Performance of LGAD sensors for the ATLAS High-Granularity Timing Detector HGT D

Irena Nikolic, on behalf of the ATLAS High Granularity Timing Detector Group
TIPP 2021 Conference
Towards the High-Luminosity LHC

- To extend the discovery potential, both the LHC accelerator and experiments are scheduled for an upgrade.
- “HL-LHC” is expected to start ~ 2027, reaching 5 to 7 times the nominal luminosity.

ATLAS detector will need major upgrades due to:
- Pile-up challenge: $\langle \mu \rangle \sim 30$ in Run 2 up to $\langle \mu \rangle \sim 200$
- More radiation damage
- Higher Trigger rates

Among upgrades: High-Granularity Timing Detector: HGTD

See also the HGTD talk by Abdellah Tnourji at TIPP-2021.
Motivations for HGTD: Pileup challenge

- Main challenge for HL-LHC is pile-up:
  \[ \mathcal{L}_{\text{inst}} = 7.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \text{ and } <\mu> = 200 \]
  Interaction region will spread out over 50 mm in z direction.
- ITk provides good resolution on track impact in the central region.
- To discriminate between pile up and hard scattering interaction, HGTD is added in the forward region with the goal is to have 30-50 ps per track time resolution (beginning-end).
  Impact on physics: track/jet reconstruction, electron ID, b-tagging.
- Requirements for the detector: Compact and Radiation Hard

Choice of Silicon-based timing detector with LGAD sensors
HGTGD System

• $|z|=3.5$ m, 7.5 cm width
• Coverage $2.4 < \eta < 4.0$
  12 cm $< R < 64$ cm
• 2 disks/side, 2 sensor layers/disk
• 2-3 hits/track
• Nu of channels : 3.6 M

Baseline:
• Time resolution :
  $\sigma_t = 35 - 70$ ps per hit
  $\sigma_t = 30 - 50$ ps per track
  over the lifetime of HL-LHC
• Maximum fluence:
  $2.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$
  TID of 2MGy by end of HL-LHC, 4000 fb$^{-1}$

Sensors will be operated at -30°C using a common CO$_2$ cooling system with ITk

HGTGD provides also a luminosity measurement : gives the number of hits per ASIC in two time windows per bunch crossing
HGTD detection technology: LGAD sensors

- **Low Gain Avalanche Detectors**

  n-in-p Si detector with an additional p-type doped layer inducing charge multiplication.
  - Sensor internal gain >20 before irradiation and > 8 at the end of lifetime. $V_{\text{bias}} < 800 \text{ V}$
  - Sensor gain controlled by doping level, depth and material
  - Fast rise time: 0.5 to 0.8 ns
  - Excellent timing resolution: 35 - 70 ps per hit
  - For good timing: minimum collected charge 4 fC /MIP/hit after $2.5 \times 10^{15} n_{\text{eq}} \text{ cm}^2$
  - Hit efficiency > 95 % at the end lifetime
  - Pad size: 1.3x1.3 mm² (occupancy <10%).

8032 modules of 15x30 pads (each sensor bump-bonded to 2 ALTIROC ASICS)

Threshold of the ALTIROC electronic discriminator: $Q_{\text{coll}} > 2$ fC.

- LGAD originally developed by CNM and RD50
- HGTD tested prototypes from CNM (Spain), HPK (Japan), BNL (USA), FBK (Italy), IME, NDL (China)
HGTD Radiation Hardness

Requirements for good time resolution:
- maximum fluence: $2.5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$
- TID: 2 MGy

Coping with high radiation environment: segment the HGTD detector into 3 replaceable rings:
- Inner (12-23 cm) every 1000 fb$^{-1}$
- Middle (23-47 cm) every 2000 fb$^{-1}$
- Outer (47-64 cm) never replaced

Safety factors applied:
- x 1.5 for sensors
- x 2.25 for the electronics
Strong timing constraints on sensor choice

- **Time resolution**

  Time resolution less than 70 ps/hit after irradiation level $2.5 \times 10^{15}$ n$_{eq}$/cm$^2$ is beyond standard HEP silicon devices.

$$
\sigma_{tot}^2 = \sigma_{Landau}^2 + \left( \frac{t_{rise}}{S/N} \right)^2 + \left( \left[ \frac{V_{thr}}{S/t_{rise}} \right]_{RMS} \right)^2 + \left( \frac{TDC_{bin}}{\sqrt{12}} \right)^2 + \sigma_{clock}^2
$$

- **Jitter**
- **Time-walk**
- **(negligible)**

  - $\sigma_{Landau} < 25$ ps. Intrinsic Landau contribution coming from charge deposition non-uniformities is reduced for thin sensors: choice of 50 µm in HGTD.
  - $\sigma^2_{jitter} + \sigma^2_{TimeWalk} < 25$ ps (70 ps at 4000 fb$^{-1}$) -> fast signal and excellent S/N
  - $\sigma_{clock} < 15$ ps
  - Time-walk contribution can be corrected with the Time of Arrival (TOA) and the Time over Threshold (TOT)
  - At low S/N, noise jitter is dominating and Landau term takes over at high S/N
HGTD detection technology: LGAD tests

Sensor with a 2x2 array of pads
(1 pad : 1.3x1.3 mm²)

Arrays tested:
5x5
15x15

Sensor tests
- In laboratory:
  with β-source (⁹⁰Sr) or lasers in control environment and in climate chamber for irradiated sensors.
  Custom made HGTD-specific readout boards.
  Electrical measurement: I-V, C-V, Gain, time-resolution, rise time and inter gap
- In test beams:
  ✓ at CERN (120 GeV Pions)
  ✓ at DESY (5 GeV e-).
Sensors integrated into a beam telescope providing track position with 3µm resolution

Sensors irradiated at various fluencies. Results for $3 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ max are shown here. C-enriched sensors: promising idea to improve radiation hardness.
Sensor performance in lab: $\sigma_t$ vs charge

- Time resolution vs collected charge, for HPK 3.2 and FBK sensors at various fluencies and up to $2 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$
- 4fC corresponds to a gain = 8
- Results obtained with dedicated electronics. Time walk is corrected.
- Typical error bar $\sim$ 3ps
- 50 $\mu$m thickness

- Sensors from different vendors have different operation voltage.
- Similar $\sigma_t$ can be achieved with sensors while biased at different voltages.
- Time resolution improves with increasing gain.
Sensor performance in lab: charge

- Collected charge as a function of bias voltage from various vendors.
- Sensors from a variety of vendors satisfy collected charge requirement: HPK 3.2: Collected Charge > 4 fC after irradiation to $3 \times 10^{15}$ n$_{eq}$/cm$^2$ with neutrons.
- Superior performance for FBK sensors with C enriched gain layer. Same charge for lower bias voltage. Testing continues.
Sensor performance in lab: time resolution

- Time resolution as a function of bias voltage for different fluencies and vendors
- Maximum allowed resolution of 70 ps is achieved for HPK 3.2 at $3 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$
- Superior performance for FBK sensors with C enriched gain layer
IV and $V_{BD}$ map in HPK non-irradiated arrays

- 25 pads from a 5x5 non-irradiated HPK 3.2 array, measured in laboratory by a probe card and at room temperature.
- Uniform behavior of pads: $V_{BD}$ variations ~ few Volts
HGTD Test Beam campaigns

Measure $Q_{\text{coll}}$, $\sigma_t$, efficiency, uniformity for sensors from different vendors, with different dopings, and irradiated with n or p, at different fluencies up to $3 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$

- **2016 - 2018: CERN, 120 GeV pions**
  - 2016+2017: Unirradiated CNM and HPK. Irradiated CNM
  - 2018: Unirradiated and irradiated CNM and HPK
    - CNM sensors: Boron implanted
    - CNM sensors: Boron implanted with Carbon diffused
    - CNM sensors: Gallium implanted
    - HPK sensors: doped with Boron, different doping profiles
    - FBK Boron+ Carbon infused
    - 2x2 array ALTIROC 0

- **2019: DESY, 5 GeV electrons**: mostly irradiated sensors
  - single pad HPK
  - CNM sensors doped with Boron; Boron + Carbon; Gallium
    - 5x5 ALTIROC1 coupled to non irradiated HPK 3.2

- **2020**: only one campaign at DESY with HPK, NDL, FBK and CNM sensors
  - others campaigns cancelled due to pandemic

- **2021**: Hope for a DESY test beam in June and at CERN at end of 2021
Test beam setup

Test beam with pion/electron beams (CERN/DESY)
- Telescope Mimosa planes to provide track reconstruction
- Inside a cooling device
- Oscilloscope records wave-forms to perform analysis
- Cerenkov Quartz bar and SiPM ($\sigma = 10$-$40$ ps) for independent time reference
- ASIC + sensor testing: ALTIROC chip is used for readout + oscilloscope for debug
Collected charge measurement in test beam

- Charge computed as the integral of signal waveform divided by the transimpedance of the readout circuit

- For each bias voltage, the collected charge is given by the MPV of the Landau-Gaussian fit of the charge distribution

- For Boron doped CNM sensor irradiated with neutrons at $6 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$ and $V=390\text{V}$
  
  \[ Q = 4.2 \text{ fC} \]

- For Gallium doped CNM sensor irradiated with neutrons at $3 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ at $HV=740\text{V}$
  
  \[ Q = 5.3 \text{ fC} \]

- Achieved HGTD requirement of 4fC
Time resolution measured in test beam

Boron doped HPK 3.2 sensors, irradiated with neutrons

- Time resolution is computed from time difference between the sensor and SiPM time (or with another sensor):
  \[ \sigma^2 (t_i - t_j) = \sigma^2 (t_{\text{sensor}_i}) + \sigma^2 (t_{\text{sensor}_j}) \]
  4 sensors/SiPM give a constrained system

- HPK n-irradiated at \(1.5 \times 10^{15}\) \(n_{\text{eq}}/\text{cm}^2\)
  \[ \sigma = 36 \text{ ps} \]
  at 600 V and for \(Q_{\text{coll}} = 22.8 \text{ fC}\).

- Tested sensors that have a collected charge greater than 4 fC have a time resolution better than 40 ps at higher bias voltage
Efficiency measurement in test beam

\[ \varepsilon = \frac{\text{Tracks with } Q > 2\text{fC in central part}}{\text{Total Tracks in the central part}} \]

- The threshold at 2 fC for the collected charge corresponds to the threshold of the ALTIROC.

- For CNM n-irradiated, Ga doped sensors, at \(3 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2\)
  \[ \varepsilon = 99.7\% \]
  for \(V = 740\ \text{V}\) and \(Q_{\text{coll}} = 5.3\ \text{fC}\)

Gallium doped CNM sensors
- unirradiated
- irradiated with neutrons or protons
2D efficiency maps at test beam

CNM with 2x2 arrays, irradiated with neutrons at $6 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$.

- A mean efficiency in the pad center is maintained up to the threshold of 5 times the noise level.
- Time resolution has 3ps variations across the pad center.
Conclusions

- Timing information from ATLAS-HGTD is expected to play a key role in mitigating the impact of pile-up in the forward region and for very challenging HL-LHC conditions.

- HGTD will use the LGAD technology to improve ATLAS performance in forward region.

- LGAD technology and layout for HGTD are optimized to reach a per-track resolution of 30 - 50 ps up to the end of the detector lifetime.

- Irradiated LGAD sensors with different doping profiles and irradiation levels were tested in test beams and in laboratories. Required performances are reached for several vendors.

- The overall design and construction works are progressing. Intense R&D ongoing to improve radiation hardness. Installation is foreseen in 2026-27.

- The HGTD Technical Design Report has been approved in Sept 2020. [https://cds.cern.ch/record/2719855]
Backup
Impact of HGTD

Relative pileup jet rate as a function of jet pseudorapidity, for jets with $30\text{GeV} < p_T < 50\text{GeV}$, with and without HGTD.

Efficiency for electrons to pass track-isolation criteria, denoted as $\varepsilon (p_T^{iso})$, as function of the local vertex density with or without HGTD.
At 1 GeV and $\eta=3$, $\sigma_{z_0} = 2.5$ mm: selection window of 5 mm around vertex position. The forward track is compatible with 13 vertices: Significant pile-up contamination.
Resolution per track 50 ps with several hits and 70 ps per hit

Figure 3.6: The HGTD timing resolution is shown as function of the radius for four timing scenarios. The sensor resolution and the contribution from the electronics are considered, added in quadrature.
Luminosity measurement

Precise knowledge of luminosity is a key to many physics studies

HGTD provides precise bunch-by-bunch luminosity measurement in its outmost ring

High granularity → great linearity between measurements and luminosity

Unique two timing window scheme at ASIC level give in-situ measurement of noise/afterglow
Measuring time

Time resolution defined by jitter and time walk and clock stability (defining t0).

short collection ($\tau_p$), large signal S/N

not in the domain of sensor
## Sensor parameters and requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>Silicon Low Gain Avalanche Detector (LGAD)</td>
</tr>
<tr>
<td>Time resolution</td>
<td>$\approx 35$ ps (start); $\approx 70$ ps (end of lifetime)</td>
</tr>
<tr>
<td>Time resolution uniformity</td>
<td>No requirement</td>
</tr>
<tr>
<td>Min. gain</td>
<td>20 (start); 8 (end of lifetime)</td>
</tr>
<tr>
<td>Min. charge</td>
<td>4 fC</td>
</tr>
<tr>
<td>Min. hit efficiency</td>
<td>95%</td>
</tr>
<tr>
<td>Granularity</td>
<td>$1.3 \text{ mm} \times 1.3 \text{ mm}$</td>
</tr>
<tr>
<td>Max. inter-pad gap</td>
<td>100 $\mu$m</td>
</tr>
<tr>
<td>Max. physical thickness</td>
<td>300 $\mu$m</td>
</tr>
<tr>
<td>Active thickness</td>
<td>50 $\mu$m</td>
</tr>
<tr>
<td>Active size</td>
<td>$39 \text{ mm} \times 19.5 \text{ mm}$ (30 $\times$ 15 pads)</td>
</tr>
<tr>
<td>Max. inactive edge</td>
<td>500 $\mu$m</td>
</tr>
<tr>
<td>Radiation tolerance</td>
<td>$2.5 \times 10^{15}$ $n_{eq}$ cm$^{-2}$, 1.5 MGy</td>
</tr>
<tr>
<td>Max. operation temperature on-sensor</td>
<td>$-30$ $^\circ$C</td>
</tr>
<tr>
<td>Max. leakage current per pad</td>
<td>5 $\mu$A</td>
</tr>
<tr>
<td>Max. bias voltage</td>
<td>800 V</td>
</tr>
<tr>
<td>Max. power density</td>
<td>100 mW/cm$^2$</td>
</tr>
</tbody>
</table>
## Irradiation Facilities/sensor properties

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Name</th>
<th>Thickness [µm]</th>
<th>Gain layer dopant</th>
<th>C implant</th>
<th>Gain layer depth [µm]</th>
<th>Gain layer depletion [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPK</td>
<td>HPK-3.1</td>
<td>50</td>
<td>Boron</td>
<td>No</td>
<td>1.6</td>
<td>40</td>
</tr>
<tr>
<td>HPK</td>
<td>HPK-3.2</td>
<td>50</td>
<td>Boron</td>
<td>No</td>
<td>2.2</td>
<td>55</td>
</tr>
<tr>
<td>FBK</td>
<td>FBK-UFSD3-C</td>
<td>60</td>
<td>Boron</td>
<td>Yes</td>
<td>0.6</td>
<td>20</td>
</tr>
<tr>
<td>CNM</td>
<td>CNM-AIDA1/2</td>
<td>50</td>
<td>Boron</td>
<td>No</td>
<td>1.0</td>
<td>45</td>
</tr>
<tr>
<td>NDL</td>
<td>NDL-33µm</td>
<td>33</td>
<td>Boron</td>
<td>No</td>
<td>1.0</td>
<td>20</td>
</tr>
</tbody>
</table>

| Manufacturer | Name               | Full depletion [V] | $V_{BD}$ | Nominal IP [µm] | Nominal SE [µm] | Max. Array Size |
|--------------|--------------------|--------------------|----------|-----------------|-----------------|-----------------
| HPK          | HPK-3.1            | 50                 | 200      | 30-95           | 200-500         | 15 × 15        |
| HPK          | HPK-3.2            | 65                 | 70       | 30-95           | 200-500         | 15 × 15        |
| FBK          | FBK-UFSD3-C        | 25                 | 170      | 37              | 200-500         | 5 × 5          |
| CNM          | CNM-AIDA1/2        | 50                 | 220/50   | 37-57           | 200-500         | 5 × 5          |
| NDL          | NDL-33µm           | 35                 | 70       | 55              | 450             | 15 × 15        |

<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>$≈$1 MeV n</td>
<td>0.9</td>
<td>0.01</td>
<td>6</td>
<td>0.06</td>
<td>all</td>
</tr>
<tr>
<td>CYRIC ($p$CY)</td>
<td>70 MeV p</td>
<td>1.5</td>
<td>0.81</td>
<td>2.5</td>
<td>4.0</td>
<td>HPK-3.1/3.2, NDL FBK-UFSD3-C</td>
</tr>
<tr>
<td>Los Alamos ($p$LA)</td>
<td>800 MeV p</td>
<td>0.7</td>
<td>0.43</td>
<td>6</td>
<td>0.4</td>
<td>early prototypes</td>
</tr>
<tr>
<td>CERN PS ($p$PS)</td>
<td>23 GeV p</td>
<td>0.6</td>
<td>0.44</td>
<td>6</td>
<td>2.7</td>
<td>early prototypes</td>
</tr>
</tbody>
</table>
ALTIROC front end chip in test beam

Test beam measurement at DESY in 2019 for unirradiated ALTIROC1 modules
-> TOA corrected for time-walk

- Estimated resolution of **46 ps** after time-walk correction and including Landau contribution (25 ps). Estimated jitter contribution: **39 ps**

- In test beam configuration, improved DAQ (with FPGA) should improve jitter resolution by 35% achieving ~25 ps target

5x5 ATLIROC1 devices with HPK and CNM sensors

**ATLAS HGTD**
Test Beam
November 2019
### Road to specifications – many prototypes

#### TDR samples

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Name</th>
<th>Thickness [μm]</th>
<th>Gain layer dopant</th>
<th>C implant</th>
<th>Gain layer depth [μm]</th>
<th>Gain layer depletion [V]</th>
</tr>
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<tbody>
<tr>
<td>HPK</td>
<td>HPK-3.1</td>
<td>50</td>
<td>Boron</td>
<td>No</td>
<td>1.6</td>
<td>40</td>
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<tr>
<td>HPK</td>
<td>HPK-3.2</td>
<td>50</td>
<td>Boron</td>
<td>No</td>
<td>2.2</td>
<td>55</td>
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<tr>
<td>FBK</td>
<td>FBK-UFSD3-C</td>
<td>60</td>
<td>Boron</td>
<td>Yes</td>
<td>0.6</td>
<td>20</td>
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<tr>
<td>CNM</td>
<td>CNM-AIDA1/2</td>
<td>50</td>
<td>Boron</td>
<td>No</td>
<td>1.0</td>
<td>45</td>
</tr>
<tr>
<td>NDL</td>
<td>NDL-33μm</td>
<td>33</td>
<td>Boron</td>
<td>No</td>
<td>1.0</td>
<td>20</td>
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#### NEW SAMPLES

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</thead>
<tbody>
<tr>
<td>HPK (HPK-P2)</td>
<td>P2 (4 splits)</td>
<td>50</td>
<td>2.2</td>
<td>50.5-54.5</td>
<td>30-95</td>
<td>200-500</td>
<td>15 x 15</td>
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<tr>
<td>FBK</td>
<td>UFSD 3.2</td>
<td>50</td>
<td>2</td>
<td>35-50</td>
<td>B/YES</td>
<td>28</td>
<td>Single, 2x2</td>
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<tr>
<td>NDL</td>
<td>V3</td>
<td>50</td>
<td>~1</td>
<td>29</td>
<td>B/NO</td>
<td>2x2</td>
<td></td>
</tr>
</tbody>
</table>

**FBK prototype run – very ambitious – 19 wafers processed exploring wide range of parameters (C, B, depth, width)**
Gain layer – crucial for LGAD operation

- Gain decreases as boron substitutional atoms get deactivated (“acceptor removal”) \(\rightarrow\) reduction of the field.

- Ways to mitigate degradation of gain layer:
  - Make the implant thinner (IW) and more doped \(N_B\) \(\approx\) \(1 \times 10^{17} \text{ cm}^{-3}\), reduces the acceptor removal constant \(c \approx 2.7 \times 10^{-16} \text{ cm}^2\).
  - Increase the bias voltage \(\rightarrow\) after depletion increase of electric field in the GL is \(\Delta E \approx \Delta V_{bias}/\text{thickness}\).
  - Make the implant deeper (increase of GL):
    - Larger multiplication region.
    - Easier to recuperate the electric field \(\Delta V_{GL}/\text{GL}\) compensated by \(\Delta V_{bias}/\text{thickness}\).
  - Replacement of gain layer implantation material or co-implantation of material that decreases the acceptor removal rate (carbon).

We do not specify these parameters, but work closely with producers for them to establish the most effective way of reaching our requirements.
Specifications - terminology

TERMINOLOGY:
- $V_{gl}$ - gain layer depletion voltage
- $V_{fd}$ - full depletion voltage
- $V_{bd}$ - break down voltage
- $I_{gen}$ - generation current
- $I_{leak}$ - leakage current -> $I_{leak} = I_{gen} \text{ Gain}$
- $V_{op}$ - operation voltage:
  - $S/N > 7$
  - Increase of noise <20% low $V_{bias}$
  - $Q > 4 \text{ fC}$
  - long term operation assured
  - no/low rate ghost/spurious hits
Optimization of sensor thickness

We investigated sensors of different thickness:

- Smaller thickness – faster signal – less Landau fluctuations
- Smaller bias voltage required for given gain after irradiation – less power
- Larger capacitance
- Less charge generated by mip particle
- Steeper dQ/dV – difficult to control the $V_{op}$ particularly for sensors where the variation of fluence is significant over the sensors
Main tools used to evaluate detectors

CV/IV – probe station \( (V_{gl}, V_{fd}, I_{gen}) \)

- most of the capacitance measurements done at 20\(^\circ\)C and 2-10 kHz
- current measurements done also at lower temperatures
- probe card measurements for large arrays

Beta scope

Timing and Charge measurements

similar setups at different labs
- some without Sci+PM
- systems inter-calibrated

Laser/TCT measurement

convenient to study multi electrode arrays in absence of readout ASIC

UCSC boards is mostly used
- transimpedance amp (470\(\Omega\))
- wideband width \(>3\) GHz
- 4 Ch. version exists
Planned operation voltage for LGAD vs luminosity / R
IV, CV and $V_{BD}$ curves
Sensor Inter pad

Inter pad with laser for several HPK-3.3
Test beam setup

- **Sensors** - between 2 arms of a **TELESCOPE EUDET-type** (3 MIMOSA planes per arm) inside a **cooling** readout by **oscilloscopes** (2 oscilloscopes at CERN, 1 at DESY)
- **On same oscilloscope**, a Cerenkov light Quartz bar + Si PM provide **independent time reference**
- **Trigger by FE-I4** plane with a ROI geometrically optimized around sensors position
- **Two plastic scintillators** at each extremity of the telescope is also part of the TLU
Data analysis scheme

**Tracking program**
- Noisy pixels removal
- Clustering
- Telescope plane alignment
- Tracks fitting
  - Hit position in DUT plane

**Data from telescope**

**LGAD waveform processing**
- Pedestal substraction
- Signal start and stop
- Compute noise, charge, rise time, time at different CFD fraction or with CTD…

**Data from oscilloscope**

**Root-tuple for user analysis**
- DUT signal information
- hit position

Tracks reconstructed asking exactly one hit in FE-I4 plane.
Tracks fitting:
- straight lines for CERN data (120 GeV Pions)
- multiple scattering for DESY data (5 GeV electrons) with EUTelescope
Efficiency vs charge threshold

For the highest bias voltage point of a given sensor, efficiency is computed for different charge thresholds.

\[ \varepsilon = \frac{\text{Tracks in the central area (0.5x0.5 mm}^2) \text{ with } Q > \text{ threshold}}{\text{Tracks in the sensor center}} \]

The threshold at 2 fC for the collected charge corresponds to the threshold of the electronic discriminator

CNM sensors doped with Gallium
- unirradiated
- irradiated with neutrons or protons