A High-Granularity Timing Detector (HGTD)
for the Phase-II upgrade of ATLAS
Detector concept, description and R&D and first beam test results

EPS HEP, Ghent
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Alexander Leopold, on behalf of HGTD
High-Granularity Timing Detector

- ATLAS upgrade detector for the high luminosity - LHC
- uses LGAD sensors to measure time with $\sigma_t \sim 30-50\text{ps per track}$ until end of HL-LHC
- covers range $2.4 \leq |\eta| \leq 4.0$
- two disks positioned at $z = \pm 3.5\text{m}$ from the interaction point
Motivation

- at HL-LHC (average pile-up (PU) of 200 p-p collisions per bunch crossing) expecting average vertex density of ~1.4 vertices/mm
- in very forward region track-vertex association with the inner tracker (ITk) alone becomes ambiguous
- HGTD takes advantage of spread in time of collisions (~180ps)

Basic idea:
★ Tag particle tracks with a time
★ Assign a time to the HS interaction
★ Remove tracks that are out of time relative to this reference to reduce pile-up
★ application in PU-jet rejection, b-tagging, lepton isolation, …
Detector Layout - overview

- active area:
  \[120 \text{ mm } (|\eta|=4) < r < 640 \text{ mm } (|\eta|=2.4)\]
- overall thickness of 12.5 cm
- 3.59 M channels
- active area 6.4 m²
- occupancy <10%
- max. expected radiation levels of \(5.1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2\) (including safety factors and replacement of inner ring at 2000 fb-1)
- \(N_{\text{hits}}\) transmitted in reduced eta range \((2.4 < |\eta| < 3.1)\) at 40MHz for online luminosity measurement
Detector Layout - active area

- detector consists of two double sided layers in each end cap
- overlap of sensors on the front- and backside of the respective layers of 80% (20%) for \(|\eta|>3.1\) (\(|\eta|<3.1\))
- time resolution of \(\sigma_t \approx 40-85\) ps per hit until end of HL-LHC
- track time resolution target requires 2 hits per track on average
- better coverage and more homogeneous response achieved by rotating layers by 15° in opposite direction

\[ \begin{array}{c|c|c}
 R < 320 \text{ mm} & R > 320 \text{ mm} \\
 \text{\((|\eta| > 3.1)\)} & \text{\((|\eta| < 3.1)\)} \\
 \hline
 N_{\text{hits}} \geq 2 & 88\% & 72\% \\
 N_{\text{hits}} = 0 & 1.6\% & 2.8\% \\
 \langle N_{\text{hits}} \rangle & 2.8 & 1.9 \\
 \end{array} \]

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Modules

• 1 **LGAD** sensor
• 2 **ALTIROC** readout chips bump bonded to sensor
• 1 **FLEX** cable glued to bare module, wire-bonded to ASIC (signals, low and high voltage)

Overview of contributions to the time resolution:

\[
\sigma^2_{hit} = \sigma^2_{Landau} + \sigma^2_{jitter} + \sigma^2_{time-walk} + \sigma^2_{TDC} + \sigma^2_{clock}
\]

- ~25 ps (thin sensor)
- <25 ps at large gain after correction
- <10 ps from clock distribution, <10 ps
- Bin width, 20 ps / \sqrt{12}

- 7984 modules
- Total thickness of ~1mm
- Glued to support plates (staves and rings)
- Plates screwed to cooling plate
Sensor (LGAD)

- Low Gain Avalanche Detector
- n-on-p silicon detector with extra highly doped p-layer
  – internal amplification

- sensor size of **2x4 cm²**
- per sensor **450** pixels with a pitch size of **1.3x1.3 mm²**
- Thickness of <300 µm, active thickness of 50 µm
- allows for a **gain of 20** before irradiation

- target time resolution \( \sigma_t < 40\text{ps} \) at start of operations, and **70-85** ps at end of lifetime
- sustain radiation levels of up to **5.1 x 10^{15} n_{eq}/cm²**
- maximum leakage current of 5 µA
Front-end ASIC (ALTIROC)

- 225 readout channels per ASIC, 2 ASICs per module
- bump bonded to LGAD sensor
- sends digitised output to peripheral electronics

- measures **time of arrival** (TOA), **time over threshold** (TOT) and **number of hits**

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**Discriminator Threshold (DAC Units)**

- **Before TimeWalk Correction**
- **After TimeWalk Correction**

**Preliminary HGTD Testbeam October 2018**

- **Jitter [ps]** = 3.5 pF - Threshold 1 fC

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**Schematic of the single-channel readout electronics**

- **Bias Blocks**
- **Control unit**
- **Hit Data Formatting**
- **Luminosity**

- **Fast command (link from lpGBT)**
- **320MHz clock from lpGBT**
- **32Gb/s, 64Gb/s or 128Gb/s link to lpGBT**
- **64Gb/s link to lpGBT**

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- **64Gb/s link to lpGBT**

**Common digital part:** transmit digitized data, receive slow control, generate and align clocks

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**Alexander Leopold**

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**measures time of arrival (TOA), time over threshold (TOT) and number of hits**
Sensor performance

2D maps showing efficiency and time resolution before and after irradiation

in pad center:

\(<\text{eff}>_{\text{unirr}} \sim 99\%\)

\(<\text{eff}>_{\text{irr}} > 95\%\)

very homogeneous time resolution over the sensor pad
Time resolution

σₜ depending on the bias voltage for different fluence levels (4 different sensors)

can achieve σₜ < 35 ps up to $1.5 \times 10^{15}$ n$_{eq}$/cm$^2$

Landau fluctuations determine maximum reachable time resolution
Collected charge and leakage current

- minimum required collected charge of **2.5 fC**
- maximum tolerated leakage current **5 µA**
Physics performance - selection

### Pile-up jet suppression

<table>
<thead>
<tr>
<th>Rejection of pile-up jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITk-only</td>
</tr>
</tbody>
</table>

ATLAS Simulation Preliminary

\( \sqrt{s} = 14 \text{ TeV}, <p_T> = 200 \text{ GeV} \)

HGTD Pythia8 di-jets

\( 30 < p_T < 50 \text{ GeV} \)

\( 2.5 < |\eta| < 3.8 \)

### Light-jet mis-tagging efficiency

<table>
<thead>
<tr>
<th>Ratio to ITk</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

ATLAS Simulation Preliminary

\( \sqrt{s} = 14 \text{ TeV}, <p_T> = 200 \text{ GeV} \)

MV1 70% fixed cut WP

### B-tagging

\( \eta = 14 \text{ TeV}, <p_T> = 200 \text{ GeV} \)

\( Z \rightarrow \mu^+\mu^- \)

\( 2.4 < |\eta| < 4.0 \)

HGTG

\( |\Delta R(\mu, T)| > 0.5 \)

ATLAS Full Simulation Preliminary

\( \sqrt{s} = 14 \text{ TeV}, <p_T> = 200 \text{ GeV} \)

\( Z \rightarrow e^+e^- \)

\( |\Delta R(e, T)| > 0.5 \)

### Lepton isolation

\( \eta = 14 \text{ TeV}, <p_T> = 200 \text{ GeV} \)

\( Z \rightarrow e^+e^- \)

\( |\Delta R(e, T)| > 0.5 \)

ATLAS Full Simulation Preliminary

\( \sqrt{s} = 14 \text{ TeV}, <p_T> = 200 \text{ GeV} \)

\( Z \rightarrow e^+e^- \)

\( |\Delta R(e, T)| > 0.5 \)

ATLAS Full Simulation Preliminary

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\( Z \rightarrow e^+e^- \)

\( |\Delta R(e, T)| > 0.5 \)
Summary

• conditions at HL-LHC make track-vertex association a very challenging task, especially in the forward region

• HGTD adds time measurements to tracks in order to mitigate pile-up in the forward region

• extensive R&D of sensors and electronics to achieve the targeted performance goals, testing in lab and under beam conditions

• HGTD Technical Proposal approved by LHCC and the Technical Design Report is planned for April 2020

• currently re-optimising the layout with 3 rings to mitigate the max. radiation levels to $3 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ (2 to 3 replacements of the most inner rings during HL-LHC)
Pile-up density

ATLAS Preliminary
HGTD-Si Simulation
Electrons $p_T = 45$ GeV

- Run $\langle q_1 \rangle = 30, \sigma_z = 45$ mm
- Nominal $\langle q_1 \rangle = 200, \sigma_z = 45$ mm

Arbitrary units vs. pileup density [vertex/mm]
2x2 LGAD array

taken from arxiv 1804.00622
## Sensors for testing

<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-3.1-50</td>
<td>50</td>
<td>Boron</td>
<td>No</td>
<td>1.6</td>
<td>40</td>
</tr>
<tr>
<td>HPK</td>
<td>HPK-3.2-50</td>
<td>50</td>
<td>Boron</td>
<td>No</td>
<td>2.2</td>
<td>55</td>
</tr>
<tr>
<td>HPK</td>
<td>HPK-PROTO-30</td>
<td>30</td>
<td>Boron</td>
<td>No</td>
<td>1.6</td>
<td>50</td>
</tr>
<tr>
<td>FBK</td>
<td>FBK-UFSD3-C-60</td>
<td>60</td>
<td>Boron</td>
<td>Yes</td>
<td>0.6</td>
<td>20</td>
</tr>
<tr>
<td>CNM</td>
<td>CNM-AIDA-50</td>
<td>50</td>
<td>Boron</td>
<td>No</td>
<td>1.0</td>
<td>45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Name</th>
<th>Full depletion [V]</th>
<th>$V_{BD}$ $-30^\circ$C [V]</th>
<th>Nominal IP [µm]</th>
<th>Nominal edge[µm]</th>
<th>Max. Array Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPK</td>
<td>HPK-3.1-50</td>
<td>50</td>
<td>200</td>
<td>30→95</td>
<td>200→500</td>
<td>$15 \times 15$</td>
</tr>
<tr>
<td>HPK</td>
<td>HPK-3.2-50</td>
<td>65</td>
<td>70</td>
<td>30→95</td>
<td>200→500</td>
<td>$15 \times 15$</td>
</tr>
<tr>
<td>HPK</td>
<td>HPK-PROTO-30</td>
<td>75</td>
<td>110</td>
<td>-</td>
<td>-</td>
<td>Single</td>
</tr>
<tr>
<td>FBK</td>
<td>FBK-UFSD3-C-60</td>
<td>25</td>
<td>170</td>
<td>37</td>
<td>200→500</td>
<td>$5 \times 5$</td>
</tr>
<tr>
<td>CNM</td>
<td>CNM-AIDA-50</td>
<td>50</td>
<td>220</td>
<td>37→57</td>
<td>200→500</td>
<td>$5 \times 5$</td>
</tr>
</tbody>
</table>
Efficiency

**HGTD Test Beam Preliminary**

- **Efficiency**
  - 0.1% noise occupancy
  - 0.01% noise occupancy

Charge [fC]

- 8x10^-11
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- 15
- 16
- 17
- 18
- 19
- 20
Collected charge

![Graphs showing collected charge vs bias voltage for different samples.](image-url)
Collected charge

**HGTD Preliminary**

Collected charge for $3 \times 10^{15} \text{N}_e/\text{cm}^2$
- HPK-3.1-50
- HPK-3.2-50
- FBK-UFS3-C-60
- WF2 simulation deep B+C (N. Cartiglia)

Collected charge for $6 \times 10^{15} \text{N}_e/\text{cm}^2$
- HPK-3.1-50
- HPK-3.2-50
- WF2 simulation deep B+C (N. Cartiglia)
Array measurements

**HGTD Preliminary**

HPK Type 3.1
5x5 array W8 P11

Voltage [V]

Current [A] $\times 10^{-9}$

0.2 0.4 0.6 0.8 1.0 1.2 1.4

0 50 100 150 200 250

Voltage [V] $V_{BD}$

Array Row

Array Column

HGTD Preliminary
HPK-3.1-50
15x15 Array

Preliminary HGTD
HPK-3.1-50
15x15 Array

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Test beam setup

taken from arxiv 1804.00622