PROCEEDINGS OF SCIENCE

Design and construction of the ATLAS High-Granularity Timing Detector

Stefano Terzo[a,*] **on behalf of the ATLAS HGTD Collaboration**

[a] *Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Edifici CN, UAB campus, 08193 Bellaterra (Barcelona), Spain*

E-mail: stefano.terzo@cern.ch

The increase of the particle flux (pile-up) at the HL-LHC with instantaneous luminosities up to $L \sim 7.5\times10^{34}\ n_{eq}/cm^2$ will have a severe impact on the ATLAS detector reconstruction and trigger performance. The end-cap and forward regions, where the liquid Argon calorimeter has coarser granularity and where the inner tracker has poorer momentum resolution, will be particularly affected. A High-Granularity Timing Detector (HGTD) will be installed in front of the LAr endcap calorimeters for pile-up mitigation and luminosity measurement. The HGTD is a novel detector introduced to augment the new all-silicon Inner Tracker in the pseudo-rapidity range from 2.4 to 4.0, adding the capability to measure charged-particle trajectories in time as well as space. Two silicon-sensor double-sided layers will provide precision timing information for minimum-ionising particles with a resolution as good as 30 ps per track in order to assign each particle to the correct vertex. Readout cells have a size of 1.3×1.3 mm^2, leading to a highly granular detector with 3.7 million channels. Low Gain Avalanche Detectors (LGAD) technology has been chosen as it provides enough gain to reach the large signal over noise ratio needed. The requirements and overall specifications of the HGTD will be presented as well as the technical design and the project status of the different activities.

The 32nd International Workshop on Vertex Detectors (VERTEX2023)
16-20 October 2023
Sestri Levante, Genova, Italy

*Speaker

PoS(VERTEX2023)029

1. The High-Granularity Timing Detector

By the end of 2026, the CERN Large Hadron Collider (LHC) is set to undergo a major upgrade, aiming to boost the instantaneous luminosity up to $7.5 \times 10^{34}\,\mathrm{n_{eq}/cm^2}$. The upgraded High Luminosity LHC (HL-LHC) will deliver up to 200 proton-proton interactions to the ATLAS experiment, with an average of 1.5 primary vertexes per millimeter. The significant increase in proton interactions (pile-up) of a factor 4 with respect to the present run, poses challenges for track reconstruction and trigger performance in the future ATLAS detector design. Specifically, vertex reconstruction and physics performance will degrade noticeably in the forward region compared to the central area due to the reduced resolution of the new Inner Tracker in this region. To tackle these issues, the High-Granularity Timing Detector (HGTD) is designed to provide precise timing information, of the order of 30–50 ps per track, with the purpose of enhancing pile-up rejection and object reconstruction in the forward region of the ATLAS detector.

1.1 Detector layout

The HGTD position within ATLAS and its layout are outlined in Figure 1 [1]. The detector

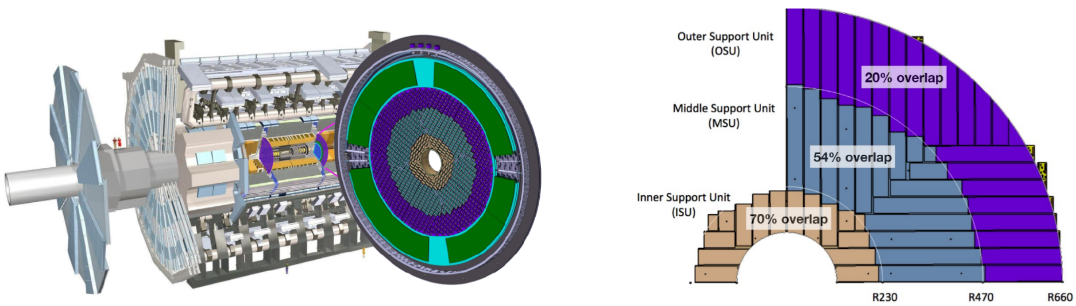


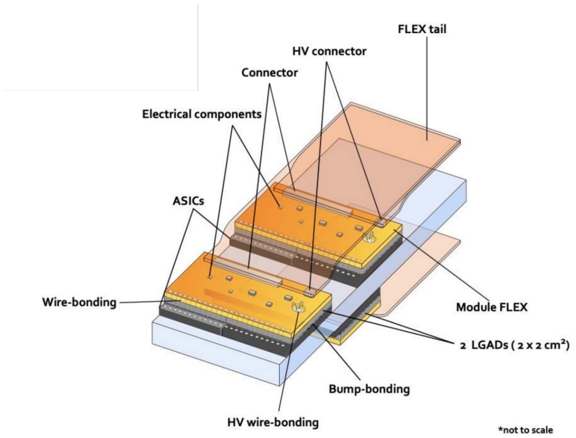
Figure 1: Layout of the ALTAS detector highlighting the position of the two HGTD endcaps (left). Schematic of the three HGTD ring layout.

consists of two endcaps hosted between the barrel and the forward calorimeters at about ±3.5 m from the interaction point. The active area of the detectors covers a pseudorapidity range between η of 2.4 and 4 with a radius from 120 to 640 mm. Each endcap is made of two disks with detector units mounted on both sides and overlapping with different staggering to guarantee and average between 1 and 2 hits per track per disk. Moreover, each disk is segmented into three replaceable rings which, depending on their distance from the interaction point, will be exposed to different radiation doses. A replacement of two innermost rings is foreseen after a total Non-Inonising Energy Loss (NIEL) damage of $2.5 \times 10^{15}\,\mathrm{n_{eq}/cm^2}$ and a Total Ionising Dose (TID) of 2 MGy. These radiation levels are expected for the first and the second rings after an integrated luminosity of $1000\,\mathrm{fb^{-1}}$ and $2000\,\mathrm{fb^{-1}}$, respectively. The endcaps are completed by Peripheral Electronics Boards (PEB) for managing data transmission, power distribution and monitoring which are located in the outermost ring of each disk between 660 and 920 mm.

The HGTD is also designed to provide Luminosity measurement counting the number of hits at 40 MHz (bunch-by-bunch) with the goal of 1 % luminosity uncertainty.

2. The HGTD modules

The HGTD detector will consist of 8032 modules arranged within each disk in rows and connected to the PEB through flexible Printed Circuit Board (PCB), called "flexes". The sketch of a module is shown in Figure 2. Each HGTD module is made of two hybrid pixel detectors, hereby



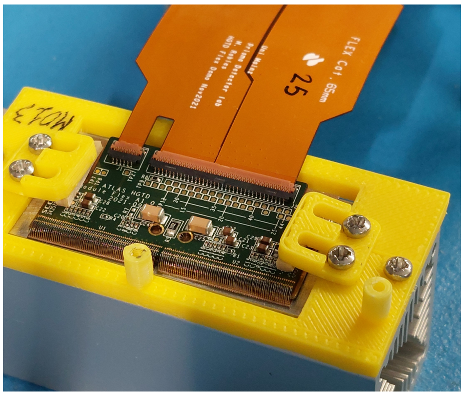


Figure 2: Schematics of HGTD modules (left). An HGTD prototype module assembled on a module carrier for testing.

called "hybrids", attached and readout by the same flex. Each hybrid is composed of an ASIC with 15×15 channels bump bonded to a passive silicon sensor with a pixel size of $1.3\times1.3\,\text{mm}^2$. The total HGTD module dimension is approximately $2\times4\,\text{cm}^2$ ($2\times2\,\text{cm}^2$ per hybrid). To ensure the necessary timing performance for HGTD, each module must provide a time resolution of 35 ps per Minimum Ionising Particle (MIP) at the beginning of the HL-LHC period and no more than 70 ps at the end of the lifetime of the detector. To achieve such low time resolution Low Gain Avalanche Detectors (LGADs) have been chosen as sensor technology for HGTD.

2.1 LGAD sensors

The LGADs designed for HGTD consist of n-on-p planar silicon sensors with an additional highly doped p-type implantation layer buried below the n-type pixel implant. The high electric field created by this additional implantation enable the multiplication of the charge carriers drifting below the collecting electrode resulting in a significantly faster and larger signal with respect to standard planar devices. The doping profile of this, so called, gain layer is tuned to allow operations in the linear regime with a gain of the order of 10 which allows to improve the signal-to-noise ratio and the signal slope keeping the noise levels under control. The sensors have an active thickness of 50 µm which allows to push the performance of LGAD sensors down to the required time resolution by reducing the effect of the Landau flactuations [2].

Another critical aspect for the LGAD sensors in HGTD is the radiation hardness. The HGTD modules are expected to operate for several years in a dense particle environment where they are required to keep their time resolution and hit efficiency performance after exposition to a total particle fluence of $2.5\times10^{15}\,\text{n}_{\text{eq}}/\text{cm}^2$. After irradiation, the boron doping in the gain layer becomes less active due to the acceptor-removal effect induced by radiation [3] which degrades the LGAD performance, reducing the signal gain. As a consequence, irradiated LGAD sensors require a higher bias voltage to recover performance levels comparable to those attained before irradiation. At the same time, the operational voltage of LGAD sensors is limited by the so called Single Event Burnout (SEB) where a single particle depositing enough energy (of the order of tens of MeV) can lead to a destructive breakdown due to the collapse of the electric field in presence of a high concentration of free charge carriers. Lifetime tests on irradiated sensors ($\sim 2.5 \times 10^{15}$ n_{eq}/cm^2) confirmed that SEB issue occurs when the electric field is larger than 11 V/µm (which is 550 V for 50 µm thick LGADs) [4]. To overcome these issues, the HGTD LGAD sensors are further processed with carbon doping which mitigates the acceptor-removal effect.

LGAD sensors from different vendors have been extensively studied during the R&D phase of HGTD working in close contact with the sensor foundries to bring their process up to the standards required by HGTD. Presently the LGAD sensor pre-production is ongoing, which involves the testing of the final prototypes through quality assurance and quality control protocols, including measurements of the sensor performance before and after irradiation. In addition to IV and CV measurement, the gain and time resolution of the different sensors are studied before and after irradiation in the laboratory with ^{90}Sr beta radioactive sources. Charge collection and time resolution of irradiated LGAD sensor produced by different vendors for HGTD are presented in Figure 3. From this results it is possible to appreciate how IHEP-IME, USTC-IME and FBK sensors, which are carbon-enriched, can provide a signal larger than 4 fC (as required for the HGTD ASIC) and a time resolution lower than 50 µm with less than 550 V.

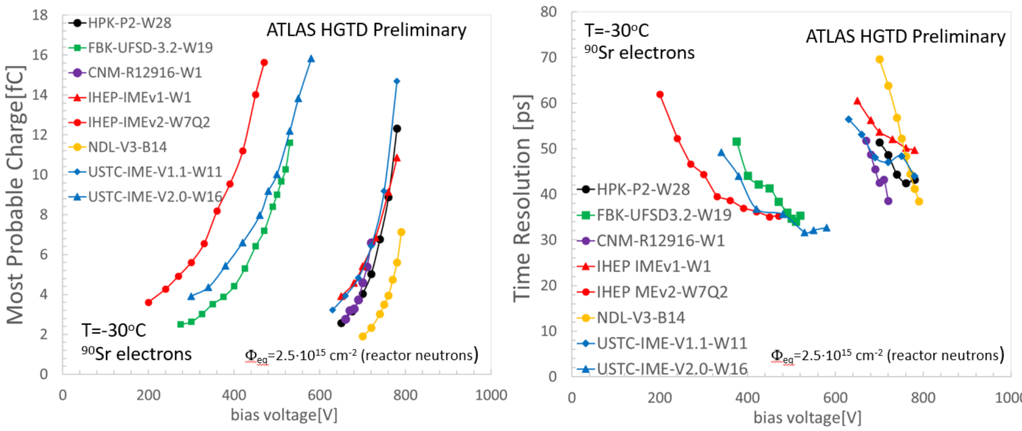


Figure 3: Most probable charge (left) and time resolution (right) as a function of the bias voltage for sensors irradiated to 2×10^{15} n_{eq}/cm^2 with reactor neutrons. Results obtained with a ^{90}Sr telescope at $-30\,°$C. IHEP-IMEv2 (red circles), USTC-IME-V2 (blue triangles) and FBK-UFSD (green squares) are carbon-enriched sensors while the others are not.

A more extensive characterisation is obtained through testbeam experiments where it is possible to determine also the hit efficiency. Results of carbon-enriched sensors obtained in two testbeam campaigns at CERN SPS and DESY, Hamburg, are shown in Figure 4 [5]. For all sensor it was possible to reach the required performance in terms of charge collection (≥4 fC), high hit efficiency (≥95 %) and time resolution (≤70 ps) within the operational voltage limits imposed by the SEB.

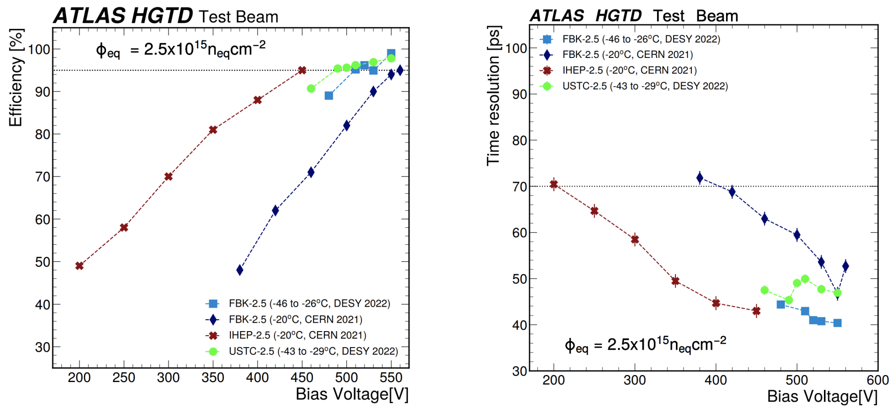


Figure 4: Hit efficiency (left) and time resolution (right) as a function of the bias voltage for carbon-enriched sensors irradiated to 2×10^{15} n_{eq}/cm^2 and measured in test beam. Sensors from three vendors (FBK, USTC-IME and IHEP-IME) are shown.

2.2 The ALTIROC ASIC

The HGTD ASIC, named ALTIROC, is designed for 130 nm CMOS technology from TSMC and is crucial component of the HGTD modules to exploit the performance of the LGAD sensors. For this purpose it is required to maintain a jitter below 25 ps for signals exceeding 10 fC (anticipated for a non-irradiated LGAD sensor) and below 70 ps for signals of 4 fC (the minimum specified post-irradiation signal for LGADs). Additionally, the chip itself must exhibit radiation hardness up to 2 MGy and ensure a minimum discriminator threshold of 2 fC.

Initial prototypes, ALTIROC0 and ALTIROC1, focused on the analog front end, with results detailed in [6, 7], while ALTIROC2 is the first full size prototype including a full electronic chain. HGTD modules assembled with the LGAD sensors and the ALTIROC2 have been extensively tested in the laboratory with radioactive sources and in testbeam campaigns. On one hand the modules were able to reach the required performance of 25 ps jitter for a signal of 10 fC which was found stable with gamma irradiation up to a TID of 220 Mrad. On the other hand the threshold could only be tuned down to a 3.8 fC with a jitter that degrades for signals lower than 8 fC as shown in Figure 5. This was understood to be caused by a parasitic inductance leading to different sensor-amplifier grounds. The ALTIROC3, which is the latest prototype presently under test, includes fixes to this problem and it is designed up to specifications for the radiation levels expected in HGTD.

3. Detector units, Peripheral Electronics Boards

Once assembled, the HGTD modules are glued to support units made of PEEK (PolyEther Ether Ketone) to build a Detector Unit (DU) as shown in Figure 6. Flex tails produced with different lengths connect each module to the Peripheral Electronics Boards (PEBs) located in the outer ring. The PEB are integral components of the detector system which play a crucial role in managing data transmission (for both timing and luminosity measurements), power distribution, system control and monitoring. There is an intensive work ongoing for the characterisation of all individual components with PEB prototypes including: DC-DC converter Point Of Load regulators (bPOL); lpGBTs (Low Power Giga Bit Transceiver) which are CERN-developed radiation-tolerant

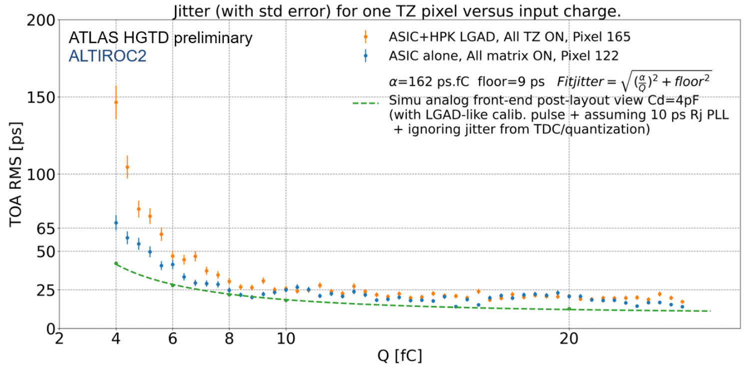


Figure 5: ALTIROC2 jitter as a funcion of the charge injected in the pre-amplifier. The jitter is measured as the Root Mean Square (RMS) of the Time Of Arrival (TOA) for the ASIC alone (blue) and an hybrid (ASIC + LGAD sensor). The post layout simulation (gree dotted line) is also shown for comparison.

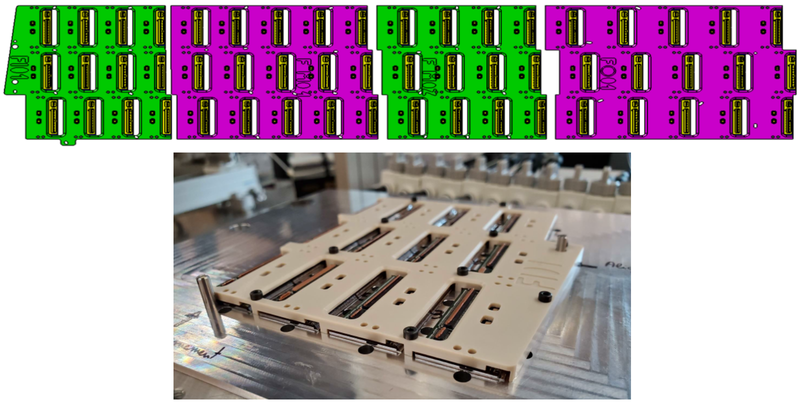


Figure 6: Layout of a detector unit (top) and a picture of the first modules loaded in a PEEK support for the demonstrator (bottom).

data transmission ASICs; and MUX64 analogue multiplexer for monitoring ASIC power and temperature.

4. Conclusion

The High Granularity Timing Detector (HGTD) for the ATLAS upgrade at HL-LHC aims at enhancing track and vertex reconstruction, as well as pile-up rejection, by incorporating precise timing information for tracks in the forward detector region. To ensure the necessary time resolution throughout the detector lifetime, carbon-enriched LGADs have been selected for their improved radiation hardness. Characterization of LGADs from various vendors has demonstrated their capability to operate safely up to 550 V, delivering the required charge collection, hit efficiency, and time resolution for the HGTD detector up to a particle fluence of 2.5×10^{15} n_{eq}/cm^2. Ongoing quality evaluations of the latest LGAD pre-production runs are taking place and will continue through planned testbeam campaigns in the coming year.

The full-size ALTIROC2 ASIC prototype has undergone successful testing, and the new ALTIROC3 is currently undergoing characterisation. This recently released ASIC represents the final radiation-hard prototype before entering production.

Multiple demonstrator initiatives are currently underway for the cooling with dedicated heater modules [8], for the Data Acquisition (DAQ) [9] and for the detector units. A full demonstrator is foreseen to integrate heater and DAQ demonstrator efforts with 54 full modules (ALTIROC + LGAD) on detector units to be mounted on a cooling plate. The primary objective is to validate system integration and electronic functionalities. Simultaneously, ongoing efforts are dedicated to advancing methods and tools for module assembly. HGTD assembly sites have already delivered approximately 25 prototype modules, primarily dedicated to the demonstrator initiative. The initial detector units have been successfully constructed, and testing is currently in progress.

Acknowledgments

This work was partially funded by: grant PID2021-124660OB-C21 funded by MCIN/AEI/ 10.13039/501100011033 and by the MCIN with funding from the European Union NextGenerationEU (PRTR-C17.I1) and by the Generalitat de Catalunya. IFAE is also partially funded by the CERCA program of the Generalitat de Catalunya. Parts of the measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

References

[1] ATLAS Collaboration, *Technical Design Report: A High-Granularity Timing Detector for the ATLAS,Phase-II Upgrade*, CERN-LHCC-2020-007 (2020).

[2] F. Cenna et al., *Weightfield2: A fast simulator for silicon and diamond solid state detector*, Nucl. Instrum. Meth. A **796** (2015) 149–153.

[3] G. Kramberger et al., *Radiation Hardness of Thin Low Gain Avalanche Detectors*, Nucl. Instrum. Meth. A **891** (2018) 68–77.

[4] L.A. Beresford et al., *Destructive breakdown studies of irradiated LGADs at beam tests for the ATLAS HGTD*, JINST **18** (2023) P07030.

[5] S. Ali et al., *Performance in beam tests of carbon-enriched irradiated Low Gain Avalanche Detectors for the ATLAS High Granularity Timing Detector*, JINST **18** (2023) P05005.

[6] C. Agapopoulou et al., *Performance of a Front End prototype ASIC for picosecond precision time measurements with LGAD sensors* JINST **15** (2020) P07007.

[7] C. Agapopoulou et al., *Performance of a front-end prototype ASIC for the ATLAS High Granularity timing detector* JINST **18** (2023) P08019.

[8] V. Raskina, *Research and development of the High-Granularity Timing Detector (HGTD) for the ATLAS Detector as the preparation of the High-Luminosity LHC operation phase*, Ph.D. thesis, LPNHE Paris, 2023, CERN-THESIS-2023-175.

[9] L. Han et al., *Demonstration system of the HGTD peripheral electronics boards for ATLAS phase II upgrade*, Nucl. Instrum. Meth. A **1045** (2023) 167651.