Making Tracks at DØ

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What Does a Tracker Do?

- It finds tracks (well, duh!)
  - Particle ID (e/γ separation, b-tagging...)
- Measurements of
  - Momentum
  - Electric Charge
  - Impact Parameters
  - Position and Trajectory
Measuring Momentum

\[ \frac{L}{R} = \Delta \phi = \frac{\Delta p_T}{p_T} \]

\[ p_T = q B R \]

\[ \frac{1}{p_T} = \frac{\Delta \phi}{qBL} \]

Spatial resolution of outermost tracking layer

\[ d \left( \frac{1}{p_T} \right) = \frac{\Delta \phi}{qBL^2} ds \]

Momentum resolution gains more from tracking volume than magnetic field

<table>
<thead>
<tr>
<th></th>
<th>B (Tesla)</th>
<th>L (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DØ</td>
<td>2</td>
<td>52</td>
</tr>
<tr>
<td>CDF</td>
<td>1.4</td>
<td>140</td>
</tr>
</tbody>
</table>
Impact Parameters

$\mathbf{b} = D \sin \theta = D \frac{p_T^A}{p^A}$

Assume massless decay products...

$D = \gamma_D c \tau_D$  \hspace{1cm} \sin \theta = \frac{1}{\gamma_D}$

Impact parameter independent of boost!

- Impact parameter measurements for b-tagging, flavor physics, lepton ID...
- IP resolution driven by hit resolution
- Get hits close to original collision

<table>
<thead>
<tr>
<th></th>
<th>c$\tau$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^\pm$</td>
<td>312</td>
</tr>
<tr>
<td>$D^0$</td>
<td>123</td>
</tr>
<tr>
<td>$B^\pm$</td>
<td>491</td>
</tr>
<tr>
<td>$B^0$</td>
<td>457</td>
</tr>
</tbody>
</table>
Detector Technologies

- Bubble chambers:
  - Very good resolution
  - Way too slow for colliders

- Scintillators
  - High material budget
  - Speed $O(10 \text{ ns})$
  - Resolution $O(100 \ \mu\text{m})$

- Drift chambers/tubes
  - Low material budget
  - Speed $O(100 \text{ ns})$
  - Resolution $> 100 \ \mu\text{m}$

- Silicon
  - High material budget
  - Speed $O(10 \text{ ns})$
  - Resolution $O(10 \ \mu\text{m})$
Silicon Detectors

- Band gap is 1.12 eV for Silicon
- Really 3.6 eV needed for ionization (heating)
- MIP deposits 79 keV
- 22k electrons, 3.5 fC

Drift time \(~\sim\) 7ns

Depends on voltage and sensor thickness

Resolution depends on strip spacing

MIP = Minimum Ionizing Particle

Source: http://ecee.colorado.edu/~bart/book
A Problem

- Signal size is 22k electrons
- Charge carrier density in conduction band: $10^{11}$/cm$^3$
- Typical sensor dimensions
  - 300 $\mu$m thick
  - 6 cm long
  - 50 $\mu$m strip spacing (more relevant than width)
A Problem

- Signal size is 32k electrons
- Charge carrier density in conduction band: $10^{11}$/cm$^3$
- Typical sensor dimensions
  - 300 μm thick
  - 6 cm long
  - 50 μm strip spacing (more relevant than width)
- $10^8$ background charge carriers in neighborhood of signal
- Electron-hole pairs recombine easily
A Problem

- Signal size is 32k electrons
- Charge carrier density in conduction band: $10^{11}/\text{cm}^3$
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Behold, the Power of Diodes

$$I = I_0 \left( e^{\frac{qV}{kT}} - 1 \right)$$

O (10 nA), depends on temperature, doping

Depletion Region

Charge fixed to lattice fights the external voltage

Reverse bias
Depletion Voltage

- Voltages and fields from Poisson's equation
- Charge density:
  - Set by doping concentration ($N_{\text{eff}}$)
  - Zero outside depletion region
- p-side very thin, heavily doped
- Need full depletion for full efficiency

\[- \frac{d^2 V}{dx^2} = \frac{dE}{dx} = \frac{q}{\epsilon \epsilon_0} N_{\text{eff}}\]

\[V_{\text{depl}} = \frac{q_0}{2 \epsilon \epsilon_0} |N_{\text{eff}}| d^2\]
Closer to Reality

Double-Sided Sensor

- $V/2$
- $-V/2$
- $p^-$
- $n^-$
- $Al$ strip
- $300 \, \mu m$
- $SiO_2$
- $Si_3N_4$
- $n$-type bulk

Single-Sided Sensor

- $V/2$
- $V$
- $p^+$
- $n^+$
- $Al$ strip
- $300 \, \mu m$
- $SiO_2$
- $Si_3N_4$
- $n$-type bulk

Readout Chips

Double-sided Double-Metal

1\textsuperscript{st} metal layer: sensor strips

2\textsuperscript{nd} metal layer: bring signals to chips
Performance

CFT Axial Layer 8

\[ \sigma = 190 \ \mu m \]

IP resolution degraded by multiple scattering

Layer 0 NIM

SMT B3-1-3 (Layer 1)

\[ \sigma = 15 \ \mu m \]

Compare to B/D
c\tau = O(100 \ \mu m)
### Radiation Damage

#### Bulk Damage
- Ionization effects not important
- Non-ionizing: atoms knocked out of lattice
- Effectively induces p-type doping
- Changes depletion voltage

#### Surface Damage
- Charge trapping in insulating layer
- Increases in leakage current
- Large electric fields near surface
- Breakdowns at high voltage
Signs of Aging

\[ V_{\text{depl}} = \frac{q_0}{2 \varepsilon \varepsilon_0} |N_{\text{eff}}| d^2 \]

- If applied voltage too high (~150 V):
  - Noise increases dramatically (microdischarge)
  - Coupling capacitors breakdown (non-recoverable)

n-type semiconductor |N_{\text{eff}}| decreasing

p-type semiconductor |N_{\text{eff}}| increasing
Summary

- Tracking detectors are an important component of collider experiments
- Semiconductor devices satisfy key requirements of speed and precision
- Reverse biased diode configurations make signal to noise ratio manageable
- Lifetime of silicon detectors limited by radiation induced effects
  - Microdischarge
  - Changes in depletion voltage
For Further Information

- *The Physics of Particle Detectors*, Dan Green
- *Semiconductor Radiation Detectors*, Gerhard Lutz
- *Silicon Particle Detectors - Why they are useful and how they work*, William Trischuk
- *Depletion Voltage for the DØ Silicon Microstrip Tracker Using the n-side Noise Method*, DØ Note 4917 (S. Burdin and S. Lager)
Backup Slides
Measuring Depletion Voltage

Determine depletion voltage by looking at signal size vs applied voltage

Can also look at noise levels

Plots stolen from Masato
The DØ Silicon Tracker

Staggered sublayers to avoid $\phi$ gaps

In total, 731,136 readout channels

2 H-Disks
6 Barrels
12 F-Disks

Double sided barrel

Layer 0
Layer 1
Layer 2
Layer 3
Layer 4

r-z view
The DØ Tracking System

- **SMT**: 50 μm (strip spacing)
- **CFT**: 835 μm (fiber width)

**Diagram:**

- Central Calorimeter Cryostat Wall
- Solenoid
- CFT
- SMT

**Measurements:**

- Strips and spacing
- Fiber width

**Graph:**

- Tracking System Pt Resolution (1 GeV/c Pt track)
- ΔP / P (%)

**Notes:**

- Without H-disks
- With H-disks

End View (CFT)
Lorentz Drifts

\[ E = \frac{V}{d} \]

Drift velocity
\[ \mathbf{v} = \mu \mathbf{E} = \mu \frac{\mathbf{V}}{d} \]

Mobility (cm\(^2\)/Vs)

<table>
<thead>
<tr>
<th></th>
<th>electrons</th>
<th>holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility</td>
<td>1400</td>
<td>450</td>
</tr>
</tbody>
</table>

Hall Mobility (cm\(^2\)/Vs)

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<thead>
<tr>
<th></th>
<th>Hall Mobility</th>
<th>tan θ</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrons</td>
<td>1670</td>
<td>0.33</td>
</tr>
<tr>
<td>holes</td>
<td>370</td>
<td>0.74</td>
</tr>
</tbody>
</table>