Time resolution of single pixel irradiated 3D devices up to $10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$ at 120 GeV SPS pion beams

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University of Zurich
• 3D Sensors

Timing at Extreme Fluences

3D Sensors: Decoupling of charge generation and drift volume
(Standard columns, TimeSpot, Hex geometries etc.)

Pros
• High radiation tolerance up to several times $10^{16} \text{n}_{\text{eq}}/\text{cm}^2$
• Short drift distances with fast rise times
• Reduced Landau fluctuation, practically non-existent for perpendicular tracks

Cons
• Non-uniform field geometry
• High cost
• Increased cell capacitance

Double Sided
(thicker, more expensive)

Single Sided
(thinner, simpler process)

Pixel Size vs Field Uniformity

ATLAS IBL Type
✓ Double sided n-on-p process
✓ Pixel Size 55 × 55 μm²
✓ Active thickness 230 μm
✓ High Resistivity (> 2 kΩm × cm) Fz silicon

ATLAS Pre-Production type
✓ Single sided n-on-p process
✓ Pixel Size 25 × 100 μm²
✓ Active thickness 150 μm
✓ High Resistivity (> 2 kΩm × cm) Fz silicon
✓ Single sided n-on-p process
✓ Pixel Size 50 × 50 μm²
✓ Active thickness 150 μm
✓ High Resistivity (> 2 kΩm × cm) Fz silicon
3D Sensors - Timing

- Extremely fast rising edge (< 180 psec)
- Linear stable behavior with CFD, good SNR control

\[
\sigma_{\text{tot}} = \sigma_{\text{timewalk}}^2 + \sigma_{\text{fitter}}^2 + \sigma_{\text{conversion}}^2 + \sigma_{\text{clock}}^2
\]

Time Resolution: \[
\sigma_{\text{tot}}^2 = \sigma_{\text{Dist.}}^2 + \sigma_{\text{Landau}}^2 \left( \frac{t_{\text{rise}}}{S/N} \right)^2 + \left( \frac{TDC_{\text{bin}}}{\sqrt{12}} \right)^2
\]

Fixed Term: \( \sim 5-7 \) psec
• 3D Sensors – Signal Integrity

- Frequency of radioactive decay events follows Poisson law
- Record trigger time and convert to event frequency

\[ f(n) = \frac{e^{-\mu} \mu^n}{n!} \]

\[ n' = n \ast \Delta \]

Where: \( n \) number of events in interval
\( \mu \) mean
\( f(n) \) frequency

\[ f(n') = A \ast \left( \frac{n'}{C} \right)^{B/C} \ast e^{-\frac{B}{C}} \]

\[ \Gamma \left( \frac{n'}{C} + 1 \right) \]

Where: \( A \) Normalization parameter
\( B/C \) mean
\( f(n) \) Scaled frequency

- Efficiency dependent on bandwidth
- Signal distribution in the Fourier domain highly depends on bias
- Minimum time over threshold effect for trigger latching of instrument affect efficiency

V. Gkougkousis, 35th RD50 workshop on radiation hard silicon detectors
"Efficiency estimation on irradiated LGAD with respect to sensor stability"
**Planar Sensors**

**Sensors:** CERN EP-R&D n-on-p planar sensor run with ADVACAM at 50, 100, 200 and 300 μm active thickness

**Test Structures**
- Small diodes (3.14 mm² active area) Circular diodes for timing studies due to lower capacitance
- Big diodes (28.27 mm² active area) Circular diodes for radiation damage studies
- 5x5 Pixel matrix (0.003 mm² active area) for charge sharing and interpixel efficiency – timing studies

**Issues**
- Early breakdown due to high p-spray concentration leading to impact ionisation at the interface between p-spray and electrode implant
- Breakdown first visible in guard ring due to bigger interface region compared to pad

**Irradiations**

<table>
<thead>
<tr>
<th>Neutron @ JSI (Ljubljana)</th>
<th>Proton @ PS</th>
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</thead>
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<tr>
<td>✓ 1 × 10^{15} n_{eq}/cm²</td>
<td>✓ 1 × 10^{15} n_{eq}/cm²</td>
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<td>✓ 8 × 10^{15} n_{eq}/cm²</td>
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</tr>
<tr>
<td>✓ 6 × 10^{16} n_{eq}/cm²</td>
<td>✓ 6 × 10^{16} n_{eq}/cm²</td>
</tr>
<tr>
<td>✓ 1 × 10^{17} n_{eq}/cm²</td>
<td>✓ 1 × 10^{17} n_{eq}/cm²</td>
</tr>
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</table>
Part I - Test Beams

Tet Beams 2022
- Several periods but only two as primary user
- Main target irradiated Planar / 3D sensors
- No / Limited possibility of extension
- Extensive infrastructure developments

The Setup
- AIDA Telescope
- Custom Cold Box
- DUTs on individual motorized individual stages
- Pixelated alignment & ROI plane

<table>
<thead>
<tr>
<th>Week</th>
<th>Mar</th>
<th>Apr</th>
<th>Mai</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
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</tr>
</tbody>
</table>

- Primary user
- Parallel user
- Parasitic user

25 May – 8 June
15 – 29 June
6 July – 13 July
17 August - 14 September
21 September - 12 October
26 October – 2 November
- Coincidences between DUTs and LGADs required for timing
- Alignment crucial to increase data efficiency
- Efficiency defined by largest overlapping region
- Micrometric on-line alignment using projections on FEi4 matrix
- ROI defined in addition to other trigger conditions
• Trigger Interface Board (TiB)

- Oscilloscope in fast readout mode with binary format
- Event readout only between SPS-spills or when event buffer full to increase efficiency
- TLU Synchronization by vetoing data taking during read-out
- RJ-45 or HDMI for EUDET TLU communication (EUDET 2 compatible)
- Versatile design, I/Os Reconfigurable and microcontroller Reprogrammable via USB

Diagram:
- Spill 1, Spill 2, Spill 3, Spill 4
- SPS Early warning, SPS Spill Start, SPS End of Spill
- Triggers from TLU, Trigger Veto
- Oscilloscope readout
- Recorded Events in data stream
- LVDS I/O Drivers
- TTL Trigger out
- Microcontroller interface (1 interrupt, 7 GPIO lines)
- Quad bus multiplexers (switch between setting and communication)
- Input timing signal optocouplers
- Interrupt multiplexer (cycle through input timing signals)
- SPS synchronization signals
- To EUDET TLU

E. L. Gkougkousis
• The importance of bandwidth
The importance of bandwidth

- 60% less amplitude
- 20% more charge
- If bandwidth not correct, we are probing electronics transfer function
Single EVENT Burn-Out was also observed in 3D sensors but in much higher fields than LGADs (~ 25 V/μm) but 1e16 (not 1e17)

- Charge generation and charge drift directions not parallel, **very high angles**
  - Drifting charges do not add up to the avalanche created at the seed point
- Much smaller capacitance (20-80 fF), smaller stored energy in the sensor to be released once conductive channel forms ➔ **Recoverable Breakdown**
- Effect observed when concentration of defects high enough statistically
  - **BUT**
  - Carriel lifetime (trapping) should be sufficient to allow for the avalanche to evolve

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V. Gkougkousis, “LGAD Safety and Stability Concerns” – HGTD Sensor Meeting April 2018
CERN-OPEN-2023-017
Assuming a linear field dependence and a -15 V operation point at 35 \( \mu \text{m} \) column distance:

\[ |E| \approx 0.43 \text{ V/\mu m} \]

Estimating drift velocity for electrons:

\[
\nu_{\text{drift}} = \frac{\mu_0, e \times E}{\left[ 1 + \left( \frac{\mu_0, e \times E}{\nu_{\text{sat.}}} \right) \beta_e \right]^{1/\beta_e}}
\]

with \( \nu_{\text{sat.}} = 107 \text{ \mu m/ns} \), \( \mu_0, e = 1417 \text{ \cm^2 V/s} \), \( \beta_e = 1.109 \)

\[ \nu_{\text{drift}} \approx 41.4 \text{ \mu m/ns} \]

Extrapolated Rise time and Frequency:

\[ t_{\text{Rise}} \approx \frac{1}{3} \times t_s = \frac{1}{3} \times \frac{d/2}{\nu_{\text{drift}}} \approx 140 \text{ psec} \Rightarrow 2.3 \text{ GHz} \]
- Optimized design for uniform response with frequency
- No sharp gain change discontinuities
- No undershoot/overshoot observed
- Gain moderated to ~70 for a two-stage configuration
- 20% Higher SNR than UCSC board (with both stages)
- 2 x SNR with respect to UCSC board + niniCircuits second stage amplifier
- On going energy and transimpedance simulation
Mean noise (~RMS) of 1.2 mV for a gain of ~ 70
Tested with a 55 x 55 μm 3D double sided sensor of 230 μm
Not frequency optimized for this sensor geometry with fast dropout at lower scale
Leads to bipolar signal due to the increased trans-impedance at lower frequencies
• Conclusions

3D Pixels - Planar measurement campaign

• Several productions under investigation of different pixel size and thickness

• **Estimate filed non-uniformity impact on time resolution vs pixel size**

• **Determine minimal acceptable thickness for time resolution applications (SNR)**

• **Investigate effects after irradiation up to 1e17 n_{eq}/cm^2 in protons and neutrons**

Test-Beam Setup

• **Trigger Interface board:** Versatile, allows interfacing any acquisition instrument with EUDET

• **Control Software:** Polymorphic UI with seeming-less multi-instrument support

• **Cooling:** XPS cold box with web interface temperature controllable system @ -18°C

• **Mechanics:** Micrometric alignment with individual DUT stages

• **Analysis Framework:** Advanced framework with signal shapes, iterative re-fitting and shape-based noise rejection

Primary Goals
1. SiMS measurements & Simulation, Varied bias rail geometry structures characterization and TCAD simulation
2. Doping profile Simulations and measurements
3. Study of irradiated NinN production and LGAD doping profiles
4. Test beam and clean room studies of ATLAS PPS modules with alternative bias rail geometries
5. LGAD and irradiated doping profiles
6. Neutron Irradiated doping profile evaluation
7. Timing performance and gain analysis of heavily irradiated LGAD diodes
8. Radiation hardness of 6" Sol CNM LGADs
9. Acceptor removal and gain Reduction in proton and neutron irradiated LGADs
10. Efficiency estimation on irradiated LGAD with respect to sensor stability
11. Comprehensive mip particle measurement and analyses system
12. Comparative doping profile evaluation of Carbonated LGADs
13. Time resolution of single cell 3D devices on SPS pion beams
14. Time resolution and field uniformity study of single cell 3D pixel structures neutron and proton irradiated

42th RD50 Workshop @ CERN
43th RD50 Workshop @ CERN
• Backup

There is only one God and his name is Backup. And there is only one thing we say to Backup. Not today.
**Readout Electronics**

**First Stage amplifier**
- High frequency SiGe (~12 GHz) common emitter first stage charge amplifier (470Ω trans-impedance)
- Fully enclosed faraday cage surrounding sensor
- Mean sensor + amplifier noise < 1.8 mV
- Use of identical sensors for calibration and comparison

**Second Stage amplifier**
- Mini-circuits (Gali 52+) Gallium arsenate voltage amplifier with a 2 GHz bandwidth for LGADs
- Mini-circuits (ZX60-V63+) 6 GHz microwave voltage amplifier for 3D and planar planes
- Amplification factor of ~ 10 at 12 and 5 V respectively
- Amplifiers mounted directly on the boards and placed inside the cold box

**Sensor pad**

**Gali 52+**
- GaAs, <2Ghz, 50Ω

**ZX60-V63+**
- 50 - 6000 MHz, 50Ω
Signal Evolution with bias in LGADs

Signal FFT - 1e14n, -30C
**Signal Analysis LGADs**

**FFT**

- FFT vs Voltage presents an asymptotic behavior towards a frequency
- Asymptotic frequency depends on fluence and remaining gain
- Signal frequency increases with voltage and decreases on the onset of multiplication

**Asymptotic point ~ 250 MHz**

**FFT vs Voltage** presents an asymptotic behavior towards a frequency. Asymptotic frequency depends on fluence and remaining gain. Signal frequency increases with voltage and decreases on the onset of multiplication.
Towards the Future: Sampic

The ASIC (SAMPIC)

- Technology: AMS 0.18μm
- Sampling: between 3 and 8.4 GS/sec on 16 channels (depends on DAC setting)
- 16 channels per chip
- Signal Bandwidth of 1.6GHz
- Discrimination noise 2 mV, chip noise < 1.3 mV RMS
- Max input Signal: 1V unipolar (0.1V to 1.1V)

ADC

- 8 to 11 bit Wilkinson ADC at 1.3GHz
- Upon triggering 64 samples digitalized in parallel per channel
- Resolution adjustment possible to improve timing by reducing bit count
- Time resolution between 5 ps (calibrated) and 15ps (uncalibrated)

Calibration

- Calibration files provided for all operational points of the ADC
- Channel by channel calibration to be performed by user
- 64 channels x 4 operation points = 256 calibration runs

Connectivity

- USB2.0 + LabWindows based software (provided)
- UDP Based Ethernet, direct PC connection – no router support
**Multi-model Support with Polymorphic UI**

- 9x HV channels
- 16x LV channels
- Constant monitoring & logging
- Live protection

Precompiled executable available on GitLab: [here](#)

High voltage KEITHLEY

2400/2410 series

363X series 364X series HMP4040 PL330DP PL303QMD
**Temperature Regulation**

- Running at a crisp **-18 °C**
- Glycol cooling with temperature feedback - Labview control
- Humidity regulation though N₂ feeds

**Environmental Expander V2.0 (EnvIE)**

- ESP8266 based with integrated 10-bit ADC, I2C and WiFi 802.11b
- Integrated OLED 128X64 pixel screen
- High precision voltage dividers and sensor decoupling
- ARDUINO / LoUA core web interface
- Temperature resolution of 0.8 °C ± 0.06 %
- Humidity resolution 0.1 % with temperature compensation

- 6 c.m. thick XPS foam insulation
- Outer dimensions of 50 x 48 x 48 cm³
- Use of commercial water-cooling block ([link](#))
- 3 x Axial Fan DC 80x80x25mm 24V 111.6m³/h - low temperature tested to -20°C ([link](#))
- Total cost ~ 400 CHF
Setup @ SPS

V. Gkougkousis, 10th Beam Telescopes and Test Beams Workshop
“Tracking the time: Single pixel 50μm pitch 3D cell time resolution map”

XPS Cold Box
Environmental Control
Slow Control DAQ
Dedicated Trigger Board

E. L. Gkougkousis
• Test Beam Configuration

Pixelated plane

LGAD1
CH2A
CH3A
CH4A
LGAD2
CH2B
CH3B
CH4B
FEi4

LGAD Planes

BEAM

3D single cell sensors

6 X DUTs
2 x Timing References (HPK LGADs)
1 x Alignment / ROI matrix (FEi4B planar)

Equipment List

➢ 2 x Oscilloscopes
➢ 9 x Keithley 2410
➢ 6 x TTi PL303
➢ 8 Second stage amplifiers
➢ 6 micro-positioning stages
➢ Humidity – Temperature monitoring system (EnViE)
➢ Cold Box for -20°C operation
➢ Trigger Interface Board V2.0
➢ SMA Cables

V. Gkougkousis, 40th RD50 Workshop on Radiation hard semiconductor devices for very high luminosity colliders
"Time resolution of single cell 3D devices on SPS pion beams"
• Tracking and ROI

Telescope Planes
• 6 MIMOSA planes for tracking
• Plane no. 5 known to be bad
• Expected 5µm tracking resolution
• Estimated acquired number of events ~1M

• Limited beam control as parasitic user
• Suffer from low intensity and low data rates of EUDAQ
### Event by Event Strategy

- A four sequential step analysis approach
- Analysis escalates in a pyramid structure

---

**Five preliminary sequential steps before we even start looking at the waveform**

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Set Waveform values</th>
<th>Determine polarity</th>
<th>Find max, min point</th>
<th>Find start, stop point</th>
<th>Determine if noise</th>
<th>Determine if pulse within window</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Step 2</th>
<th>Define noise points</th>
<th>Use Gaussian fit for noise/Pedestal</th>
<th>Pedestal subtraction/inversion</th>
<th>Recalculate start, stop points, min, max</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Step 3</th>
<th>Compute charge</th>
<th>Determine rise time</th>
<th>Determine CFD time</th>
<th>Compute dV/dT</th>
<th>Determine Trigger Time</th>
<th>Estimate Trigger &amp; CFD ToT</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Step 4</th>
<th>Perform CFD time to voltage Correction (Time Walk)</th>
<th>Signal FFT</th>
<th>Noise FFT</th>
</tr>
</thead>
</table>

---

**Event Analysis Algorithm**

- If \( SD_{\text{maxima}} > SD_{\text{minima}} \)
  - \( D_m(\text{max}) > D_m(\text{min}) \)
- or \( SD_{\text{maxima}} < 1.05 \ast SD_{\text{minima}} \)
  - \( D_m(\text{max}) > D_m(\text{min}) \)

Positive polarity

- Number of points with 0.8 \( V_{\text{max}} \)
- If \( N_{\text{points}} > 2 \) test 0.7, 0.6 & 0.5 \( V_{\text{max}} \) to account for wavy waveforms
- If \( N_{\text{points}} > 2 \) then require \( dN_{\text{points}} < 8/12/16/20 \)

---

**File:** Waveform.png

---

**E. L. Gkougkousis**

---

**Figure:**

- Pulse
  - 1st Derivative
  - 2nd Derivative
  - Second derivative < 0

---

**Graph:**

- Points between \( V_{\text{max}} \)
  - \( = 0 \)

---

**Table:**

- \( V_{\text{max}} \)

---

**Chart:**

- Event by Event Strategy
• Iterative re-fitting and re-binning algorithm
• Fitting of discrete and variable binning quantities
• Bayesian uncertainties at efficiency level
• Event by event FFT transimpedance correction

Four main classes with dedicated header and implementation files, one wrapper class handling user interaction

- LGADUtils
  - LGADBase: Wrapper to handle user I/O and pass arguments
  - Basic framework function and infrastructure
  - Timing resolution, CFD maps, multi DUT operations
  - Mean pulse shape, mean pulse properties form entire run
  - Single Waveform properties and time walk corrections
  - Selector Class with auto-set 64 channel support

- LGADRun
  - Timing resolution, CFD maps, multi DUT operations

- LGADChannel
  - Mean pulse shape, mean pulse properties form entire run

- WaveForm
  - Single Waveform properties and time walk corrections

Bonus: LGADSel

Four main classes with dedicated header and implementation files, one wrapper class handling user interaction

- LGADUtils
  - LGADBase: Wrapper to handle user I/O and pass arguments
  - Basic framework function and infrastructure
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  - Timing resolution, CFD maps, multi DUT operations

- LGADChannel
  - Mean pulse shape, mean pulse properties form entire run

- WaveForm
  - Single Waveform properties and time walk corrections

Bonus: LGADSel

Code available on git: https://gitlab.cern.ch/egkougko/lgadutils
### Template Method

- Centralized fitter engine for all fits
- Fully automated, including limits, method and Minuit minimization
- 36 Iterations per fit with limits and bin size variation to determine best combination
- Over-binning protection, automatic variable discreetness test
- Variable binning for FFT, frequency histograms
- Supported ROOFit, Standalone Minuit, Integral optimization or Shape

#### Dataset Type Statistic Categorization Bin Selection Criteria

<table>
<thead>
<tr>
<th>Discrete Datasets</th>
<th>Lower 3 bin number variations</th>
<th>Optimum Bin number</th>
<th>Higher 3 bin number variations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ \lim_{a} \text{High} - \lim_{a} \text{Low} \sigma &lt; \sqrt{\text{N}<em>{\text{element}}} &lt; \sqrt{\text{N}</em>{\text{max,proj}}} ]</td>
<td>[ \sqrt{\text{N}<em>{\text{element}}} - n \times \frac{\lim</em>{a} \text{High} - \lim_{a} \text{Low}}{\sigma} ]</td>
<td>[ \sqrt{\text{N}<em>{\text{element}}} + n \times \frac{\lim</em>{a} \text{High} - \lim_{a} \text{Low}}{\sigma} ]</td>
</tr>
</tbody>
</table>
|                   | with \( 1 < n < 3 \) | \[ \sqrt{\text{N}_{\text{element}}} \] | \[ \sqrt{\text{N}_{\text{element}}} + n \times \sqrt{\text{N}_{\text{max,proj}}} \] | with \( 1 < n < 3 \) **

<table>
<thead>
<tr>
<th>Continuous Datasets</th>
<th>Lower 3 bin number variations</th>
<th>Optimum Bin number</th>
<th>Higher 3 bin number variations</th>
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<tr>
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<td>[ \lim_{a} \text{High} - \lim_{a} \text{Low} \sigma &lt; \sqrt{\text{N}_{\text{element}}} ]</td>
<td>[ \sqrt{\text{N}<em>{\text{element}}} - n \times \frac{\lim</em>{a} \text{High} - \lim_{a} \text{Low}}{\sigma} ]</td>
<td>[ \sqrt{\text{N}<em>{\text{element}}} + n \times \frac{\lim</em>{a} \text{High} - \lim_{a} \text{Low}}{\sigma} ]</td>
</tr>
</tbody>
</table>
|                    | with \( 1 < n < 3 \) | \[ \sqrt{\text{N}_{\text{element}}} \] | \[ \sqrt{\text{N}_{\text{element}}} + n \times \sqrt{\text{N}_{\text{max,proj}}} \] | with \( 1 < n < 7 \) **

#### Iterative Re-fitter & signal templates

- Point by Point projection of all time-walk corrected (though CFD) signal pulses
- Landau X Gauss fit on projected point by point distribution
- Extraction of a “characteristic” signal composed of the MPVs of the Point by point projection fits
- RooKeyPdf for analytical description of signal
- Re-iteration on all events and fit of each waveform with the extrapolated analytical signal description
- Re-calculate all quantities
Sensor Daughterboard

Sensor board

- Two types of designs. (15x15 mm and 5x5 mm central pad).
- 41 x 41 mm square shape.
- Rogers 4350B for the high speed signals.
- Connector area reinforce with 0.3 μm FR4.
- Under sensor pad thickness of 100 μm.
- Multiple drills design on the central pad to place different types and sensors sizes.
- 140 boards produced at Gacem.
<table>
<thead>
<tr>
<th>Category</th>
<th>Function</th>
<th>Description</th>
<th>Github Project Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronics</td>
<td>TiB Board</td>
<td>Interface and synchronize oscilloscope with AIDA TLU</td>
<td>Trigger Interface Board - TiB</td>
</tr>
<tr>
<td></td>
<td>FEi4 HitOr Converter</td>
<td>Convert CMOS level output to TTL level necessary for ROI trigger</td>
<td>HitOr Converter</td>
</tr>
<tr>
<td></td>
<td>Environmental Expander (EnviE)</td>
<td>Monitor Temperature / Humidity at DUT level</td>
<td>Environemental Monitoring Expander - EnviE</td>
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<tr>
<td></td>
<td>Front-End readout board</td>
<td>12 GHz fast transimpedance amplifier with integrated faraday cage</td>
<td>Single Channel Board</td>
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<tr>
<td>Mechanics</td>
<td>Cold-Box and DUT Support</td>
<td>XPS foam enclosure for -20C operation and individual DUT alignment</td>
<td>Test beam Mechanics</td>
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<tr>
<td>Software</td>
<td>Oscilloscope Fast DAQ</td>
<td>SCPI layer DAQ program for oscilloscope readout</td>
<td>Oscilloscope DAQ</td>
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<tr>
<td></td>
<td>Power/ Temp Control Software</td>
<td>Labview based Low Voltage and HV control software with integrated single event burnout protection</td>
<td>TiCAS - Timing Control Automation Software</td>
</tr>
<tr>
<td></td>
<td>Trimming analysis Software</td>
<td>LGADUtils timing analysis framework</td>
<td>LGADUtils</td>
</tr>
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