Tracking Detectors

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NEPPSR-V
August 14-18, 2006
Craigville, Cape Cod
Basic Tracking Concepts

■ Moving object (animal) disturbs the material
  ➔ A track ➔

■ Keen observers can learn
  ■ Identity
    ■ What made the track?
  ■ Position
    ■ Where did it go through?
  ■ Direction
    ■ Which way did it go?
  ■ Velocity
    ■ How fast was it moving?
Charged Particles

- Charged particles leave tracks as they penetrate material

- “Footprint” in this case is excitation/ionization of the detector material by the incoming particle’s electric charge

Discovery of the positron
Anderson, 1932

16 GeV $\pi^-$ beam entering a liquid-H$_2$ bubble chamber at CERN, circa 1970
Coulomb Scattering

- Incoming particle scatters off an electron in the detector

\[ \text{charge } Z e \]
\[ \text{energy } E \]
\[ \theta \]
\[ \text{charge } e \]
\[ \text{mass } m_e \]
\[ \text{recoil energy } T = dE \]

- Transform variable to \( T \) ➔

\[ \frac{d\sigma}{dT} = \frac{2\pi z^2 e^4}{mc^2 \beta T^2} \]

- Integrate above minimum energy (for ionization/excitation) and multiply by the electron density

- See P. Fisher’s lecture from NEPPSR’03

Rutherford

\[ \frac{d\sigma}{d\Omega} = \frac{z^2 e^4}{4 p v} \csc^4 \theta \frac{\theta}{2} \]
Bethe-Bloch Formula

- Average rate of energy loss [in MeV g⁻¹ cm²]

\[
\frac{dE}{dx} = -Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \gamma^2 \beta^2 T_{max}}{I^2} - \beta^2 - \delta \right]
\]

- \( I \) = mean ionization/excitation energy [MeV]
- \( \delta \) = density effect correction (material dependent)

- What’s the funny unit?

\[
K = 4\pi N_A r_e^2 m_e c^2
\]
\[
= 0.307 \text{MeV g}^{-1} \text{cm}^2
\]

How much energy is lost?
\(-dE \text{ [MeV]}\)

How much material is traversed?
\(dx = \text{thickness [cm]} \times \text{density [g/cm}^3]\)
Bethe-Bloch Formula

\[
\frac{dE}{dx} = -Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \gamma^2 \beta^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta}{2} \right]
\]

- \(dE/dx\) depends only on \(\beta\) (and \(z\)) of the particle

- At low \(\beta\), \(dE/dx \propto 1/\beta^2\)
  - Just kinematics
- Minimum at \(\beta\gamma \sim 4\)
- At high \(\beta\), \(dE/dx\) grows slowly
  - Relativistic enhancement of the transverse \(E\) field
- At very high \(\beta\), \(dE/dx\) saturates
  - Shielding effect
Minimum Ionizing Particles

- Particles with $\beta \sim 4$ are called minimum-ionizing particles (mips)
- A mip loses 1–2 MeV for each g/cm$^2$ of material
  - Except Hydrogen
- Density of ionization is
  \[
  \frac{(dE/dx)_{\text{mip}}}{I}
  \]
  - Determines minimal detector thickness

<table>
<thead>
<tr>
<th>Gas</th>
<th>Primary [/cm]</th>
<th>Total [/cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>35</td>
<td>107</td>
</tr>
<tr>
<td>C$_2$H$_6$</td>
<td>43</td>
<td>113</td>
</tr>
</tbody>
</table>
Primary and Secondary Ionization

- An electron scattered by a charged particle may have enough energy to ionize more atoms.

- Signal amplitude is (usually) determined by the total ionization.
- Detection efficiency is (often) determined by the primary ionization.

$$\varepsilon = 1 - e^{-5} = 0.993$$

A realistic detector needs to be thicker.

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Ex: 1 cm of helium produce on average 5 primary electrons per mip.
Multiple Scattering

- Particles passing material also change direction

\[ \theta \propto \frac{1}{p} \] for relativistic particles

- Good tracking detector should be light (small \( x/X_0 \)) to minimize multiple scattering

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

\( \theta \) is random and almost Gaussian

\[ \langle \theta^2 \rangle = \theta_0^2 = 0.038 \langle X_0 \rangle \]

- \( \theta \) is Gaussian in the plane of observation

<table>
<thead>
<tr>
<th>Material</th>
<th>Radiation length ( X_0 ) [g/cm²]</th>
<th>[cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂ gas</td>
<td>61.28</td>
<td>731000</td>
</tr>
<tr>
<td>H₂ liquid</td>
<td></td>
<td>866</td>
</tr>
<tr>
<td>C</td>
<td>42.70</td>
<td>18.8</td>
</tr>
<tr>
<td>Si</td>
<td>21.82</td>
<td>9.36</td>
</tr>
<tr>
<td>Pb</td>
<td>6.37</td>
<td>0.56</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>45.47</td>
<td>34035</td>
</tr>
</tbody>
</table>
Optimizing Detector Material

- A good detector must be
  - thick enough to produce sufficient signal
  - thin enough to keep the multiple scattering small

- Optimization depends on many factors:
  - How many electrons do we need to detect signal over noise?
    - It may be 1, or 10000, depending on the technology
  - What is the momentum of the particle we want to measure?
    - LHC detectors can be thicker than BABAR
  - How far is the detector from the interaction point?
Readout Electronics

- Noise of a well-designed detector is calculable
  - Increases with $C_d$
  - Increases with the bandwidth (speed) of the readout
- Equivalent noise charge $Q_n =$ size of the signal that would give $S/N = 1$
  - Typically 1000–2000 electrons for fast readout (drift chambers)
  - Slow readout (liquid Ar detectors) can reach 150 electrons

- More about electronics by John later today
Imagine a piece of pure silicon in a capacitor-like structure

- \( dE/dx_{\text{min}} = 1.664 \, \text{MeVg}^{-1}\text{cm}^2 \)
- Density = 2.33 g/cm³
- Excitation energy = 3.6 eV

- 10⁶ electron-hole pair/cm
- Assume \( Q_n = 2000 \) electron and require \( S/N > 10 \)
- Thickness > 200 \( \mu \text{m} \)

Realistic silicon detector is a reverse-biased p-n diode

- Lightly-doped n layer becomes depleted
- Heavily-doped p layer

Typical bias voltage of 100–200 V makes \( \sim 300 \, \mu \text{m} \) layer fully depleted
BABAR Silicon Detector

- Double-sided detector with AC-coupled readout

- Aluminum strips run X/Y directions on both surfaces
Wire Chambers

- Gas-based detectors are better suited in covering large volume
  - Smaller cost + less multiple scattering
- Ionization < 100 electrons/cm ➔ Too small for detection
  - Need some form of amplification before electronics

<table>
<thead>
<tr>
<th></th>
<th>Encounters/cm</th>
<th>$t_{99}$ (mm)</th>
<th>Free electrons/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>5</td>
<td>9.2</td>
<td>16</td>
</tr>
<tr>
<td>Ne</td>
<td>12</td>
<td>3.8</td>
<td>42</td>
</tr>
<tr>
<td>Ar</td>
<td>25</td>
<td>1.8</td>
<td>103</td>
</tr>
<tr>
<td>Xe</td>
<td>46</td>
<td>1.0</td>
<td>340</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>27</td>
<td>1.7</td>
<td>62</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>35</td>
<td>1.3</td>
<td>107</td>
</tr>
<tr>
<td>C$_2$H$_6$</td>
<td>43</td>
<td>1.1</td>
<td>113</td>
</tr>
</tbody>
</table>

From PDG
A. Cattai and G. Rolandi
Gas Amplification

- String a thin wire (anode) in the middle of a cylinder (cathode)
- Apply high voltage
- Electrons drift toward the anode, bumping into gas molecules
- Near the anode, $E$ becomes large enough to cause secondary ionization
- Number of electrons doubles at every collision

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

$$V(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \ln \frac{r}{a}$$

$C =$ capacitance / unit length
Avalanche Formation

- Avalanche forms within a few wire radii

- Electrons arrive at the anode quickly (< 1ns spread)
- Positive ions drift slowly outward
  - Current seen by the amplifier is dominated by this movement
Assuming that positive ion velocity is proportional to the E field, one can calculate the signal current that flows between the anode and the cathode

\[ I(t) \propto \frac{1}{t + t_0} \]

This “1/t” signal has a very long tail

- Only a small fraction (~1/5) of the total charge is available within useful time window (~100 ns)
- Electronics must contain differentiation to remove the tail
Gas Gain

- Gas gain increases with HV up to $10^5$–$10^6$
  - With $Q_n = 2000$ electrons and a factor $1/5$ loss due to the $1/t$ tail, gain = $10^5$ can detect a single-electron signal
- What limits the gas gain?
  - Recombination of electron-ion produces photons, which hit the cathode walls and kick out photo-electrons
    - Continuous discharge
  - Hydrocarbon is often added to suppress this effect
Drift Chambers

- Track-anode distance can be measured by the drift time

\[ x = \int_0^t v_D(t') dt' \]

- Need to know the \( x \)-vs-\( t \) relation

- Time of the first electron is most useful

Drift velocity
Depends on the local E field
Drift Velocity

- Simple stop-and-go model predicts
  \[ \vec{v}_D = \frac{e\tau}{m} \vec{E} = \mu \vec{E} \]
  \( \tau = \text{mean time between collisions} \)
  - \( \mu = \text{mobility (constant)} \)
  - This works only if the collision cross section \( \sigma \) is a constant
  - For most gases, \( \sigma \) is strongly dependent on the energy \( \varepsilon \)
    - \( v_D \) tends to saturate
    - It must be measured for each gas
    - c.f. \( \mu \) is constant for drift of positive ions

\[ G_{vD} = \frac{e\tau}{m} \]
\[ G_E = \mu \]
\[ \tau = \text{mean time between collisions} \]
Drift Velocity

- Example of $v_D$ for Ar-CF$_4$-CH$_4$ mixtures
  - “Fast” gas
- Typical gas mixtures have $v_D \sim 5$ cm/$\mu$s
  - e.g. Ar(50)-C$_2$H$_6$(50)
  - Saturation makes the $x$-$t$ relation linear
- “Slow” gas mixtures have $v_D \propto E$
  - e.g. CO$_2$(92)-C$_2$H$_6$(8)

T. Yamashita et al., NIM A317 (1992) 213
Spatial Resolution

- Typical resolution of a drift chamber is 50–200 \( \mu m \)
  - **Diffusion**: random fluctuation of the electron drift path
    \[
    \sigma_x(t) = \sqrt{2Dt} \quad D = \text{diffusion coefficient}
    \]
    - Smaller cells help
    - “Slow gas” has small \( D \) \{Micro vertex chambers (e.g. Mark-II)\}

- **Primary ionization statistics**
  - Where is the first-arriving electron?

- **Electronics**
  - How many electrons are needed to register a hit?
  - Time resolution (analog and digital)

- **Calibration** of the \( x-t \) relation

- **Alignment**
Other Performance Issues

- **$dE/dx$ resolution** – particle identification
  - Total ionization statistics, # of sampling per track, noise
  - 4% for OPAL jet chamber (159 samples)
  - 7% for BABAR drift chamber (40 samples)
- **Deadtime** – how quickly it can respond to the next event
  - Maximum drift time, pulse shaping, readout time
  - Typically a few 100 ns to several microseconds
- **Rate tolerance** – how many hits/cell/second it can handle
  - Ion drift time, signal pile up, HV power supply
  - Typically 1–100 kHz per anode
  - Also related: radiation damage of the detector
Design Exercise

- Let’s see how a real drift chamber has been designed
  - Example: BABAR drift chamber
Requirements

- Cover as much solid angle as possible around the beams
  - Cylindrical geometry
- Inner and outer radii limited by other elements
  - Inner radius $\sim 20$ cm: support pipe for the beam magnets
  - Out radius $\sim 80$ cm: calorimeter (*very* expensive to make larger)
- Particles come from decays of $B$ mesons
  - Maximum $p_t \sim 2.6$ GeV/$c$
  - Resolution goal: $\sigma(p_t)/p_t = 0.3\%$ for 1 GeV/$c$
  - Soft particles important $\Rightarrow$ Minimize multiple scattering!
  - Separating $\pi$ and $K$ important $\Rightarrow$ $dE/dx$ resolution 7%
- Good (not extreme) rate tolerance
  - Expect 500 k tracks/sec to enter the chamber
In a $B$ field, $p_t$ of a track is given by

$$p_T = 0.3B\rho$$

If $N$ measurements are made along a length of $L$ to determine the curvature

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_x p_T}{0.3BL^2} \sqrt{\frac{720}{N + 4}}$$

Given $L = 60$ cm, a realistic value of $N$ is 40.

To achieve 0.3% resolution for 1 GeV/c

$$\frac{\sigma_x}{B} = 80 \mu m/T$$

We can achieve this with $\sigma_x = 120 \mu m$ and $B = 1.5$ T.
Multiple Scattering

- Leading order: \( \theta_0 = \frac{13.6 \text{MeV}}{\beta c p} z \sqrt{L/X_0} \)

- Impact on \( p_T \) measurement: \( \sigma(p_T) = p_T \theta_0 = 0.0136 \sqrt{L/X_0} \)

- For an argon-based gas, \( X_0(\text{Ar}) = 110 \text{ m}, L = 0.6 \text{ m} \)
  \( \Rightarrow \sigma(p_T) = 1 \text{ MeV/c} \Rightarrow \text{Dominant error for } p_T < 580 \text{ MeV/c} \)

- We need a lighter gas!

- \( \text{He}(80)-\text{C}_2\text{H}_6(20) \) works better
  - \( X_0 = 594 \text{ m} \Rightarrow \sigma(p_T) = 0.4 \text{ MeV/c} \)

- We also need light materials for the structure
  - Inner wall is 1 mm beryllium (0.28\%\(X_0\))
  - Then there are the wires
Wires

- **Anode wires** must be thin enough to generate high $E$ field, yet strong enough to hold the tension
  - Pretty much only choice: 20 $\mu$m-thick Au-plated W wire
  - Can hold $\sim$60 grams
  - BABAR chamber strung with 25 g
- **Cathode wires** can be thicker
  - High surface field leads to rapid aging
  - Balance with material budget
  - BABAR used 120 $\mu$m-thick Au-plated Al wire
- Gas and wire add up to 0.3%$X_0$
Anode wire are located at an **unstable equilibrium** due to electrostatic force
- They start oscillating if the tension is too low
- Use numerical simulation (e.g. Garfield) to calculate the derivative $dF/dx$
- Apply **sufficient tension** to stabilize the wire
- Cathode wire tension is often chosen so that the **gravitational sag** matches for all wires

Simulation is also used to trace the electron drift and predict the chamber’s performance
Cell Size

- Smaller cells are better for high rates
  - More anode wires to share the rate
  - Shorter drift time $\Rightarrow$ shorter deadtime
- Drawbacks are
  - More readout channels $\Rightarrow$ cost, data volume, power, heat
  - More wires $\Rightarrow$ material, mechanical stress, construction time
- Ultimate limit comes from electrostatic instability
  - Minimum cell size for given wire length
- BABAR chose a squashed hexagonal cells
  - 1.2 cm radial $\times$ 1.6 cm azimuthal
  - 96 cells in the innermost layer
Wire Stringing In Progress
Gas Gain and Electronics

- With He(80)-C$_2$H$_6$(20), we expect 21 primary ionizations/cm
  - Simulation predicts ~80 $\mu$m resolution for leading electron
  - Threshold at 2–3 electrons should give 120 $\mu$m resolution
- Suppose we set the threshold at 10000 $e$, and 1/5 of the charge is available ($1/t$ tail) $\Rightarrow$ Gas gain $\sim 2\times10^4$
  - Easy to achieve stable operation at this gas gain
  - Want to keep it low to avoid aging
- Drift velocity is $\sim 25 \mu$m/ns
  - Time resolution must be <5 ns
  - Choose the lowest bandwidth compatible with this resolution
    - Simulation suggests 10–15 MHz
Actual Performance

Drift Chamber Hit Resolution

Average resolution = 125 μm

BABAR

σ = 7.5 %
Further Reading

- F. Sauli, *Principles of Operation of Multiwire Proportional and Drift Chambers*, CERN 77-09
- C. Joram, *Particle Detectors*, 2001 CERN Summer Student Lectures
- A. Foland, *From Hits to Four-Vectors*, NEPPSR-IV, 2005