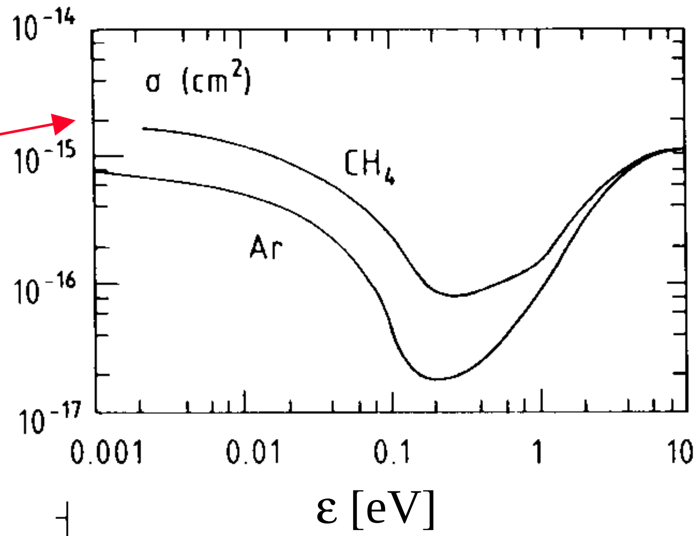


l_e : fractional energy loss / collision

$t = \frac{1}{Nsv}$ v: instantaneous velocity

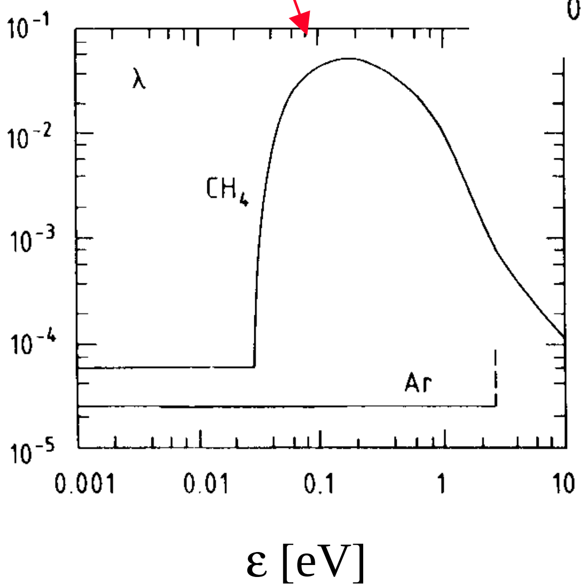
$\Rightarrow v_D^2 = \frac{eE}{mNs}\sqrt{\frac{l}{2}}$

$\sigma = \sigma(\varepsilon)$!



(B. Schmidt, thesis, unpublished, 1986)

$\lambda = \lambda(\varepsilon)$!



Typical electron drift velocity: **5 cm/ms**

Ion drift velocities: ca. 1000 times smaller

In the presence of electric and magnetic fields, drift and diffusion are driven by $\vec{E}\times\vec{B}$ effects

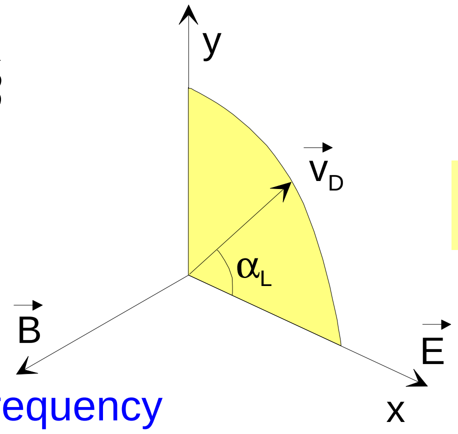
Look at 2 special cases:

Special case: $\vec{E}\perp\vec{B}$

$\tan \alpha_L = \omega\tau$

α_L: Lorentz angle

$\omega = \frac{e\vec{B}}{m}$ cyclotron frequency



$\vec{v}_D \not\parallel \vec{E}$

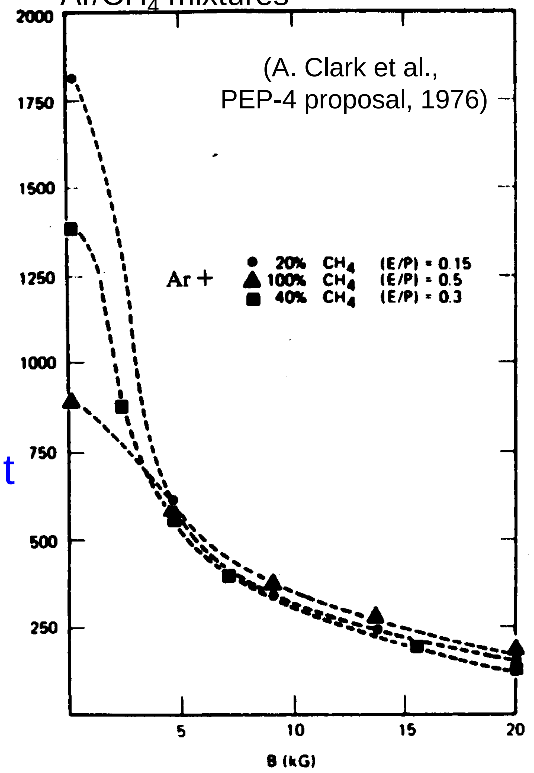
Special case: $\vec{E}\parallel\vec{B}$

The longitudinal diffusion (along B-field) is unchanged.
In the transverse projection the electrons are forced on circle segments with the radius v_T/ω.
The transverse diffusion coefficient appears reduced

$$D_T(B) = \frac{D_0}{1+\omega^2\tau^2}$$

Very useful… see later !

Transverse diffusion σ (μm) for a drift of 15 cm in different Ar/CH_4 mixtures

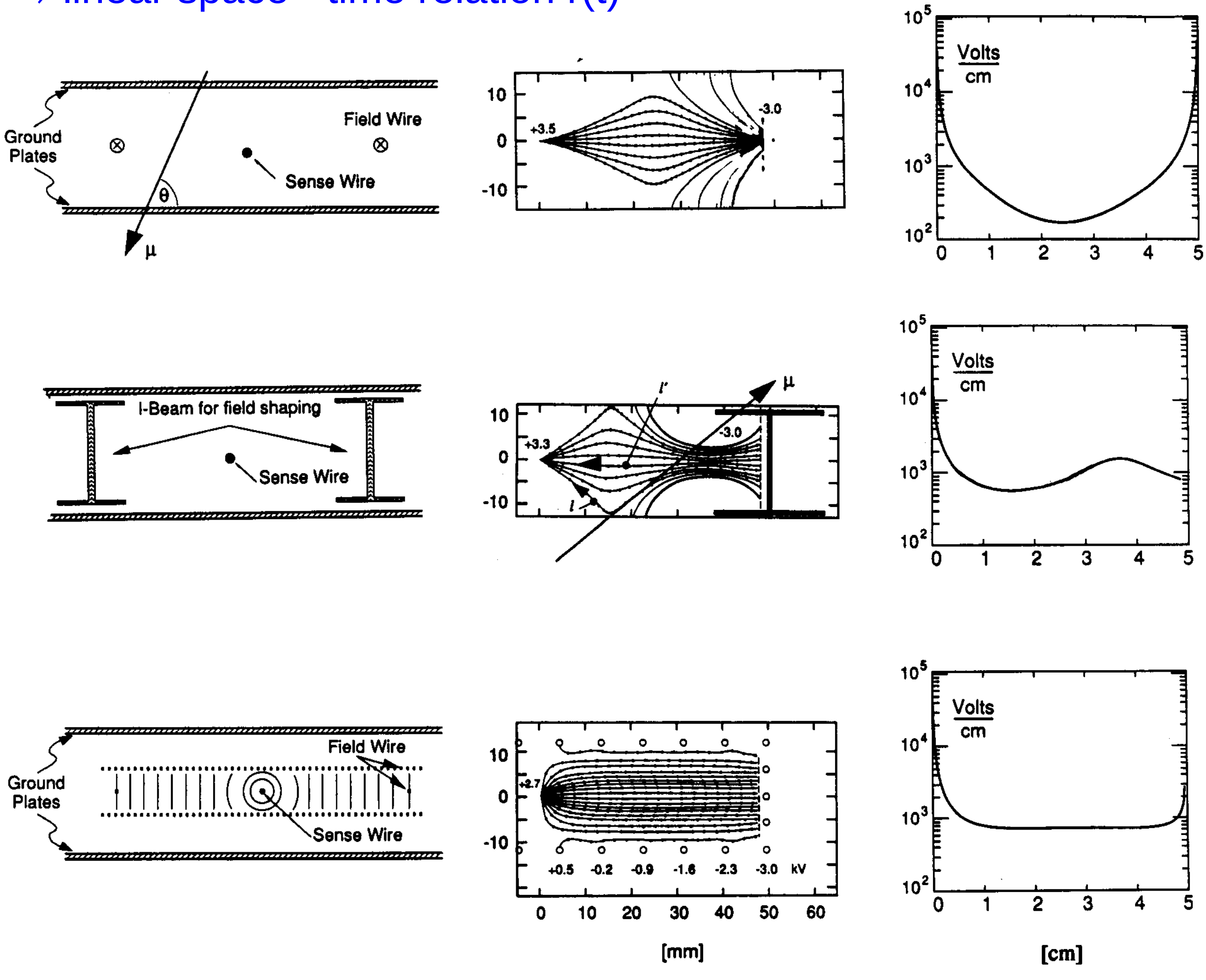


Some planar drift chamber designs

Optimize geometry $\rightarrow$ constant E-field

Choose drift gases with little dependence $v_D(E)$

$\rightarrow$ linear space - time relation r(t)



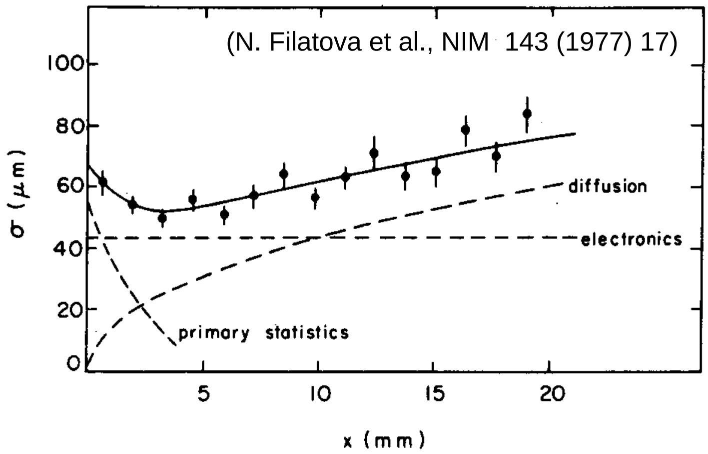
(U. Becker, in: Instrumentation in High Energy Physics, World Scientific)

The spatial resolution is not limited by the cell size

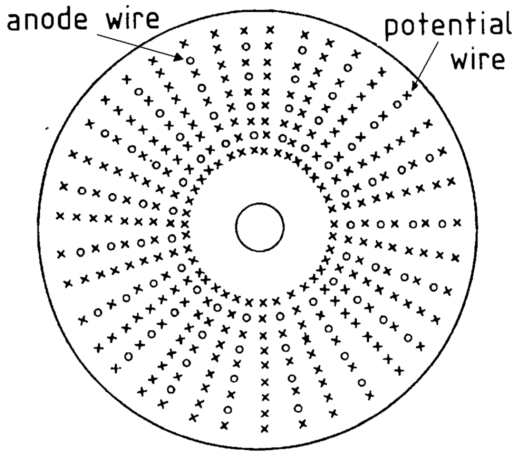
$\rightarrow$ less wires, less electronics,

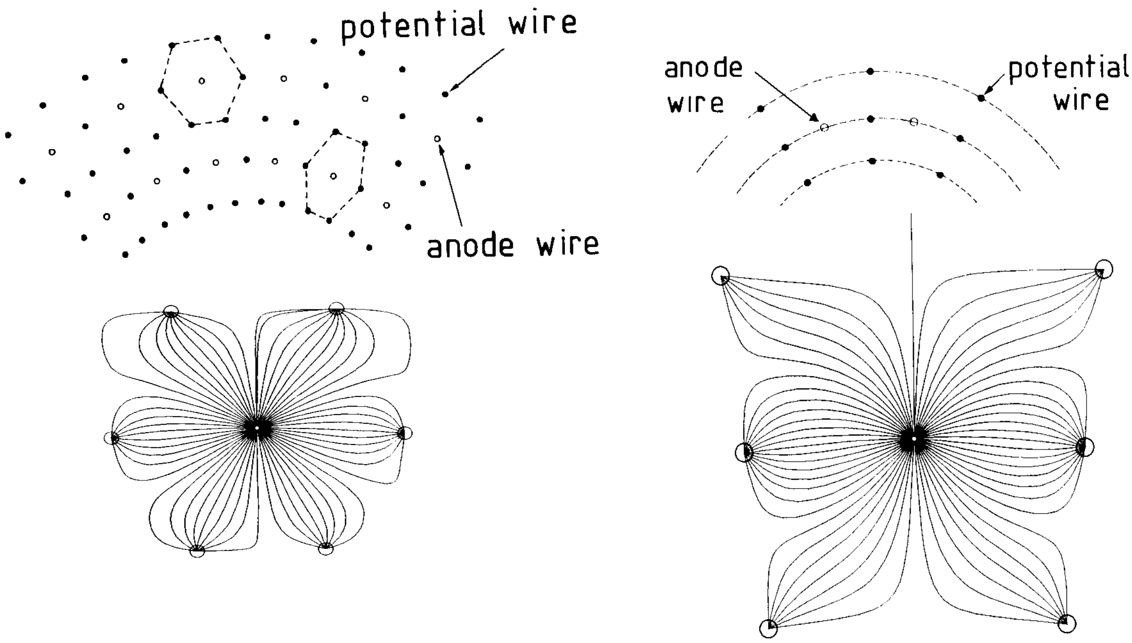
less support structure than in MWPC.

Resolution determined by
- diffusion,
- path fluctuations,
- electronics
- primary ionization statistics



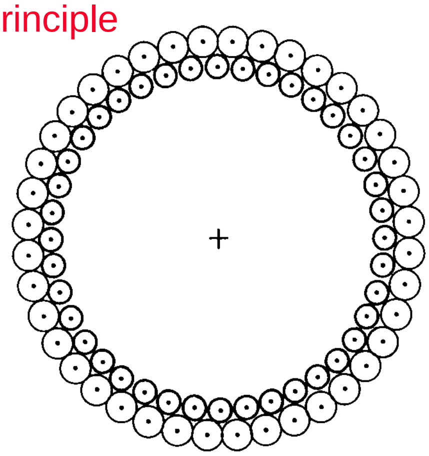
Various geometries of cylindrical drift chambers





Straw tubes: Thin cylindrical cathode, 1 anode wire

principle

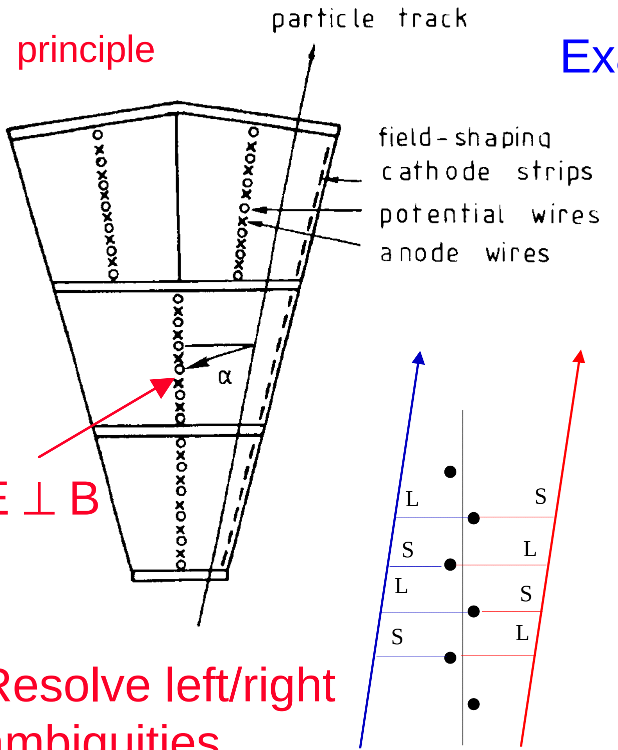


Example: DELPHI Inner detector

5 layers with 192 tubes each
tube ∅ 0.9 cm, 2 m long,
wall thickness 30 µm (Al coated polyester)
wire ∅ 40 µm
Intrinsic resolution ca. 50 µm

Jet chambers: Optimized for maximum number of measurements in radial direction

principle

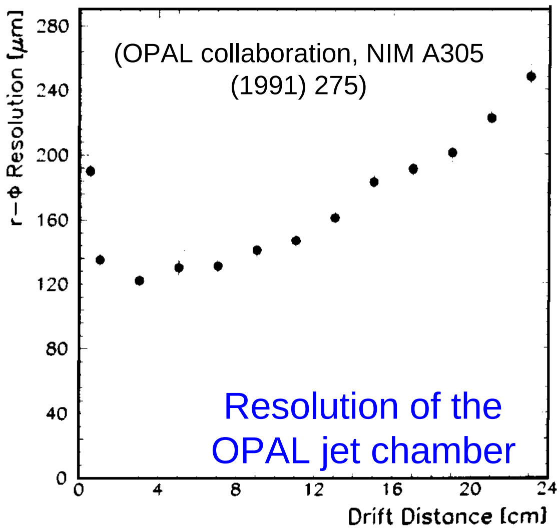


E ⊥ B

Resolve left/right ambiguities

Example: OPAL Jet chamber

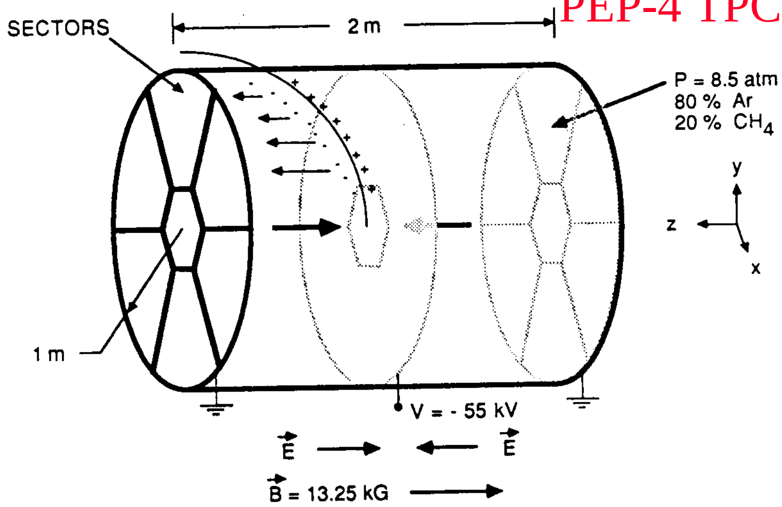
Ø=3.7m, L=4m, 24 sectors à 159 sense wires (±100 µm staggered). 3 cm < l_{drift} < 25 cm



Time Projection Chamber ® full 3-D track reconstruction

- x-y from wires and segmented cathode of MWPC
- z from drift time
- in addition dE/dx information

PEP-4 TPC



Diffusion significantly reduced by B-field.

Requires precise knowledge of $v_D \rightarrow$ LASER calibration + p,T corrections

Drift over long distances → very good gas quality required

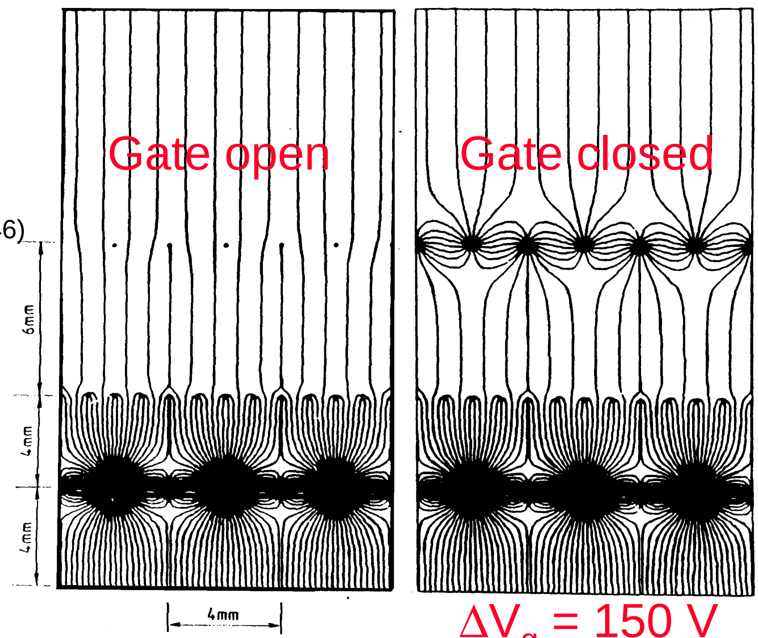
Space charge problem from positive ions, drifting back to midwall → gating

ALEPH TPC

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

Ø 3.6M, L=4.4 m

$\sigma_{R\phi} = 173\ \mu m$
$\sigma_z = 740\ \mu m$
(isolated leptons)



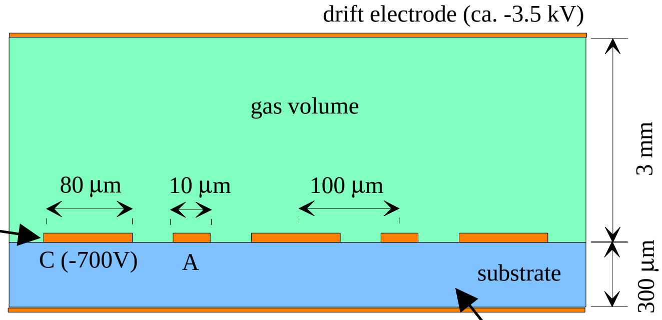
$\Delta V_g = 150$ V

Faster and more precision ? → smaller structures

◆ Microstrip gas chambers (A. Oed, NIM A 263 (1988) 352)

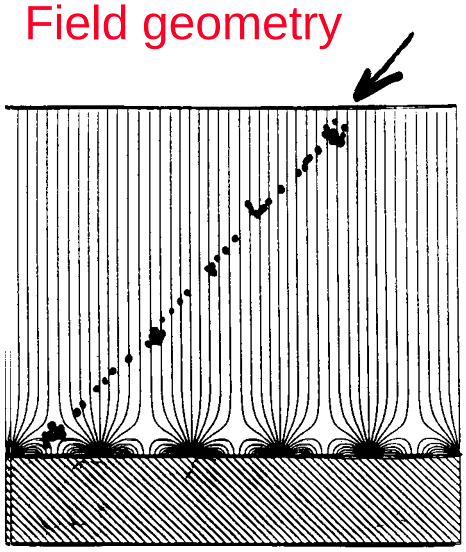
geometry and typical dimensions
(former CMS standard)

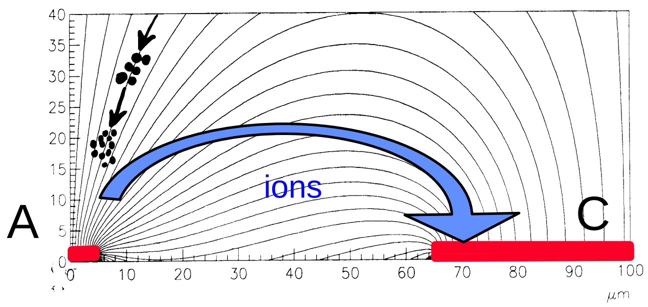
Gold strips
+ Cr underlayer



Glass DESAG AF45 + S8900 semiconducting glass coating, $\rho = 10^{16}\ \Omega/\square$

Field geometry



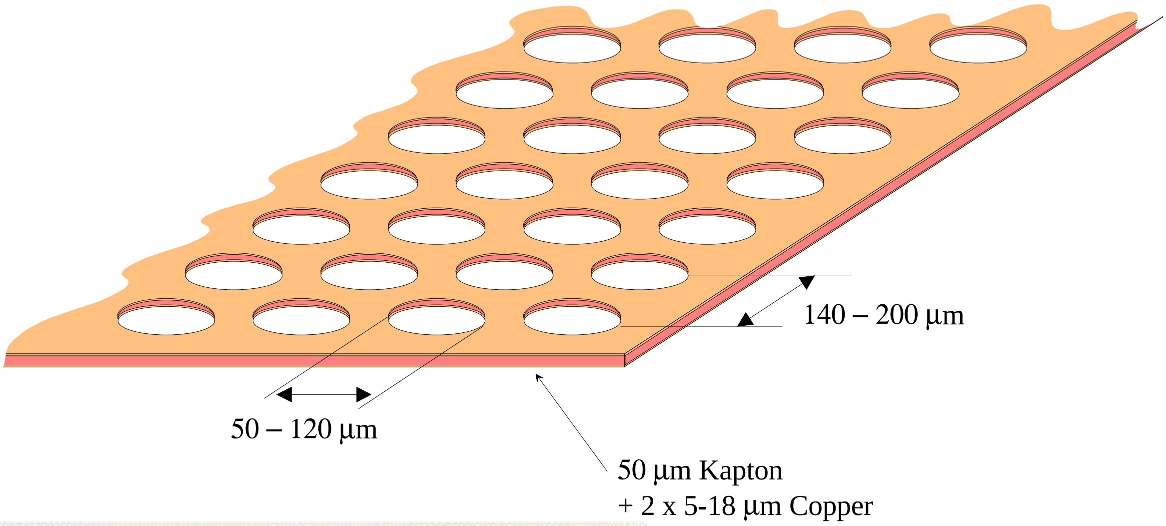


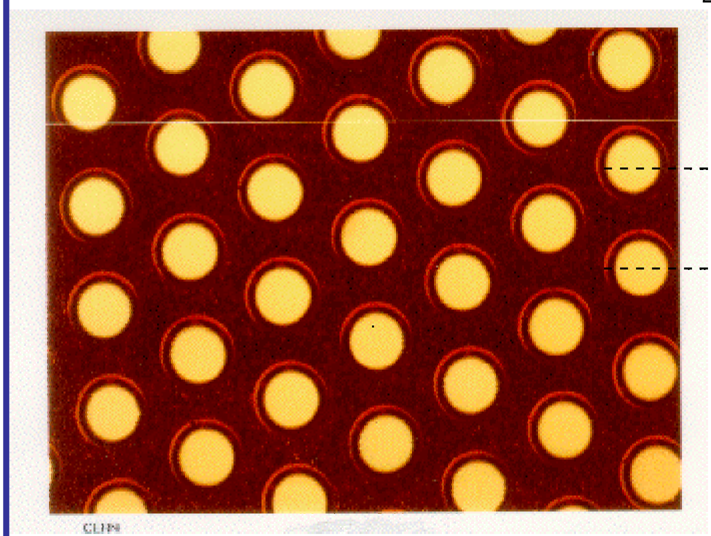
Fast ion evacuation → high rate capability $\approx 10^6$ /(mm^2·s)

Gas: Ar-DME, $\underbrace{\text{Ne-DME (1:2), Lorentz angle } 14^{\circ} \text{ at 4T,}}_{\text{CMS}}$
Gain $\leq 10^4$
Passivation: non-conductive protection of cathode edges
Resolution: $\approx$ 30..40 µm
Aging: Seems to be under control.
10 years LHC operation $\approx$ 100 mC/cm

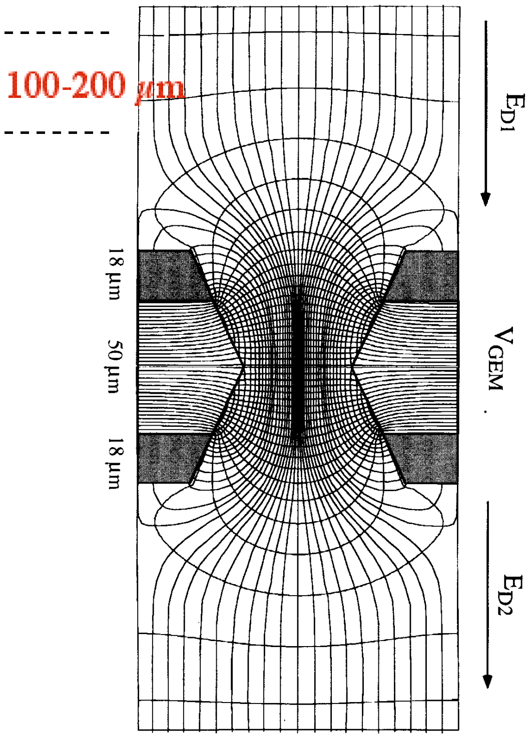
GEM: The Gas Electron Multiplier

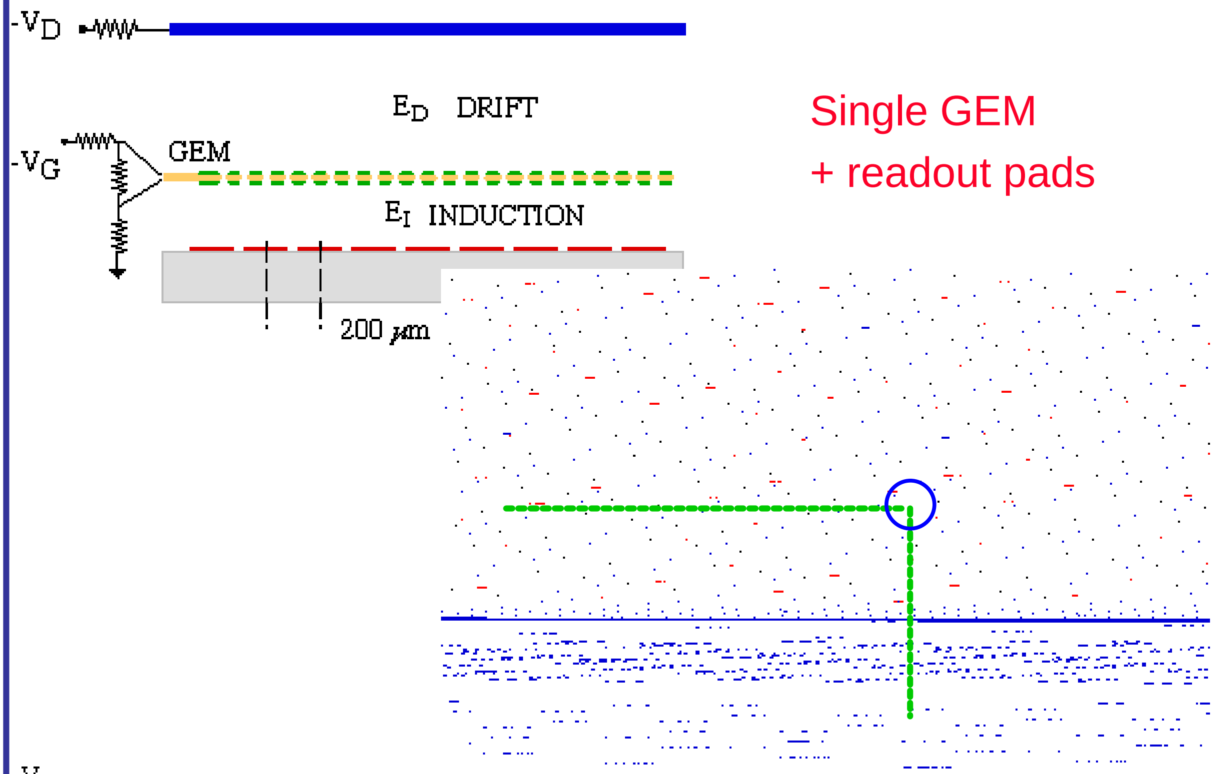
(R. Bouclier et al., NIM A 396 (1997) 50)



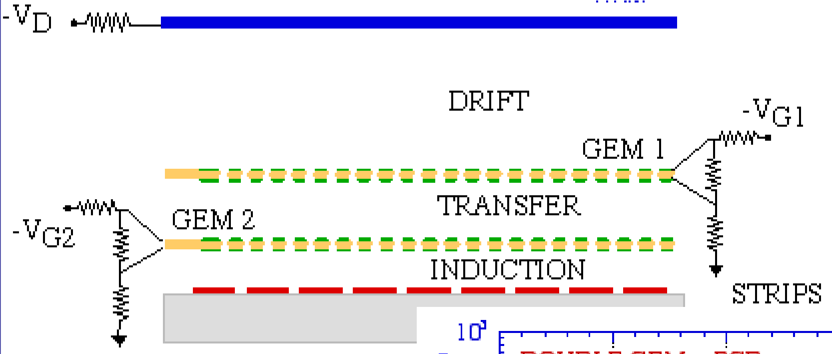


Micro photo of a GEM foil



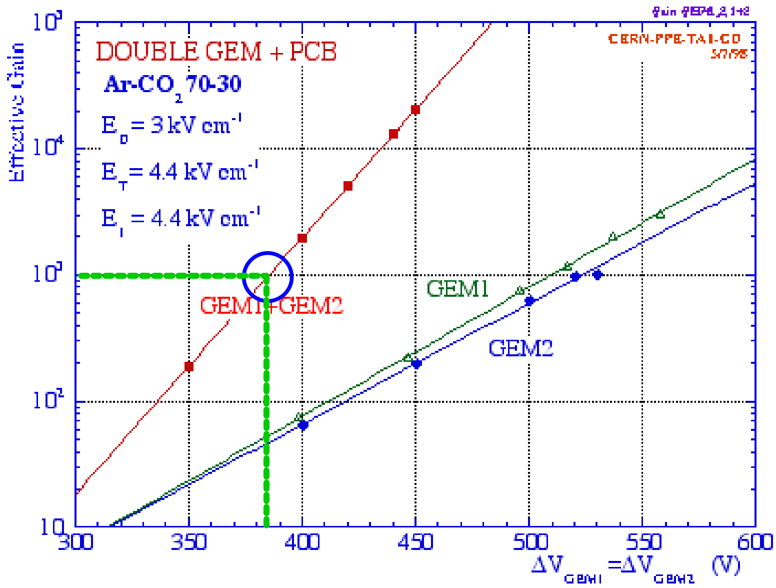


Single GEM
+ readout pads



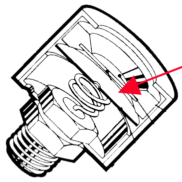
Double GEM
+ readout pads

- ➢ Same gain
  at lower voltage
- ➢ Less discharges



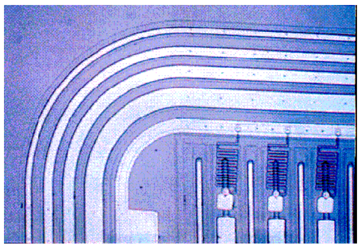
Silicon detectors

Solid state detectors have a long tradition for energy measurements (Si, Ge, Ge(Li)).



Si sensor

Here we are interested in their use as precision trackers !

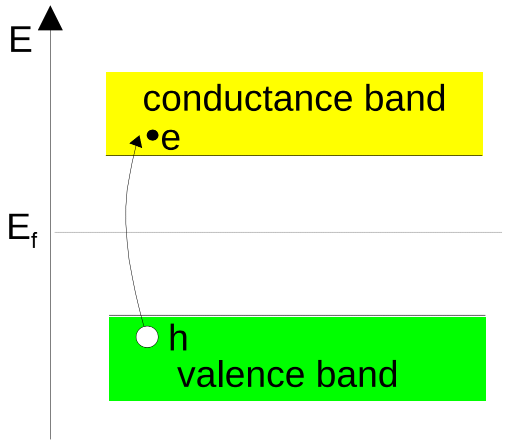


ATLAS SCT

Some characteristic numbers for silicon

- Band gap: E_g =1.12 V.
- E(e^--hole pair) = 3.6 eV, ($\approx$ 30 eV for gas detectors).
- High specific density (2.33 g/cm^3) $\rightarrow$ ΔE/track length for M.I.P.'s.: 390 eV/μm $\approx$ 108 e-h/ μm (average)
- High mobility: μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs
- Detector production by microelectronic techniques $\rightarrow$ small dimensions $\rightarrow$ fast charge collection (<10 ns).
- Rigidity of silicon allows thin self supporting structures. Typical thickness 300 μm $\rightarrow$ $\approx$ 3.2 $\cdot 10^4$ e-h (average)
- But: No charge multiplication mechanism!

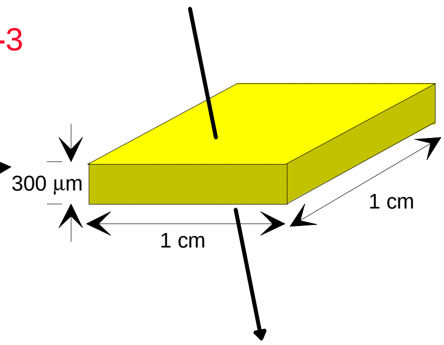
How to obtain a signal ?



In a pure intrinsic (undoped) material the electron density n and hole density p are equal. $n = p = n_i$

For Silicon: $n_i \approx 1.45 \cdot 10^{10}$ cm^{-3}

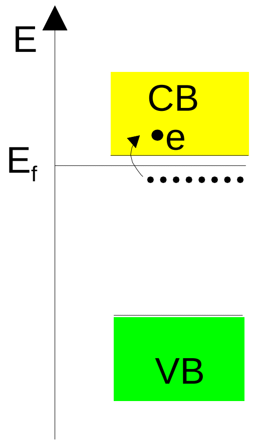
In this volume we have $4.5 \cdot 10^8$ free charge carriers, but only $3.2 \cdot 10^4$ e-h pairs produced by a M.I.P.

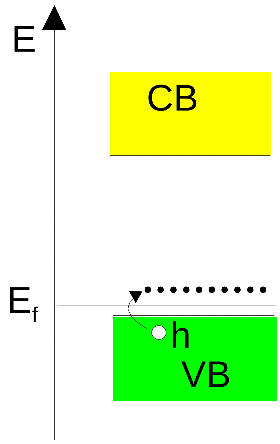


→ Reduce number of free charge carriers, i.e. deplete the detector

Most detectors make use of reverse biased p-n junctions

Doping

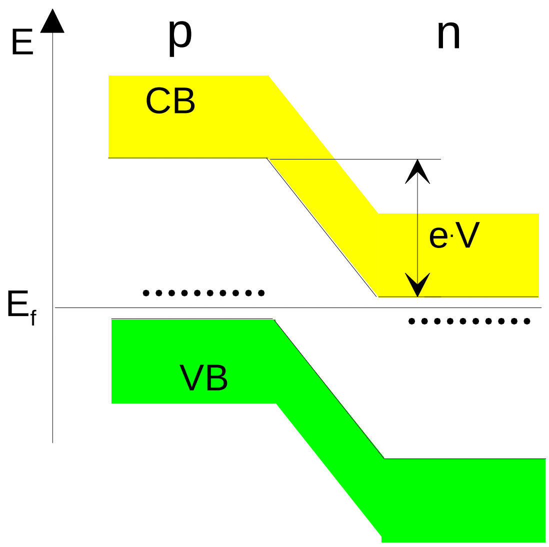




n-type: Add elements from Vth group, donors, e.g. As. Electrons are the majority carriers.

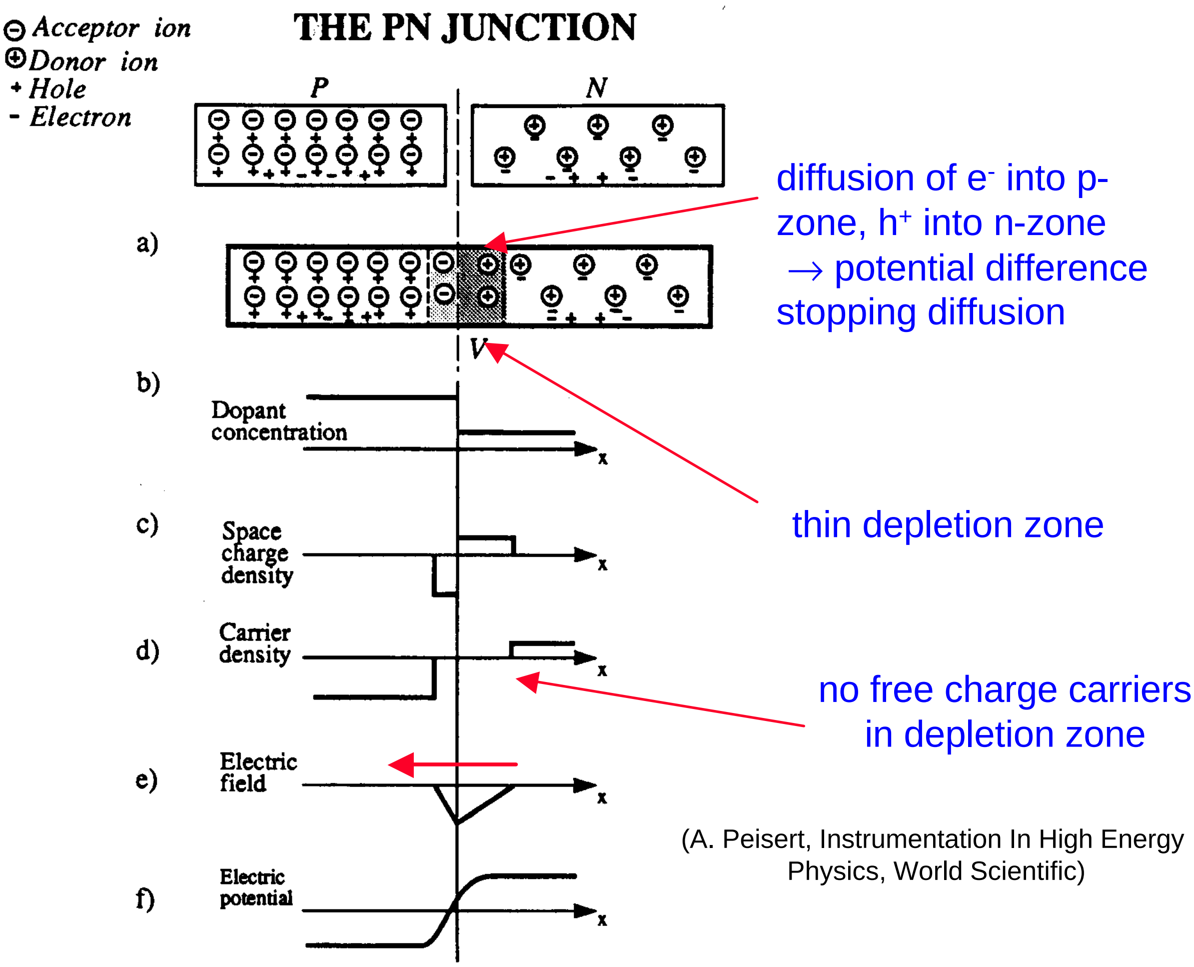
p-type: Add elements from IIIrd group, acceptors, e.g. B. Holes are the majority carriers.

	detector grade	electronics grade
doping concentration	10^{12} cm^{-3} (n) - 10^{15} cm^{-3} (p$^+$)	$10^{17(18)}$ cm^{-3}
resistivity	≈ 5 kΩ·cm	≈1 Ω·cm



pn junction

There must be a single Fermi level !
Deformation of band structure → potential difference.



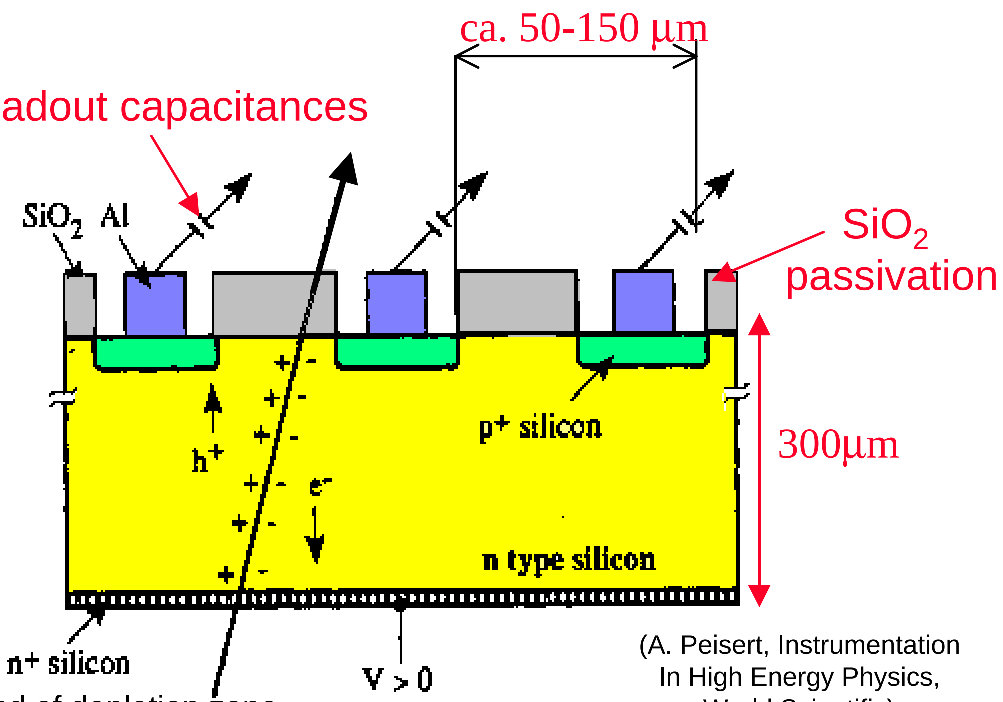
(A. Peisert, Instrumentation In High Energy Physics, World Scientific)

- Application of a reverse bias voltage (about 100V) → the thin depletion zone gets extended over the full junction → fully depleted detector.
- Energy deposition in the depleted zone, due to traversing charged particles or photons (X-rays), creates free e^--hole pairs.
- Under the influence of the E-field, the electrons drift towards the n-side, the holes towards the p-side → detectable current.

Spatial information by segmenting the p doped layer →

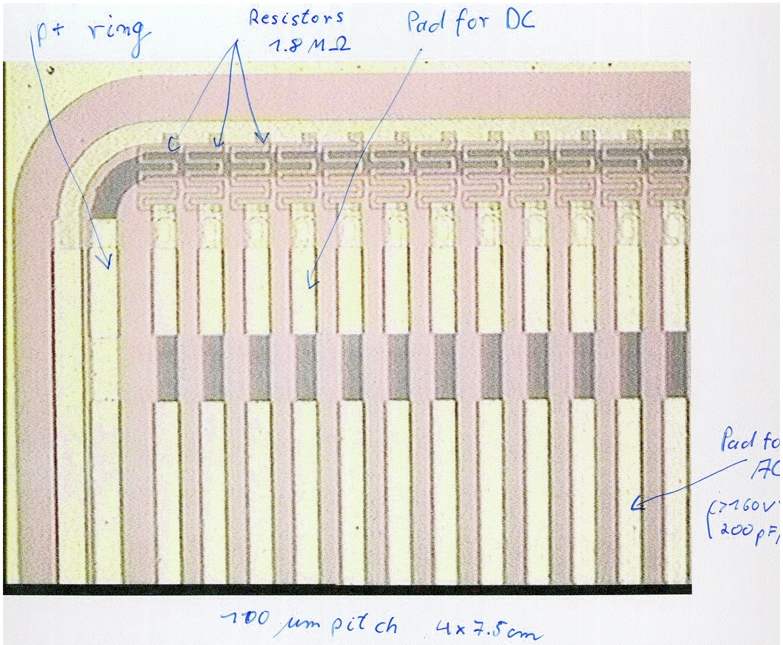
single sided microstrip detector.

Schematically !



defines end of depletion zone
+ good ohmic contact

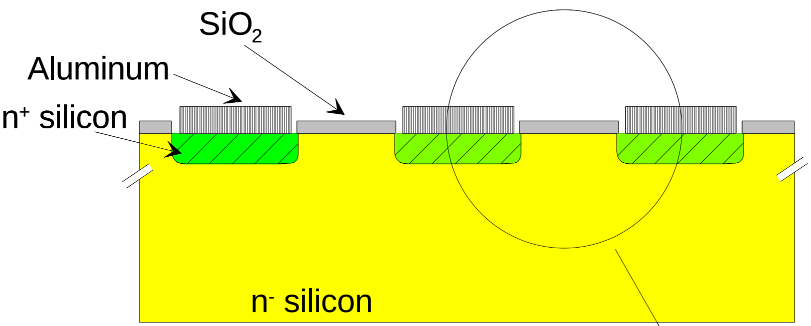
(A. Peisert, Instrumentation In High Energy Physics, World Scientific)



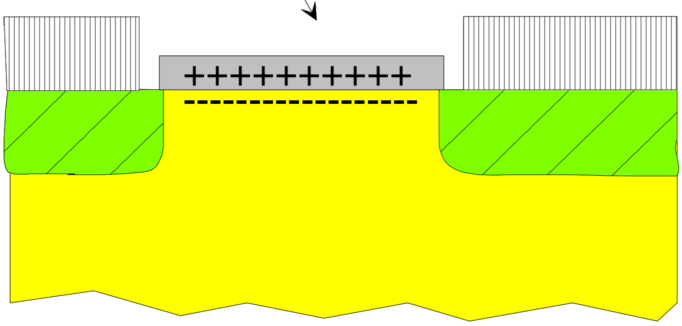
ALICE: Single sided micro strip prototype

Segmenting also the n doped layer → Double sided microstrip detector.

But:

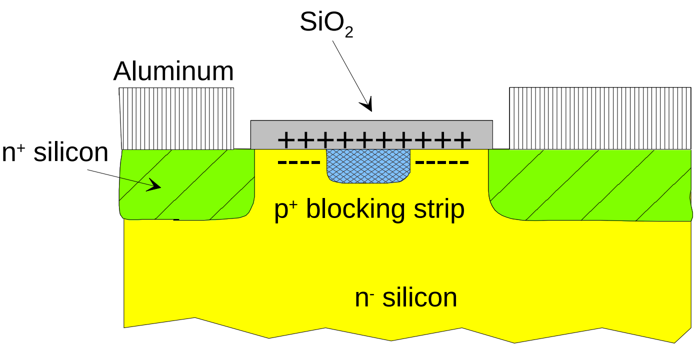


Positive charges in SiO_2 attract e^- in n^- layer. Short circuits between n^+ strips.

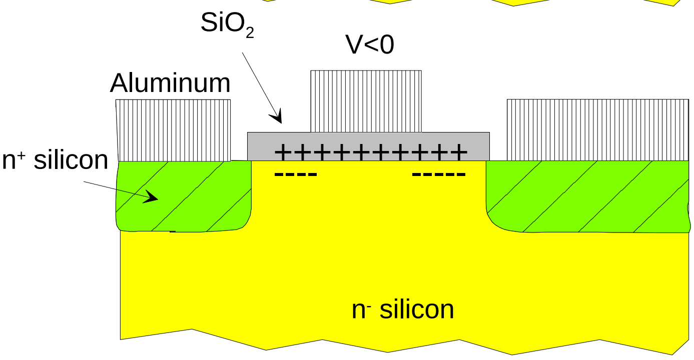


Two solutions:

Add p^+ doped blocking strips

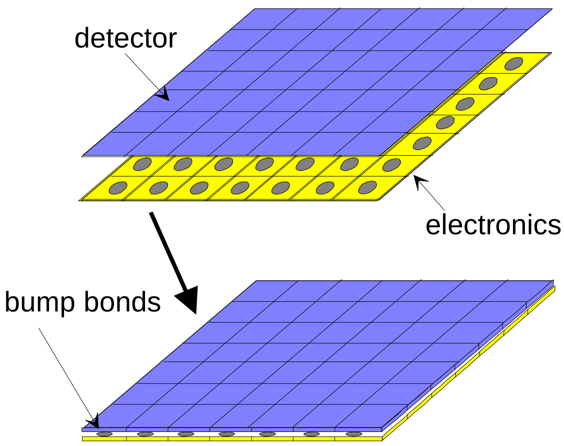


Add Aluminum layer on top of SiO_2
Negative biased MOS (metal oxide semiconductor) structure repelling e^-



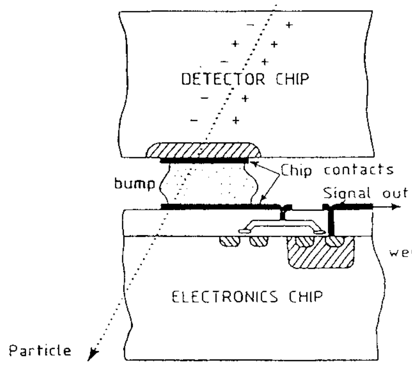
◆ Silicon pixel detectors

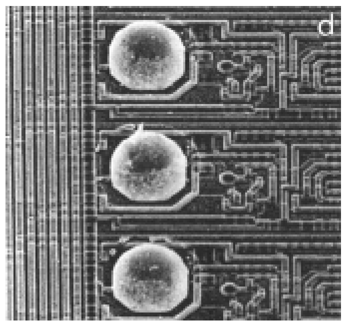
- Segment silicon to diode matrix
- also readout electronic with same geometry
- connection by bump bonding techniques



RD 19, E. Heijne et al., NIM A 384 (1994) 399

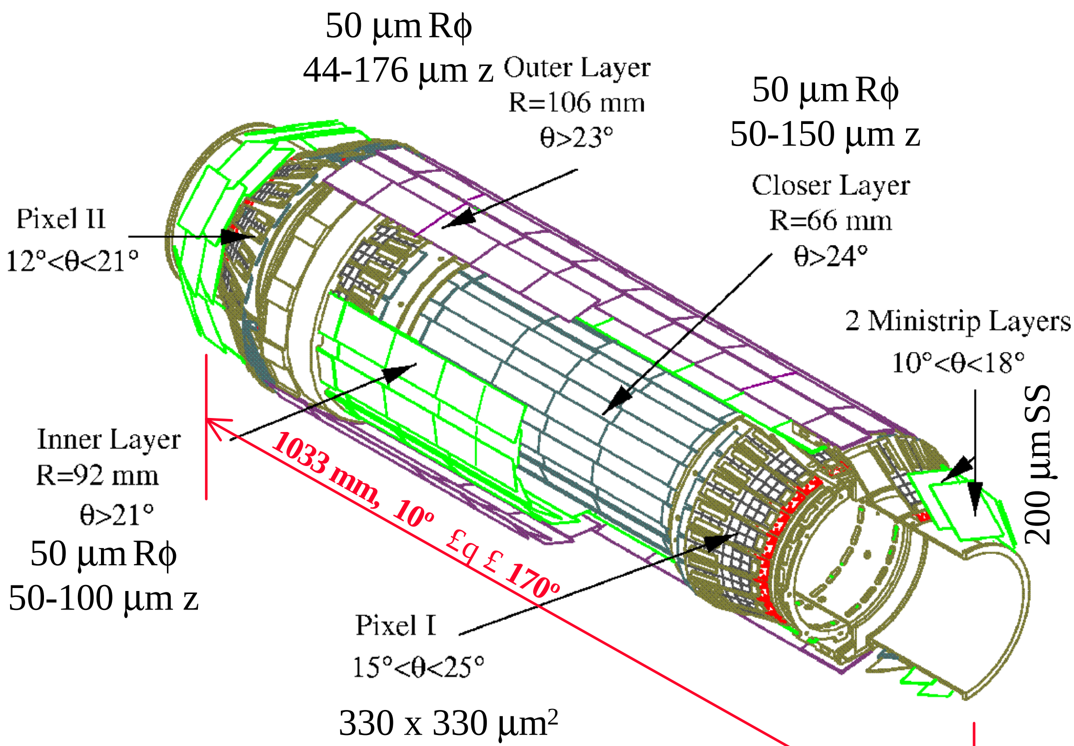
Flip-chip technique





- Requires sophisticated readout architecture
- First experiment WA94 (1991), WA97
- OMEGA 3 / LHC1 chip (2048 pixels, 50x500 μm^2) (CERN ECP/96-03)
- Pixel detectors will be used also in LHC experiments (ATLAS, ALICE, CMS)

◆ The DELPHI micro vertex detector (since 1996)

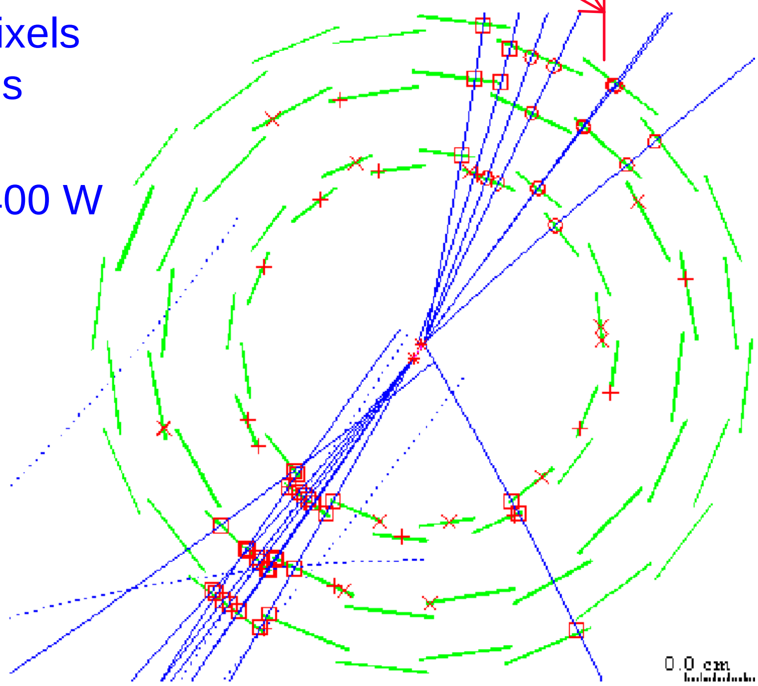


readout channels
ca. 174 k strips, 1.2 M pixels
total readout time: 1.6 ms

Total dissipated power 400 W
→ water cooling system

Hit resolution in barrel part ≈ 10 µm
Impact parameter resolution (rϕ)

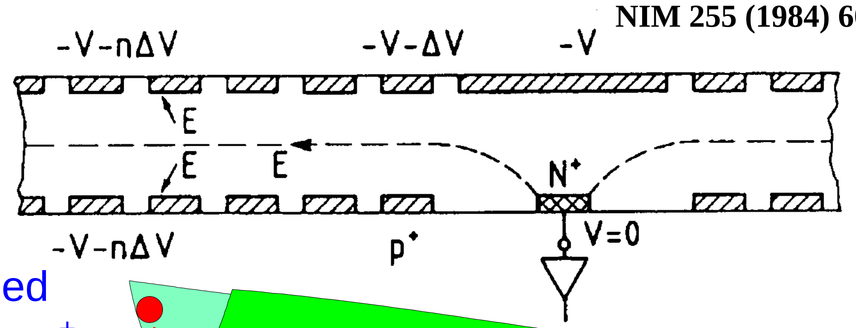
$$28mm \oplus 71/\left(p\sin^{\frac{3}{2}} q\right)$$



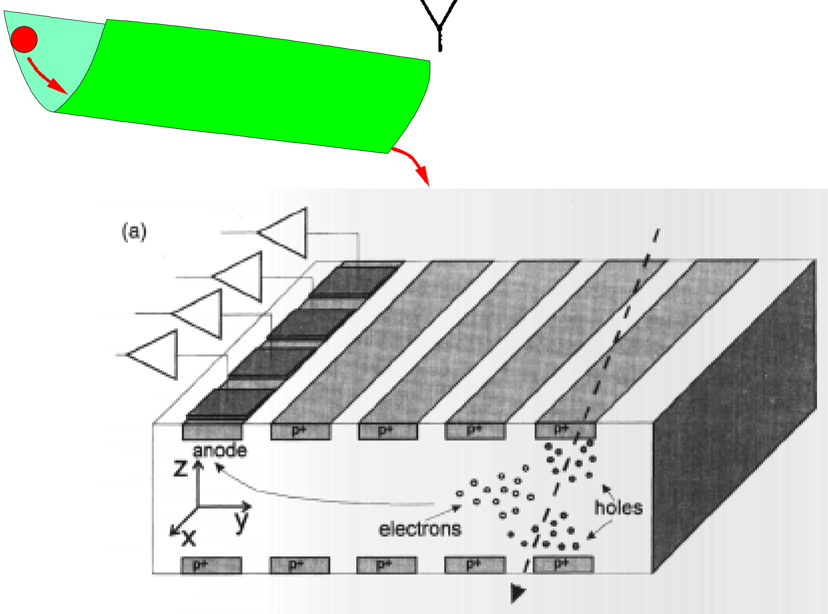
◆ Silicon drift chamber

(First proposed by
E. Gatti and P. Rehak,
NIM 255 (1984) 608)

principle:



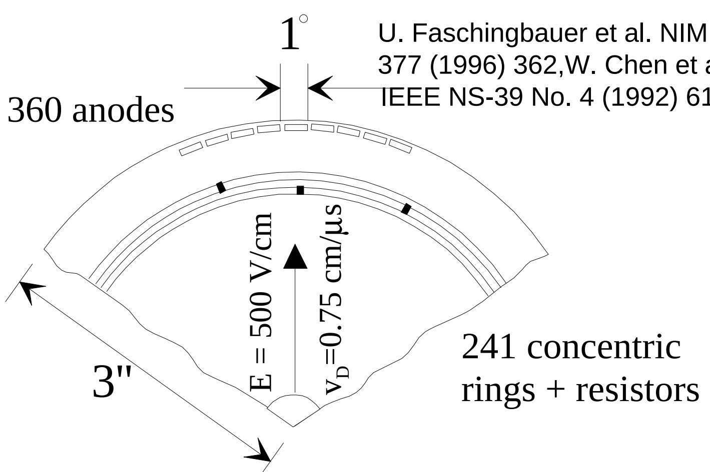
Define graded potentials on p^+ implants.
Measure arrival time at n^+ strip



Segmentation of n^+ strip into pads
→ 2-D readout

CERES (NA45):
doublet of 3'' radial Si drift chambers

Intrinsic resolution:
$\sigma_R \approx 20\ \mu m$, $\sigma_\phi \approx 2$ mrad

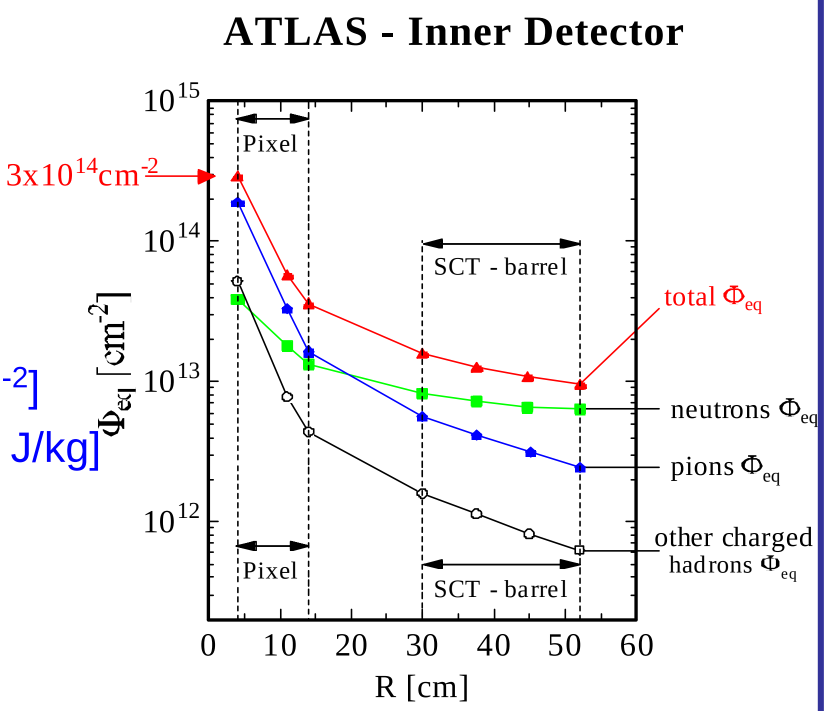


U. Faschingbauer et al. NIM A 377 (1996) 362, W. Chen et al, IEEE NS-39 No. 4 (1992) 619

The whole charge is collected at one small collecting electrode. Small capacity (100 fF) → low noise.

Radiation damage in silicon sensors

A major issue for
LHC detectors !



Some definitions

- fluence: $\Phi = N/A$ [cm^{-2}]
- dose: $D = E/m$ [Gy = J/kg]

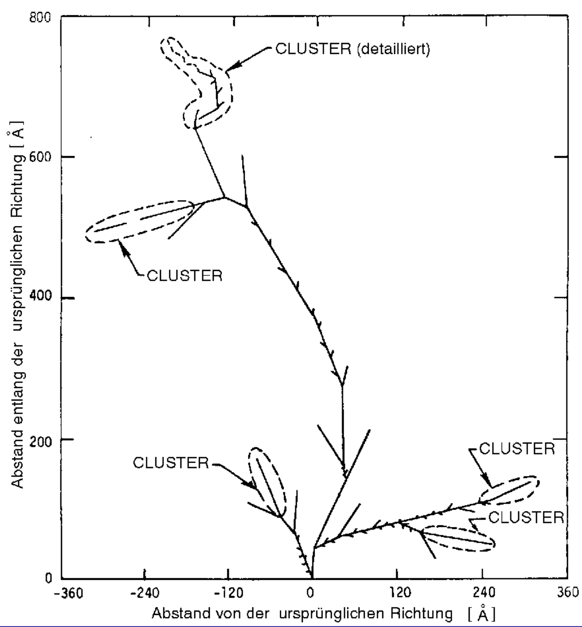
However: Specification of absorbed dose / fluence is not sufficient. Damage depends both on particle type (e,π,n,γ..) and energy !

Many effects and parameters involved (not all well understood)!

Damage caused by
Non Ionising Energy Loss

Bulk effects: Lattice damage, vacancies and interstitials.

Surface effects: Oxide trap charges, interface traps.

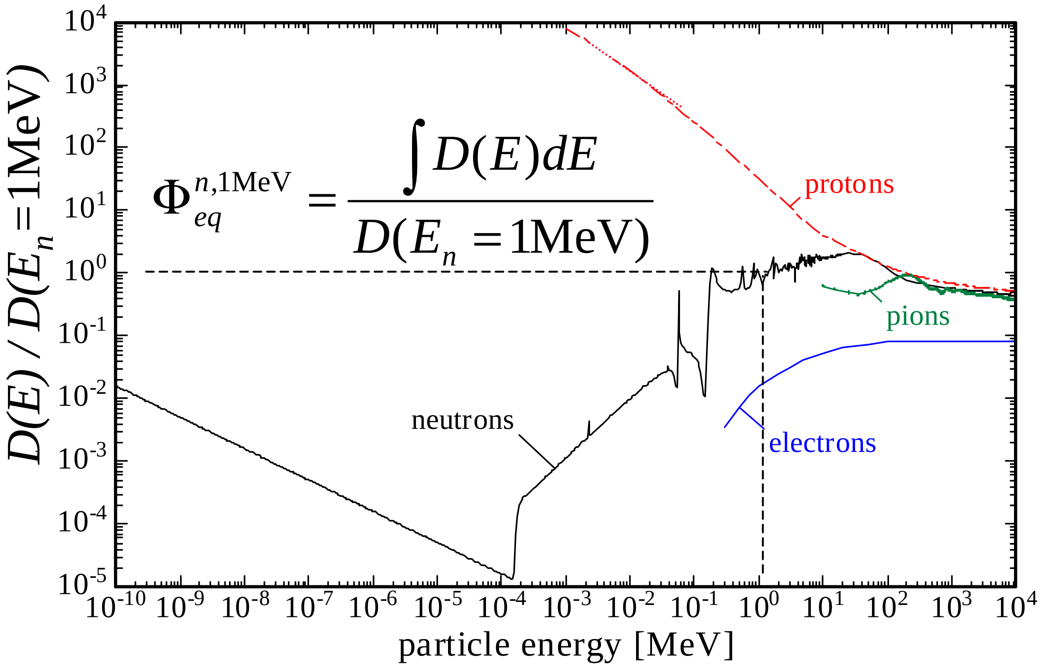


NIEL hypothesis (not fully valid !):

damage ∝ energy deposition in displacing collisions

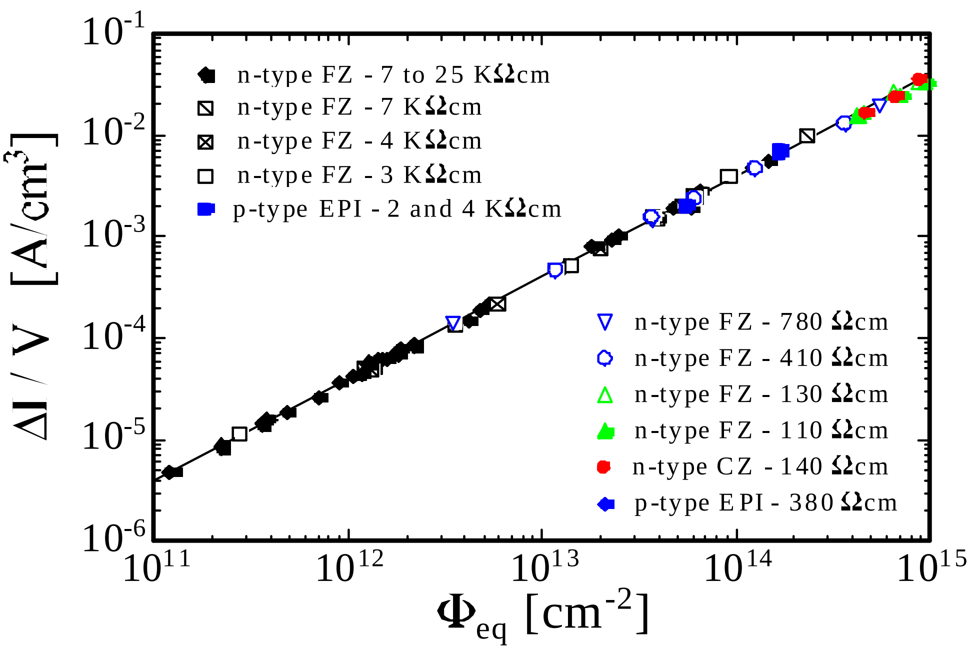
Rel. damage function

(normalized to neutrons of 1 MeV)

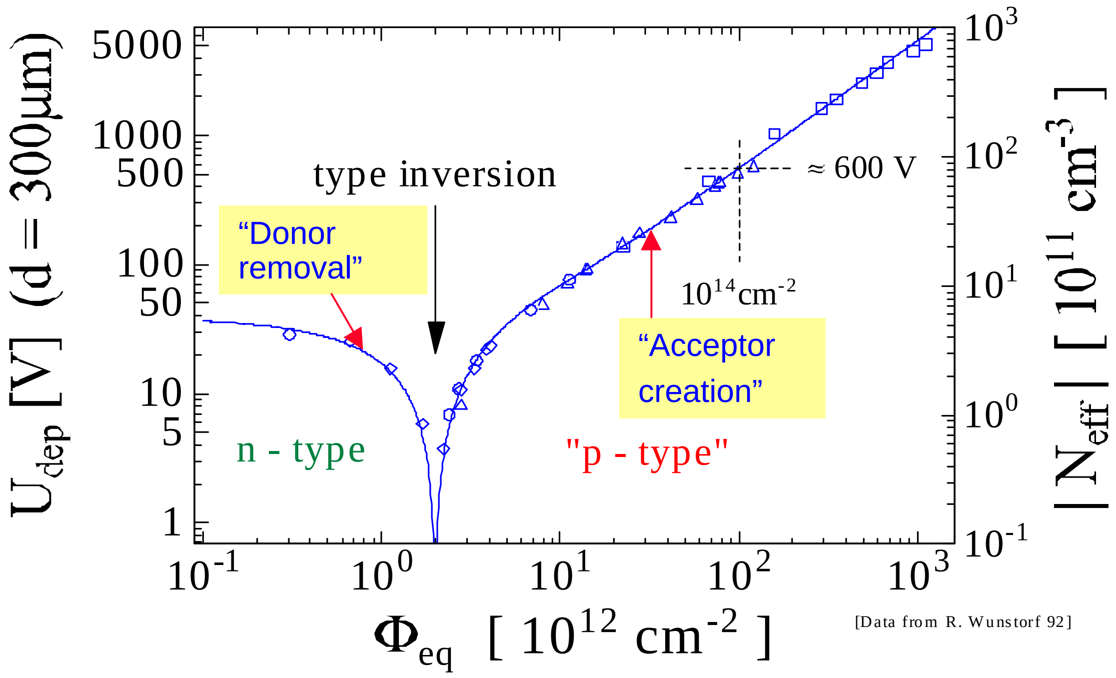


Main radiation induced macroscopic changes:

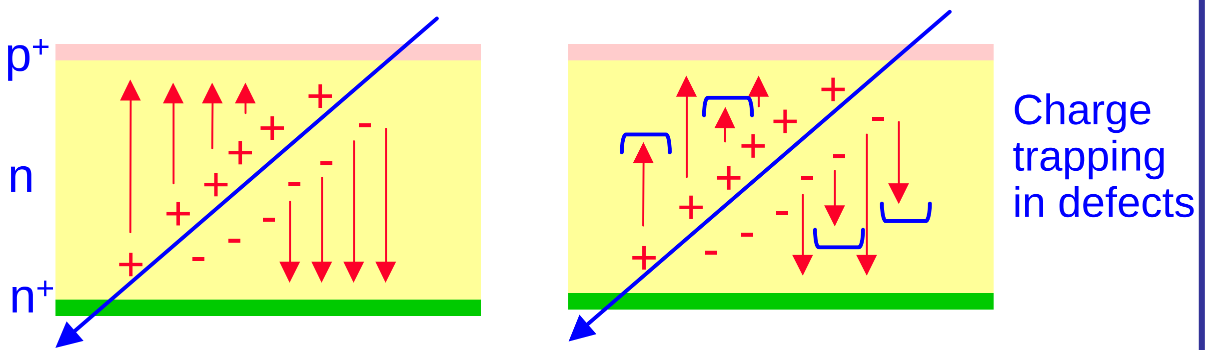
1. Increase of sensor leakage current



2. Change of depletion voltage. Very problematic.



3. Decrease of the charge collection efficiency



How to cope with the radiation damage ?

Possible strategies:

- Geometrical: build sensors such that they stand high depletion voltage (500V)
- Environmental: keep sensors at low temperature (≈ -10ºC).

→ Slower reverse annealing. Lower leakage current.

More advanced methods

- Defect engineering.

ROSE / RD48
http://cern.ch/rd48

Introduce specific impurities in silicon, to influence defect formation. Example Oxygen.

Diffusion Float Zone Oxygenated (DOFZ) silicon used in ATLAS pixel detector. Gain a factor 3.

- Cool detectors to cryogenic temperatures (optimum around 130 k)

RD39
http://cern.ch/rd39

"zero" leakage current, good charge collection (70%) for heavily irradiated detectors ($1 \cdot 10^{15}$ n/cm^2). "Lazarus effect"

- New materials

RD42
http://cern.ch/rd42

Diamond. Grown by Chemical Vapor Deposition. Very large bandgap (≈ 6 eV). No doping and depletion required! Material is still rather expensive. Still more R&D needed.

- New detector concepts

"3D detectors" → "horizontal" biasing
faster charge collection
but difficult fabrication process