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

\[
\frac{dN}{N} = \frac{1}{\sqrt{4\pi D t}} e^{-\left(x^2/4D t\right)} dx
\]

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

External electric field:
“stop and go” traffic due to scattering from gas atoms → drift

\[ \bar{v}_D = \mu \bar{E} \quad \mu = \frac{e \tau}{m} \quad \text{(mobility)} \]
in the equilibrium ...

\[ \frac{x}{v_D \tau} \lambda_\varepsilon \varepsilon = eEx \]

\( \lambda_\varepsilon \): fractional energy loss / collision

\( \tau = \frac{1}{N \sigma v} \): instantaneous velocity

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

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

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

Typical electron drift velocity: 5 cm/μs

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!
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 $r(t)$

\begin{itemize}
  \item The spatial resolution is not limited by the cell size
  \item less wires, less electronics,
  less support structure than in MWPC.
\end{itemize}

Drift chambers

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

Various geometries of cylindrical drift chambers

(N. Filatova et al., NIM 143 (1977) 17)
Drift chambers

Straw tubes: Thin cylindrical cathode, 1 anode wire

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

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

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

Resolve left/right ambiguities
Drift Chambers

Time Projection Chamber $\rightarrow$ 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 $\rightarrow$ very good gas quality required

Space charge problem from positive ions, drifting back to midwall $\rightarrow$ gating

ALEPH TPC

(Contributed by W. Atwood et. al., NIM A 306 (1991) 446)

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

\[ \Delta V_g = 150 \ V \]
Faster and more precision? \(\rightarrow\) smaller structures

\[\text{Microstrip gas chambers} \quad (A. Oed, NIM A 263 (1988) 352)\]

Geometry and typical dimensions (former CMS standard)

Gold strips + Cr underlayer

Field geometry

Gas: Ar-DME, Ne-DME (1:2), Lorentz angle 14° at 4T

Gain \(\leq 10^4\)

Passivation: non-conductive protection of cathode edges

Resolution: \(\approx 30\, \ldots 40 \, \mu m\)

Aging: Seems to be under control.

10 years LHC operation \(\approx 100 \, \text{mC/cm}\)
Micro gap chambers

2-dimensional readout with MGC (Bellazini)

F. Angelini, NIM A 335 (1993) 69

INFN Pisa
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
  - Single GEM 1
  - Single GEM 2

- Double GEM + readout pads
  - Double GEM 1
  - Double GEM 2

- GEM 1
- GEM 2

- DRIFT
- INDUCTION
- TRANSFER

- Same gain at lower voltage
- Less discharges

Effective Gain vs. $\Delta V_{\text{geom}}$ (V)

- GEM 140/80 Argon-\(\text{CO}_2\) 70-30
  - $E_r = 1.6$ kV cm\(^{-1}\)
  - $E_i \sim 5$ kV cm\(^{-1}\)
  - Same gain at lower voltage
  - Less discharges
Micro gaseous detectors (backup)

- **Micro Gap Wire Chamber**
  
  (E. Christophel et al., NIM A 398 (1997) 195)

  - Gold cathode on ceramic substrate
  - 5 µm wire on 40 µm wide polyimide strips
  - Gain > $10^5$ (prototype 2.6 x 2.6 cm²)

- **MICROMEGAS**
  
  (G. Charpak et al., CERN-LHC/97-08)

  - Gas: Ar-DME (≈80:20)
  - High rate capability ($10^9$ / (mm².s), prototype in test beam)
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$^3$) $\rightarrow \Delta E/\text{track length}$ for M.I.P.’s: $390$ eV/$\mu$m $\approx 108$ e-h/$\mu$m (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 $\mu$m $\rightarrow \approx 3.2 \cdot 10^4$ 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
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>detector grade</th>
<th>electronics grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{12} cm^{-3} (n) - 10^{15} cm^{-3} (p^+)</td>
<td>10^{17(18)} cm^{-3}</td>
<td></td>
</tr>
</tbody>
</table>

| resistivity | ≈ 5 kΩ·cm | ≈ 1 Ω·cm |

pn junction

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

- 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.

(A. Peisert, Instrumentation In High Energy Physics, World Scientific)
Spatial information by segmenting the p doped layer → *single sided microstrip detector*.  

Schematically:

- Silicon detectors
- Spatial information by segmenting the p doped layer
- Single sided microstrip detector
- Readout capacitances: ca. 50-150 μm
- SiO₂ passivation
- Schematic diagram showing silicon layers, SiO₂, Al, and electrical connections
- n⁺ silicon defines end of depletion zone + good ohmic contact
- V > 0
- ALICE: Single sided microstrip prototype

(A. Peisert, Instrumentation in High Energy Physics, World Scientific)
Segmenting also the n doped layer → **Double sided microstrip detector**.

But:

Positive charges in SiO₂ attract e⁻ in n⁻ layer. Short circuits between n⁺ strips.

**Two solutions:**

- Add p⁺ doped blocking strips
- Add Aluminum layer on top of SiO₂ 
  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

Flip-chip technique

- 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)

- Inner Layer
  - $R=92$ mm
  - $\theta>21^\circ$
  - $50 \mu m \, R_\phi$
  - $50-100 \mu m \, z$

- Outer Layer
  - $R=106$ mm
  - $\theta>23^\circ$
  - $50 \mu m \, R_\phi$
  - $44-176 \mu m \, z$

- Closer Layer
  - $R=66$ mm
  - $\theta>24^\circ$
  - $50 \mu m \, R_\phi$
  - $50-150 \mu m \, z$

2 Ministrip Layers
- $10^\circ<\theta<18^\circ$

Pixel I
- $12^\circ<\theta<21^\circ$
- $50 \mu m \, R_\phi$
- $330 \times 330 \mu m^2$

Pixel II
- $1033 \, mm, \, 10^\circ<\theta<170^\circ$
- $50 \mu m \, R_\phi$
- $10^\circ<\theta<21^\circ$

- Total dissipated power 400 W
  → water cooling system

- Hit resolution in barrel part $\approx 10 \mu m$
- Impact parameter resolution ($r_\phi$)

$$28 \mu m + 71 \left( \frac{p \sin \frac{3}{7} \theta}{3} \right)$$

- Readout channels
  - ca. 174 k strips, 1.2 M pixels
  - Total readout time: 1.6 ms
◆ Silicon drift chamber

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

Silicon detectors (backup)

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.
Monolithic integration of detector and electronics

Motivation:  
- reduce strip or pixel dimensions  
- avoid connection problems (bonding)  
- improve performance (capacity, noise)  
- reduce number of components

But silicon quality is very different for detectors and electronics!

2 possibilities:  
1) build special electronics components on detector wafers

2) grow detector grade silicon on electronics wafers

MIMOSA concept

J.D. Berst et al.  
LEPSI -99-15

Y. Gormuskin et al.,  
VCI 2001  
submitted to NIM A
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 \text{energy deposition in displacing collisions}

\[ \Phi_{eq}^{n,1\text{MeV}} = \int \frac{D(E) dE}{D(E_{n=1\text{MeV}})} \]

Main radiation induced macroscopic changes:

1. Increase of sensor leakage current
2. Change of depletion voltage. Very problematic.

How to cope with the radiation damage?

Possible strategies:

- Geometrical: build sensors such that they stand high depletion voltage \(500\text{V}\)
- Environmental: keep sensors at low temperature \((\approx -10^\circ\text{C})\). → 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 Oxyenated (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 required and depletion required! Material is still rather expensive. Still more R&D required.

- **New detector concepts**
  “3D detectors” → “horizontal” biasing faster charge collection but difficult fabrication process