The ATLAS High Granularity Timing Detector

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Abstract

The addition of The High Granularity Timing Detector (HGTD) in ATLAS offers to solve many challenges that are faced in the High Luminosity LHC (HI LHC) Conditions. It covers the forward region of $2.4 < |\eta| < 4.0$, and decreases the effects of the pile-up. The sensors$'$ choice are the Low Gain Avalanche Detector (LGAD). The results that are presented in this paper are obtained from test beams in June 2018 with a pion beam. The two chosen LGAD sensors are W9LGA35 and BNL W1835 from batch 1xx, their charactersistics (e.g charge and amplitude distributions) were investigated from a reference (SiPM) in order to study their performance and measure the time resolution using Constant Fraction Discriminator (CFD) method.

Both sensors were performing poorly due to a technical issue in the reference. However, W9LGA35$'$s performance was showing better results.

Acknowledgements

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Finally, I owe an extreme praise to the European Organization for Nuclear Research CERN for allowing me to experience this beautiful oppurtuinity, gain priceless knowledge and allowing me to contribute to the world′s largest particle physics laboratory.

1 Introduction

The Large Hadron Collider (LHC) is the largest and most powerful particle accelerator in the world, it was built and developed by the European Organization for Nuclear Research (CERN). It attempts to study the predictions of a variety of theories in particle physics and help to answer open questions in physics, including elementary particles and their interactions, properties of the Higgs boson, structure of space and time, extra dimensions and dark matter.

The LHC consists of a 27-kilometer ring of superconducting magnets and accelerating structures to boost and add energy to the hadrons all over the way. Inside the accelerator, there are two beam pipes where two highly energetic beams travel in opposite directions before they are made to collide, as they are directed by strong magnetic fields maintained by the superconducting magnets. In order for the magnets to efficiently conduct electricity with zero resistance and no losses at all, it is required to cool them down to -271.3 C which is done by connecting the magnets to a distribution system of liquid Helium.

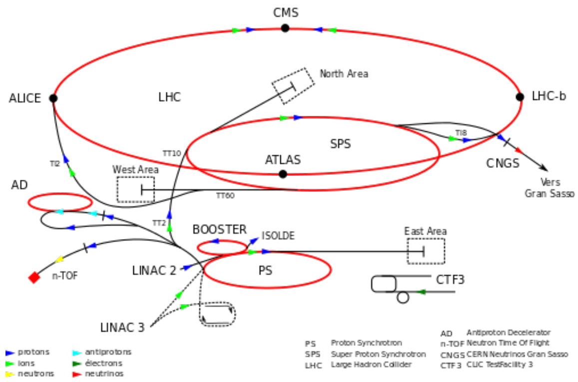

Figure 1: LHC accelerator complex.

The accelerator compound is a series of accelerators of increasing energies, where each machine injects the beam into the next part that increases the beam′s energy more. The brief story of the accelerating beams in the accelerator compound starts with a gas cylinder filled with Hydrogen atoms, they are fed to the chamber of a linear accelerator (Linac 2) where they get ionized leaving behind them Hydrogen nuclei, positively charged protons. Their positive charge enables them to be accelerated by an electric field. Then, they are injected to the Proton Synchrotron Booster (PSB) where they are repeatedly exposed to an electric field to be accelerated, and powerful electromagnets are used to bend the beam of protons round the circle. After that, the beam is flown to the Proton Synchrotron (PS) where the beams reach 99.9% the velocity of light so the added energy can not anymore translate as increasing velocity, instead it is translated as increasing mass that makes the proton heavier.

Protons are sent to the into the Super Proton Synchrotron (SPS) where they are sufficiently energized to finally be launched to the orbit of the Large Hadron Collider (LHC). There are two vacuum pipes within the LHC containing the proton beams travelling in opposite direction, as they cross over in the detectors′ points where they are made to collide.

The collisions in the LHC are tracked in detectors, there are seven experiments installed: A Toroidal LHC ApparatuS (ATLAS) , Compact Muon Solenoid (CMS), A Large Ion Collider Experiment (ALICE), the LHC beauty (LHCb), the LHC forward (LHCf), the TOTal Elastic and diffractive cross section Measurement (TOTEM) and Monopole and Exotics Detector at the LHC (MoEDAL). Each of them has different purposes, design and working mechanisms, ATLAS is the considered experiment in this project.

ATLAS is a general-purpose detector investigating a wide range of physics, from precision of properties and measurements of the Higgs boson to looking for new physics beyond the standard model and extra dimensions. ATLAS is the largest collider detector ever constructed, it is made up of eight superconducting magnet coils, they are organized to form a cylinder around the proton beam pipe that are located in the center of the detector.

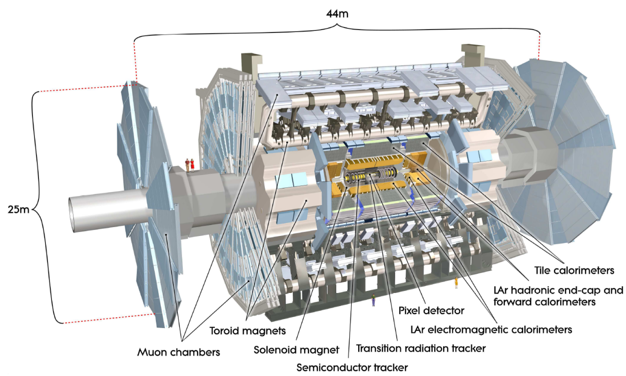

Figure 2: ATLAS detector and subsystems.

2 Theoretical Background

2.1 Detectors

A particle detector, also known as a radiation detector, is a device used to track, detect and identify ionizing particles. The goal of particle detectors is to measure the momenta and discover the identity of the particles that pass through it after being produced in an event, which might be a collision that occurs in the detector resulting many particles that decay into many more or a decay that occurs naturally. The interaction point is the exact location in space where the event occurs.

Furthermore, it is required to measure the mass and momenta of the particles in order to completely reconstruct the event, meaning to identify the particles produced in the collision and plot the paths they take. Particles produced normally travel in a straight line, but in existence of magnetic field charged particles change their original straight line path to a curve. The curvature of the path gives us a clue about particle′s identity, as higher the momentum the less the curve, and vice versa.

ATLAS is considered from hermetic detectors, which are the modern large-scale detectors encompassing several tracking chambers and calorimeters that surround the interaction point completely.

Modern particle detectors are made of layers of sub-detectors that are different in purposes, properties and design. Tracking devices are used to follow up the path of the particle, and calorimeters are used to absorb and measure the energy of the particle.

Tracking devices show the track of charged particles as they travel and interact with suitable substances, as neutral particles are not affected by the magnetic field so they maintain the straight line. Usually, tracking devices do not directly show us the particle′s paths in a visible way. They instead, record small electrical signals that particles produce as they travel, then a computer program translates the signals to recorded pattern of tracks.

Calorimeters measure the energy of the particles that pass through it, it usually entirely stops the particle coming from an event or absorb most of it′s energy, as it forces the particle to deposit all of its energy within the detector itself.

2.2 ATLAS Detector

A Toroidal LHC ApparatuS (ATLAS) is a general purpose detector, and the largest detector ever constructed. It has cylinder dimensions, 46m long, 25m diameter and weighs 7,000 tonnes. Used to detect the tiniest and most energetic particles.
ATLAS is an instrument consisting of six layers of sub-detectors wrapped around the collision point to measure the momenta, energy and trajectory of particles, which allows the particles to be measured and identified.

The four major components of ATLAS are the inner detector, calorimeter, magnet system and Muon spectrometer.
The inner detector of ATLAS is the first component that the particles travel through, which means it is very compact and sensitive. It tracks the particles from the LHC beam pipe to the electromagnetic calorimeter system. The inner detector composes of three main components, the Pixel Detector, the Semiconductor Tracker (SCT) and the Transition Radiation Tracker (TRT). Moreover, The main functions are tracking the reconstruction of charged particles (curve of paths), momentum reconstruction, finding vertex, which means finding the reconstructed location of an individual particle collision, and for particle identification.

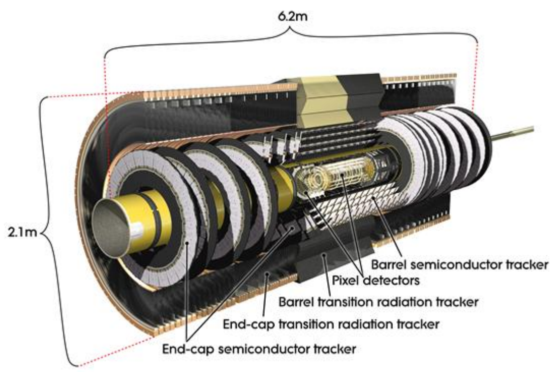

Figure 3: The Inner Detector of ATLAS Detector.

Calorimeters in ATLAS measure the energy of the charged particles by absorbing them within the detectors material forcing them to deposit their energy. They usually consist of layers of high density and absorbing materials, like Lead for example. ATLAS calorimeter system composes of Liquid Argon Calorimeter (LAr) and Tile Hadronic Calorimeter.

Electromagnetic Calorimeters are used to calculate the energy of electrons and photons that interact with materials, as the Hadronic Calorimeters calculate the energy of hadrons that interact with atomic nuclei. The only particles that can pass through calorimeters without being absorbed are Muons and Neutrinos. ATLAS calorimeter system composes of Liquid Argon Calorimeter (LAr) and Tile Hadronic Calorimeter.

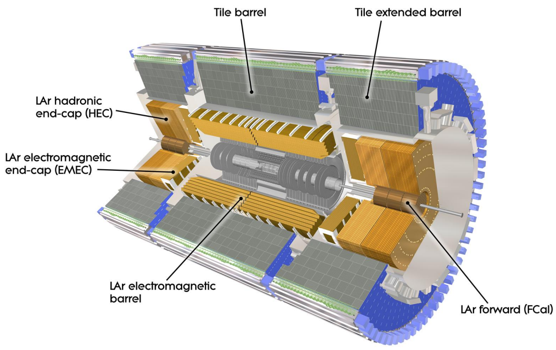

Figure 4: Calorimeter System in ATLAS Detector.

The superconducting magnets named Barrel Toroid, the End-Cap Toroids and the Central Solenoid together combine with the magnet power system, controls and refrigeration plant to form the ATLAS **Magnet System**. The Magnet system by its turn tends to provide the bending power for charged particles paths, as the neutral particles are not affected by it, which makes tracking particles and measuring their momentum easier to do.

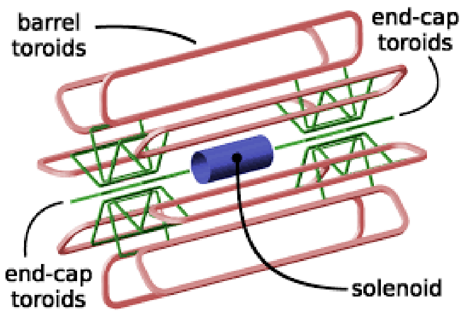

Figure 5: ATLAS Detector′s Magnet System.

Muons are able to penetrate all the previously mentioned three layers because they are extremely highly energetic. **The Muon Spectrometer** in ATLAS consists of four subsections, Thin Gap Chambers, Resistive Plate Chambers, Monitored Drift Tubes, and Cathode Strip Chambers. The Muon Spectrometer uses muon chambers in four different technologies in order to determine their direction, momenta and electric charge. Muon chambers are made up of thousands of metal tubes with central wire and filled gas, so when muons travel through it leaves a trail of charged ions and electrons, which possibly helps us to determine the position of muons as they pass through.

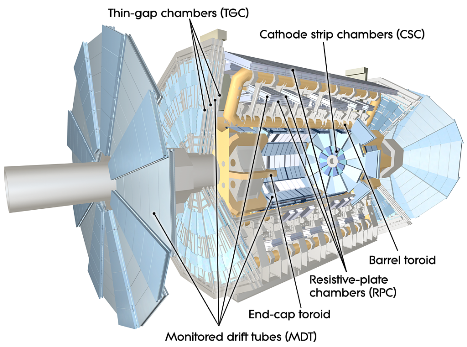

Figure 6: Muon Spectrometer′s subsections in ATLAS Detector.

2.3 The High Luminosity LHC Upgrade

The High Luminosity LHC (HL-LHC) is the Phase II upgrade of the LHC that aims to provide an instantaneous luminosity a factor of five beyond than the LHCs design value, and to increase the potential of discoveries by enlarging the data sample of the experiments.

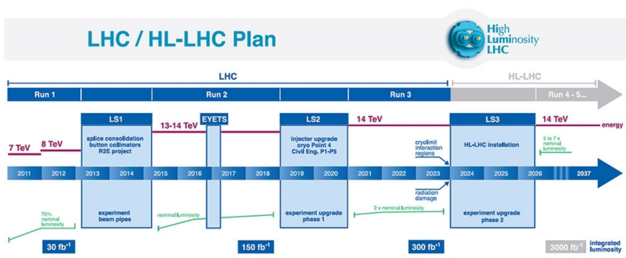

Figure 7: LHC′s Upgrades Plan.

The HL-LHC will reach an instantaneous luminosity, which is a measurement of number of collisions that can be produced in a detector per cross-section per second, of $5\times10^{34} cm^{-2}s^{-1}$. The luminosity illustrates the performance, or efficiency, of a collider, as it is directly proportional to the number of collisions in a given amount of a time, giving us more data. The higher the luminosity, the more data experiments can intake increasing the probability to observe more rare processes. The most direct way to boost the luminosity is to decrease the cross-section by focusing and tightening the beam more in interaction points, or to increase the number of bunches or number of protons per-bunch.

On the other hand, it will reach an integrated luminosity, which is the integral of the delivered luminosity over time, of 3000 fb^{-1}. The integrated luminosity is a measurement of the collected data size, it is an important value to characterize the performance of an accelerator. IN more details, the full exploitation of the physics accessible with a total integrated luminosity of 3000 fb^{-1}, with approximately 2500 fb^{-1} that is collected in the HL-LHC.

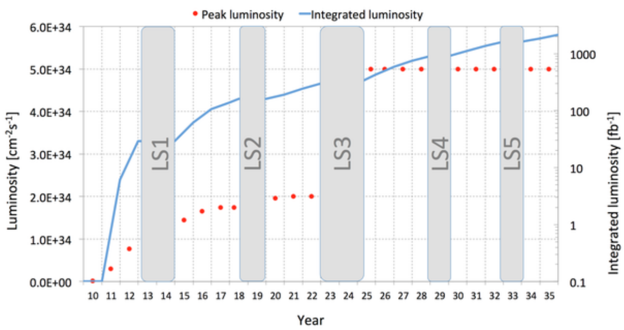

Figure 8: Luminosity and Integrated Luminosity at the LHC by time.

The upgraded experiments will have to maintain or improve the performance as the current experiments at the LH-LHC conditions, meaning to cope with high radiation doses, increased pile-up and challenging trigger rates. The program of the upgrade consists of replacing old electronics and detectors which reach the end of their life-time, and upgrading the systems. For instance, upgrading the trigger and data-flow systems, calorimeter systems, Muon system and the Inner tracking system, which is what we are interested in. The current inner detector does not fulfill the requirements of the high luminosity upgrade, so a new inner detector will be built in place of the current one, and the High Granularity Timing Detector will be added.

2.4 The High Granularity Timing Detector (HGTD)

The increase of the luminosity in the HL-LHC will rise the number of collisions so high that the tracking mission will get very complicated due to the huge amount of pile-up. Pile-up comes when the readout of a particle detector includes information from more than one primary beam interactions, or it occurs when the detector measures objects that do not come from the Primary Vertex (PV) where the hard scattering, meaning having energy scales more than a few GeV, occurs. The pile-up are those multiple interactions, or the interactions that we are not interested in.

Generally, pile-up events have low energies and can be estimated by simulations. There are two types of pile-up, the in-time pile-up, which comes from the same bunch of protons from the interaction of interest, and can be resolved by setting the interaction points location by identifying vertices, measure their distances and compare them to the primary vertex. The second type is out-time pile-up, which comes from other proton bunches when the detector hasnt yet recorded the signal completely due to dead time, the time needed for a certain detector to be able to record an event after a previous one, or other reasons, and it can be determined by silicon detectors since they have a time resolution equal to the time per-bunch crossing, 25 ns.

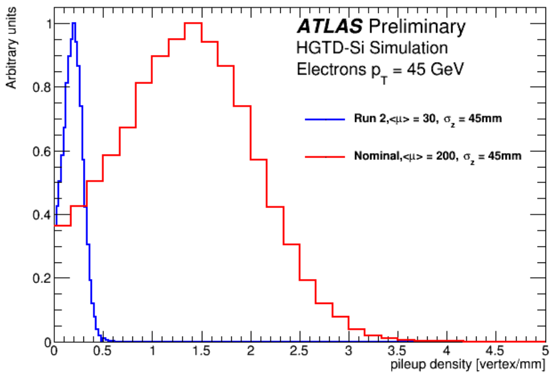

Figure 9: Local pileup vertex density simulation.

One of the most difficult challenges in the high luminosity upgrade of the LHC is the suppression of the detectors signals that are caused by the additional low energetic proton-proton collisions, which are the pile-up, they are produced by a nominal average of $\mu = 200$ per-25 ns per-bunch crossing. Therefore, ATLAS is proposing a **High Granularity Timing Detector**.

First, the Liquid Argon (LAr) Calorimeter was arranged to have a fine granularity in the first sampling layer over much of its acceptance, motivated by the probability of measuring the pointing of photons coming from the primary vertex.

At the time of construction, simulations showed that precision physical measurements can not exceed much beyond $|\eta| > 2.5$, for this reason, and to reduce the total cost of the electronics, the end-cap Electromagnetic Calorimeter inners wheel was decided to be designed with only two longitudinal segmentations, instead of three. This did not show a major degradation in the energy resolution. But on the other hand, at the HL-LHC conditions, where the pile-up increases, the performance of the EM Calorimeter degrades significantly in the forward region, which is caused by the noise in channels.

When moving from the nominal luminosity to the high luminosity, a big increase in the noise energy coming from the pile-up and electric noise is noticed, which degrades the resolution of the calorimeter.

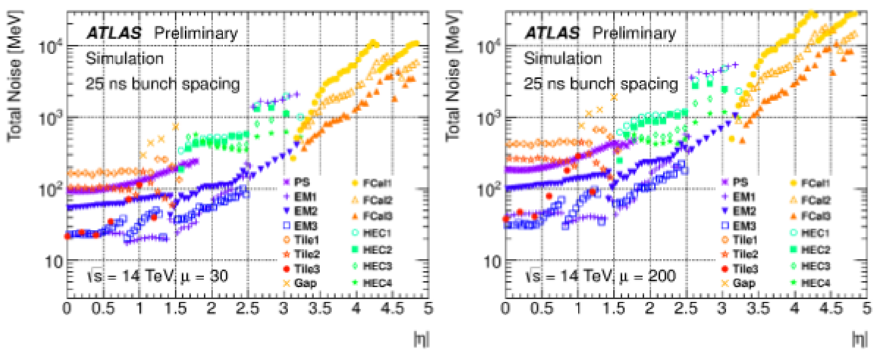

Figure 10: Noise in calorimeter cell (a) μ= 30, (b) μ= 200.

The High Granularity Timing Detector (HGTD) offers a new and powerful technique to get over the pile-up obstacle by taking advantage of the time spread of interactions, so we can distinguish between the interactions that occur very close in space but separated in time. Providing a time resolution, which is the precision of measurement with respect to time, of approximately 30 ps, it will be covering the forward region of $2.4 < |\eta\ | < 4.0$ where the pile-up is going to be rejected.

In addition, it will be a powerful tool to improve the performance in the forward and for luminosity measurement. High time-precision leads to a performance consistent of that in the central region because it improves the track-to-vertex association significantly.

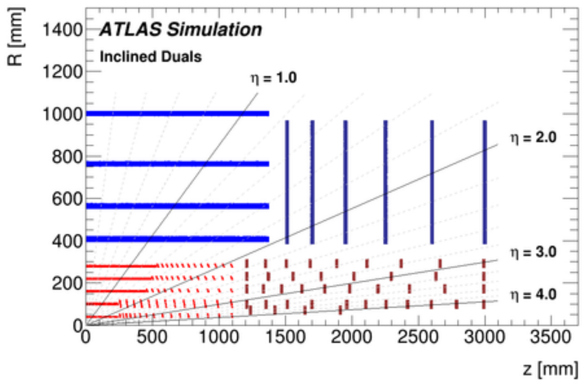

Figure 11: ATLAS Inner Tracker (ITk) simulation and coverage.

The HGTD is going to be added in front o the end cap and forward calorimeters $|z| = 3.5m$, it is assembled of forward and backward detector disks with central half rings and stave concepts, and has a total of $6m^2$ of Silicon sensors. Basically, it is made up from an active area of sensors, off-detector electronics and moderators and support. The front cover provides protection, thermal shielding and tighten dry volume.

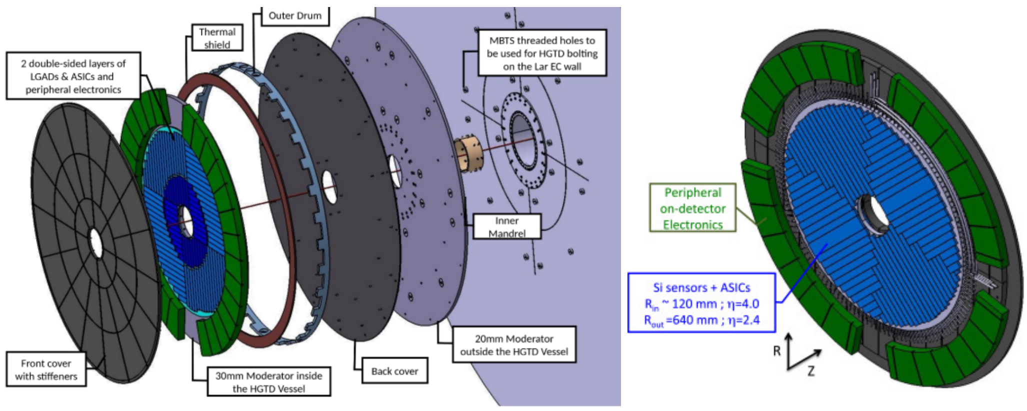

Figure 12: Assembly of HGTD.

2.5 The Low Gain Avalanche Detector (LGAD)

Silicon radiation detectors, are widely used in collider experiments, they are based on PIN diodes that are operated with an external reverse bias, meaning negative voltage, in full depletion, so the potential drop across the potential region is at it maximum. They generate signals that are directly proportional to the energy deposited by incident particles or radiation. Silicon detectors are widely used for many magnificent properties, for instance, their high spatial resolution, their compact size, and they have a high quantum efficiency for a large range of wavelengths.

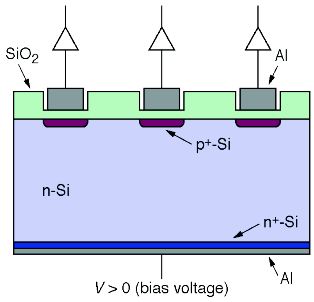

Figure 13: Single sided Silicon Detecor.

The Avalanche Photo-diode (APD) was developed in order to measure low energy particles and x-rays, such detectors show an internal signal gain proportional to the applied bias voltage, they also show an output of signals that is proportional to the absorbed energy accompanied by a gain factor of range 50 to 1000, resulting the detection of low intensity particles signals. On the other hand, the current leakage level associated with it is way too high, and the noise associated with the gain deceives the noise to signal ratio.

Modifying the Avalanche Photo-diode (APD) in the doping levels assisted in producing the Low Gain Avalanche Detectors (LGAD), with a gain factor of a range 5 to 70. They are operated in linear mode for proportional response of increasing signal due to higher energy deposited, and vice versa. In addition, they require high resistivity to attain full depletion due to the low operated voltage.

The sensors choice for the High Granularity Timing Detector (HGTD) are the **Low Gain Avalanche Detectors (LGAD)**, with low energy requirement, they give a moderate multiplication (gain) on the charge that is collected, which leads to a significant improvement of the signal to noise ratio.

The sensors are thin pixelated n-on-p silicon sensors. The structure of LGAD includes a thick highly Boron doped p-type layer between the high resistivity p-type bulk and the n^+ implant, so it simulates a high field charge multiplication layer with a gain factor of a range 5 to 70. LGAD has a nominal thickness of $50/micros$, experiments will tell that this is the best choice of thickness for these sensors, as it helps maintaining low noise levels, reduces bulk of radiation effects, decreases the collection time and it shows significant improvements in time resolution.

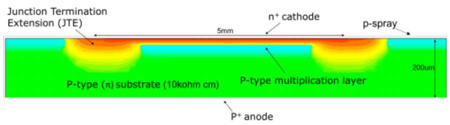

Figure 14: Cross-section of LGAD sensor.

The Low Gain Avalanche Detector can be assembled in two ways, Single Pad LGA, or 2×2 Pad Array. Single Pad LGA has an overall active area of $1.3 \times 1.3mm^2$, but the multiplication layer has only $1.0 \times 1.0mm^2$, it contains a small gap in the metal on the top for light injection tests, and it is surrounded by the Junction Termination Extension (JTE), which is a deep n^+ implant. JTE protects the single pad LGA as a whole from high fields, which will lead to an early breakdown. On the other hand, 2×2 Pad Array has an overall active area of $2.063 \times 2.063mm^2$ or $3.063 \times 3.063mm^2$, but the multiplication layer with only $2.0 \times 2.0mm^2$ and $3.0 \times 3.0mm^2$, respectively. Moreover, the JTE surrounds the whole array, not each pad by itself.

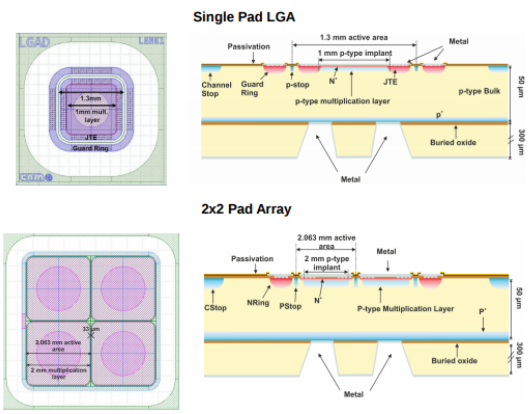

Figure 15: Single Pad LGA versus 2×2 Pad Array.

2.6 Time Resolution

Time resolution of a detector is defined as the accuracy of measuring the time at which particles are detected, dispersion is when the energy is deposited non-uniformly along the sensors which causes fluctuations in the Landau distribution (σ_{Landau}), and of the electronic noise (σ_{elec}), which is determined by two effects: the jitter (σ_{jitter}), and time walk ($\sigma_{timewalk}$). The time resolution is a quadratic sum of these three terms.

$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{jitter}^2 + \sigma_{timewalk}^2$$

$$\sigma_{jitter} = \frac{N}{dV/dt} = \frac{t_{rise}}{(S/N)}$$

$$\sigma_{timewalk} = [\frac{V_{th}}{S/t_{rise}}]_{RMS} \propto [\frac{N}{dV/dt}]_{RMS}$$

N: Electronic noise
t_{rise}*: Rise time of signal.*
S: Signal amplitude.
V_{th}*: Threshold voltage to determine time of arrival.*

There are two extra terms in this equation, depending on the size of the time-to-digital converter (TDC) bin, and precision of the clock distribution, but an oscilloscope was used instead of a TDC, so they will not be considered.

The method that is used to calculate the time resolution is the Constant Fraction Discriminator (CFD) method, it is mostly used in measurements assuring excellent time resolution. It depends on the width and fitting of the gaussian.

It uses a constant fraction (f_{CFD}), the value of the of it has to be chosen according to the signal, to maximize the slope at the instant of the threshold crossing, the chosen value in this case is $f_{CFD} = 0.2$, which is chosen according to previous experiments.

3 Results and Analysis

The results in this paper include studies of BNL W1835 and W9LGA35, taking a reference of SiPM1. The voltage applied on W9LGA35 is 200V and is maintained the same, while the voltage applied on BNL W1835 changes from 140V to 200V. Considering to temperatures of -30^{o}C and -20^{o}C. The bias voltage applied on the reference, SiPM1, is 26V.

All the results and graphs are produced using codes built by ATLAS-HGTD team, PyAna and TimeRes, and have been extracted using ROOT.

3.1 Amplitude and Charge

Pulse amplitude and charge distributions of the W9LGA35 and BNL W1835 are represented in the below figures. Correspoding to different voltages and temperates, the charge distributions are fitted with a Landau function convoluted with a Gaussian function to extract the most probable value.

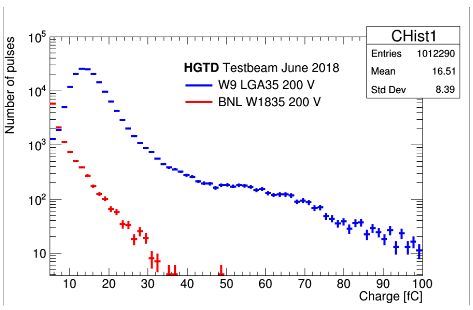

Figure 16: Charge distribution at temperature -20^{o}C.

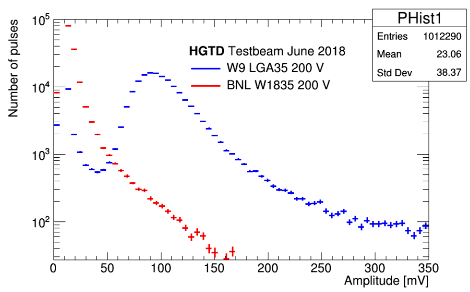

Figure 17: Pulse amplitude distribution at temperature -20^{o}C.

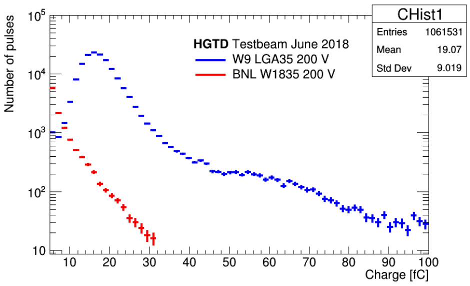

Figure 18: Charge distribution at temperature -30^{o}C.

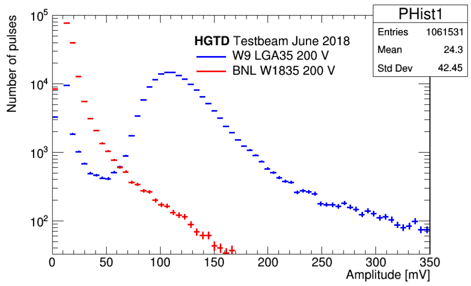

Figure 19: Pulse amplitude distribution at temperature -30^{o}C.

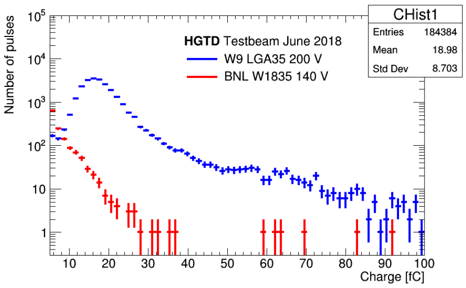

Figure 20: Charge distribution at temperature -30^{o}C.

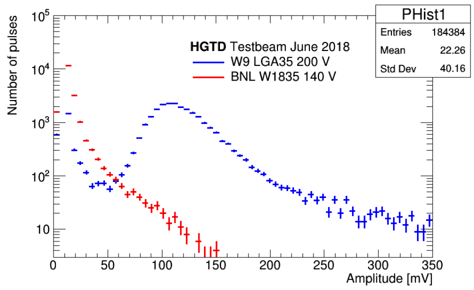

Figure 21: Pulse amplitude distribution at temperature -30^{o}C.

The performance of the sesonrs counts on the charactersitics of the pulse shape (e.g charge, amplitude and rise time). As seen, the increase of temperature shifts the graph in a very tiny amount, which is expected because the change of temperate approximately doesn't effect the results due to the high voltage applied. In addition, the increase of voltage boosts the number of pulses for both charge and amplitude distributions.

3.2 Time Resolution

Time difference graphs for both W9LGA35 and BNL W1835 are represented below for different tempratures, -30^{o}C and -20^{o}C, with a constant voltage for W9LGA35, 200V, and two voltages for BNL W1835, 140V and 200V.

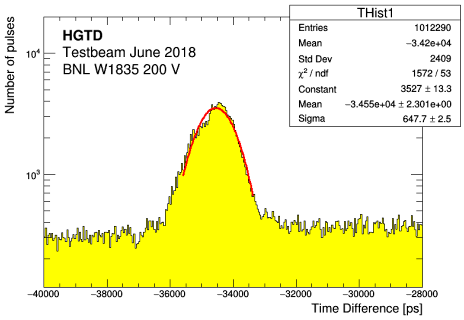

Figure 22: Time difference distribution at temperature -20^{o}C.

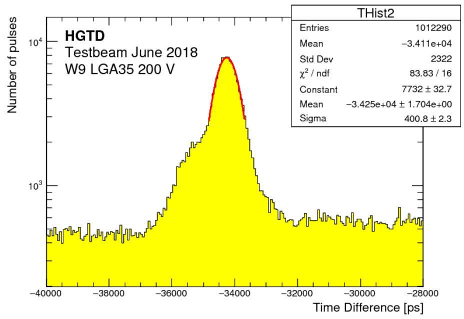

Figure 23: Time difference distribution at temperature -20^{o}C.

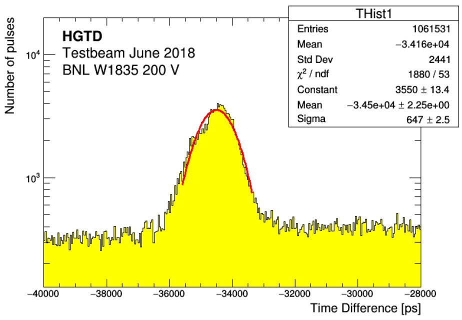

Figure 24: Time difference distribution at temperature 30^{o}C.

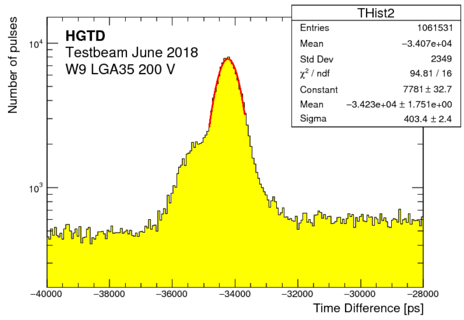

Figure 25: Time difference distribution at temperature -30^{o}C.

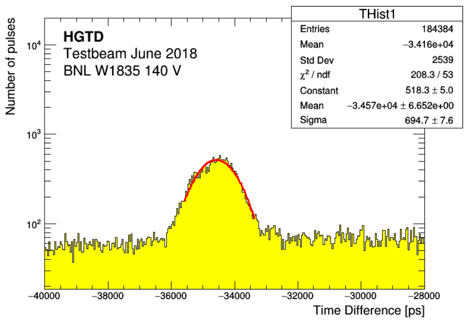

Figure 26: Time difference distribution at temperature -30^{o}C.

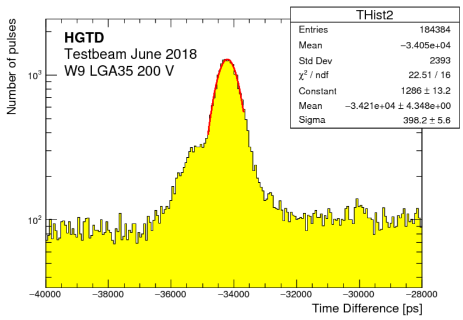

Figure 27: Time difference distribution at temperature -30^{o}C.

These results help in calculating the time resolution of the sensors, as mentioned previously, CFD method is used. By fitting the Gaussian function, and measuring the width of the fitting, the time resolution is calculated and illustrated.

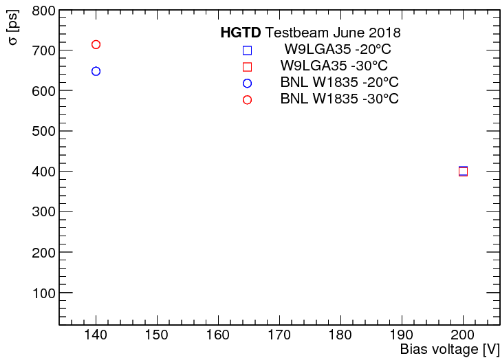

Figure 28: Time resolution for W9LGA35 and BNL W1835.

The goal is to reach to a time resolution of 30ps, it is clear that the time resolution is very high for both W9LGA35 and BNL W1835, even though, W9LGA35 is much lower, which is better. After investigations, the set of data that is used is in bath 1x, which was different than the other batches. The silicon photomultiplier in this batch were running at 26V, instead of 27V, which was used in the other batches. The voltage was too low, and as a result the timing resolution of the referece, SiPM, was very poor. So taking the time difference of the LGAD (W9LGA35 and BNL W1835) and SiPM, the resolution is limited to the worst one, which is the SiPM in this batch because of the incorrect voltage.

4 Conclusion

The High Luminosity Upgrade, which is starting in 2023, will include several upgrades in different systems, including the High Granularity Timing Detector (HGTD). The High Granularity Timing Detector covers the forward region with better radiation protection and effeciency than the Hadronic Calorimeter which was assigned for this mission first. It also solved the most challenging difficulties in the upgrade, like the huge amount of pile-up and high trigger rates.

The results were obtained for two sensors, W9LGA35 and BNL W1835, from data collected during a test beam campaign in June 2018 using a pion beam with energy of 120 GeV at the CERN SPS. Several measurements of single-pad Low Avalanche Gain Detector (LGAD) sensors were investigated and studied. Charge, amplitude and time difference distributions were obtained leading to measuring the time resolution, using the CFD method and Gaussian fittings of the graphs, which is the main aim.

Better performance and time resolution was shown in the first channel, which is corresponding to the sensor W9LGA35, while the second channel, corresponding to BNL W1835, showed a very poor performance. The voltage of W9LGA35 in constant, but when the voltage of the BNL W1835 sensor goes up, the same happens for the number of pulses in the charge and amplitude distributions. Both sensors were not affected significantly because of the change of temperature due to the high voltage.

Both sensors had really poor performance and time resolution compared to what was required, due to the low voltage applied on the reference (SiPM). Increasing the voltage applied on SiPM , from 26V to 27V, resulted in a better data sets compared to the data in batch 1xx.

5 References

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