First Bulk and Surface Results for the ATLAS ITk Stereo Annulus Sensors


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11th International “Hiroshima” Symposium
On the Development and Application of Semiconductor Tracking Detectors
Outline

- Background
- Stereo Annulus Geometry and Its Advantages
- The R0 Prototype Sensor
  - With comparison to conventionally shaped comparable sensor
- Bulk Sensor Characteristics
  - With evaluation of irradiated performance
- Surface Property Investigation
  - With evaluation of irradiated performance

See talk by Vladimir Cindro: “Design of the first full size ATLAS ITk Strip sensor for the endcap region”

See poster by Carlos Lacasta Llacer: “Design of the first full size ATLAS ITk Strip sensor for the endcap region”

See also, R0 Prototype poster by Carlos Garcia Argos: “Assembly and Electrical Tests of the First Full-size Forward Module for the ATLAS ITk Strip Detector”
The HL-LHC and Challenges Faced

- 10x more premier p+ p+ data (3000fb⁻¹)
  ⇒ Higher sensitivity for LHC measurements
  ⇒ A leading possibility to uncover new physics

- 500-750% increase in instantaneous luminosity (levelled 5-7.5x10³⁴ cm⁻² s⁻¹)

- 600%-850% increase in number of interactions per 25ns bunch crossing (levelled 140-200 vs. 23/40 avg/peak)

- 170% increase in projected lifetime (27yr vs 10yr)

- 10x more radiation damage (10¹⁶ n$_{eq}$/cm² NIEL, 10⁷ Gy TID)

⇒ High granularity, reliability, radiation hardness required from detector upgrades
The ITk; Home of the First Stereo Annulus Sensor

- **ITk**; all-silicon HL-LHC replacement of ATLAS ID utilizing pixels and strips
- **The Strip Detector**; ~165m² silicon surface area
- **Endcaps**; two each with six disks each with 32 petals
- **Petal**;
  - Double-sided (mirror image)
  - Nine sensors per side in six designs
    - All stereo annulus
The Stereo Annulus Geometry

- What is the best way to do strip tracking in the restricted endcap geometry?
  
  - **Primary** dimension to measure is the azimuthal angle (bending dimension)
    - Use the most sensitive feature ⇒ **strips oriented radially**
  
  - **Secondary** dimension is the radius from the beam-pipe
    - Add a small (20-40mrad) **stereo angle** to vastly improve resolution
  
  - **Tertiary dimension** is the axial distance and is obtained from the disk location
The Stereo Annulus Design; ‘Reinventing’ the Wheel

Conventional Geometry: *Symmetric Trapezoidal Wedge* (Sensor itself is rotated by stereo angle)

Upgraded Geometry: *Stereo Trapezoidal Wedge*

Optimized Geometry: *Stereo Annulus*

**Disadvantages:**
- Most difficult interlocking
- Space is limited on petals
- Incomplete coverage at large and small radii
- Uneven strip lengths

- Truncated and orphaned strips
- Interlocking is more manageable
- Incomplete coverage at large and small radii
- Uneven strip lengths
- Inexperience
The R0 Prototype Sensor

- Prototype of innermost endcap sensor ("the R0"): **first stereo annulus sensor ever produced**
  - Annular edges obtained with 16 flat cuts
- Large surface: **90.0 cm² bias ring area**
- $n^+$-in-p, ac-coupled, single-sided, 20 mrad stereo
- 6”, FZ-grown, ~325 μm thick, <100> wafer
- Optimized common p-stops, gated PTP
- **Stealth diced slim edge width: 450-500 μm**
- SiO₂ and AlN:H passivation
- 4360 strips with constant angular pitch in each of the four segments
- **Hamamatsu Photonics**
- **72 sensors delivered to ATLAS from two batches**

### R0 Prototype Sensor Strip Specifications

<table>
<thead>
<tr>
<th>Row</th>
<th>Length (mm)</th>
<th>I-pitch (μm)</th>
<th>O-pitch (μm)</th>
<th>Pitch (μrad)</th>
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<tr>
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<td>18.981</td>
<td>74.314</td>
<td>77.983</td>
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<td>78.434</td>
<td>83.929</td>
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</table>
Bulk Character Comparison Samples

**R0 Prototype (Stereo Annulus)**
- Large surface area: (90.0cm², 91.8cm²)
- n⁺-in-p, ac-coupled, single-sided
- 6”, FZ-grown, ~325 μm thick, <100> wafer
- Optimized common p-stops, gated PTP
- SiO₂ and AlN:H passivation
- Similar strip and contact pad numbers (4360, 5128 strips in 4 segments)
- Hamamatsu Photonics

**ATLAS12 (Conventional Barrel)**
- Square with parallel strips of constant pitch (74.5 μm) and length (23.9 mm)
- Slim edge width for 25% of sensors (450 μm with a standard 980 μm)
- ~120 sensors from 4 batches

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See talks by Liv Wiik-Fuchs and Andy Blue for annealing and irradiated testbeam performance of ATLAS12. Coming up soon!

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Surface Properties; Irradiated Samples

- **730 (1cm)$^2$ minis**
  - i.e. square with parallel strips

- **252 minis** have already been irradiated up to $2.2 \times 10^{15}$ n$_{eqv}$/cm$^2$ with protons and neutrons

- Minis have ~8 mm long strips and come with variant pitch, coupling, and punch through protection configurations

Narrow / Default / Wide pitch (μm): 70 / 75 / 85

(R0 Prototype pitches range from approximately 73-84μm)

- **Today’s results**: AC-coupled, PTP minis from one mini test set irradiated with $p^+$ and annealed 80 minutes at 60°C

A Mini Test Set:

<table>
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<tr>
<th>Pitch</th>
<th>Coupling</th>
<th>PTP</th>
<th>0x</th>
<th>5x</th>
<th>10x</th>
<th>20x</th>
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<td>Yes</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>8</td>
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<tr>
<td></td>
<td>DC</td>
<td>Yes</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>DC</td>
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<td>2</td>
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<td>2</td>
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<td>6</td>
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<tr>
<td></td>
<td>DC</td>
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<td>1</td>
<td>1</td>
<td>3</td>
<td></td>
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<tr>
<td></td>
<td>DC</td>
<td>No</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td></td>
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<td>1</td>
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<td>6</td>
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<tr>
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<td>0</td>
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<td>Total</td>
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<td>10</td>
<td>10</td>
<td>12</td>
<td>10</td>
<td>42</td>
</tr>
</tbody>
</table>

Fluence unit: $x 10^{14}$ n$_{eqv}$/cm$^2$

Radiation Projections for the R0 Sensor

- **NIEL Fluence:** $3.8 \times 10^{14}$ n$_{eqv}$/cm$^2$
- **TID:** 9.8 Mrad

- **NIEL Fluence:** $1.2 \times 10^{15}$ n$_{eqv}$/cm$^2$
- **TID:** 50.4 Mrad

4500 fb$^{-1}$ (1.5 safety factor)


Three mini test sets are each irradiated with:

- **$n$**
  - reactor neutrons
  - Ljubljana Reactor
  - Jožef Stefan Institute, Slovenia

- **$p^+$**
  - 70MeV protons
  - CYRIC
  - Tohoku University, Japan

See talk by Vladimir Cindro for irradiated bulk performance including $n$ irradiation. Coming up next!
Test Setups

- Tests conducted in probestation or with sensor wirebonded into custom jigs
- Clean environment, dry storage
- Irradiated devices tested cold (in freezer or with a cooled chuck)

Unirradiated Devices +20°C to +30°C
Irradiated Devices -20°C to -30°C

R0 Prototype Test Institutes
Visual Inspection

- Sensors in good condition
- Observed $\sim 10 \, \mu m$ meander on annular edge flats correlated with crystal orientation

**Specification:** Devoid of chips or cracks extending 50 $\mu m$ inward

"Experienced Objective"
Metrology; Sensor Bow

- Considerations for stresses in assembled components restricts the sensor bow
- Sensors had typical dome-like bow profiles well within specification

Specification: < 200μm
**Metrology; Sensor Bow**

- High consistency across all 40 samples measured
- Well within specification
- Thickness also within specification

**Sensor Bow (μm) * Number of Sensors (Batches) in Sample**

<table>
<thead>
<tr>
<th></th>
<th>ATLAS12</th>
<th>R0 Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow</td>
<td>51.72 ± 12.36</td>
<td>51.18 ± 9.30</td>
</tr>
<tr>
<td>Batches</td>
<td>100 (4)</td>
<td>40 (2)</td>
</tr>
</tbody>
</table>

*RMSE against a Gaussian (Default in following tables)

**Specification:** &lt; 200μm

**ATLAS12**

- Thickness: ~320-325 μm

**Specification:** 310 ± 25 μm
Depletion Capacitance

- Low full depletion voltage (high resistivity) is especially desired due to the high fluence expectations
- High active depth to full thickness ratio is desired to maximize charge collection

- Excellent consistency in full depletion voltage
- High active depth proportion inferred from active area and depleted capacitance
Depletion Capacitance

- High consistency in full depletion voltage
- 93% of full thickness active depths (302.3 ± 1.4 μm)
- Resistivity meets specification

**Calculated resistivity:** 3.24 ± 0.03 kΩ cm

**Specification:** >= 3 kΩ cm

### Active Depletion Depth

<table>
<thead>
<tr>
<th></th>
<th>Full Depletion Voltage [V]</th>
<th>Resistivity (kΩ cm)</th>
<th>Number of Sensors (Batches) in Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS12</strong></td>
<td>365.2 ± 8.61</td>
<td>~2.5</td>
<td>98 (4)</td>
</tr>
<tr>
<td><strong>R0 Prototype</strong></td>
<td>303.04 ± 4.17</td>
<td>3.24</td>
<td>58 (2)</td>
</tr>
</tbody>
</table>

### Full Depletion Voltage

- **R0 Prototype**
- **ATLAS12**
**Leakage Current – IV Curve**

- Sensors must have low leakage current to maintain a feasible power budget at end-of-lifetime.
- For reliability sensors must be stable up to the voltage of -600V.

Orders of magnitude sufficient leakage current obtained.

Levels of instability are very reasonable.
**Leakage Current – IV Curve**

- Vast majority of sensors show very low leakage current \([O(1\text{nA/cm}^2)]\)
- Orders of magnitude within specification
- Lower level of leakage instability than the conventional sensor shape (ATLAS12)
- Instability attributed to passivation

**20°C and Bias Ring Area Normalized Leakage Current at -600V**

![Graph showing leakage current distribution](image)

**ATLAS12**

<table>
<thead>
<tr>
<th></th>
<th>20°C Leakage Current at -600V [-nA/cm²]</th>
<th>Percentage of Sensors with Increased Leakage below -600V (-1kV)</th>
<th>Number of Sensors (Batches) in Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS12</td>
<td>14.62 ± 59.35</td>
<td>14 (28)</td>
<td>118 (4)</td>
</tr>
<tr>
<td>R0 Prototype</td>
<td>1.95 ± 1.87</td>
<td>7 (15)</td>
<td>59 (2)</td>
</tr>
</tbody>
</table>

**Breakdown or Microdischarge Onset Voltage**

- No onset up to -1kV

**Specification:**
- < 2\(\mu\text{A/cm}^2\) @ 20°C and -600V
- No microdischarge onset below -600V
Microdischarge Humidity Dependence

- Sensors with early microdischarge onset show a humidity dependency in the onset voltage
  → Lower humidity, higher microdischarge onset voltages

- Similar observations for previous generations

**Percentage of R0 sensors with leakage instability below -600V (-1kV):** 7 (15)

**Specification:** No microdischarge onset below -600V

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**ATLAS12**
Long Term IV Stability

- Many sensors perform very well; fluctuations O(10nA) over several days even at elevated humidity
- Some sensors show sensitivity to higher humidities
  - Especially prevalent in the sensors with early breakdown/microdischarge
  - Some are recoverable after dry storage and sensor ‘training’ exercise
- Observations of instability correlated with changes in the rate of humidity change
Instability Conclusions

- Sensors showing early onset leakage instability exhibit much higher humidity sensitivity than their well-behaved counterparts.
- Lowered microdischarge breakdown effect is recoverable after long-term dry storage.
- Similar observations for conventional sensor shape of comparable size and complexity; not an issue with the stereo annulus geometry.
- Evidence for mobile ions and interface trap activation (passivation issues).

(Dry storage = 0.1%)
Strip Isolation: Bias and Interstrip Resistances

Bias Resistance

- Must be large to isolate strips
- Must be large and consistent across the sensor to distribute bias effectively
- High consistency, safely within specification observed in all samples measured

Full Segment Average: $1.59 \pm 0.01 \ \text{M}\Omega$

*No. of Strips Measured: 1026

Other Measurements Range: 1.47-1.52 M\(\Omega\)

**No. of Strips (Sensors) Measured: 10 (3)

Specification: $1.5 \pm 0.5 \ \text{M}\Omega$
**Strip Isolation: Bias and Interstrip Resistances**

**Interstrip Resistance**

- Must be much greater than the bias resistance to maintain channel isolation
- In the ATLAS ITk design the inversion channel inherent in the n+-in-p sensor is overcome with a narrow common p-stop
  - Orders of magnitude within specification

**Measurements:**

- All above 10GΩ

**Specification:**

- `R_{bias}` at 300V (150MΩ)

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*No. of Strips Measured: 26*
Strip Isolation after Proton Irradiation

- Strip isolation requirements met at 50V for a fluence of $2.2 \times 10^{15} \text{n}_{\text{eqv}}/\text{cm}^2$
- Bias Resistance shows very small, positive fluence and negative temperature dependencies
- Interstrip Resistance decreases with fluence and increases smoothly with bias after irradiation
- Measurements very comparable to previous generations
Coupling Capacitance

- Must be large to maximize signal and its integrity
- Very consistent and within specification
- Follows expected trends in strip length
- No radiation induced change
- Dielectric breakdown voltage is twice the specified value of 100V (~170V for negative voltage on the implants, ~210V for positive)

Full Segment Average: $25.21 \pm 0.02 \text{ pF/cm}^*$
*No. of Strips Measured: 1026

Other Measurements Range: $24.89-28.37 \text{ pF/cm}^{**}$
**No. of Strips Measured: 35

Specification: $> 20 \text{ pF/cm}$
Interstrip Capacitance

- Needs to be small to minimize noise at the front end and needs to be much smaller than coupling capacitance for isolation of channels
- Capacitance follows expected trends in pitch
- Good consistency
- No change with proton irradiation
- All measurements within specification

Range: **0.61 – 0.89 pF/cm** (at 700V)*

*No. of Strips Measured: 15

**Specification:** < 0.9 pF/cm @ 300V, 1 MHz

**IRRADIATED MINIS**

1 MHz

$2.2 \times 10^{15}$ $n_{eqv}/cm^2$

Coupling capacitance range: **24.89-28.37 pF/cm**
Punch Through Protection (PTP)

- Protects the coupling capacitor in the event of large charge liberation in the bulk.
- Desire early onset voltage and high current flow at -100V.
- Onset voltage increases with fluence but is only -30V at $2.2 \times 10^{15}$ n$_{eqv}$/cm$^2$ (at $V_{bias} = -600$V).
- Suitable PTP performance.

Surface Property Investigation

Summary and Conclusions

- Stereo annulus is an optimized geometry for the restricted space of an endcap strip tracker
  - Stereo angle gains in secondary resolution without negative effects
  - Equal length strips and better annular disk coverage

- The first R0 prototype sensors show excellent results
  - Meets specification in all categories
  - High consistency in bulk character
  - Low leakage and good levels of leakage instability
  - Also high consistency in the surface processing
  - All structures performing as expected

- The stereo annulus geometry is considered to have negligible effect on sensor performance from the comparisons of the R0 prototype to the ATLAS12
  - Instability is not isolated to the R0 prototype and is attributed to passivation
    - The passivation issue will be addressed in the next iteration of R0 prototype sensor
The research was supported and financed in part by Canada Foundation for Innovation, the National Science and Engineering Research Council (NSERC) of Canada under the Research and Technology Instrumentation (RTI) grant 23 SAPEQ-2016-00015; the Ministry of Education, Youth and Sports of the Czech Republic coming from the project 24 LM2015058 - Research infrastructure for experiments at CERN; USA Department of Energy, Grant DE-SC0010107; the Federal Ministry of Education and Research, BMBF, Germany
BACKUP
The Itk Strip Detector: Home of the First Stereo Annulus Sensors
The ITk Strip Detector: Home of the First Stereo Annulus Sensors

The ITk (Silicon Micro-)Strip Detector: \( \sim 6\text{m} \times 70\text{cm} \)

Approximately 165m² silicon surface detection area.
# ITk Justifications

<table>
<thead>
<tr>
<th>Operational Parameter</th>
<th>ID, LHC, and ATLAS Design Limits</th>
<th>HL-LHC Capabilities and Upgraded ATLAS Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment Lifetime</td>
<td>10 years</td>
<td>Current age: ~7 years Age at upgrade: 14 years Full duration: 27 years</td>
</tr>
<tr>
<td>Peak Instantaneous Luminosity (x $10^{34}$ cm$^{-2}$ s$^{-1}$)</td>
<td>1.0</td>
<td>Nominal: 5.0 Ultimate: 7.5 *with leveling</td>
</tr>
<tr>
<td>Pileup (proton collisions per 25 ns bunch crossing)</td>
<td>Design: 23 Operational Max: ~40 (peak), ~24 (avg.)</td>
<td>Nominal: 140 Ultimate: 200 *with leveling</td>
</tr>
<tr>
<td>ATLAS Trigger Rate (kHz)</td>
<td>Level-1: 100</td>
<td>Single Mode: Level-0: 1000 Dual Mode: Level-0: 4000 Level-1 (new): 400-600</td>
</tr>
<tr>
<td>Integrated Luminosity (fb$^{-1}$)</td>
<td>Pixels: 400 SCT: 700 Inserted Beam Layer: 850</td>
<td>Nominal: 3000 Ultimate: 4000</td>
</tr>
<tr>
<td>Maximum High Energy Particle Fluence (x $10^{15}$ 1 MeV n$_{eq}$ cm$^{-2}$)</td>
<td>Pixels: 5.0 SCT: 0.2</td>
<td>ITk Pixel: 18.7 ITk Strip: 1.2</td>
</tr>
<tr>
<td>Maximum Total Ionizing Dose (MGy)</td>
<td>Pixels: 3.0</td>
<td>ITk Pixel: 12.7 ITk Strip: 0.5</td>
</tr>
</tbody>
</table>

The ID was not designed for the HL-LHC and **will not survive it**.

### Background


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### Petals and ITk Strip Component Numerology

#### Barrel Layer

<table>
<thead>
<tr>
<th>Layer</th>
<th>Radius [mm]</th>
<th># of staves</th>
<th># of modules</th>
<th># of hybrids</th>
<th># of ABCStar</th>
<th># of channels</th>
<th>Area [m²]</th>
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<tr>
<td>L0</td>
<td>405</td>
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<td>15680</td>
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<tr>
<td>L1</td>
<td>562</td>
<td>40</td>
<td>1120</td>
<td>2240</td>
<td>22400</td>
<td>5.73M</td>
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<td>L2</td>
<td>762</td>
<td>56</td>
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<td>1568</td>
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<td>L3</td>
<td>1000</td>
<td>72</td>
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<td>2016</td>
<td>20160</td>
<td>5.16M</td>
<td>19.26</td>
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<tr>
<td>Total half barrel</td>
<td>196</td>
<td>5488</td>
<td>7392</td>
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<td>18.92M</td>
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<tr>
<td>Total barrel</td>
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<td>10976</td>
<td>14784</td>
<td>147840</td>
<td>37.85M</td>
<td>104.86</td>
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</tbody>
</table>

#### End-cap Disk

<table>
<thead>
<tr>
<th>Disk</th>
<th>z-pos. [mm]</th>
<th># of petals</th>
<th># of modules</th>
<th># of hybrids</th>
<th># of ABCStar</th>
<th># of channels</th>
<th>Area [m²]</th>
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<tbody>
<tr>
<td>D0</td>
<td>1512</td>
<td>32</td>
<td>576</td>
<td>832</td>
<td>6336</td>
<td>1.62M</td>
<td>5.03</td>
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<tr>
<td>D1</td>
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<td>32</td>
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<td>832</td>
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<td>832</td>
<td>6336</td>
<td>1.62M</td>
<td>5.03</td>
</tr>
<tr>
<td>Total one EC</td>
<td>192</td>
<td>3456</td>
<td>4992</td>
<td>43008</td>
<td>11.01M</td>
<td>30.2</td>
<td></td>
</tr>
<tr>
<td>Total ECs</td>
<td>384</td>
<td>6912</td>
<td>9984</td>
<td>86016</td>
<td>22.02M</td>
<td>60.4</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>776</td>
<td>17888</td>
<td>24768</td>
<td>233856</td>
<td>59.87M</td>
<td>165.25</td>
<td></td>
</tr>
</tbody>
</table>

---

## Stereo Annulus Sensors of the ITk Endcaps

### The Stereo Annulus Design


### Sensor Specifications

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Number of Sensors</th>
<th>Shape</th>
<th>Number of Rows</th>
<th>Channels per Sensor</th>
<th>Min/Max Pitch (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-strips</td>
<td>3808</td>
<td>Square</td>
<td>4</td>
<td>5128</td>
<td>75.5</td>
</tr>
<tr>
<td>Long-strips</td>
<td>7168</td>
<td>Square</td>
<td>2</td>
<td>2564</td>
<td>75.5</td>
</tr>
</tbody>
</table>

### Ring/Row Parameters

<table>
<thead>
<tr>
<th>Ring/Row</th>
<th>Inner Radius [mm]</th>
<th>Strip Length [mm]</th>
<th>Strip Pitch [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 0 Row 0</td>
<td>384.5</td>
<td>19</td>
<td>75.0</td>
</tr>
<tr>
<td>Ring 0 Row 1</td>
<td>403.5</td>
<td>24</td>
<td>79.2</td>
</tr>
<tr>
<td>Ring 0 Row 2</td>
<td>427.5</td>
<td>29</td>
<td>74.9</td>
</tr>
<tr>
<td>Ring 0 Row 3</td>
<td>456.4</td>
<td>32</td>
<td>80.2</td>
</tr>
<tr>
<td>Ring 1 Row 0</td>
<td>489.8</td>
<td>18.1</td>
<td>69.9</td>
</tr>
<tr>
<td>Ring 1 Row 1</td>
<td>507.9</td>
<td>27.1</td>
<td>72.9</td>
</tr>
<tr>
<td>Ring 1 Row 2</td>
<td>535</td>
<td>24.1</td>
<td>75.6</td>
</tr>
<tr>
<td>Ring 1 Row 3</td>
<td>559.1</td>
<td>15.1</td>
<td>78.6</td>
</tr>
<tr>
<td>Ring 2 Row 0</td>
<td>575.6</td>
<td>30.8</td>
<td>75.7</td>
</tr>
<tr>
<td>Ring 2 Row 1</td>
<td>606.4</td>
<td>30.8</td>
<td>79.8</td>
</tr>
<tr>
<td>Ring 3 Row 0</td>
<td>638.6</td>
<td>32.2</td>
<td>71.1</td>
</tr>
<tr>
<td>Ring 3 Row 1</td>
<td>670.8</td>
<td>26.2</td>
<td>74.3</td>
</tr>
<tr>
<td>Ring 3 Row 2</td>
<td>697.1</td>
<td>26.2</td>
<td>77.5</td>
</tr>
<tr>
<td>Ring 3 Row 3</td>
<td>723.3</td>
<td>32.2</td>
<td>80.7</td>
</tr>
<tr>
<td>Ring 4 Row 0</td>
<td>756.9</td>
<td>54.6</td>
<td>75.0</td>
</tr>
<tr>
<td>Ring 4 Row 1</td>
<td>811.5</td>
<td>54.6</td>
<td>80.3</td>
</tr>
<tr>
<td>Ring 5 Row 0</td>
<td>867.5</td>
<td>40.2</td>
<td>76.2</td>
</tr>
<tr>
<td>Ring 5 Row 1</td>
<td>907.6</td>
<td>60.2</td>
<td>80.5</td>
</tr>
</tbody>
</table>
An ATLAS12EC Sensor
## Sensor Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ATLAS12EC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer size</td>
<td>150 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>$310 \pm 25 \mu m$</td>
</tr>
<tr>
<td>Orientation</td>
<td>$\langle 100 \rangle$</td>
</tr>
<tr>
<td>Type</td>
<td>P</td>
</tr>
<tr>
<td>Ingot</td>
<td>FZ</td>
</tr>
<tr>
<td>Resistivity</td>
<td>$&gt;3 , \text{k} \Omega \text{cm}$</td>
</tr>
<tr>
<td>Strip segments</td>
<td>4</td>
</tr>
<tr>
<td>Strip implant</td>
<td>N</td>
</tr>
<tr>
<td>Strip implant Width</td>
<td>16 $\mu$m</td>
</tr>
<tr>
<td>Strip bias resistor</td>
<td>Polysilicon</td>
</tr>
<tr>
<td>Strip bias resistance ($R_b$)</td>
<td>1.5$\pm$0.5 MΩ</td>
</tr>
<tr>
<td>Strip readout coupling</td>
<td>AC</td>
</tr>
<tr>
<td>Strip readout metal</td>
<td>Pure Aluminium</td>
</tr>
<tr>
<td>Strip readout metal width</td>
<td>20 $\mu$m</td>
</tr>
<tr>
<td>Strip AC coupling capacitance</td>
<td>$&gt;20 , \text{pF/cm}$</td>
</tr>
<tr>
<td>Strip isolation</td>
<td>$&gt;10 \times R_b$ at 300 V</td>
</tr>
<tr>
<td>Strip isolation method</td>
<td>Narrow-common p-stop</td>
</tr>
<tr>
<td>Gap between strip segments</td>
<td>56 $\mu$m (rail region)</td>
</tr>
<tr>
<td></td>
<td>70 $\mu$m (no rail region)</td>
</tr>
<tr>
<td>Microdischarge onset voltage</td>
<td>$&gt;600 , \text{V}$</td>
</tr>
<tr>
<td>Maximum operation voltage ($^{(1)}$)</td>
<td>600 V</td>
</tr>
<tr>
<td>Leakage current</td>
<td>$&lt;2 , \mu A/cm^2$ at 600 V</td>
</tr>
<tr>
<td>Radiation tolerance</td>
<td>$1.5 \times 10^{13} , \text{1-MeV n}_{eq}/\text{cm}^2$</td>
</tr>
</tbody>
</table>

$^{(1)}$ The voltage rating of the external high voltage cable is 500V and tested 1 KV.
**ATLAS ITk Prototype Sensors**

**ATLAS07**
- First full size sensor (~100cm²)
- Half of strips rotated by 40mrad


**ATLAS12**
- Slim edge width for ~30% of sensors (450μm)
- Two variants
  - Same as A07 (half of strips stereo rotated)
  - All four strip segments unrotated (2)


Wafer layouts of the ATLAS ITk Strip prototype sensors.

[i] ATLAS05  
[ii] ATLAS06  
[iii] ATLAS07  
[iv] ATLAS12A  
[v] ATLAS12M  
[vi] ATLAS12EC  
[vii] ATLAS17LS

See talks by Liv Wiik-Fuchs and Andy Blue for annealing and irradiated testbeam performance of ATLAS12. Coming up soon!
**ATLAS12EC Mini Sensors**

Mini distribution:

<table>
<thead>
<tr>
<th>Pitch</th>
<th>Coupling</th>
<th>PTP</th>
<th>Total</th>
<th>Irradiated</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>AC</td>
<td>Yes</td>
<td>166</td>
<td>48</td>
<td>118</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>Yes</td>
<td>166</td>
<td>48</td>
<td>118</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>No</td>
<td>166</td>
<td>48</td>
<td>118</td>
</tr>
<tr>
<td>Narrow</td>
<td>AC</td>
<td>Yes</td>
<td>58</td>
<td>36</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>Yes</td>
<td>29</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>No</td>
<td>29</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td>Wide</td>
<td>AC</td>
<td>Yes</td>
<td>58</td>
<td>36</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>Yes</td>
<td>29</td>
<td>0</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>No</td>
<td>29</td>
<td>0</td>
<td>29</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>730</strong></td>
<td><strong>252</strong></td>
<td><strong>478</strong></td>
</tr>
</tbody>
</table>

Irradiation test set: \((x10^{14} n_{eqv}/cm^2)\)

<table>
<thead>
<tr>
<th>Pitch</th>
<th>Coupling</th>
<th>PTP</th>
<th>0x</th>
<th>5x</th>
<th>10x</th>
<th>20x</th>
<th>TOTAL</th>
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<tr>
<td>Default</td>
<td>AC</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>DC</td>
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<td>8</td>
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<tr>
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</tr>
<tr>
<td></td>
<td>DC</td>
<td>Yes</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>No</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Wide</td>
<td>AC</td>
<td>Yes</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>Yes</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>No</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>10</strong></td>
<td><strong>10</strong></td>
<td><strong>12</strong></td>
<td><strong>10</strong></td>
<td><strong>42</strong></td>
</tr>
</tbody>
</table>

Three mini test sets are each irradiated with:

- **n** reactor neutrons
  - Ljubljana Reactor
  - Jožef Stefan Institute, Slovenia

- **p^+** 70MeV protons
  - CYRIC
  - Tohoku University, Japan
First ATLAS12EC Module

See poster by Carlos Garcia Argos: “Assembly and Electrical Tests of the First Full-size Forward Module for the ATLAS ITk Strip Detector”
Measurement Techniques

ATLAS12EC Sensors
More Visual Inspection Results

Bulk Sensor Characteristics
More Metrology Results

- High consistency *well within* specification

"Turtle-shell" relic believed to be setup related
Full Depletion Kink

- Sensors from one institute removed from CV plot due to systematic parasitic capacitance that is not yet fully understood
  - 9 sensors sit above the 49 sensors in the lower curve seen
- This systematic does not affect the full depletion voltage extraction, as seen
CV Curves (Over the Generations)


IV Curves (Over the Generations)


IV Hysteresis

- Observed in sensors with and without strenous humidity history
  - Evidence for bias activated interface states
Hysteresis of Interstrip Capacitance

Surface Property Investigation

---

**Graph 1:**
- Title: VPX22728-W015 (R0 sensor)
- Description: Consecutive measurements with $V_{bias} = -400V$ between.

**Graph 2:**
- Title: C_{inter ramp} [pF]
- Description: Capacitance measurements before and after 2 weeks.

**Graph 3:**
- Title: C_{eff} [pF/cm]
- Description: Electric field measurements with RH 33%.

**Graph 4:**
- Title: C_{ef} [pF/cm]
- Description: Capacitance measurements over time.
Hysteresis in ATLAS07 and ATLAS12

ATLAS12 C_{bulk}

consecutive measurements \( V_{\text{const}} = -600 \text{V} \) between

ATLAS12 C_{cis}

ATLAS07 C_{cis} Strip Isolation Structure Comparison

p-stop

consecutive measurements \( V_{\text{const}} = -600 \text{V} \) between

p-spray

consecutive measurements \( V_{\text{const}} = -600 \text{V} \) between
Humidity Sensitivity – A Tale of Two Sensors

- W042 showed good IV character
- Both poor and well behaved sensors (in an IV curve respect) can show humidity sensitivity
- Recovery of sensors after long-term dry storage
  - Complete recovery of microdischarge onset
  - Some hysteresis remains (ion activated interface traps)

(Dry storage = 0.1%)

After weeks in dry storage
After 24hr at 700V, 36% and then 26hrs in dry storage.
After 3 hr at 55% and 13hr at 35%
After nearly six months in dry storage
Humidity Sensitivity – A Tale of Two Sensors

- W048 showed early onset microdischarge and a humidity dependency therein
- Both poor and well behaved sensors (in an IV curve respect) can show humidity sensitivity
- Recovery of sensors after long-term dry storage
  - Complete recovery of microdischarge onset
  - Some hysteresis remains (ion activated interface traps)

(Dry storage = 0.1%)

Bulk Sensor Characteristics

Taken consecutively.
Consecutive after weeks in dry storage
Consecutive after 24hr at 400V, 55% and then 48hr in dry storage
After 24hr at 280V, 40%
After 24hr at 280V, 25% and 15hr in dry storage
After nearly six months in dry storage
Long Term IV Stability and Humidity

Bulk Sensor Characteristics
More Evidence for Passivation Issues

- Immediate response to changes in humidity in long term tests

400V

Triple peak at end of run:
1st peak: ~51.5% up, quick I decrease
2nd peak: ~50.5% up, quick I decrease
3rd peak: ~49.75% up, leave fan slow to bring down H slow, instability lasts to lower H than with quick fall
ATLAS12 Humidity Sensitivity

Bulk Sensor Characteristics
Dielectric Breakdown Voltage

- Understandable discrepancy between negative and positive voltage breakdowns
  - Sensor unbiased, inversion layer opposes the positive strip voltage, reinforces the negative

**Postive Voltage on Strips:**
~200V-210V

**Negative Voltage on Strips:**
~150V-170V

**Specification:** > 100V
Strip and Implant Resistance

- Must be ‘small’ to maximize signal integrity and consistent for comparable channel response

**Aluminum Strip Resistance**

Range: 12.1 – 21.05 Ω/cm*

*No. of Strips Measured: 17

Specification: < 30 Ω/cm

**n± Implant Resistance**

Average: 20.38 ± 0.21 kΩ/cm*

*No. of Strips Measured: 7

Specification: < 50 kΩ/cm
Frequency Dependence of Interstrip Capacitance

Surface Property Investigation

Unirradiated

100kHz is chosen as test frequency (sits well into the plateau region)
More Measurements of Coupling Capacitance

<table>
<thead>
<tr>
<th>Segment</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Measurements</td>
<td>17</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Range (pF)</td>
<td>46.42-46.95</td>
<td>58.21-59.02</td>
<td>69.75-72.28</td>
<td>76.24-77.42</td>
</tr>
<tr>
<td>Average (pF)</td>
<td>46.70</td>
<td>58.51</td>
<td>70.90</td>
<td>77.00</td>
</tr>
<tr>
<td>Average (pF/cm)</td>
<td>25.24</td>
<td>24.90</td>
<td>24.88</td>
<td>24.55</td>
</tr>
</tbody>
</table>

Sensor ID | $C_{coup}$ [pF] |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>W031</td>
<td>24.25</td>
</tr>
<tr>
<td>W034</td>
<td>27.55</td>
</tr>
<tr>
<td>W084</td>
<td>28.19</td>
</tr>
<tr>
<td>W086</td>
<td>28.37</td>
</tr>
</tbody>
</table>

$f = 1$kHz, CR Parallel

Average $C_{coup} = 28.12$ pF/cm
Specs. $C_{coup} > 20$ pF/cm
More Results for Bias and Interstrip Resistance

- **Polysilicon Bias Resistor (R_{BIAS})**
  - Average \( R_{BIAS} = 1.52 \, \text{M}\Omega \)
  - Specs. \( R_{BIAS} = (1.5 \pm 0.5) \, \text{M}\Omega \)

- **Interstrip Resistance (R_{int})**
  - Average \( R_{int} = 142.06 \, \text{G}\Omega \)
  - Specs. \( R_{int} > 15 \, \text{M}\Omega \) (10x\( R_{BIAS} \))

<table>
<thead>
<tr>
<th>Sensor ID</th>
<th>( R_b ) [M\Omega]</th>
<th>( R_{ls} ) [G\Omega]</th>
</tr>
</thead>
<tbody>
<tr>
<td>W031</td>
<td>1.47</td>
<td>10-120</td>
</tr>
<tr>
<td>W084</td>
<td>1.52</td>
<td>271</td>
</tr>
<tr>
<td>W086</td>
<td>1.49</td>
<td>99.8</td>
</tr>
</tbody>
</table>

---

3 random strips per sensor
(Irradiated) Performance of the PTP

Surface Property Investigation

unirradiated
Irradiated Performance of the Interstrip Capacitance

Surface Property Investigation

Unirradiated

\[ 2.2 \times 10^{15} \]

\[ 5.6 \times 10^{14} \]

\[ 1.1 \times 10^{15} \]