The ATLAS Tracker Upgrade: Short Strip Detectors for the SLHC

Urmila Soldevila on behalf of the ATLAS SCT Collaboration
7 October 2009

11th ICATPP Conference on Astroparticle, Space Physics, Detectors and Medical Physics Applications
Villa Olmo (Como, Italia) 5-9 October 2009
LHC vs. SLHC

Inner Detector (ID)

Upgrades to the ATLAS Inner Detector

Upgrade ID Layout

Radiation Hard Technologies: n-on-p

- Miniature sensors:
  - Charge Collection under neutron and proton irradiation
  - Full Depletion Voltage

- Full size prototypes sensors:
  - Electrical Characterization

Module Integration Concepts

- Barrel Stave
- End-Cap Stave (Petal)
- Super-Module

Conclusions
LHC

- Designed for luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$
- In the first 5 years 700 fb$^{-1}$ integrated luminosity
- First Colliding beams in November 2009

Super-LHC (SLHC)

- Designed for luminosity of $10^{35}$ cm$^{-2}$s$^{-1}$
- SLHC Upgrade plans envision 3000 fb$^{-1}$ (5 years)
- Starting around 2018-2020
Inner Detector (ID)  

Inner Detector → Vertex (pixel) + Tracker (Silicon Strips, TRT)  

High Occupancy:  

- 20 collisions per beam crossing  
- 400 collisions per beam crossing  

**LHC**  

- L = $10^{34} \text{ cm}^2 \text{s}^{-1}$  
- 700 track multiplicity

**SLHC**  

- L = $10^{35} \text{ cm}^2 \text{s}^{-1}$  
- 1400 track multiplicity

- TRT unable to cope with SLHC occupancy → All Silicon ID  
- Finer granularity for the detectors to keep the occupancy at the same level of LHC  
- This supposes for services:  
  - x5 number of channels (for SCT)  
  - In the same space !!
Inner Detector (ID)

Particle Fluence:


- Neutrons > 50% at R ≥ 25 cm
- Strip detector damage largely due to neutrons

Designed fluences for sensors:
- B-layer at 3.7 cm: $2.2 \times 10^{16}$ 1MeV n-equivalent/cm²
- Outer pixel layers: $3 \times 10^{15}$ 1MeV n-equivalent/cm²
- Middle strip layer at 38 cm: $10^{15}$ 1MeV n-equivalent/cm²
- Outer strip layer at 95 cm: $4 \times 10^{14}$ 1MeV n-equivalent/cm²

This implies higher radiation hardness for sensors
The ID will be replaced and technologically improved → R&D in RD50

Barrel SCT Upgrade: 38 < R < 95 cm
- New Detector Layout: Only silicon pixel and strips.
- Radiation hard technologies: n-on-p silicon strips.
- New Module Integration Concepts (low material budget).
- New Powering schemes (serial powering or DC-DC) to reduce the number of cables.
- Improved cooling system to maintain silicon temperature below -20°C (CO₂ or C₃F₈).
- Installation: Limited access time inside the cavern.
**Pixels**: considered options → 3-D or diamond detectors for innermost layer and n-on-p or n-on-n detectors for 3 outer layers

**Strips**: 5 barrel layers: @ 38, 49, 60, 75, and 95 cm
- 3 inner layers: SHORT STRIP LAYERS (24 mm-long strips)
- 2 outer layers: LONG STRIP LAYERS (96 mm-long strips)
- 5 double sided disks on each End-Cap
- **The 3 outer layers + the end-caps will replace the TRT**
- The design is expected to keep the occupancy below 1.6% at the innermost radius.
Radiation Hard Technologies: n-on-p

- p-bulk strip sensors (HPK ATLAS07) are investigated for the ATLAS ID upgrade. Their performance has been evaluated in terms of radiation damage on bulk.
  - 6 inch (150 mm) wafers
    - FZ1<100>(~6.7k Ωcm)
    - FZ2<100>(~6.2k Ωcm)
  - P-stop and p-stop+p-spray isolation
  - pitch 74.5 µm, thickness 320 µm
  - Miniature sensors (1 cm x 1 cm, 128 strips) 
  - Full size prototype sensors (9.75 cm x 9.75 cm, 1280 strips)

- The sensors are being developed by the R&D collaboration:

  H. Chen, J. Kierstead, J.R. Carter, L.B.A. Hommels, D. Robinson, Univ. of Cambridge
  Z. Li, D. Lynn, Brookhaven National Laboratory
  J. Jakobs, M. Köhler, U. Parzefall, Physikalisches Institut, Univ. Freiburg
  A. Clark, D. Ferrière, S. Gonzalez Sevilla, Univ. of Geneva
  R. Bates, C. Rutter, L. Ekhard, V. O'Shea, Dept. of Physics and Astronomy, Univ. of Glasgow
  Y. Unno, S. Terada, Y. Ikegami, T. Kobriki, Institute of Particle and Nuclear Study, KEK
  A. Chilingarov, H. Fox, Physics Dept., Lancaster University
  A. Affolder, P. P. Allport, H. Brown G. Casse, A. Greenall, Olivier Lodge Lab, Univ. of Liverpool
  V. Cindro, G. Kramberger, I. Mandič, M. Mikuž, Jožef Stefan Institute and Dep. of Physics, Univ. of Ljubljana
  I. Gorelov, M. Hoefferkamp, J. Metcalfe, S. Seidel, K. Toms, Dept. of Physics and Astronomy, Univ. of New Mexico
  Z. Dolezal, P. Kodys, Faculty of Mathematics and Physics, Charles Univ. in Prague.
  J. Bohm, M. Mikešikova, Academy of Sciences of the Czech Republic
  C. Betancourt, N. Dawson, V. Fadeyev, M. Gerling, A. A. Grillo,
  S. Lindgren, P. Maddock, F. Martinez-McKinney, H. F.-W. Sadowitzki, Z. Li, D. Lynn, Brookhaven National Laboratory
  S. Sattari, A. Seiden, J. Von Wilpert, J. Wright, SCIPP, UC Santa Cruz
  R. French, S. Paganis, D. Tsionou, Dept. of Physics and Astronomy, The Univ. of Sheffield
  K. Hara, N. Hamasaki, H. Hatano, S. Mitsui, M. Yamada, School of Pure and Applied Sciences, Univ. of Tsukuba
  C. García, C. Lacasta, S. Marti i Garcia, M. Miñano, U. Soldevila, IFIC (Centro Mixto CSIC-UV)
Good agreement between sites/systems. Systematic differences under control.

**Miniature Sensors:** Charge Collection

**ATLAS institutes involved:**
- **Valencia** uses Beetle based system (MPV charge, analogue data, 25ns shaping time)
- **Ljubljana** and **Liverpool** use SCT128A based system (MPV charge, analogue data, 25ns shaping time)
- **Tsukuba/KEK** uses a CAMAC 4-ch system with discrete amps (MPV charge, analogue data, 20ns PT)
- **UC-Santa Cruz** uses PTSM based system (Median charge, binary data, 100 ns shaping time)
Ljubljana and Tsukuba/KEK annealed for 80 minutes at 60°C → CCE increases by ~25%+/−10%  
Liverpool and Valencia do not anneal (with annealing correction i.e. CCE reduced by -20%+/−10%)

<table>
<thead>
<tr>
<th>@500V</th>
<th>CC</th>
<th>Expected noise</th>
<th>S/N achievable</th>
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<tbody>
<tr>
<td>@ 5x10^{14} n/cm²</td>
<td>14-16 Ke-</td>
<td>950e-</td>
<td>~16</td>
</tr>
<tr>
<td>@ 1x10^{15} n/cm²</td>
<td>11-13 Ke-</td>
<td>600e-</td>
<td>~20</td>
</tr>
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<td>950e-</td>
<td>~18  Good!</td>
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<td>@ 1x10^{15} n/cm²</td>
<td>11-14 Ke-</td>
<td>600e-</td>
<td>~20</td>
</tr>
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Performance of n-on-p FZ sensors produced at Micron and Hamamatsu are the same after all measured irradiation sources. HPK data shown from all sites. Pion irradiation measurements corrected for annealing during run.
Protons: FDV~700V @10^{15} cm^{-2}

Neutrons: FDV~800V @ 5 \times 10^{14} cm^{-2}

operation in partial depletion is foreseen

Full Size Prototype Sensors: Electrical Characterization

ATLAS institutes involved:

- University of Cambridge: 2 sensors: W15, W16
- Stony Brook University: 9 sensors: W19, W21-23, W25-29
- University of Geneva: 2 sensors: W17, W18

Total number of tested sensors: 19

ATLAS07 Full Size Sensors

- 9.75 cm x 9.75 cm
- 4 segments:
  - two with “axial” strips. 74.5 μm pitch
  - two with “stereo” strips. 74.4 μm pitch, 40mrad
Radiation Hard Technologies: n-on-p

Full Size Prototype Sensors: Bias Scan

- No microdischarges with exception one sensor (Vbd~420V).
- Sensors satisfy the ATLAS07 Technical Specification (<200um @ 600V)
- IV scan was repeated after bias scan and strip scan.
- Current was usually higher by 10%-20% and breakdown for 2 sensors at ~380V.

- Estimated values of Vdep:
  - 6 sensors (Prague) 199-203V
  - 2 sensors (Cambridge) 235-245V
- All tested sensors satisfy specifications: Vdep < 500V
All tested sensors:

\[ \text{Cint } \sim 0.75-0.80 \text{ pF/cm} \]

\[ < 1.1 \text{ pF/cm (ATLAS specification)} \]

\[ \text{Cint/strip } = 1.86 \text{pF/strip} \]

- Measurements taken on central strip with either neighbour grounded.
  Including next-to-neighbours results in 10-15% higher readings.
Full Size Prototype Sensors: Strip Scan

For 5 sensors

Ccpl = 66-68pF/strip

ATLAS07 Specification:
Ccpl/strip>47.6pF
Strip length =2.38cm

Rbias=1.30MΩ -1.45MΩ

ATLAS07 Specification:
Rbias=1.5±0.5MΩ
Module Integration Concepts

Barrel Stave

- Hybrid glued to sensors. These glued to bus tape. This glued to cooling substrate.

60 cm, 9 cm strip, 4 chips wide

Stave-06

1 m, 3 cm strip, 6 chips wide

Stave-07

- Results agree with ABCD performance

• Individual hybrids/modules work well electrically. Good noise performance. All are 900e-9
• Tested 6 module on stave with ABCD chips. Serial Powering lines.
• Working ongoing

Under Construction: 1.2 m, 2.5 cm strip, 10 chips wide (20 chips/hybrid)

Stave-09

- P-type sensors
- ABCN25 chips
- Kapton Hybrid
- Embedded Bus Cable
- Stave mechanical core

C.Haber (LBL)

1st prototype module from Liverpool
Module Integration Concepts

Petal

- Follows quite closely the barrel stave concept
- 2 carbon facings + Honeycomb sandwich core
- Independent e-services + Bus Cable
- Independent C02 cooling pipe

- Petal surface: 830 cm²
- 5 disks on each end-cap
- 32 petals/disk (16 on each side)
- 6 different detector types mounted on petal
- 9 different hybrid types
- 116 chips/petal

Thermal simulations to explore the behaviour at critical points:
- Assumed -30°C coolant temperature (-27°C on the return pipe)
- The simulation results show that the temperature on sensors is within safety range (to be confirmed with prototypes).

C. Lacasta (IFIC, Valencia)

Images:
- Petals and disks diagram
- Thermal runaways graph

Simulations of a disk. Issues: Layout, modularity, powering

11th ICATPP Conference

Urmila Soldevila (IFIC, Valencia)
Module Integration Concepts

Super-Module

1) Build individual modules:
   - Double sided module
   - 2 silicon (short) microstrip sensors: n+-on-p, 10x10 cm²
   - 4 bridged hybrids with ABCN asics each

2) Insert modules into a frame: Super-module (Based on SCT experience)
   2 proposals for module integration into cylinders:
   - Lateral insertion (KEK): Installation of the Super-Modules, cylinder by cylinder
   - End-insertion (Geneva): Barrel structures can be assembled before the Super-Modules are integrated.
Conclusions

- The tracker of ATLAS will have to be replaced for the LHC upgrade.
- Lots of R&D has already been carried out and ideas are near to converge.
- **Strip community** are investigating the short (2.4cm) and the long strips (9.6 cm) sensors for barrel and EC with stave or petal concept.
- Miniature and Full Size p-type sensors have been manufactured by Hamamatsu (HPK):
  - Good performance in terms of charge collection efficiency under neutron and proton irradiation. S/N of ~20 (16) should be achievable with short (long) strip detector.
  - Sensors will operate at partial depletion $\rightarrow$ p-bulk sensor good candidate.
  - All tested full size sensors satisfy ATLAS07 Technical Specification for leakage current, full depletion voltages, Cint measured in the bias voltage scan.
  - Strip scan was performed on 5 full size sensors. Ccoupling and Rbias were uniform across the whole sensor and within specifications.
- Prototyping for Module Integration is progressing.
- Good progress but important decisions to take.

- Thank you -
- Backup -
Services:

- The required high granularity supposes (in the same space)
  - x5 number of channels
  - x5 number of cables

New options in powering (not individual powering)

<table>
<thead>
<tr>
<th>Current ID</th>
<th>Area (m²)</th>
<th>Channels</th>
<th>Upgrade</th>
<th>Area (m²)</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>1.8</td>
<td>80M</td>
<td>Pixels</td>
<td>5</td>
<td>~300M</td>
</tr>
<tr>
<td>SCT</td>
<td>61</td>
<td>~6.3M</td>
<td>Short Strips</td>
<td>60</td>
<td>~30M</td>
</tr>
<tr>
<td>TRT</td>
<td>400K</td>
<td></td>
<td>Long Strips</td>
<td>100</td>
<td>~15M</td>
</tr>
</tbody>
</table>
Backup

• Several options on powering: DC/DC or serial.
  – Cannot have individual module powering → too much material and no space.
  – Requirements: High power efficiency, low noise, safety (overcurrent, overvoltage, overtemperature).

Serial Powering scheme has been shown to perform well on 6 and 30 module staves (Stave06, Stave07)
• Excellent noise performances
• Current issues:
  • Protection schemes (shunt regulators) possible integration into FE chips
  • Custom current source

DC/DC scheme:
• Only 1 power line/stave (10-12V)
• Distribution with 2 conversion stages:
  • Stage 1 → 2converters: 2.5V analog and 1.8V digital
  • Stage 2 → On-chip switched capacitor
• High granularity of the power distribution
• Very flexible
Currently anticipated evolution of the ATLAS upgrade

(http://atlas.web.cern.ch/Atlas/GROUPS/UPGRADES/)

<table>
<thead>
<tr>
<th><strong>Milestone</strong></th>
<th><strong>Date</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Straw Man &amp; options fixed</td>
<td>Dec 2006</td>
</tr>
<tr>
<td>R&amp;D towards inner detector conceptual design</td>
<td>2007-2010</td>
</tr>
<tr>
<td>LoI</td>
<td>May 2010</td>
</tr>
<tr>
<td>Technical Proposal, Initial MoU and Costing</td>
<td>April 2012</td>
</tr>
<tr>
<td>Inner Tracker TDR</td>
<td>Dec 2013</td>
</tr>
<tr>
<td>Production readiness reviews and ramp up production</td>
<td>2014</td>
</tr>
<tr>
<td>New Insertable B-layer Installation</td>
<td>End 2014</td>
</tr>
<tr>
<td>Procure parts, Component assembly</td>
<td>2014 - 2016</td>
</tr>
<tr>
<td>Surface assembly</td>
<td>September 2016 - end 2017</td>
</tr>
<tr>
<td>Surface testing</td>
<td>2018</td>
</tr>
<tr>
<td>Stop LHC</td>
<td>Sep 2018</td>
</tr>
<tr>
<td>Remove old detectors, install new</td>
<td>Oct 2018 - Dec 2019</td>
</tr>
<tr>
<td>Commission new detectors</td>
<td>Jan 2020 - Mar 2020</td>
</tr>
<tr>
<td>Take data</td>
<td>April 2020</td>
</tr>
</tbody>
</table>
**Backup**

**Current Inner Detector**

Pixels (*n*-on-*n* sensor technology): 3 barrels + 2x3 discs (5 < R < 15cm)

Strips (SCT) (*p*-on-*n* sensor technology): 4 barrels + 2x9 discs (30 < R < 51cm)

TRT: Barrel + Wheels (4mm diameter straw drift tubes) (55 < R < 105cm)

**Designed fluences for sensors:**

- Pixel layer 0: $1 \times 10^{15}$ 1MeV n-equivalent /cm²
- SCT Barrel layer 1: $8 \times 10^{14}$ 1MeV n-equivalent /cm²
- SCT End-cap disc 9: $7 \times 10^{14}$ 1MeV n-equivalent /cm²
- TRT outer radius: $3 \times 10^{13}$ 1MeV n-equivalent /cm²
The current SCT sensors use **p-on-n** technology. They are not sufficient radiation hard for the LHC upgrade.

**P-on-N**
- Holes collected
- Type inversion
  - Deposited charge can not reach electrode in the corresponding collection time

**N-on-N**
- Electron collected
  - Higher mobility
  - Longer trapping time
- Type inversion
  - Deposited charge can reach the electrode
  - It can work under-depleted
- Doubled-sided processing
  - Most expensive
  - Limited suppliers

**N-on-P**
- Electron collected → Higher mobility
- No type inversion
  - It can work under-depleted
- Single-sided processing
  - ~50% less expensive than n-on-n
  - More suppliers
- Maybe as radiation hard as n-on-n
### Strips Detector in numbers

<table>
<thead>
<tr>
<th>Layer</th>
<th>Type</th>
<th>Radius [cm]</th>
<th>Phi segmentation</th>
<th>Number of modules per half single sided stave</th>
<th>Number of 128-ch FEIC per half single sided stave</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Short Strips</td>
<td>38</td>
<td>28</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>1</td>
<td>Short Strips</td>
<td>49</td>
<td>36</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>Short Strips</td>
<td>60</td>
<td>44</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
<td>Long Strips</td>
<td>75</td>
<td>56</td>
<td>19</td>
<td>190</td>
</tr>
<tr>
<td>4</td>
<td>Long Strips</td>
<td>95</td>
<td>72</td>
<td>19</td>
<td>190</td>
</tr>
</tbody>
</table>

**Total number of staves for the Barrel**: 236

**Total number of modules for the Barrel**: 14,336

**Total number of FEIC for the Barrel**: 270,060

**Total number of staves for one End-cap**: 1,152

**Total number of 128-ch FEIC for the two End-cap**: 57,088

**Total number of 128-channel FEICs**: 327,168

**Total amount of channels**: 41,877,504

- **Current SCT detector**
  - 4088 modules
  - 49k 128-channel FEIC
  - 6.3M channels

*Philippe Farthouat (CERN)*
The damage constant (slope) ~ consistent with n-bulk damage constant ($\alpha \sim 4 \times 10^{-17} \text{ A/cm}$)

- The leakage current of non-irradiated p-bulk sensors is at the similar level to HPK n-bulk sensors

Agreement between sites (Tsukuba/KEK and Liverpool)

- proton/neutron damages contribute similarly to leakage current increase