High-Granularity Timing Detector for the Phase-II upgrade of the ATLAS Calorimeter system

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ON BEHALF OF THE ATLAS LAr – HGT D GROUP

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• Overview

• HL-HLC Conditions
  • $\mu = 200$ pileup conditions
  • Calorimeter performances
  • Pileup efficiency

• HGTD Motivation
  • Time-Pileup rejection
  • Important EW channels

• The Detector
  • Geometry
  • Jet, electron and muons performances

• Sensors
  • Technologies, LGADs
  • Design and testing
  • Test Beam Results
  • Radiation Hardness

• Electronics
• Conclusions and Outlook
• HL-HLC Conditions

HL-LHC Conditions

**Luminosity**
- Phase I: $< 2.2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (300 fb$^{-1}$)
- Phase-II: $5 - 7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (3000 fb$^{-1}$)

**Conditions**
- 14 TeV beam
- 6000 primary tracks per event
- No. of collisions per crossing from 23 to 200 at 150 ps in 50 mm space
- Extended tracking up to $|\eta| < 4.0$
• HL-HLC Conditions

Calorimeter and Pileup efficiency

- EM calorimeter noise increases by an order of magnitude
- Pileup rejection is impacted at high $\eta$
- Energy resolution in the EM calorimeter heavily degrades for the low $P_T$ ( > 20GeV) regions towards the end caps
- Up to 20% reduction on the energy resolution for the interesting 20 – 50 GeV $P_T$ region
• **HGTD Motivation**

**Time – Pileup Rejection**

- High probability of vertices in close proximity
- Time information helps pileup rejection
- Pileup distribution extremely peaked at forward $1.8 < |\eta| < 3.2$ were tracker not completely implemented
- Track confirmation rejection at 2% for central region but degrades towards end caps

![Graph showing pileup rejection](image)

![Graph showing efficiency and particle time distributions](image)
### HGTD Motivation

**Important EW channels**

- Potential of HGTD as a L (40MHz) Time trigger for the VBF 0-channel
- Lower jet $P_T$ thresholds and extend accessible phase space
- Largest potential in hadronic final state VBF channels (also offline), preferentially forward peaked:
  
  \[ H \rightarrow bb, \ H \rightarrow Inv., \ HH \rightarrow bbbb \]

*Pre-shower option:*

- Improve forward electron /photon reconstruction
- Interesting for search in
  \[ H \rightarrow aa \rightarrow \gamma\gamma jj \]

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<table>
<thead>
<tr>
<th>Trigger</th>
<th>SD value</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>di-$\gamma$</td>
<td>25-25 GeV</td>
<td>di-photon</td>
</tr>
<tr>
<td>di-$\tau$</td>
<td>40-30 GeV</td>
<td>$H \rightarrow \tau\tau$</td>
</tr>
<tr>
<td>4-jet</td>
<td>75 GeV</td>
<td>$H \rightarrow bb, HH \rightarrow 4b$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>200 GeV</td>
<td>$H \rightarrow \text{Inv.}$</td>
</tr>
</tbody>
</table>
HGT-D System

Geometry

- HGT-D-Si: 4 si layers
- HGT-D-SiW: 4 si layers + 3X_0 W 2.4 < \eta < 3.2 (R_{min} = 285 mm)

Specifications for 2023

<table>
<thead>
<tr>
<th>Coverage</th>
<th>2.4 &lt; \eta &lt; 4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_{min}</td>
<td>11 cm</td>
</tr>
<tr>
<td>R_{max}</td>
<td>65 cm</td>
</tr>
<tr>
<td>\Delta z</td>
<td>\sim 6 cm</td>
</tr>
<tr>
<td>\Delta t</td>
<td>&lt; 50 ps</td>
</tr>
<tr>
<td>Cell Size</td>
<td>1 mm^2</td>
</tr>
</tbody>
</table>

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• **HGTID System**

### Performance

#### Muons
- 1 TeV muons simulation
- 98.88% efficiency for 4 layers
- 0.044 MeV/muon at 150 μm
- 50% of inefficiency from zones

#### Electrons
- $Z \rightarrow ee$ sample at $\mu = 200$
- 45 GeV $P_T$ e and $\gamma$
- 6 mm radius EM clusters
- 70 HGTID cells per cluster
- Dynamic range of 50 psec/MIP

#### Jets
- H(125 GeV) → Inv. sample with jet $P_T = 72$ GeV
- Expected peak in time distribution
- ~90% signal purity at $\Delta R < 0.1$
• Sensors

Technology and requirements

Low Gain Avalanche Diodes (LGAD)
✓ Most promising technology
✓ Secondary implant introducing moderate gain
✓ HPK, CNM, FBK produced sensors

Jitter
Timewalk
Conversion time

\[
\sigma_{\text{tot}}^2 = \sigma_{\text{elec.}}^2 + \sigma_{\text{Landau}}^2
\]

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

Where:
- \( S \) signal
- \( N \) noise
- \( V_{\text{thr}} \) CFD threshold
- \( t_{\text{rise}} \) rise time

Fast time resolution:
✓ Maximize slope (large fast signals)
✓ Correct time walk with CFD
✓ Minimize noise
✓ Thin sensors with integral gain
• Sensors

Design and test

- CNM SoI wafers on 300µm handle wafer
- High resistivity sensor region
- Varied amplification implants
- Single diodes and 2x2 arrays

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<th>Dose</th>
<th>Thickness</th>
<th>C_p (pF)</th>
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<tr>
<td>Single pad</td>
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<td>1.9 • 10^{13}</td>
<td>45 µm</td>
<td>3.5 pF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0 • 10^{13}</td>
<td>45 µm</td>
<td>3.5 pF</td>
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<tr>
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<td>45 µm</td>
<td>11 pF</td>
</tr>
<tr>
<td>3 x 3</td>
<td></td>
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<td>45 µm</td>
<td>23 pF</td>
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• Sensors

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Testbeam Results

Single Diodes

Time Resolution

ATLAS Preliminary
HGTGD test beam Aug. 2016
120 GeV pions
(1.2 x 1.2)mm² wide 45μm thick

Gain

Efficiency / mean

2x2 Arrays (3 x 3 mm)

ATLAS Preliminary
HGTGD test beam Oct 2016
120 GeV pions

Gain

Bias voltage [V]

Efficiency / mean

1% efficiency variation

Signal Slope

ATLAS Preliminary
HGTGD test beam Aug. 2016
120 GeV pions
(1.2 x 1.2)mm² wide 45μm thick

Bias voltage [V]

Rise time 20-80% [ps]

26 psec @ gain of 50

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• Sensors

Radiation Hardness

- Similar results Fluka - GCALOR
- Max. ($\eta = 4.2$) after 3000 fb$^{-1} \sim 4 \times 10^{15}$ n/cm$^2$
- $W$ increases the dose by a factor 3 for $R > 30$cm in HGTD, possible mitigation by 5mm moderator

- Thermal neutron irradiation single pad diodes
- Rise time within 10% between fluences
- Time resolution in the order of 40 ps for gain of 10 - 15
• Electronics

ASIC prototype

Chip Layout with wire bonds in the periphery

ASiC bump-bonded to 2x2 array in multiple points

**ATLAS LGAD Timing Integrated ReadOut Chip (ALTiRoC)**

- TSMC 130nm CMOS Technology
- 3.4 x 3.4 mm total area
- 300µm substrate thickness
- Directly bonds to 2 x 2 arrays
- Four readout channels dedicated for 2 pf/channel, 10 pf/channel and 20 pf/channel sensors
- Channel area 200 x 100 µm
- Integrated Preamplifiers, ToT and CFD
- Under fabrication, expected in April

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<th>3 mm pad</th>
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<tr>
<td>Power con.</td>
<td>800 µA</td>
<td>3.2 mA</td>
</tr>
<tr>
<td>$V_{in} (Q_{in}/C_d)$</td>
<td>2.5 mV</td>
<td>0.625 mV</td>
</tr>
<tr>
<td>Sim. $V_{out}$</td>
<td>21 mV</td>
<td>17.7 mV</td>
</tr>
<tr>
<td>Noise</td>
<td>0.44 mV</td>
<td>0.66 mV</td>
</tr>
<tr>
<td>S/N</td>
<td>48</td>
<td>27</td>
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**Inner Layers**
- Jitter (at G = 10) | 23 ps
- Jitter (at G = 20) | 11.5 ps

**Large Radius**
Conclusions and Outlook

Sensors, ASIC, Integration and Radiation Hardness

So far....

Physics

✓ Very promising results for pileup rejection in the high $\eta$ region where VBF and exotics will benefit
✓ High jet single purity for invisible searches, L0 trigger for VBF channel at 40MHz

Sensors

✓ 26 ps time resolution for single 1mm$^2$ diodes
✓ 95% uniformity with low inefficiencies in the inter-pad regions
✓ Operations up to $2\times10^{15}$ at moderate gains with degradation of time resolution due to breakdown

Integration

✓ Fixed and simulated geometry and vital space
✓ Flex and mechanics designs considered
✓ Tests with different detector sizes and electronics
✓ First ASIC prototype designed and submitted
• Conclusions and Outlook

Sensors, ASIC, Integration and Radiation Hardness

To do...

**Physics**
- Investigate performance improvements in individual analysis channels at the context of HL-LHC
- Integrate and produce fully simulated samples with final geometry

**Sensors**
- Scale from single pads and 2 x 2 arrays to 2cm x 2cm matrices
- Improve radiation hardness for neutron irradiated, do proton-pion irradiation
- Key players with design optimization (HPK, CNM, FBK) to improve inefficiencies

**Integration**
- Final geometry and segmentation decisions with respect to occupancy and readout
- ASIC Test in upcoming test beams, optimization and scaling to full size matrices
- Services and flex design and simulation, final decisions about integration
The work at SCIPP was supported by the USA Department of Energy, Grants DE-FG02-13ER41983 and DE-FG02-04ER41286.

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