4D Tracking Devices: Low Gain Avalanche Detectors


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Work done in the framework of the RD50 CERN Collaboration
National Microelectronics Centre

- Capability to develop and fabricate new technologies.
- Technical and technological support.

Research laboratories
- Characterisation and testing
- Reverse engineering
- Simulation/CAD
- Mechanical works

Low Gain Avalanche Detectors (LGADs) were first developed at CNM-Barcelona.
Large Hadron Collider

- Located at CERN (Geneva, Switzerland).
- 27 km in circumference, 100-m mean depth.
- Proton and Pb beams.
- Maximum luminosity: $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Highest fluence inner tracking detectors: $\sim 10^{15} \text{ cm}^{-2} \text{ n}_{eq}/\text{cm}^2$
High Luminosity Upgrade of the LHC

LHC / HL-LHC Plan

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4 - 5...</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS1</td>
<td>EYETS</td>
<td>LS2</td>
<td>LS3</td>
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<tr>
<td>2011</td>
<td>2015</td>
<td>2019</td>
<td>2024</td>
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<td>2012</td>
<td>2016</td>
<td>2020</td>
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<td>2018</td>
<td>2022</td>
<td>2027</td>
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<tr>
<td>splice consolidation button collimators R2E project</td>
<td>13 TeV</td>
<td>injector upgrade cryo Point 4 DS collimation P2-P7(11 T dip.) Civil Eng. P1-P5</td>
<td>14 TeV</td>
</tr>
<tr>
<td>experiment beam pipes</td>
<td>13.5-14 TeV</td>
<td>experiment upgrade phase 1</td>
<td>14 TeV</td>
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<tr>
<td>7 TeV</td>
<td>8 TeV</td>
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- Energy: 7 TeV to 8 TeV
- Experiment phase 1: 30 fb⁻¹
- Experiment phase 2: 150 fb⁻¹
- HL-LHC installation: 300 fb⁻¹
- Integrated luminosity: 3000 fb⁻¹
- Nominal luminosity: 75%
High Luminosity Upgrade of the LHC

Currently underway

LGADs implemented in CMS CT-PPS
High Luminosity Upgrade of the LHC

Currently underway

Main motivation for LGADs

LGADs implemented in CMS CT-PPS
Current status of LGADs

- Installed in the CMS CT-PPS experiment
- Foreseen projects
  - ATLAS HGT D
  - CMS ETL
  - AFP
  - TOTEM
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Projects that could benefit from LGADs...
- CEPC
- SPPC
HL-LHC Challenges

HL-LHC Upgrade:
- Increase in luminosity.
- Radiation levels up to $1.6 \times 10^{16}$ cm$^{-2}$.
  - 10 times the current fluence.
- Higher event pile-up.
  - Better timing resolution needed (aiming for $\sim 30$ ps).
- Maintain spatial accuracy.
4D Tracking - Timing

- Spatial information only not enough to unequivocally reconstruct the tracks.
- **Time tagging**: overlapping vertices can be disentangled.

Possible solution: Detectors with intrinsic gain.
Sensors with intrinsic gain

- Internal multiplication of charge: increase in signal.
  - Better signal-to-noise ratio, even after irradiation.
  - Better timing capabilities.
- One possible technology:
  - Low Gain Avalanche Detectors (LGAD).

![Low Gain Avalanche Detector (LGAD)](image)
**Gain Mechanism in LGADs**

- Planar silicon sensors (n+/p/p-).
  - n+ implant, p substrate.
  - p-type multiplication layer.

- High electric field region in the multiplication layer.
  - Charges undergo impact ionisation.
  - Gain depends on:
    - multiplication layer doping,
    - bias voltage,
    - temperature.

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*S. Otero Ugobono et al., Radiation Tolerance of Proton-Irradiated LGADs, IEEE TNS (2018) vol. 6, no. 8, pp. 1667-1675*
Benefits of low gain

- Low gain (~10 to 30).
  - Optimum gain required for accurate time measurements.
- Signal increase.
- Low noise.
  - Noise increases faster than signal.
- Low risk of breakdown.
- Low power consumption.

V. Sola et al., Ultra-Fast Silicon Detectors for 4D Tracking, JINST (2017) 12 C02072
**LGAD design**

- Active thickness: 45 µm
- Bulk resistivity: 12 kΩ cm
- Various possible active-area sizes.
- Thick devices (300 um) also available.
- Available layouts:
  - individual pads,
  - pad arrays.

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J. Lange et al., JINST (2017) 12 P05003
LGAD performance

- Up to $3 \times 10^{14}$ n$_{eq}$/cm$^2$:
  - Gain recovery with an increase in bias voltage.
  - Time resolution below 30 ps (-20°C).
**LGAD performance**

- Using multiple sensor layers improves:
  - timing (even at $10^{15} \text{n}_{eq}/\text{cm}^2$),
  - fill-factor.

- Radiation hardness can be improved with:
  - carbon implantation,
  - thinner sensors.

- Possibility of replacing sensors after half of the lifetime of the detector.

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Replaceable

ATLAS Collaboration, CERN-LHCC-2018-023
**Improving the fill factor: iLGAD**

**LGAD**

N on P microStrip

Segmented multiplication layer:
- Spatially inhomogeneous gain.
- Degraded resolution for inter-strip hits.
- Fill-factor problem.

**iLGAD**

P on P microStrip

Non-segmented multiplication layer:
- Uniform gain distribution.
- Promising timing results: ~20 ps.
  - Unirradiated 285-µm iLGAD, laser-induced signal at 20ºC.
- Thinner sensors under development.

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E. Currás et al., arXiv:1904.02061
**Alternative technologies: 3D sensors**

- **100% fill factor.**
- **Very high radiation tolerance.**
  - Up to $10^{16}$ $n_{eq}/\text{cm}^2$ for small cell sizes.
- **Timing capabilities under study, promising results.**
  - 75-ps time resolution at 20°C for $^{90}\text{Sr}$ electrons (50x50 $\mu\text{m}^2$ cell, 300 $\mu\text{m}$ thickness).


Simulations predict ~30 ps at -20°C
Thank you very much for your attention
Backup Slides
\[ \sigma_t^2 = \sigma_{\text{Time walk}}^2 + \sigma_{\text{Landau noise}}^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{Jitter}}^2 + \sigma_{\text{TDC}}^2 \]

- **Time walk** is the variation in time of arrival produced by the difference in signal amplitude. 
  \[ \sigma_{\text{Time walk}} = \left[ \frac{V_{th}}{S/t_{\text{rise}}} \right]_{RMS} \propto \left[ \frac{N\sigma_n}{dV/dt} \right]_{RMS} \]

- For a given MIP hit, the amount of deposited energy per unit length is not uniform. These additional fluctuations, specific to each event, produce irregularities in the current signal, referred to as **Landau noise**.

- **Signal distortion**: variations in signal shape due to inhomogeneities in the drift velocity and/or the weighting field throughout the active volume of the sensor.

- The signal noise can produce variations in the time at which the signal crosses the fixed threshold. This fluctuation is known as **jitter**. 
  \[ \sigma_{\text{Jitter}} = \frac{\sigma_n}{dV/dt} \approx \frac{t_{\text{rise}}}{S/\sigma_n} \]

- When digitised, the time of arrival obtained is stored in a time bin of width \( \Delta T \). The **TDC** contribution to the timing resolution is \( \Delta T / \sqrt{12} \)
Each disk of the HGTD is double-sided, i.e., the modules with sensors and on-detector electronics are mounted on the front and back sides of the cooling plate.

The modules on the two sides of a disk are arranged to overlap so that the number of hits exceeds the number of disks.

The resulting layout gives a relatively flat timing resolution as a function of radius, also after the detector has been exposed to the expected radiation dose.