Status of radiation damage of the ATLAS SCT detector

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Taka Kondo (KEK) on behalf of the ATLAS SCT Collaboration
• 61 m² of silicon with 6.3 million readout channels
• 4088 silicon modules in 4 Barrels and 18 EC Disks
• $C_3F_8$ Cooling (-7°C to +6°C silicon)
Sensors

• Single sided p-on-n
• 285μm thick
• 768+2 AC-coupled strips

Barrel
• 8448 barrel sensors
• 8081 sensors with <111>
• 367 (4.4%) sensors with <100>
  mounted on B3, B5 and B6
• 64.0 x 63.6mm
• 80μm strip pitch
• 100% Hamamatsu Photonics

Endcap
• 6944 wedge sensors
• 56.9-90.4μm strip pitch
• 5 flavours
• 82.8% Hamamatsu Photonics
  17.2% CiS (some oxygenated)
Barrel Modules and Layout

• 2112 barrel modules, 4 sensors/module
• back-to-back with 40 mrad stereo angle
• 12 chips (6 each side) with binary readout
• bridge-shape hybrids of flex circuit
• 5.6W/module (rising up to ~9W)

• 4 barrel layers
• 12 eta modules |Z|<80.5cm

<table>
<thead>
<tr>
<th>Layer</th>
<th>radius</th>
<th>modules</th>
<th>T(sensor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B3</td>
<td>29.9 cm</td>
<td>384</td>
<td>~ -2°C</td>
</tr>
<tr>
<td>B4</td>
<td>37.1 cm</td>
<td>480</td>
<td>~ -2°C</td>
</tr>
<tr>
<td>B5</td>
<td>44.3 cm</td>
<td>576</td>
<td>~ -1.3°C</td>
</tr>
<tr>
<td>B6</td>
<td>51.4 cm</td>
<td>672</td>
<td>~ +6°C</td>
</tr>
</tbody>
</table>
SCT performance

- 99.9 % efficiency for charged particles in Barrel

- Keeping low percentage of defect chips/modules mainly thanks to the built-in redundancy.

Table 2: Numbers of Disabled SCT Detector Elements.

<table>
<thead>
<tr>
<th>Component</th>
<th>Endcaps</th>
<th>Barrel</th>
<th>SCT</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modules</td>
<td>20</td>
<td>10</td>
<td>30</td>
<td>0.73</td>
</tr>
<tr>
<td>Strips</td>
<td>6992</td>
<td>3681</td>
<td>10673</td>
<td>0.07</td>
</tr>
<tr>
<td>Chips</td>
<td>40</td>
<td>16</td>
<td>56</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Dead chip bypassed
All fibres ok
Radiation level by the end of 2011 @ Point-1

1 MeV n-eq fluence received
Integrated luminosity delivered = 5.84 fb⁻¹
+ using the Fluka simulation
Leakage current

Status of Layer B5 as of Dec. 7, 2011

Note (1) two hybrid temperatures agree well.
(2) no difference between <111> and <100> modules.
Leakage current and Sensor temperature

- All the current measured in the HV power supply at 150V are assumed to be due to generation current in the silicon bulk.

- They are converted to the value at the temperature of 0°C using the temperature scaling formula [1]

\[
\frac{I(T_{0^\circ C})}{I(T_{\text{sensor}})} = \left( \frac{T_{0^\circ C}}{T_{\text{sensor}}} \right)^2 \exp \left( -\frac{E_{\text{gen}}}{2k_B} \left[ \frac{1}{T_{0^\circ C}} - \frac{1}{T_{\text{sensor}}} \right] \right)
\]

with \( E_{\text{gen}} = 1.21 \text{ eV} \) following the RD50 recommendation [2].

- Sensor temperature
  - When cooled:
    \[
    T_{\text{sensor}} = \frac{T_{\text{hybrid\ (link\ -\ 0)}} + T_{\text{hybrid\ (link\ -\ 1)}}}{2} - 3.7^\circ C
    \]
    where 3.7°C is a difference estimated via FEA for barrel modules.
  - When the cooling is off, T the environmental temperature (17.5°C during 2010-2011 winter shutdown) is used.

All layers (except B3) showed quite uniform leakage current distributions. No phi dependences are seen.
Prediction of the SCT leakage current

- Two models of bulk leakage currents are used for comparison:
  1. Hamburg/Dortmund model [1][2]
     Summary of small sample tests mostly at or above room temperature.
     The damage constants were obtained from four 24 GeV proton
     beam tests using ATLAS SCT sensors cooled at -10°C ~ -8°C.

- Radiation fluences at sensors are estimated using the results of
  FLUKA simulation of 7 TeV pp collision by Ian Dawson et al.

- Integrated Luminosity is the total “delivered” 7TeV collisions at
  Point-1 including non-Stable beam collisions.

- Uncertainties of predictions are estimated assuming the errors of
  model parameters and measurements are independent. Errors of
  the FLUKA simulation are not included (not known).

Good agreements between data and model predictions. The Harper model predicts ~10% less but within uncertainties. Note that there are no parameter re-adjustments.
Noise

Two ways of measuring ENC:

(1) **Response Curve at 2 fC:**
Fitting the threshold S-curves by complementary error function in 3 point gain calibration runs. ENC is obtained by dividing with the gain.

(2) **Noise Occupancy (NO) fit:**
NO is related to the threshold charge \( q_{th} \)

\[
NO \propto \exp\left(-\frac{(q_{th})^2}{2\langle ENC \rangle^2}\right)
\]

A linear fit of the distribution of \( \ln(NO) \) vs \( q_{th}^2 \) gives an ENC for each channel.

Fairly good chip-by-chip correlations have been observed in 2008 and 2010.
Systematic decrease of $<\text{ENC}>$ was observed in fall 2010. The amount of decrease depends on the chip location!!
"Eye-glass" plots for July 2010 to Jan. 2011

Note: initial bow-shape may be due to chip temperature profile along the hybrid length. Chips 0, 5, 6 and 11 are close to cooling anchors.
Time dependence of chip-averaged noises (ENC)

**Layer B3**

- B3: 3.3x10^8, 8.4x10^9, 5.4x10^10, 5.0x10^11, 9.7x10^11 cm^-2
- G3: 0.14, 3.5, 22.6, 206, 403 Gy

**Layer B6**

- B6: 2.8x10^8, 4.6x10^9, 2.7x10^10, 5.3x10^11, 3.0x10^10 cm^-2
- G3: 0.05, 1.4, 8.9, 81, 158 Gy

**Luminosity**

- B3: 7%

**ATLAS Preliminary**

- Integ. luminosity delivered: 100, 10, 1
Some points of the “SCT noise mystery”

(1) ~ 7% decrease in <ENC> was observed in Sep-Oct. 2010 runs at the fluence level of $10^{10}\text{cm}^{-2}$ (a few Gy).

(2) Its time profile indicates a radiation induced phenomenon.

(3) It occurred systematically on all chips of the Barrel and EC modules. More complex in EC case (not mentioned here).

(4) It depends strongly on the chip location on the flex hybrid.

(5) The <ENC> of <100> modules, however, stayed constant. They are ~10% lower from the beginning.

(6) No further decrease was observed in 2011. Some increase. Most of <ENC>s are now back closed to original values.

(7) Noise Occupancy (NO) exhibited similar drops.

(8) Disconnected strip channels showed no such drops.

(9) A PS beam test with low rate done in 2011 fall reproduced the effects at similar dose level.
The gain has been very stable till mid 2011. Then gradually decreased. All chips simultaneously changed. Checked no effects on performance such as hit efficiency for tracks.
Summary

• The Barrel layer B3 received $\sim 10^{12}/\text{cm}^2$ 1MeV n-eq fluence by the end of 2011.

• Leakage current at 150V steadily increased. Barrel layers show very flat distribution in eta (except B3).

• Model predictions with annealing effects reproduce the Barrel leakage current within $1\sigma$ ($\sim 20\%$) with no parameter re-adjustments.

• The noise(ENC) and gain have been monitored frequently. The noises initially decreased by up to 7% with strong dependence on chip location and crystal orientation. Their behaviors in 2011 are different and rather complex.
Backup slides
Barrel hybrid

![Diagram of Barrel Hybrid](image)

- Link-0: chip-0 to chip-5
- Link-1: chip-6 to chip-11

- Thermistor (10K)
- BeO facing
- ABCD chip
- Air gap (0.4mm)
- Cu/polyimide flex
- Carbon-carbon bridge
- TPG
- Si sensor

[20]
Hamburg/Dortmund Model

Based on Moll’s thesis [1], the leakage current coefficient $\alpha$ is given by Krasel [2] is

$$\alpha(t) = \alpha_l \cdot \exp(-\frac{t}{\tau_l}) + \alpha_0^* - \beta \cdot \ln(\Theta(T_a) t / t_0)$$

$$\alpha_l = (1.23 \pm 0.06) \cdot 10^{-17} \text{ A/cm}$$

$$\frac{1}{\tau_l} = k_{0l} \cdot \exp(-\frac{E_I}{k_B T_a}), \quad t_0 = 1 \text{ min.}$$

$$k_{0l} = 1.2^{+5.3}_{-1.0} \cdot 10^{13} \text{ s}^{-1}, \quad E_I = (1.11 \pm 0.05) \text{eV}$$

$$\Theta(T_a) = \exp\left[-\frac{E_I^*}{k_B T_a} \left(\frac{1}{T_a} - \frac{1}{T_{\text{ref}}}\right)\right]$$

$$\alpha_0^* = 7.07 \cdot 10^{-17} \text{ A/cm}$$

$$\beta = 3.29 \cdot 10^{-18} \text{ A/cm}$$

$$E_I^* = (1.30 \pm 0.14) \text{eV}$$

$$T_{\text{ref}} = 21 ^\circ \text{C}$$

$$G_i = G_i^{\text{exp}} + G_i^{\log}$$

$$G_i^{\text{exp}} = \sum_{j=1}^{i} \Phi_{eq,j} \alpha_l \exp\left(-\frac{t_i^l}{\tau_l(20^\circ \text{C})}\right)$$

$$t_i^l = \sum_{j=1}^{i} \Delta t_j \cdot \frac{\tau_l(20^\circ \text{C})}{\tau_l(T_j)}$$

$$G_i^{\log} = \sum_{j=1}^{i} \Phi_{eq,j} \left(\alpha_0^* - \beta \cdot \ln\left(\frac{t_i^{\log}}{t_0}\right)\right)$$

$$t_i^{\log} = \sum_{k=j}^{i} \Delta t_k \cdot \Theta(T_k)$$

These two equations in [2] are corrected here.

Harper Model

Leak current formula by R. Haper [1] is used for prediction. 
$F$: $n_{eq}$ fluence, $V$: volume

$$I = g(\Theta(T_A)t_{ir}, \Theta(T_A)t') \cdot \alpha \cdot \Phi \cdot V$$

$$g(\Theta(T_A)t_{ir}, \Theta(T_A)t') = \sum_{i=1}^{n} \left\{ A_i \frac{\tau_i}{\Theta(T_A)t_{ir}} \left[ 1 - \exp \left( -\frac{\Theta(T_A)t_{ir}}{\tau_i} \right) \right] \exp \left( -\frac{\Theta(T_A)t'}{\tau_i} \right) \right\}$$

$$\Theta(T_A) = \exp \left( \frac{E_I}{k_B} \left[ \frac{1}{T_R} - \frac{1}{T_A} \right] \right)$$

$T_R = 20^\circ C$

$E_I = 1.09 \pm 0.14$ eV \[2\]

<table>
<thead>
<tr>
<th>$\alpha_{eq}$ $(-7^\circ C)$</th>
<th>$(7.00 \pm 0.20) \times 10^{-18}$ A $\cdot$ cm$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(min)</td>
<td></td>
</tr>
<tr>
<td>$\tau_1$</td>
<td>$(1.2 \pm 0.2) \times 10^6$</td>
</tr>
<tr>
<td>$\tau_2$</td>
<td>$(4.1 \pm 0.6) \times 10^4$</td>
</tr>
<tr>
<td>$\tau_3$</td>
<td>$(3.7 \pm 0.3) \times 10^3$</td>
</tr>
<tr>
<td>$\tau_4$</td>
<td>$124 \pm 25$</td>
</tr>
<tr>
<td>$\tau_5$</td>
<td>$8 \pm 5$</td>
</tr>
<tr>
<td>$A_1$</td>
<td>$0.42 \pm 0.11$</td>
</tr>
<tr>
<td>$A_2$</td>
<td>$0.10 \pm 0.01$</td>
</tr>
<tr>
<td>$A_3$</td>
<td>$0.23 \pm 0.02$</td>
</tr>
<tr>
<td>$A_4$</td>
<td>$0.21 \pm 0.02$</td>
</tr>
<tr>
<td>$A_5$</td>
<td>$0.04 \pm 0.03$</td>
</tr>
</tbody>
</table>

Changed from original value of 6.90+-0.20 due to $E_g = 1.12 \rightarrow 1.21$ eV change.

Estimate of uncertainties of Hamburg/Dortmund model prediction

\[
\alpha(t) = \alpha_I \cdot \exp\left(-\frac{t}{\tau_I}\right) + \alpha_0^* - \beta \cdot \ln(\Theta(T_a) t / t_0), \quad \frac{1}{\tau_I} = k_{0I} \cdot \exp\left(-\frac{\mathcal{E}_I}{k_B T_a}\right)
\]

<table>
<thead>
<tr>
<th>No.</th>
<th>parameter</th>
<th>value</th>
<th>1σ</th>
<th>I@0°C with -1σ</th>
<th>I@0°C with +1σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>center value</td>
<td></td>
<td></td>
<td>5.177 μA/cm³ (for B3 at 2011.12.31)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>(\alpha_I)</td>
<td>1.23x10(^{-17}) A/cm</td>
<td>0.06x10(^{-17}) A/cm</td>
<td>5.166 (-0.21%)</td>
<td>5.188 (+0.21%)</td>
</tr>
<tr>
<td>2</td>
<td>(k_{0I})</td>
<td>1.2x10(^{13}) s(^{-1})</td>
<td>(+5.3,-1.0)x10(^{13}) s(^{-1})</td>
<td>6.108 (-17.98%)</td>
<td>4.951 (-4.37%)</td>
</tr>
<tr>
<td>3</td>
<td>(\mathcal{E}_I)</td>
<td>1.11 eV</td>
<td>0.05 eV</td>
<td>4.951 (-4.37%)</td>
<td>6.188 (+19.53%)</td>
</tr>
<tr>
<td>4</td>
<td>(\alpha_0^*)</td>
<td>7.07x10(^{-17}) A/cm</td>
<td></td>
<td>4.708 (-9.06%)</td>
<td>5.646 (+9.06%)</td>
</tr>
<tr>
<td>5</td>
<td>(\beta)</td>
<td>3.29x10(^{-18}) A/cm</td>
<td></td>
<td>5.398 (+4.28%)</td>
<td>4.956 (-4.28%)</td>
</tr>
<tr>
<td>6</td>
<td>(\mathcal{E}_I^*)</td>
<td>1.30 eV</td>
<td>0.14 eV</td>
<td>5.134 (-0.84%)</td>
<td>5.216 (+0.75%)</td>
</tr>
<tr>
<td>7</td>
<td>(\mathcal{E}_g)</td>
<td>1.21 eV</td>
<td>+0.04, -0.09 eV</td>
<td>5.934 (14.62%)</td>
<td>4.872 (-5.89%)</td>
</tr>
<tr>
<td>8</td>
<td>(T_{sensor})</td>
<td>(T_{hybrid} - 3.7°C)</td>
<td>1°C or 2°C</td>
<td>5.469 (+5.63%)</td>
<td>4.921 (-4.94%)</td>
</tr>
<tr>
<td>9</td>
<td>fluence</td>
<td>Lum*Fluka simul.</td>
<td>3.7%</td>
<td>4.986 (-3.70%)</td>
<td>5.369 (+3.70%)</td>
</tr>
</tbody>
</table>

Adding percent deviations quadratically: 25.27% (for B3 at 2011.12.31)

Note: Uncertainties of parameters 4, 5, 7 and 8 are unknown. These values are set by hand here.
Temperature scaling issue

Harper model is based on experiments at -10°C ~ -8°C.

Hamburg/Dortmund model is given with $T_{\text{ref}} = 21°C$.

14 % difference at 0°C with $T_{\text{ref}} = 20°C$. 

Normalization point

Factor = $(\frac{T}{T_{\text{ref}}})^2 \exp\{-\frac{E_{\text{gen}}}{2k_B}(\frac{1}{T}-\frac{1}{T_{\text{ref}}})\}$

$E_{\text{gen}} = 1.12$ eV

$E_{\text{gen}} = 1.21$ eV
Comparison of data and models: ratios

Hamburg/Dortmund model

$E_{\text{gen}} = 1.12 \text{ eV}$

Hamburg/Dortmund model

$E_{\text{gen}} = 1.21 \text{ eV}$