Measurement of the radiation field at the Collider Detector at Fermilab

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Motivation / Outline

What
We present here the first measurement of the radiation field in a hadron collider

Why
We use silicon to detect charged particles produced in proton-antiproton collisions, but radiation damages it and limits its useful lifetime

How
We use Thermal Luminescent Dosimeters (TLDs) to construct an accurate map of the ionizing radiation field

Results
Radiation prediction from silicon observations agrees with expectations from radiation field measurements
Experimental environment: the collider

Tevatron:

- Proton-antiproton collider, at Batavia, IL, of 1 km radius
- Circulating protons and antiprotons collide every $\sim 396$ ns at two designated points around the Tevatron
- Collision energy $= 2$ TeV
Experimental environment: the detector

The Collider Detector at Fermilab (CDF):

- Cylindrically symmetric detector surrounding one of the collision points and measuring the produced particles
- Precise measurement of charged particles with silicon sensors intercepting them (each collision produces ~ 8 primary charged particles traversing our tracking volume)
Experimental environment: radiation

But radiation is a problem:

- Radiation damages the silicon detector
- Knowing the amount of radiation seen by the silicon detectors allows prediction of the device’s useful lifetime

⇒ Important when designing the experiment and planning for replacement devices

Measure radiation field with Thermal Luminescent Dosimeters:

Advantages:
+ Industry standard
+ Continuously integrate radiation
+ Passive devices (no active readout, no power)
+ Large dynamic range: 1 mRad to 200 kRad
+ Very good precision
+ On site TLD reader → fast turn around

Disadvantages:
- Require harvesting and reading individual dosimeters
- Large amount of handling

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Radiation measurement: How?

Two types of Thermal Luminescent Dosimeters:

- **TLD-700 (\(^7\text{LiF}\)):** sensitive to ionizing radiation
- **TLD-600 (\(^6\text{LiF}\)):** sensitive to both ionizing radiation and low energy neutrons (\(E < 200\) keV)

**TLD calibration:**

- **Ionizing radiation:** 1 Rad exposure to a \(^{137}\text{Cs}\) source
  - \(\sim 1\%\) reproducibility and \(\sim 3\%\) chip-to-chip variation

- **Neutron calibration:** 10 mRad exposure to \(^{252}\text{Cf}\) source
  - \(\sim 10\%\) reproducibility and \(\sim 15\%\) chip-to-chip variation.

Place \(\sim 1000\) TLDs in the detector, in triplets for redundancy:
Radiation measurement: TLD exposure

Losses of incoming proton ($p$) and antiproton ($\bar{p}$) beams: monitored by scintillator counters and by ionization chambers, on each side of CDF close to the beam pipe.

Number of collisions (luminosity at CDF location): measured by Cherenkov radiation counters.

Two TLD exposure periods analyzed:
  Feb. - May 2001: loss dominated period
  May - Oct. 2001: collision dominated period

<table>
<thead>
<tr>
<th>Period</th>
<th>Beam ($\times 10^{19}$)</th>
<th>Losses ($\times 10^9$)</th>
<th>$\int L dt$ (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p$</td>
<td>$\bar{p}$</td>
<td>$p$</td>
</tr>
<tr>
<td>Feb. - May 2001</td>
<td>0.0703</td>
<td>0.0082</td>
<td>15.3</td>
</tr>
<tr>
<td>May - Oct. 2001</td>
<td>1.56</td>
<td>0.137</td>
<td>40.9</td>
</tr>
</tbody>
</table>

Feb. - May 2001: Proton Losses / Collisions = $264 \times 10^9$/pb$^{-1}$

May - Oct. 2001: Proton Losses / Collisions = $3.9 \times 10^9$/pb$^{-1}$

(Note: 1 pb$^{-1}$ corresponds to $\sim 5 \times 10^{10}$ $p\bar{p}$ interactions)
Ionizing radiation measurements

Feb - May 2001 Exposure
- $r = 34$ cm (ISL space tube)
- $r = 17$ cm (SVX space tube)

May - Oct 2001 Exposure
- $r = 34$ cm (ISL space tube)
- $r = 17$ cm (SVX space tube)

$p \xrightarrow{\text{C}} \bar{p}$

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**Ionizing radiation:** ~ 98% Collisions + ~ 2% Losses

### Collisions
- SVX space tube (r=17.7 cm)
- ISL space tube (r=34.7 cm)
- p-Loss Scale Uncertainty

### Proton Losses
- SVX space tube (r=17.7 cm)
- ISL space tube (r=34.7 cm)
\[ \frac{L}{C} = 3.9 \times 10^9 / \text{pb}^{-1} \]

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Neutron radiation measurements

- Feb - May 2001 Exposure
  - $r = 34$ cm (ISL space tube)
  - $r = 17$ cm (SVX space tube)

- May - Oct 2001 Exposure
  - $r = 34$ cm (ISL space tube)
  - $r = 17$ cm (SVX space tube)

$p \rightarrow \bar{p}$

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Modeling the ionizing radiation field


- Cylindrical symmetry about the beam

- Field follows power law in $1/r$ ($r = \text{distance from beam}$)

$$\text{Dose}(x, y) = A \left( \frac{1}{\sqrt{(x-x_0)^2+(y-y_0)^2}} \right)^\alpha$$

In the silicon region: $\alpha \approx 1.5 - 1.8$ (z dependent)

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At $r = 3$ cm: $\text{Dose}|_{r=3\text{cm}} = 300 \pm 60 \text{ rad/pb}^{-1}$
The silicon as a radiation monitor

Particle flux
↓
increase in leakage current, $I$
(more difficult to get the signal out of the increased noise)
↓

$$\Delta I = \alpha_{\text{damage}} \Phi \text{ Volume}$$

$\Phi = \text{particle fluence}$
$= \text{time integrated number of particles per unit area}$

$\alpha_{\text{damage}} = \text{“damage factor”}$
$= 3 \times 10^{-17} \text{ A/cm for minimum ionizing particles going through silicon kept at a temperature of } 20^{\circ}\text{C}$

→ Damage factor depends on temperature: apply corrections for the actual silicon sensor’s temperature ($\sim 8^{\circ}\text{C}$)

• Convert dose measured by TLDs into fluence for comparison:
  $1 \text{ Rad} = 3.8 \times 10^7$ minimum ionizing particles / cm$^2$
What the silicon saw

Total particle fluence (particles/cm²) per pb⁻¹ of collisions:

![Graph]

The curve is NOT a fit

Model from TLD measurements agrees with silicon measurements: extrapolation by a factor of 10 in 1/r works!

Note: Modulation is due to beam axis not the same as detector z axis: → x₀ ≠ 0 and y₀ ≠ 0
Summary

- Installed ~ 1000 TLDs in the tracking volume of the Collider Detector at Fermilab:
  measured ionizing and low energy neutron ($E_n < 200$ keV) radiation

- TLDs provide accurate measurement of the radiation fields:
  Ionizing radiation ~ 5% uncertainty
  Low energy neutron radiation ~ 20% uncertainty

- Separate radiation due to collisions and losses
  Given the beam conditions we predict the radiation field

- Build a simple model for the ionizing radiation field

- Measurements of leakage currents in silicon give fluence of particles comparable to prediction from the simple radiation field model

THE END
# Appendix 1: TLD locations

![Diagram of TLD locations]

<table>
<thead>
<tr>
<th>Location</th>
<th># phi</th>
<th># z</th>
<th># r</th>
<th>Total # Holders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plug faces</td>
<td>8</td>
<td>2</td>
<td>5</td>
<td>80</td>
</tr>
<tr>
<td>SVX</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>ISL</td>
<td>8</td>
<td>5</td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>TOTAL # of TLD chips</td>
<td></td>
<td></td>
<td></td>
<td>916</td>
</tr>
</tbody>
</table>

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Appendix 2: Dosimetry

Ionizing radiation dosimetry:

\[ D_\gamma = C \cdot k_\gamma R_{700} - D_{\gamma,\text{control}} \]

- \( R_{700} \): TLD-700 reading (nC)
- \( k_\gamma \): ionizing radiation calibration constant (Rad/nC)
- \( C \): non-linearity correction
- \( D_{\gamma,\text{control}} \): control dosimeters’ ionizing dose (background level)

Neutron radiation dosimetry:

\[ D_n = \frac{k_n}{k_\gamma} (C \cdot k_\gamma R_{600} - D_\gamma) - D_{n,\text{control}} \]

- \( R_{600} \): TLD-600 reading (nC)
- \( k_\gamma \): ionizing radiation calibration constant (Rad/nC)
- \( k_n \): Neutron radiation calibration constant (Rad/nC)
- \( C \): non-linearity correction
- \( D_\gamma \): ionizing radiation dose, from the TLD-700’s at the same spot
- \( D_{n,\text{control}} \): control dosimeters’ neutron dose (background level)
Appendix 3: TLD response, linearity

TLD-700 response to ionizing radiation ($^{137}$Cs):

TLD-600 response to ionizing radiation ($^{137}$Cs):
Appendix 4: $^6$Li neutron absorption

Neutron absorption cross section of $^6$Li and $^7$Li

Neutron emission spectrum of $^{252}$Cf

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