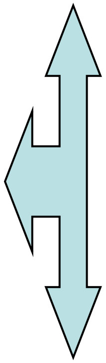
Detectors in Nuclear and High Energy Physics

RHIG “summer student meeting”

June 2014

“Physics” or Knowledge of Nature

- Experimental Data
- Analysis
- Theory



(application)

Experimental Data

- Initial Conditions / Source / State
  - ➢ Accelerator beam(s) (e, μ, p, A, A*, n, γ, ν, π, K, Σ, …) ($\vec{P}$, E, $\vec{X}$, t, …)
  - ➢ Targets
  - ➢ R/A source
  - ➢ Polarization
- Result (“event”)

  -- N of particles, $\vec{P}$, E, $\vec{X}$, PiD, t, …   ($K^0 \rightarrow \pi^0 + \nu + \nu$)
- “Passive equipment”

  -- magnets, E and B equipment, reflectors, crystal, collimator, …
- Detectors

  -- to detect (measure) a particle interaction with the matter
- FEE, DAQ, Computing, Trigger, On-line, …

Particle has to interact to be detected

- Interactions: EM, Strong, Weak, …
- Detectors “perturb, disturb, destroy, …”, and “transfer the interaction result” to measurable value.

Any Detector should be:

-- studied (R&D, response simulation)

-- constructed (“mass production”)

-- calibrated (response, alignment)

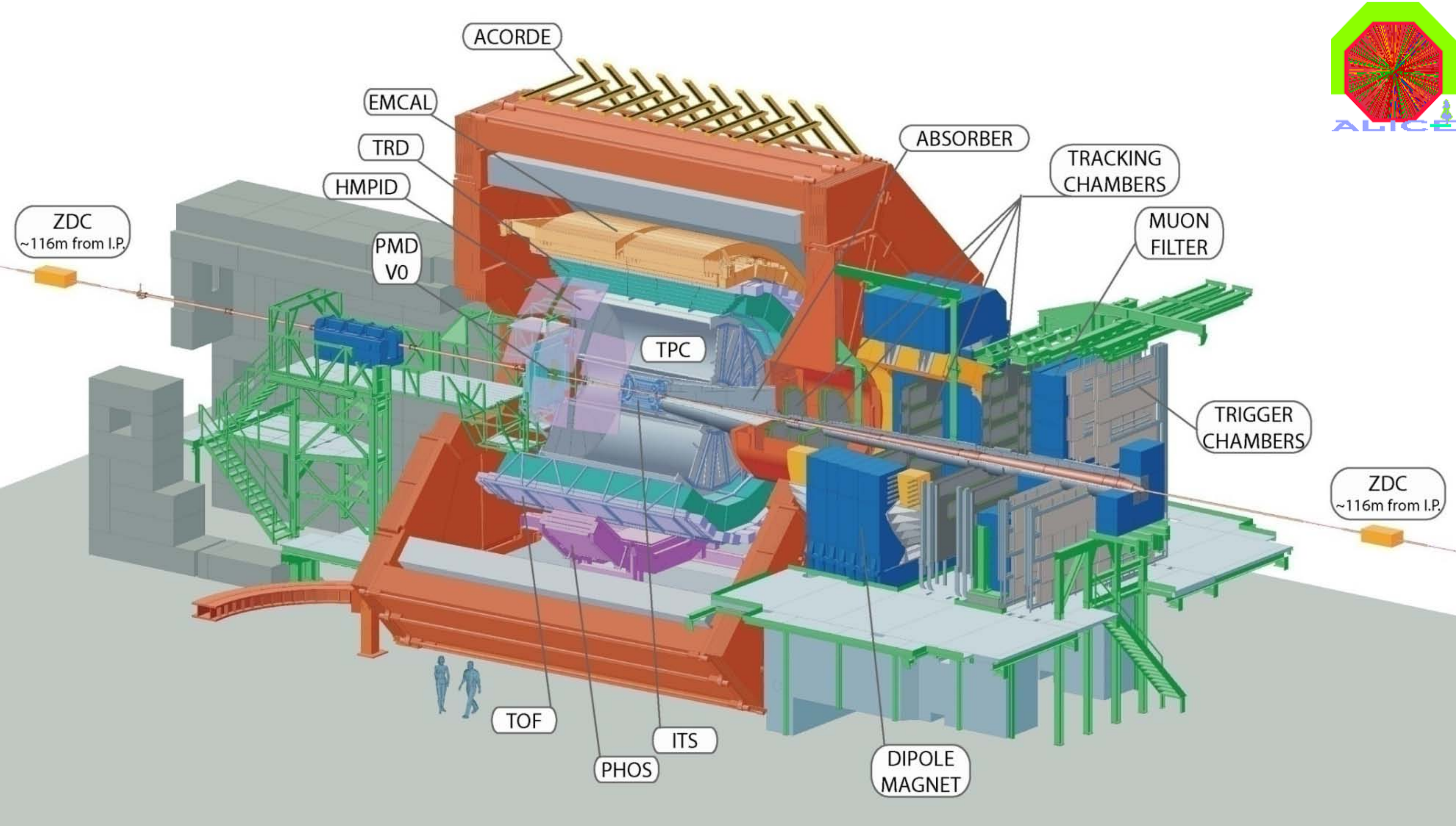
-- controlled (quality, cooling, aging, radiation damage, …)

Conventional Classification

- Vertex
- Tracking
- PiD
- Calorimeter

- Detector response simulation
- Experimental Set-Up; simulation and selection
- To-day and future experiments

The ALICE Heavy Ion Experiment



Tracking Detectors (in a combination with Magnetic Field)

- As charged particles pass through a tracking detector, they deposit energy (usual by ionization) which can be detected

- ➢ - positions in space of energy deposits in discrete detector elements (“hits”; 1d, 2d, 3d)
- ➢ - track finding
- ➢ - momentum reconstruction
- ➢ - points of origin (“vertex”) and initial directions

We will discuss different tracking detectors:
hits precision, detector thickness, timing (rate), triggering and on-line, radiation hardness, aging, “environment” sensitivity (t^0, p, cost …)

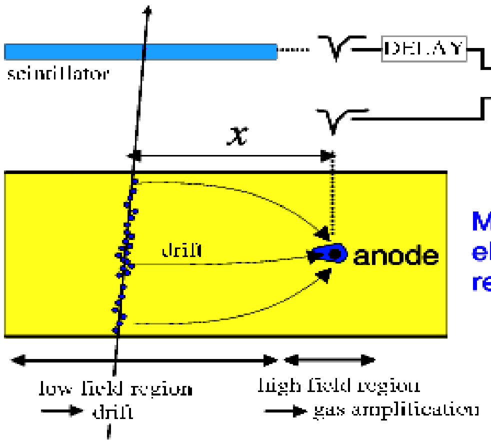
Tracking Detectors

- Gas Detectors
  - -- general gas properties
  - -- gas amplification and “signal”
  - -- MWPC, Drift Det, RPC, MicroPattern Det., …

- Solid state Detectors

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.

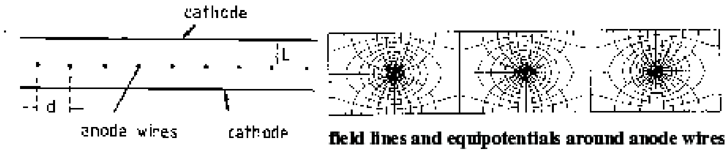
$$x = \int v_D(t)\,dt$$

What happens during the drift towards the anode wire ?

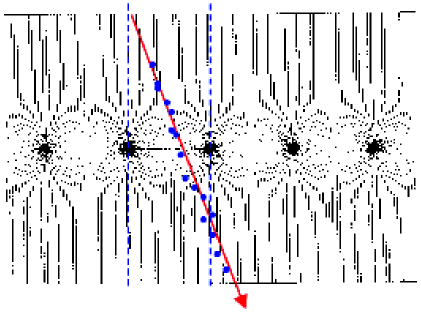
- **Diffusion ?**
- **Drift velocity ?**

Multi wire proportional chamber (MWPC)

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



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 $\sigma_x \approx \frac{d}{\sqrt{12}}$ (d=1mm, σ_x=300 µm)

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

Drift and diffusion in gases

No external fields:

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

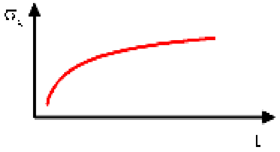
$$\varepsilon \quad \frac{3}{2}kT \approx 40\ \text{meV}$$

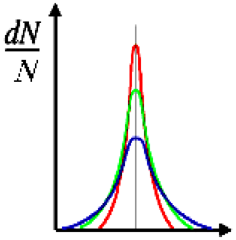
Undergoing multiple collisions, an originally localized ensemble of charges will diffuse

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

D: diffusion coefficient

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



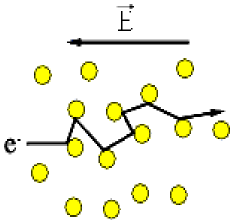


External electric field:

"stop and go" traffic due to scattering from gas atoms

→ drift

$$v_D = \mu \bar{E} \qquad \mu \quad \frac{e\tau}{m} \ \text{(mobility)}$$



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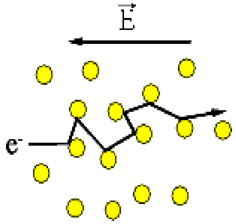
in the equilibrium ...

$$\frac{x}{v_D\tau}\lambda_c \varepsilon = eEx$$



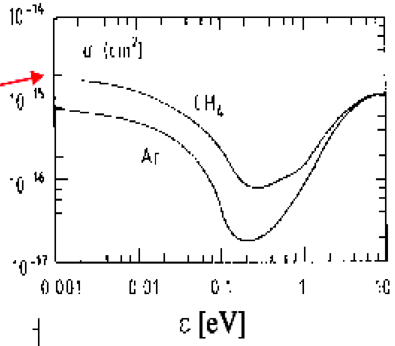
λ_c : fractional energy loss / collision

$\tau \quad \frac{1}{N\sigma v}$ v: instantaneous velocity

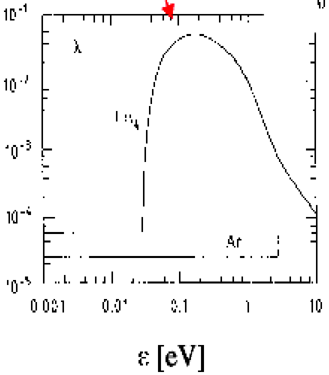
$$\Rightarrow v_D^2 = \frac{eE}{mN\sigma}\sqrt{\frac{\lambda}{2}}$$

σ − σ(ε) !

λ = λ(ε) !



(B. Schmidt, thesis, unpublished, 1986)



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

Ion drift velocities: ca. 1000 times smaller

Drift and diffusion in gases

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

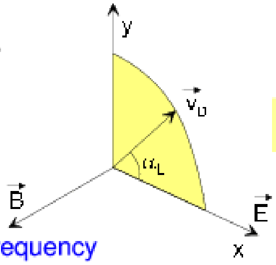
Look at 2 special cases:

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

$\tan \alpha_L = \omega \tau$

α_L: Lorentz angle

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



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

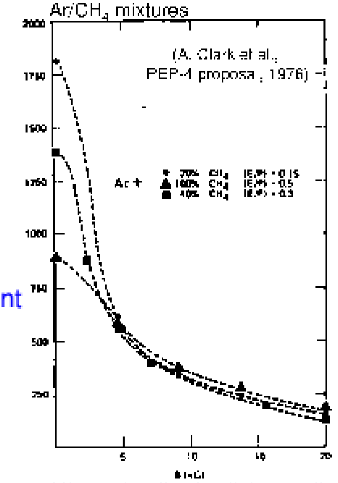
Special case: $\vec{E} \parallel \vec{B}$

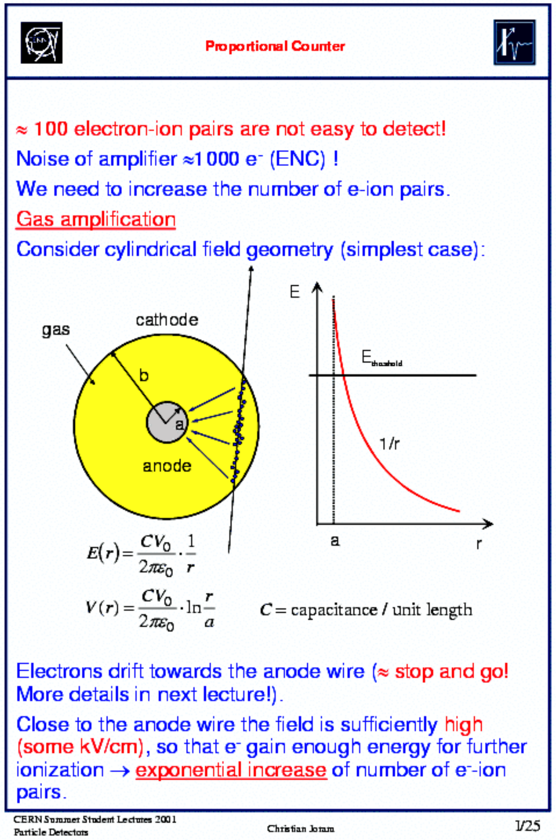
The longitudinal diffusion (along B-field) is unchanged.
In the transverse projection the electrons are forced on circle segments with the radius v_T/ω.
The transverse diffusion coefficient appears reduced

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

Very useful… see later !

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





Proportional Counter

≈ 100 electron-ion pairs are not easy to detect!

Noise of amplifier ≈1000 e⁻ (ENC) !

We need to increase the number of e-ion pairs.

Gas amplification

Consider cylindrical field geometry (simplest case):

$$E(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \frac{1}{r}$$

$$V(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \ln\frac{r}{a} \qquad C = \text{capacitance / unit length}$$

Electrons drift towards the anode wire (≈ stop and go! More details in next lecture!).

Close to the anode wire the field is sufficiently high (some kV/cm), so that e⁻ gain enough energy for further ionization → exponential increase of number of e⁻-ion pairs.

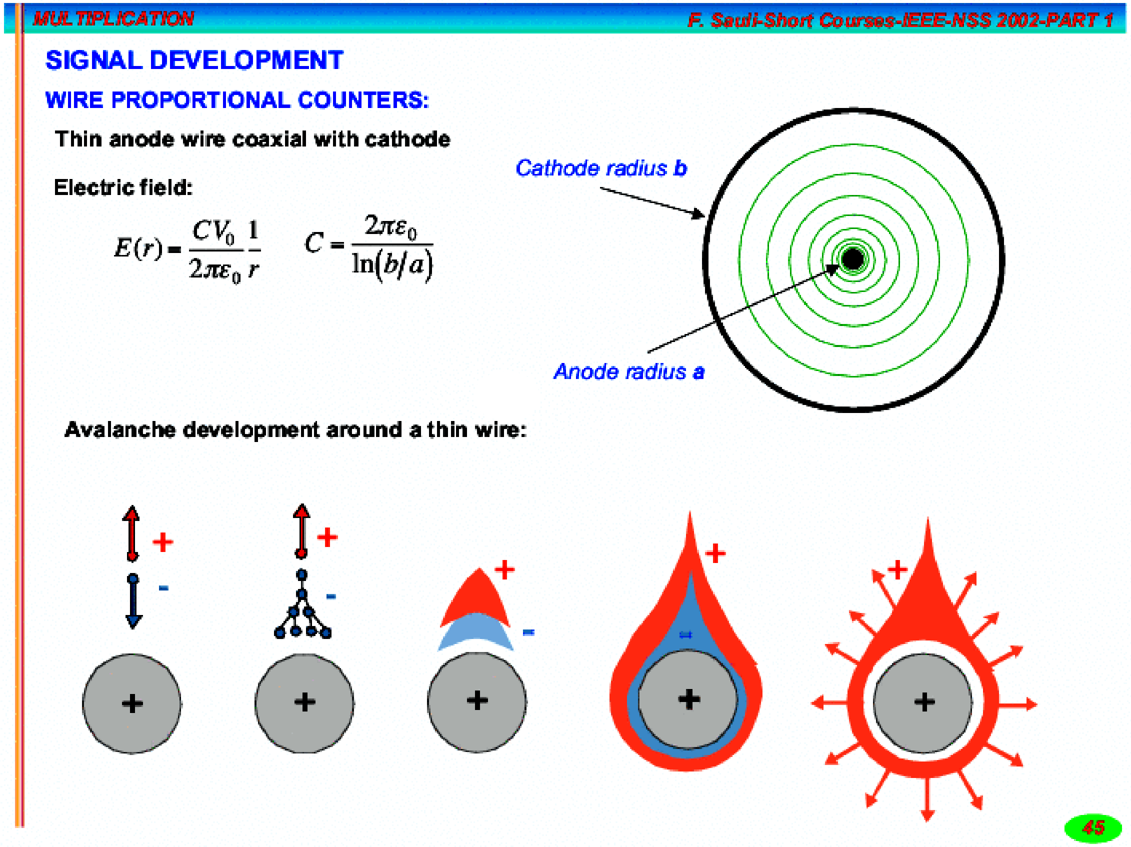
CERN Summer Student Lectures 2001
Particle Detectors

Christian Joram

1/25

Avalanche formation within
a few wire radii (~ 100 µm)
and within t < 1. ns!
Very short distance to drift.

But ions (from avalanche) have
to drift back to Cathode – long
distance (~ 3 mm) and drift time
~ k*100 µs.



MULTIPLICATION

F. Sauli-Short Courses-IEEE-NSS 2002-PART 1

SIGNAL DEVELOPMENT

WIRE PROPORTIONAL COUNTERS:

Thin anode wire coaxial with cathode

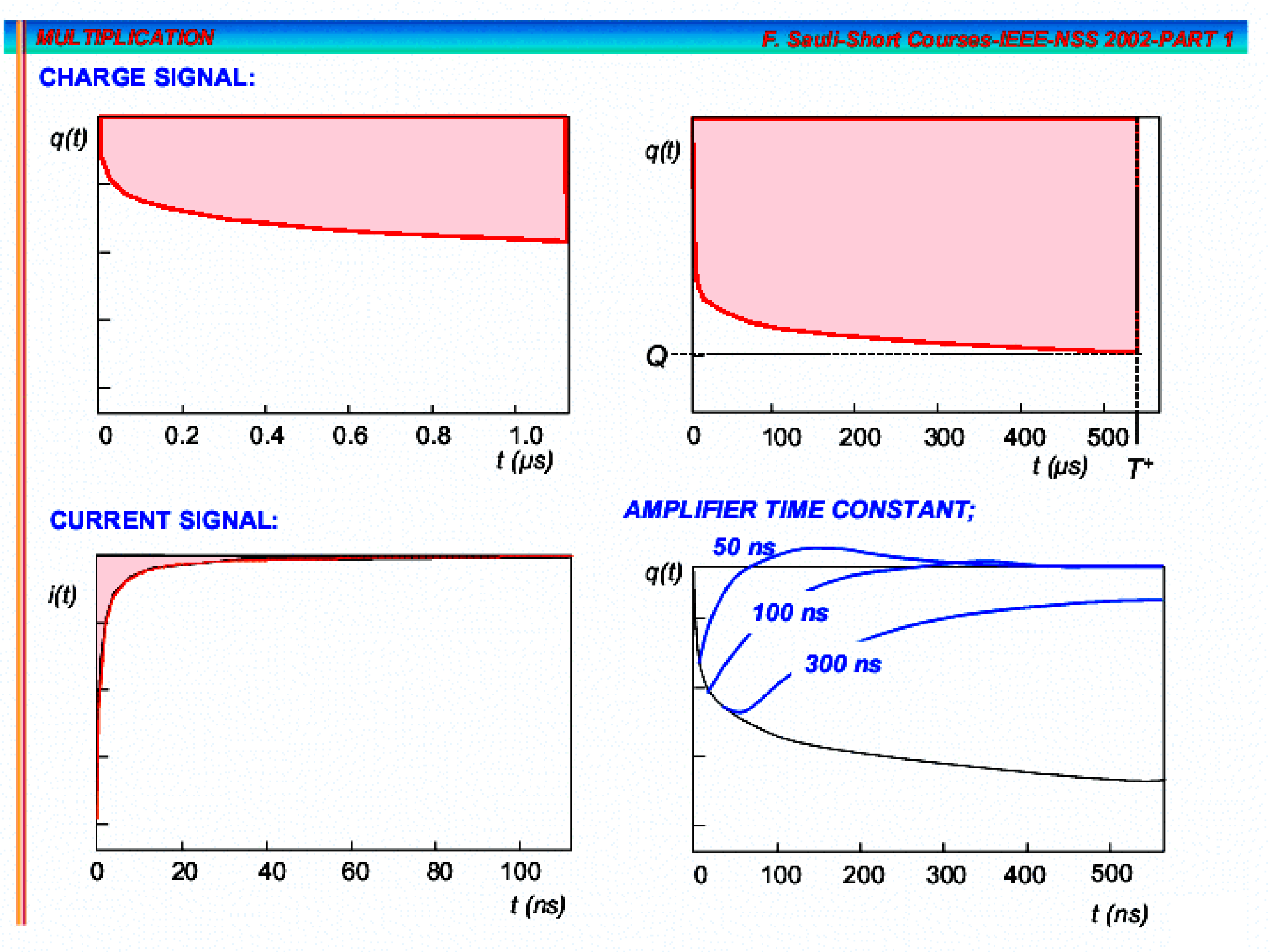
Electric field:

$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r} \qquad C = \frac{2\pi\varepsilon_0}{\ln(b/a)}$$

Avalanche development around a thin wire:

45

“Oscilloscope picture”



MULTIPLICATION

F. Sauli-Short Courses-IEEE-NSS 2002-PART 1

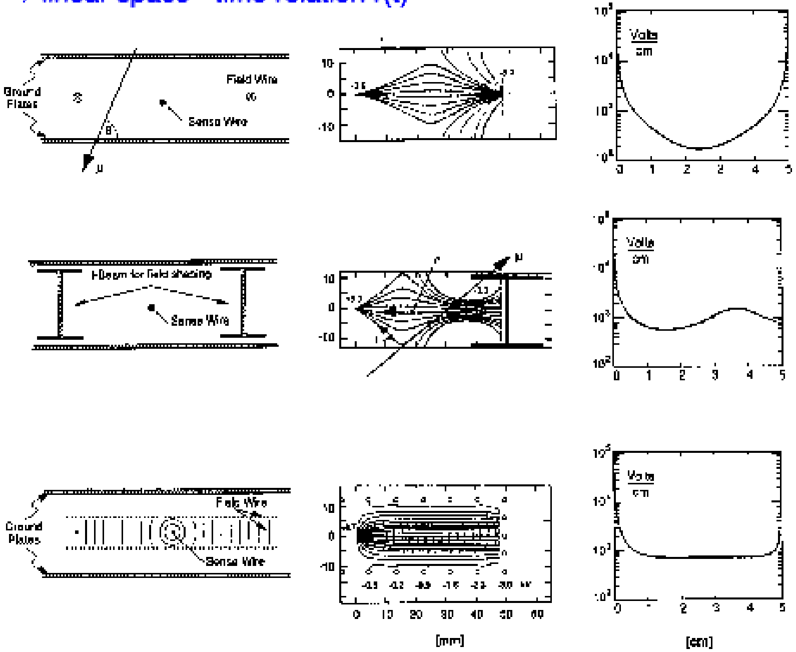
CHARGE SIGNAL:

CURRENT SIGNAL:

AMPLIFIER TIME CONSTANT;

Some planar drift chamber designs

Optimize geometry → constant E-field
Choose drift gases with little dependence $v_D(E)$
→ linear space - time relation r(t)



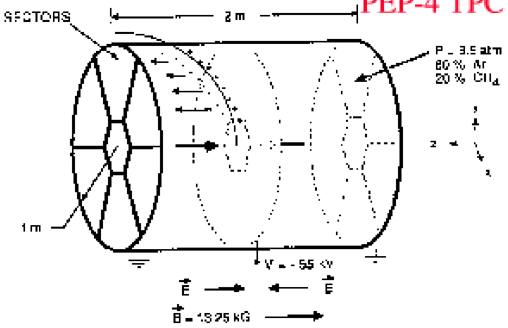
(U. Becker, in: Instrumentation in High Energy Physics, World Scientific)

The spatial resolution is not limited by the cell size
→ less wires, less electronics,
less support structure than in MWPC.

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 →
LASER calibration +
p,T corrections

Drift over long distances → very good gas quality required

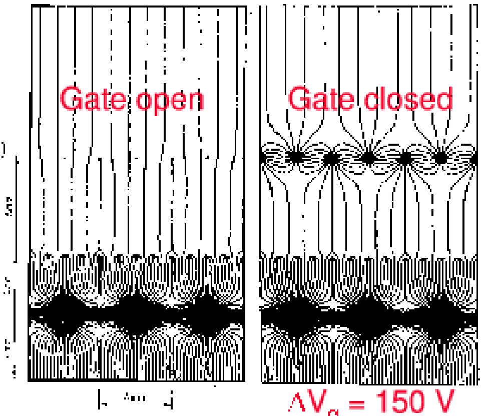
Space charge problem from positive ions, drifting back to midwall → gating

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 μm
σ_z = 740 μm
(isolated leptons)

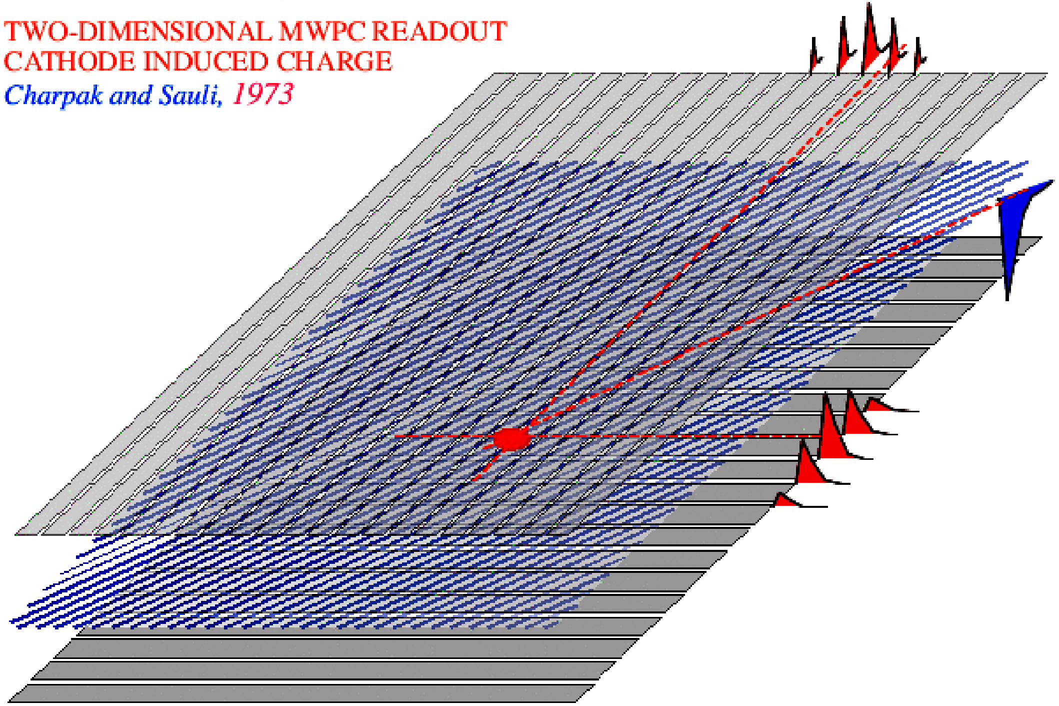


ΔV_g = 150 V

2-D READOUT

TWO-DIMENSIONAL MWPC READOUT
CATHODE INDUCED CHARGE

Charpak and Sauli, 1973



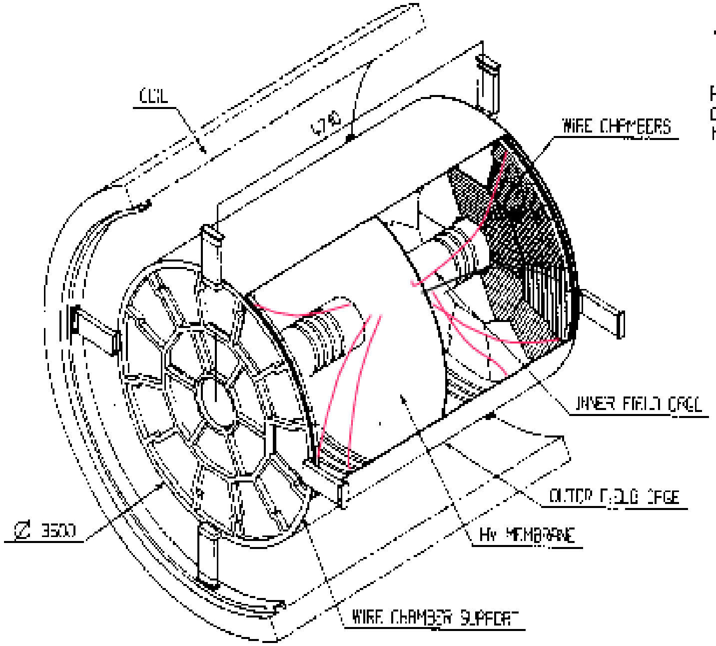
⇨ *E. Gatti et al, Optimum geometry for strip cathodes … Nucl. Instr. and Meth. 163(1979)83*

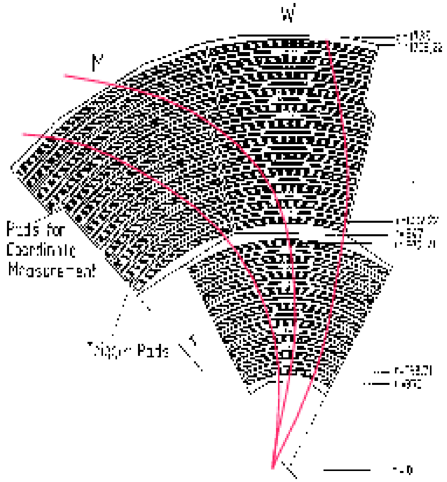
Space accuracy: 40 - 70 µm

“Chevron” and “floating strips” approaches

3-D (points in space) read-out; Drift & Wires & Multi-Pads, Low-Mass

TIME PROJECTION CHAMBER (TPC)
D. NYGREN, LBL ~1976



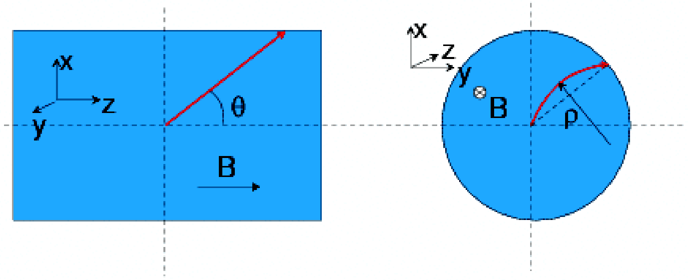


ALEPH TPC AT CERN-LEP:

As a “future step” (e+e-LC):
B=4. T, σ=150 μm, n=100
$d(p_t) / p_t = 2 \times 10^{-5}\, p_t$

Momentum Measurement (backup)

Momentum measurement in experiments with solenoid magnet:



$$p_T = p \sin\theta$$

polar angle has to be determined from a straight line fit x=x(z).

N equidistant points with error *σ(z)*

$$\sigma(\theta)\big|^{meas.} = \frac{\sigma(z)}{L}\sqrt{12(N-1)/(N(N+1))}$$

+ multiple scattering contribution….

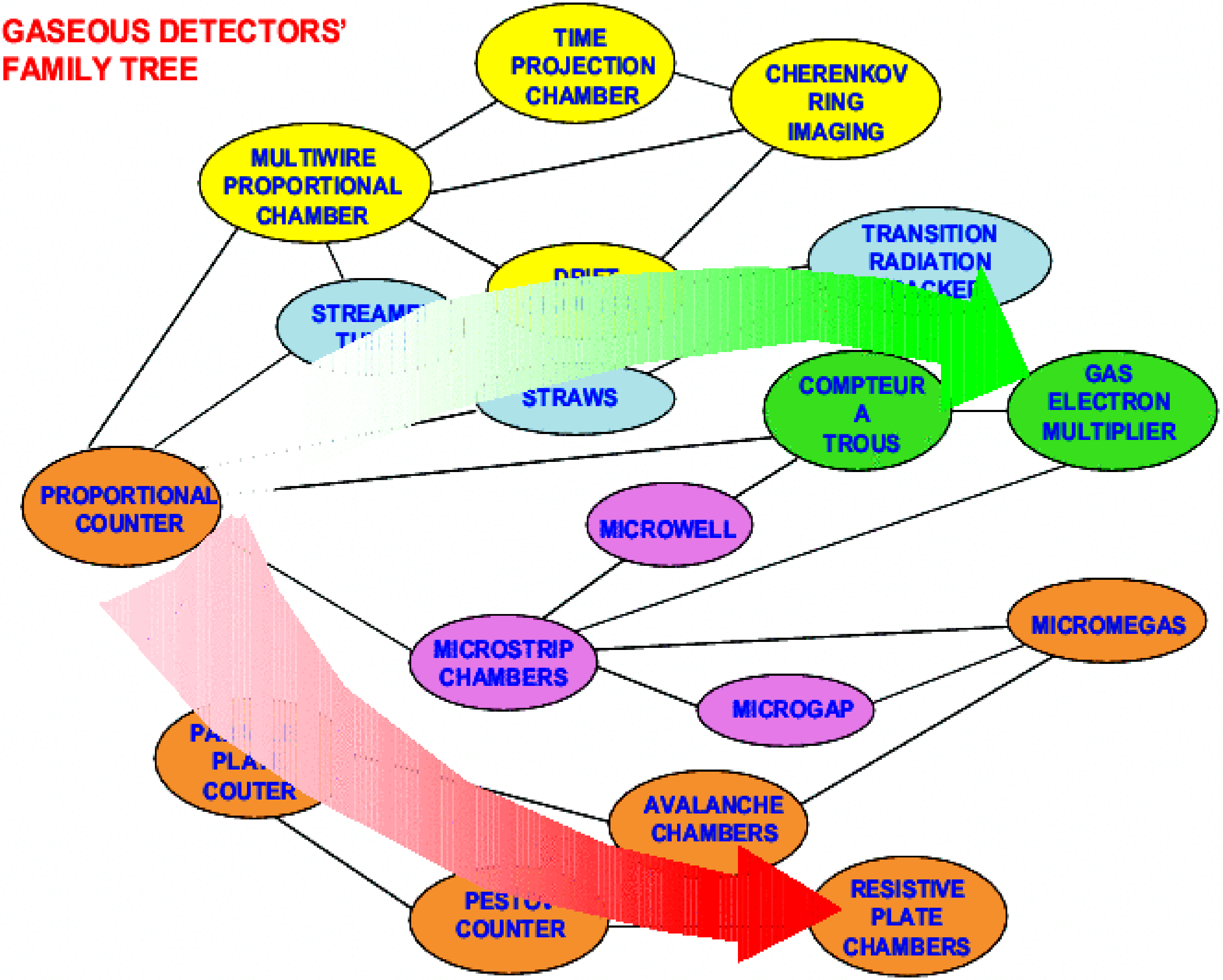
normally small

In practical cases: $\frac{\sigma(p)}{p} \approx \frac{\sigma(p_T)}{p_T}$

In summary:

$$\boxed{\frac{\sigma(p)}{p}\bigg|^{meas.} \propto \frac{\sigma(x)\cdot p}{BL^2}\frac{1}{\sqrt{N}}}$$

GASEOUS DETECTORS' FAMILY TREE



TIME PROJECTION CHAMBER

CHERENKOV RING IMAGING

MULTIWIRE PROPORTIONAL CHAMBER

TRANSITION RADIATION TRACKER

DRIFT

STREAMER TU

STRAWS

COMPTEUR A TROUS

GAS ELECTRON MULTIPLIER

PROPORTIONAL COUNTER

MICROWELL

MICROMEGAS

MICROSTRIP CHAMBERS

MICROGAP

PA PLA COUTER

AVALANCHE CHAMBERS

PESTO COUNTER

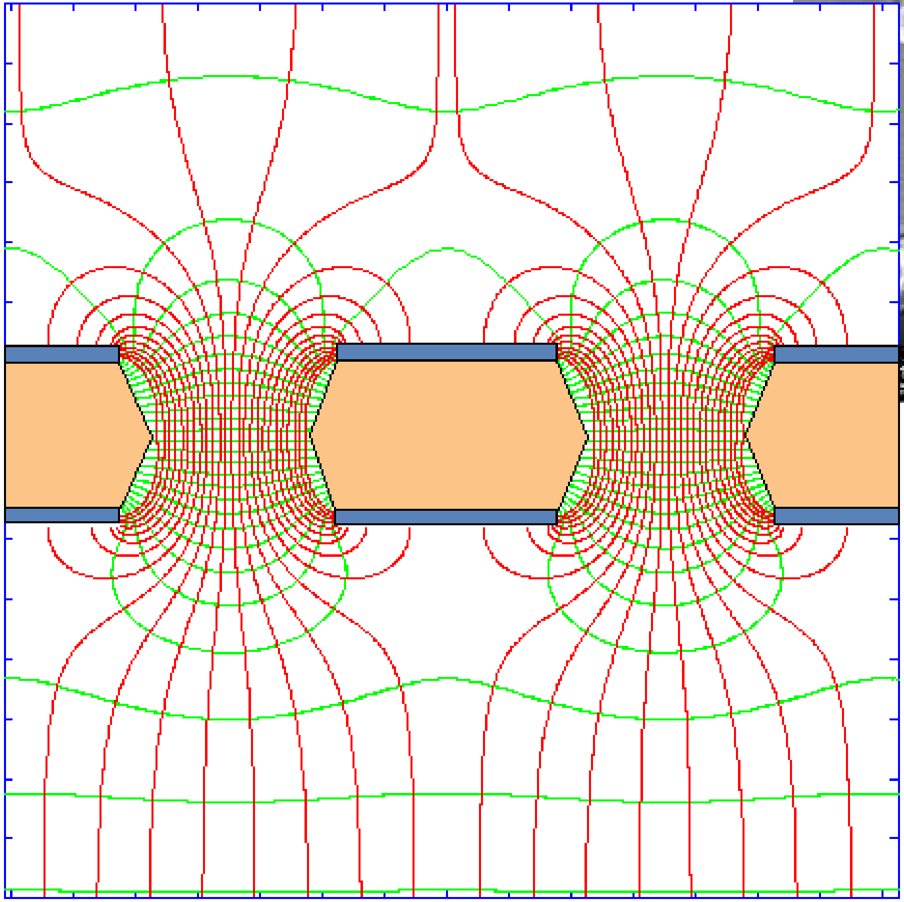
RESISTIVE PLATE CHAMBERS

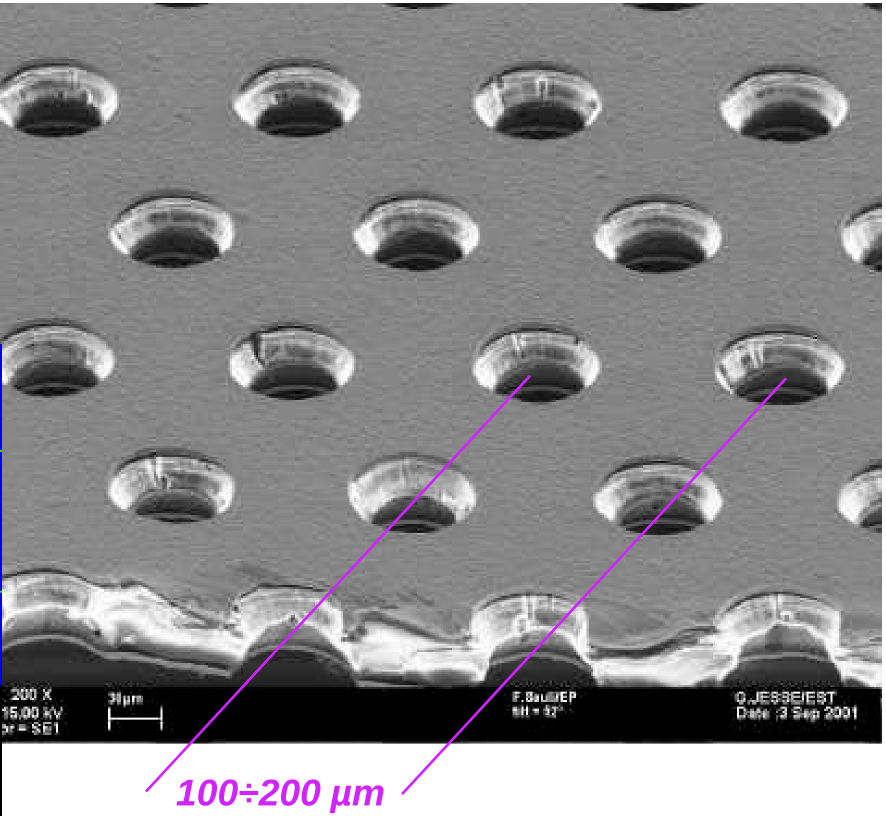
But, “Sun has spots”

- in MWPC the position of the electrodes can be distorted by electrostatic and gravitational forces
- an entire sector of an MWPC is disabled when a wire breaks and short-cuts others
- a strong frame is needed in MWPC to maintain the tension forces of the wires
- the wire length is limited (L3 Muon Chambers)
- the possible distortion of the wire position limits the wire spacing to a minimum distance of 1 mm, this limits position resolution and time shaping. Moreover, as the ions are not removed quickly enough, the occurrence of space charge hampers full avalanche development at count rates above 10^2-10^3 counts/sec/mm^2.

GEM

Thin, metal-coated polymer foil with high density of holes:





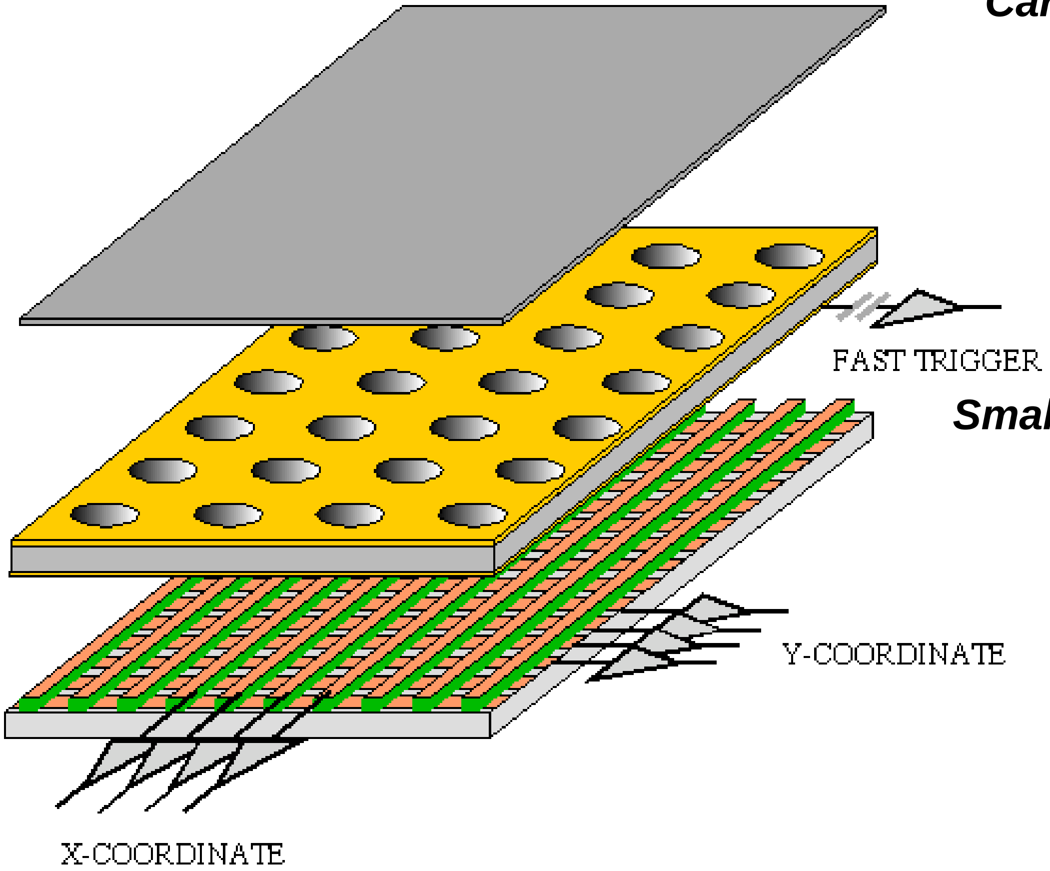
100÷200 µm

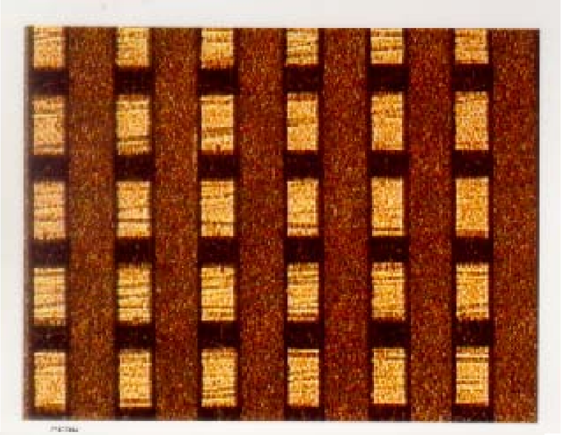
Typical geometry:
5 µm Cu on 50 µm Kapton
70 µm holes at 140 mm pitch

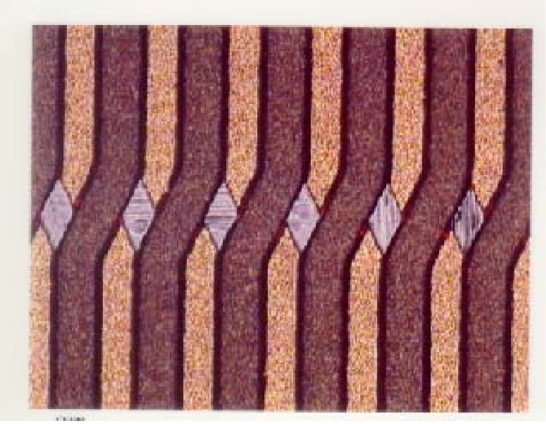
F. Sauli,
Nucl. Instrum. Methods A386(1997)531

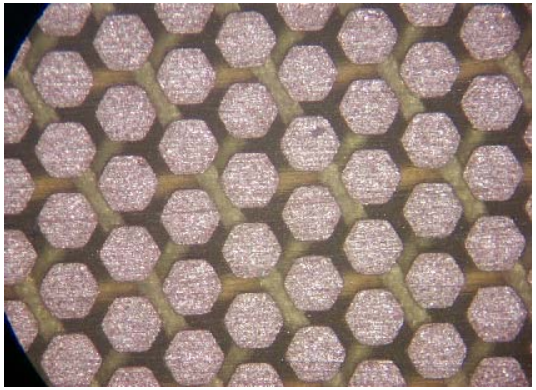
GEM DETECTOR:

- *multiplication and readout on separate electrodes*
- *electron charge collected on strips or pads: 2-D readout*
- *fast signal (no ion tail)*
- *global signal detected on the lower GEM electrode (trigger)*




Cartesian


Small angle

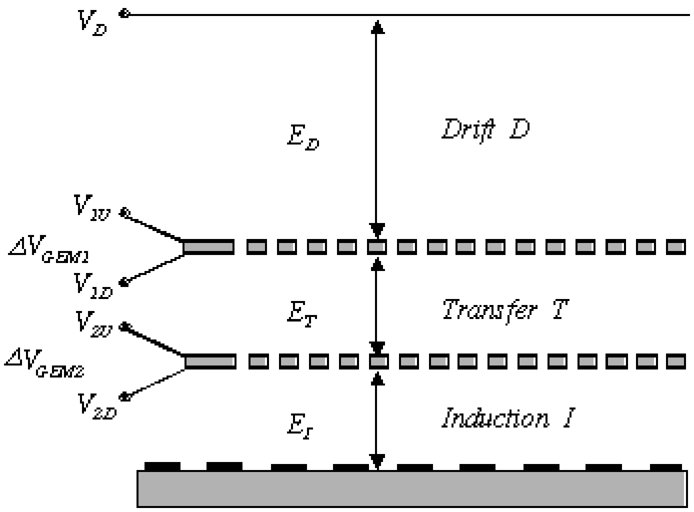

Pads

A. Bressan et al, Nucl. Instr. and Meth. A425(1999)254

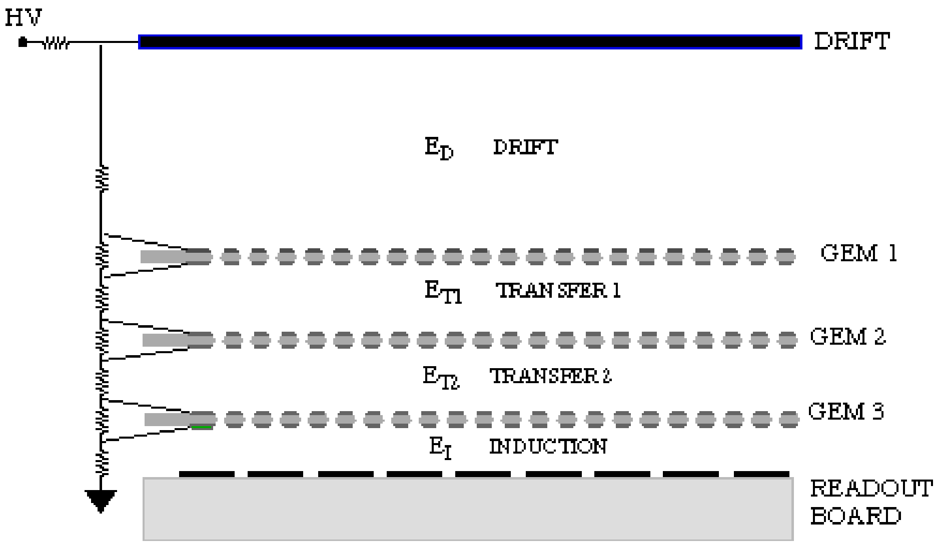
MULTIPLE GEM STRUCTURES

Cascaded GEMs permit to attain much larger gains before discharge

Double GEM



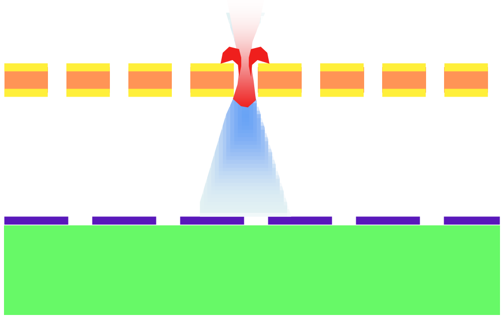
Triple GEM

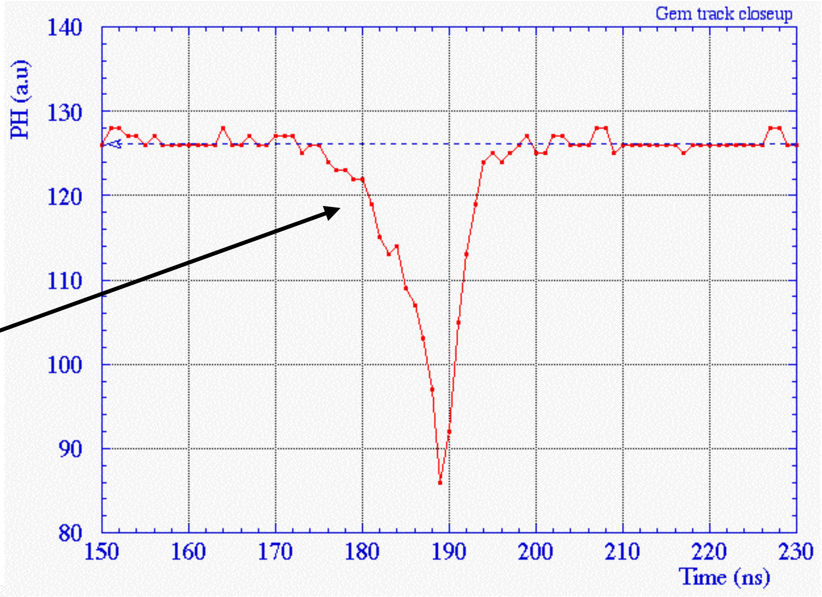


C. Buttner et al, Nucl. Instr. and Meth. A 409(1998)79
S. Bachmann et al, Nucl. Instr. and Meth. A 443(1999)464

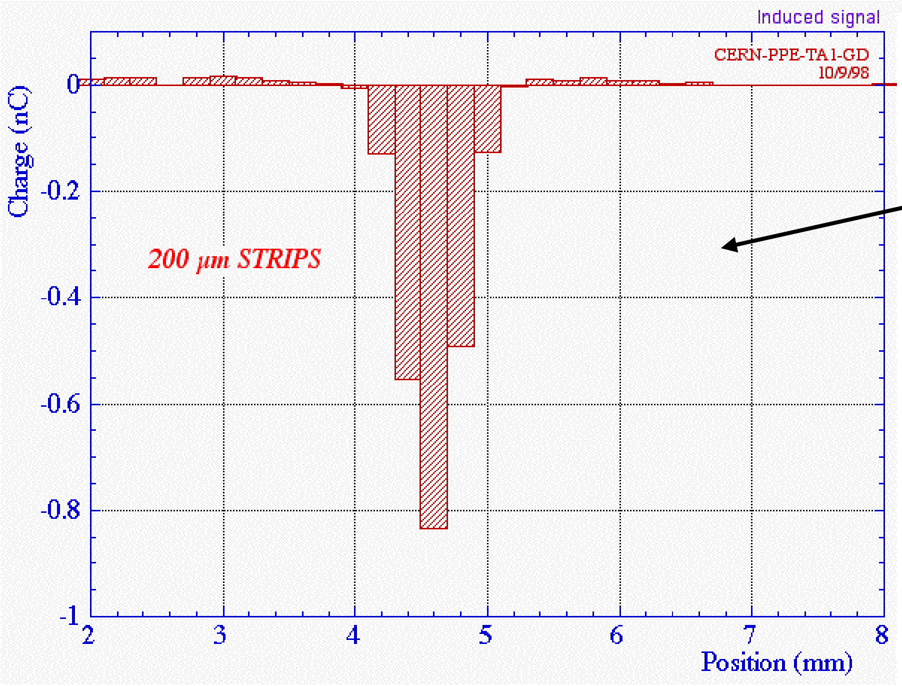
FAST ELECTRON SIGNAL (NO ION TAIL)

The total length of the detected signal corresponds to the electron drift time in the induction gap:





Full Width 20 ns
(for 2 mm gap)



Induced charge profile on strips
FWHM 600 µm

Good multi-track resolution

Why use a Solid State Detector?

- Physics requires
  - high rate capability
    - rare processes imply huge event rates
  - high efficiency and low dead time
  - good signal./noise ratio
  - good resolution
  - electronics r/o
  - high speed

Solid State Detectors became a central tool in Nuclear and High Energy Physics (and a lot of applications). Intensive R&D activities mainly take place in Europe

Scintillator Detectors
- "Radiators" (scintillators, UV-light (LeadGlass))
- Phototubes, Photodiods, HPD, ….

Si Detectors
- strip, pad, drift, CCD, APS, DEPFET, …
- NIM A521 (2003) 1-452, NIM A541 (2005) 1-466.

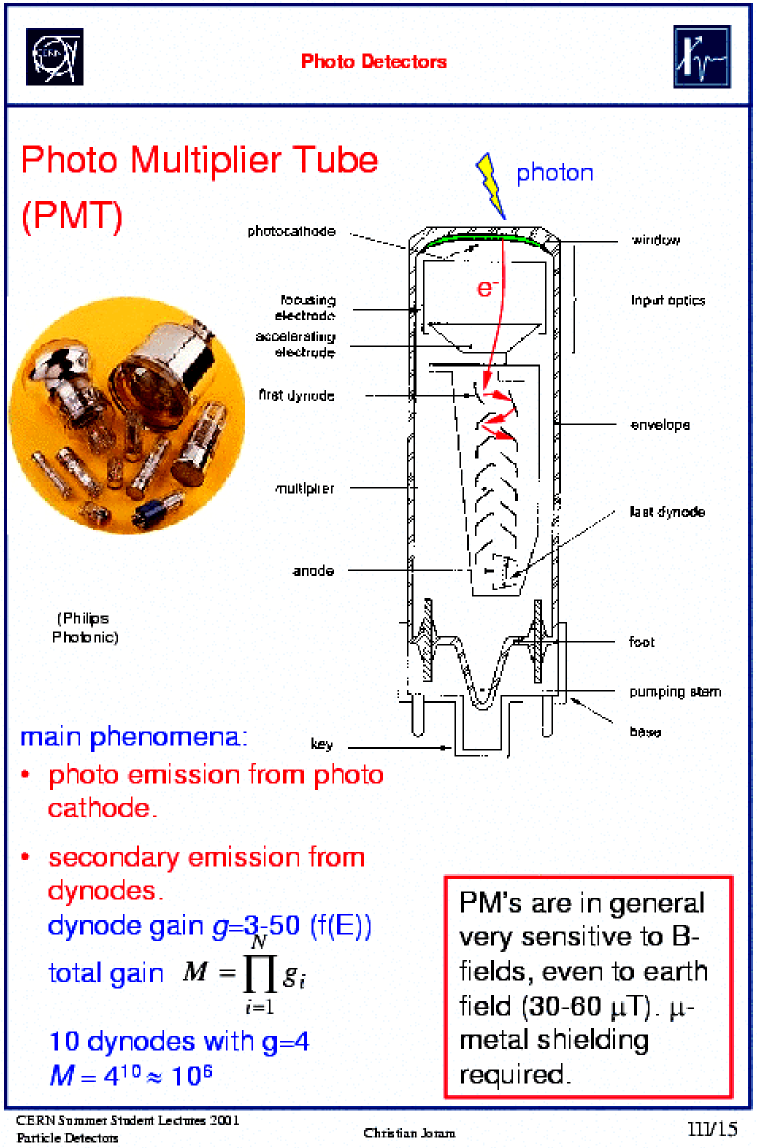


Photo Multiplier Tube (PMT)

(Philips Photonic)

main phenomena:

- photo emission from photo cathode.
- secondary emission from dynodes.

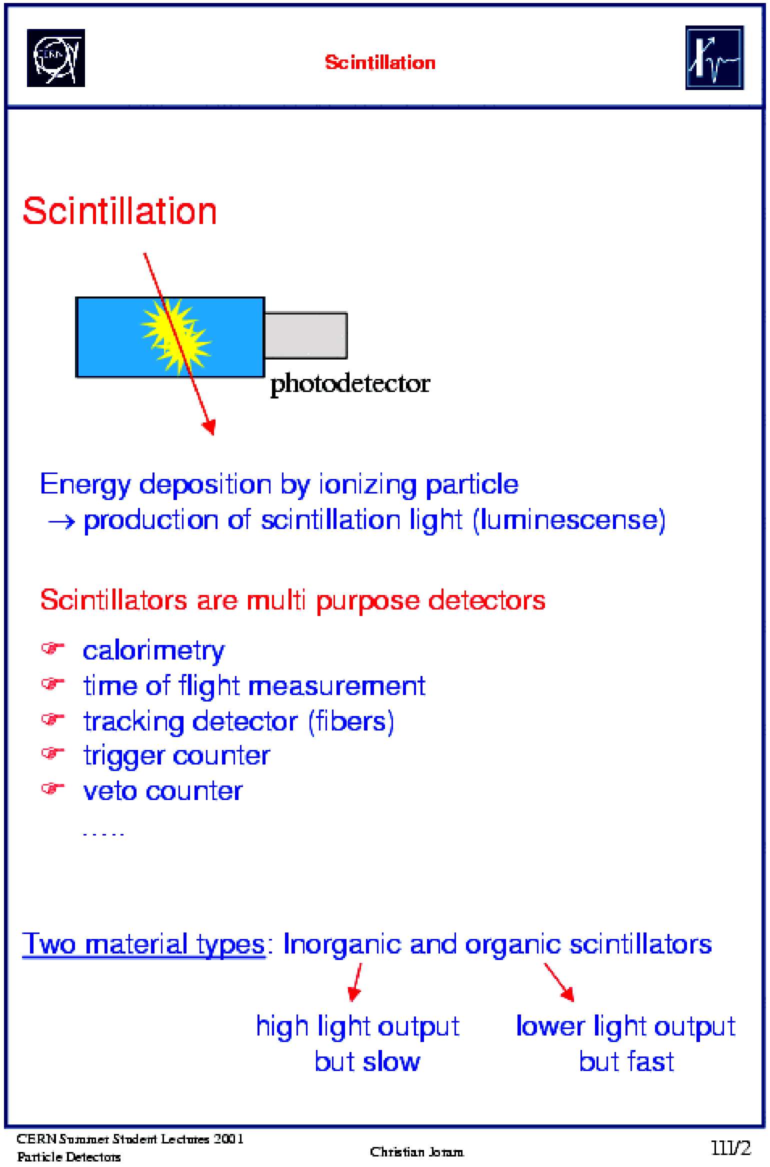
dynode gain g=3-50 (f(E))

total gain $M = \prod_{i=1}^{N} g_i$

10 dynodes with g=4

$M = 4^{10} \approx 10^6$

PM's are in general very sensitive to B-fields, even to earth field (30-60 μT). μ-metal shielding required.



Scintillation

Energy deposition by ionizing particle
→ production of scintillation light (luminescense)

Scintillators are multi purpose detectors

- calorimetry
- time of flight measurement
- tracking detector (fibers)
- trigger counter
- veto counter
- .....

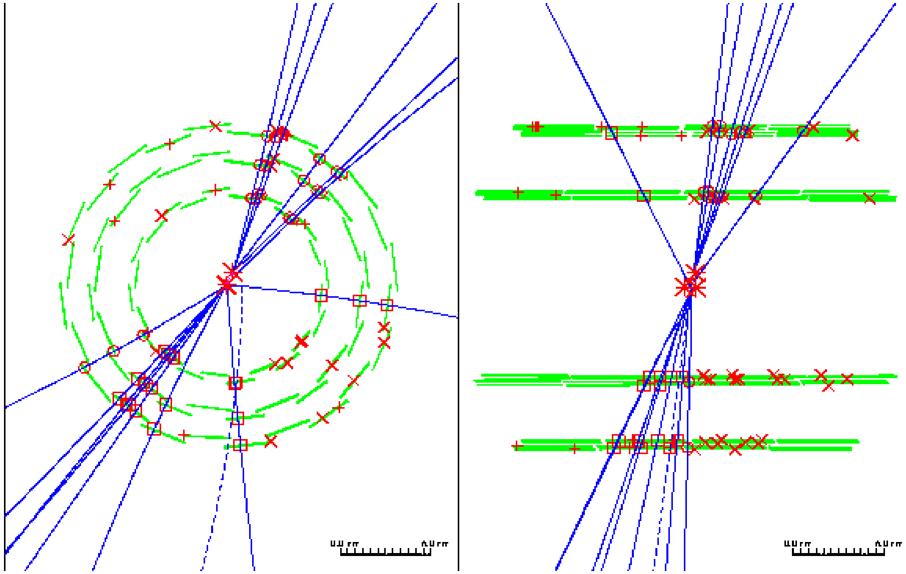
Two material types: Inorganic and organic scintillators

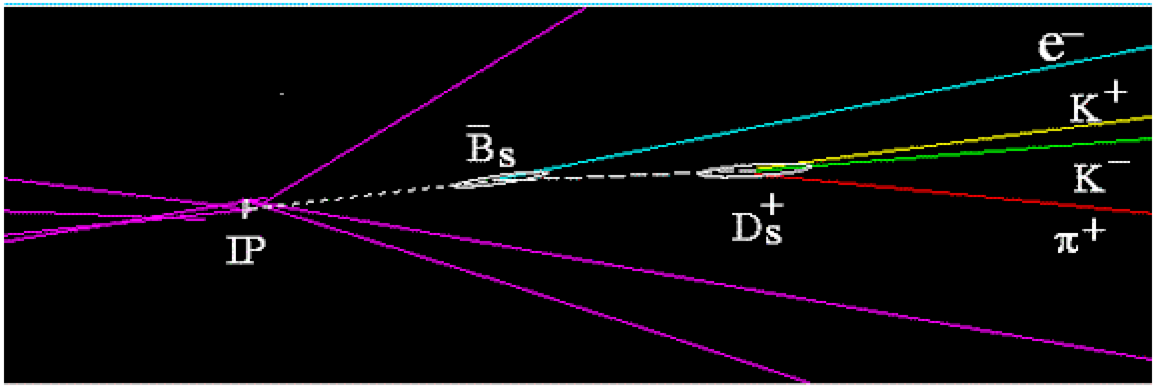
Inorganic	organic
high light output but slow	lower light output but fast

Scintillation in Gas → Cherenkov and RICH Detectors

B-physics at LEP

- Detecting vertices ...

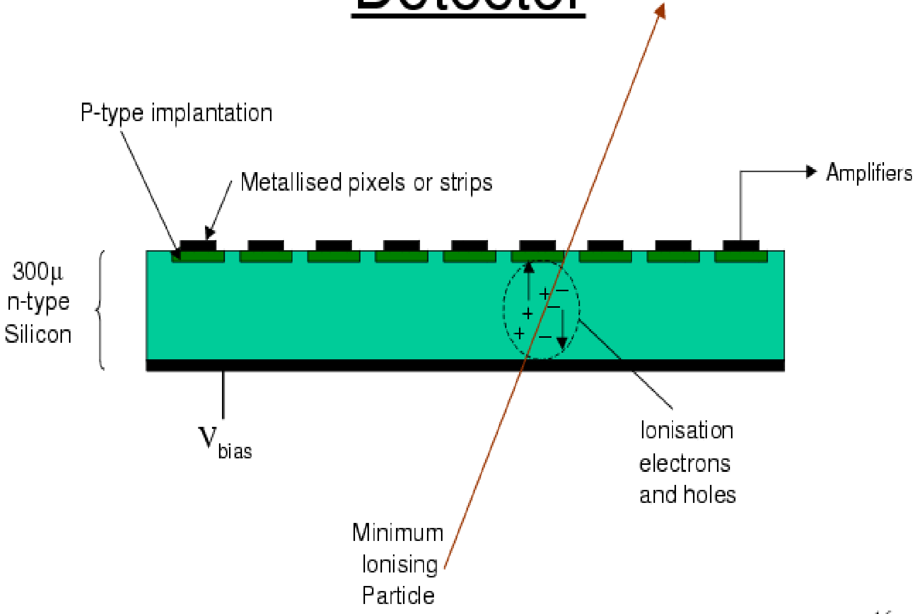




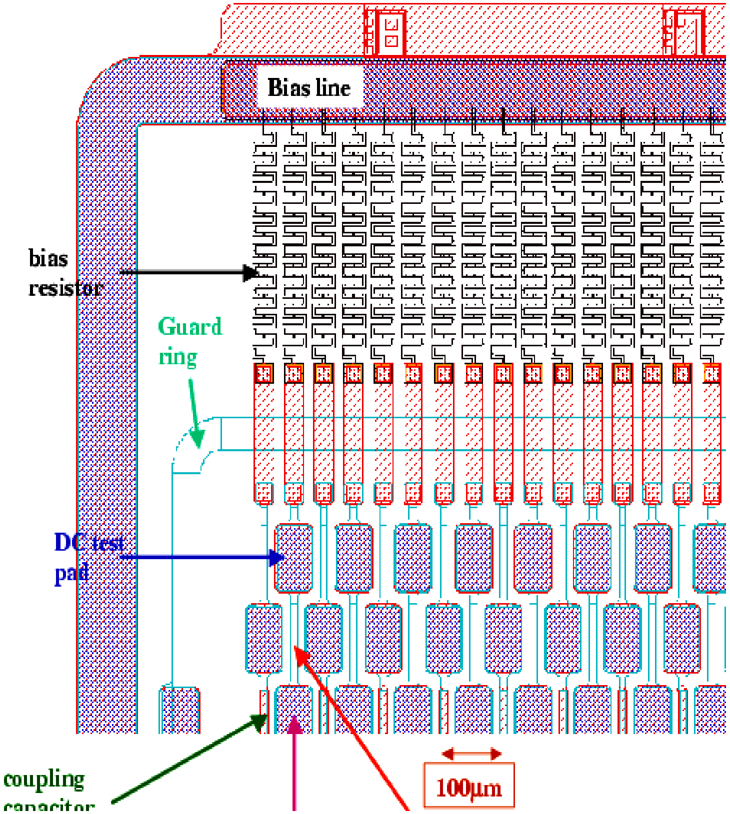
Silicon Properties

- Electron-hole production at few eV
  - compare with 30eV in gas
- Density reduces deltas
  - remember bubble chamber photos(!)
- ~100 e-h pairs/micron
- solid
  - easy to install close to interaction point

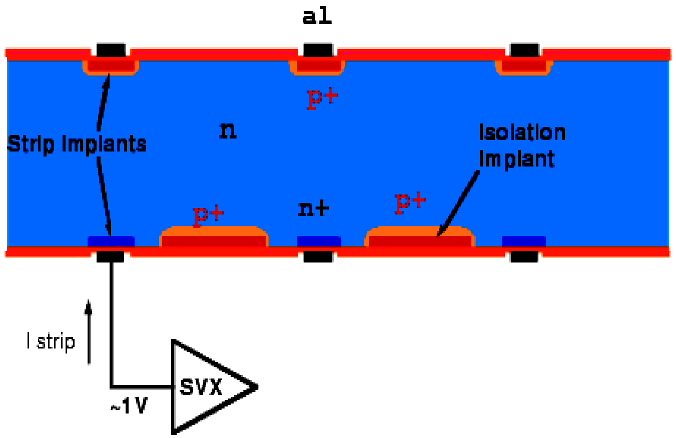
Cross-Section of a Silicon Detector



Detector Design - single sided devices



Detector Design - double sided devices



AC Coupling:

- Add a thin (2000A) SiO2 layer between the p+ and aluminum, This forms an “integrated” capacitor.
- Bias the strips with:
  - Simple “FOXFET” or punchthrough structure
  - polysilicon (CVD amorphous silicon)

Readout of signal induced on the n (ohmic) side

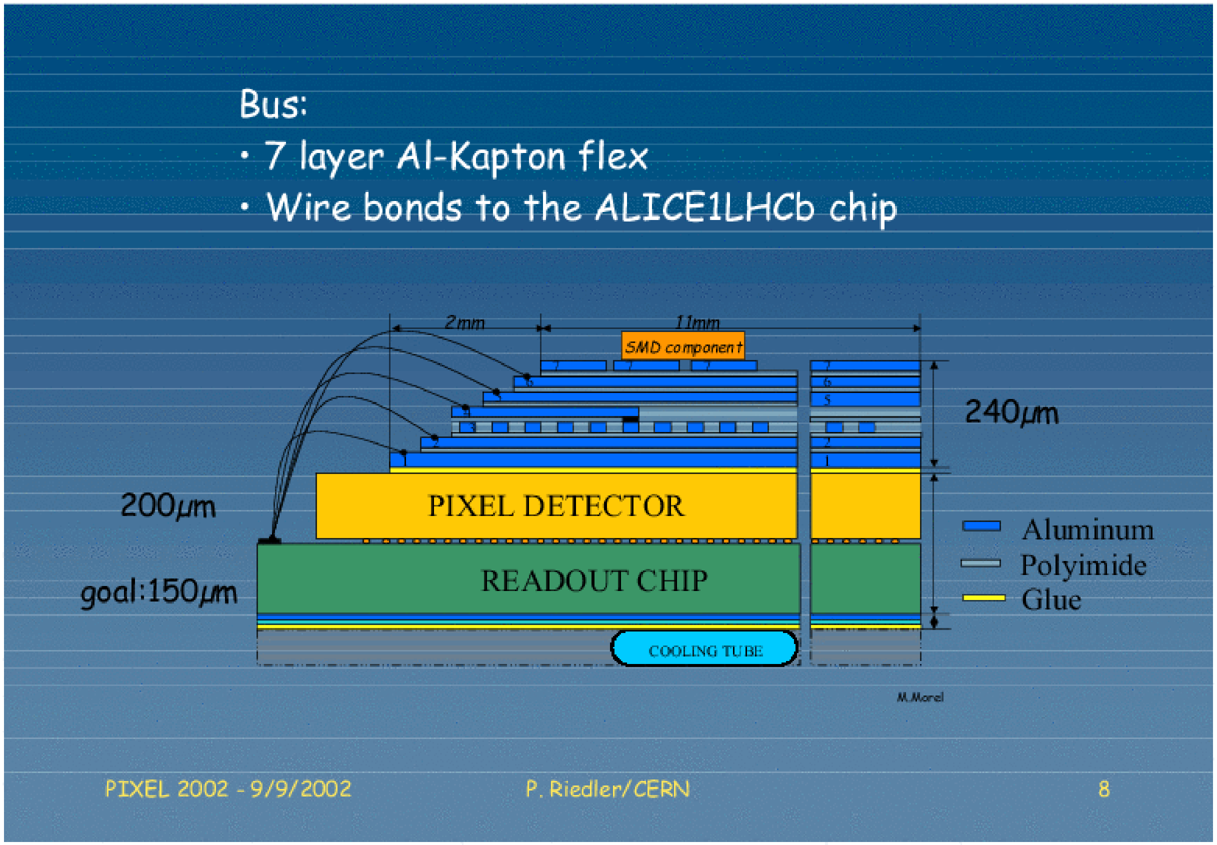
- n side implants are “naturally” shorted to each other and must be separated electrically. Charges present in the oxide layer tend to induce conducting channels between n side strips
- Add p+ “blocking” strips to ensure strip isolation after the device is fully depleted

upport bias voltage

plex device than SS: 14 vs 7 “mask steps” to produce

- Less mass per point, less multiple scattering

Silicon Pixel

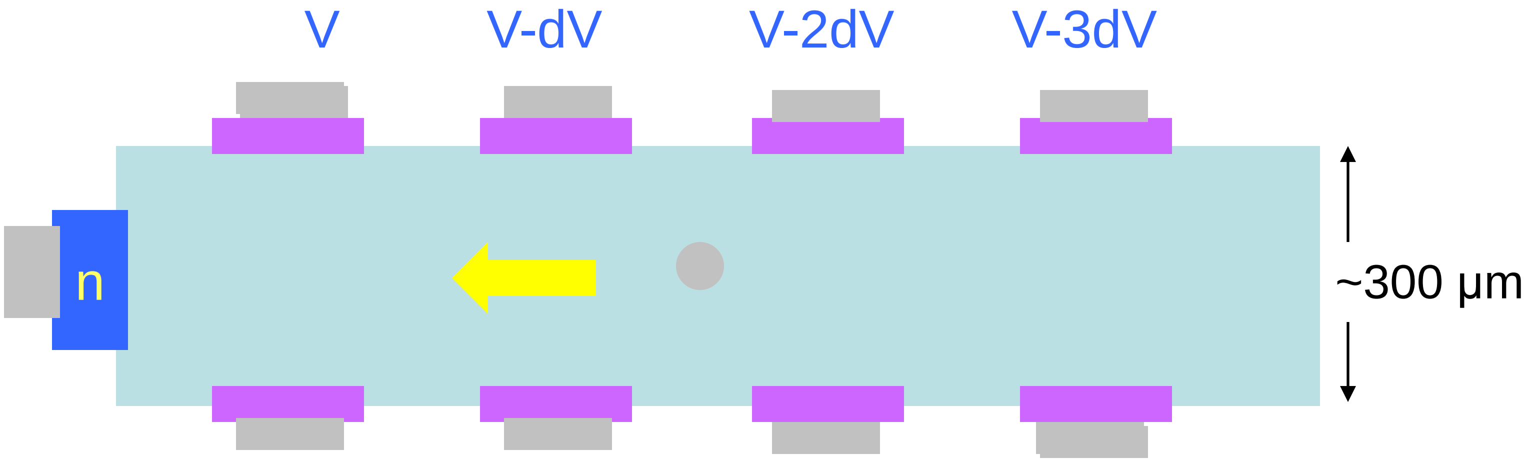


Bus:

- 7 layer Al-Kapton flex
- Wire bonds to the ALICE1LHCb chip

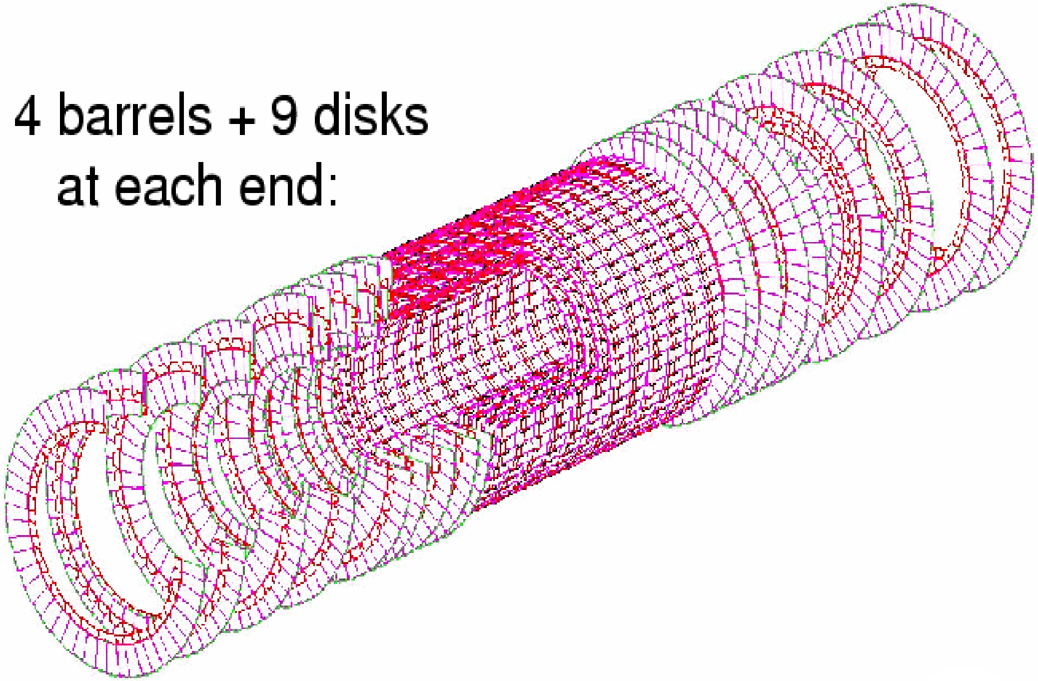
PIXEL 2002 - 9/9/2002 P. Riedler/CERN 8

Silicon Drift



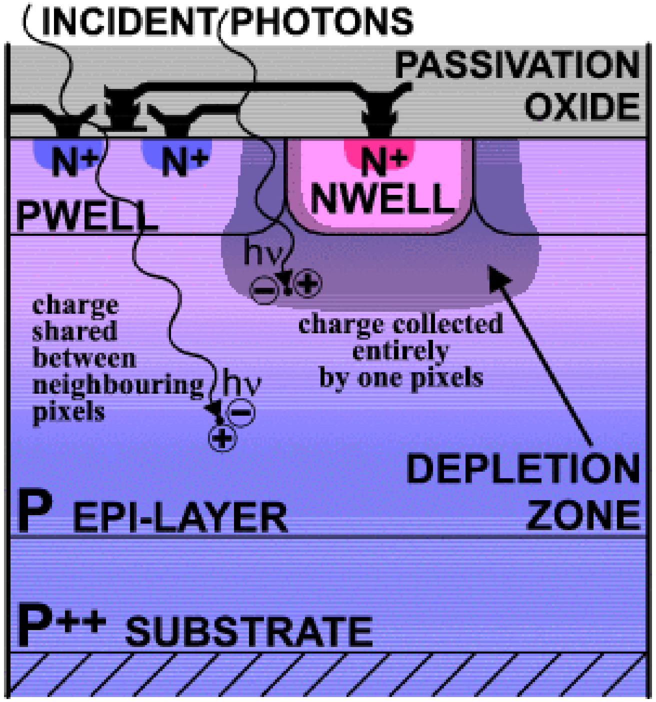
The Atlas SCT Detector

4 barrels + 9 disks
at each end:

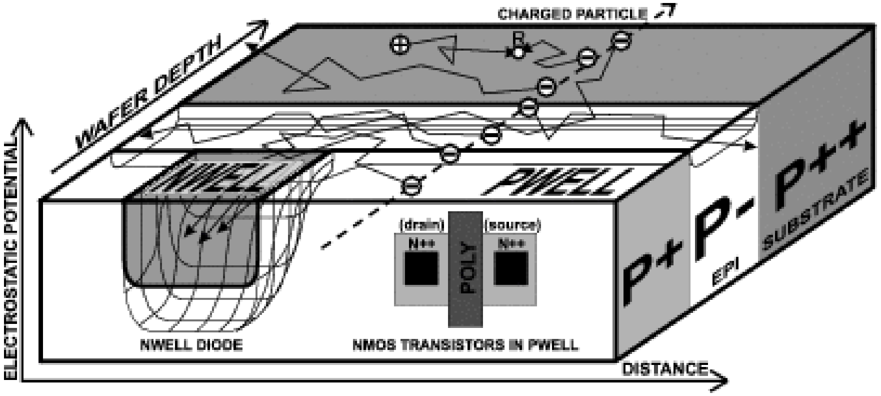


☑ Operation Principle of CMOS Sensors for Particle Detection

- In visible light CMOS cameras, moderately doped epitaxial layer provides long minority carrier lifetime ...



- Charge generated in non-depleted region collected through thermal diffusion (or it recombines…) ...



- Potential barriers at layer interfaces confine the charge - improving collection efficiency ...

- Active volume underneath the readout electronics ⇨ 100% fill factor; charge collected by deep n-well/p-epi diode.

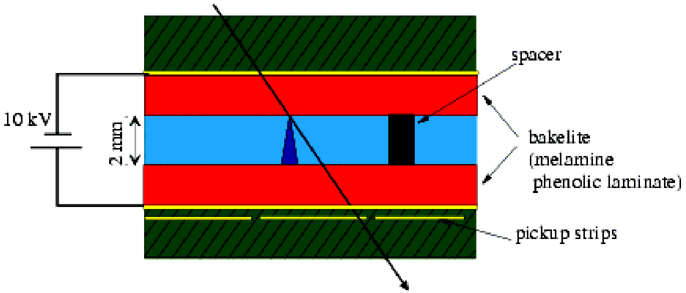
Detectors for neutral particles

- n, π^0, γ, ʋ, …
- “Calorimeter” (ECAL, HCAL)

Detectors for Particle Identification

- **dE/dX** (energy loss in matter; $f(\beta\gamma)$)
- **Cherenkov and RICH** (light when $\beta > \beta c$)
- **TRD** (radiation is emitted when a particle moves across the interface of two media with different dielectric constants; $f(\gamma)$)
- **ToF** (path length, start-stop, β)
- **ECAL, HCAL** (E → number of interactions → number of “secondary” particles)
- **μ - detectors** (additional material (absorber) to “stop” all particles ; Fe (B))
- **Secondary vertexes and mass decay particle reconstruction ($\Lambda \rightarrow p + \pi^-$)**

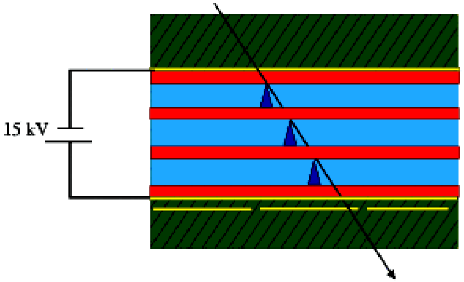
- Resistive plate chambers (RPC) No wires !



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.