Electrical characterization of surface properties of the ATLAS17LS sensors after neutron, proton and gamma irradiation


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12th Hiroshima symposium, Hiroshima, 14 to 18 December, 2019
**ATLAS Inner Tracker (ITk) strip sensors**

- Single-sided $n^+$ - in - $p$ (FZ) $<100>$
- 6-inch wafer processing
- Thickness 300-320 $\mu$m
- AC-coupled readout, strips biased via poly-silicon bias resistors
- Common $p$-stop isolation ($4 \times 10^{12}$ ions/cm$^2$)
- ITk includes: 2 barrel types: Short Strips (SS) and Long Strips (LS)
  - 6 End-Cap types: R0-R5

**Maximal nominal radiation fluences (doses) based on 4000 fb$^{-1}$**

- Strip barrel: $6.4 \times 10^{14} \text{n}_{eq}/\text{cm}^2$ (0.29 MGy)
- Strip end-cap: $10.6 \times 10^{14} \text{n}_{eq}/\text{cm}^2$ (0.44 MGy)

**Testing with safety factor 1.5**

**High radiation fluence impact on sensor properties:**

- **Bulk damage:**
  - Increase of leakage current
  - Depletion characteristics and CCE change
- **Surface damage:**
  - Charge raise at the Si-SiO$_2$ interface
  - Influences break-down voltage,
  - Inter-electrode isolation and
  - Other electrical surface parameters

**Verification of sensor properties before and after irradiation by protons, neutrons and gammas at many ATLAS institutions**
ATLAS ITk strip sensor prototypes

Last 2 main sensor prototype submissions:

- **ATLAS12EC** (R0 EndCap) HPK
  - First main ATLAS ITk sensor for EC region
  - Minis with variant pitch, coupling and PTP structure configurations

- **ATLAS17LS** (barrel LS) HPK and IFX
  - Qualifying vendors as a part of ATLAS strip sensors *Market Survey Step3*
  - New features from 12 design: strip pitch 74.5 -> 75.5um; passivation
  - Mini sensors: 1×1cm, SS(1×2.6cm), LS(1×5cm), diodes, TEST structures

This talk summarizes results from surface evaluation of HPK latest prototype submission of ATLAS17LS main and mini sensors after irradiation by protons, neutrons and gammas and compares results with ATLAS12EC main sensors.
Step-3 Qualification requirements from Market Survey MS-4086/EP for ATLAS Strip Tracker Upgrade

- The final qualification step required the production of full-size and fully featured prototype sensors according to the specifications stated in MS-4086/EP document.

- **Sensor shall fulfill the following electrical specifications before and after irradiation:**

  **3.6.1 Electrical Specifications by ATLAS**
  Electrical measurements to be performed by the contractor(s) on each sensor (except where otherwise stated). Only sensors fulfilling the electrical requirements will be accepted.

  **3.6.1.1 Specifications for quality assurance**
  Electrical measurements to be performed by the contractor on each sensor (except where otherwise stated),

  - Full depletion voltage: \(< 330 \text{ V (preference for } < 150 \text{ V)}\)
  - Maximum operating voltage: \(600 \text{ V} \)
  - Poly-silicon bias resistors: \(1-2 \text{ MOhm}\)
  - Inter-strip resistance: \(> 10 \times R_{\text{bias}} \text{ at } 300 \text{ V at } 23 \text{ C}\)
  - Inter-strip capacitance: \(< 1 \text{ pF/cm at } 300 \text{ V, measured at } 100 \text{ kHz}\)
  - Coupling capacitance: \(> 20 \text{ pF/cm at } 1 \text{ kHz}\)
  - Resistance of readout AI strips: \(< 15 \text{ Ohm/cm}\)
  - Resistance of n-implant strip: \(< 20 \text{ kOhm/cm}\)
  - Onset of micro-discharge at: \(> 600 \text{ V (preferred)}\)
  - Total initial leakage current, including guard ring: \(< 0.1 \mu\text{A/cm}^2 \text{ at } 600 \text{ V at room temperature}\)
  - Number of strip defects: \(< 1\% \text{ per strip/segment and } < 1\% \text{ per sensor (due to dielectric punch-through, metal and implant strip defects (opens and shorts), micro-discharging strip or bias resistor failures)}\)

  **3.6.1.2 Measurements after irradiation**
  Sensors shall fulfill the following requirements after being subjected to irradiation with ionizing and non-ionizing radiation to a fluence of \(2 \times 10^{15} \text{neq/cm}^2\) (60 Mrad). Irradiations and the subsequent measurements will be performed by ATLAS.
  Measurements are performed at \(T = -20\text{ C}\),
  - Onset of micro-discharge at: \(> 600 \text{ V or } V_{\text{fl}} + 50 \text{ V after irradiation (if lower)}\)
  - Inter-strip resistance: \(> 10 \times R_{\text{bias}} \text{ at } 400 \text{ V and for } T = -20\text{ C}\)
  - Collected charge: \(> 7500 \text{ electrons per MIP at } 500\text{ V}\)
### Irradiations

#### Total number of samples irradiated

<table>
<thead>
<tr>
<th></th>
<th>ATLAS17LS</th>
<th>ATLAS12EC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HPK</td>
<td>IFX</td>
</tr>
<tr>
<td><strong>Protons</strong></td>
<td>567 (2 mains)</td>
<td>102 (2 mains)</td>
</tr>
<tr>
<td>(24 GeV) at CERN PS</td>
<td>89 (1)</td>
<td>0</td>
</tr>
<tr>
<td>(70 MeV) at CYRIC, Tohoku Uni</td>
<td>139</td>
<td>58 (1)</td>
</tr>
<tr>
<td>(28 MeV) at Birmingham</td>
<td>88</td>
<td>0</td>
</tr>
<tr>
<td>(23 MeV) at KIT</td>
<td>55</td>
<td>0</td>
</tr>
<tr>
<td><strong>Neutrons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ljubljana TRIGA reactor</td>
<td>121 (1)</td>
<td>21 (1)</td>
</tr>
<tr>
<td><strong>Gammas</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>((^{60})Co) at UJP Praha</td>
<td>75</td>
<td>23</td>
</tr>
</tbody>
</table>

#### Co in UJP Praha
- Diameter of sensor irradiation area: 6 cm
- Homogeneity in irradiation area: ±5%

![Dose profile of Co-60 source to sample distance - 55 mm](image)

**60Co**

**60Co Terabalt, UJP Praha**

**CERN PS**

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## Institutions participating in evaluation of ATLAS17LS sensors

<table>
<thead>
<tr>
<th>Institution</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFIC (CERN, Valencia)</td>
<td>IV/CV, CCE, Test beam</td>
</tr>
<tr>
<td>Toronto</td>
<td>IV/CV Surface studies, CCE, Test beam</td>
</tr>
<tr>
<td>KEK/Tsukuba U.</td>
<td>IV/CV, Surface studies, CCE</td>
</tr>
<tr>
<td>DESY (Zeuthen), Humboldt U (Berlin)</td>
<td>Surface studies, TCT, Test beam</td>
</tr>
<tr>
<td>DESY (Hamburg)</td>
<td>IV/CV, Surface studies, Test beam</td>
</tr>
<tr>
<td>Simon Fraser University (Vancouver)</td>
<td>IV/CV, Surface studies, CCE</td>
</tr>
<tr>
<td>Santa Cruz</td>
<td>IV/CV, Surface studies, CCE</td>
</tr>
<tr>
<td>Cambridge</td>
<td>IV/CV, Surface studies, Test beam</td>
</tr>
<tr>
<td>Institute of Physics (Prague)</td>
<td>IV/CV, Surface studies, Test beam</td>
</tr>
<tr>
<td>CNM (Barcelona)</td>
<td>IV/CV, Surface studies</td>
</tr>
<tr>
<td>Carleton (Ottawa)</td>
<td>IV/CV, Surface studies, Test beam</td>
</tr>
<tr>
<td>Liverpool</td>
<td>CCE</td>
</tr>
<tr>
<td>Freiburg</td>
<td>CCE, TCT, Test beam</td>
</tr>
<tr>
<td>IJS (Ljubljana)</td>
<td>CCE, Edge TCT</td>
</tr>
<tr>
<td>Birmingham</td>
<td>CCE, Test beam</td>
</tr>
<tr>
<td>UCT (Cape Town), RAL, University of Dortmund, Charles University (Prague)</td>
<td>Test beam</td>
</tr>
</tbody>
</table>
Electrical tests of sensors

- IV (current, breakdown voltage)
- Inter-strip Resistance ($R_{\text{int}}$)
- Inter-strip Capacitance ($C_{\text{int}}$)
- Bias Resistance ($R_{\text{bias}}$)
- Coupling Capacitance ($C_{\text{coup}}$)
- Implant and Metal Resistance
- PTP (beam loss protection) Effectiveness

Measurement conditions:
- **Non-irradiated sensors**: measured mainly in probe stations at RT
- **Irradiated sensors**: wire bonded to PCB board or a jig tested in freezer (at -20°C or lower) in dry N₂ atmosphere
IV and onset of microdischarge: main ATLAS12EC and ATLAS17LS

ATLAS Specs for these submissions: Onset Voltage of Microdischarge ($V_{MD}$) > 600V

- No onset of microdischarge observed in main sensors after proton or neutron irradiations

![Graphs showing IV and onset of microdischarge](image-url)
IV and Onset of Microdischarge: proton and gamma irradiated mini ATLAS17LS

ATLAS Specs for these submission: Onset Voltage of Microdischarge \((V_{MD}) > 600V\)

- **ATLAS17LS mini - PS CERN**

  \[ \text{Current [\mu A]} \]
  \[ \text{Voltage (V)} \]
  \[ T = -20°C \]
  \[ RH \sim 0% \]

- **ATLAS17LS mini - CYRIC**

  \[ \text{Cur [A]} \]
  \[ T = -20°C \]
  \[ T = 20°C \]
  \[ RH \sim 0% \]

- **ATLAS17LS mini – n, p(KIT), γ**

  \[ \text{Current [A]} \]
  \[ \text{Bias Voltage (V)} \]
  \[ T = -20°C \]
  \[ RH \sim 0% \]

- **ATLAS17LS mini – PS CERN**

  \[ \text{Current [\mu A]} \]
  \[ \text{Voltage (V)} \]
  \[ T = -20°C \]
  \[ RH \sim 10% \]

- Results of all institutions in agreement
- After irradiations: 1 mini sensor out of 80 has onset voltage of microdischarge bellow 600V

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Inter-strip capacitance: ATLAS12EC and ATLAS17LS

- $C_{int}$ contributes to the input capacitance of FE electronics and determines the noise level of the detector
- $C_{int}$ measured by LCR meter between the central strip and its first neighbors (others floating)
- next 2nd and 3rd neighbors add ~10%

**ATLAS Specs:** < 1 pF/cm at 300V for non-irrad. at 400V after irrad.

- **ATLAS12EC main - CERN PS**
  - $T= -20^\circ C$
  - $1.5 \times 10^{15}$ $n_{eq}/cm^2$

- **ATLAS17LS main - neutron**
  - $5.1 \times 10^{14}$ $n_{eq}/cm^2$

- **ATLAS17LS mini - CYRIC**
  - Non-irrad. tests: $T= +20^\circ C$
  - Irrad. tests: $T= -40^\circ C$

- **ATLAS17LS mini – n, p(KIT), γ**

- No change of $C_{int}$ after proton, neutron or gamma irradiations
- All tested main and mini sensors of both ATLAS12EC and ATLAS17LS types are within specs before and after irradiation

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Inter-strip capacitance: gamma irradiated mini ATLAS17LS

ATLAS Specs: < 1 pF/cm at 400V

- All mini sensors within specifications both before and after gamma irradiations
- No change of $C_{int}$ after gamma irradiation
Inter-strip resistance: **main ATLAS12EC** and **ATLAS17LS**

Measurements of Inter-strip resistance ($R_{int}$) - verification of neighboring strips isolation

**ATLAS Specs:**
- **non-irradiated:** $R_{int} > 15\, \text{MOhm}$ at 300V at $+23^\circ\text{C}$
- **irradiated:** $R_{int} > 15\, \text{MOhm}$ at 400V at $-20^\circ\text{C}$

**ATLAS12EC – non-irradiated**

- $T = +20^\circ\text{C}$

**ATLAS12EC – CERN PS**

- $T = -20^\circ\text{C}$

**ATLAS17LS – neutrons**

- $5.1 \times 10^{14}\, \text{n}_{eq}/\text{cm}^2$
  - $T = -20^\circ\text{C}$

**Non-irradiated main sensors:**
- $R_{int}/\text{strip} = 15-80\, \Omega$
- $R_{int}$ is independent of $V_{bias}$

**Irradiated sensors:**
- $R_{int}$ increases with bias voltage - Bias field reduces conductivity between strips
- $R_{int} \approx 1\, \text{GOhm}$ at 400V for neutrons
- $R_{int} > 70\, \text{MOhm}$ at 400V for protons

Main sensors irradiated by neutrons and protons fulfill specifications
Inter-strip resistance: $\gamma$ irradiated mini ATLAS17LS

ATLAS Specs: $R_{\text{int}} > 10 \cdot R_{\text{bias}}$ @ 400 V

Inter-strip resistance (T= -20°C Post-Annealing)

Inter-strip resistance vs TID (T= -20°C Post-Annealing)

Unirrad $R_{\text{int}}$ @ 400 V = 38.76 $\pm$ 2.61 GΩ
10MRad $R_{\text{int}}$ @ 400 V = 0.43 $\pm$ 0.07 GΩ
35MRad $R_{\text{int}}$ @ 400 V = 0.22 $\pm$ 0.05 GΩ
70MRad $R_{\text{int}}$ @ 400 V = 0.06 $\pm$ 0.02 GΩ

$R_{\text{int}}$ decreases with increasing gamma dose but all sensors fulfill specs even at highest TID.

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Inter-strip resistance vs. total ionizing dose (protons, neutrons and gammas)

- TID in irradiated sensors at $1 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ has been assessed to be:

<table>
<thead>
<tr>
<th>$1 \times 10^{15} \text{n}_{eq}/\text{cm}^2$</th>
<th>TID [Gy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrons</td>
<td></td>
</tr>
<tr>
<td>reactor</td>
<td>minis</td>
</tr>
<tr>
<td></td>
<td>main</td>
</tr>
<tr>
<td>protons</td>
<td></td>
</tr>
<tr>
<td>B’ham</td>
<td></td>
</tr>
<tr>
<td>KIT</td>
<td></td>
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<tr>
<td>CYRIC</td>
<td></td>
</tr>
<tr>
<td>CERN PS</td>
<td></td>
</tr>
</tbody>
</table>

All irradiated sensors fulfill specs up to max. predicted TID

Max. TID expected with 1.5 safety factor
Bias resistance: proton and gamma irradiated ATLAS17LS

**ATLAS Specs:** $1.5 \pm 0.5 \text{ M}\Omega^*$

*no temperature specified

- Bias resistance ($R_{\text{bias}}$) is slightly temperature dependent
- Non-irradiated sensors: $R_{\text{bias}} \approx 1.5 \text{ M}\Omega$ at 20°C; $R_{\text{bias}} \approx 1.8-1.9 \text{ M}\Omega$ at −20°C
- $R_{\text{bias}}$ is slightly increasing with proton fluence
- $R_{\text{bias}}$ doesn’t change after gamma irradiation
- $R_{\text{bias}}$ is at limit of ATLAS specs if measured at cold

**ATLAS17LS mini - CYRIC**

**ATLAS17LS mini - gamma**

Method for non-irradiated sensors

Method for irradiated sensors

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Punch–Through Protection: ATLAS17LS gamma

- PTP structures: to protect the AC coupling capacitors against large signal current, induced for example by beam splash
- Different designs during prototyping, PTP structure with full gate coverage chosen in main ATLAS12EC, ATLAS17LS
- The effectiveness of PTP structure measured with DC method

\[ R_{\text{eff}} = \frac{V_{\text{test}}}{I_{\text{test}}} \]

Initial increase of PTV from 0 to 10 Mrad, followed by a decrease with increasing TID
- Good performance of PTP structure
PT voltage increases with increasing bias voltage and stays quite stable with increasing proton fluence.
## Summary of surface parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specifications for non-irradiated and irradiated production sensors</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset voltage of microdischarges</td>
<td>&gt; 500 V</td>
<td>100% sensors after irradiation</td>
</tr>
<tr>
<td>Resistance of Al read-out strips</td>
<td>&lt; 30 kΩ/cm</td>
<td>A12EC: 13-20 Ω/cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A17LS: 8.8±0.5 Ω/cm</td>
</tr>
<tr>
<td>Resistance of n-implant strip</td>
<td>&lt; 50 kΩ/cm</td>
<td>A12EC: 20.5-21 kΩ/cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A17LS: 8.85 kΩ/cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>gamma irradi. &lt;20 kΩ/cm</td>
</tr>
<tr>
<td>$R_{\text{bias}}$ (Poly-silicon) of bias resistor</td>
<td>1.5 ± 0.5 MΩ</td>
<td>Non-irrad: 1.5 MΩ at 20°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.9 MΩ at −20°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Irrad: 2-2.4 MΩ if measured at -20; -40°C</td>
</tr>
<tr>
<td>Interstrip resistance</td>
<td>10 x $R_{\text{bias}}$ at 300V at RT (non-irrad)</td>
<td>Non-irrad: 15-80 GΩ</td>
</tr>
<tr>
<td></td>
<td>400V at -20°C (irradiated)</td>
<td>Irrad: 1 GΩ for n (5.1e14 n_{eq}/cm²) ,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200 MΩ for p (1.5e15 n_{eq}/cm²)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60 MΩ for γ (70 Mrad)</td>
</tr>
<tr>
<td>AC coupling capacitance</td>
<td>≥ 20 pF/cm, measured at 1 kHz</td>
<td>25 pF/cm, no change with irradiation</td>
</tr>
<tr>
<td>Interstrip capacitance</td>
<td>&lt; 1 pF/cm at 300V at RT (non-irrad),</td>
<td>100% of tested sensors before and after</td>
</tr>
<tr>
<td></td>
<td>400V at -20°C (irradiated) measured at 100 kHz for main</td>
<td>irradiation $C_{\text{int}}$ &lt; 1 pF/cm</td>
</tr>
<tr>
<td></td>
<td>(at 1 MHz for mini)</td>
<td></td>
</tr>
</tbody>
</table>

Parameters within the specifications
Conclusions

• HPK ATLAS12EC and ATLAS17LS sensors were measured by ATLAS ITk institutes before and after irradiation

• ATLAS17LS as a part of Market Survey Step 3 qualification process

• ATLAS17LS-HPK sensors, non-irradiated and irradiated with gamma, protons and neutrons fulfill all the ATLAS Specs imposed for the Market Survey Step 3

• Specifications for production sensors were updated: maximal operational voltage got reduced to 500V due to max HV decision

• ATLAS12EC and ATLAS17LS sensors satisfy the ATLAS ITk performance requirements
Backup slides
Inter-strip resistance ATLAS17LS mini

ATLAS17LS - CERN PS

Interstrip resistance (MΩhm)

Voltage (-V)

- 1e15 neq, thin (W044-mini4)
- 1e15 neq, thin (W044-mini8)
- 1e15 neq, std (W036-mini7)
- 1e15 neq, std (W033-mini4)
- 2e15 neq, thin (W045-mini2)
- 2e15 neq, thin (W045-mini6)
- 2e15 neq, std (W038-mini6)
- 2e15 neq, std (W034-mini2)
Coupling Capacitance: **main ATLAS12EC, mini ATLAS17LS**

**ATLAS Specs:** > 20pF/cm

**Main ATLAS12EC – non-irrad**

- $C_{\text{coupl}}$ must be large to maximize signal and its integrity
- $C_{\text{coupl}}$ doesn’t change with gamma or proton irradiations
- $C_{\text{coupl}}$ meets the specs

**ATLAS17LS - gamma**

- Non-irrad $C_{\text{coupl}} = 25.49 \pm 1.06$ pF/cm
- 10 Mrad $C_{\text{coupl}} = 27.00 \pm 0.24$ pF/cm
- 35 Mrad $C_{\text{coupl}} = 26.07 \pm 0.09$ pF/cm
- 70 Mrad $C_{\text{coupl}} = 26.29 \pm 0.06$ pF/cm

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Coupling Capacitance: mini ATLAS17LS

\[ C_{\text{coup}} \text{ doesn't change with gamma, neutron or proton irradiations} \]
\[ C_{\text{coup}} \text{ meets the specs} \]
Metal and Implant resistance: ATLAS17LS

**Metal resistance: ATLAS Specs:** $< 30 \, \Omega/cm$

**Implant resistance: ATLAS Specs:** $< 50 \, \Omega/cm$

**ATLAS17LS mini - gamma**

- Non-irrad. ATLAS12EC: $R_{metal} = 13 - 20 \, \Omega/cm$
- ATLAS17LS: $R_{metal} = 8.8 \pm 0.5 \, \Omega/cm$
- $R_{metal}$ does not change with TID
- Non-irrad. ATLAS12EC: $R_{imp} = 20.5 - 21k\Omega/cm$
- Non-irrad. ATLAS17LS: $R_{imp} = 8.8 \pm 2.8 \, k\Omega/cm$
- $R_{imp}$ increases after gamma irradiation, $<20 \, k\Omega/cm$

**ATLAS17LS fulfill the Specs before and after gamma irradiation**

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Very good performance of “C” type (full gate) structure also after proton irradiation:
• steep increase in current
• small PTP onset voltage (~20V)
• largest current at $V_{PTP}=-100V$.

The novel full gate PTP structure “C” doubles the allowable current without increasing the onset voltage.

modest increase of $V_{PTP\text{onset}}$ up to $2\times 10^{15}$
$V_{PTP\text{onset}} < 25V$

large $I(V_{\text{TEST}}=-100V)$ even at $1\times 10^{16}$
2.5mA=2.5mC/s=6e11 mips/s/strip