A High-Granularity Timing Detector (HGTD) for the Phase-II upgrade of the ATLAS detector

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ABSTRACT: The expected increase of the particle flux at the high-luminosity phase of the LHC (HL-LHC) with instantaneous luminosities up to \( L = 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) will have a severe impact on the ATLAS detector performance. The pile-up is expected to increase on average to 200 interactions per bunch crossing. The reconstruction and trigger performance for electrons, photons as well as jets and transverse missing energy will be severely degraded in the end-cap and forward region, where the liquid Argon based electromagnetic calorimeter has coarser granularity and the inner tracker has poorer momentum resolution compared to the central region. A High Granularity Timing Detector (HGTD) is proposed in front of the liquid Argon end-cap calorimeters for pile-up mitigation and for bunch per bunch luminosity measurements.

This device should cover the pseudo-rapidity range of 2.4 to about 4.0. Two Silicon sensors double-sided layers are foreseen to provide a precision timing information for minimum ionizing particle with a time resolution better than 50 pico-seconds per hit (i.e. 30 pico-seconds per track) in order to assign the particle to the correct vertex. Each readout cell has a transverse size of 1.3 mm \( \times \) 1.3 mm leading to a highly granular detector with about 3 millions of readout electronics channels. Low-Gain Avalanche Detector (LGAD) technology has been chosen as it provides an internal gain good enough to reach large signal over noise ratio needed for excellent time resolution.

Extensive LGAD research and development (R&D) campaigns are carried out to investigate the suitability of this new technology as timing sensors for HGTD. The related readout ASIC is also being studied extensively.

KEYWORDS: Timing detectors; Charge transport and multiplication in solid media; Particle tracking detectors
1 HL-LHC and ATLAS upgrade

The high-luminosity phase of the Large Hadron Collider (HL-LHC) at CERN is scheduled to start in 2026 and will deliver an integrated luminosity of up to 4000 fb\(^{-1}\) over the decade that follows. The instantaneous luminosity will reach up to \(7.5 \times 10^{34}\) cm\(^{-2}\)s\(^{-1}\), corresponding to an increase by an approximate factor of 5 compared to the typical luminosities of Run 2. An extended period without physics operation, Long Shutdown 3 from 2024 until mid 2026, is anticipated prior to the HL-LHC phase. The ATLAS [1] detector will undergo several upgrades to face the challenges of the high-luminosity phase.

In the new condition of HL-LHC pile-up will be one of the main challenges. In the nominal operation scheme, the interaction region will have a Gaussian spread of 45 mm along the beam axis\(^1\) and a pile-up of 200 simultaneous \(pp\) interactions on average \(\langle \mu \rangle = 200\), corresponding to an average interaction density of 1.8 collisions/mm as seen in figure 1 (left).

A major challenge for the tracking detectors is to efficiently reconstruct the charged particles created in the primary interactions and correctly assign them to the production vertices. This requires the resolution of the longitudinal track impact parameter \(z_0\), provided by the Inner Tracker (ITk), to be much smaller than the inverse of the average pile-up density (0.6 mm). The \(z_0\) resolution is well below this limit in the central region, but becomes very large in the forward region, reaching up to

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\(^1\)The ATLAS experiment uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the \(z\)-axis along the beam pipe. The \(x\)-axis points from the IP to the centre of the LHC ring, and the \(y\)-axis points upward. Cylindrical coordinates \((r, \phi)\) are used in the transverse plane, \(\phi\) being the azimuthal angle around the \(z\)-axis. The pseudorapidity is defined in terms of the polar angle \(\theta\) as \(\eta = -\ln \tan(\theta/2)\).
Figure 1. Current and HL-LHC local pile-up vertex density (left). The resolution of the longitudinal track impact parameter, $z_0$, as a function of $\eta$ for different $p_T$ values [2] (right).

5 mm for particles with low transverse momentum ($p_T$) as seen in figure 1 (right). As a result, tracks cannot be associated to the correct vertices in an unambiguous way, leading to reduced performance in terms of heavy-flavour tagging, lepton isolation and the identification of jets originating from pile-up interactions.

2 High Granularity Timing Detector (HGTD)

A powerful new way to address the challenging pile-up conditions of HL-LHC is to exploit the time spread of the collisions in each bunch crossing to distinguish between tracks originating in collisions occurring very close in space but well separated in time. This requires the ability to measure the time of individual tracks with a precision much smaller than the spread of the collision times. In the nominal operating scheme of the HL-LHC, this distribution has a Gaussian spread of 175 ps. This timing information is complementary to the spatial information and kinematic measurements provided by the tracker and calorimeters, and thus helps resolve ambiguities. A visual representation of vertex position vs. time can be see in figure 2.

In this context, the High-Granularity Timing Detector (HGTD) is proposed [2, 3]. With an expected time resolution per hit for minimum-ionising particles (MIPs) of approximately 30 ps, corresponding to the performance of the currently available technology, this device will be able to assign each incident charged particle to an interaction vertex with significantly improved accuracy, effectively reducing the amount of pile-up by a factor of $\frac{175}{30} \approx 6$. The HGTD detector layout will give an average of three (two) hits per track at $R < 320$ mm ($R > 320$ mm). The HGTD will improve the performance for the reconstruction of forward jets, leptons, and the tagging of heavy-flavour jets up to the level expected in the central region. In addition, the HGTD offers unique capabilities for the online and offline luminosity determination, and can provide a minimum-bias trigger.

The space available to install new detectors in front of the ATLAS end-cap calorimeters is limited and this constrains the location and acceptance of the HGTD. The detector will be located at $z = \pm 3.5$ m, in the volume currently occupied by the Minimum-Bias Trigger Scintillators (MBTS), just outside the ITk volume and in front of the end-cap and forward calorimeters. The radial extent of the active area is 120 mm to 640 mm, yielding an acceptance in pseudorapidity from 2.4 to 4.0.
Figure 2. Visualisation in the z-t plane of an event with a hard scatter (red ellipse) with about 200 pile-up interactions (blue ellipses) superimposed. The dashed vertical lines represent the positions of reconstructed vertices [2].

| Pseudorapidity coverage | $2.4 < |\eta| < 4.0$ |
|-------------------------|---------------------|
| Thickness in z          | 75 mm (+50 mm moderator) |
| Position of active layers in z | 3435 mm < z < 3485 mm |
| Radial extension:       |                     |
| Total                   | 110 mm < R < 1000 mm |
| Active area             | 120 mm < R < 640 mm |
| Time resolution per track | 50 ps               |
| Number of hits per track: |                   |
| $2.4 < |\eta| < 3.1$ | 2                   |
| $3.1 < |\eta| < 4.0$ | 3                   |
| Pixel size              | $1.3 \times 1.3$ $\text{mm}^2$ |
| Pixel thickness         | 50 $\mu$m           |
| Number of channels      | 3.59 M              |
| Active area             | 6.4 $\text{m}^2$   |

Table 1. Main parameters of the HGTD [2].

In addition, to protect the ITk and the HGTD from back-scattered neutrons, 50 mm of moderator material will be installed in front of the end-cap calorimeters, as in the current ATLAS detector. The position of the two vessels for the HGTD is shown in figure 3. The main parameters of the HGTD are found in table 1.

The HGTD detector has to withstand a 1 MeV neutron equivalent particle fluence of $5.1 \times 10^{15}$ $n_{\text{eq}}$/cm$^2$, assuming one replacement of the inner part ($3.1 < |\eta| < 4.0$) after half of the total integrated luminosity of 4000 fb$^{-1}$. 

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3 Sensors

For the construction of HGTD a silicon-based timing detector technology is preferred due to the space limitations. The sensors must be also thin and configurable in arrays. LGADs are planar silicon detectors with internal gain generated by a thin highly doped multiplication layer. They have been pioneered by the Centro Nacional de Microelectronica (CNM) Barcelona [4] and developed during the last 5 years within the CERN-RD50 community [5]. Additional background and details are given in Reference [6].

The main characteristic of LGADs is the gain\(^2\) (which can be extracted from the collected charge) and the time resolution. Two major effects from the electronics which determine the time resolution are the time walk and the time jitter. Both depend inversely on the signal slope (voltage slope at the output of the amplifier) \(dV/dt\):

\[
\sigma_{\text{TimeWalk}} = \frac{V_{\text{th}}}{S_{\text{rise}}} \text{RMS} \propto \left[ \frac{N}{dV/dt} \right] \text{RMS}, \quad \sigma_{\text{Jitter}} = \frac{N}{(dV/dt)} \approx \frac{t_{\text{rise}}}{(S/N)}, \quad (3.1)
\]

where \(S\) refers to the signal, \(N\) to the noise, \(t_{\text{rise}}\) to the rise time and \(V_{\text{th}}\) to the threshold voltage. The best time resolution, i.e. the largest slope, is achieved with thin sensors and large gain (20–30). The time walk is further reduced by using as time reference a percentual constant fraction (or a time over threshold correction) of the rising edge of the signal pulse. Furthermore the time resolution is limited for large gain (20–30) by the Landau fluctuations on the energy deposit, this limit depends on the sensor thickness.

A pixel size of \(1.3 \times 1.3\) mm\(^2\) ensures occupancies below 10% at the highest expected levels of pile-up and low sensor capacitance (~ 4 pF) which is important for the time resolution. An inter-pad gap between pads less than 100 \(\mu\)m also ensures a fill factor (active area fraction) of 90%. A cross section of a LGAD array can be seen in figure 4.

\(^2\)The collected charge over the collected charge in a same size and thickness PiN diode.
Figure 4. Cross section of a $2 \times 2$ LGAD array of CNM run 10478 including a JTE around each sub-pad (Si-Si wafer).

### 3.1 R&D program

An extensive R&D program is progressing quickly towards sensors that provide the required timing resolution in harsh radiation environments. The sensor development is going forward in close collaboration with RD50 [5] and several LGAD manufacturers: Hamamatsu-photonics (HPK, Japan), Fondazione Bruno Kessler (FBK, Italy), Centro National de Microelectronica (CNM, Spain), Brookhaven National Laboratory (BNL, US).

An LGAD active thickness of 50 µm has been adopted as the baseline and studied in detail. LGADs of 35 µm active thickness are studied as an option with an even larger signal slope at the expense of an increased capacitance. Thinner silicon sensors have an increased capacitance, with respect to the thicker ones, but also a smaller collected charge, that for certain electronics read-out can have a non-negligible impact. Different doping concentrations as well as implantation depths have been tested to maximize the collected charge, time resolution and radiation hardness. The performance of Gallium has been studied as dopand instead of Boron (which is the baseline for silicon sensors), furthermore the addition of Carbon implantation in the gain layer has been shown to increase radiation hardness [7, 10].

### 3.2 Irradiation

Radiation damage in silicon mainly results in the reduction of the effective doping concentration, the introduction of trapping centers that reduce the mean free path of the charge carrier, and the increase of the leakage current [5]. For LGADs, one of the main effects is the degradation of gain with fluence at a fixed voltage [8, 9], which implies the need to increase the applied bias voltage after irradiation to at least partly compensate for this.

To study the LGAD performance after irradiation, the sensors have been irradiated at various facilities with different particle types and energies up to fluences of $6 \times 10^{15}$ n$_{eq}$/cm$^2$: reactor neutrons (about 1 MeV) at the TRIGA reactor in Ljubljana, 24 GeV/c protons at the CERN Proton Synchrotron (PS) IRRAD facility, 80 MeV/c protons at the CYRIC facility, 800 MeV/c protons at Los Alamos.

### 3.3 LGAD characterization before and after irradiation

The LGAD sensors have been tested before and after irradiation by various HGTD groups, as well as within the RD50 community. Electrical measurements including capacitance-voltage (C-V) and current-voltage (I-V) characteristics have been performed in laboratory probe stations. A
characteristic of LGADs is the flat part in the C-V distribution (called foot) corresponding to the
depletion of the gain layer. After irradiation the doping concentration of the gain layer is reduced
and thus also the foot becomes shorter. The effect can be clearly seen for a 50 µm thin HPK detector
irradiated at difference fluences in figure 5.

Figure 5. $\frac{1}{C^2}$ vs. bias voltage for a 50 µm thin HPK detector at room temperature before irradiation and at
−20°C after neutron irradiation to the fluences indicated [10].

The dynamic properties of LGADs, such as charge collection, gain and time resolutions, have
been measured in response to ionising particles, both in the laboratory with $^{90}$Sr β particles [6, 8–12]
and in beam tests with pions at CERN, protons at Fermilab and electrons at SLAC, DESY [11–13].
An overview of the gain and time resolution development with radiation damage, measured in
laboratory, for a 50 µm and a 35 µm thick HPK sensor can be seen in figure 6.

Figure 6. Gain (left) and time resolution (right) as a function of fluence for a 50 µm and a 35 µm thick HPK
sensor [14]. The bias voltage applied for each fluence is the one with the minimum time resolution.

Another crucial parameter of HGTD is the sensor fill factor, corresponding to the portion of
the detector which is actually able to detect particles efficiently. The dead area of LGAD arrays was
probed with TCT laser and at beam test. Furthermore the gain, efficiency and time resolution as a
function of position of the pad was measured at beam test facilities both before and after irradiation
(figure 7).
Figure 7. 2D maps of efficiency (left) and time resolution (right) before irradiation for a $2 \times 2$ array from CNM run 10478 as measured in HGTD beam tests [13, 15]. Time resolution was not measured for one pad because it was not perfectly aligned with the time reference.

4 Electronics

The readout of the sensors will be done with an ASIC chip, ALTIROC [2, 15, 16], that will be bump-bonded to the LGAD sensor. The requirements of the ASIC are driven by the targeted 30ps time resolution per MIP after irradiation obtained through the combination of two or three hits. The ASIC will have to withstand high radiation levels. As in the case of the sensors, some ASICs will have to be replaced during the HL-LHC period.

The preamplifier dynamic range will be from around 2 fC up to 100 fC (10 MIPs), determined by simulating electron showers in the HGTD detector. The electronics jitter for a charge of about 10 fC (equivalent to the charge deposited by a MIP in an 50 $\mu$m thick LGAD with a gain of 20) is required to be smaller than 25 ps, i.e. smaller than the dispersion induced by the Landau fluctuations on the energy deposit which limits the time resolution to 25 ps at large sensor gain. The contribution to the time resolution from the TDC is expected to be negligible. The time walk should be smaller than 10 ps over the 10 MIPs dynamic range after time over threshold correction.

In order to measure the online bunch-by-bunch luminosity, each ASIC will report the sum of hits within two different time windows to have an online pile-up suppression. To limit the bandwidth required for the luminosity measurement, the hit summary information of only a subset of the ASICs is used.

4.1 Architecture

Each pixel readout channel will consist of a preamplifier cascaded by a discriminator, both critical elements for the overall electronics time performance. The time of the pulse will be determined using a discriminator that follows the preamplifier. As a consequence, a time-walk correction needs to be applied in order to account for the dispersion in the Time of Arrival (TOA) due to the different pulse heights. The baseline design of the ALTIROC ASIC uses a voltage sensitive preamplifier (VPA). This is a broadband preamplifier with a cascaded Common Source configuration, consisting of an input transistor and a follower transistor.
4.2 First beam test results

Preliminary beam test studies showed that a first version of the ALTIROC chip bump bonded to an LGAD can reach 35 ps of time resolution after applying time walk correction, as seen in figure 8.

Figure 8. TOA as a function of the probe amplitude (left), Time resolution as a function of the threshold [15] (right).

5 Physics and performance

The precision time measurement capability of the HGTD enhances the performance for tagging jets/b-jets, missing transverse momentum $E_T^{\text{miss}}$ and lepton isolation in the forward region. The physics performance improvements enabled by the HGTD can enhance the physics potential of ATLAS in several ways [2, 15].

The improved suppression of pile-up jets is particularly important for searches for or measurements of VBF processes, which produce forward dijet pairs with large invariant masses. The improved $b$-tagging performance in the forward region can benefit physics analyses with forward $b$-quarks in the final state and in which the dominant backgrounds do not contain a large fraction of $b$-quarks in the forward region. The improved lepton efficiency can enhance the precision of important Standard Model measurements at high-luminosity that require forward leptons, such as the measurement of the weak mixing angle. The capability of the HGTD to assign a time to nearly all vertices can enable the reconstruction of masses of long-lived particles that decay within the HGTD acceptance.

Furthermore the HGTD will provide a precise luminosity measurement. The uncertainty on the measurement of the integrated luminosity affects the majority of physics analyses at the LHC. It is especially relevant for precision measurements, for which the total uncertainty is dominated by systematic effects such as the luminosity estimate.

6 Conclusion

The ATLAS HGTD project is going forward as scheduled, the technical proposal [2] is already public and the TDR will be released in the near future. The R&D phase will continue until mid-2020 and the production phase will start in mid 2022. The installation will start in 2025 and the detector is expected to be fully operational for the start of HL-LHC operation.
The development of LGADs in the scope of the HGTD collaboration showed the extraordinary properties of these sensors in terms of time resolution and radiation harness. Thanks to LGAD technology the exploitation of a timing detector in the high flux end-cap region of the ATLAS detector was made possible. The HGTD will improve the physics performance of the ATLAS detector in the dense environment of HL-LHC. The application of timing tracking in high energy particle detectors will be most likely widespread in the following decades. Furthermore the technological development is opening new possibilities of application of LGAD sensors in fields other than particle physics.

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