**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:
\(L=5\text{mm}, \ d=1\text{mm}, \ a_{\text{wire}}=20\text{mm}.\)

Normally digital readout:
spatial resolution limited to \(\sigma_x \approx \frac{d}{\sqrt{12}}\)
(\(d=1\text{mm}, \ \sigma_x=300 \text{ \mu m}\))

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).

\[
\frac{y}{L} = \frac{Q_B}{Q_A + Q_B} \quad \sigma \left( \frac{y}{L} \right) \text{ up to } 0.4\%
\]

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

\[
\sigma (\Delta T) = 100 \text{ ps}
\]

\[
\rightarrow \sigma (y) \approx 4 \text{ cm} \quad (\text{OPAL})
\]

- 1 wire plane + 2 segmented cathode planes

Analog readout of cathode planes.

\[
\rightarrow \sigma \approx 100 \mu m
\]
Some ‘derivatives’

- Thin gap chambers (TGC)

Cathode pads

Ground plane

G10 (support)

Graphite

Gas: CO$_2$/n-pentane ($\approx$ 50/50)

Operation in saturated mode. Signal amplitude limited by the resistivity of the graphite layer ($\approx$ 40k$\Omega$/□).

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

Application: OPAL pole tip hadron calorimeter.
G. Mikenberg, NIM A 265 (1988) 223

Resistive plate chambers (RPC)  

Gas: $\text{C}_2\text{F}_4\text{H}_2, (\text{C}_2\text{F}_5\text{H}) + \text{few \% isobutane}$

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

Time dispersion $\approx 1\ldots 2\ \text{ns} \rightarrow$ suited as trigger chamber

Rate capability $\approx 1\ \text{kHz} / \text{cm}^2$

Double and multigap geometries $\rightarrow$ improve timing and efficiency

Problem: Operation close to streamer mode.
**Drift chambers**

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 $\rightarrow$ thermalization

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

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

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

$D$: diffusion coefficient

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

External electric field:

“stop and go” traffic due to scattering from gas atoms $\rightarrow$ drift

$$\vec{v}_D = \mu \vec{E} \quad \mu = \frac{e\tau}{m} \quad \text{(mobility)}$$
Drift and diffusion in gases

in the equilibrium ...

\[
\frac{x}{\nu_D \tau} \lambda_\epsilon \epsilon = eEx
\]

\( \lambda_\epsilon \) : fractional energy loss / collision
\( \tau = \frac{1}{N\sigma \nu} \) \( \nu \): instantaneous velocity

\[
\nu_D^2 = \frac{eE}{mN\sigma} \sqrt{\frac{\lambda}{2}}
\]

\( \sigma = \sigma(\epsilon) \) !

\( \lambda = \lambda(\epsilon) \) !

Typical electron drift velocity: 5 cm/\( \mu \)s

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

$$\tan \alpha_L = \omega \tau$$

$\alpha_L$: Lorentz angle

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

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 $v_T/\omega$.

The transverse diffusion coefficient appears reduced

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

Very useful… see later!

Transverse diffusion $\sigma (\mu m)$ for a drift of 15 cm in different Ar/CH$_4$ mixtures

(A. Clark et al., PEP-4 proposal, 1976)
Some planar drift chamber designs

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


The spatial resolution is not limited by the cell size
→ 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

Example: **DELPHI Inner detector**
- 5 layers with 192 tubes each
- tube $0.9 \text{ cm}$, 2 m long,
- wall thickness 30 $\mu\text{m}$ (Al coated polyester)
- wire $0.4 \mu\text{m}$
- Intrinsic resolution ca. 50 $\mu\text{m}$

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

Example: **OPAL Jet chamber**
- $\Omega=3.7 \text{m}$, $L=4 \text{m}$, 24 sectors à 159 sense wires ($\pm 100 \mu\text{m}$ staggered). $3 \text{ cm} < l_{\text{drift}} < 25 \text{ cm}$

Resolve left/right ambiguities

Resolution of the OPAL jet chamber
Drift Chambers

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


$\Phi$ 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

geometry and typical dimensions (former CMS standard)

Gold strips + Cr underlayer

Field geometry

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

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

◆ GEM: The Gas Electron Multiplier

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

Micro photo of a GEM foil
Micro gaseous detectors

- 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)).

Here we are interested in their use as precision trackers!

Some characteristic numbers for silicon

- Band gap: $E_g = 1.12$ V.
- $E(\text{e}^-\text{-hole pair}) = 3.6$ eV, ($\approx 30$ eV for gas detectors).
- High specific density (2.33 g/cm$^3$) $\rightarrow$ $\Delta E$/track length for M.I.P.’s.: $390$ eV/µm $\approx 108$ e-h/ µm (average)
- High mobility: $\mu_e = 1450$ cm$^2$/Vs, $\mu_h = 450$ 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: $n_i \approx 1.45 \cdot 10^{10} \text{ cm}^{-3}$

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
### Silicon detectors

#### 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.

<table>
<thead>
<tr>
<th>Doping concentration</th>
<th>Resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>detector grade</td>
<td>electronics grade</td>
</tr>
<tr>
<td>$10^{12}$ cm$^{-3}$ (n) - $10^{15}$ cm$^{-3}$ (p$^+$)</td>
<td>$10^{17(18)}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$\approx 5$ kΩ·cm</td>
<td>$\approx 1$ Ω·cm</td>
</tr>
</tbody>
</table>

#### pn junction

There must be a single Fermi level! Deformation of band structure $\rightarrow$ potential difference.
• 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.**

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

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**Silicon detectors**

Ca. 50-150 μm

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**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

- Requires sophisticated readout architecture
- First experiment WA94 (1991), WA97
- OMEGA 3 / LHC1 chip (2048 pixels, 50x500 \(\mu\text{m}^2\)) (CERN ECP/96-03)
- Pixel detectors will be used also in LHC experiments (ATLAS, ALICE, CMS)
The DELPHI micro vertex detector (since 1996)

- **Silicon Detectors**

- **The DELPHI micro vertex detector (since 1996)**

![Diagram of silicon detector](image)

- **Pixel II**: 12°<θ<21°
- **Inner Layer**: R=92 mm, θ>21°, 50 µm Rφ, 50-100 µm z
- **Outer Layer**: R=106 mm, θ>23°, 44-176 µm z
- **Closer Layer**: R=66 mm, θ>24°, 50 µm Rφ, 50-150 µm z
- **2 Minisip Layers**: 10°<θ<18°

**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)

\[ 28 \mu m \oplus 71/\left( p \sin^{3/2} \theta \right) \]
Silicon drift chamber

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:
σ_R ≈ 20 μm, σ_φ ≈ 2 mrad

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 ($e, \pi, n, \gamma..$) 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 $\propto$ energy deposition in displacing collisions

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 ($\approx -10^\circ$C).
  $\rightarrow$ Slower reverse annealing. Lower leakage current.
More advanced methods

- **Defect engineering.**
  
  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)
  
  “zero” leakage current, good charge collection (70%) for heavily irradiated detectors \((1 \cdot 10^{15} \text{ n/cm}^2)\). “Lazarus effect”

- **New materials**
  
  Diamond. Grown by Chemical Vapor Deposition. Very large bandgap \((\approx 6 \text{ eV})\). 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