The ATLAS High Granularity Timing Detector

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HGT D Motivation

- LHC will be upgraded in 2024-2026 to High Luminosity LHC (HL-LHC)
  - Instantaneous luminosities up to \( L \approx 7.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \) about 5 times the current
  - Pile up \( \langle \mu \rangle \approx 200 \) simultaneous interactions per bunch crossing
  - On average 1.5 vertex/mm along beam line at collision point

- In the forward region the tracker (new ATLAS tracker ITK) has less longitudinal resolution → degraded vertex resolution
A new layer of silicon detectors with precise timing, High Granularity Timing Detector (HGTD), in front of the liquid argon end-cap calorimeters improves performance by combining:

- HGTD precise timing
- ITK position information
HGT TD Requirements

- Two endcap disks at $z = \pm 3.5\ m$
- $6.3\text{m}^2$ active area: $120\text{mm} < R < 640\text{mm} \Rightarrow 2.4 < |\eta| < 4.0$
- Time resolution better than 30 ps per track (50 ps per hit in a 2 layer geometry)
- Sensors on both sides of two cooling plates with varying overlap $\Rightarrow$
  - $\langle n_{\text{hits}} \rangle = 3$ for $R < 320\text{mm}$ (80% overlap)
  - $\langle n_{\text{hits}} \rangle = 2$ for $R > 320\text{mm}$ (20% overlap)
- Requirement of occupancy $< 10% \Rightarrow 1.3\ \text{mm} \times 1.3\ \text{mm}$ pixels
- 15x30 pixel sensors
- Sensors bump bonded to readout ASIC (ALTIROC) (15x15 chip)
- Wire bonded to flex cable
- Intotal 3.59 M channels

Constrained by available space and harsh environment
Radiation levels

• Total fluence ($n_{eq}$) and dose to be sustained (new updated numbers compared to fig):
  - $R < 32 \text{ cm} \rightarrow 5.1 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ and 4.7 MGy
  - $R > 32 \text{ cm} \rightarrow 3.9 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ and 1.9 MGy

• A safety factor 1.5 for $n_{eq}$ (sensor) and 2.25 for dose (ASIC) and replacement of inner wheel $< 32 \text{ cm}$ (~32% of sensors and ASICs) at mid run of HL-LHC are taken into account

• Sensors will be operated at -30 °C using shared CO$_2$ cooling system with ITK
Low Gain Avalanche Detectors (LGADs)

- n-on-p planar silicon layer with additional p-layer for moderate gain (10-50) (increases signal, limits noise)
- Time resolution < 30 ps before irradiation
- Thin (base line 50 μm) => small \( t_{\text{rise}} \)

R&D program to provide sensors with required time resolution, radiation hardness and fine segmentation

- New doping materials, substrates and geometries
- Prototypes tested from CNM, HPK, BNL, FBK
- >1000 single pad sensors tested
- Several 5x5 and 15x15 sensors tested. Very uniform leakage current and breakdown voltage
Contributions to timing resolution

\[ \sigma_{\text{timing}}^2 = \sigma_{\text{Landau}}^2 + \sigma_{\text{jitter}}^2 + \sigma_{\text{time walk}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{clock}}^2 \]

- Landau term: < 25 ps, reduced for thin sensors (35-50 \( \mu \)m)
- Jitter term
  \[ \sigma_{\text{jitter}} \approx \frac{t_{\text{rise}}}{S/N} \]
  < 25 ps
- Time walk, minimised by correcting for time over threshold (or for beam tests using constant fraction discriminator (CFD))
- Digitisation granularity ~ 5ps
- Clock distribution < 10 ps
Sensors have been irradiated at IJS (Lubiana) and protons at PS-IRRAD (CERN):

- From $1 \times 10^{14}$ to $1 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$ ($5.1 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ need for HGTGD)
- Reduction of gain partially compensated by increasing bias voltage (higher breakdown voltage)

Hit efficiency and timing resolution has been studied with pion beams at CERN SPS North Area

~ 50 sensors tested so far

- Un-irradiated sensors CNM, HPK, BNL
- Irradiated sensors (neutron & proton) CNM and HPK
- $2 \times 2$ array sensors
- $2 \times 2$ array sensors with ALTIROC0_v2
- Arrays with different inter-pad gaps

Beam tests have also been performed at Fermilab and SLAC and in future also DESY
Results from test beam measurements

Hit efficiency

Before irradiation

After $6 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$

Efficiency still $\sim 100\%$ in center

Broken channel in read-out board
Results from test beam measurements

Timing resolution

A SiPM is used as time reference. Its 40 ps contribution is subtracted.

Before irradiation

Timing resolution slightly worse after radiation

After $6 \times 10^{14}$ n$_{eq}$/cm$^2$

[Graphs showing timing resolution before and after irradiation]
Results from test beam measurements

Signal efficiency in the interpad region
as function of X (mm) for 3 different voltage thresholds

Before irradiation

After $6 \times 10^{14}$ $n_{eq}/cm^2$

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**HGTD Test beam Sep. 2017**

Unirradiated, 120 V, 20°C

**HGTD Test beam Sep. 2017**

$6 \times 10^{14}$ $n_{eq}/cm^2$, 250 V, -21°C
ATLAS LGAD Timing Integrated ReadOut Chip (ALTIROC)

- Broad band voltage pre-amplifier
  - Input transistor size chosen to minimize noise and power consumption
  - Provide TOA (9 bits, 20 ps bins) and ToT (7 bits, 40 ps bins)
  - Rise time ~0.5-1 ns (as sensor) to minimise jitter
  - Designed for 5 \( \mu \)A sensor leakage current

Bunch by bunch luminosity measurement capability
- Sums hits in two time windows to evaluate luminosity and background per ASIC
- Only ASICS at R> 320 mm will use luminosity readout
Developed in phases:

- **ALTIROC0**: single pixel analog readout (pre-amp + discrim)
  - Test bench measurements satisfactory
  - Beam tests → see next slide
- **ALTIROC1**: full single pixel (analog + TDC) readout in 5×5 array
  - Test bench measurements on-going
    (preliminary results show similar behaviour as ALTIROC0)
  - Irradiation and beam tests in Q1 2019
- **ALTIROC2**: final 15×15 version.
  - Submission expected end 2019
ALTIROC0_v2 Test beam results

- ALTIROC0_v2 bump bonded to an un-irradiated CNM 2×2 LGAD array
  - TOA of signal corrected for time walk (using probe amplitude)
  
  - Best achieved time resolution after correction: 35 ps

Graphs showing the TOA vs. probe amplitude and the distribution of values before and after time walk correction.
• The HGTD will mitigate pile-up effects and improve performance in the ATLAS forward region

• Technical proposal was approved 2018

• After a fluence of $6 \times 10^{14} \text{n}_{eq}/\text{cm}^2$
  • Efficiency in bulk is still $\sim 100$
  • Time resolution of 40-50 ps is achieved
  Link to HGTD beam test paper

• Intense R&D program during 2019-2020

• New sensors are under tests, including 5x5 and 15x5 arrays

• Technical Design Report (TDR) under preparation (5 April)
Backup: Pile-up rejection

- Pileup-jet rejection as a function of hard-scatter jet efficiency in forward region
- No HGT D (black) and HGT D with different $\sigma(t)$

With initial and final timing resolution ($\sigma(t) = 30$ ps), rejection improved by factor of 1.6-4
Fixed pileup-jet eff of 2%, HS eff vs $\eta$
Time resolution worsens with radiation (higher dose at lower radius)
Compensated by more hits/track at lower radius. (≥ 3 hits at R<320 mm, ≥2 hits at > R)
Examples:

- **forward pile-up suppression**
- **forward b-tagging**
- **forward lepton isolation**
- **Timing measurements**

**VBF final states**

\[
VBF \ H \to \ tau \ tau
\]

- **Searches and measurements with forward b-quarks**
  \[t(H \to bb)\]

- **Searches and measurements with forward leptons**
  \[\sin^2 \theta_W\]

- **Long-lived slow particles**
Light-jet rejection versus $b$-jet efficiency within the HGTD acceptance →

At 70% WP, light-jet rejection improved by a factor of $\sim 1.6$

*Particularly useful for physics with reducible bg from mis-tagged light jets!*
Backup: Physics use-cases

- Light-jet rejection versus $b$-jet efficiency within the HGTD acceptance →
- At 70% WP, light-jet rejection improved by a factor of $\sim 1.6$
- At high $\eta$ rej. improved by factor $\sim 3$

*Particularly useful for physics with reducible bg from mis-tagged light jets!*
Backup: Physics use-cases

- Efficiency for **electron isolation** selection as a function of pileup vertex density
- No HGT (black) and HGT with different $\sigma(t)$ scenarios
- HGT removes the majority of the effects of pileup, recovers 15% for average HL-LHC vertex density
- $\sigma(t) < 30$ ps does not help much
Physics: Impact on $tH$ (final state with $\geq 2$ $b$-tagged jets)

- Probes sign of top-Yukawa coupling directly (left, if negative $\Rightarrow \sigma(tH) \times 10$), complementary to $ttH$

- Sensitivity to $tH$ increased by 11% using HGTD

- Primarily due to improved $b$-tagging

$|\eta|$ for most forward light-jet shown in the $3b$ region for $tH$ followed by $H \rightarrow bb$ and the backgrounds from $tt$ and $ttH$ production