A High-Granularity Timing Detector (HGTGD) for the ATLAS Phase-II upgrade:

detector concept, description and R&D and beam test results

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Pileup challenges at high luminosity

Average number of interactions per bunch crossing $\langle \mu \rangle$

- End of LHC Run 2: $\sim 36$
- HL-LHC: $\sim 200$

HL-LHC will bring increased particle densities ($\sim 1.8$ collisions/mm)

- Requires excellent longitudinal (z) resolution for reliable track-to-vertex association
- Silicon inner tracker (ITk) upgrade provides coverage up to $|\eta| = 4.0$
- z resolution degrades even more severely in forward region
“4-D tracking” in the forward region

**Time spread of vertices ~175 ps**
- Exploit time information in addition to space spread of tracks
- Extend pileup rejection capabilities in the forward region (2.4<|η|<4.0)
- Use track time to improve track-to-vertex association

**With a time resolution of 30 ps → ~6× more pileup rejection**
- Improve physics and object reconstruction performance
- Reduce jets from pileup vertices
- Reduce tracks from pileup vertices being associated with hard-scatter jets
A High-Granularity Timing Detector (HGTD)

- Inserted within unoccupied region in each endcap ($\Delta z=75$ mm)
- Two double-sided layers mounted on cooling disks in each endcap

- Instrumented with silicon Low Gain Avalanche Detectors (LGADs)
- Specially designed ASIC ATLIROC front-end
- Total active area = 6.4 m$^2$
- Time resolution/track 25-50 ps
**HGST design concepts**

**Coverage**

- Module overlap optimised for uniformity
- 15° rotation of each disk in opposite directions to avoid gaps

**ATLAS HGTD Preliminary**

- 1st disk
- Front modules
- Back modules

**ATLAS Simulation Preliminary**

- Muons, $p_T = 45$ GeV
- HGTD

Number of hits/track: 2 for $2.4 < |\eta| < 3.1$
3 for $3.1 < |\eta| < 4.0$
**Radiation effects**

In HL-LHC lifetime:

- Integrated luminosity \(\sim 4000 \text{ fb}^{-1}\)
- Total ionising dose (TID) \(\sim 3.6 \text{ MGy}\) (with safety factor of 2.25)
- Fluence \(\sim 3.7 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}\) (with 1.5 safety factor)

**HGTD design concepts**

- CO\(_2\) cooling for sensor operation at \(-30^\circ\text{C}\).
- LGAD thickness 50 \(\mu\text{m}\) - faster rise time lower impact from radiation.
- Replace innermost parts of detector to maintain good performance.

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**Graphical representation**

- ATLAS Simulation Preliminary
- FLUKA Simulation

- Rear layer
- Front layer

**To withstand high radiation levels at low radius replace inner ring at 2000 fb\(^{-1}\)**
**HGT D design concepts**

**Low occupancy**
- Small size to reduce multiple hit probability
- Minimise noise from electronics

\[
\sigma^2_t = \sigma^2_{\text{Landau Noise}} + \sigma^2_{\text{Time Walk}} + \sigma^2_{\text{Jitter}} + \sigma^2_{\text{TDC}}
\]

**Excellent time resolution**
- Time walk correction for time over threshold
- Digitisation granularity < 5 ps
- Thin LGAD sensors (50 µm) for faster rise time; moderate gain to increase S/N
- Small Landau fluctuations with \( \sigma_{\text{Landau Noise}} < 25 \) ps (pre-irradiation)

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**ATLAS Simulation Preliminary**
Min. bias, \( \langle \mu \rangle = 200 \)
HGT D, LGADs 1.3×1.3 mm²
Low Gain Avalanche Detectors (LGADs)

- Developed by Barcelona CNM and CERN RD50 Collaboration
- Manufacturers: CNM (Spain), HPK (Japan), FBK (Italy), BNL (USA), IHEP-NDL (China)

**LGAD:** n-p silicon detector with highly-doped p-layer

- High E-field $\rightarrow$ internal gain ($\sim$10 - 50)
- Low rise time ($\sim$400 ps)
- Fast charge collection ($\sim$1 ns)

**Past and ongoing sensor studies**

- Laboratory measurements (IV, CV)
- Laboratory $\beta$ tests (collected charge, gain, time resolution)
- Beam tests (timing, time resolution, collected charge, uniformity, hit efficiency)
Full scale LGAD arrays

Full size LGAD sensors for HGTD module:
- 15 × 30 pixels (each pixel 1.3 × 13 mm²)
- Studies of 15 × 15 arrays ongoing
- Demonstrate feasibility of large-size LGAD arrays

Uniformity measurements
- Measured using automatic probe station
- Excellent uniformity (leakage current, gain, breakdown voltage)
**LGAD time resolution**

Require $\sigma_t < 50$ ps at full lifetime.

- Sensor irradiation campaigns at CERN (PS-IRRAD) & Ljubljana (IJS).
- CERN pion test beam results using 2x2 CNM array.
- Slight radiation impact visible.

![Before irradiation vs After irradiation](image)

**Before irradiation**

- **HGT D Test beam Sep. 2017**
  - Unirradiated, 120 V, 20°C

**After irradiation (6×10^{14} n_{eq} cm^{-2})**

- **HGT D Test beam Sep. 2017**
  - 6×10^{14} n_{eq}/cm², 250 V, -21°C
LGAD efficiencies

Hit efficiency above 99% for collected charge > 2 fC.

- CERN pion test beam results using 2x2 CNM array.
- Inter-pad gap region slightly more efficient after irradiation.
ATLIROC ASIC

ATLAS LGAD Timing Integrated ReadOut Chip

• Bump-bonded to LGAD
• Single pad readout (225 channels/ASIC)
• Provide time over threshold (TOT) and time of arrival (TOA)
• 300 ps pre-amp rise time to minimise jitter
• Reads out number of hits for each ASIC at 40 MHz
  • *Per bunch luminosity measurement capabilities*

ALTIROC0: single pixel analogue readout for 2 × 2 sensors (done)

ALTIROC1: 5 × 5 channel readout bump-bonded to sensors (already tested in test beam)

ALTIROC2: full scale version with 15 × 15 channel readout (available Spring 2020)
ATLIROC ASIC

ALTIROC0 (bump-bonded to 2 x 2 array) test beam results

• Time of arrival as a function of preamplifier probe amplitude - polynomial fit used to correct for time walk effect.

• Time resolution of 35 ps achievable after time walk correction (sensor+jitter).

\[ \sigma^2_{\text{TimeWalk}} = \left( \frac{V_{\text{threshold}}}{S/t_{\text{rise}}} \right)_{RMS}^2 \]
Collected charge and jitter

Test bench measurements of jitter vs injected charge

- Optimisation of sensor+ASIC
- Large increase in jitter at < 4 fC
- Important to collect sufficient charge over full lifetime
  - Require collected charge > 4 fC at $2.5 \times 10^{15} \text{n_{eq} cm^{-2}}$

Sensor collected charge measured for fluences up to $6 \times 10^{15} \text{n_{eq} cm^{-2}}$

- Collected charge decreases at fluences above $10^{15} \text{n_{eq} cm^{-2}}$
- HPK 3.2 & FBK can achieve 4 fC at $3 \times 10^{15} \text{n_{eq} cm^{-2}}$
New three-ring layout

- R&D suggests we can’t maintain > 4 fC at $2.5 \times 10^{15}$ n$_{eq}$ cm$^{-2}$ with two-ring layout
- New three-ring proposal for Technical Design Report
- Number of hits/track $\geq 2$ for new layout

- Replace inner ring after each 1000 fb$^{-1}$
- Replace middle ring after 2000 fb$^{-1}$
- Ensures operation with > 4 fC at $2.5 \times 10^{15}$ n$_{eq}$ cm$^{-2}$ over full lifetime
HGTD module: Sensor+ASIC

- Module size $2 \times 4 \text{ cm}^2$
- Sensor ($15 \times 30$ pixels) bump-bonded to 2 ALTIROC readout chips (225 channels / ALTIROC)
Conclusions and outlook

• The HL-LHC will provide challenging conditions in which to perform track-to-vertex association.

• The HGTD project will make use of time information to mitigate the effects of increased pileup in the forward region.
  • Intense R&D program
  • Lab and beam tests performed with single pads and arrays
  • Time resolution of < 50 ps achievable up to $2.5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ with 50 μm LGADs
  • Expect full-size $15 \times 30$ arrays to become available mid 2020

• Technical Proposal approved by LHCC
• Technical Design Report target April 2020
Back up