A **High-Granularity Timing Detector** for the Phase-II upgrade of the ATLAS Calorimeter system
Detector concept description and first beam test results

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On behalf of the ATLAS LAr-HGTD group

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**ATLAS EXPERIMENT**

**CHEF 2017**
Calorimetry for the High Energy Frontier
CALORIMETERS: Today and for future projects
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**LPNHE**
**CNRS**
**IN2P3**
Outline

• High luminosity LHC
• ATLAS detector at high luminosity LHC
• HGTD motivations

• Detector overview
• Requirements and main parameters
• Modules design and Assembly

• Sensor technology: Low-Gain Avalanche Detectors
• Readout electronics

• HGTD prototypes testing
• Beam test results
• Sensors performance after irradiation

Nikola Makovec – Thursday 15h20:
“A High-Granularity Timing Detector (HGTD) in ATLAS: Performance at the HL-LHC”
High Luminosity LHC

- Start in 2026
- Instantaneous luminosities at HL-LHC up to $L \approx 7.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
- Integrated luminosity of 4000 fb$^{-1}$ after 10 years

Simulated LHC event collision at the ATLAS detector with 200 additional pile-up interactions. Yellow squares indicate the reconstructed hard plus pileup interactions, occurring at different positions along the z-axis.

Pile-up: other pp collisions in addition to the one of interest
- Adds energy to reconstructed hard-scatter jets
- Produces pile-up jet
ATLAS detector at high luminosity LHC
HGTD motivations

Spread in interaction region:
50 mm RMS along the beam axis
180 ps RMS in time
1.6 collisions/mm for \( \mu = 200 \)
30 ps time resolution increases the pile-up rejection

HGTD Motivation
Pile-up mitigation
Improve track-to vertex association, b tagging, lepton isolation, jet/Etmiss perf
Luminosity measurement

Parameterization of the longitudinal track impact parameter resolution as a function of \( \eta \) for different \( p_T \) values
\( z_0 \) resolution grows with \( |\eta| \) and at low \( p_T \)

Distribution of the reconstructed time and \( z \) position of the tracks associated to the hard-scatter vertex in a VBF Higgs to invisible event with 200 additional interactions.
Detector overview

ATLAS layout, showing the gap between the endcap calorimeter (left) and the tracking detector (right) – opened for maintenance

HGTD will be placed between the tracker and the calorimeter (tight Z space = 75 mm)

Currently, the space is occupied by the MBTS, white disk in front of the endcap calorimeter

HGTD installed in front of the endcap calorimeter cryostat with different components

Central blue parts = active area
Green blocks = off-detector electronics.
Grey cylinder = moderator needed to shield the back-scattered neutrons from the endcap calorimeter
Detector requirements and main parameters

<table>
<thead>
<tr>
<th>Requirement/Parameter</th>
<th>Specification/Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudo rapidity coverage</td>
<td>$</td>
</tr>
<tr>
<td>Position in $z$ (mm)</td>
<td>$3420 &lt; z &lt; 3545$ including 50 mm of moderator</td>
</tr>
<tr>
<td>Position of the active layers (mm)</td>
<td>$3435 &lt; z &lt; 3485$</td>
</tr>
<tr>
<td>Radial extension (active area)</td>
<td>$110 -1100$ mm (120 – 640 mm)</td>
</tr>
<tr>
<td>Number of layers</td>
<td>4 per side</td>
</tr>
<tr>
<td>Time resolution</td>
<td>30 ps / mip ($&lt; 60$ ps / mip / layer)</td>
</tr>
<tr>
<td>Sensor size</td>
<td>1.3x1.3 mm$^2$</td>
</tr>
<tr>
<td>Active thickness</td>
<td>50 $\mu$m</td>
</tr>
<tr>
<td>Number of channels</td>
<td>6.3 M</td>
</tr>
<tr>
<td>Number of Si modules (2x4 cm$^2$ each)</td>
<td>13952</td>
</tr>
<tr>
<td>Number of ASICs (2x2 cm$^2$ each)</td>
<td>27904</td>
</tr>
<tr>
<td>Total active area (Si sensors)</td>
<td>11.6 m$^2$</td>
</tr>
</tbody>
</table>

4 silicon layers made of Low Gain Avalanche Diode (LGAD)

Pad size determined by requirements of $<10\%$ occupancy, minimization of dead areas and the detector capacitance (time resolution)

Maximum radiation level in inner region 9.0 MGy, $9 \times 10^{15}$ n/cm$^2$
Detector modules design

LGAD sensor connected to ASIC using bump bonding process. ASIC glued to flex cable - HV and ASIC lines wirebonded to flex cable.

Longest stave: 542 mm – 2x15 modules – 15 flex superimposed at outer radius
Central detector at low radius: replaced at half time of HL-LHC

9.0 MGy, 9 $10^{15}$ n/cm$^2$ ➔ 4.5 MGy, 4.5 $10^{15}$ n/cm$^2$
Detector assembly

One quadrant of one layer of HGTD detector
23 staves of different lengths

4 HGTD active layers installed on the cooling plates, including front and back covers and the moderator
Sensor technology: Low-Gain Avalanche Detectors

- Planar n-on-p silicon with internal gain
- Extra highly doped p-layer
- A large current generated in p+ region
- Extra doping layer: high field and S/N
- Needs cooling to -30°C
- Manufacturers: CNM (within RD50), FBK and HPK

Top and side view of a single pad produced at CNM

HPK – Hamamatsu structures
Single pad and array

Various structures: single pad - array – various dimensions
Readout electronics

| Pad size | 1.3x1.3 mm² |
| Detector capacitance | 3.4 pF |
| TID and neutron fluence | Inner region 4.5 MGy, 4.5 $10^{15}$ n/cm² |
| Outer region 2.1 MGy, 4.0 $10^{15}$ n/cm² | 225 |
| Number of channels / ASIC | |
| Collected charge (1 mip) at gain=20 | 9.2 fC |
| Dynamic range | 20 mips |
| Jitter at gain = 20 | < 20 ps |
| Time walk contribution | < 10 ps |
| Total power per area (ASIC) | < 200 mW/cm² (< 800 mW) |
| E-link driver bandwidth | 320 Mb/s, 640 Mb/s and 1.28 Gb/s |

Sensors readout by on detector front electronics
ASIC keeping the excellent time resolution of LGAD

Off-detector electronics at the periphery (flex cables)
Transmission by optical fibres

One readout channel: preamplifier+discriminator;
time walk corrected using TOT or CFD;
TDC for TOT & TOA; FIFO

Layout of the first ASIC prototype – ALTIROC 0; 8 channels;
4 with 2 pF; accommodate the bump bonding to a sensor
Jitter measurement: 27 ps for 10 fC
HGTD prototypes testing

- I-V and C-V measurements; beta source; red and infrared laser – performed in lab

- Beam tests performed at H6 beam line of the CERN-SPS with 120 GeV pions

- Irradiation tests at JSI research reactor in Ljubljana up to fluences of $6 \times 10^{15}$ n/cm$^2$
**HGT D beam test results for non-irradiated sensors**

Efficiency in percent as a function of the position on the pad

- Measured using an external telescope for reference tracks
- Efficiency = Hits in sensor / total number of tracks
- Array = 97.0% +/- 0.1%
- Single pad = 96.7% +/- 0.1%
- Size of the plateau at 99.9% = 876 µm; at 50% = 960 µm
HGTD beam test results for non-irradiated sensors

**Time resolution**
- Zero Crossing Discriminator method
- Best resolution = 27 ps for a single pad

**Gain measurements**
- Gain: collected charge in LGAD / charge of no-gain PIN diode
- Measured as a function of the position with telescope data
- Circular structure in single pad = opening in metal layer
- Array sensors G=10 to 20 depending on the voltage
HGTD sensors performance after irradiation

Gain evolution after irradiation:
Gain or most probable charge dependence on bias voltage measured with $^{90}\text{Sr}$ $\beta$ particles
- UCSC measurements at -20°C of HPK sensors
- JSI measurements of CNM diodes with medium dose and with very high dose at -10°C
- Gains decrease after irradiation (loss of effective doping)
- Little difference between PIN diode and LGAD
- Sensors operated close to breakdown
- Very good temperature control and voltage stability mandatory
HGTD sensors performance after irradiation

Time resolution

- Performance of CNM LGAD irradiated up to 2 \(10^{15}\) n/cm\(^2\); measurements at -6 to -20°C
- Similar performance at 3 \(10^{14}\) n/cm\(^2\) at lower temperature = 30 ps
- Degradation of the time resolution to 57 ps at 1 \(10^{15}\) n/cm\(^2\) - to 75 ps at 2 \(10^{15}\) n/cm\(^2\)

Time resolution

- Performance of HPK LGAD irradiated up to 6 \(10^{15}\) n/cm\(^2\); measurements at -20°C
- Degradation of the time resolution at high fluences for different operating voltages
- 50-60 ps time resolution at 6 \(10^{15}\) n/cm\(^2\)

Time resolution requirement: 30 ps / mip ; < 60 ps / mip / layer
Conclusion

An initial design of a new ATLAS sub-detector, the **High-Granularity Timing Detector**, is ready after 2 years of active R&D by 23 institutes and 120 collaborators.

- **HGTD detector**
  - Si-based detector with low gain avalanche diode
  - 30 ps time resolution for minimum ionising particles
  - 1.3x1.3 mm$^2$ granularity – pseudo rapidity region 2.4 - 4.2 with 4 layers at z=3.5m

- **Prototypes testing**
  - Electrical measurements in different institutes
  - Dynamic properties of LGAD in the laboratory and in beam tests performed in 2016-17
  - R&D on LGAD sensors still in progress in RD53 collaboration
  - First version of the ASIC tested in September 2017 in beam test
  - First nominal module with one (at least) ASIC bump-bonded: end of 2019

- **Approval process**
  - ATLAS Initial Design Review: September 22$^{nd}$
  - LHCC: December 1$^{st}$
  - Technical Design Review: end of 2018

Nikola Makovec – Thursday 15h20:
“A High-Granularity Timing Detector (HGTD) in ATLAS: Performance at the HL-LHC”
Backup slides
HGTD radiation levels (4000 fb-1)

- Max doses after 4000 fb−1 + Safety factors = 9 × 10^{15} \text{ neq/cm}^2 and 9 \text{ MGy}.

- ~ 20% of Sensors + ASICs (R<30 cm) should be replaced at ½ life time of HL-LHC and will see max. doses = 4.5 × 10^{15} \text{ neq/cm}^2 and 4.5 \text{ MGy}.
HGTD as a luminosity meter

Measuring the total number of hits in HGTD:
• Bunch per bunch measurement (online)
• No afterglow problems
• Easier to spot drifts

Tasks to explore:
• Amount of data
• Robust algorithms:
  acceptance selection
  linearity

Beam condition monitoring:
• Timing distribution of hits can be exploited to monitor the cavities performance
• $t_0$ re-synchronization : monitor expected timing with measured one for each BCiD (drift)
Cavern installation

Global view of the HGTD detector installed in front of the endcap calorimeter cryostat. Details of the bolting system currently used in ATLAS to fix the MBTS scintillators and to be reused for the HGTD installation.
Cavern installation

Various components of HGTD at the outer radius, including the 4 active layers (in blue), the off-detector electronics boards (in green).

The grey material is the moderator needed to shield the back-scattered neutrons from the endcap calorimeter. The services come out at the outer radius through the feedthroughs.
Moderator – Cooling system

On detector cooling pipes distribution

Inner radius part of the HGTD detector
2 moderator pieces located inside and outside the HGTD vessel
ASIC Sensor interconnection

a) X-ray image of the 250 m bump balls of the VIP mechanical sample
b) Shear test to determine the force needed to break the solder ball connections
c) Imprint of the UBM pad on the solder bump, demonstrating good connectivity

Under bump metallization of both ASIC and sensor (I)
Solder bump deposition on ASIC (II)
Flip-chip (III)
Connection step through thermal cycle
Reflow

a) ALTIROC and sensor dummy production masks overlaid
b) Sensor after UBM
c) ALTIROC after UBM and bump deposition
Dummy structures and ALTIROC prototypes

a) Four dummy samples that match the mechanical characteristics of the foreseen ALTIROC HGTD prototypes.
b) X-ray inspection indicating good connectivity of all the bumps.
c) One device glued to a PCB and wire-bonded to test the effect of UBM on the wire-bond pads.

- First HGTD prototypes assembled at IFAE in July 2017.
- ALTIROC chip designed by Omega and produced at TSMC in the 130 nm technology.
- LGAD sensors produced at CNM.

d) X-ray inspection indicating good connectivity of all the bump bonds
e) Two devices glued and wire-bonded to a dedicated PCB.
Voltage distribution and signal readout

Main purposes:
- Hold the ASIC and the LGAD of a stave to the cooling plate.
- Supply High Voltage (HV) to the LGAD.
- Power to the ASIC and elinks for data transmission, clock and slow control signals.

Flex cable layout taking into account mechanical requirements (30 modules one the longest stave - maximal thickness of the flex cable 300 µm etc…)

Types of signals for two ASIC included in the flex cable design

<table>
<thead>
<tr>
<th>Signal type</th>
<th>Signal name</th>
<th>Number of wires</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV, POWER, GROUND</td>
<td>1 kV max.</td>
<td>2</td>
<td>Clearance</td>
</tr>
<tr>
<td></td>
<td>1x V_{vddu}, 1x V_{vddd}</td>
<td>2</td>
<td>Minimise voltage drop</td>
</tr>
<tr>
<td></td>
<td>1 plane</td>
<td></td>
<td>Dedicated layer</td>
</tr>
<tr>
<td>Slow Control</td>
<td>Data, ck, (opt. +rst, error)</td>
<td>2 to 4</td>
<td>I2C link</td>
</tr>
<tr>
<td>Input clocks</td>
<td>320 MHz, Fast command elink, (opt. 40 MHz(L1))</td>
<td>6 or 8</td>
<td>LVDS</td>
</tr>
<tr>
<td>Data Out lines</td>
<td>Readout data (TOT, TOA, Lumi)</td>
<td>4 pairs</td>
<td>4 elinks Differential SLVS.</td>
</tr>
<tr>
<td>ASIC reset</td>
<td>ASIC_rst</td>
<td>1</td>
<td>Digital</td>
</tr>
</tbody>
</table>
HGTD sensors performance after irradiation

- Performance of HPK LGAD irradiated up to $6 \times 10^{15}$ n/cm$^2$; measurements at -20°C
- Degradation of the time resolution at high fluences for lowest gains

- Performance of CNM LGAD irradiated up to $2 \times 10^{15}$ n/cm$^2$; measurements at -6 to -20°C
- Similar performance at $3 \times 10^{14}$ n/cm$^2$ at lower temperature
- Degradation of the time resolution to 57 ps at $2 \times 10^{15}$ n/cm$^2$ - to 75 ps at $2 \times 10^{15}$ n/cm$^2$