BaBar SVT: Radiation Damage and Other Operational Issues

Gabriele Simi
SLAC
Outline

• Intro to BaBar and SVT
• Radiation Environment
• Damage to Si Detectors
• Damage to Front End Electronics
• Performance Degradation
• Other mysteries
BaBar Detector

- SVT for tracking and precision vertexing
- DCH for charged particle tracking
- DIRC for $K/\pi$ separation
- CsI Calorimeter for Photon and $K_L$ detection
- IFR for $\mu$ identification
- Y(4S) C.M. Energy: 9.0 GeV
- Y(4S) C.M. Energy: 3.1 GeV
SVT Requirements and Constraints

PEP-II Constraints

- Permanent dipole (B1) magnets at +/- 20 cm from IP.
  - Polar angle restriction: $17.2^\circ < \theta < 150^\circ$.
  - Must be clam-shelled into place after installation of B1 magnets

- Radiation exposure at innermost layer (nominal background level assumed at time of construction):
  - Average: 33 kRad/year.
  - In beam plane: 240 kRad/year.

Performance Requirements

- $\Delta z$ resolution < 130 $\mu$m.
- Single vertex resolution < 80 $\mu$m.
- Stand-alone tracking for Pt<100MeV/c.
• Double sided n-bulk silicon sensors, 6-30 kΩ cm
• Custom front-end chips (honeywell 0.8 µm)
• Arch shaped outer layer modules to reduce $L_{\text{rad}}$
• Stand alone tracking for $70 \text{ MeV} < p_t < 120 \text{ MeV}$
• Angular acceptance limited by bending magnets
Geometry

- Inner 3 layers for angle and impact parameter resolution
- Outer 2 layers for pattern recognition and low $p_t$ tracking

<table>
<thead>
<tr>
<th>Layer</th>
<th>Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.3 cm</td>
</tr>
<tr>
<td>2</td>
<td>4.0 cm</td>
</tr>
<tr>
<td>3</td>
<td>5.9 cm</td>
</tr>
<tr>
<td>4</td>
<td>9.1 to 12.7 cm</td>
</tr>
<tr>
<td>5</td>
<td>11.4 to 14.6 cm</td>
</tr>
</tbody>
</table>

(Arched wedge wafers not shown)
SVT in Numbers

- 5 layers, double sided
  - Barrel design, L4 and L5 not cylindrical
  - 340 wafers, 6 different types
  - ~1m$^2$ of silicon area
- 104 Double-sided HDI
  - Outside tracking volume
  - Mounted on Carbon Fiber cones (on B1 magnets)
- 1200 Atom chips
- 140K readout channels
- 0.3 million micro bonds
**Performance**

- Hit Efficiency typically 97%
- Soft efficiency >70% for $pt>50$ MeV/c
- Hit Resolution for $pt>1$ GeV/c, $\perp$ wafers
  - Layer 1-3: 10-15 $\mu$m
  - Layer 4-5: 30-40 $\mu$m
Non uniform irradiation
Concentrated in the bending plane of the beams
Particles overbent by the B1 permanent magnets near the IP
Originates from beam-gas scattering along the ring
Radiation Monitoring

- 12 reverse-biased PIN diodes
  - 6 forward, 6 backward
  - Active area: 1cm x 1cm x 300 μm
- MID plane dose budget:
  - 4 MRad by July 2005
- TOP/BOM budget
  - 4 MRad by 2009
Radiation Effects

- Damage to the silicon detectors
- Damage to the front end electronics
- Occupancy and performance degradation
- Unexpected effects
Damage to the Silicon Detectors

- Details of the silicon wafers
- Depletion voltage shift
- Leakage current increase
- Disuniform irradiation
- P-stop shorts creation
- Leakage current in real SVT
- Radiation distribution
- Charge Collection Efficiency
Silicon Wafers

Manufactured at Micron
300 μm thick
n-bulk, 4-8 kΩ cm

AC coupling to strip implants.
Polysilicon Bias resistors on wafer, 5 MΩ
Damage Mechanism

- Displacement of a primary knock on atom ($E_{th} = 25\text{eV}$), creation of interstitial and vacancy

- Details of the damage can be very complicated but in the Non Ionizing Energy Loss hypothesis the damage is linearly proportional to the energy imparted in displacing collisions.

- The damage function $D(E)$ relates different types of particles and energies.

\[
\frac{dE}{dx} = \phi D(E)
\]

- $1\text{GeV} \text{e}^-$ are $\sim 1/10$ less effective than the reference $1\text{MeV} \text{neutrons}$
Depletion Voltage

- Si detectors with strips and test structures irradiated with 900MeV e⁻
- Depletion voltage shift extracted from diode structures
Effective Doping Concentration

- $N_{\text{eff}} = \frac{V_{\text{depl}} 2\varepsilon}{e d^2}$

- Inversion of type occurs around 2.5 Mrad
Depletion Voltage and Reverse Leakage Current

- Accordance with NIEL scaling
  - Exponential donor removal
  - Linear acceptor creation
- Leakage current increase dominated by bulk generation
  $2\mu$A/cm$^2$/Mrad@23°C
- Strip isolation OK
Non-uniform Irradiation: Spatial Resolution

- Assumptions:
  - \( N_d = N_a \)
  - bias voltage just enough to deplete uniformly doped region
  - \( l = 1\,\text{cm} \quad d = 300\,\text{um} \)

\[
s = \frac{\delta}{2} = \frac{d}{2} \tan \theta \\
\tan \theta = \frac{h}{l/2} = \frac{h}{l/2} = d \left( \frac{\sqrt{2} - 1}{2} \right) \frac{2}{l} = 0.12 \\
s = \frac{\delta}{2} = 9\,\mu\text{m}
\]

smaller than the resolution
I-V Characteristic in Real SVT

Measure 1: used

Leakage Current
- N strips + guard
- P strips
- P guard

Leakage Current vs. Volts

Measure 2: used

Leakage Current
- N strips + guard
- P strips
- P guard

Leakage Current vs. Volts

plots/FL2M4 ILeak vs Dose

\[
\chi^2 / \text{ndf} = 3.97 / 7
\]

- \( p_0 = 0.009468 \pm 0.0008771 \)
- \( p_1 = 0.4926 \pm 0.0271 \)

Strip leakage current vs. Dose (Mrad)

- 2003
- 1999
The average leakage current increase measured on real SVT is 1μA/cm²/Mrad@ 23°C.

Compute the dose assuming the above coefficient.

1/r² dependence.
Instantaneous Damage to Detectors

- Intense burst of radiation
- => discharge of detector capacitor
- => $V_{\text{bias}}$ (40V) momentarily drops across the coupling capacitors
- -deposited charge needed

$$Q_R = (C_D + \frac{C_N C_P}{C_N + C_P}) V_{\text{Bias}} \approx 2.6 \text{ nC/strip}$$

on a time scale $< t = R_{\text{Bias}} \cdot C_{\text{det}} \sim 1\text{ms}$

=> critical radiation: 1 Rad/1 ms
• All the sensors have been tested for AC breakdown up to 20V during construction

• A later study on detectors with a pitch similar to the SVT inner layers has shown an expected rate of failures of about 1-2%

• The effect has been observed in the real system:
  – 65 pin-holes /20k channels in L1,2
Trickle Injection

- Trickle injection $\Rightarrow$ intense bursts of radiation associated to injected bunch $\Rightarrow$ instantaneous damage?

- We measured deposited charge in the detector after the injected pulse using the silicon sensors themselves: limit is 2600nC/HM/1ms

- $\Rightarrow$3 orders of magnitude safety
Rad Damage to the Si: CCE

- Creation of traps in the bulk $\rightarrow$ inefficiency in collecting charge
- Irradiation of detector with 0.9 GeV e$^-$ at Elettra (Trieste)
- Front-end chips not irradiated, needed for readout
- Spot size $y = 1.44$ mm to simulate non-uniform radiation environment
- Peak dose: 10 MRad. in 6 steps
CCE: method

- Illuminate silicon sensor with penetrating LED $\lambda=1060$ nm, $\sigma=0.5$ mm

- Determine “50% turn-on point” of threshold ($T(i)$) as a function of light intensity ($V_{led}$) for each channel $i$

- Fit for the slope of $T(i)$ vs $V_{led}$, correct for measured gain, sum all channels:

$$\sum \frac{slope(i)}{gain(i)} = B \times CCE \ , \ \text{B depends only on the LED shape and disappears in the ratio} \ \frac{\sum slope_{after}}{\sum slope_{pre}} = \frac{CCE_{after}}{CCE_{pre}}$$
CCE: results

- Illuminate silicon sensor with penetrating LED $\lambda=1060$ nm, $\sigma = 0.5$ mm

- At 5.5 Mrad (after type inversion) the ratio is $94\% \pm 4\%$ -> we start to see inefficiency

Measure the CCE ratio on a 30x30 grid
Damage to the Electronics

- AToM characteristics
- Noise increase and gain decrease
  - In $^{60}$Co irradiation
  - In the real SVT
- Threshold Shift
  - Real SVT
  - Chip Irradiation
The AtoM chip

- AToM = A Time Over threshold Machine
- Custom Si readout IC designed for BaBar by: LBNL, INFN-Pavia, UCSC

**FEATURES**
- 128 Channels per chip
- Rad-Hard CMOS (Honeywell 0.8μm)
- Simultaneous
  - Acquisition
  - Digitization
  - Readout
- Sparsified readout
- Time Over Threshold (TOT) readout
- Internal charge injection
The AtoM chip

- Block diagram
**60Co Irradiation**

- Controlled irradiation of Atom chips up to 5MRad in 2001 at SLAC and LBL
- Chips were powered and running during the irradiation
- No digital failures observed
- Noise = $\alpha + \beta \times C_{\text{load}}$

---

**Gain**

- Decrease ~ 3%/Mrad

**Noise (enc)**

- Increase ~ 16%/Mrad
- $\alpha$ term
- $\beta$ term
- Noise vs $C_{\text{load}}$

---

Gabriele Simi
AToM degradation Observed in SVT

- Radiation estimated from the nearest pin diode
- 1-2 MRad depending on the module
- Analog parameters degradation on installed chips is consistent with $^{60}$Co measurements
- New unexpected effects seen on threshold offset
Noise prediction as a function of dose

SVT L1-Signal/Noise vs dose

5Mrad limit: Soft S/N deterioration
Things we know we don't know

- Not consistent with $^{60}$Co irradiation
- Affects chips in the bending plane
- Onset at 1 Mrad
- Goes back at 2 Mrad
- Gain is OK
Is it a function of the radiation?

- The horizontal axis represents the peak dose but the radiation is not uniform across the chip channels.

- Rescaling the dose using the radiation profile...
Threshold Shift in controlled irradiation

- To understand/reproduce the pedestal shift effect, FEE chips (one L1 HDI, one L2 spare HM) have been irradiated at Elettra synchrotron (1GeV e⁻) in Trieste
  - Dose rate between 1 and 10 krad/s at fluence peak
  - Doses up to 9 Mrad
- A pedestal shift of comparable magnitude as in the real SVT has been observed, but...
  - Gain doesn’t drop as much as in SVT
  - Pedestal is not going back (beside annealing)
  - Dose scale is different
- Irradiation with a neutron source is also planned
**AToM Irradiation Setup**

- Rate of 10 Krad/s, integrated dose exceeding 6 Mrads on chip 0-1-2-3
- To study the effect of instantaneous rate, chip 4 has been irradiated at a lower rate

*Beam line: module mounted on xy stage*
Module setup

Gain and Threshold change vs channel after 6 Mrad

Threshold change vs dose

Chips 0-3 (10krad/s)

Chip 4 (1krad/s)

10 hours annealing

2 weeks annealing
First indications from analysis

- We can reproduce the threshold shift using 1 GeV electrons, but:
  - beside annealing there is no indication of pedestal going back to non irradiated levels
  - the dose scale is different
  - Gain doesn't show a significant change

- Any ideas on the generating mechanism?
**Rotate or not rotate?**

- No Rotation
- Rotation Scenario
- Dose < 5 Mrad but spreads the threshold shift around
Reversible degradation

• The machine background radiation not only degrades the performance of the SVT detector in expected (and unexpected) ways because of the integrated dose, but also the instantaneous rate has a significant impact.

• The performance degrades with occupancy which in the inner layer is proportional to the background rate.

![Graph showing the relationship between FW: MID dose rate and FL1M04-phi Occupancy in percent. The graph includes a linear trend line with a slope of 4.4 mrad/s per % and an intercept of 5.3 mrad/s.](image)
Performance with high instantaneous background rate

- Look in data at hit efficiency and resolution as a function of occupancy in the FEE

The effect is expected to be significant in 1/10 of layer 1

Hit efficiency

Hit resolution

Slope is 6 μm/10%
Occupancy projections

- Use parametrization fitted on background studies data to extrapolate to future running conditions

\[ \text{bkgd} = a + b \cdot I_{\text{HER}} + c \cdot I_{\text{LER}} + d \cdot \text{Luminosity} \]

<table>
<thead>
<tr>
<th>Year</th>
<th>HER</th>
<th>LER</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOW</td>
<td>1.2 A</td>
<td>1.9 A</td>
<td>7.2x10^{33} cm^{-2}s^{-1}</td>
</tr>
<tr>
<td>2004</td>
<td>1.6 A</td>
<td>2.7 A</td>
<td>12.1x10^{33} cm^{-2}s^{-1}</td>
</tr>
<tr>
<td>2005</td>
<td>1.8 A</td>
<td>3.6 A</td>
<td>18.2x10^{33} cm^{-2}s^{-1}</td>
</tr>
<tr>
<td>2006</td>
<td>2.0 A</td>
<td>3.6 A</td>
<td>23.0x10^{33} cm^{-2}s^{-1}</td>
</tr>
<tr>
<td>2007</td>
<td>2.2 A</td>
<td>4.5 A</td>
<td>33.0x10^{33} cm^{-2}s^{-1}</td>
</tr>
</tbody>
</table>

- Inside a given chip each bin is one year
Summary

- SVT originally designed for 240krad/yr has now integrated 2.4Mrad in the worst case
- Extensive studies have been made to understand the effects of radiation damage
- Si: Leakage current increased x 10
- Electronics degradation: S/N=10 @ 5Mrad
- Unexpected effects reproducible, not understood
- Soft degradation after 5 Mrad
What if we Lose the Mid-plane?

A = perfect

E = midplane chips off in L1& 2 (32 ICs)

F = E with 2 additional dead chips

H = midplane modules off in L1&2