Radiation Campaign of HPK Prototype LGAD sensors for the High-Granularity Timing Detector (HGTD)

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On behalf of ATLAS Collaboration

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ATLAS HGTD Layout - with 3 rings

• **Ring boundaries:** 12-23 cm ; 23-47 cm ; 47 - 64 cm
  • 12 cm < inner ring < 23 cm replaced every 1000 fb-1
  • 23 cm < middle ring < 47 cm replaced at 2000 fb-1
  • 47 cm < outer ring < 64 cm never replaced

Radiation tolerance: \(2.5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}, 2.0 \text{ MGy}\)
New fluences with 3 layers

HGT Rad levels (Sept 2019) w/ SF=1.5 MAX =2.5x10^15 neq/cm²
inner (12-23 cm) replaced each 1000 fb-1, midle (23-47 cm) every 2000 fb-1;
outer (47-64 cm) untouched until 4000 fb-1;

12-23 cm  23-47 cm  47-64 cm

Max 2.5x10^15
Low Gain Avalanche Detectors (LGAD)

- LGAD Schematics

![Schematic Diagram](image)

- HPK-3.1: 15x15 array

![Photo](image)

- HPK Prototype 3.1 / 3.2:
  - Thickness 50 µm
  - Gain layer dopant Boron
  - Gain layer depth 1.6 / 2.2µm
  - Gain layer depletion 40 / 55V
  - VBD (-30C) 200V / 70V

Table 5.1: Sensor parameters and requirements.

- Time resolution:
  - 2.4 < |h| < 2.7 ➔ 40 ps (start); ➔ 70 ps (end of lifetime)
  - 3.5 < |h| < 4.0 ➔ 40 ps (start); ➔ 70 ps (end of lifetime)

- Gain ➔ 20 (start); ➔ 8 (end of lifetime)

- Minimal charge 4 fC
- Hit efficiency >95%
- Granularity 1.3 mm × 1.3 mm
- Physical thickness <300 µm
- Active thickness 50 µm
- Active size 39 mm × 19.5 mm (30 × 15 pads)
- Inactive edge <500 µm
- Radiation tolerance 2.5 × 10^15 n eq cm^2, 2.0 MGy

Introduction of the technology is given in Chap. 4. Additional background and details are given in Reference [32].

(a) Cross section of a 2 × 2 array.
(b) Photo of a 15 × 15 array.

Figure 5.1:
(a) Cross section of a 2 × 2 array including a JTE around each sub-pad (SiSi wafer, CNM design) [33].
(b) Microscope photo of an HPK-3.1 15 × 15 array.

Three major effects determine the time resolution: time walk from amplitude variations, jitter from electronic noise and "Landau fluctuation" from charge deposition uniformities along the particle path. Time walk and noise jitter depend on the type of readout electronics chosen. Both depend inversely on the signal slope (voltage slope at the output of the...
Breakdown voltage using I-V @ Room Temp

- Uniform breakdown voltage observed
Doping profile for the gain layer from CV

- Gain layer doping concentrations decreased after irradiation
Collected charge vs. bias voltage for different fluences

- Higher bias voltage needed to reach the required 4fC charge collection
- Thicker gain layer (type 3.2) behaves better
Comparison with test beam and beta source

- Higher bias voltage required to reach the similar level of charge collection for sensors after irradiation
  (N.B. Neutron uncertainty ~10%)
Power vs. fluence for 4fC

- Power density below the maximum acceptable 100 mW/cm$^2$
Time resolution vs. Bias voltage vs. fluence

- Resolution of 40ps is achieved up to 1.5E15 n_{eq}/cm^2
Summary

• LGAD is proposed to be used for the ATLAS HGTD with 3 layers layout, with radiation tolerance of $2.5 \times 10^{10}$ $n_{eq}$ cm$^{-2}$ and TID 2 MGy.

• Two prototypes of LGADs developed by HPK with thickness 50$\mu$m have been irradiated up to the $3 \times 10^{10}$ $n_{eq}$ cm$^{-2}$.

• Properties such as the charge collection, power density, and time resolutions showed have been evaluated with promising results towards the goal of operating the HGTD.

• Further studies will be performed with dedicated readout ASICs.
Backup
## Sensor parameters and requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology</strong></td>
<td>Silicon Low Gain Avalanche Detector (LGAD)</td>
</tr>
<tr>
<td>Time resolution 2.4 &lt;</td>
<td>η</td>
</tr>
<tr>
<td>Time resolution 2.7 &lt;</td>
<td>η</td>
</tr>
<tr>
<td>Time resolution 3.5 &lt;</td>
<td>η</td>
</tr>
<tr>
<td>Gain</td>
<td>≈ 20 (start); &gt; 8 (end of lifetime)</td>
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<tr>
<td>Minimal charge</td>
<td>4 fC</td>
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<tr>
<td>Hit efficiency</td>
<td>&gt;95%</td>
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<tr>
<td>Granularity</td>
<td>1.3 mm × 1.3 mm</td>
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<tr>
<td>Physical thickness</td>
<td>&lt;300 µm</td>
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<tr>
<td>Active thickness</td>
<td>50 µm</td>
</tr>
<tr>
<td>Active size</td>
<td>39 mm × 19.5 mm (30 × 15 pads)</td>
</tr>
<tr>
<td>Inactive edge</td>
<td>&lt;500 µm</td>
</tr>
<tr>
<td>Radiation tolerance</td>
<td>2.5 × 10^{15} n_{eq} cm^{-2}, 2.0 MGy</td>
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<tr>
<td>Maximum operation temperature on-sensor</td>
<td>–30 °C</td>
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<tr>
<td>Maximum leakage current per pad</td>
<td>5 µA</td>
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<tr>
<td>Maximum bias voltage</td>
<td>800 V</td>
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<tr>
<td>Maximum power density</td>
<td>100 mW/cm^2</td>
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</table>
Irradiation facilities

<table>
<thead>
<tr>
<th>Facility &amp; Abbreviation</th>
<th>Particle Type</th>
<th>Hardness Factor</th>
<th>TID [MGy] / $10^{15}$ n$_{eq}$ cm$^{-2}$</th>
<th>Max. Fluence [10$^{15}$ n$_{eq}$ cm$^{-2}$]</th>
<th>Max. TID [MGy]</th>
<th>LGAD Types Irradiated</th>
</tr>
</thead>
<tbody>
<tr>
<td>JSI Ljubljana ($n$)</td>
<td>$\approx$1 MeV n</td>
<td>0.9</td>
<td>0.01</td>
<td>6</td>
<td>0.06</td>
<td>all</td>
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<td>CYRIC ($p$CY)</td>
<td>70 MeV p</td>
<td>1.5</td>
<td>0.81</td>
<td>5</td>
<td>4.0</td>
<td>HPK-3.1/3.2, NDL FBK-UFSD3-C</td>
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<td>Los Alamos ($p$LA)</td>
<td>800 MeV p</td>
<td>0.7</td>
<td>0.43</td>
<td>1</td>
<td>0.4</td>
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<td>CERN PS ($p$PS)</td>
<td>23 GeV p</td>
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<td>PSI ($pi$)</td>
<td>192 MeV pions</td>
<td>1</td>
<td>0.32</td>
<td>2</td>
<td>0.6</td>
<td>early prototypes</td>
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Table 5.4: Irradiation facilities and parameters and maximum achieved fluence and TID, as well as LGAD types irradiated.