A High-Granularity Timing Detector (HGTD) for the Phase-II upgrade of the ATLAS detector ^{1 2}

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

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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 x 1.3 mm leading to a highly granular detector with about 3 millions of readout electronics channels. Low Gain Avalanche Detectors (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.

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 $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, corresponding to an increase by an approximate factor of 5 compared to the typical luminosities of Run 2. Two extended periods without physics operation, Long

Shutdown 2 in 2019–2020 and Long Shutdown 3 from 2024 until mid 2026, are 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 pileup 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 axis¹ and a pileup 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 Fig. 1 (Left).

Figure 1: Left: Current and HL-LHC local pileup vertex density. Right: The resolution of the longitudinal track impact parameter, z_0 , as a function of η for different p_T values [2].

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 pileup 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 5 mm for particles with low transverse momentum (p_T) as seen in Fig. 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 pileup interactions.

2 High Granularity Timing Detector (HGTD)

A powerful new way to address the challenging pileup 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 seen in Fig. 2.

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, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$.

Figure 2: Visualisation in the z - t plane of an event with a hard scatter (red ellipse) with about 200 pileup interactions (blue ellipses) superimposed. The dashed vertical lines represent the positions of reconstructed vertices [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 pileup by a factor of $175/30 \approx 6$. The 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 expected level 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.

Pseudorapidity coverage	$2.4 < \eta < 4.0$
Thickness in z	75 mm (+50 mm moderator)
Position of active layers in z	$3435 \text{ mm} < z < 3485 \text{ mm}$
Radial extension:	
Total	$110 \text{ mm} < R < 1000 \text{ mm}$
Active area	$120 \text{ mm} < R < 640 \text{ mm}$
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 μm
Number of channels	3.59M
Active area	6.4 m^2

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

The space available to install new detectors in front of the ATLAS endcap 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 endcap 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. 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 endcap calorimeters, as in the current ATLAS detector. The position of the two vessels for the HGTD is shown in Fig. 3. The main parameters of the HGTD are found in Tab. 1.

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

Figure 3: Position of the HGTD within the ATLAS Detector [2]

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 with a sufficient fill factor. LGADs are planar silicon detectors with internal gain, depending on the doping dose of the multiplication layer and diminishing with radiation fluence. 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].

An LGAD active thickness of $50 \mu\text{m}$ has been adopted as the baseline and studied in detail. LGADs of $35 \mu\text{m}$ active thickness are studied as an option with an even larger signal slope at the expense of an increased capacitance. The performance of Gallium has been studied as dopant instead of Boron, furthermore the addition of Carbon implantation in the gain layer has been shown to be very promising [7, 8].

A pixel size of $1.3 \times 1.3 \text{ mm}^2$ ensures occupancies below 10% at the highest expected levels of pileup, small dead areas ($< 100 \mu\text{m}$) between pixels and low sensor capacitance ($\sim 4 \text{ pF}$) which is important for the time resolution. A cross section of an LGAD array can be seen in Fig. 4. A custom application-specific integrated circuit (ASIC), which will be bump-bonded to the sensors, is being developed (ALTIROC chip) to meet the requirements on time resolution and radiation hardness. The ASIC will also provide functionality to count

the number of hits registered in the sensor and transmit this at 40 MHz to allow unbiased, bunch-by-bunch measurements of the luminosity and the implementation of a minimum-bias trigger.

Figure 4: Cross section of a 2 x 2 LGAD array of CNM run 10478 including a JTE around each sub-pad (Si-Si wafer)

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 Nacional de Microelectronica (CNM, Spain), Brookhaven National Laboratory (BNL, US).

3.1 Irradiation

Radiation damage in silicon mainly results in the change 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 [9, 10], 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 $6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$: Reactor neutrons (about 1 MeV) at the TRIGA reactor in Ljubljana, 23 GeV protons at the CERN Proton Synchrotron (PS) IRRAD facility, 80 MeV protons at the CYRIC facility, 800 MeV protons at Los Alamos.

3.2 LGAD characterization

The LGAD sensors have been tested before and after irradiation by various HGTD groups, as well as within the RD50 community. The main characteristic of LGADs is the gain ² (which is proportional to 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 :

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

where S refers to the signal, N to the noise, t_{rise} to the rise time and V_{th} to the threshold voltage. The best time resolution, i.e. the largest slope, is achieved with thin sensors and large gain. The time walk is further reduced by using as time reference a percentual constant fraction of the rising edge of the signal pulse.

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

²the collected charge over the collected charge in a same size and thickness PiN diode

gain layer is reduced and thus also the foot becomes smaller. The effect can be clearly seen for a 50 μm thin HPK detector irradiated at difference fluences in Fig. 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 [11].

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, 8–13] and in beam tests with pions at CERN, SLAC, DESY and Fermilab [12–14]. 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 Fig. 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 [15].

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 testbeam. Furthermore the gain, efficiency and time resolution as a function of position of the pad was measured at Test Beam facilities both before and after irradiation (Fig. 7).

Figure 7: 2D maps of efficiency (left) and time resolution (right) before irradiation for a 2×2 array from CNM run 10478 as measured in HGTD beam tests [14, 16].

4 Electronics

The readout of the sensors will be done with an ASIC chip, ALTIROC, that will be bump-bonded to the LGAD sensor. The requirements of the ASIC are driven by the targeted 30 ps time resolution per MIP after irradiation obtained through the combination of multiple 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 up to 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 μm 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 should be negligible. The time walk should be smaller than 10 ps over the 20 MIPs dynamic range.

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 pileup 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 followed 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 testbeam results

Preliminary test beam 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 Fig. 8.

Figure 8: Left: TOA as a function of the probe amplitude. Right: Time resolution as a function of the threshold [16].

5 Physics and performance

The precision time measurement capability of the HGTD enhances the performance for tagging jets, missing transverse momentum E_T^{miss} tagging b -jets, 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.

The improved suppression of pileup 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 actual production 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 endcap region of the ATLAS detector was made possible. It was also proven that 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 technologic development is opening new possibilities of application of LGAD sensors in fields other than particle physics.

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