Radiation Damage and Operational Experience in the CDF-II Silicon Detector

And a few words on the D0 silicon detector Radiation Damage

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(on behalf of the CDF II Silicon group)

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HEP Detectors at the Tevatron

**Tevatron**: proton-antiproton collider at $\sqrt{s} = 1.96$ TeV

- Luminosity: more than $8\, \text{fb}^{-1}$ delivered
- Expected $11\, \text{fb}^{-1}$ delivered by 2011

Two multi-purpose, multi-layered detectors: CDF & DØ

**CDF II**: Tracking Volume

- Double sided, multilayered silicon strip detectors designed for $\sim 3\, \text{fb}^{-1}$
- Large open-cell drift chamber

**DØ**: Tracking Volume

- Double sided, multilayered silicon strip detector, with recent inner layer upgrade
- Scintillating fiber outer tracker
Running beyond 2011?

- The Tevatron is going strong: ~100 publications last year alone.
- The current LHC 2010/11 plan announcements is:
  
  \[ 1 \text{ fb}^{-1} @ 7 \text{ TeV} \text{ by end of 2011 & down in 2012 for 1-1.5 yrs} \]

- Tevatron will remain highly competitive in a variety of physics programs, especially including the low mass SM Higgs searches.

There is a strong physics case for running the Tevatron for 3 more years after 2011 (20 fb\(^{-1}\))

Can the silicon detectors provide efficient data that long?

With projected improvements achieved (x1.5 in sensitivity from now)
Overview:

- Three components: SVX-II, ISL, L00
- 7-8 layers, 722k readout channels
- 3D hit information
- SVX3 chips for the silicon readout

**SVX:** Double sided silicon Layers 0,1,3 (Hamamatsu) perpendicular strips, Layer 2+4 (Micron) small angled strips

**ISL:** Additional layers, Hamamatsu+Micron add forward coverage

**L00:** Single-sided “Narrows” (SGS Thomson and 2 Micron) “Wides” (Hamamatsu)
Radiation Damage

Two general types of radiation damage to the sensors:

- **Crystal damage** due to Non-Ionizing Energy Loss (NIEL): displacement damage, crystal defects.
  - increase of shot noise, change of effective doping concentration, increase of charge carrier trapping.

- **Surface damage** from Ionizing Energy Loss (IEL) causing accumulation of charge in the SiO2 and the Si/SiO2 interface.
  - Inter-strip capacitance, breakdown behavior etc.

Crystal damage to the sensors is the main concern for sensor longevity
Aging Studies – Variables of Interest

- Information on integrated radiation dose in a sensor is obtained from:
  - **evolution of bias current**: provides “direct” information on the crystal condition, due to increase in leakage current. Change in leakage current is linear with the absorbed dose $\Delta I_{\text{leak}} = \alpha \Delta \Phi_{\text{eq}}$ ($\alpha$ measured in 2004 to be $1.65 \pm 0.12$)

- **evolution of depletion voltage**: gives information on our ability to deplete the sensors in the future. Its extrapolation predicts the need to raise applied bias voltage and its limit.

- **Signal-over-noise (S/N) studies**: provide estimates of usability of the detector in charged particle tracking and in turn for physics analyses.
Depletion Voltage Measurement

- **From charge (signal) collection efficiency:**
  - Charge collection is proportional to the depleted volume
  - Fully depleted sensor → charge collection efficiency saturates

- **From noise at the n-side:**
  - Thermal noise from free carriers on the n-side is reduced with depletion (on the p-side)
Depletion Voltage Study -- Signal Vs. Bias

- Plot charge for different bias voltages

- Define depletion voltage, $V_d$, as voltage that collects 95% of the charge at the plateau

- Depletion Voltage as a function of integrated luminosity
  - 3rd order polynomial fit around the inversion point
  - Linear fit to extrapolate to the future
Depletion Voltage Projection L00-L0

- Prediction for L00
- Prediction for SVX-L0

We will be able to fully deplete most of the sensors until 11 fb⁻¹

82×10^{12} 1MeV equivalent neutrons [cm²]
Depletion Voltage Projection - L1

Then, are the outer layers of no concern?
Some ladders in L2 and L4 had a recent efficiency drop (9 out of 172)
- Layers became under-depleted as they aged.
- All 9 had their bias increased with no increases in noise.

**Readout Time**
- Increases in noise in increases in the detector readout time, which increases the Likelihood of harmful “wire bond resonance” conditions.

- Recent work on noisy ladders ADC thresholds has reduced our average readout time, and allowed increases the L1 trigger rate from 25kHz to 31kHz (first of our 3 level trigger system)
SVXII Signal / Noise Projection

Signal from $J/\psi \rightarrow \mu^+\mu^-$ tracks strip cluster charge,
Noise estimation from regular calibrations
Not only the sensors are in a radiation environment

Main components:
- **Silicon Readout Controller (SRC):** “brain” of the system
- **Fiber Interface Board (FIB):** control signals and optical readout
- **Portcard:** chip commands and optical transmitters (DOIMs)
Leaving NO Ladder Behind

- Detector was designed for Run IIa (2-3 fb⁻¹)

- Currently ~90% ladders integrated, ~80% good (< 1% error rate), ~10% bad with an average error rate of 10%

- Maintaining this level of integrity means a lot of work from the group; we use almost every opportunity for diagnostic and repair work

- Great performance after 9 years of running!
Some of the common failure modes:

- Detector = Port-cards, Junction Cards, cables, and sensors issues.

- Optical = errors from the TX data transmitters in the port-cards

- Jumper failures = chip damage due to resonances

- AVDD2 = a SVX3D chip failure mode caused by thermal cycles
Other Operational Challenges

- **CAEN SY527 Power Supplies**
  - Communication loss, corrupted read-back, spontaneous switch off, leaking capacitors
  - A significant fraction of the supplies has been repaired

- **ISL Cooling Repairs**
  - Glycol-water mix turned acidic causing corrosion.
  - Repairs are challenging, access is possible only from inside the cooling conduits.
  - Repairs during the 2007 and 2009 shutdowns have significantly improved the tightness of the system.
  - Additional repairs to conical manifolds are planned for this summer

- **Maintaining spare electronic components** is a challenge but we have been successful in maintaining our spare pool
DOIM Longevity

- Dense Optical Interface Modules (DOIMs) are mounted on the Port Cards, inside the bore, 10 cm from the beam axis.
- Chosen for high bandwidth data transmission with low mass optical fibers.
- Array of 9 edge laser diodes.
Solid state device that experiences the same kind of radiation damage as the silicon sensors themselves

Beam tests which measured the decrease in output intensity linear with total dose: $80\pm20\%$ for 400 krad dose.

Integrated luminosity of 20 fb$^{-1}$ is about 0.5 Mrad to the most exposed DOIMs.

No evidence so far of significant losses, but a compilation and analysis is underway to study this effect further

Amplification nevertheless is in principle possible.
DØ Silicon Micro-strip Tracker

Provided by the DØ silicon group

6 Barrels with 4 super layers

12 F Disks

2 H Disks

<table>
<thead>
<tr>
<th>Layer</th>
<th>Barrel</th>
<th>F Disk</th>
<th>H Disk</th>
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</thead>
<tbody>
<tr>
<td>Channels</td>
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<td>387072</td>
<td>258048</td>
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<tr>
<td>Inner R</td>
<td>1.61 cm</td>
<td>2.7 cm</td>
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<td>Outer R</td>
<td>1.77 cm</td>
<td>10.1 cm</td>
<td>10.5 cm</td>
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</table>

all AC-Coupled readout
Upper: Only showing data points from p-side charge collection study (We have also determined full depletion voltage by looking at noise measurements in bias scan. Measurements using both methods agree with each other).

→Layer 1 sensors might no longer be fully depleted by the end of the Tevatron Run II.

Anticipated and compensated by Layer0.
Full Depletion Voltage vs Radiation

- Layer 0
- Layer 1 Inner
- Layer 1 Outer
- Layer 2 Inner

Full Depletion Voltage [V] vs 1MeV Equivalent Neutrons [cm²]
The CDF Run II silicon detectors are in good health after 9 years of operation.

The inner layers have long progressed through inversion and exhibit consistent post-inversion behavior.

Most ladders in SVX-L0 and SVX-L1 layers and the rest of the detector are expected be operable with high efficiency to 11 fb$^{-1}$

L0 (in $D\bar{0}$ L1) will begin to be affected beyond that point, which does not significantly affect the CDF b-vertex detection ($D\bar{0}$ might be more sensitive to loosing its inner layer)

$D\bar{0}$ is currently performing further studies to determine their ability to run beyond 2011

For CDF, Collecting up to 20 fb$^{-1}$ seems possible, the biggest challenges might not be the sensors themselves.
Backup Slides
Fluence in the CDF detector volume is dominated by the physics collisions - related to the delivered luminosity.

The fluence – integrated luminosity relationship depends on distance of the sensor to the beam, and is computed by extracting the fluence from the change in bias current.

Using a 95 pb\(^{-1}\) data sample collected in 2004, a damage factor of 1.65 ± 0.12 was extracted from bias current data (P. Dong et al. CDF/7275).

Bias evolution and TLD measurements agree well.
<table>
<thead>
<tr>
<th>SVX layer</th>
<th>$r$ (cm)</th>
<th>pitch ($\mu$m)</th>
<th>stereo angle (deg.)</th>
<th>$N$ module</th>
<th>$%X_o$ avg.</th>
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<tr>
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