The ATLAS Strip Detector System for the High-Luminosity LHC

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On behalf of the ATLAS ITk Strip Community

Instrumentation for Colliding Beam Physics
Novosibirsk, Russia
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Future of the LHC

LHC / HL-LHC Plan

Run 1 | Run 2 | Run 3 | Run 4 - 5...
---|---|---|---
LS1 | LS2 | LS3 |
splice consolidation button collimators R2E project | Diodes Consolidation LIU Installation 11 T dipole coll. Civil Eng. P1-P5 | 14 TeV
7 TeV | 8 TeV | 13 - 14 TeV
experiment beam pipes EYETS 2 x nominal Lumi
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
radiation damage
ATLAS - CMS upgrade phase 1 ALICE - LHCb upgrade
ATLAS - CMS HL upgrade
30 fb⁻¹ 190 fb⁻¹ 350 fb⁻¹
5 to 7.5 x nominal Lumi
3000 fb⁻¹
4000 (ultimate)

HL-LHC TECHNICAL EQUIPMENT:

- DESIGN STUDY
- PROTOTYPES
- CONSTRUCTION
- INSTALLATION & COMM.
- PHYSICS

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ATLAS upgrade. Why?

- HL-LHC $L_{\text{int}} \sim 4000$ fb$^{-1}$
  - Requires increased radiation hardness
- Pile-up from $\sim 50$ to $\sim 200$
  - Requires increased granularity to maintain the current performance
- Faster readout, higher data bandwidth
- Increase $|\eta|$ coverage of tracking to 4

New all-silicon Inner Tracker (ITk)
ATLAS ITk Strip Detector

- ITk Detector
  - All-silicon tracking detector
  - Pixel and strips
  - Total area of silicon $\sim 180 \text{ m}^2$
  - 10 times the current number of readout channels

- ITk Strip
  - Barrel and end-caps follow same design philosophy
  - Single-sided modules on both sides of a carbon support structure
ITk Strip Sensor

- ~300 μm thick n<sup>+</sup>-in-p float zone (FZ) silicon sensors
- Required to be radiation tolerant up to
  - $1.6 \times 10^{15}$ n<sub>eq</sub>/cm<sup>2</sup>
  - 81 Mrad
- Bias voltage 100 – 500 V (depending on radiation damage)

### Barrel

- Rectangular ~97 × 97 mm<sup>2</sup>
- Parallel strips
- Pitch 75 μm
- 2 designs (Short Strips, Long Strips)
- Strip length 4 rows 24 mm, 2 rows 48 mm

### End-cap

- Trapezoidal shape (R – φ coverage)
- Radial strips
- Pitch 70 – 81 μm
- 6 designs R0-R5
- Strip length 15 – 60 mm
Hybrids, Front-End

- **Hybrids**
  - 4 layer Kapton PCB
  - Front-end ASICs (ABCStar)
    - Binary hit determination
    - Stores events until requested
  - Aggregation ASIC (HCCStar)
    - Communicates with up to 640 Mbits
    - Clock-control-readout requests are provided to all ABC

- **Powerboard**
  - Converts 11 to 1.5 V for hybrids
  - Autonomous monitor and control chip (AMAC)
    - Measures temperatures, voltages, currents
    - Controls LV, power states, switch off HV
ITk Strip Module

- Silicon sensor
- Hybrids and powerboard glued directly on the sensor
- Wire bonds for connections (25 μm aluminium)
- Modules glued and wire-bonded to stave/petals

17,888 strip modules required (barrel + end-cap)
Module design following mass production scheme with dedicated tools for module assembly
ITk Module Support

- Mechanical support (low-mass carbon-fiber)
  - Staves (Barrel) and Petals (for the End-Caps)
  - Common electrical, optical and cooling services
- Cooling via embedded Titanium tubes with evaporative CO$_2$ cooling (at -35°C)
- Copper/kapton co-cured bus tape (power, TTC, data, detector control system)
- Interface between staves and petals with the off-detector electronics through the End-Of-Substructure Card (EoS)

End-cap loaded support structure (petal)

EoS Card on an "ear" of the support structures

Barrel loaded support structure (stave)
Module testing at test beams

- 4.4 GeV electron beam @DESY
- 120 GeV Pion beam @CERN SPS
- EUDET-type telescope resolution:
  - 5-10 μm @DESY
  - 3-5 μm @CERN
- Track time tagging from telescope with USBPix system with FE-I4 chip.
- Dry ice cooling box used for irradiated modules
Module testing. Long Strip

- Module built using ATLAS17LS sensor and ABCStar chipset
  - Strip pitch 75 µm
  - Implant size 16 µm
  - Aluminum strip 22 µm

- Binary readout → infer charge collection in leading strip from threshold scan
- Edges shown:
  - lower median charge → charge sharing

<table>
<thead>
<tr>
<th>Median Charge (fC)</th>
<th>Full</th>
<th>Center</th>
<th>Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perpendicular to the beam</td>
<td>3.65</td>
<td>3.72</td>
<td>3.37</td>
</tr>
</tbody>
</table>
Module Testing. Irradiated Long Strip

- Testing of irradiated modules performance at the “end-of-life” expected fluence in the HL-LHC is a key point of the ATLAS upgrade project

ITk requirements:
- Efficiency: > 99%
- Noise-occupancy: < 0.1%
- Signal-to-noise ratio: > 10

Proton irradiated sensor to $5.1 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$
Gamma irradiated hybrids to 25 Mrad

Between $\sim 0.37 - 0.55 \text{ fC}$
Signal-to-noise ratio 15.9

Requirements are satisfied!
Module Testing. Irradiated R0

- Testing of irradiated modules performance at the “end-of-life” expected fluence in the HL-LHC is a key point of the ATLAS upgrade project

ITk requirements:
- Efficiency > 99%
- Noise-occupancy < 0.1%
- Signal-to-noise ratio > 10

Proton irradiated sensor to $1.5 \times 10^{15}$ n$_{eq}$/cm$^2$
Gamma irradiated hybrids to 35 Mrad

Innermost segment in endcap

Between $\sim$0.4 – 0.55 fC
Signal-to-noise of 11.7

Requirements are satisfied!
Module testing. Double-sided R0

- First double-sided ITk module prototype
- Stereo angle allows reconstruction of space points
  - Expectation for resolution of ITk strip detector: 540 µm in direction “along” strips
- Stereo angle α below nominal - 31 instead of 40 mrad. Only two layers at test beam

\[ \sigma_R = \frac{p}{\sqrt{24} \sin \phi/2} \approx 1.1 \text{ mm} \]
Summary and conclusions

- Results from sensor, readout, and module testing are well within the specification.
- Irradiated modules prove:
  - Operational requirements of efficiency and noise occupancy of the ITk strip detector are satisfied.
- After 15 years of designing, building prototypes, and testing we are confident the ITk Strip detector will be able to deliver the desired performance under the HL-LHC conditions.
- Preproduction starts this year:
  - Plenty of production components to test.
- More than 20000 modules to build during production.
Thanks
Backup Slides

- Basic building block of ATLAS ITk Strip detector:
  - Staves for the barrel. Built from long and short strip modules
  - Petals for the endcaps
- Prototyping phase based on long and short strip modules for the barrel and R0 module for the endcap
Data Reconstruction and Analysis

- **Reconstruction**
  - Track reconstruction by EUTelescope software using General Broken Lines algorithm
  - DUT positions in beam not precisely known from the setup
  - Tracks are used to (re)align each new beam impact position

- **Analysis**
  - Timing window: select particles in phase with 25 ns clock
  - Time matching of hit on timing plane
  - Only good tracks chi2/NDF

**Endcap sensors**
- Have in-sensor stereo angle implementation ("radial geometry")
- Custom EUTelescope modifications
Irradiated ITk Strip Modules

- Typical irradiations:
  - Proton and neutron irradiation to the end-of-life fluence including safety factor of 1.4
  - X-ray irradiation of hybrids, chips and power boards

<table>
<thead>
<tr>
<th>Module</th>
<th>Tested</th>
<th>Proton irradiation$^\dagger$ (10^{14} \text{n}_{\text{eq}}/\text{cm}^2)</th>
<th>X-ray hybrids* irradiation (Mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>June</td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td>Long Strip</td>
<td>September</td>
<td>5.1</td>
<td>25</td>
</tr>
</tbody>
</table>

$^\dagger$ Only silicon sensor
*Fully populated hybrids (ABCStar, HCCStar)
ITk Module Global Support

- Cylinders in barrel and disks in end-cap region provide structural support for insertion of staves and petals, respectively.
- Services (cooling lines and cables) via interface at end of structures.
Full-sized sensors have undergone an extensive irradiation (protons, neutrons, pions and gammas) tests at the expected end-of-life dose $2 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ and 70 Mrad.

At expected fluence still signal larger than 10,000 electrons compared to expected noise values of below 1,000 electrons.

Signal-to-noise ratio within design specification.

Good agreement for neutron and fair for proton irradiation between averaged results of A12 and A17 sensors.
Signal-to-noise ratio

- From experience it has been proven that a signal-to-noise ratio higher than 10 guarantees the existence of an operational window where the efficiency (> 99%) and the noise occupancy (< 0.1%) requirements are satisfied.

<table>
<thead>
<tr>
<th>Module (ABCStar)</th>
<th>Signal [fC] (e.)</th>
<th>S/N</th>
</tr>
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<tbody>
<tr>
<td>Unirrad. LS (400 V)</td>
<td>3.28 (20500)</td>
<td>23.8</td>
</tr>
<tr>
<td>Unirrad. R0S (400 V)</td>
<td>3.28 (20475)</td>
<td>29.3</td>
</tr>
<tr>
<td>Irrad. R0 innermost ring (500 V)</td>
<td>1.65 (9281)</td>
<td>14.8</td>
</tr>
<tr>
<td>Irrad. R0 second ring (500 V)</td>
<td>1.71 (9619)</td>
<td>13.2</td>
</tr>
<tr>
<td>Irrad. R0 third ring (500 V)</td>
<td>1.80 (10125)</td>
<td>11.9</td>
</tr>
<tr>
<td>Irrad. R0 outermost ring (500 V)</td>
<td>1.84 (10350)</td>
<td>11.6</td>
</tr>
<tr>
<td>Irrad. LS (500 V)</td>
<td>1.59 (9956)</td>
<td>15.9</td>
</tr>
</tbody>
</table>

It is clear that all the modules with the ABCStar readout chip tested satisfied the requirements!
Stereo Annulus Geometry of EC Sensors

- Stereo angle directly implemented in the sensor (20 mrad)
- Non-parallel strips
- No stereo angle implementation in module assembly required (total 40 mrad)