Lifetime of the CDF RunII Silicon

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(with help from the CDF Radiation Monitoring and CDF Silicon Groups)
Outline

- Is the CDF silicon measurably damaged by radiation?
  - Measuring the radiation field
    - Leakage current measurements
    - TLD measurements from the tracking volume
    - Depletion voltage measured from noise
- Lifetime of the Run IIa silicon
  - How does the silicon ‘die’?
    - Signal
    - Noise
    - Degradation in b-tagging
- How long can it live?
- Conclusions
Is there measurable Radiation Damage at CDF? (YES!)

- Leakage current increases from surface and bulk damage
- Depletion voltage changes too...

We now have both radiation damaged silicon from a hadron collider environment, and models with which to compare.
Leakage Current vs Integrated Luminosity

- 326 pb⁻¹ delivered to CDF

- Current vs Luminosity well measured
  - measured for a stable run period
  - 100.7 pb⁻¹, from 8/15/02 to 1/21/03
  - Large variations seen module-to-module, especially for Micron sensors
  - Using (guard+bias)/volume

<table>
<thead>
<tr>
<th>Layer</th>
<th>ΔI/ ladder [µA]</th>
<th>RMS [µA]</th>
<th>Fluence 1 MeV n 1E12 /cm²/fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 00 narrow</td>
<td>4.89</td>
<td>1.57</td>
<td>30</td>
</tr>
<tr>
<td>Layer 00 wide</td>
<td>6.47</td>
<td>1.93</td>
<td>20</td>
</tr>
<tr>
<td>Layer 0</td>
<td>10</td>
<td>1.99</td>
<td>9.3</td>
</tr>
<tr>
<td>Layer 1</td>
<td>8.1</td>
<td>2.00</td>
<td>5.1</td>
</tr>
<tr>
<td>Layer 2</td>
<td>5.2</td>
<td>2.94</td>
<td>2.4</td>
</tr>
<tr>
<td>Layer 3</td>
<td>5.88</td>
<td>1.60</td>
<td>1.8</td>
</tr>
<tr>
<td>Layer 4</td>
<td>4.37</td>
<td>2.41</td>
<td>1.2</td>
</tr>
</tbody>
</table>

[Graph showing Luminosity vs Store #]
Run II Measurements vs. Run I Predictions

- Predictions from Run I vs. recent measurements
  - Currents measured in Run Ia and Run Ib average to be
    \[ I(24C,3\text{cm}) = 0.69 \pm 0.11 \text{ nA/strip/pb}^{-1} \]
  - Using \( \alpha = (3.0 \pm 1.0) \times 10^{-17} \text{A/cm} \) and scaling temperature, we predict
    \[ \Phi(1\text{MeVn},L0) = (0.50 \pm 0.16) \times 10^{13} \text{ 1MeVn/cm}^2/\text{fb}^{-1} \]
  - Measurement from Run II is
    \[ \Phi(1\text{MeVn},L0) = (0.93 \pm 0.26) \times 10^{13} \text{ 1MeVn/cm}^2/\text{fb}^{-1} \]

- Why are they different? Not sure, but...
  - CDF has been substantially reconfigured
  - Run II detector has much more material
  - Errors are still large; difference is only \( \sim 2\sigma \)
  - We are colder now, should probably use different \( \alpha \)...

- What does this mean for the LHC?
  - Had been quoting CDF Run I measurements as check of simulations
  - LHC has more/different material
Noise as a measure of Depletion Voltage?

- Noise drops on n-side as Si is depleted
  - With double-sided silicon, might provide convenient monitor of Vdep
  - Operating voltages set to 20V (5V) above Vdep for Hamamatsu (Micron) Silicon
  - Can be automated and measured quickly, without collisions
  - “dnoise” = common mode subtracted noise

- Several measurements made:
  - Mar  •  179 pb⁻¹
  - July □  273 pb⁻¹
  - Aug +  302 pb⁻¹
  - Sept *  326 pb⁻¹

- Differences with CV and signal collection under study
n-side Noise vs Bias scans
(preliminary results)

- Automate procedure for all layers and wedges
  - “Vdep” defined to be noise increase by >4%
  - Data for all layers of ISL, SVX

- Change in Vdep Evident
  - Nominal settings are vendor CV +20V (+5V) for Hamamatsu (Micron)
  - L0 shows average 15V decrease in Vdep

- Charge collection vs Vdep and L00 changes to be studied with signal scan
Measuring the Radiation Field: TLDs

- Thermo-luminescent Dosimeters (TLDs) have many advantages
  - Industry standard
  - Passive devices
  - Large range (mRad to 0.2 Mrad)
  - Excellent accuracy; 3% chip-to-chip variation, 1% reproducibility

- They also have some drawbacks
  - Require a lot of handing
  - Must be ‘harvested’ and read out

- TLDs with sensitivity to ionizing particles or neutrons are available.
Tracking Volume TLDs

- TLDs with $^7\text{Li}$, $^6\text{Li}$
  - Sensitive to $\gamma$, $n$

TLD placement

- TLD holders attached to kapton film and pulled into place like a 'clothesline'
- Kapton leads fed through cables for silicon and drift chamber
- Finding the ends can be difficult!
TLD data

- Data from three exposure periods
  - First one during loss-dominated period
  - Second period was a mix of losses and collisions
  - Final measurement almost all collisions

<table>
<thead>
<tr>
<th>Period</th>
<th>Fraction of Dose From Losses (%)</th>
<th>Integrated Lum (pb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 01 – May 01</td>
<td>80-90</td>
<td>0.06</td>
</tr>
<tr>
<td>May 01 – Oct 01</td>
<td>15-25</td>
<td>10.7</td>
</tr>
<tr>
<td>Oct 01 – Jan 03</td>
<td>5-10</td>
<td>159</td>
</tr>
</tbody>
</table>
Latest TLD results
(preliminary)

- New measurement over long stable data taking period
- Last two measurements compare well
  - May 2001 to Oct 2001 (10.7 pb\(^{-1}\))
  - Oct 2001 to Jan 2003 (159 pb\(^{-1}\))
  - Raw ionizing radiation dose rates vs. z are very similar
“Death” of the Silicon; Modeling the S/N

- We expect that the inner silicon layers will eventually be unusable due to low S/N
  - Displaced track triggering will be good to S/N = 8.
  - B-tagging will be degraded at low S/N (in Run I, $\varepsilon$ was lost below S/N ~6)

- Noise
  - Shot noise calculated from leakage current
  - Chip noise measured in controlled irradiations

- Signal
  - Double-sided AC-coupled silicon $\rightarrow$ voltage across readout caps
  - ~170V maximum depletion, from burn-in (180V) and other concerns
  - Axial strips are on p-side; can’t get axial info while underdepleted
  - Depletion voltage estimates are therefore critical
  - We assume full charge collection throughout Run II
Noise Model for CDF

- **Shot noise**
  - Shot noise (108 ns int time) is given by
    \[
    Q_{\text{shot}} = 900e^- \times \sqrt{I(\mu A)} \\
    I_{L0} = 0.39 \text{ nA/strip/pb}^{-1}
    \]
  - Radial scaling is estimated by using the TLD central data ($1/r^{1.590\pm0.008}$)

- **Chip noise**
  - Chip noise varied from 52 to 100 e$^-$/pF in 0-15 Mrad
  - Zero-load noise varied from 650 to 1100 e$^-$ in 0-15 Mrad

- **Inputs to model of leakage vs dose and initial noise now well measured**

### Sample values for 4 fb$^{-1}$:

<table>
<thead>
<tr>
<th>Layer</th>
<th>Luminosity</th>
<th>Shot</th>
<th>Chip</th>
<th>Shot+Chip</th>
<th>S/N(20ke$^-$)</th>
<th>Noise (ADC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0-phi</td>
<td>4</td>
<td>1125</td>
<td>1740</td>
<td>2072</td>
<td>9.7</td>
<td>3.5</td>
</tr>
<tr>
<td>L0-Z</td>
<td>4</td>
<td>1124</td>
<td>2175</td>
<td>2449</td>
<td>8.2</td>
<td>4.1</td>
</tr>
<tr>
<td>L1-phi</td>
<td>4</td>
<td>776</td>
<td>1665</td>
<td>1837</td>
<td>10.9</td>
<td>3.1</td>
</tr>
<tr>
<td>L1-Z</td>
<td>4</td>
<td>776</td>
<td>2081</td>
<td>2221</td>
<td>9.0</td>
<td>3.7</td>
</tr>
</tbody>
</table>
Noise Model; Results

- Noise degrades more steeply at first, then gradually.
- $S/N$ follows same trend (assuming full signal collection) and does not quite reach 6 for $L_0$.

$S/N$ begins near 12.5, and is expected to decline gradually.
Depletion Voltage Model

We parameterize the Depletion Voltage in three parts (Hamburg model):
\[ \Delta N_{\text{eff}}(T, t, \Phi) = N_A + N_C + N_Y \]

- **Short term annealing** \((N_A)\)
  \[ N_A = \Phi_{eq} \sum_i g_{a,i} \exp(-k_{a,i}(T)t) \]
  - Reduces \(N_Y\) (beneficial)
  - Time constant is a few days at 20 °C

- **Stable component** \((N_C)\)
  \[ N_C = N_{c0}(1-\exp(-c \Phi_{eq}))+g_c \Phi_{eq} \]
  - Does not anneal (does not depend on time or temperature)
  - Partial donor removal (exponential or limited exponential)
  - Creation of acceptor sites (linear)

- **Long term reverse annealing** \((N_Y)\)
  \[ N_Y = N_{Y,\infty}[1-1/(1+ N_{Y,\infty}k_Y(T)t)], N_{Y,\infty}= g_Y \Phi_{eq} \]
  - Strong temperature dependance
  - Can be significant long term; must cool Si

Fig. 13: Annealing behaviour of the radiation induced change in the effective doping concentration \(\Delta N_{\text{eff}}\) at 60°C.
Depletion Voltage Model – cont.

- Estimated overvoltage is included
  - We use a geometric model to estimate overvoltage \[ \text{[SCIPP 93/16]} \];
    \[
    V_{\text{dep}} = V_{\text{planar}}(1+(p/d)F(w/p))
    \]
    \[
    F(x) = -0.00111x^{-2} + 0.0586x^{-1} + 0.240 - 0.651x + 0.3555x^2
    \]
  - Provides a large multiplicative factor for CV \( V_{\text{planar}} \), especially with narrow strips with wide pitches

- Long term (reverse) annealing is significant only at the end of the run

<table>
<thead>
<tr>
<th>Parameter ( g_y ) [10^{-2}\text{cm}^{-1}]</th>
<th>Value ( 4.6 \pm 0.3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g_c ) [10^{-2}\text{cm}^{-1}]</td>
<td>( 1.77 \pm 0.07 )</td>
</tr>
<tr>
<td>( N_{c0} ) [10^{11}\text{cm}^{-3}]</td>
<td>( 5.0 \pm 0.2 )</td>
</tr>
<tr>
<td>( E_a ) [\text{eV}]</td>
<td>( 1.31 \pm 0.04 )</td>
</tr>
<tr>
<td>( c ) [10^{-13}\text{cm}^2]</td>
<td>( 2.0 )</td>
</tr>
</tbody>
</table>
Luminosity and Temperature Model

- Luminosity Model provided by the Tevatron Beams Division (July ‘03)
  - “Design” goal is ~6.5 fb\(^{-1}\) by mid 2008
  - “Base” goal is ~3.6 fb\(^{-1}\) by mid 2008
  - Expected shutdown periods included
  - Numbers are far more realistic than in the past... unfortunately also lower

- Temperature modeled on current operating conditions
  - Chiller temperature is -6 °C
  - Warm parts of SVXII silicon are 12±2 °C cold, 16 °C warm (design temperature)
  - We can probably go colder
**Depletion Voltage Results**

- **Results for “Base” luminosity**
  - Indicates full depletion throughout RunIIa
  - Bands indicate approximate errors
  - Red dot is measurement from noise study

- **Results for “Design” luminosity**
  (assumes reasonable TeVatron improvement)
  - Silicon inner layer will die from radiation
  - Long term annealing becomes important
  - Errors are rather large, driven by large ladder to ladder RMS
An example “Real World” effect: Beam Offset

- The CDF detector and Tevatron beam are not perfectly co-axial
  Assuming a $1/r^{1.6}$ radial dependence, the top sensors of LOO receive
  $\sim$50% more radiation than the bottom ones.

- Offset will be corrected in an upcoming shutdown

<table>
<thead>
<tr>
<th></th>
<th>$x$ [mm]</th>
<th>$y$ [mm]</th>
<th>$x'$ [$\mu$m]</th>
<th>$y'$ [$\mu$m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVXII</td>
<td>-1.0625</td>
<td>1.5003</td>
<td>756</td>
<td>-314</td>
</tr>
<tr>
<td>Beam</td>
<td>-1.8</td>
<td>4.5</td>
<td>600</td>
<td>100</td>
</tr>
<tr>
<td>difference</td>
<td>-0.74</td>
<td>3.00</td>
<td>-156</td>
<td>414</td>
</tr>
</tbody>
</table>

The models can be used as a guide, but the errors are often larger in the “real world”
Will the CDF Silicon “Age Gracefully”? 

We use simulation to study the degradation in tracking and b-tagging performance vs. integrated luminosity.

- Generate $t\bar{t} \rightarrow Wb(Wb)$ events and use CDF detector simulation
- To degrade the simulation we
  - Add shot and chip noise on all strips, according to expectations
  - Degrade resolution with noise
  - Recluster the silicon strips with new thresholds
  - Assume no trapping and full depletion
  - Remove Si layers as they ‘die’ from underdepletion
- Measure how often a b quark in the detector results in a ‘tag’
  (nb: not a quantity the physics groups usually look at)
  \[ \varepsilon = \frac{\text{#tagged b's}}{\text{#b's}} \]
- Iterate over different radiation damage scenarios
Degradation in b-tag efficiency
(preliminary results)

- **Secondary Vertex Tagging (b jets)**
  - HERWIG Monte Carlo study
  - Secondary vertex (b) tagged events
  - Remove L0 from tracking at 6-8 fb⁻¹ (orange points)
  - Remove L1 at 10-12 fb⁻¹

- **Requirements:**
  - b is in the detector (|η|<1.1)
  - b yields a jet w/ at least two tracks
  - L00 not included
    - Not yet in the 'default' tracking
    - Not studied yet for tagging

- **Results**
  - efficiency still good after S/N degraded
  - L00 must be fully integrated and must survive to maintain tag efficiency
Conclusion

We now have Run II radiation measurements and models of S/N to compare

Assuming reasonable luminosity, we expect L0 will 'die' from underdepletion

The Run IIa silicon should continue to provide good vertex information until (at least) 6 fb\(^{-1}\).

CDF Run IIa silicon was designed for 2 fb\(^{-1}\) and 2 years of operation...
Two years done, only 6 more years to go!
Backup – D0 vs CDF

- D0 should live to “at least 4 fb-1”, CDF to 6fb-1, but…
  - D0 is ~10 °C colder
  - D0 inner layer is at 3cm, CDF is at 2.5cm

- Some things to consider are…
  - Resistivity differs in inner layer (Micron vs. Hamamatsu)
    - Initial Vdep for D0 is 20-30V
    - Initial Vdep for CDF is 70-80V
  - 170V depletion for CDF without problems, less for D0
    - Microdischarge problems on one side due to alignment of implant and metal
    - Burn-in voltages lower?? (not sure…)
  - 7-8 barrel layers for CDF, much less for D0
  - Different models for Vdep
## Backup – Losses/Beam Detail

### Table of Integrated Losses and Beam Details

<table>
<thead>
<tr>
<th>Period</th>
<th>Beam (x10^{19})</th>
<th>Losses (x10^9)</th>
<th>Integrated Lum (pb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 01 - May 01</td>
<td>p 0.07, p 0.008</td>
<td>p 15.3, p 2.0</td>
<td>0.06</td>
</tr>
<tr>
<td>May 01 - Oct 01</td>
<td>1.56, 0.14</td>
<td>40.9, 10.2</td>
<td>10.7</td>
</tr>
<tr>
<td>Oct 01 - Jan 03</td>
<td>9.65, 0.657</td>
<td>621, 440</td>
<td>159</td>
</tr>
</tbody>
</table>

### Graphs
- **Dose vs. Rad**
  - **Preliminary**
  - **Equation**: $Dose = Ar^{-\alpha}$
- **Dose vs. Z (cm)**
  - **Preliminary**
  - **Equation**: $Dose = Ar^{-\alpha}$


Backup – Vdep L1 Model

Depletion Voltage

Fiscal Year
(4 = Oct 2003)
Backup - RunI b-Tag vs S/N

Figure 3: MC Run 1B relative b-tag efficiency versus S/N. Each point is determined with the same simulation. Corresponding integrated luminosity are shown along the top of the plot. The error bars are statistical and systematic uncertainties. All S/N is in pb^{2} to equation (3). The integrated luminosity for the different runs are indicated along the bottom of the plot. The error bars are statistical and systematic uncertainties. The data for layer 0 is shown as a square (statistical error only).
## Backup – Resolutions (input to Monte Carlo)

<table>
<thead>
<tr>
<th>layer</th>
<th>phi-side resolutions</th>
<th>z-side resolutions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-strip</td>
<td>2-strip</td>
</tr>
<tr>
<td>0</td>
<td>0.0011</td>
<td>0.0009</td>
</tr>
<tr>
<td>1</td>
<td>0.0013</td>
<td>0.0011</td>
</tr>
<tr>
<td>2</td>
<td>0.0013</td>
<td>0.0011</td>
</tr>
<tr>
<td>3</td>
<td>0.0013</td>
<td>0.0011</td>
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<tr>
<td>4</td>
<td>0.0013</td>
<td>0.0011</td>
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<tr>
<td>5</td>
<td>0.0014</td>
<td>0.0012</td>
</tr>
<tr>
<td>6</td>
<td>0.0024</td>
<td>0.0021</td>
</tr>
<tr>
<td>7</td>
<td>0.0024</td>
<td>0.0021</td>
</tr>
</tbody>
</table>