A HIGH-GRANULARITY TIMING DETECTOR FOR THE PHASE-II UPGRADE OF THE ATLAS CALORIMETER SYSTEM: BEAM TEST RESULTS

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Motivation

- At the High-Luminosity phase of LHC (HL-LHC)
  - Instantaneous luminosities up to \( L \approx 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) (\( \times 5 \text{ current } L_{\text{inst}} \))
  - Pile-up: \( <\mu> = 200 \) interactions per bunch crossing \( \rightarrow 1.5 \text{ vertex/mm on average} \)
  - Vertex reconstruction and physics objects performance will be significantly degraded in the forward region where compared to the central region
    - Liquid Argon based electromagnetic calorimeter has coarser granularity
    - Inner tracker has poorer momentum resolution
- A **High Granularity Timing Detector** (HGTD) is proposed in front of the Liquid Argon end-cap calorimeters for pile-up mitigation
  - Improve performance in the forward region by combining
    - HGTD precise timing
    - ITk (new ATLAS tracker) position information
HGTD requirements

- Detector quite constrained by the space available and the harsh environment
- Time resolution better than 30 ps per track (50 ps per hit in a 2 layer geometry)
  - Recovers electron ID, track & jet reconstruction and b-tagging
- **Low Gain Avalanche Detectors (LGAD) technology has been chosen**
  - It provides an internal gain good enough while providing a large S/N ratio
- Design optimized for <10% occupancy

| Pseudorapidity coverage | 2.4 < |η| < 4.0 |
|-------------------------|------------|
| Thickness in z          | 75 mm (+50 mm moderator) |
| Position of active layers in z | 3435 mm < z < 3485 mm |
| Radial extension:       |                         |
| Total                   | 110 mm < R < 1000 mm    |
| Active area             | 120 mm < R < 640 mm     |
| Time resolution per track | 30 ps                |
| Number of hits per track: |                         |
| 2.4 < |η| < 3.1 | 2 |
| 3.1 < |η| < 4.0 | 3 |
| Pixel size              | 1.3 × 1.3 mm²           |
| Number of channels      | 3.54M                  |
| Active area             | 6.3 m²                 |

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Radiation levels in HGTD

- Maximum $n_{eq}$ fluences and dose for HL-LHC
  - $R < 32$ cm $\rightarrow 3.7 \times 10^{15} n_{eq}/cm^2$ and 4.1 MGy
  - $R > 32$ cm $\rightarrow 3 \times 10^{15} n_{eq}/cm^2$ and 1.6 MGy
  - A safety factor of $\sim 2$ and replacement of inner ring at half life time are taken into account

- $\sim 30\%$ sensors and ASIC ($R < 32$ cm) need to be replaced at half HL-LHC running period because of radiation damage

- Sensors will be operated at $-30 \, ^{\circ}C$ using a common CO$_2$ cooling system with the inner detector (ITk)
Detection technology: LGAD

- **Low Gain Avalanche Detectors** (LGADs) originally developed by CNM
  - n-p silicon planar detector + multiplication layer that amplifies the signal
  - High E field
  - Moderate internal gain (10-50)
  - Typical rise time 0.5ns
  - Excellent time resolution <30 ps before irradiation
- R&D programme to deliver thin sensors to provide the required time resolution (30 ps per track), fine segmentation, radiation hardness
  - New doping materials, substrates and new geometries
  - Prototypes tested from CNM, HPK, BNL, FBK

CNM LGAD for HGTD  HPK LGAD for HGTD
Contributions to timing

- Landau term <25 ps
  - Reduce for thin sensors: 35-50 μm
- Jitter term <15 ps and time walk term <10 ps
  - Low noise and fast signals
- Digitization granularity ~5 ps
- Clock distribution <10 ps

- Time walk corrections on beam test data using the Constant Fraction Discriminator (CFD) technique
  - Considering the time at a fraction of 50% of the amplitude

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

- **ATLAS LGAD Timing Integrated ReadOut Chip (ALTIROC)**
  - Minimize noise and power consumption
  - Provide Time Of Arrival (TOA) and Time Over Threshold (TOT) measurements
  - Target time resolution <25 ps
  - Developed in various phases
    - **ALTIROC0:** single-pixel analog readout (pre-amplifier + discriminator)
      - Test bench measurements satisfactory
      - Beam tests → see next slides
    - **ALTIROC1:** full single-pixel analog readout (analog + digital) in 5×5 arrays
      - Test bench measurements on-going
      - Irradiation campaigns and beam tests in Q1 2019
    - **ALTIROC2:** final 15×15 version
      - Submission expected end of 2019
Beam test campaigns

- CERN North Area SPS H6A & B beamlines (120 GeV pion beam)
  - ACONITE telescope in H6A and AIDA telescope in H6B

- SLAC beam tests → See talk “HGTD testbeam at the SLAC beamline” by S. Mazza

**Un-irradiated sensors**

- **2016**
  - Un-irradiated CNM, HPK, BNL

- **2017**
  - Un-irradiated and irradiated CNM sensors
    - Single pads and arrays
    - Un-irradiated HPK sensors

- **2018**
  - Neutron vs Proton irradiated
    - Boron implanted CNM sensors
    - Carbon diffused CNM sensors
    - Gallium implanted CNM sensors
    - HPK sensors
  - 2×2 array sensors with ALTIROC0_v2
  - Arrays with different inter-pad gaps

**SiPMs**

**DUTs**

ACONITE telescope (6 MIMOSA planes)
• 50 sensors (un-irradiated, $p$- and n-irradiated) tested so far
• LGAD readout boards with trans-impedance first stage amplifier
• Voltage second stage amplifiers with hermetic E/B cover design

- Sensor attached to board using double-sided conductive tape
- Amplifier input coupled to metallization layer via wire bonds
- Guard ring grounded

- Gain of $\sim 10$
- 2 GHz Bandwidth

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Timing reference system

- 4 quartz bars
  - UVFS window
  - $3 \times 3 \times 10$ mm$^3$
  - 6 side-polished
- Translucent optical grease
- 4 single channel SIPMs from sensL
  - $4 \times 4$ mm$^2$ base
  - 0.7 mm thickness
- 4 SIPM readout and amplification boards
  - Shielding for amplification circuitry
- 3D printed quartz light-tight enclosure
  - Main cover and top plate
  - Holes for pins, screws, bar and SIPM

SIPM detects Cherenkov photons generated by charged pions in quartz
Beam test equipment

- L-shape support mechanics for sensors → easy installation and good board alignment
- Cooling box for sensors and light-tight boxes for timing reference system
- Chillers
  - 1 for sensors in H6A
  - 2 room temperature for SIPMs
- Cooling loops
- PI x-y translation stages
- Low (HMP4040) and high voltage (Keithley 2410) power supplies
- Agilent Infinium (10 Gs/s @ 5 GHz) series and Lecroy WaveRunner oscilloscopes
- Trigger pulse converter (TTL to NIM)
- SPS cycle USB catcher
- Storage array → Lacie RAID array with 4×2 TB Seagate hybrid drives
Beam test software and running conditions

• Software:
  • DAQ script compatible with all versions of Agilent and Lecroy oscilloscopes
  • Low voltage and SIPM high voltage controls LabVIEW based
    • Continuous monitoring
    • Compliance and voltage adjustment
  • ISEG control for LGADs bias voltage
  • Run EUDAQ for combined data taking (RunControl, STcontrol)
  • Use standalone dataMonitor.py and EUDAQ OnlineMon.exe for data sanity checks

• Running conditions:
  • IV measurements performed in the laboratory before sensor on-board assembly
  • Select highest operating voltages using IV derivative method (8 std. dev. from stable region)
    • 4 operating voltages 1M events
    • Highest operating voltage 3M events for efficiency maps
  • Run at -20 °C and -30 °C
HGTD beam test DAQ and trigger system

- Definition ROI mask in FE-I4 $\rightarrow$ only accept tracks passing through small area covering all LGADs
- Use inverted signal from HitOr (TTL $\rightarrow$ NIM)
- Delay ($\sim$100 ns) scintillator NIM signal to match in TLU trigger window with HitOr signal
- 5 ns trigger window in TLU $\rightarrow$ triggers oscilloscope, MIMOSA readout, MMC3/USBpix
- A track on LGAD $\rightarrow$ look back in time and a waveform is recorded
- Data are saved in two separated files (oscilloscope, MIMOSA + FE-I4)
Results from 2017 campaigns

- Comparison between un-irradiated and irradiated at fluence $6 \times 10^{14} \ \text{n}_{\text{eq}}/\text{cm}^2$ arrays of four LGAD sensors of $1.1 \times 1.1 \ \text{mm}^2$ each
Efficiency using standalone tracking software

- Standalone tracking software developed to reconstruct tracks in raw data from telescope and match event information with oscilloscope data.
- Efficiency is obtained as \( \frac{\text{tracks on LGADs with signals larger than a threshold}}{\text{all reconstructed tracks on LGADs}} \).
- Efficiency in the bulk is larger than 98-99%.

![Graphs showing efficiency plots with and without broken channels.](image)
Efficiency vs threshold

- Signal amplitude in the bulk of LGAD pads
- Signal efficiency in the bulk of LGAD pads as a function of the voltage threshold
- Dashed line shows the default threshold corresponding to 3 times the noise
LGAD timing performance

- Time resolution as a function of the X and Y coordinates (in mm)
- The time resolution is larger in the guard rings around the pads where there is no multiplication of the charge
- The fluctuations are dominated by statistical fluctuations since very small bins are used in order to show the structure around the pad
**Inter-pad studies**

- Signal efficiency in the inter-pad region as a function of $X$ (in mm) for 3 different voltage thresholds

![Graphs showing signal efficiency as a function of X for different voltage thresholds.](image-url)
Preliminary results from 2018 campaigns

- First efficiency results using EUTelescope tracking software
- ALTIROC preliminary results
Efficiency using EUTelescope tracking software

- Motivation using EUTelescope software
  - Crosscheck results with standalone tracking software
  - Algorithm providing better resolution and to be used for analysis of future DESY beam test data
- Reconstruction procedure using iLCsoftware v01-19-02, EUTelescope version master, EUDAQ version branch/1.x-dev

Native data from telescope ➔ Geometry in gear file: 6 MIMOSA + 1 FE-I4 ➔ EUTelescope jobtasks: converter, clustering, hitmaker, align, fitter ➔ Ntuple containing track info at MIMOSA and FE-I4 planes

- Match event information between oscilloscope and telescope ntuples
- Fit track x-z and y-z points on all MIMOSA planes and extrapolate to LGADs z position
- Conditions to calculate the efficiency:
  - Select tracks passing through FE-I4 within the defined ROI mask
  - Have a hit on LGAD (waveform is recorded in oscilloscope)
  - LGAD signal amplitude > threshold

Eff. in bulk 95-100%

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ALTIROC preliminary results

- ALTIROC0v2 bump bonded to a un-irradiated CNM 2×2 LGAD array
- TOA of signal corrected for time walk effects
  - TOA vs amplitude of pre-amplifier probe
  - Black points correspond to profile of 2D distribution
  - Red line corresponds to polynomial fit used to correct for time walk effects
- Best achieved time resolution 35 ps after time walk correction
  - Time resolution vs discriminator threshold (in DAC units) before and after time walk correction
  - Amplitude of pre-amplifier probe used to correct for time walk
  - 30% improvement
  - A SIPM is used as time reference where its 40 ps contribution is subtracted
Summary and perspectives

• The HGTD is proposed to mitigate pile-up effects and improve the performance in the ATLAS forward region
  • Challenging requirements
  • Technical proposal was approved [link to HGTD Technical Proposal]
• After a fluence $6 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$ (test-beam 2017)
  • Efficiency in the bulk is still $\sim 100\%$
  • Time resolution of 40-50 ps is achieved
  • More results published on HGTD testbeam paper [link to HGTD beam test paper]
• A 4 period test-beam campaign in 2018 is complete
  • An extensive list of LGAD prototypes have been tested from different technologies and manufacturers
  • First efficiency results using EUTelescope software are presented
  • ALTIROC results look promising
  • Lots of data recorded and analysis is on-going
  • A paper with 2018 beam test results is in preparation
• Next beam tests at DESY are scheduled in March and May 2019
  • Investigate the integration of LGAD and ALTIROC readouts in EUDAQ
HGTD module and stave

- 7984 modules:
  - 2 15×15 pixels ALTIROC ASIC (2×2 cm²)
  - 1 15×30 pixels LGAD with 1.3×1.3 mm² pads (2×4 cm²)
  - Schematic drawing of two adjacent modules
  - Double sided layer with a cooling plate in between
  - Modules mounted on thin support plates → up to 18 on a stave
  - Wire bonded to flex cables going to peripheral electronics

- Layout:
  - For R< 32 cm → stave designed to have 3 hits with a 80% module overlap
  - For R> 32 cm → stave designed to have 2 hits with a 20% module overlap

bump bonded together
Summary

- The HGTD group is working hard to deliver TDR by 5th April 2019
  - LGAD from CNM, HPK, FBK up to 15×15 channels (½ final size)
  - Complete 2018 test beam campaigns
  - Performance with final detector layout and full simulation
  - ASIC-ALTIROC1 up to 5×5 channels w/ analog+dig. part
  - (ASIC+ LGAD +flex cable): 5×5 results in lab and bump bonding R&D
  - Peripheral electronics and BE electronics: design/concept and components tests
  - Services layout and mock-up in surface
  - Develop path for construction/tests of a demonstrator (cooling plate+stave+flex+peripheral elect.)
  - Strategy for installation and maintenance
  - Update CORE and manpower evaluation for construction
• ALTIROC ASIC will provide *Time Of Arrival (TOA)* and *Time Over Threshold (TOT)* measurements

• TOA of signal corrected for time walk effects using TOT technique
  • Charge injection tests with an estimated input capacitance of 4.3 pF
  • Two different pre-amplifiers
    • Voltage
    • Trans-impedance (shorter TOT)
  • After correction <10 ps contribution

• Other techniques as the *Constant Fraction Discriminator* (CFD) can be used to correct for time walk
Beam test campaigns in 2018

- CERN North Area SPS H6A & B beamlines (120 GeV pion beam)
  - ACONITE telescope in H6A and AIDA telescope in H6B
  - April – May 2018
    - Neutron vs Proton irradiated Boron implanted CNM sensors
  - June – July 2018
    - Proton irradiated Carbon diffused CNM sensors
    - Un-irradiated Gallium implanted HPK sensors
    - 2×2 array sensors with ALTIROC0_v2
  - September 2018
    - Neutron irradiated Carbon diffused CNM sensors
    - Proton irradiated Gallium sensors
  - October 2018
    - Neutron irradiated Gallium sensors
    - Arrays with different inter pad gaps
    - ALTIROC

- SLAC beam tests → See talk “HGTD testbeam at the SLAC beamline” by S. Mazza
Figure 9: Signal-to-noise ratio (a) and charge and gain (b) as a function of the bias voltage for single-pad sensors and arrays. Statistical uncertainties are negligible and smaller than the marker size. [link to HGTD beam test paper]
HGTD beam test layout

- North Area SPS H6A line
- Telescope with 6 MIMOSA planes
- FE-I4 used as reference plane
- HGTD DUTs: 6 LGADs
- Time reference system: quartz bars + SIPMs
- Trigger: FE-I4 + scintillator after MIMOSA 6

Diagram:

- Cooling box
- LGADs
- MIMOSA 1, 2, 3, 4, 5, 6
- BEAM
- Light-tight box
- SIPMs
- t1, t2, t3, t4, t5, t6
Tracking using EUTelescope software

- Using iLCsoftware v01-19-02, EUTelescope version master, EUDAQ version branch/1.x-dev
- Start point: native data from telescope (September 2018)

Steps:
- Implement test beam geometry (6 MIMOSA planes + 1 FE-I4 plane) in gear file
- Fill run list in a .csv file
- Prepare steering and configuration files including required processors, parameters and variables
- Submit EUTelescope jobtasks: converter, clustering, hitmaker, align, fitter
- Resulting ntuple contains track information on FE-I4 plane / MIMOSA planes
- Develop analysis to combine data from oscilloscope and telescope files (same number of events)
Efficiency using EUTelescope tracking software

- Reconstruction procedure
  - Using iLCsoftware v01-19-02, EUTelescope version master, EUDAQ version branch/1.x-dev

Native data from telescope ➔ Geometry in gear file: 6 MIMOSA + 1 FE-I4 ➔ EUTelescope jobtasks: converter, clustering, hitmaker, align, fitter ➔ Ntuple containing track info at MIMOSA and FE-I4 planes

- Match event information between oscilloscope and telescope ntuples (same number of events)
- Fit track x-z and y-z points on all MIMOSA planes and extrapolate to LGADs z position

- Conditions to calculate the efficiency:
  - Select tracks passing through FE-I4 within the defined ROI mask
  - Have a hit on LGAD (waveform is recorded in oscilloscope)
  - LGAD signal amplitude > threshold
MIMOSA and FE-I4 hit maps

- FE-I4 plane is rotated 90 degrees
- ROI mask containing LGADs and SIPMs is clearly seen
- Z in log scale to see FE-I4 mask on MIMOSA planes