5. Tracking Detectors

5.1 Momentum reconstruction in a magnetic field

5.2 Magnetic spectrometers

5.3 Multi-wire proportional chambers

5.4 Drift chambers

5.5 Time projection chambers

5.6 Microstrip gas chambers

Silicon-based tracking detectors are discussed in Chapter 6 (together with impact parameter resolutions)
5.1 Introduction: The motivation for tracking detectors

- Main purpose: measure coordinates of charged particles with high precision in a magnetic field
- Measure the curvature → momentum (or more general: five track parameters)
- Curvature measurement requires the reconstruction of track patterns in an ensemble of measured hits in detectors → pattern recognition (reconstruction software)
- Additional tasks: vertex reconstruction extrapolate tracks back to their origin → primary vertex at the interaction point or secondary vertex
- Determination of impact parameter w.r.t. primary vertex → lifetime tags (b-tagging)
Motivation for tracking detectors (cont.)

• Recognition and reconstruction of charged particle trajectories (tracks)

• Measurement of momentum (and sign of charge) in a magnetic field

• Vertex reconstruction and lifetime “tag” (via secondary vertices)

• $dE/dx$ measurement (requires measurement of charge) and contribution to particle ID
Momentum reconstruction

- Equation of motion (general form):

  \[
  \mathbf{F} = m \cdot \gamma \cdot \mathbf{a} = q(\mathbf{v} \times \mathbf{B})
  \]

  \[
  \ddot{x} = \frac{q}{m \cdot \gamma} \dot{x} \times \mathbf{B}(x)
  \]

  2nd order differential equation:

- There are in general two types of experimental setups:

  (i) Fixed target experiments

  (ii) Collider experiments

  Measured coordinates: \( x(z_i), y(z_i) \)

  \[ \phi (r_i), \ z(r_i) \]

- General equation (fixed target approach):

  \[
  \frac{dx}{dt} = x' \quad \frac{dy}{dz} = y'
  \]

  \[
  p \cdot y''(z) = \sqrt{1 + y'(z)^2 + x'(z)^2} \left\{ \mathbf{B}_z x' + \mathbf{B}_y y' x' - \mathbf{B}_x (1 + y'^2) \right\}
  \]

  \[
  p \cdot x''(z) = \sqrt{1 + y'(z)^2 + x'(z)^2} \left\{ -\mathbf{B}_z y' - \mathbf{B}_x y' z' + \mathbf{B}_y (1 + x'^2) \right\}
  \]

  Solution has four integration constants + momentum \( p \rightarrow \) five parameters

  \( \rightarrow \) at least five independent coordinate measurements (3 space points) needed
Case of a homogenous magnetic field, e.g. solenoid field in collider experiments

\[ \vec{F} = \dot{\vec{p}} = q \left( \vec{v} \times \vec{B} \right) \quad \Rightarrow \quad \dot{\vec{v}} = \frac{q}{\gamma m} \left( \vec{v} \times \vec{B} \right) \]

**Solution** is a rotating vector \( \vec{v}_T \) in plane perpendicular to \( \vec{B} \)

\[
B_1 = B_2 = 0, \quad B_3 = B > 0
\]

\[
\omega_B = \frac{|q| B}{\gamma m}
\]

\[
v_1 = v_T \cos(\eta \omega_B t + \psi)
\]

\[
v_2 = -v_T \sin(\eta \omega_B t + \psi)
\]

\[
v_3 = v_3
\]

Equations also hold relativistically \( \omega_B = \omega_B(\gamma); E = \gamma m \)

**Integration yields** spatial trajectory

\[
x_1 = \frac{v_T}{\eta \omega_B} \sin(\eta \omega_B t + \psi) + x_{10}
\]

\[
x_2 = \frac{v_T}{\eta \omega_B} \cos(\eta \omega_B t + \psi) + x_{20}
\]

\[
x_3 = v_3 t + x_{30}
\]

Curvature radius

\[
R = \sqrt{(x_1 - x_{10})^2 + (x_2 - x_{20})^2} = \frac{v_T}{\omega_B} = \frac{\gamma m v_T}{|q| B} = \frac{p_T}{|q| B}
\]
The Helix…. as seen in an experiment

Event from the ALEPH experiment at LEP

- For low momenta $y$ is a periodic function of $z$
- For high momenta $y$ is a linear function of $z$
The Helix as explicit track model:

\[ x = x_0 + R (\cos(\psi_0 - \eta \psi) - \cos \psi_0) \]
\[ y = y_0 + R (\sin(\psi_0 - \eta \psi) - \sin \psi_0) \]
\[ z = z_0 + \frac{\psi R}{\tan \theta} . \]

The representation of the circular projection can be expanded for large \( R \) → parabolic equation

\[ y = y_0 + \sqrt{R^2 - (x - x_0)^2} \]
\[ y = y_0 + R \left( 1 - \frac{(x - x_0)^2}{2R^2} + \ldots \right) = \left( y_0 + R - \frac{x_0}{2R^2} \right) + \frac{x_0}{R} x - \frac{1}{2R} x^2 + \ldots \]
\[ \approx a + bx + cx^2 \]
What do we need to do?

- Once we have measured the transverse momentum and the dip angle the total momentum is
  \[ P = \frac{P_\perp}{\cos \lambda} = \frac{0.3BR}{\cos \lambda} \]

- The error on the momentum is given by the measurement errors on the curvature radius \( R \) and the dip angle \( \lambda \)
  \[ \frac{\partial P}{\partial R} = \frac{P_\perp}{R} \]
  \[ \frac{\partial P}{\partial \lambda} = -P_\perp \tan \lambda \]

\[ \left( \frac{\Delta P}{P} \right)^2 = \left( \frac{\Delta R}{R} \right)^2 + \left( \tan \lambda \Delta \lambda \right)^2 \]

relative error (%)

- We need to study (for solenoid magnets)
  - the error on the radius measured in the bending plane \( r - \phi \)
  - the error on the dip angle in the \( r - z \) plane

- ... and also
  - The contribution of multiple scattering to the momentum resolution

- Comment:
  - in a hadron collider like LHC the main emphasis is on transverse momentum measurement
  - elementary processes take place among partons that are not at rest in the laboratory frame
  - use momentum conservation only in the transverse plane
Estimation of Track parameters and their uncertainties

\[ S = \sum_{i=1}^{N} \sum_{j=1}^{N} (\xi_i^{\text{meas}} - \xi_i^{\text{fit}}) V_{y,ij}^{-1} (\xi_j^{\text{meas}} - \xi_j^{\text{fit}}) = \sum_{i=1}^{N} \frac{(\xi_i^{\text{meas}} - \xi_i^{\text{fit}}(\theta))^2}{\sigma_i^2} \]

\( \chi^2 \) minimization of \( S \) (see lecture on Statistical Methods)

if \( V \) is diagonal
General track fit in matrix formalism \((x-y\text{ space})\)

- \(f\) be a \textbf{linear} function of the parameters \(\theta_i\):
  \[
  f(x|\theta) = \theta_1 f_1(x) + \ldots + \theta_m f_m(x) = \sum_{j=1}^{m} \theta_j f_j(x)
  \]

- then the expectation values for the measurement points at positions \(x_i\) are:
  \[
  \eta_i = \theta_1 f_1(x_i) + \ldots + \theta_m f_m(x_i) = \sum_{j=1}^{m} \theta_j f_j(x_i) = \sum_{j=1}^{m} H_{ij} \theta_j
  \]

- the minimization requirement then reads:
  \[
  S = (\bar{y} - H \theta)^T V_y^{-1} (\bar{y} - H \theta) \rightarrow \text{min}
  \]

  with solution
  \[
  \hat{\theta} = (H^T V_y^{-1} H)^{-1} H^T V_y^{-1} \bar{y} = A \bar{y}
  \]

  \(\Rightarrow\)

  \[
  \hat{y} = \sum_{j=1}^{m} \hat{\theta}_j f_j(x)
  \]

  (error propagation = linear trafo of \(V_y\))

  and errors
  \[
  V_\theta = A V_y A^T = (H^T V_y^{-1} H)^{-1}
  \]

  \[
  \Rightarrow \quad \sigma_y^2 = \sum_{i=1}^{m} \sum_{j=1}^{m} \frac{\partial y}{\partial \theta_i} \frac{\partial y}{\partial \theta_j} V_{\theta,ij} = \sum_{i=1}^{m} \sum_{j=1}^{m} f_i(x) f_j(x) V_{\theta,ij}
  \]

  error of best fit coordinate

  \(n \times m\) matrix

  best coord. estimate for given \(x\)
Application to a straight line:

\[ f_1(x) = 1, \quad f_2(x) = x \]

\[ \theta_1 = a, \quad \theta_2 = b \]

\[ y = f(x|\theta) = a + bx \]

N measurements

**fit**  \[ \hat{y} = \sum_{j=1}^{m} \hat{\theta}_j f_j(x) \]

best estimate of \( y \) for a given \( x \)

with errors (on parameters)

\[ V_\theta = AV_y A^T = (H^T V_y^{-1} H)^{-1} \]

... and errors on position estimates

\[ \sigma_y^2 = \sum_{i=1}^{m} \sum_{j=1}^{m} \frac{\partial y}{\partial \theta_i} \frac{\partial y}{\partial \theta_j} V_{\theta,ij} \]

\[ \sigma_a^2 = \frac{\sigma^2}{N} \]

\[ \sigma_b^2 = \frac{\sigma^2}{N} \frac{12(N-1)}{(N+1)L^2} \]

\[ \sigma_{ab} = 0 \]

cf. choice of coord. system

\[ \sigma_y^2 = \sigma_a^2 + x_0^2 \sigma_b^2 = \frac{\sigma^2}{N} + \frac{\sigma^2}{N} \frac{12(N-1)}{(N+1)L^2} x_0^2 \]

\( x_0 \) is a specifically chosen x-value
Application to a linearized circle:

\[ y = y_0 + \sqrt{R^2 - (x - x_0)^2} \]

\[ \Rightarrow y \approx a + bx + \frac{1}{2}cx^2 \]

errors

\[ V_\theta = AV_y A^T = (H^T V_y^{-1} H)^{-1} \]

\[ \sigma_y^2 = \sum_i \sum_j \frac{\partial y}{\partial \theta_i} \frac{\partial y}{\partial \theta_j} V_{\theta,ij} \]

\[ \Rightarrow \quad \sigma_y^2 = \sigma_a^2 + x_0^2 \sigma_b^2 + \frac{1}{4}x_0^4 \sigma_c^2 + x_0^2 \sigma_{ac} \]

\[ \begin{align*}
\sigma_a^2 &= \sigma^2 \frac{3N^2 - 7}{4(N - 2)N(N + 2)} \\
\sigma_b^2 &= \frac{\sigma^2}{L^2} \frac{12(N - 1)}{N(N + 1)} \\
\sigma_c^2 &= \frac{\sigma^2}{L^4} \frac{720(N - 1)^3}{(N - 2)N(N + 1)(N + 2)} \\
\sigma_{ab} &= \sigma_{bc} = 0 \\
\sigma_{ac} &= \frac{\sigma^2}{L^2} \frac{30N}{(N - 2)(N + 2)}
\end{align*} \]

\[ = \frac{\sigma^2}{N} \left( 1 + \frac{x_0^2}{L^2} \frac{12(N - 1)}{(N + 1)} + \frac{x_0^4}{L^4} \frac{180(N - 1)^3}{(N - 2)(N + 1)(N + 2)} + \frac{x_0^2}{L^2} \frac{30N^2}{(N - 2)(N + 2)} \right) \]

\( x_0 \) is a specifically chosen x-value
Important application: A solenoidal magnetic field

Beam position can often be used as additional constraint.

Measure: \((r_i, \phi_i)\) or \((r_i, \phi_i, z_i)\)

In general a helix model with the following five parameters is used:

\[ \kappa = \pm 1/R, \, \psi_0, \, d_0, \, \theta, \, z_0 \]

\[ x_0 = d_0 \cos \psi_0, \text{ and } y_0 = d_0 \sin \psi_0 \]
The precision of a measurement of the momentum in a homogeneous magnetic field is determined by the precision of the sagitta measurement \( s \).

\[
p_T = \frac{|q| B R}{\kappa} = \frac{q B}{\kappa}
\]

Relation between \( R \) and \( s \):

\[
\frac{R-s}{R} = \cos \frac{\alpha}{2} \approx 1 - \frac{\alpha^2}{8}
\]

\[
\frac{L}{2R} = \sin \frac{\alpha}{2} \approx \frac{\alpha}{2}
\]

\[\Rightarrow s = \frac{R \alpha^2}{8} = \frac{1}{8} \frac{L^2}{R} = \frac{1}{8} L^2 |\kappa|
\]

\[\Rightarrow \text{the precision of the momentum measurement depends on the precision of the sagitta measurement:}
\]

For three distinct points (see drawing):

\[
s = y_3 - \frac{y_1 + y_2}{2}
\]

\[\Rightarrow \sigma_s = \sqrt{\sigma_{\text{mess}}^2 + \frac{1}{4} 2 \sigma_{\text{mess}}^2} = \sqrt{\frac{3}{2}} \sigma_{\text{mess}}
\]

For \( N \) equidistant measurements one obtains from the linearized circle approximation:

\[
\sigma_\kappa = \frac{8}{L^2} \sigma_s
\]

\[
\sigma_\kappa = \frac{\sqrt{96}}{L^2} \sigma_{\text{mess}}
\]

\[
\sigma_\kappa = \frac{\sigma_{\text{mess}}}{L^2} \sqrt{\frac{720(N-1)^3}{(N-2)N(N+1)(N+2)}} \approx \frac{\sigma_{\text{mess}}}{L^2} \sqrt{\frac{720}{N+4}}
\]
From the measurement on the curvature to the $p_T$ measurement:

$$p_T = |q| B R = \frac{q B}{\kappa}$$

For the uncertainty on $p_T$ one obtains:

$$\sigma_{p_T} = \frac{p_T^2}{|q| B} \sigma_\kappa = \frac{p_T^2}{0.3 |z| B} \sigma_\kappa$$

→ for the relative uncertainty on $p_T$ one obtains the famous **Gluckstern formula** for $N$ equidistant measurements with a precision $\sigma_\text{mess}$:

$$\left( \frac{\sigma_{p_T}}{p_T} \right)_\text{mess} = \frac{p_T}{0.3 |z| L^2 B} \sqrt{\frac{720}{N + 4}}$$

$p_T = \text{GeV}/c$, $[L] = \text{m}$, $[B] = \text{T}$

**Major dependencies:**
- Relative resolution is directly proportional to $p_T$
- Directly proportional to the detector resolution $\sigma_\text{mess}$ (→ aim for high resolution)
- $1 / L^2$ → measurement volume enters quadratically
- $\sim 1 / B$: gain linearly with higher magnetic fields
- $\sim 1 / \sqrt{N}$: gain with number of measurements, however, only with square root
The influence of Coulomb Multiple Scattering:

- The scattering angle has a distribution that is almost gaussian.
- At large angles deviations from gaussian distributions appear that manifest as a long tail going as \( \sin^{-4} \theta/2 \) (Moliere theory).
- In “thick” detectors the distribution of the lateral displacement \( y_{\text{plane}} \) should also be considered.

\[
\sigma_{\kappa} = \left( \frac{8}{L^2} \sigma_s \right) = \left( \frac{8}{L^2} \frac{1}{4\sqrt{3}} \right) x \theta_0 \approx L
\]

\[
\theta_0 = \frac{13.6 \text{ MeV/c}}{p \beta} z \sqrt{\frac{x}{X_0}} \left( 1 + 0.038 \ln \left( \frac{x}{X_0} \right) \right)
\]

\[
\frac{0.0136 \text{ GeV/c}}{p \beta L} z \sqrt{\frac{L}{\sin \theta}} X_0 \left( \sqrt{1.33} - \sqrt{1.43} \right)
\]

\( N = 3 \) \( N > 10 \)
Total momentum resolution:

\[
\sigma_{p_T} = \frac{p_T^2}{|q| B} \sigma_{\kappa} = \frac{p_T^2}{0.3 |z| B} \sigma_{\kappa} \quad \Rightarrow \\
\left( \frac{\sigma_{p_T}}{p_T} \right)_{\text{MS}} = 0.0136 \sqrt{\frac{1.43}{0.3}} = 0.054 \\
\left( \frac{\sigma_{p_T}}{p_T} \right)_{\text{mess}} = \frac{p_T}{0.3 |z| L^2 B} \frac{\sigma_{\text{mess}}}{N + 4} \sqrt{\frac{720}{L / \sin \theta}} \\
[p_T] = \text{GeV/c}, \ [L] = m, \ [B] = T
\]

for \( N > 10 \)

cannot get better than this w/ detectors

example: OPAL

\( L = 1.6 \text{ m}, \ B = 0.435 \text{ T}, \ N = 159, \ \sigma_{\text{mess}} = 135 \mu m \)

\[
\frac{\sigma_{p_T}}{p_T} = \sqrt{(0.0015 p_T)^2 + (0.02)^2} \\
p_T \text{ in GeV}
\]
5.2 Magnetic Spectrometers

Nearly all particle physics experiments at accelerators have a magnetic spectrometer to measure the momentum of charged particles.

Commonly used magnets: **Solenoids, Dipoles and Toroids**

- **Dipole**
  - **rectangular symmetry**
    - **deflection** in $y - Z$ plane
    - **tracking** detectors are arranged in parallel planes along $z$
    - **measurement** of curved trajectories in $y - Z$ planes at fixed $Z$
  - $B \approx \frac{\mu_0 N I}{h}$

- **Solenoid**
  - **cylindrical symmetry**
    - **deflection** in $x - y$ ($r - \phi$) plane
    - **tracking** detectors are arranged in cylindrical shells along $r$
    - **measurement** of curved trajectories in $r-\phi$ planes at fixed $r$
  - $B \approx \frac{\mu_0 N I}{L}$
Toroid

azimuthal symmetry
- deflection in (r - z) - plane
- tracking detectors are (in ATLAS) also arranged in cylindrical shells
- but measurement of curved trajectories in r-z planes at fixed r

ATLAS: 0.5 T
Tracking in LHCb: Dipole field (forward region, fixed target)

- Velo
  - μ-strip detector
  - 46 half planes
  - 180,000 channels

- TT
  - μ-strip detectors
  - 1 station w/ 4 planes
  - σ ~ 50 μm
  - 145,000 channels

- IT + OT
  - IT = μ-strip detectors; OT = gas straw tubes
  - 3 stations w/ 4 planes each
  - 130,000 strips + 55000 straw tubes
Tracking in LHCb: Dipole field (forward region, fixed target)
Tracking in CMS: Solenoid field

Magnetic field of 3.8 Tesla
Muons in ATLAS: Toroidal field
5.3 Multi-wire proportional chamber

- In order to extract space / coordination information efficiently, Multi-Wire-Proportional Chambers (MWPCs) were used for long time.

G. Charpak (1968, Nobel prize, 1992)

- Principle:
  - Put many anode wires in parallel, in one volume
  - High voltage: each wire acts as an independent proportional counter (gas amplification)
• Every wire acts as an independent proportional tube

→ every anode wire is read out separately → space information

• Typical parameters:
  distance between wires: \( d = 2 \text{ mm} \)
  distance anode-cathode: \( L = 7-8 \text{ mm} \)
  diameter of anode wires: \( 10 – 30 \mu\text{m} \)
  (thin wire → high electric field → gas amplification)

• Achievable coordinate resolution:
  \( \sigma = \frac{d}{\sqrt{12}} \approx 600 \mu\text{m} \)

This resolution is not adequate for today’s LHC experiments;
(however, was sufficient for experiments in the 1970/80s)
Electrical field configuration:

- Homogeneous field, except in the vicinity of the anode wire.
- Lines of equal potential are parallel to cathode in large part of ionisation volume.
- Every wire is read out individually, indicating spatial information, however, a larger number of readout channels is required.
- Electrons drift to the next anode wire, while positive ions drift to the cathode.
- The functionality of the MWPC can be significantly increased if induced signals on the cathode are also read out, indicating a second coordinate.

*Fig. 6.8. Electric field lines and potentials in a multiwire proportional chamber. The effect of a small displacement on the field lines is also shown (from Charpak et al. [6.16]).*
Principle of gas amplification and ion drift:

- $1/r$ E-field in region of anode wire $\rightarrow$ gas amplification ($A \sim 10^5$)

- Typical gas mixtures used:
  - $\text{Ar} + \text{CH}_4$,
  - $\text{Ar} + \text{CO}_2$,
  - $\text{Ar} + \text{isobutane}$, ..

- Electrons drift to next anode wire

- Positive ions drift to cathode

Time structure of the anode signal of a MWPC, recorded with a short electronics response / shaping time ($\tau < 10 \text{ ns}$) [from Ref. 3]

$\rightarrow$ very fast rise time of individual avalanches
Possibilities for second coordinate measurement:

(i) Crossed chambers (90°), chamber positions known in z-direction

→ measurements of both coordinates at fixed z-positions \((x,z_1)\) and \((y,z_2)\)

MWPC-precision (~600 μm) in each coordinate
• Possibilities for second coordinate measurement:

(i) Crossed chambers (90°), chamber positions known in z-direction

\[\rightarrow\] measurements of both coordinates at fixed z-positions \((x,z_1)\) and \((y,z_2)\)

MWPC-precision (~600 \(\mu\)m) in each coordinate

Ambiguities, for more than one particle
\[\rightarrow\] ghost points

Not well suited for high particle multiplicities
(ii) Stereo layers (small stereo angles, $\alpha = 3-5^\circ$)

$\rightarrow$ Reduced ambiguity problem due to smaller overlap

often so-called triplet layers are used ($-3^\circ$, $0^\circ$, $+3^\circ$) $(u, x, v)$ coordinates

However, degraded resolution in the second coordinate

$0^\circ$ layers: $\rightarrow \sigma_x \sim 600 \ \mu m$

stereo layers: $\rightarrow \sigma_y \sim \sigma_x / \sin \alpha$

for stereo angle $\alpha = 3-5^\circ$

$\rightarrow \sigma_y \sim O(cm)$
(iii) Cathode strip readout (segmented cathode)

→ Improvement of the coordinate resolution by calculating centre-of-gravity (weighted by charge = pulse height) of the cathode signals

\[ y = \frac{\sum (Q_i \cdot y_i)}{\sum Q_i} \]

where: 
- \( Q_i \) = Charge on cathode strip \( i \)
- \( y_i \) = strip position

→ achievable resolution: 50 – 100 μm!
(iv) Charge division (on anode wire)

Readout the anode wire (resistive wire) at both ends (two amplifiers) and use the fact that the resistivity is proportional to the wire length.

\[ y = L \frac{Q_A}{Q_A + Q_B} \]

Typical resolutions achieved: \(~1\%\) of the wire length

\[ \Theta \text{ (cm)} \]
5.4 Drift chambers

- Measure not only the pulse height, but also the time when a signal appears with respect to an external trigger signal

- Get external time reference $t_0$ (fast scintillator or beam timing)

- Measure arrival time $t_1$ of electrons at the anode

- Coordinate reconstruction:

  \[ x = \int_{t_0}^{t_1} v_D(t) \, dt \]

  Requires a precise knowledge of the drift velocity $v_D(t)$
  
  typical drift velocity: $v_D = 5 \text{ cm} / \mu\text{s}$

  (as function of the position in the detector, or space-drift time relation)

- Drift chambers have, like MWPC, a left-right ambiguity
Main advantages of a drift chamber:

- Position perpendicular to the anode wire can be extracted from a space-drift-time relation
  (has to be known, it is linear, if the drift velocity is constant over the drift volume)

  However, it requires an additional time measurement (TDC)

- Typical drift distances: 5 – 15 cm
  → more economical, less readout channels,
  a much larger sensitive volume can be covered per readout channel

- Improved coordinate resolution, typical values: \( \sigma \sim 50 – 200 \mu m \)

  It is limited by diffusion of the drifting electron clouds, electronics (time measurements)

- However, challenging mechanics for large surface drift chambers (> 2 x 2 m²)
  electrostatic repulsion of wires → oscillations
  sagging of wires (due to gravitation) → field inhomogeneities, affect spatial precision
  → wires have to be strained (large chambers, several thousand wires, tension can reach a few tons on end plates)
Electric field formation:

- So-called field forming wires are introduced to avoid low-field regions, i.e. long drift times
- Introduce additional wires on negative potential between anode wires
  (cathode on ground, anode on positive potential)
Electric field formation:

- Drift cells can be defined by putting negative potential at cell boundaries, and using voltage divider chains to define a graded potential on cathode strips

→ well defined equipotential lines, uniform field gradient

![Diagram of electric field formation](image)

**Fig. 7.9.** Resolution of the left–right ambiguity in a drift chamber.

**Fig. 7.10.** Illustration of the field formation in a large-area drift chamber.

The anode are the main limiting factors. The determination of the coordinate along the wires can again be performed with the help of cathode pads.

The relation between the drift time and the drift distance in a large-area (80 cm x 80 cm) drift chamber with only one anode wire is shown in Fig. 7.11. The chamber was operated with a gas mixture of 93% argon and 7% isobutane.

Field formation in large-area drift chambers can also be achieved by the attachment of positive ions on insulating chamber surfaces. In these chambers an insulating foil is mounted on the large-area cathode facing the drift space (Fig. 7.12). In the time shortly after the positive high voltage on the anode wire has been switched on, the field quality is insufficient to expect a reasonable electron drift over the whole chamber volume (Fig. 7.13 a). Positive ions which have been produced by the penetrating particle now start to drift along the field lines to the electrodes. The electrons will be drained by the anode wire, but the positive ions will get stuck on the inner side of the insulator on the cathode there by forcing the field lines out of this region. After a certain while ('charging-up time') no field lines will end on the covers of the chamber and an ideal drift-field configuration will have been formed (Fig. 7.13 b, [20, 21]). If the chamber walls are not completely insulating, i.e., their volume or surface resistance is finite, some field lines will still be present.

![Graph of space-drift-time relation](image)

Space-drift-time relation for a large drift chamber (80 cm x 80 cm) with only one anode wire (from Ref. [3]).
Contribution to the spatial resolution:

1. Time resolution of the electronics

   \[ \sigma_t \sim 1 \text{ ns}, \quad v_D = \frac{5 \text{ cm}}{\mu \text{s}} \Rightarrow \sigma_x = v_D \sigma_t = 50 \mu \text{m} \]

2. Diffusion of drifting electrons
   (dominant for large drift distances)

3. Statistical fluctuations in the primary ionization
   and differences in drift paths
   (important for small distances to the anode wire)

4. Mechanical tolerances
   (accuracy of the wire position, sagging, etc…,
   depends on the chamber dimensions)

5. Inhomogeneities on the electrical field strength
Total spatial resolution:

Example of the spatial resolution achieved in a small drift chamber (80 cm wires) and the decomposition into the various components (from Ref. [3])

- Diffusion is dominant for large drift distances
- Fluctuations in path length and primary ionization statistics dominate the resolution for short drift distances
Reconstruction of the second coordinate:
(along the wire, i.e. z-coordinate in cylindrical drift chambers)

- Charge division

- Small angle stereo layers

- Cathode strips work only for planar chambers

Resolution of the left-right ambiguity:

- Staggered layers in planar chambers, shift by half a drift cell

- Jet-chamber geometry, staggered anode wires (red) in cylindrical geometries
Corrections for the Lorentz-angle:

In general the E and B-fields are perpendicular in cylindrical drift chambers

→ Lorentz angle, Drift velocity has a component in E x B-direction

$$\bar{v}_D = \frac{\mu |\hat{E}|}{1 + \omega^2 \tau^2} \left[ \hat{E} + \omega \tau \hat{E} \times \hat{B} + \omega^2 \tau^2 (\hat{E} \cdot \hat{B}) \hat{B} \right]$$

→ space-drift-time relation affected, has to be taken into account

Drift trajectories of electrons in an open rectangular drift cell without (left) and (inside) a magnetic field B perp. to E (from Ref. [3])
Cylindrical Drift Chambers:

- Used in inner tracking volume of collider experiments in solenoidal magnetic fields
- Characteristica: cylindrical symmetry, open drift cell geometry
- Require: simple space-time relation, given the E-, B-fields and drift cell geometry

Illustration of three neighbouring drift cells (from Ref. [3])

Illustration of a cylindrical drift chamber for a collider experiment (from Ref. [3])

- anode wire: ~30 μm diameter
- potential wires: ~100 μm diameter
Different Drift Cell Geometries for cylindrical drift chambers

Closed geometry: better field quality, however, more wires have to be stretched; The hexagonal structure represents a compromise solution
Example of a closed drift cell, as built for the drift chamber of the ARGUS experiment at DESY, Hamburg. Shown in yellow are lines with the same drift time.
Octant of the drift chamber of the ZEUS experiment at DESY Hamburg;

Magnetic field 1.6 Tesla

Drift cells oriented to compensate the Lorentz angle
“Jet Chamber” geometry

Important features:

- Large number of signal wires in the centre of large trapezoidal drift cells
  → allows for good dE/dx measurement
- Large drift cells → long drift times
- Left-right ambiguities resolved by staggered anode wires

JADE: $B = 0.45$ T
  Lorentz-angle: $18.5^\circ$

Prominent experiments with Jet Chambers:
- JADE at PETRA (DESY, 1980s)
- OPAL at LEP (CERN, 1990s)
Jet structures seen in the JADE Jet Chamber (reaction $e^+e^- \rightarrow qqg$)

(b) a three-jet event in the JADE detector.

strongly boosted into the parton direction and the jet structure is more evident in the practical inspection (fig. 5.1a). The transverse momentum of the jets is found with an average $\langle p_t \rangle \sim 300$ MeV, the same value as for the transverse momentum of the jets in the theoretical calculations. However, shows a different structure, the events are more planar and the jet structure is more evident (fig. 5.1b). These features can be quantified for example by the

\begin{equation}
(5.20)
\end{equation}
Jet drift chamber of the OPAL experiment (CERN)

**Description and operation**

The sensitive volume of the jet chamber is a cylinder with a length of about 4 m with conical end planes. It is divided in $\phi$ into 24 identical sectors, containing a sense wire plane with 159 anode wires, cathode wire planes that form the boundaries between adjacent sectors. The anode wires are located between radii of 255 mm and 1835 mm, equally spaced 10 mm and alternating with potential wires. The minimum drift distance varies between 3 cm and 10 cm.

To resolve left-right ambiguities, the anode wires are staggered by $±100 \ \mu m$ alternately to the left and right side of the plane defined by the potential wires. A schematic drawing of a section of a jet chamber segment is shown.
A glance in the interior of the OPAL Jet Chamber
Drift chamber of the CDF experiment (Fermilab)
A glance in the interior of the CDF drift chamber