
Low Gain Avalanche Detectors for the ATLAS High Granularity Timing Detector

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“Colui che non sa niente, non ama niente.

Colui che non fa niente, non capisce niente.

Colui che non capisce niente è spregevole.

Ma colui che capisce, ama, vede, osserva...

La maggiore conoscenza è congiunta indissolubilmente all'amore...

Chiunque crede che tutti i frutti maturino contemporaneamente come le fragole,

non sa nulla dell'uva.”

Paracelso

*We are obsessed with ourselves. We study our history, our psychology, our philosophy, our
gods. Much of our knowledge revolves around man himself,
as if we were the most important thing in the universe.
I think I like physics because it opens a window through which we can see further.
It gives me the sense of fresh air entering the house.*

Carlo Rovelli

*A Clara e Teresa.
Luogo sicuro della mia anima,
dove ritrovare me stessa ogni volta
dopo essermi persa.*

Abstract

The Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN), Geneva, will interrupt its operation in 2026, after the current Run 3, to be upgraded to the High Luminosity LHC (HL-LHC), providing $p - p$ collisions with a center-of-mass energy $\sqrt{s} = 14 \text{ TeV}$ and a luminosity of $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

ATLAS (A Toroidal LHC ApparatuS), one of the two general purpose experiments at the LHC, will have to be upgraded in order to meet the requirements given by the larger luminosity. Among the several upgrades of the ATLAS sub-detectors, the current Inner Detector will be fully replaced by the Inner Tracker (ITk), based on silicon detectors with a fine granularity and improved radiation hardness. A new detector, the High Granularity Timing Detector (HGTD), will provide precise (30 ps to 50 ps) track time information in the forward region.

The combination of the ITk and HGTD measurements will make possible the separation of vertices close in space but separated in time, improving the ATLAS reconstruction performance. In the context of this thesis, a preliminary simulation study was carried out in order to estimate the reduction of the background to Vector Boson Fusion (VBF) analyses using the HGTD.

In the framework of this thesis, the Low Gain Avalanche Detector (LGAD) technology, with which the HGTD detector will be instrumented, has been studied. These silicon sensors consist of planar n-on-p detectors with an extra highly doped p-type layer designed to increase the sensor gain through impact ionization. Thin LGAD sensors have shown a time resolution of about 30 ps on the detection of minimum ionization particles before irradiation. Studies of LGAD sensors produced by CNM with different approaches (dopants) both before and after irradiation to the HGTD required fluence were performed. Many of these exploratory studies were done for the first time in the context of this thesis.

Resumen

El Gran Colisionador de Hadrones (LHC) en la Organización Europea para la Investigación Nuclear (CERN), Ginebra, interrumpirá su operación en 2026, después del actual Run 3, para ser actualizado al High Luminosity LHC (HL-LHC), proporcionando colisiones $p - p$ con un centro de masa de energía $\sqrt{s} = 14 \text{ TeV}$ y una luminosidad de $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

ATLAS (A Toroidal LHC ApparatuS), uno de los dos experimentos de propósito general en el LHC, deberá actualizarse para cumplir con los requisitos dados por la mayor luminosidad. Entre las diversas mejoras de los subdetectores en ATLAS, el detector interno actual será reemplazado completamente por el Inner Tracker (ITk), basado en detectores de silicio con una granularidad más fina y una resistencia a la radiación mejorada. Un nuevo detector, el High Granularity Timing Detector (HGTD), proporcionará información precisa (30 ps to 50 ps) de tiempo de las partículas en la región delantera.

La combinación de las medidas de ITk y HGTD hará posible la separación de vértices cercanos en el espacio pero separados en el tiempo, mejorando el rendimiento de la reconstrucción de ATLAS. En el contexto de esta tesis, se llevó a cabo un estudio de simulación preliminar para estimar la reducción del fondo en los análisis de Vector Boson Fusion (VBF) debido al uso del HGTD.

En el marco de esta tesis, se ha estudiado la tecnología Low Gain Avalanche Detector (LGAD), con la que se instrumentará el detector HGTD. Estos sensores de silicio consisten en detectores planares n-on-p con una capa extra de tipo p altamente dopada diseñada para aumentar la ganancia del sensor a través de la ionización por impacto. Los sensores LGAD delgados han mostrado una resolución de tiempo de alrededor de 30 ps en la detección de partículas de ionización mínima antes de irradiar. Se han realizado estudios de sensores LGAD producidos por CNM con diferentes enfoques (dopantes) tanto antes como después de la irradiación a la fluencia requerida por HGTD. Muchos de estos estudios exploratorios se realizaron por primera vez en el contexto de esta tesis.

Resum

El Gran Col·lisionador d'Hadrons (LHC) de l'Organització Europea per a la Recerca Nuclear (CERN), Ginebra, interromprà el seu funcionament el 2026, després de l'actual Run 3, per actualitzar-se al High Luminosity LHC (HL-LHC), proporcionant col·lisions $p - p$ amb un centre d'energia de massa $\sqrt{s}=14\text{ TeV}$ i una lluminositat de $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

ATLAS (A Toroidal LHC ApparatuS), un dels dos experiments de propòsit general de l'LHC, s'haurà d'actualitzar per tal de complir els requisits donats per la major lluminositat. Entre les diverses millores dels subdetectors a ATLAS, el detector intern actual serà completament substituït per l'Inner Tracker (ITk), basat en detectors de silici amb una granularitat més fina i una resistència de radiació millorada. Un nou detector, el High Granularity Timing Detector (HGTD), proporcionarà informació precisa (30 ps to 50 ps) del temps de les partícules a la regió devantera.

La combinació de les mesures ITk i HGTD farà possible la separació de vèrtexs propers a l'espai però separats en el temps, millorant el rendiment de la reconstrucció d'ATLAS. En el context d'aquesta tesi, es va dur a terme un estudi de simulació preliminar per tal d'estimar la reducció del fons de l'anàlisi de Vector Boson Fusion (VBF) a causa de l'ús de l'HGTD.

En el marc d'aquesta tesi, s'ha estudiat la tecnologia Low Gain Avalanche Detector (LGAD), amb la qual s'equiparà el detector HGTD. Aquests sensors de silici consisteixen en detectors planars n-on-p amb una capa extra de tipus p altament dopada dissenyada per augmentar el guany del sensor mitjançant la ionització d'impacte. Els sensors LGAD primis han mostrat una resolució temporal d'aproximadament 30 ps en la detecció de partícules d'ionització mínima abans d'irradiar. S'han realitzat estudis de sensors LGAD produïts per CNM amb diferents enfocaments (dopants) tant abans com després de la irradiació a la fluència requerida per HGTD. Molts d'aquests estudis exploratoris es van fer per primera vegada en el context d'aquesta tesi.

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Introduction

The Standard Model (SM) of particle physics describes accurately the interactions between particles through three of the four fundamental forces: the electromagnetic, the weak and the strong force, leaving out the gravitational force. Since its formulation, the SM has been validated through several discoveries, such as the discoveries of heavy quarks (*bottom*, *top* and *charm*), the Z and $W^\pm$ bosons and gluons, whose properties were predicted by this model.

The last missing particle of the SM puzzle was the Higgs boson, H , finally observed for the first time by the ATLAS and the CMS experiments at the Conseil Européen pour la Recherche Nucleaire (CERN) Large Hadron Collider (LHC) in 2012 [1, 2].

There are still several open questions that the SM as it is cannot answer. A wide spectrum of models has been proposed by theoretical physicists to expand the SM, the so called Beyond the Standard Model (BSM) theories, with the purpose to address the open questions, such as gravity, dark matter and the observed neutrino masses.

It is expected that at the end of the LHC lifetime the statistical uncertainties will be the major contribution to the total uncertainty in the measurements of rare phenomena. For this reason, the LHC will be upgraded to the High Luminosity LHC (HL-LHC), where the instantaneous luminosity will be about 7 times larger than the LHC design luminosity. An introduction on the LHC accelerator complex and its upgrade to the HL-LHC will be given in Chapter 1 of this thesis.

As the LHC is improved, also the experiments will have to be upgraded, in order to cope with the higher rate of particles. A description of the ATLAS detector will be given in Chapter 2, together with a general view of the upgrade for the HL-LHC. The upgraded Inner Tracker (ITk) detector will be briefly presented, together with its track reconstruction performances. However, the upgraded tracker will have limited resolution power in the forward region where an additional detector will be needed.

The HL-LHC luminosity increase will cause a large number of additional $p - p$ collisions (pileup) that have a determinate effect on the physical performance of ATLAS. To disentangle the primary interaction from the pileup event, ATLAS plan to exploit the time information of the tracker with a High Granularity Timing Detector (HGTD).

The HGTD system, based on the Low Gain Avalanche Detector (LGAD) technology, will be installed in the forward region of the ATLAS experiment, with the main aim of reducing the number of pileup tracks and jets. The LGAD technology is a very recent sensor development that provides silicon devices for High Energy Physics with a timing resolution of 30 ps to 50 ps, high granularity (a pitch of 1.3 mm), and with substantial radiation hardness. The HGTD will be described in detail in Chapter 3. The physics motivation of the detector will be introduced and a detailed description of detector requirements, layout and components will be given.

The HGTD aims to improve the physics performance of ATLAS in the forward region. This means that HGTD should have a positive impact on the Vector Boson Fusion (VBF) analyses. In the context of this thesis, preliminary simulation studies were carried out on the VBF $H \rightarrow \tau\tau$ channel. These are presented in Chapter 4.

The HGTD detector will be instrumented with LGAD sensors, which are silicon detectors. Chapter 5 will be dedicated to the explanation of the basic principle of solid state detectors and to the description of silicon detectors in particular, considering especially their behaviour after irradiation. In the second part of the chapter, the LGAD technology will be described and an overview of the sensors which have been studied will be presented.

In Chapter 6, the core of this thesis work, the characterization and performance of the LGAD

sensor fabricated at the Centro Nacional de Microelectronica (CNM) are presented. In an attempt to improve the LGAD performance, several approaches and production were studied. The electrical characterization, charge collection, time resolution, hit reconstruction efficiency and device stability of the sensor are presented. The measurements were conducted at the Institut de Física d'Altes Energies (IFAE) and CNM laboratories and in various test beams at CERN and Deutsches Elektronen-Synchrotron (DESY).

Finally, the work is discussed and the outlook presented in the conclusions.

Chapter 1

The LHC accelerator complex

The LHC [3] accelerator is located at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland. The accelerator complex is a succession of machines that accelerate particles to increasingly higher energies. Each machine boosts the energy of a beam of particles before injecting it into the next machine in the sequence. The LHC became operational in September 2008, and is the last element in this chain, see Figure 1.1. The LHC is made up of a 27 km ring of superconducting magnets with a number of accelerating components along the way to raise the energy of the particles. Protons are accelerated at a speed close to the speed of light in bunches of 10^{11} particles with a 25 ns separation, in two different beam pipes which are kept at ultrahigh vacuum. The two particle beams run in opposite directions. A strong magnetic field maintained by the superconducting electromagnets guides the beams around the accelerator ring. The electromagnets are made up of coils of a special electric cable that operates in a superconducting condition, allowing electricity to flow without resistance or energy loss. This necessitates cooling the magnets to a temperature of -271.3°C , which is colder than the outer space. To cool the magnets and other supply services, a big part of the accelerator is connected to a liquid helium distribution system. To steer the beams around the accelerator, tens of thousands of magnets of various types and sizes are used. The beams are bent by 1232 dipole magnets with a length of 15 m each, while they are focused by 392 quadrupole magnets with a length of 5-7 m each, generating

The CERN accelerator complex *Complexe des accélérateurs du CERN*

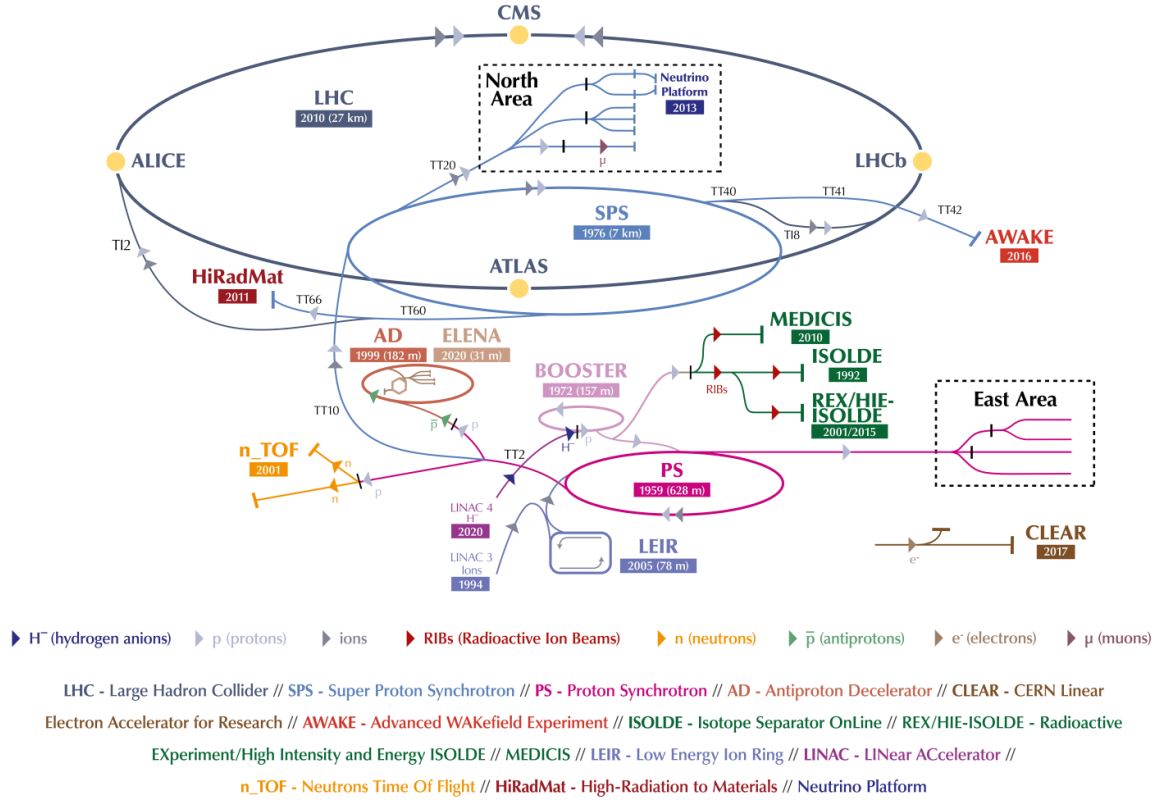


Figure 1.1: Schematic of the Large Hadron Collider accelerator complex [3].

a magnetic field of 8.3 T. Another sort of magnet is employed just before the collision to “squeeze” the particles closer together and improve the odds of collision. In the LHC, proton collision are generated at 40 MHz with a center of mass energy of 14 TeV at the design luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Heavy ions collisions are also provided in the LHC, at 5.5 TeV per nucleon pair at a luminosity of $10^{27} \text{ cm}^{-2}\text{s}^{-1}$. The beams inside the LHC are then made to collide at four points around the accelerator ring, which correspond to the location of the four bix experiments: ATLAS [4], CMS [5], A Large Ion Collider Experiment (ALICE) [6], and Large Hadron Collider beauty (LHCb) [7]. The ATLAS and the CMS are two multipurpose experiments placed at the two opposite sides of the LHC ring. Both experiments look at final states of p-p and heavy ions collisions searching for new physics and to perform precise

measurements of the SM parameters. ALICE is a detector dedicated to heavy-ion physics at the LHC. It is designed to study the physics of strongly interacting matter at extreme energy densities, where a phase of matter called quark-gluon plasma forms. The LHCb experiment investigates the differences between matter and antimatter by studying the “beauty” particle, or “ b quark”.

1.1 Upgrade for HL-LHC

The LHC restarted its operation at the beginning of 2022 after a maintenance period where its experiments have been upgraded to “Phase 1” and are now ready to take data for a period of 4 years (Run 3). It will remain the most powerful accelerator in the world for at least the next two decades. To maintain scientific progress and to exploit the machine’s full capacity, the LHC luminosity will be increased by a factor of ~ 7 in what is called the Phase-II upgrade. The HL-LHC [8, 9, 10] era is foreseen to start in 2029. It will provide a revolutionary machine configuration, which will rely on a number of critical innovative technologies that constitute outstanding technological challenges. These include cutting-edge 11-12 T superconducting magnets, very small superconducting cavities for beam rotation with ultra-precise phase control, revolutionary beam collimation technology, and high-power superconducting links with low energy dissipation. The HL-LHC targets to reach a peak luminosity of $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and an integrated luminosity of 250 fb^{-1} every year. In its entire lifetime, see Figure 1.2, the HL-LHC aims to collect up to 4000 fb^{-1} , which is almost ten times the luminosity reached for LHC in its first twelve years.

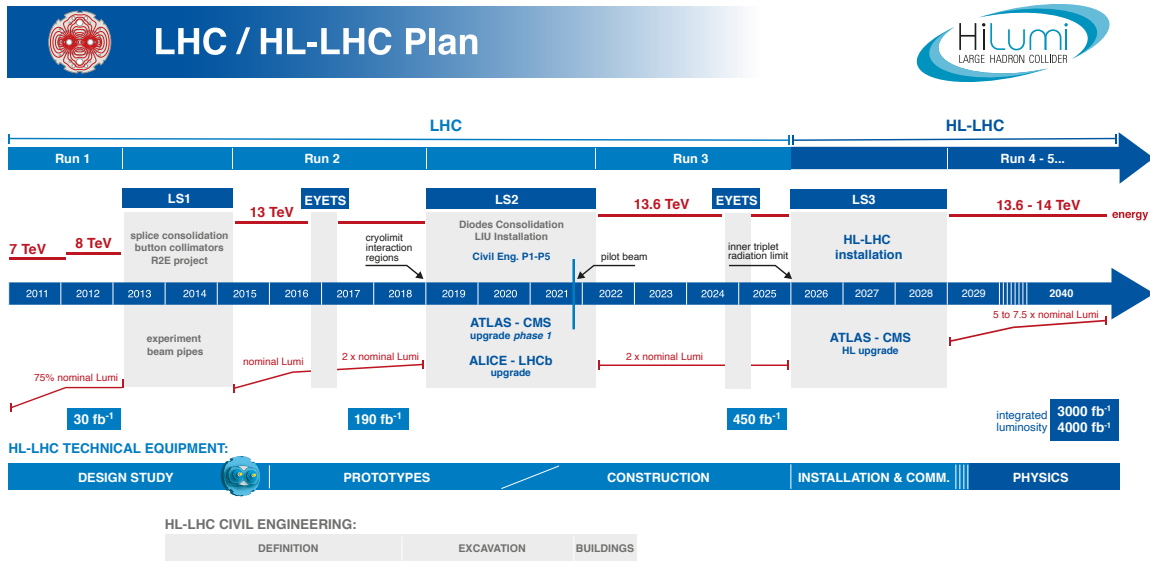


Figure 1.2: HL-LHC timeline updated in January 2022[11].

Chapter 2

The ATLAS experiment

2.1 Overview of the ATLAS detector

ATLAS is a general purpose detector located about 100 m underground at the interaction point 1 of the LHC. It has a shell-like structure and it has cylindrical and forward-backward symmetry with respect to the interaction point. Each detector component corresponds to a specific sub-detector for tracking of charged particles, electromagnetic and hadronic calorimetry and muon detection. The entire detector has a length of 44 m and a diameter of 25 m for a total weight of 7000 kg, for which a sketch is shown in Figure 2.1, ATLAS has a magnet system which consists of a superconducting solenoid surrounding the inner detector cavity, and three large superconducting toroids, two at the end-caps and one barrel around the calorimeters. The detector uses a right-hand coordinate system with its origin in the nominal interaction point. The beam direction defines the z -axis and the plane $x - y$ is transverse to the beam. The positive direction of the x -axis is pointing to the centre of the LHC ring, while for the y -axis it is pointing upwards. The side A of the detector defines the positive z -axis and the side C the negative one. The azimuthal angle, ϕ , is measured around the beam axis and the polar angle, θ , is the angle from the beam axis. The pseudorapidity is defined as $\eta = -\ln \tan(\theta/2)$. The transverse momentum, p_T , the transverse energy, E_T and the

missing transverse energy, E_T^{miss} , are defined in the $x - y$ plane. The distance, ΔR , in the pseudorapidity-azimuthal space is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ [4]. 2.1.

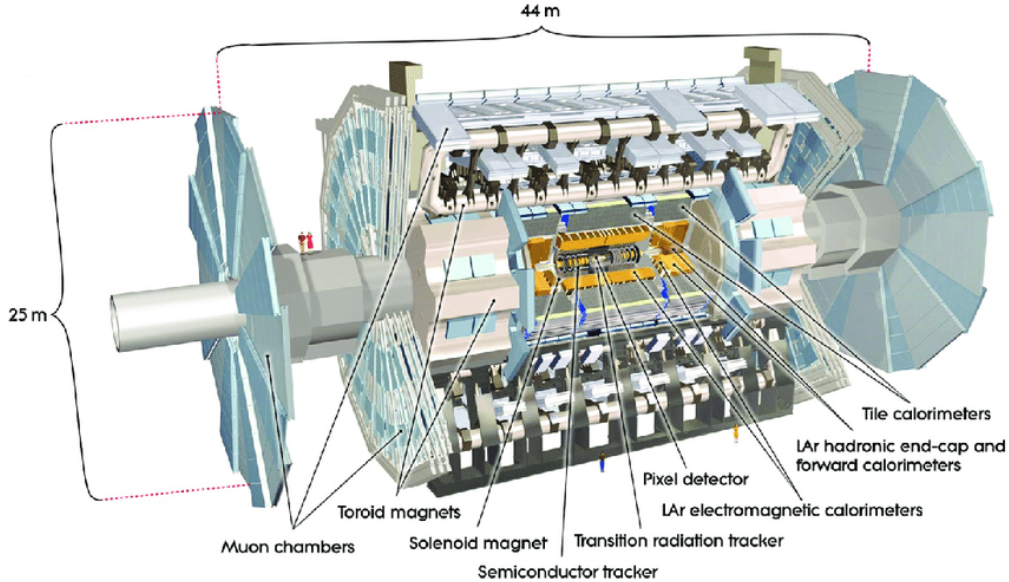


Figure 2.1: Cut-away view of the ATLAS detector. Its dimensions are 25 m in height and 44 m in length for a total weight of 7000 kg [4].

2.1.1 Inner detector

The Inner Detector (ID) is the most internal ATLAS detector system. It is designed to provide robust pattern recognition, excellent momentum resolution and primary and secondary vertex measurements for charged tracks produced in the $p - p$ collisions above a p_T threshold (nominally 0.5 GeV) and within the pseudorapidity region $|\eta| < 2.5$. It is immersed in a solenoidal magnetic field of 2 T which bends the particle trajectory giving information on their momentum. The layout of the ATLAS ID is shown in Figure 2.2 and it consists of three sub-detectors: the Pixel Detector [12] that includes the Insertable B-Layer (IBL) [13], the SemiConductor Tracker (SCT) [14] and the Transition Radiation Tracker (TRT) [15]. The Pixel and SCT detectors provide precise track measurements at inner radii in the pseudorapidity region $|\eta| < 2.5$. The measurements from the TRT detector at larger radii provides continuous tracking

to enhance the pattern recognition and improves momentum quantification.

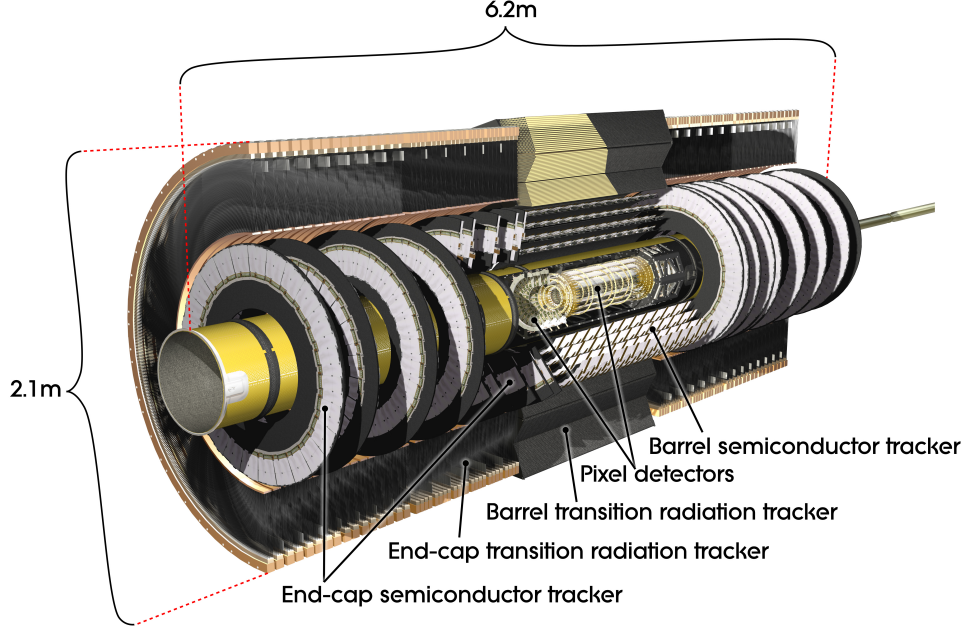


Figure 2.2: Cut-away view of the ATLAS ID [4].

Pixel Detector

Originally, the Pixel Detector consisted of three barrel layers at a radius $r_1=50.5$ mm, $r_2=88.8$ mm and $r_3=122.5$ mm with a length of 80 cm. Three end-cap discs are placed at the two ends of the Pixel detectors at $|z_1|=49.5$ cm, $|z_2|=58.0$ cm and $|z_3|=65.0$ cm. The sensing material of the Pixel Detector are silicon sensors. The sensors are operated in the temperature range from -5°C to -10°C , in order to reduce leakage current, contain annealing effects and to meet charge requirements with respect to the level of irradiation. The sensors are n-in-n standard planar sensors with a pixel size of $50\text{ }\mu\text{m} \times 400\text{ }\mu\text{m}$. Each pixel module is made of 2×8 FE-I3 readout chips [16] bump-bonded to a sensor tile of an area of $63.4\text{ mm} \times 24.4\text{ mm}$ and $250\text{ }\mu\text{m}$ -thick. A flexible printed circuit board connects the module with the readout system via a flex cable. In 2015, the IBL [13] was inserted as a fourth layer at a radius $r=32.0$ mm covering the region $|z| < 33.2$ cm. It was installed to improve the impact parameter resolution of the detector and the robustness of the system against possible failures during operation.

The central part of the IBL is made of n-in-n planar sensors, while at the ends of the barrel n-in-p 3D sensors are used. Both sensors have pixels of size $50\text{ }\mu\text{m} \times 250\text{ }\mu\text{m}$ interconnected to a FE-I4 readout chip [17]. From beam test data, it has been calculated that the Pixel Detector has a resolution of $12\text{ }\mu\text{m}$ for normal incidence, which does not significantly degrade after irradiation. The resolution for an incidence angle of 10° - 15° (expected given the IBL geometry) has been found to be $4.7\text{ }\mu\text{m}$ and $6.0\text{ }\mu\text{m}$ respectively before and after irradiation to $10^{15}\text{ n}_{eq}/\text{cm}^2$ [18].

SemiConductor Tracker

The SCT detector consists of 4088 two-sided modules and more than 6 million readout strips. It covers an area of about 60 m^2 with silicon microstrip sensors distributed in four barrel layers and nine end-caps per side. The barrels have radii $r_1=29.9\text{ cm}$, $r_2=37.1\text{ cm}$, $r_3=44.3\text{ cm}$ and $r_4=51.4\text{ cm}$ and a length of 149 cm . The microstrip sensors are made of p-in-n silicon sensors. The barrel sensors have a pitch of $80\text{ }\mu\text{m}$ and the ones in the end-caps have a pitch in the range from $50.9\text{ }\mu\text{m}$ to $90.4\text{ }\mu\text{m}$. The position of charged particles can be recorded with an accuracy of $17\text{ }\mu\text{m}$ per layer, in the transverse direction to the strips.

Transition Radiation Tracker

The TRT is a gas detector consisting of 4 mm diameter straw tubes, with 52544 straws in the barrel section with a length of 144 cm , and 122880 straws for each end-cap with a length of 39 cm , for a total volume of 12 m^3 . The barrel straws cover a radius range from $56\text{ cm} < R < 107\text{ cm}$ and the ones in the end-caps cover the interval $64\text{ cm} < R < 100\text{ cm}$ in the region $85\text{ cm} < |z| < 271\text{ cm}$. The straws are filled with a mixture of Xenon, Carbon Dioxide and Oxygen in percentage 70%/27%/3%. Each tube has a $31\text{ }\mu\text{m}$ diameter gold-plated Tungsten anode wire in the centre. Between the edge of the tube and the wire there is a potential difference of 1500 V which allows the collection of ionization charges. The achieved position accuracy is $130\text{ }\mu\text{m}$ and the hit registration efficiency is 85% at a TRT operation

threshold of 250-300 eV.

2.1.2 Calorimeters

Calorimeters are detectors whose aim is to measure the energy that a particle loses passing through the detector elements. In High Energy Physics (HEP) calorimeters are designed to absorb most of the energy of the particles coming from a collision, usually stopping them within their volume. Calorimeters can be homogeneous or sampling calorimeters. The first ones are made entirely of sensitive material and all the deposited energy contributes to the signal. Sampling calorimeters instead, consist of two different elements, a sensitive one which measure the energy of particles and a high density absorber material which stops them. This last approach allows to design more compact detectors but they have to be carefully calibrated in order to obtain the particle energy from the energy measured inside the sensing material, since the absorber element does not provide a measurement. Calorimeters can stop most of the known particles except muons and neutrinos. The ATLAS calorimeter system consists of three sampling calorimeter sub-detectors: the Electromagnetic, the Hadronic and the Forward calorimeters, with full ϕ -symmetry and coverage around the beam axis, and covers a pseudorapidity region $|\eta| < 4.9$. The full calorimeter system is shown in Figure 2.3.

Electromagnetic Calorimeter

The Liquid Argon (LAr) Electromagnetic CALorimeter (ECAL) [19] surrounds the ATLAS ID, measuring the energy of electrons, photons, and hadrons. It is designed to absorb the energy of electrons and photons in the range $50 \text{ MeV} < E < 3 \text{ TeV}$ and measures their impinging directions. In addition, it participates in the reconstruction of the initial part of hadronic jets which start their shower in the electromagnetic calorimeter. The ECAL calorimeter consists of layers of lead, used as absorber, and liquid Argon, as the sensing medium. It is divided into a barrel and two ElectroMagnetic End-Cap (EMEC) components,

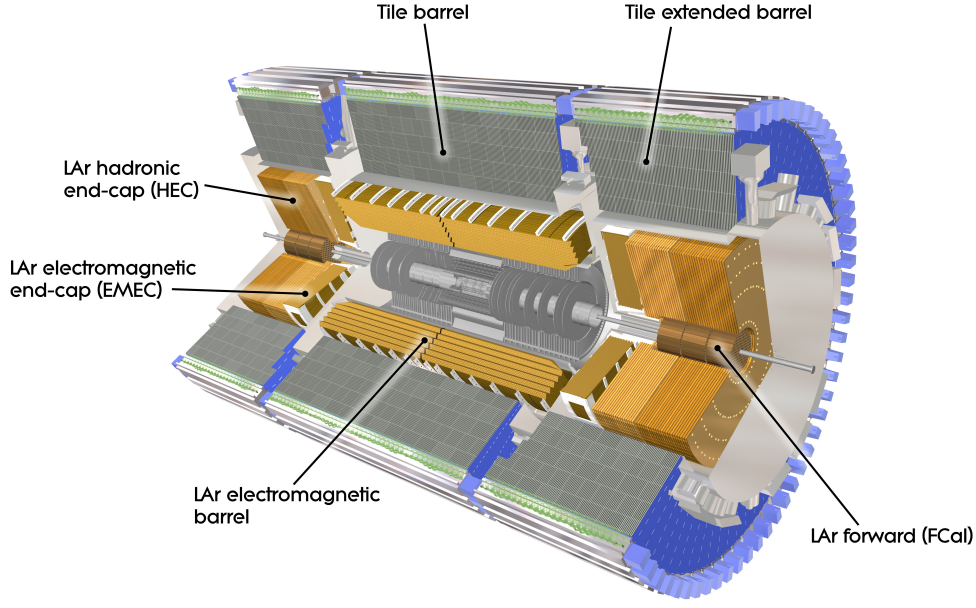


Figure 2.3: Cut-away view of the ATLAS Calorimeter system [4].

covering the pseudorapidity range $|\eta| < 1.475$ and $1.375 < |\eta| < 3.2$ respectively, each of them housed in its cryostat. The impinging particles ionize the liquid argon sandwiched between the absorbing layers, resulting in a measurable electric current. The energy of the original particle that impacted the detector can be calculated by combining the observed currents. The calorimeter is kept at -184°C to keep the Argon in liquid state. Electronic signals are sent from the cold liquid argon to the warm area where the readout electronics are placed via specially built, vacuum-sealed cylinders of cables. A half-barrel is made of 1024 accordion-shaped absorbers interleaved with readout electrodes, divided into 16 modules. The total thickness of each module is at least 22 radiation lengths (X_0), increasing from $22 X_0$ to $30 X_0$ between $|\eta|=0$ and $|\eta|=0.8$ (barrels) and from $24 X_0$ to $33 X_0$ between $|\eta|=0.8$ and $|\eta|=1.3$ (end-caps). This thickness ensures the full confinement of the electromagnetic showers in the calorimeter.

Hadronic Calorimeter

The Hadronic CALorimeter (HCAL) [20] samples the energy of particles which escapes the ECAL. These are usually jets with high energy originating from quark and gluon hadronization. The HCAL absorbs the remaining particles except muons which leave tracks in the muon spectrometer, and neutrinos which leave the detectors without depositing their energy. The HCAL consists of two parts: the Tile Calorimeter (TileCal) [20] in the central region and the Liquid Argon End-Cap (HEC) calorimeter in the forward region. The TileCal surrounds the LAr calorimeter and is a sampling calorimeter using steel as absorber and plastic scintillator as active medium. When a particle hits the steel layer a shower of new particles is generated. Photons are produced in the scintillator and are converted into an electric current which is proportional to the energy of the original particle. The TileCal is made of 420000 plastic scintillator and is the heaviest part of the ATLAS experiment, with a weight of about 2900 t. It covers the pseudorapidity region $|\eta| < 1.7$ with a central barrel in the $|\eta| < 1.0$ region and two extended barrels covering the region $0.8 < |\eta| < 1.7$. It extends radially from 2.28 m to 4.25 m and is split into three sections of 1.5, 4.1 and $1.8 \lambda^1$ (interaction lengths) in the central barrel and 1.5, 2.6 and 3.3λ in the extended barrels. The HEC calorimeter is a copper liquid-argon sampling calorimeter with a flat plate design, covering a pseudorapidity range $1.5 < |\eta| < 3.2$. It shares each of the two liquid-argon end-cap cryostats with the EMEC and the Forward Calorimeter (FCAL). It consists of two wheels with a radius of 2030 mm, each of them containing two longitudinal sections.

Forward Calorimeter

The FCAL consists of an electromagnetic calorimeter and two hadronic ones placed in a pseudorapidity range $3.1 < |\eta| < 4.9$ in order to maximize the detector acceptance at low radii. Since they are located at high η , at a distance of about 4.7 m from the Interaction Point (IP), they are exposed to a high particle flux. This resulted in a design with smaller

¹ λ is defined as the distance after which the number of elements of the hadronic shower is reduced by a factor $1/e$.

liquid-argon gaps than the 2 mm ones of the electromagnetic barrels to avoid ion build-up and to provide the highest possible density. Each FCAL is divided into three 45 cm deep modules, one electromagnetic and two hadronic. Liquid Argon is used as a detector medium and the absorber layers are Copper-based in the electromagnetic part and Tungsten-based in the hadronic ones. The depth of those calorimeters are $27.6 X_0$ for the electromagnetic part and 3.62λ and 3.55λ for the hadronic ones.

2.1.3 Muon Spectrometer

Muons escape from barrel and end-caps calorimeters without showering, for this purpose a muon spectrometer forms the outer part of the ATLAS detector. The muon detector is designed to detect charged particles and to measure their momentum in the pseudorapidity range $|\eta| < 2.7$. It is also designed to trigger on these particles in the region $|\eta| < 2.4$. The ATLAS muon spectrometer [21] system is shown in Figure 2.4 and is composed by four sub-detectors. The Monitored Drift Tube (MDT) chambers covering the pseudorapidity range $|\eta| < 2.7$, and the Cathode-Strip Chambers (CSC) covering the range $2.0 < |\eta| < 2.7$, perform momentum measurements through the curvature of muon tracks in the magnetic field produced by toroid magnets described in Section 2.1.4. The muon spectrometer is completed by detectors capable to trigger on muon tracks: the Resistive Plate Chambers (RPC) in the barrel region ($|\eta| < 1.05$) and Thin Gap Chambers (TGC) in the end-cap ($1.05 < |\eta| < 2.4$). These two measure both coordinates of the track, both in the bending (η) and non-bending (ϕ) plane. If any ambiguity in η and ϕ -assignment is present, for example by a two body decay of low mass particles, this is resolved matching the muon track candidates with tracks in the inner detector.

Monitored Drift Tube chamber

MDT consists of three to eight layers of drift tubes, achieving an average resolution of $80 \mu\text{m}$ per tube. Their basic element is a pressurised $400 \mu\text{m}$ aluminium drift tube with a diameter

of 29.970 mm filled with a mixture of Ar and CO₂ (93/7) at 3 bar. The length varies from 0.9 to 6.2 m, for a total of 1150 chambers. The achieved position resolution is about 35-50 μm for 6 or 8 layers chambers. When a charged particle passes through the tube, the electrons generated by the gas ionization are collected by the central tungsten-rhenium wire of 50 μm diameter at a potential of 3080 V. The operation of MDTs is limited in the first layer of end-cap, where the counting rates exceed the limit for safe operation in the detector. During the 2016/17 winter shutdown, new MDT drift tubes with diameter of 1.5 cm were installed to improve the muon momentum reconstruction [22].

Cathode-Strip Chamber

The CSC substitute the MDT of the first layer of the end-cap, covering the pseudorapidity range $2.0 < |\eta| < 2.7$. CSC combine high spatial, time (7 ns) and double track resolution with high-rate capability and low neutron sensitivity. CSC are multi-wire proportional chambers segmented in large and small chambers in ϕ , where the wires are oriented in the radial direction. The CSC system consists of two disks with eight chambers each, with each of them containing four CSC planes resulting in four independent measurements in η and ϕ along the track, reaching a position resolution of 60 μm . Both cathodes are segmented, one with the strips perpendicular to the wires (providing the precision coordinate) and the other with strips parallel to them (providing the transverse coordinate). The position of the track is obtained by interpolation between the charges induced on neighbouring cathode strips, while the CSC wire signals are not read out. The CSC chambers are filled with a mixture of Ar and CO₂ (80/20).

Resistive Plate Chamber

The RPC chambers offer quick information (1 ns time resolution) on muon tracks as they pass through the detector, allowing the L1 trigger logic to recognize their multiplicity and estimate their energy range. RPCs can be operated both in avalanche and streamer mode.

In the LHC environment, the avalanche mode offers the benefit of higher rate capability and rate-independent time resolution and has therefore been selected as the operation mode. At the nominal operating voltage, a signal with a width of about 5 ns is generated by the track with a streamer probability of less than 1%. In the barrel region, the trigger system consist of three cylindrical layers around the beam axis. The arm between inner and outer RPC's permits the trigger to select high momentum tracks in the energy range 9-35 GeV (high- p_T trigger), while the two inner chambers provide the low- p_T trigger in the range 6-9 GeV. RPCs are gaseous parallel electrode-plate detectors. The signal is read out through capacitive coupling to metallic strips mounted on the outer faces of the resistive plates, biased at about 10 kV. The gas used is a mixture of $C_2H_2F_4$ /Iso- C_4H_{10} / SF_6 (94.7/5/0.3) which is a good combination between low operating voltage, non-flammability and low cost, with a safe plateau for avalanche operation. RPCs cover the pseudorapidity region $|\eta| < 1.05$.

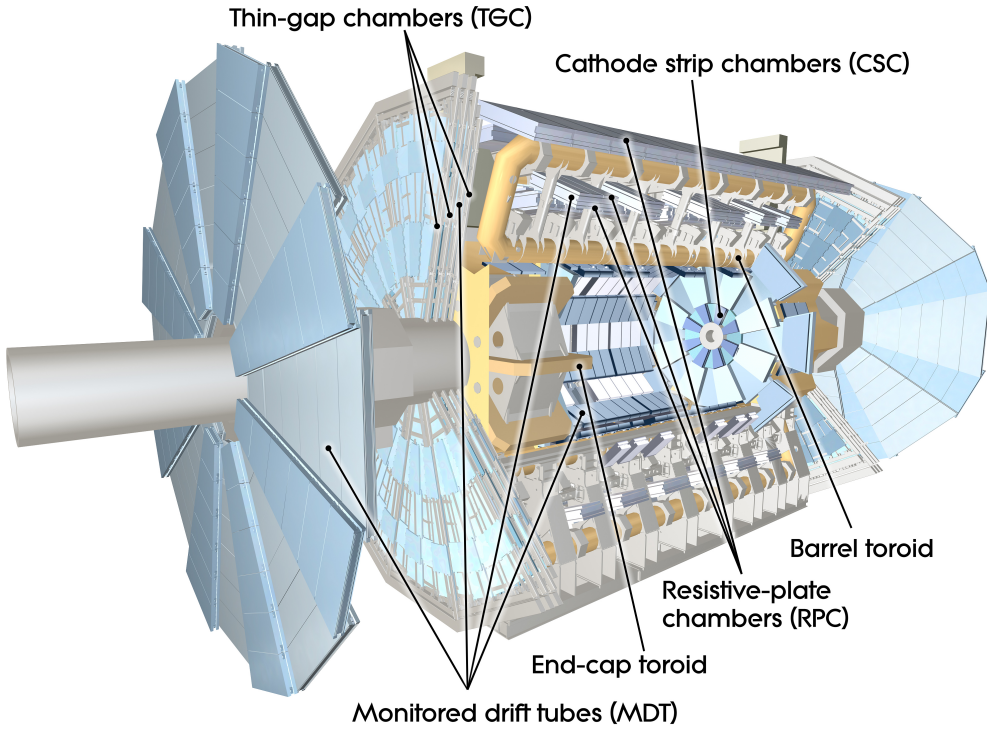


Figure 2.4: Cut-away of the ATLAS muon system [4].

Thin Gap Chamber

TGC provides muon trigger in the end-cap region of the muon spectrometer, but also the determination of an azimuthal coordinate to complement the measurements of the MDT's in the radial direction, measured by the radial strips. TGC need also good time resolution to tag the beam crossing with high efficiency and fine granularity. TGCs are multi-wire proportional chambers with a wire-to-cathode distance of 1.4 mm smaller than the wire-to-wire one (1.8 mm), covering the forward region in the range $1.05 < |\eta| < 2.4$. The gas mixture used is a highly quenching one of CO_2 and $\text{n-C}_5\text{H}_{12}$ (55/45) which allows operation in a quasi-saturated mode with a gas gain of 3×10^5 . The wire is biased at about 2.9 kV. Each chamber provides a spatial resolution of 1 mm and a time resolution of 5 ns.

2.1.4 Magnets

The ATLAS detector features a hybrid system of four superconducting magnets [23]. This system is 22 m in diameter and 26 m long, with a stored energy of 1.6 GJ. The magnet system consists of two sub-systems, a solenoid aligned with the beam axis providing 2 T axial magnetic field for the inner detector, and a barrel toroid and two end-cap toroids which produce a toroidal magnetic field of 0.5 T and 1 T for the muon detectors in the central and end-cap regions, providing the magnetic field over a volume of approximately $12\,000\text{ m}^3$. The four superconducting magnets of the ATLAS detector are shown in Figure 2.5.

Central solenoid

The central solenoid is designed to provide 2 T axial magnetic field at the nominal operational current of 7.730 kA. The solenoid windings and LAr calorimeter share a common vacuum vessel in order to keep the material thickness in front of the calorimeter as low as possible, resulting in a total of $\approx 0.66 X_0$ [24] for a normal incidence. The coils are wound with a Al-stabilized NbTi conductor developed in order to achieve high magnetic field with a reduced

thickness. The inner and outer diameters of the solenoid are 2.46 m and 2.56 m for a length of 5.8 m, with a mass of 5.4 t and a stored energy of 40 MJ.

Barrel toroid

The barrel toroid provides magnetic field in the cylindrical volume surrounding the calorimeters and both end-cap toroids. The barrel toroid consists of eight coils encased in individual vacuum vessels. The coils conductor material is Nb/Ti/Cu and is the same used for the End-Cap Toroids. Those coils are 25.3 m-long and 10.7 m high, placed at about 9 m from the beam axis. The nominal current is about 20.5 kA generating a toroidal magnetic field with a maximum of 3.9 T and a stored energy of 1.08 GJ.

End-cap toroids

The end-cap toroids generate the magnetic field required for optimizing the bending power in the end-cap regions of the muon spectrometer system. Each end-cap consists of eight flat coils elements extending from a radius of 83 cm to 5 m for a weight of 239 per side. The magnetic field range is from 0.2 T to 3.5 T and the nominal current is 20.5 kA. 2.5.

2.1.5 Forward detectors

Other detectors are located far away from the interaction point and very close to the beam axis. Those detectors have been designed for specific purposes, such as luminosity measurements and diffractive physics.

ALFA

The Absolute Luminosity For ATLAS (ALFA) detector is located at $|z| = 240$ m. It consists of scintillating fibre trackers located in four Roman Pots, two per each side. Roman Pots

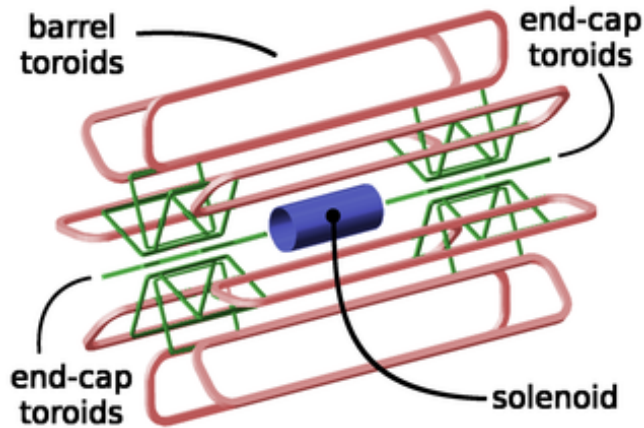


Figure 2.5: Illustration of the ATLAS detector superconducting magnets.

can be moved towards the beam for dedicated data taking runs, until reaching a distance of about 1 mm from the beam. The purpose of ALFA is to measure elastic p-p scattering in the very forward region. The elastic scattering in the very forward direction can also be used for luminosity measurements. Protons reaching the ALFA detector have an energy close to the one of the beam, and they can be detected with high position resolution ($30\text{ }\mu\text{m}$) in both directions.

AFP

The ATLAS Forward Proton (AFP) detector [25] looks for diffractive events where protons leave intact from the collision with a small diffractive angle. The AFP detector is placed at $|z| = 205\text{ m}$ (NEAR stations) and $|z| = 217\text{ m}$ (FAR stations) from the IP, with a total of four Roman Pots, two per each side of the ATLAS detector. Each Roman pot hosts tracking layers, while one Roman Pot on each side of the IP hosts a timing detector. The Silicon Tracker (SiT) is present in all four stations and it consists of four silicon 3D pixel detector planes mounted in each Roman Pot. They provide tracking with $10\text{ }\mu\text{m}$ and $30\text{ }\mu\text{m}$ position

resolution in x and y , respectively. The 3D silicon pixel sensor technology is the same used for the IBL sensors. Time Of Flight (TOF) detectors are held only in the FAR stations. They provide time information with 20 ps resolution to match the proton detected by AFP with the ATLAS primary vertex. In 2016 the first arm of the detector with SiT was installed in the tunnel and data to study tracker performances were recorded in dedicated low luminosity runs. In the 2016/2017 winter shutdown the silicon trackers were installed on both sides of ATLAS and in 2017 AFP participated in ATLAS high-luminosity data taking. A study of the performances of this detector during 2017 can be found in [26]. TOF detectors were finally installed in the 2019/2020 winter shutdown.

LUCID

The LUMinosity Cherenkov Integrating Detector (LUCID) [27] is placed at $|z| = 17$ m from the IP. It detects the inelastic $p - p$ scattering in the forward region and measures the integrated luminosity delivered to ATLAS. It is also the main ATLAS monitor for online luminosity. It is a Cherenkov light detector using aluminium tubes filled with C_4F_{10} surrounding the beam pipe.

2.1.6 Trigger System

Level-1 (L1), Level-2 (L2), and event filter are the three levels of the trigger system. Each trigger level refines the previous level's decisions and, eventually, adds more selection criteria. The L1 trigger looks for detector signals consistent with muons, electrons, photons, jets, and τ -leptons decaying to hadrons with high transverse momentum, as well as big missing and total transverse energy. It makes a choice on whether or not to analyze an event using a subset of the whole detector information, decreasing the data rate to around 75 kHz. It determines one or more Region of Interest (ROI) in each event, which are defined as the geographical coordinates in η and ϕ where the selection process has discovered interesting features. The ROI data includes details on the type of feature found and whether or not the requirements

were met. The ROI information is fed into the L2 selection via a special data route provided by the L1 trigger. In roughly 40 ms, the L2 trigger drops the trigger rate to approximately 3.5 kHz. The event filter performs the final stage of event selection, reducing the data-taking rate to around 200 Hz.

2.2 ATLAS upgrade for HL-LHC

In order to cope with the increase of proton collision rate in the HL-LHC, the ATLAS experiment has planned a series of detector improvements [28]. The data collection for the HL-LHC is planned to begin in 2029, as shown in Figure 1.2, with an average pileup of about 200 collisions per bunch crossing. Detector improvements are required to maintain performance and thus to meet the ATLAS physics objectives. The luminosity increase also poses a significant challenge to the detectors (mostly due to radiation hardness), trigger and data acquisition systems. The Phase-II upgrade programme foresees interventions in the following subdetector systems: pixel and strip trackers, LAr and Tile calorimeters, muon, trigger and data acquisition systems. Details of these improvements can be found in the technical design reports of each system [29, 30, 31, 32].

The ID will be replaced with a more radiation hard and with a finer granularity detector: a full silicon based ITk. This upgrade will be discussed in more detail in Section 2.2.1. Regarding the calorimeter system, the current electronics is not compatible with Phase-II requirements for latency, trigger rate and radiation hardness. For this reason, a new front-end and back-end electronics will be installed. The Tile Calorimeter foresees a complete replacement of photomultiplier tubes in the most exposed region and also a full replacement of on-detector and off-detector electronics. The muon system upgrade will help to reduce triggers not coming from muons in the barrel and end-cap regions and to increase geometrical coverage in the barrel region where new MDTs and RPCs will be installed. RPC will also be installed on top of the existing MDT in large sectors. In the end-cap region, new TGC will be installed. These chambers will be based on a triple layer geometry (instead of a double one), in order to allow

a more robust coincicende algorithm.

2.2.1 Inner Tracker

The ATLAS tracking system needs to be upgraded in order to maintain its performance after the HL-LHC upgrade, given the larger pileup and luminosity that have to be sustained. To face the larger pileup of approximately 200 inelastic p-p iterations per bunch crossing, finer granularity than the current detector will be used, while the large fluence requires more radiation hard detectors.

This section will discuss the baseline and the expected performance of the ITk detector, which will have to operate up to an integrated luminosity of 4000 fb^{-1} .

Detector layout

ITk is a full silicon detector which consists of two sub-detectors: a Strip Detector surrounding a Pixel Detector. The strip detector is made of four barrel layers and six end-cap petal-design disks per side. The strip detector covers the region $|\eta| < 2.7$, and it is complemented by a 5 layer pixel detector which extends the coverage until $|\eta| = 4$. The schematic layout of the ITk detector is shown in Figure 2.6. The modules are placed on both sides of the mechanical structure of the Strip Detector, with the two strips sensors having a slight stereo angle between them. The modules are placed in the barrels in a way that the strips run nearly parallel to the beam axis, while the end-caps follow the radial direction to measure the ϕ coordinate with a high resolution. The stereo angle also enables the measurement of the z and R coordinates in the barrel and end-cap regions.

Radiation dose and fluence studies

Due to the increase in luminosity and in the rate of proton-proton collisions, the expected radiation level in the ATLAS ITk will increase by an order of magnitude compared to the present

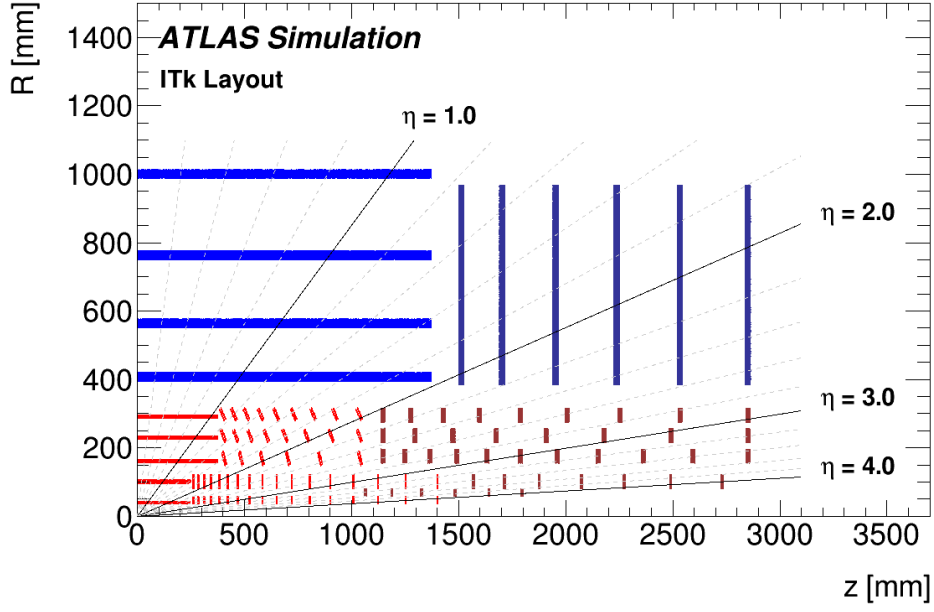


Figure 2.6: Schematic layout of the ITk detector. The active elements of the barrel and end-cap Strip Detector are shown in blue, sensors for Pixel Detector are shown in red for the barrel layer and in dark red for the end-cap rings. The horizontal axis is the beam axis with the zero being the interaction point [29].

Inner Detector. Simulations for particle fluences and ionising dose for the ITk layout assume an integrated luminosity of 4000 fb^{-1} . Figure 2.7 shows the fluence and total ionising dose distributions for the Pixel Detector for 1 MeV neutron equivalent fluence and dose normalized to 4000 fb^{-1} . In the innermost layer of the ITk pixel barrel region, fluences are dominated by particles coming from the interaction point, while in the outer barrel layers and in the end-caps this is dominated by particles coming from secondary interactions in the detectors. In the baseline scenario, the inner barrel and end-caps will be replaced after 2000 fb^{-1} , while outer pixel barrel and end-cap detector will not. A summary of the maximum 1 MeV neutron equivalent fluences and ionising doses is given in Table 2.1, where a safety factor of 1.5 is applied.

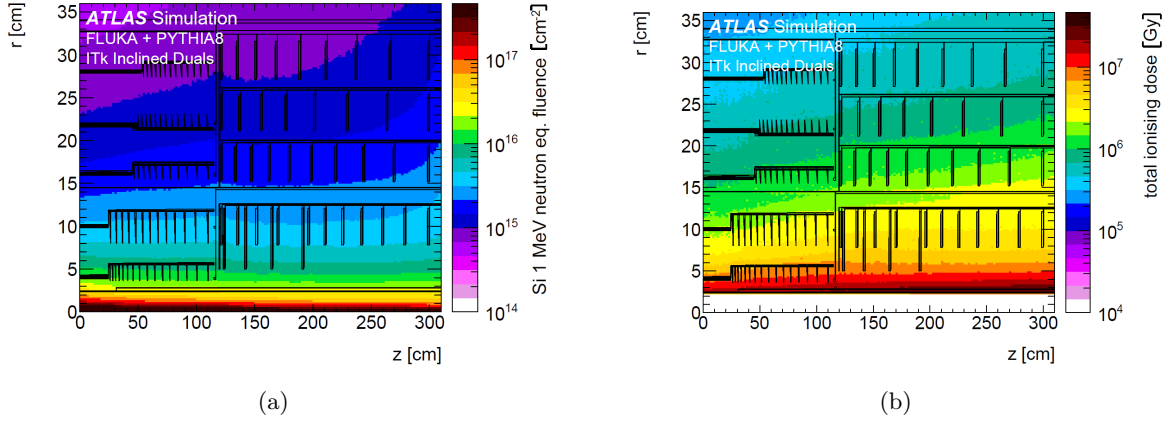


Figure 2.7: Equivalent 1 MeV/cm² neutron fluence (a) and total ionising dose (b) maps in the ITk Pixel Detector normalized to 4000 fb⁻¹ [29].

Luminosity [fb ⁻¹]	Layer	Location	R [cm]	z [cm]	Fluence [10 ¹⁴ n _{eq} /cm ²]	Dose [MGy]
2000	0	flat barrel	3.9	0.0	131	-
			4.0	24.3	-	7.2
		inclined barrel	3.7	25.9	123	-
			3.7	110.0	-	9.9
		end-cap	5.1	123.8	68	6.3
2000	1	flat barrel	9.9	24.3	27	1.5
		inclined barrel	8.1	110.0	35	2.9
		end-cap	7.9	299.2	38	3.2
4000	2-4	flat barrel	16.0	44.6	28	1.6
		inclined barrel	15.6	110.0	30	2.0
		end-cap	15.3	299.2	38	3.5

Table 2.1: Maximal 1 MeV neutron equivalent fluences and total ionising doses for different parts of the Pixel Detector, for the baseline replacement scenario of the inner section. A safety factor of 1.5 is used [29].

Pixel Detector sensors

The main change in sensor technology from the IBL to the ITk is the increase in radiation hardness requirements. In standard silicon sensors, the effect of radiation is visible in a progressive reduction of the collected charge, which can be mitigated increasing the bias voltage. This leads to an increase of the leakage current which impacts the performances of

the analogue front-end electronics, and can also cause a “thermal run-away”. For this reason, it was important to make sensor design choices for each region of the ITk in order to guarantee stable thermal operation with high hit reconstruction efficiency.

For the ITk innermost layer, 3D sensors were chosen, while the rest will be instrumented by planar sensors. 3D sensors design differs from the standard planar in the orientation of the charge collecting electrodes, which are oriented perpendicularly to the sensor surface and penetrate through it, see Figure 2.8. 3D sensors offer excellent charge collection efficiency even in case of severe bulk damage induced by radiation. The first generation of 3D sensors with a pixel size of $50\text{ }\mu\text{m} \times 250\text{ }\mu\text{m}$ and a sensor thickness of $230\text{ }\mu\text{m}$ demonstrated radiation tolerance up to $9 \times 10^{15} \text{ n}_{eq}/^2$ [33]. However, in addition to an increased radiation hardness, ITk Pixel Detector requires 3D sensors with smaller pixel sizes and thinner active area to improve position resolution and to reduce detector occupancy in the innermost layer. Production of 3D devices with different thickness and pixel sizes of $25\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ and $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$ have been carried out and characterized before and after irradiation. Test beam measurements resulted in hit efficiencies higher than 97% for sensors irradiated up to $1.4 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$ [34].

For the outer layers, planar sensors will be fabricated in the n-in-p technology, since this has advantages of simpler and cheaper fabrication procedures with respect to the n-in-n approach. A thickness of $150\text{ }\mu\text{m}$ has been chosen for the outer layers, while for Layer 1 a thickness of $100\text{ }\mu\text{m}$ will be used to guarantee performances after irradiation.

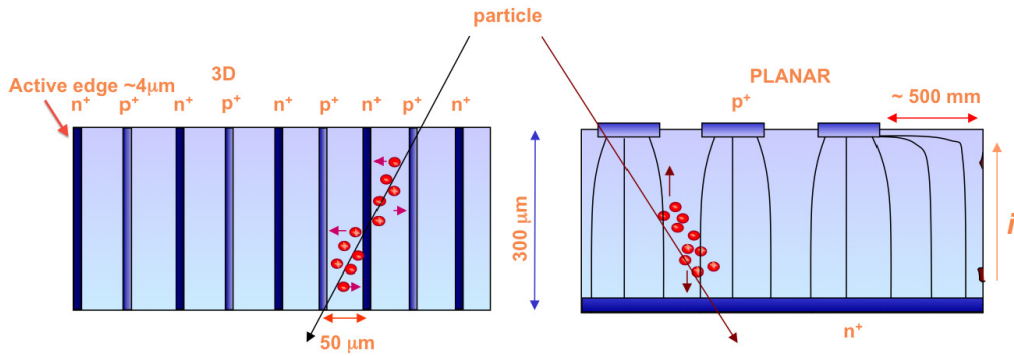


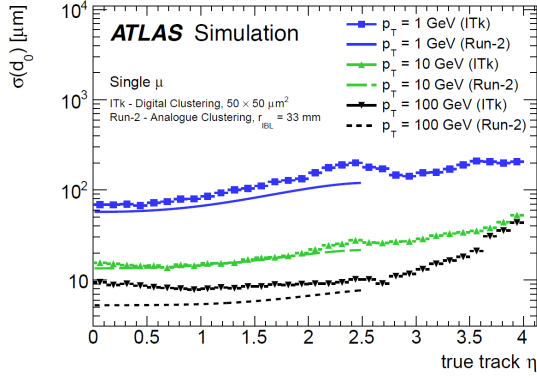
Figure 2.8: Schematic view of the electrode arrangement and charge collection in 3D (left) and planar (right) pixel sensors [29].

ITk tracking performance

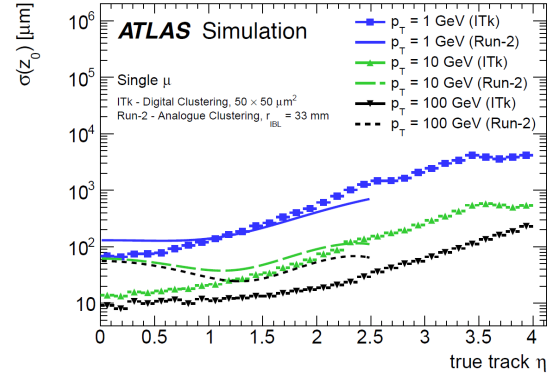
ITk measurements will be fundamental in order to obtain the trajectory of particles, their momentum (p_T) measured from their curvature, and the polar (θ_0) and azimuthal (ϕ_0) angles of the tracks. The resolution of these parameters influence the performances of the detector in terms of b -tagging and lepton and jets reconstruction. The Pixel Detector is also fundamental for the determination of the transverse (d_0) and longitudinal (z_0) impact parameters of the tracks which are critical to associate efficiently charged particles to the correct production vertex. In Figure 2.9, the track parameter resolution for a detector with $50\,\mu\text{m}\times 50\,\mu\text{m}$ pixels is shown as a function of η for a single muon. In the same plots, the performance of the ATLAS ID in Run-2 after the insertion of the IBL detector is also shown for comparison. An improvement can be seen for z_0 and θ_0 parameters due to the reduced pixel size along the beam axis. In the case of d_0 and ϕ_0 parameters, such an improvement is not seen. This can be related to the fact that there is no pixel size reduction along this direction, and also to the fact that ITk will be placed at 3.9 cm from the beam axis while the IBL is placed at 3.3 cm. The p_T resolution is improved in all the η region by a factor of 2, mostly because of the higher precision of the ITk Strip detector at large R compared to the TRT, and also to the reduced material. Another general improvement is the extension of the ITk coverage up to $|\eta| = 4$. However, in the forward region the ITk longitudinal resolution reaches 3 mm for particles with low transverse momentum, which is not good enough to face with the high level of pileup. For this purpose, another detector will be installed in the forward region: the HGTD.

2.2.2 High Granularity Timing Detector

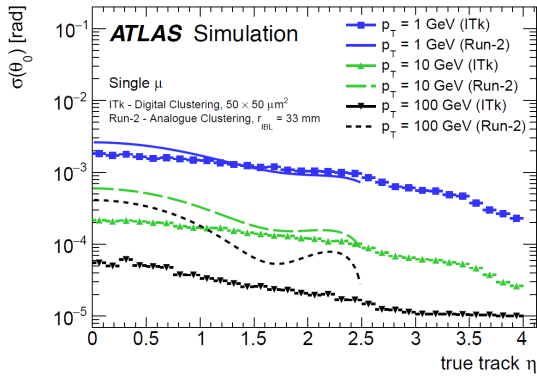
HGTD will provide a time stamp for the tracks that hit HGTD, associated to the elapsed time between the time of the last bunch crossing clock signed and the arrival of the particle to the HGTD. The time information for each track will allow to separate the hard scattered from the pileup event, if the time resolution is good enough. The HGTD detector represents



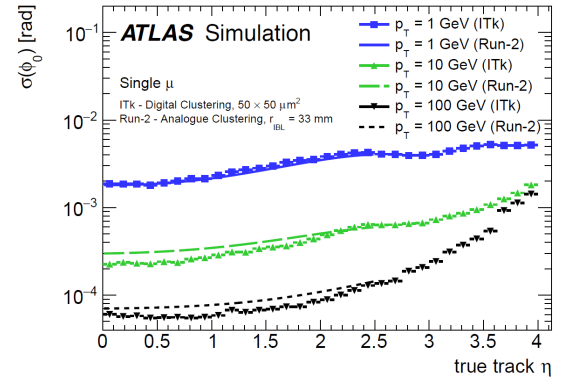
(a)



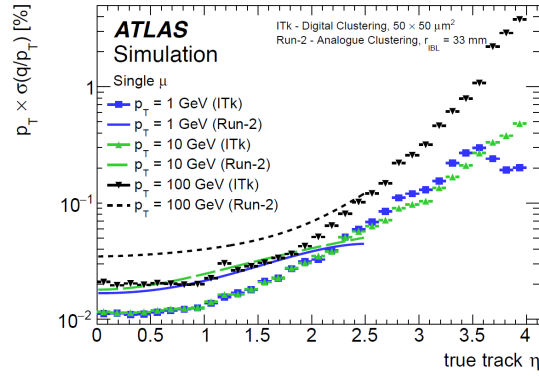
(b)



(c)



(d)



(e)

Figure 2.9: Track parameter resolution in d_0 , z_0 , θ , and p_T as a function of η for an ITk Pixel Detector with $50 \times 50 \text{ mm}^2$ pixels. Results are shown for single muons of 1, 10 and 100 GeV in p_T . The reconstruction uses digital clustering information. For comparison, the resolutions for the Run 2 Inner Detector are also shown [29].

the core of this work and it will be fully described in the next chapter.

Chapter 3

The High Granularity Timing Detector

With the increase of the luminosity up to $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in the HL-LHC, the average number of interactions per bunch crossing, $\langle \mu \rangle$, will increase from 30 to about 200. This clearly means that pileup will be one of the major challenges in the HL-LHC scenario. In Figure 3.1, the pileup density distributions for $\langle \mu \rangle = 30$ and $\langle \mu \rangle = 200$ are shown for comparison. At $\langle \mu \rangle = 200$, a most probable value of 1.44 vertices/mm is expected, degrading the vertex reconstruction and physics objects performance. To be able to associate efficiently charged particles to the correct production vertex, the resolution of the longitudinal track impact parameter z_0 has to be smaller than 600 μm , which is the inverse of the average pileup density. In the central pseudorapidity (η) region, the ITk detector provides a z_0 resolution well below this limit, but in the forward region the resolution reaches 3 mm for particles with low transverse momentum at $|\eta| \sim 4$, see Sec. 3.1.1. Also, at high $|\eta|$, the Liquid Argon (LAr)[19] electromagnetic calorimeter has coarser granularity. In this context, the time information can be used to distinguish the correct production vertex for charged particles, resolving ambiguities for nearby vertices whose distance is smaller than the track impact parameter resolution (if the time separation is sufficiently large). The development of silicon detectors with gain with

a time resolution of a few tens of ps for HEP experiments offers a solution to reduce the detrimental effect of pileup in the forward region. The time information is complementary to the track and p_T measured by the tracker and calorimeter, compensating the resolution degradation. A High Granularity Timing Detector (HGTD) is proposed to mitigate the effect of pileup and improve the overall performance of the ATLAS experiment in the forward region by combining the HGTD time measurements with the position information from the tracker.

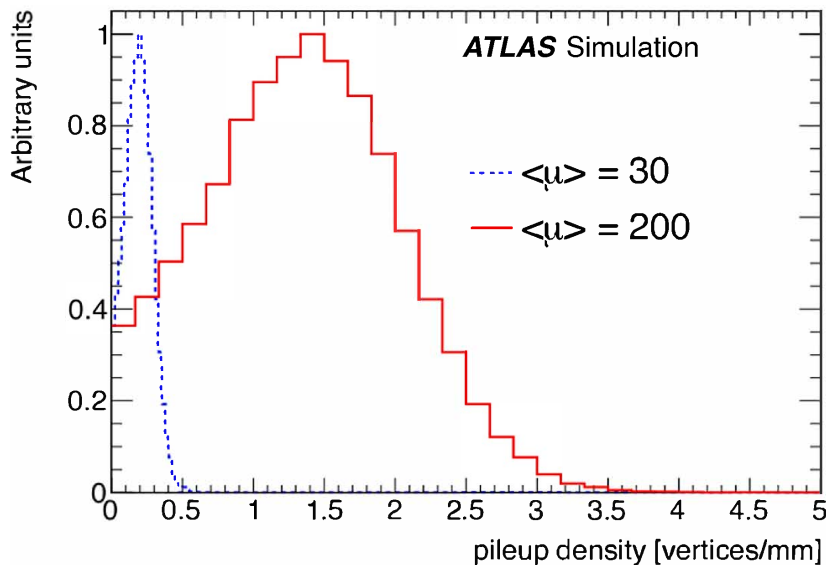


Figure 3.1: Local pileup vertex densities at generator level for $\langle \mu \rangle = 30$ (blue dashed line) and $\langle \mu \rangle = 200$ (red line).

3.1 Physics motivation

Due to the large uncertainty on the longitudinal impact parameter for tracks in the forward region, the association of tracks to vertices with only spatial information is ambiguous in high pileup environments, especially for low forward tracks. The HGTD detector is a timing detector which will provide the charged track-time information with a resolution of 30-50 ps per track. The ability to determine the time of the primary vertex of the hard-scattered process (t_0) and the time associated to each track, provides a new handle to enhance the

capability of the ATLAS detector to remove pileup tracks contaminating physics objects originating from the hard-scatter vertex. This will have an impact on physics analysis through jet reconstruction, b -tagging and lepton isolation. In this section, the impact of the HGTD on ATLAS performance will be briefly discussed.

3.1.1 Track to vertex association

The association of a track to the respective production vertex is a key element in the mitigation of pileup effects on the reconstructed event. Several processes, such as b -tagging and lepton isolation, depend strongly on the correct assignment of tracks to their primary vertices and jets. A track is associated to a vertex if the impact parameter z_0 is compatible with the vertex position z_{vertex} . To evaluate the compatibility the following equation is considered:

$$\frac{|z_0 - z_{vertex}|}{\sigma_{z_0}} < s_z, \quad (3.1)$$

where σ_{z_0} is the longitudinal impact parameter resolution of ITk and s_z is a significance cut. In Figure 3.2, the expected value of σ_{z_0} for muons is shown as a function of $|\eta|$. For a track with $p_T = 1$ GeV at $|\eta| = 3$ the resolution of the longitudinal impact parameter is about 1 mm. With a most probable value of vertex density of 1.44 vertices/mm at $\langle \mu \rangle = 200$, a track with such a low p_T can be compatible with up to 9 nearby vertices, becoming ambiguous at large pseudorapidity and high luminosity. In this context, the track-to-vertex association will critically suffer from pileup contamination. Introducing timing information is a powerful way to address this issue. Figure 3.3 shows the time dispersion as a function of the truth interactions z position from simulation, in a single bunch crossing. By requiring that all the tracks within a certain time window around the primary vertex have a common time compatible with the time of the hard-scattered vertex [35], the effect of pileup can be reduced. There are two main strategies to use timing information in order to improve the reconstruction performance: space-time track-to-vertex reconstruction and self-tagging.

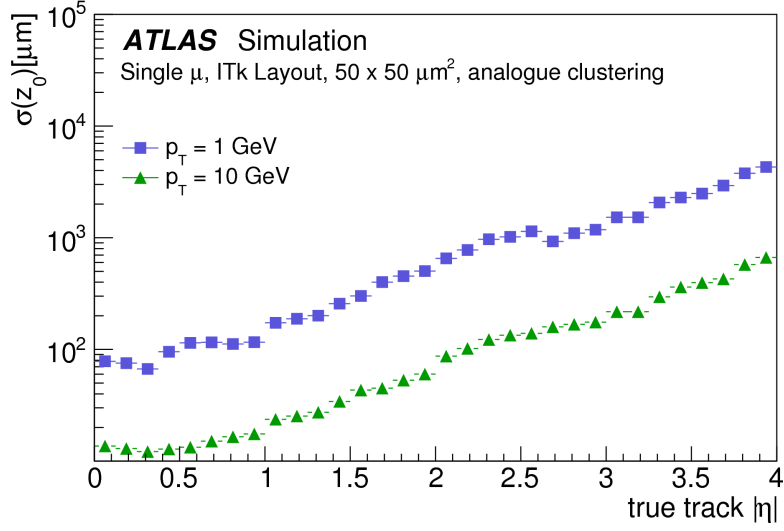


Figure 3.2: Resolution of the longitudinal track impact parameter, z_0 , as a function of η for muons of $p_T = 1 \text{ GeV}$ and $p_T = 10 \text{ GeV}$ using ITk alone.

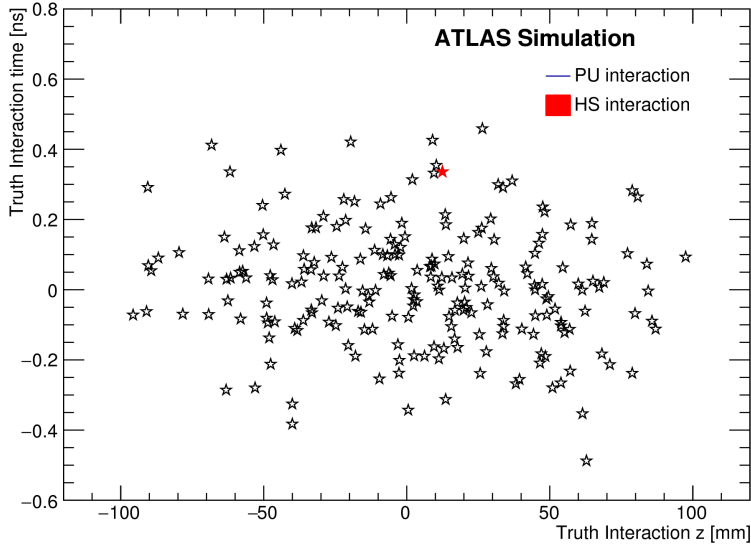


Figure 3.3: Truth interactions in a single bunch crossing in the $z - t$ plane, showing the simulated hard-scattered event interaction with the pileup superimposed ones for $\langle \mu \rangle = 200$.

Space-time track-to-vertex reconstruction

This is a natural extension of the track-to-vertex association in 4 dimensions. In this approach, the time t_0 of the hard-scattered vertex, PV_0 , is determined as a global reference to check the

compatibility of the time of the tracks associated to physics objects in that event. Once a t_0 is found, tracks have to satisfy the following equation:

$$\frac{t_{trk} - t_0}{\sigma_t} < s_t \quad (3.2)$$

where σ_t is the sum in quadrature of t_0 and the track-time, t_{trk} , and s_t is a significance cut. This approach is limited by the determination of t_0 . The experimental determination of t_0 is challenging. The key factors which affect the accurate determination of the hard-scattered vertex time are two: firstly, the hard-scattered interaction needs to have enough high p_T tracks in the HGTD acceptance region. Secondly, hadrons have a limited efficiency for correct track-time association, reducing the number of tracks accessible to calculate the time t_0 . In the Vector Boson Fusion (VBF) H to invisible sample, these two effects limit the availability of the global vertex time to approximately 65% [36].

Self-tagging

This second approach checks if the times of all tracks associated to the same physics object are consistent to each other. More generally, it entails locating clusters of compatible tracks within a jet and then dividing the jet into smaller sub-jets with consistent timings. However, this approach is limited by several factors, since it requires that a physical object has at least two tracks associated with an assigned time. The self-tagging approach can only address the case of stochastic pileup contamination, assuming that a jet consists of a set of tracks with a common time origin plus additional tracks out of time from nearby. In a hard-Quantum ChromoDynamics (QCD) pileup jet this method is not applicable since the tracks coming from the jets have a common time. Since the fraction of hard-QCD pileup jets increases with the increasing of p_T , the self-tagging method works better for low p_T tracks. Other methods, like b -tagging, missing transverse energy and particle flow are expected to benefit from the use of tracking time information to mitigate the effect of pileup. Both global t_0 and self-tagging are complementary and can be combined to maximise performances across the jet p_T spectrum.

3.1.2 Suppression of pileup jets

The high quantity of pileup jets which will be present during the HL-LHC period can have an impact on the precision of Standard Model physics measurements. Their efficient identification is a key point to enhance the physics potential of the HL-LHC. Pileup jets can increase the number of background events passing a selection criteria, and also reduce the potency of kinematics variables or discriminants used to separate signal from background. Two main processes can originate pileup jets: they can be produced from a QCD process from a pileup vertex or from a random combination of particles from multiple vertices. At low jet p_T , the second process is dominant while at high jet p_T the majority of pileup jets comes from QCD jets. The precise linkage of jets with tracks and primary vertices is a critical element to suppress pileup in jets. The R_{p_T} jet variable is a basic but effective discriminant. It is defined as the sum of all tracks inside the jet cone with their origin in the hard-scattered vertex, divided by the fully calibrated jet p_T :

$$R_{p_T} = \frac{\sum p_T^{trk}(PV_0)}{p_T^{jet}} \quad (3.3)$$

The tracks used to calculate R_{p_T} are required to have $p_T > 1 \text{ GeV}$. Hard scatter and pileup jets are distinguished by their matching to the parton level simulated jet (the “truth jets”). The reconstructed hard scatter jets are required to be within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ of a truth jet with $p_T > 10 \text{ GeV}$.

With a moderate level of pileup, the track impact parameter measurements can be used to assign track to vertices with small ambiguity. In this case, small values of R_{p_T} correspond to jets that have a small proportion of charged particle p_T coming from PV_0 and are likely to be pileup jets. However, the power of this discriminant is reduced during high pileup conditions, particularly in the forward region. In this condition the longitudinal impact parameter resolution deteriorates (see Figure 3.2) and the pileup tracks could have a greater chance to be incorrectly included in the numerator of Eq. 3.3.

When the self-tagging approach is used, the R_{p_T} variable is recomputed for each in time

cluster plus the additional track that does not have a time assigned. Then, the jet R_{p_T} is defined as the maximum R_{p_T} of all sub-jets. With this method, the self-tagging R_{p_T} will have a smaller value under the presence of pileup, improving the discrimination power of the method. When a global time vertex t_0 is available, the R_{p_T} can be recomputed after removing tracks outside $2\sigma_t$ window around the reconstructed time of the hard-scattered vertex. In Figure 3.4 the pileup jet rejection as a function of the hard-scattered jet efficiency in the forward region is shown for a VBF H to invisible particles with $\langle \mu \rangle = 200$ simulated sample. The pileup jet rejection is shown without and with the HGTD using self-tagging and t_0 approaches both separately and combining them. The combined method improves the rejection of pileup jets with $30 \text{ GeV} < p_T < 50 \text{ GeV}$ in the forward region up to a factor of ~ 1.5 at a signal efficiency of 85%. The performances in the ITk only case are consistent with what presented in [37]. In Figure 3.5, the relative pileup jet rate for low p_T jets is shown as a function of the pseudorapidity. A significant improvement is shown at large η where the σ_{z0} is worse and timing becomes more important in order to associate tracks to vertices.

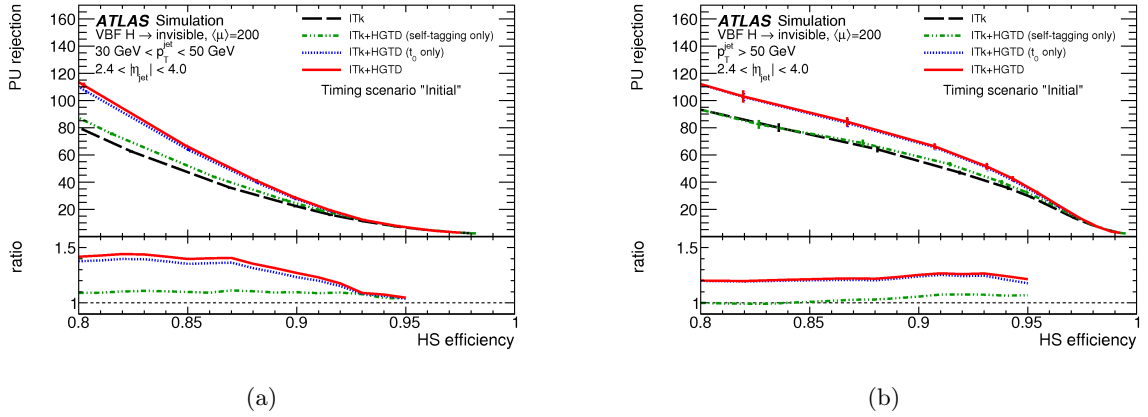


Figure 3.4: Pileup jet rejection as a function of the hard-scattered jet efficiency in the forward region at the beginning of the detector lifetime. The simulated sample is VBF H to invisible particles. Both, ITk only and ITk + HGTD, reconstructions are shown. Distributions are shown for jets with $30 \text{ GeV} < p_T < 50 \text{ GeV}$ (a) and with $p_T > 50 \text{ GeV}$ (b) [36].

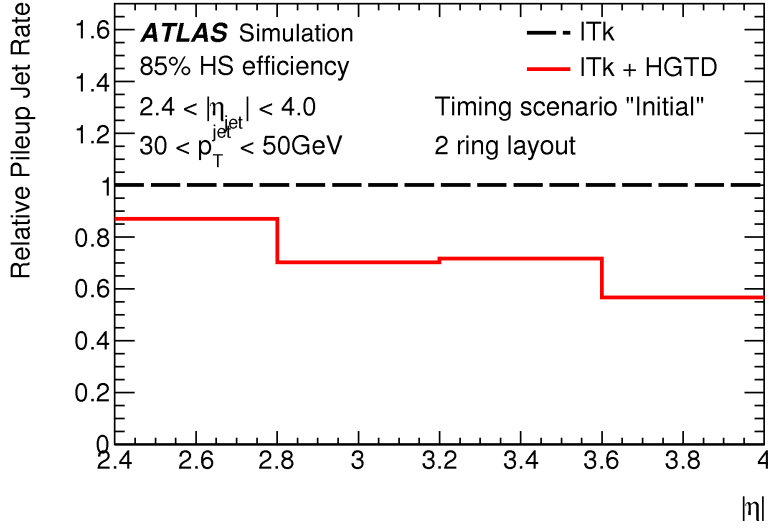


Figure 3.5: Relative pileup jet rate as a function of jet pseudorapidity, for jets with $30 \text{ GeV} < p_T < 50 \text{ GeV}$ [36].

3.1.3 Lepton track isolation

The increase of pileup contamination also degrades the isolation efficiency. The efficiency of the track-based lepton isolation, which is a way to understand a “parton” level interaction, is defined as the probability to have no additional tracks with a $p_T > 1 \text{ GeV}$ reconstructed within $\Delta R < 0.2$ of the lepton track. The time association to the lepton track can be then utilised to reject tracks within the isolation cone which come from pileup interactions with spatial vertex close to the hard-scattered one. If the time difference between the electron track and all the tracks with $p_T > 1 \text{ GeV}$ and $\Delta R < 0.2$ is larger than twice the quadratic sum of the time resolution of both tracks, or the time is not obtained, the track is discarded. In Figure 3.6, the isolation efficiency as a function of the pileup density is shown for both ITk only and ITk + HGTD scenarios for the $Z \rightarrow e^+e^-$ channel. In the only ITk case, the efficiency drops from 85 % to ~ 73 %. Using the HGTD timing information, the efficiency at low pileup density improves to $\sim 90\%$ and the drop is reduced where the efficiency is kept above 85 % up to high pileup densities for both the beginning and the end of its lifetime. HGTD timing information improves by about 10 % the electron isolation efficiency for a local pileup density of 1.6 vertices/mm. These results show that the expected HGTD performance

is good enough to achieve a similar level of lepton track isolation efficiency to the one achieved in the central region.

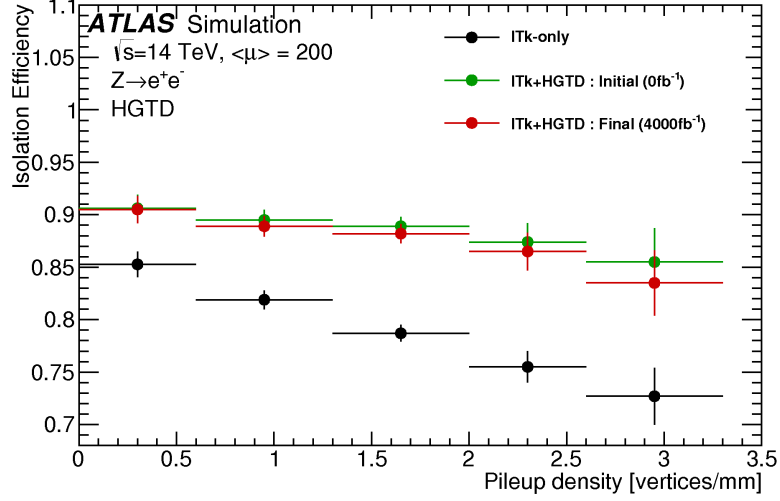


Figure 3.6: The efficiency for electrons to pass track-isolation criteria, denoted as $\epsilon(p_T^{iso})$, as a function of the local vertex density, for the ITk-only and ITk+HGTD scenarios. The isolation efficiency is shown for both the “initial” time resolution of the detector as well as the “final” time resolution at the end of the HGTD lifetime [36].

3.1.4 Other applications

The addition of time information to the whole suite of ATLAS physics object event reconstruction is likely to increase performance in areas not considered yet. Thus, the beam spot can be determined in four dimensions, providing an extra tool for understanding the beam. This can result in improvements in multiple uses, such as for example tracking and flavor-tagging in the online trigger system, offline reconstruction and calibration processes. Particle-flow jet energy reconstruction, transverse missing E_T , and forward b-jet tagging are also likely to benefit from the HGTD.

Particle-flow jet energy reconstruction relies on the ability to match charged particle tracks with calorimeter signals and primary vertices. Improving the jet energy resolution can lead to further improvements of sensitivity in other channels, such as VBF analysis. The full

integration of the HGTD into the particle flow reconstruction is a long term goal.

HGTD can be potentially utilised to enhance the resolution of the missing E_T . This would mean to use HGTD at first to improve the jet energy resolution from particle flow reconstruction, and then reducing the pileup contamination in the track-based soft-term of the missing E_T . At last, the improved pileup suppression in the forward region will be directly correlated to an improvement on the missing E_T resolution, through the rejection of jets which appear to belong to the primary vertex but do not belong to the hard-scattered interaction.

HGTD will be also very useful in the mitigation of the impact of pileup track contamination on b -tagging. In a harsh pileup environment, the presence of pileup tracks with large z impact parameter with respect to the hard-scattered vertex can create fake secondary vertices which will be then translated into a reduction in light-quark rejection. The loss of b -tagging performance at high pileup densities could be compensated by a combination of self-tagging (for high multiplicity jets) and vertex t_0 . A brief study on the mitigation of the pileup through the insertion of the time information from the HGTD detector on the $Z \rightarrow \tau\tau + jets$ background of the $H \rightarrow \tau\tau$ process will be presented in Chapter 4.

3.2 HGTD as a luminometer

A precise determination of the luminosity delivered by the HL-LHC will be crucial for physics analyses. In fact, the uncertainty on the integrated luminosity can limit the precision of several cross-section measurements. Aside the signal normalization, this can also affect the normalisation of any background not determined from data. The precision of the luminosity measurement is critical for measuring several Standard Model processes, such as W and Z boson production and single and pair production of top quarks. More detailed information on the expected performance of the luminosity determination during HL-LHC program can be found in [35]. For cross-section measurements like gluon-fusion (ggH) production of Higgs boson with decays to $\gamma\gamma$ and ZZ^* and combined gluon-fusion and VBF production of Higgs with decay to $\tau\tau$, an uncertainty of 2% on luminosity would be the largest source of uncertainty

on the results. This makes clear the importance of a precise luminosity measurement for the Higgs boson physics programme at the HL-LHC. The HGTD detector provides unique capabilities for measuring luminosity at the HL-LHC. The high granularity of the HGTD gives an excellent linearity between the average number of simultaneous $p - p$ interactions over the full range of luminosity expected at HL-LHC. From simulations, a linear relationship between the number of hits and the number of interactions was extrapolated for $\mu \sim 200$ where the predictions can be compared to the hit multiplicities extracted from fully simulated high-pileup samples. The charged-particle multiplicities within the acceptance can be determined accurately for each individual bunch crossing with the occupancy information at 40 MHz. This value is key to fully exploit the potential of the HGTD as a precision luminometer for both online and offline use. Thus, the HGTD will provide both online and offline luminosity measurements. It will be done in a reduced $|\eta|$ range $2.4 < |\eta| < 2.8$. The HGTD will have a dedicated readout path to send occupancy data for each module at 40 MHz allowing bunch-per-bunch luminosity measurements online without trigger bias. HGTD is designed to be capable to constrain many systematic uncertainties in the luminosity determination, with the goal of reducing the total uncertainty on the integrated luminosity measurements in HL-LHC compared with respect to those in Run 2, despite the harsh experimental conditions.

3.3 The HGTD detector

3.3.1 Detector overview and requirements

The HGTD has been designed for operation at 200 proton-proton collisions per bunch crossing and for a total integrated luminosity of 4000 fb^{-1} . The detector will be installed in the region between the ITk detector and the end-cap calorimeter, at a distance of $z = \pm 3.5 \text{ m}$ from the ATLAS IP. This place is currently occupied by the Minimum-Bias Trigger Scintillator (MBTS), which will be removed. The position of the two vessels for the HGTD within the ATLAS detector is shown in Figure 3.7. The detector area has a radial extension from 110 mm to 1000 mm, with an extension in z of 125 mm including moderator, supports and vessels

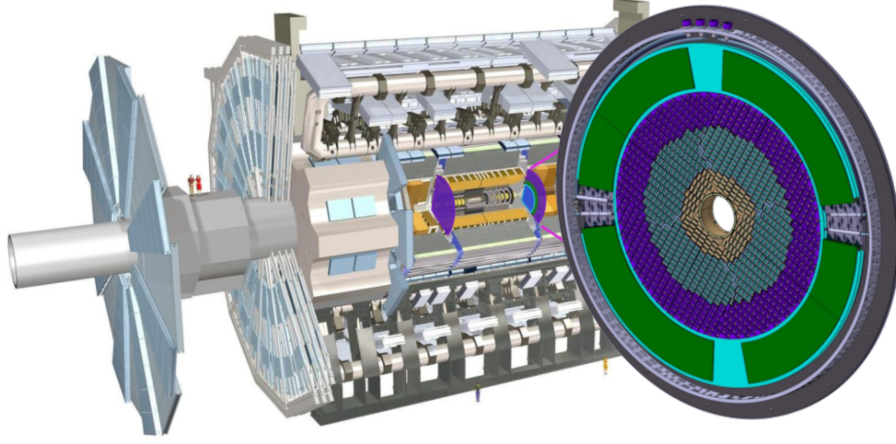


Figure 3.7: Position of the HGTD within the ATLAS detector. HGTD acceptance is defined as the surface covered by the HGTD between a radius of 120 mm and 640 mm at a position of $z = 3.5$ m along the beamline, on both sides of the ATLAS detector [36].

covers, and its active area will cover the pseudorapidity range $2.4 < |\eta| < 4.0$ ($120 \text{ mm} < r < 640 \text{ mm}$). A 50 mm-thick moderator made of borated polyethylene will be placed behind the detector to reduce the back-scattered neutrons created by the calorimeters. The tight space available in z is one of the main motivation to use a compact silicon technology for the HGTD, with sensors required to be thin and configurable in arrays while providing excellent time resolution (~ 30 ps). LGADs [38] with pads of a size of $1.3 \text{ mm} \times 1.3 \text{ mm}$ and an active thickness of $50 \mu\text{m}$ were chosen for the HGTD. The reason of this choice will be explained in the next section and in Chapter 5.11. To mitigate the impact of radiation, sensors will be operated at -30°C , as explained in Chapter 5. A custom Application-Specific Integrated Circuit (ASIC), the ATLAS LGAD Time Read Out Chip (ALTIROC), will be bump-bonded to the sensors and it is currently being developed to meet the HGTD requirements in terms of time resolution and radiation hardness. The ASIC will also provide functionality to count the number of hits registered in the sensors and transmit it at 40 MHz to allow bunch-per-bunch luminosity measurements, and the implementation of a minimum-bias trigger.

Each HGTD end-cap is made of one hermetic vessel, two instrumented double-sided layers mounted on cooling and support disks, and two moderator pieces both inside and outside the hermetic vessel. The two layers are rotated in opposite directions (with respect to the

other) by 15° to 20° in order to maximise the hit efficiency. HGTD is based on a three ring layout with the following active regions: $120\text{ mm} < r < 230\text{ mm}$, $230\text{ mm} < r < 470\text{ mm}$ and $470\text{ mm} < r < 640\text{ mm}$. The peripheral electronics will be located beyond the third ring. The reason for the three ring layout is explained in Section 3.3.4. The global view of the HGTD is shown in Figure 3.8 and its requirements are listed in Table 3.1 and will be discussed in the next sections.

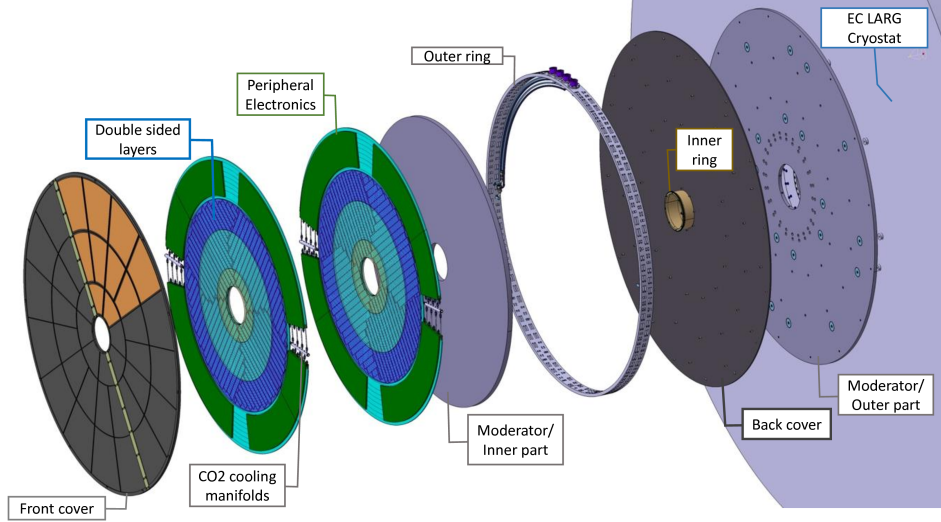


Figure 3.8: Global view of the HGTD to be installed on each of the two end-cap calorimeters. The various components are shown: hermetic vessel (front and rear covers, inner and outer rings), two instrumented double-sided layers (mounted in two cooling disks with sensors and ASICs on the front and back of each cooling disk), two moderator pieces placed inside and outside the hermetic vessel [36].

3.3.2 Detector Layout

The capability of the ATLAS detector to link tracks to primary vertices is determined by the longitudinal impact parameter resolution of the ITk (as discussed in Section 2.2.1), which is limited in the forward region. The HGTD aims to provide the best possible track time resolution to suppress pileup effect in the forward region.

The pad size of the HGTD sensor (LGAD) is $1.3\text{ mm} \times 1.3\text{ mm}$ for the entire detector. This pad size ensures occupancies below 10% at the highest expected instantaneous luminosity, low

Pseudorapidity coverage	$2.4 < \eta < 4.0$
Thickness in z	75 mm (+50 mm moderator)
Position of active layers in z	± 3.5 mm
Weight per end-cap	350 kg
Radial extension	
Total	$110 \text{ mm} < r < 1000 \text{ mm}$
Active area	$120 \text{ mm} < r < 640 \text{ mm}$
Pad size	$1.3 \text{ mm} \times 1.3 \text{ mm}$
Active sensor thickness	50 μm
Number of channels	3.6 M
Active area	6.4 m^2
Module size	15×15 pads ($2 \text{ cm} \times 2 \text{ cm}$)
Modules	8032
Collected charge per hit	$> 4 \text{ fC}$
Collected hit per track	
$2.4 < \eta < 2.7$ ($470 \text{ mm} < r < 640 \text{ mm}$)	≈ 2.0
$2.7 < \eta < 3.5$ ($230 \text{ mm} < r < 470 \text{ mm}$)	≈ 2.4
$3.5 < \eta < 4.0$ ($120 \text{ mm} < r < 230 \text{ mm}$)	≈ 2.6
Average time resolution per hit	$\approx 35 \text{ ps}$ (start), $\approx 70 \text{ ps}$ (end)
Average time resolution per track	$\approx 30 \text{ ps}$ (start), $\approx 50 \text{ ps}$ (end)

Table 3.1: Main requirements of the HGTD detector. the average time resolution is listed for both the start and end of lifetime.

double hit probability for the same sensor in one bunch crossing, and sufficiently low sensor capacitance, which is important for the time resolution. Moreover, for small pad sizes the electronic noise and the physics occupancy are smaller, while the number of channels and the total inactive area between the pads are larger. On the other hand, as a baseline, an active thickness of 50 μm was adopted as the best compromise between capacitance and deposited charge (favouring large thickness) and signal slope and Landau fluctuations (favouring a small thickness). Each HGTD sensor consists of 15×15 LGAD pads, with a total area of approximately $2 \text{ cm} \times 2 \text{ cm}$. A HGTD module consists of two LGAD sensors coupled to two ALTIROC ASICs. The total amount of modules in HGTD is 8032. The module layout has been designed in order to maximize the coverage and minimizing the non-instrumented region. The HGTD module will be discussed in detail in Section 3.4.

Due to radiation damage, the time resolution will be degraded as the integrated luminosity increases. The radiation level in the detector depends strongly on r , where higher radiation level

occurs at inner radius. The detector replacement strategy will be discussed in Section 3.3.4.

Each layer of the detector is double-sided, with sensors mounted both in the front and back sides of the cooling disk. As shown in Figure 3.9, the modules on the two sides are arranged to overlap. Simulation studies were performed to determine the optimal overlap between the modules in the three rings to fulfill requirements for time resolution. For the inner ring an overlap of 70% is expected, for the middle ring an overlap of 54% and for the outer ring an overlap of 20%.

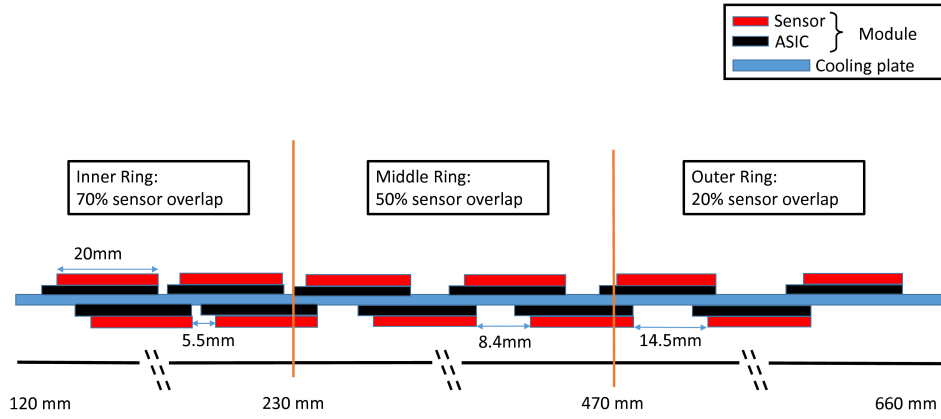


Figure 3.9: Schematic drawing showing the overlap between the modules on the front and back sides of a cooling disk [36].

The expected number of hits per track as a function of the radius is shown in Figure 3.10, with an average of 2.6 for the inner ring, an average of 2.4 for the middle ring and 2.0 for the outer ring.

The time resolution per hit and per track as a function of the radius are shown in Figure 3.11. The plot is made for several values of integrated luminosity during the HL-LHC lifetime, corresponding to the different replacement scenarios of the detector (that will be described in Section 3.3.4).

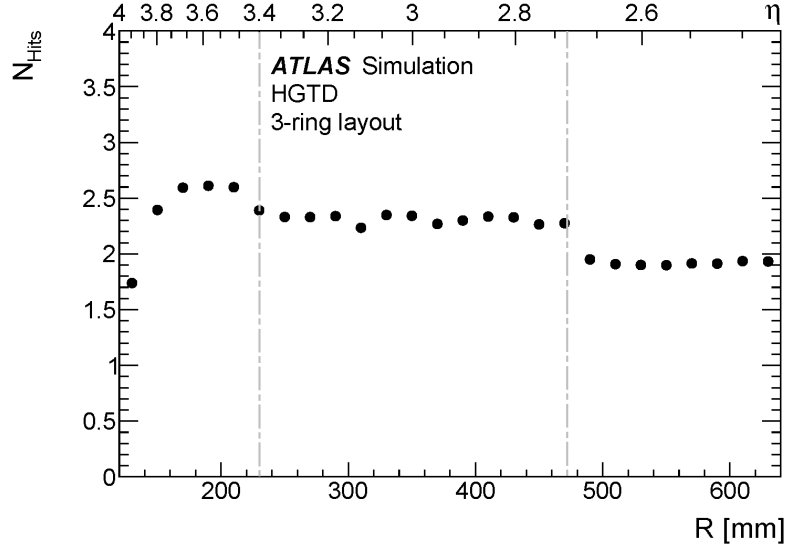


Figure 3.10: Hit multiplicity as a function of R . The figure was made using a simplified simulation, resulting in a 10% uncertainty compared to the full simulation studies of the HGTD. The vertical dashed line are representative of the separation between the rings [36].

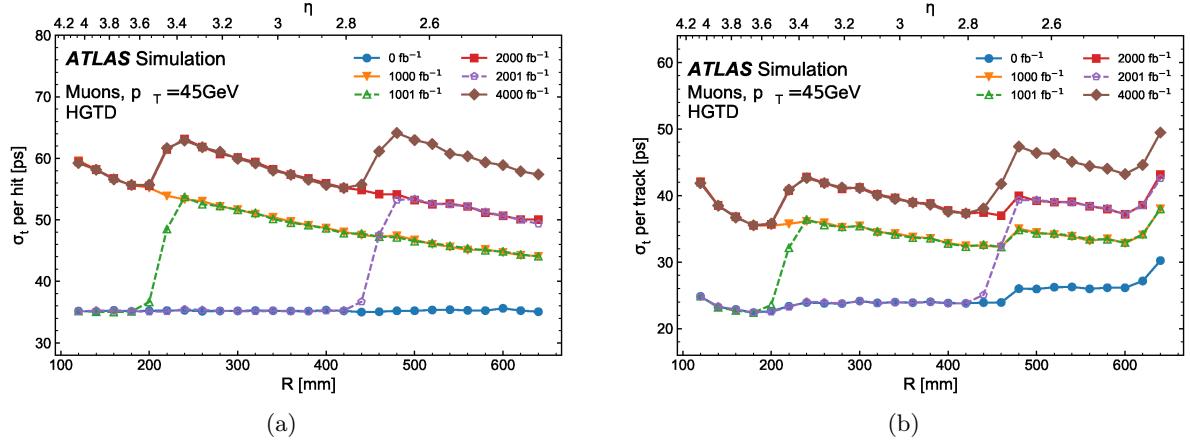


Figure 3.11: Time resolution per hit (left) and per track (right) within the HGTD acceptance region as a function of the radius. The time resolution is shown for different integrated luminosities. The improvement at high luminosity corresponds to the replacements of the innermost rings during the detector lifetime [36].

3.3.3 Time resolution

The time resolution provided by the LGAD sensors is a key parameter of the HGTD. To ensure a good timing performance, the front-end electronics requires a minimum charge value

of 4 fC for irradiated sensors. This will be discussed in Section 3.4. The target time resolution per track is 30 ps at the start and 50 ps at the end of lifetime, as shown also in Table 3.1. This means that the time resolution per hit should be around 35 ps at the start and 70 ps at the end of lifetime, given the number of hits per track. The main contributions to the time resolution of a detector are:

$$\sigma_{total}^2 = \sigma_{Landau}^2 + \sigma_{Electronics}^2 + \sigma_{Clock}^2 \quad (3.4)$$

where σ_{Landau}^2 indicates the Landau fluctuations in the deposited charge, $\sigma_{Electronics}^2$ is the contribution from the electronics and σ_{clock}^2 is the contribution from the non-deterministic jitter contribution from the clock distribution.

From test beam results, it has been understood that thin sensors help to reduce the contribution from Landau fluctuations. For 50 μm -thick LGAD, the Landau contribution is about 25 ps.

The electronics contribution can be kept around 25 ps with a fast detector with large signal-to-noise ratio, for a *minimum ionizing particle* (mip) at the beginning of the HL-LHC period. The electronics contribution to the time resolution will be explained in more detail in Section 3.5.2.

When accounting for the expected clock jitter from the component of the readout system and LHC bunch crossing time drift, the clock contribution can be kept below 15 ps. If other unknown sources of jitter are present, the timing correction procedure can reduce the total jitter to 20 ps. There are several contributions to it coming from the readout system, such as the front-end electronics and the FLEX cables. The timing correction procedure assumes that the time offset from different channels are not correlated. However, in each channel the time offsets are expected to be in some way correlated from both global and local effects. The correction procedure assumes the worst case scenario of no correlation and applies corrections per ASIC level.

The detector design has been tweaked to get close to a flat time resolution as η increases. The

time resolution of the detector will deteriorate as the integrated luminosity delivered by the LHC increases owing to radiation degradation. This radiation is significantly influenced by r , with more radiation closer to the beam axis. The expected radiation level for the HL-LHC lifetime will be examined in the next section.

3.3.4 Radiation hardness

One of the most essential parameters of the HGTD detector is the radiation hardness of both sensors and electronics. The HGTD will cover the region $2.4 < |\eta| < 4.0$. It is important that the detector can withstand the radiation level throughout the HL-LHC operation period in order to maintain its performance. At $r = 120$ mm, the neutron equivalent fluence is expected to reach $5.6 \times 10^{15} \text{ n}_{eq} \text{ cm}^{-2}$ and a total ionising dose (TID) of about 3.3 MGy, as shown in Figure 3.12.

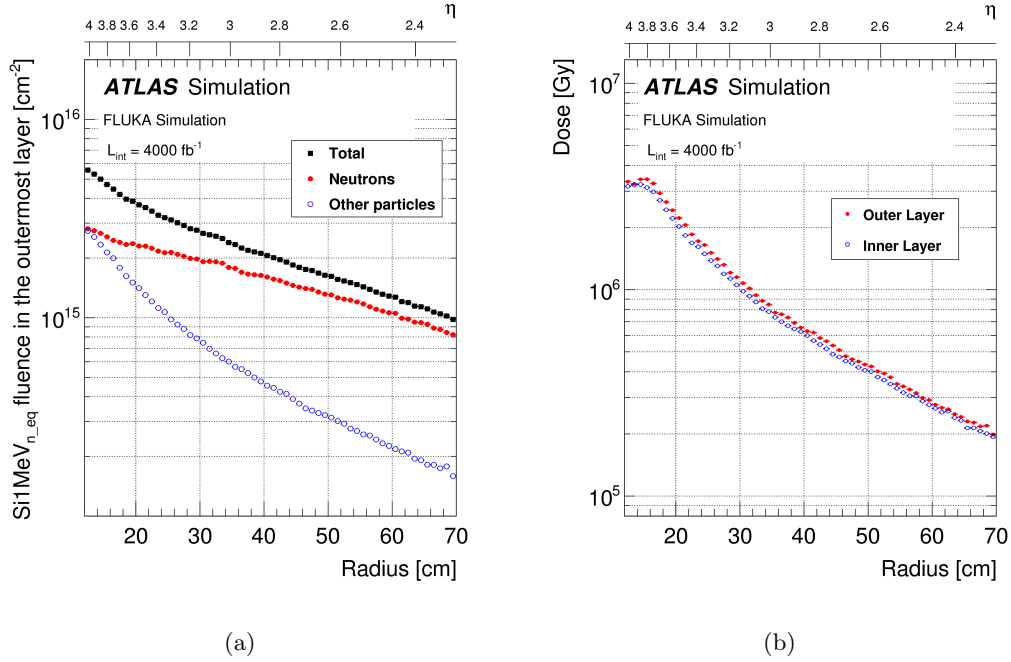


Figure 3.12: Expected nominal Si1MeV $_{n_{eq}}$ fluence (a) and ionising dose (b), using Fluka simulation, as a function of the radius in the outermost sensor layer of the HGTD for 4000 fb^{-1} , before including safety factors. The contribution from hadrons is included in “Others” [36].

After applying a safety factor of 1.5 for sensors and 2.25 for electronics (which is more sensitive

to the TID), the HGTD detector needs to withstand $8.3 \times 10^{15} \text{ n}_{eq} \text{ cm}^{-2}$ and 7.5 MGy. Through an intense R&D campaign carried out during the last years, a minimum charge of 4 fC can be reached up to a radiation damage of $2.5 \times 10^{15} \text{ n}_{eq} \text{ cm}^{-2}$ and 2.0 MGy. Since the radiation is influenced by the r , this has been translated into a three ring layout, already described in Section 3.3.2, with different replacements intervals for each ring. Sensors and electronics at the lowest radius ($r < 230 \text{ mm}$) will be replaced after each 1000 fb^{-1} , for a total of three times in the HGTD lifetime, while the ones in the middle region ($230 \text{ mm} < r < 470 \text{ mm}$) will be replaced once after 2000 fb^{-1} . The outer ring is not replaced over the entire lifetime. In this way, the maximum fluence and TID do not exceed $2.5 \times 10^{15} \text{ n}_{eq} \text{ cm}^{-2}$ and 2.0 MGy. In Figure 3.13, the maximum fluence (a) and TID (b) as a function of the radial position,

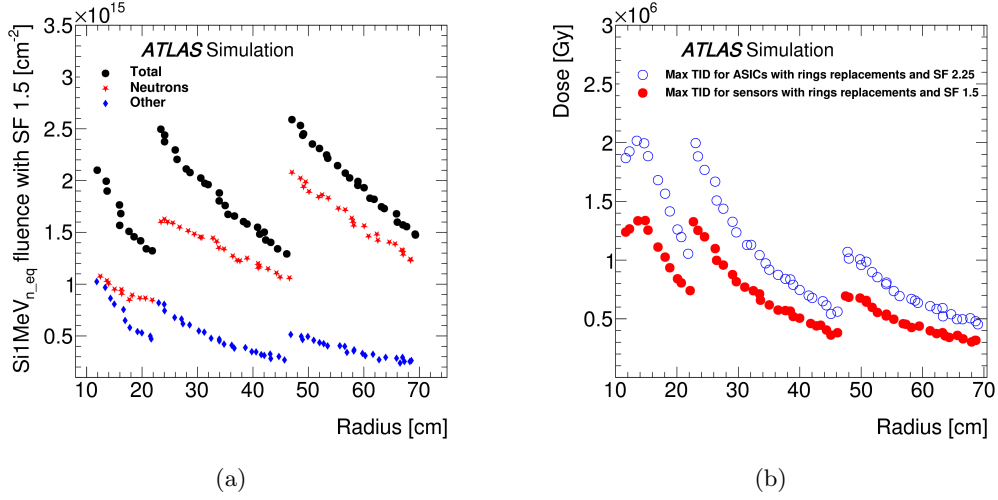


Figure 3.13: Si1MeV_{n_{eq}} fluence for HL-LHC with scale (a) and ionising dose for HL-LHC with scale factor applied and considering ring replacements of the inner ring every 1000 fb^{-1} and of the middle ring after 2000 fb^{-1} . The contribution from charged hadrons is included in “Others”. To account for simulation uncertainties, those plot includes a safety factor of 1.5. An additional 1.5 is applied to the TID to account for low dose-rate effects on the electronics, leading to a safety factor of 2.25 [36].

including the replacement of the three rings, are shown. The total fluence is a combination of neutrals and charged particles with different contribution in different regions. In the inner-most region, the contribution from neutral and charged particles is similar, with the maximum fluence from charged particles being around $\times 10^{15} \text{ n}_{eq} \text{ cm}^{-2}$ and the one from neutrons being $2 \times 10^{15} \text{ n}_{eq} \text{ cm}^{-2}$. The charged particle contribution decreases with radius, in this way

in the outer region the field is dominated by neutrons because of back-scattering from the calorimeter.

3.4 HGTD module

The HGTD module consists of two hybrids (or bare modules), each of them made of LGAD sensors (with 15×15 pads of a size of $1.3 \text{ mm} \times 1.3 \text{ mm}$ for a total of 225 channels), with an approximate size of $2 \text{ cm} \times 2 \text{ cm}$. Each pad will be connected to ALTIROCs (of 15×15 channels) held together by a single flexible printed circuit board (the module flex). The sensor and the ASIC are connected through a flip-chip bump bonding process, also called hybridization. The backside (ohmic side) of the two sensors are glued to the module flex, the signal lines to the ASIC are wire bonded to the module flex, and the bias voltage is provided to the back-side of the sensors through holes in the module flex. The module size has been defined in order to optimize the coverage at the inner radius and to provide a good yield for the hybridization process. HGTD will be equipped with 8032 modules. In Figure 3.14, a stave with three modules is shown. The flex cable provides the connections between the ASIC and the peripheral electronics. It transmits the signal from the module to the peripheral electronics boards, as well as the power, clock and bias voltage that are sent to the module from the peripheral electronics. They have a varying length, from 3 cm up to 60 cm, depending on the position of the module inside the detector. The module flex uses two connectors. One connector is dedicated to the high voltage connection, while the other is used for other signals such as clock, data, monitoring, analog and digital power to reduce the possibility of interference on the high voltage lines with the rest of the signals.

3.5 Front-end electronics

The performance of the LGAD sensors, which is the main topic of this thesis and will be discussed in Chapter 6, are strongly linked to the performance of the front-end electronics.

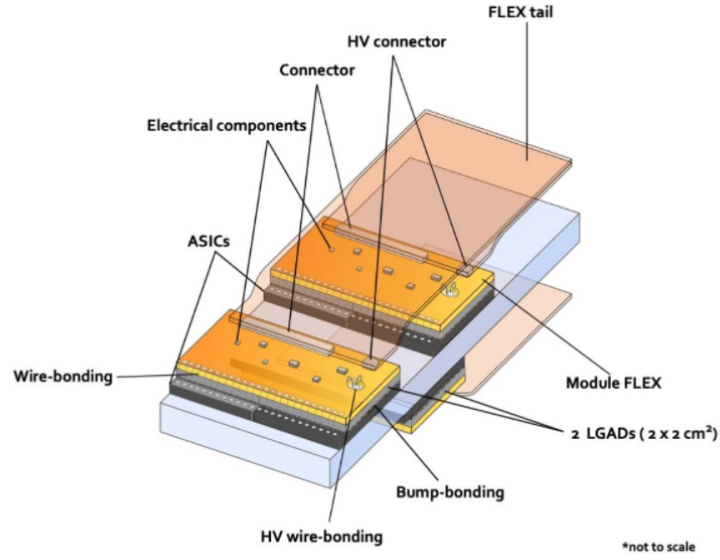


Figure 3.14: View of three HGTD hybrid modules (not to scale and qualitative) mounted on a cooling plate (grey plate). The wire-bonds for both ASICs and sensors HV are indicated.

The ASIC challenge will be to have a small enough contribution to the time resolution in order to match with LGAD's performances. This contribution, as shown by Eq- 3.4, comes mainly from time walk and jitter components. Those contributions will be analyzed and discussed in Section 3.5.2. The measurements of the Time Of Arrival (TOA) and Time Over Threshold (TOT) are digitized by two Time-to-Digital Converter (TDC) and stored in a local memory at channel level. The End Of Column (EOC) logic is implemented to collect information. The largest part of the ASIC will be occupied by the 15×15 channel matrix which will have an area of $19.5 \text{ mm} \times 19.5 \text{ mm}$ on a total ASIC area of $19.9 \text{ mm} \times 21.7 \text{ mm}$. The difference between these areas will be needed to accommodate the EOC logic and the digital blocks.

The ASIC have been designed using the 130 nm TSMC¹ technology. This has been tested up to 4 MGy even though a radiation hard digital library is not available. However, the ASIC has been designed to ensure its radiation hardness. The ASIC digital part is composed by several blocks necessary to generate and align the clocks, receive the slow control commands and configure the ASIC to be able to transmit the digitized data. Up to now, several versions

¹Taiwan Semiconductor Manufacturing Company

of the ALTIROC have been produced and tested. The first prototype was ALTIROC0, a 2×2 channel array which included the analog part of a single channel readout, composed by a preamplifier and a discriminator. Results of this version from test beams and test bench studies show that using unirradiated 2×2 LGAD sensors, for a charge of 20 fC a time resolution of 46 ps and a jitter of 39 ps were achieved [39]. The second prototype, ALTIROC1, consisted of a 5×5 matrix with the addition of digital components to the single channel readout with respect to the previous version. The last prototype, ALTIROC2, integrates all the functionality of the final ASIC and has the final size with a 15×15 pixel matrix. This prototype is currently under tests in the laboratory and preparation for the testbeam setup is ongoing.

3.5.1 General ASIC requirements

The ASIC requirements are divided into two main areas: its operational environment, such as powering and electrical connections, and its performances to reach the target time resolution. The latter are listed in Table 3.2.

Maximum leakage current	5 μ A
Single pad noise (ENC)	$< 3000 e^- = 0.5$ fC
Cross-talk	$< 5\%$
Threshold dispersion after tuning	$< 10\%$
Maximum jitter	25 ps (70 ps) at 10 fC (4 fC)
TDC contribution	< 10 ps
Time walk contribution	< 10 ps
Minimum threshold	2 fC
Dynamic range	4 fC-50 fC
TDC conversion time	< 25 ns
Trigger rate	1 MHz L0 or 0.8 MHz L1
Trigger latency	10 μ s L0 or 35 μ s L1
Clock phase adjustment	100 ps

Table 3.2: ASIC's performance requirements. The values for noise, minimum threshold and jitter consider a detector capacitance of $C_d = 4$ pF.

The ASICs have to withstand high radiation levels. As for sensors, ASICs will be replaced during HL-LHC period, as presented in Section 3.3.4. Each channel readout is connected to a

sensor pad, so it will be capable to handle up to a leakage current of 5 μA without degrading the ASIC performance. Since the sensor performance will degrade with irradiation, it should be possible to set a discriminator threshold for small input charge. A minimum threshold of 2 fC should provide a hit efficiency above 95% for an input charge of 4 fC. The main target for the electronics is to be able to read out signals from 4 fC to 50 fC for the entire HGTD lifetime. The electronics jitter is required to be smaller than 25 ps for a charge of 10 fC. This is equivalent to the deposited charge of a MIP in a 50 μm -thick LGAD with a gain of 20. A detector capacitance of 4 pF is considered. The TDC contribution to the time resolution should be negligible (<10 ps), this leads to a 20 ps TDC bin for the TOA measurements and a 40 ps for the TOT measurements. The time walk should be smaller than 10 ps over the range after correction. Both TOA and TOT information are transferred to the data acquisition system only upon L0/L1 trigger reception with a latency up to 35 μs , necessitating a large memory. The global phase adjustment of the clock should be guaranteed with a precision of 100 ps in order to center the 2.5 ns measuring window at the bunch-crossing. The ASIC will also need to handle the information to perform luminosity measurement, computing the number of hits per ASIC on a bunch-by-bunch basis. Only the information of a subset of all the ASIC will be used, in order to limit the global bandwidth required. Finally, the power dissipation should be kept as low as possible, in order to limit the size required for the cooling system.

3.5.2 Contribution to the time resolution

The electronics contribution to the time resolution is given by Equation 3.5, and can be described as the sum of three components:

$$\sigma_{\text{Electronics}}^2 = \sigma_{\text{Jitter}}^2 + \sigma_{\text{Time Walk}}^2 + \sigma_{\text{TDC}}^2 \quad (3.5)$$

The jitter describes the uncertainty in the time measurement due to the presence of noise in the signal, as shown in Figure 3.15 (a). It can be defined as:

$$\sigma_{Jitter} = \frac{N}{(dV/dt)} \sim \frac{t_{rise}}{(S/N)} \quad (3.6)$$

The time walk effect, described in Figure 3.15 (b), is related to the fact that larger signals cross the threshold earlier than smaller ones. This happens when the time is measured using a fixed threshold, producing a dependence of the measurements on the amplitude of the signal. It can be corrected using a Constant Fraction Discriminator (CFD) method. The time walk effect can be defined as:

$$\sigma_{Time\ Walk} = \left[\frac{V_{th}}{\frac{S}{t_{rise}}} \right] \quad (3.7)$$

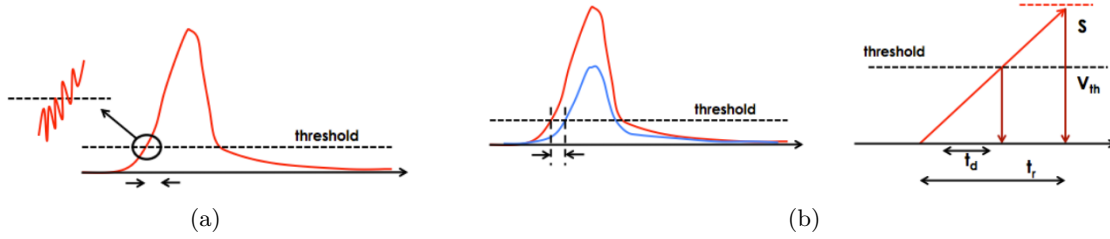


Figure 3.15: Jitter (a) and time walk (b) effects in the time measurement using a fixed threshold discriminator.

Both jitter and time walk as given by Eq. 3.6 and 3.7, depend on the inverse of the signal slope dV/dt , where S is the signal (proportional to the gain), N is the noise, t_{rise} is the rise time and V_{th} is the threshold voltage. The jitter contribution is discussed in Section 3.5.3. The time walk effect can be corrected by the measurements of the width of the pulse above the threshold level, also known as TOT, which is correlated with the pulse amplitude. HGTD chose as baseline for the time walk correction a TOT measurement with a constant threshold discriminator. With it a residual error less than 10ps is present after correction, for which the time walk effect is considered negligible. An alternative method to correct the time walk effect is the CFD method, where the time walk is minimised by defining the time of arrival as the time when the signal crosses a constant fraction of its maximum amplitude. However, this method cannot be realistically implemented in a readout circuit, due to the fact that the

maximum value is reached once the threshold has been already crossed. The CFD method will be used for the time resolution analysis of laboratory and test beam data, included in Chapter 6. The last component of Eq. 3.5 introduced an error due to the binning of the TDC circuit. This contribution is given by the following equation:

$$\sigma_{TDC}^2 = \frac{T_{bin}}{\sqrt{12}} \quad (3.8)$$

where T_{bin} is the bin size, assuming all the bins with the same size for an ideal TDC. HGTD will provide ~ 20 ps fine binning for TOA and 40 ps for TOT.

3.5.3 Single-channel readout electronics

The ALTIROC ASIC is a 225 channel matrix. The architecture of each individual readout channel can be divided into two parts, as shown in Figure 3.16. The analog front-end consists of a preamplifier, a discriminator and a TDC stage of the readout which are crucial elements for the overall electronics time performance. The digital part is responsible of the identification and storage of the hits and it contains also a separate block which is used to process luminosity information. The time of the pulse is determined using a discriminator with a fixed threshold following the preamplifier. Offline correction on the time walk is applied in order to account for the different TOA of the different pulse heights. Two TDCs are needed at the end to digitize the discriminator outputs. In this section, the components of the analog front-end will be discussed.

Preamplifier

From Eq. 3.6, the jitter contribution to the time resolution depends on the ratio between the noise and the slope of the signal pulse, such as an inverse dependence on the Signal-to-Noise ratio. Since the noise scales with the bandwidth as $\sqrt{BW}$ and the rise time grows with amplitude as S/BW , the first level of optimization relies on using a fast preamplifier. Over the last years, measurements in particle beam were performed with broadband amplifiers,

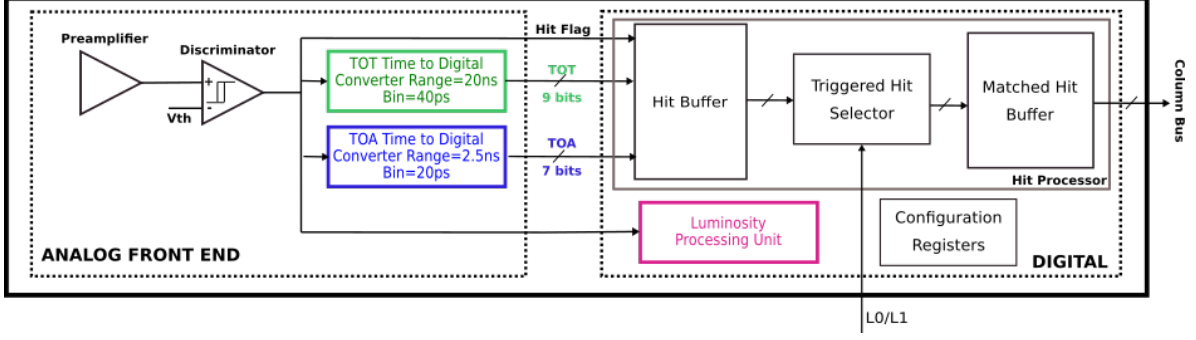


Figure 3.16: Schematic of the single-channel readout electronics. Two main blocks are identified, the analog and the digital part. The input pulse from the sensor enters the preamplifier on the left. The TOA and TOT data are read out by the column bus on the right [36].

which are voltage sensitive preamplifiers with 50Ω input impedance. Timing optimization has been published for a trans-impedance configuration in [40, 41]. For a voltage sensitive amplifier, the jitter can be calculated assuming that the detector current is a short pulse with a characteristic time t_d . The input charge is the corresponding integral of the current over the time t_d . The jitter of the preamplifier can be then written as shown in [36]:

$$\sigma_{jitter} = \frac{e_n C_d \sqrt{t_d}}{Q_{inj}} \quad (3.9)$$

where e_n is the noise spectral density and C_d is the detector capacitance. However, the jitter dependence on this is not very strong. Simulations show that for a sensor with $t_d \sim 600$ ps, if the preamplifier rise time is reduced or increased by a factor of 2 with respect the optimal matching value, the jitter would deteriorate by just 12%. With those considerations, in order to minimise the jitter, the sensor should have a small capacitance, a short pulse duration and be capable to provide a large charge.

The design of the ALTIROC chip uses a voltage sensitive preamplifier (VPA), shown in Figure 3.17 (a). This is broadband preamplifier with a cascoded Common Source configuration, which consists of an input transistor (M1) and a follower transistor (M2). The R_2 resistor is connected to a feedback to ensure the biasing of preamplifier input. To adjust the fall time of the output, the value of R_2 can be modified. A pseudo-transimpedance configuration (TZ), shown in Figure 3.17 (b), has also been integrated in some channels of the ALTIROC

prototypes, in order to choose the best performing preamplifier version. The configuration is very similar to the VPA except that the $R1$ resistor is now in the feedback of the amplifier and it corresponds to the resistive component of Z . A small input impedance Z_s results in an input that is sensitive to the input current. The output of TZ amplifiers are generally short-duration steep signals of small amplitude. TZ configurations are therefore prone to oscillation. On the contrary, if large values of Z_s ($\sim 10^3$) are used, the input become more sensitive to the input voltage V_{in} and the resulting output signals tend to be longer and more amplified. This VPA are more stable than the TZ counterpart. As mentioned before, detector capacitance is a key

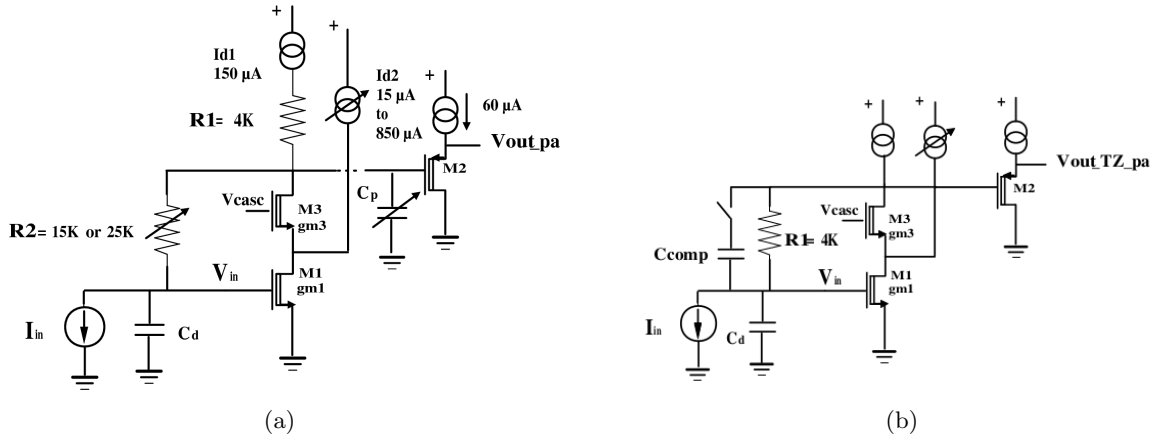


Figure 3.17: Schematic of the preamplifier implemented in the ALTIROC1 design [36]. Both voltage sensitive (a) and pseudo-transimpedance (b) preamplifiers are shown.

element to calculate the input voltage for a given input charge, depending on the relation $V_{in} = Q_{in}/C_d$. To compensate the irradiation effect on the rise time of LGAD sensors, which becomes smaller with fluence, the rise time of the preamplifier is tunable. This can be done adjusting the pole capacitance C_p .

With LGAD sensors the preamplifier speed becomes less crucial, because of the duration of the current of the sensor, which is not negligible with respect to the preamplifier rise time, and the capacitive impedance of the sensor. Both configurations are being investigated by the HGTD community and a decision will be made soon. Detailed study of the two preamplifier type's performances can be found in [42].

Discriminator

The time measurement is performed by a discriminator which follows the preamplifier and provides the measurement of the TOA on the rising edge of the pulse, and the Time Of End (TOE) on the falling edge of the pulse from the detected particles. The subtraction of the two times provides the TOT measurement. To ensure a jitter smaller than 10 ps, the discriminator is built around a high speed leading edge architecture with hysteresis to avoid re-triggering effects. Two differential stages with small input transistors are used to ensure a large gain and large bandwidth (approximately 0.7 GHz). The discriminator threshold, V_{th} , is set by an external 10-bit DAC common to all channels. An additional 7-bit DAC (not present in ALTIROC0) allows to make small V_{th} corrections individually for each channel in order to compensate for differences among them or for different values of leakage current.

Time-to-Digital Converter

The time measurement provided by the discriminator is digitised through two TDCs, one dedicated to the TOA and the other to the TOT measurements. The representation of the working principle of the TDC is shown in Figure 3.18. Since the target quantisation for the TOA is 20 ps, the Vernier delay line² configuration is used. Its configuration consists of two lines, each of them composed by a series of delay cells, controlled by a voltage signal (V_{ctrl}) that determines their delay. The timing resolution is determined by the difference in the delays of the cells in each line. The delay of the two lines is set differently, one to a smaller one (FAST) with a delay of 120 ps, and the other to a larger delay value (SLOW) where the delay is fixed to 140 ps. The TOA will be measured within a 2.5 ns window centered at the bunch crossing, with a quantisation step of 20 ps. The working principle of the TDC is the following. The START signal (rising edge of discriminator) enters the SLOW delay line and the STOP signal (next rising edge of the 40 MHz clock) enters the FAST delay line.

²A Vernier delay line consists of a pair of tapped delay lines with a flip-flop at each corresponding pair of taps. A stop signal propagates through one of the delay chain, while the start signal propagated through the other, clocking the flip-flop at each stage.

Each delay cell along the line brings the START and STOP signal closer to each other by an amount equal to the difference between the FAST and SLOW cell delays, which is 20 ps. The number of the cells necessary to the STOP signal to surpass the START signal results in the time resolution measurement with 20 ps step quantisation. The reverse START-STOP scheme is also used as power-saving strategy. The TOT TDC provides a 9-bit digitization of the discriminator width on a 20 ns range. It uses a coarse delay line made of 160 ps delay cells to extend the measurement range to 20 ns, while a Vernier delay line provides the requested resolution of 40 ps. The START and STOP signals are given by the rising and falling edge of the discriminator.

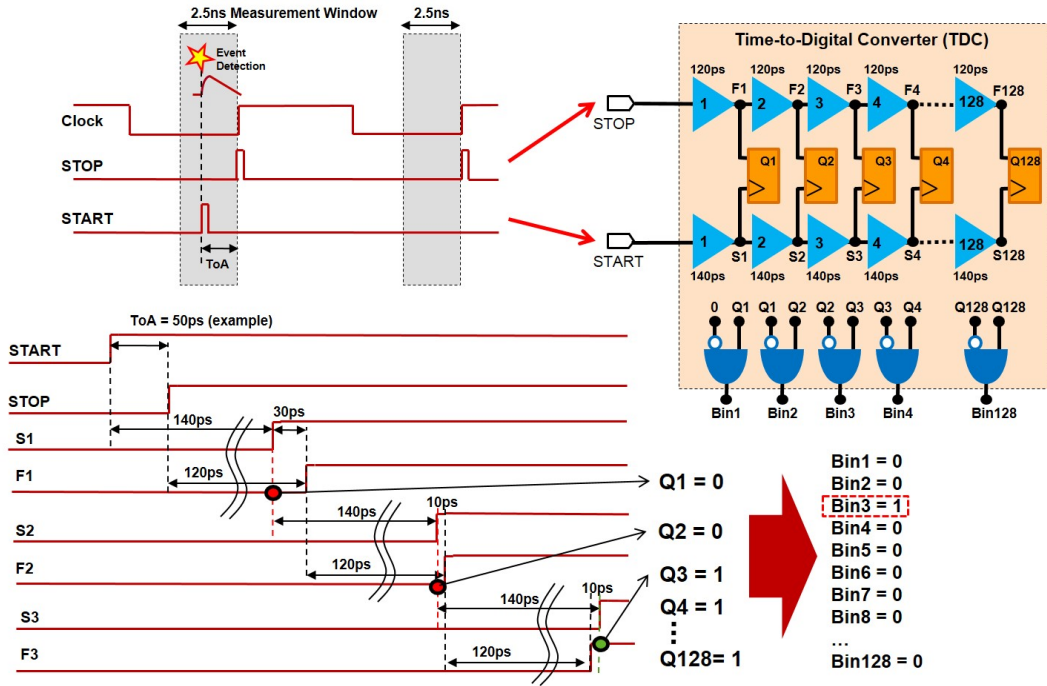


Figure 3.18: Graphic representation of the working principle of the TDC. The drawing on the top left shows how the START and STOP signals are generated, the first with the discriminator output upon event detection, the second corresponding to the next clock edge. The gray area indicates the 2.5 ns detection window. On the top right, the scheme represents the TDC, with the “slow” delay line (140 ps cells) that propagates the START signal, and the fast delay line (120 ps cells) in which the STOP signal is propagated. The difference between delays defines the bin. After each cell the signals are compared (QX), and the bin number provides the converted measurement [36].

3.6 Sensors

HGTD will be instrumented with LGAD silicon sensors. The LGAD technology will be explained in Chapter 5. The characterization of LGAD sensors before and after irradiation, in charged particles beams and in the laboratory with a radioactive source and a laser is the core of the work presented in this thesis. The results will be presented in Chapter 6.

Chapter 4

HGTD impact on VBF H analyses at the HL-LHC

4.1 Brief summary of the Standard Model

The theories and discoveries over the 20th century have yielded a remarkable understanding of matter's underlying structure: everything in the universe is made from a few basic blocks, the so called fundamental particles, which are governed by four fundamental forces. The theoretical framework which describes the dynamics of those particles and of three of the forces is the Standard Model SM of particle physics [43]. The forces included are: the electromagnetic force, governing interactions between charged particles, the weak interaction, responsible for the weak decays of particles and weak neutral currents, and the strong interaction, acting on quarks and responsible for their confinement in nuclei. The last remaining of the four fundamental forces, gravity, is currently understood in the domain of classical physics through General Relativity. Unfortunately, making this force compatible in a quantum field theory has proved to be a difficult challenge. Luckily, at the energies where the SM is tested experimentally the effect of gravity can be considered negligible. The SM was finalized in the 1970s, and it has successfully explained almost all experimental results and predicted a wide

range of phenomena, being established as a well tested theory. The last missing part of the puzzle, the Higgs boson, has been discovered by ATLAS [1] and CMS [2] experiments of the LHC in 2012, roughly 60 years after its prediction.

4.1.1 Standard Model particle content

The elementary particles in Figure 4.1 are the building blocks of matter and are considered to have no substructure. The 12 fermionic particles of spin $\frac{1}{2}$ are separated in two families, the so called *leptons* and *quarks*, each of them consisting of six particles. All of them are arranged into three “generations” of matter, each consisting of two types of quarks and two types of leptons. The types differ in their mass but interact in a similar manner. The SM also includes the antimatter variant of each particle, which differs from the particle by the sign of the charge and the other quantum numbers, and is denoted by the same symbol of the particle with a bar over it.

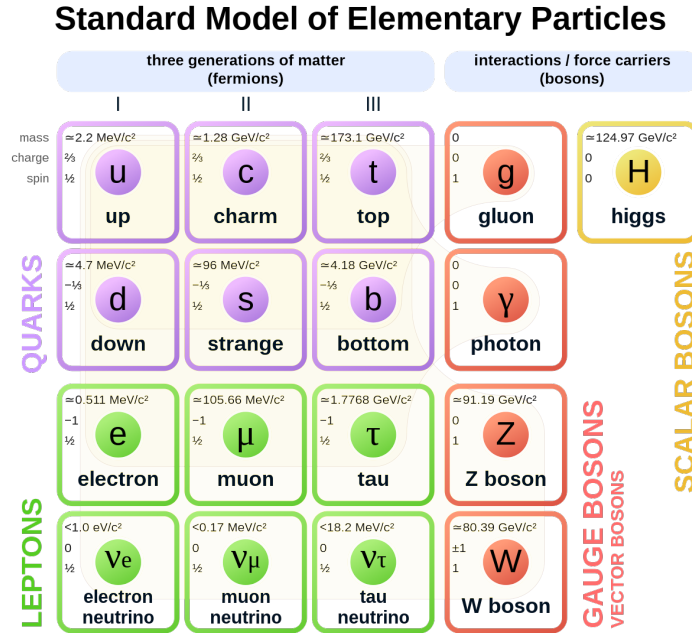


Figure 4.1: Overview of the Standard Model particle content. Properties like mass, charge and spin are also listed.

Quarks are particles that interact through the electromagnetic, weak and strong force. Up type quarks have a positive electric charge $Q = \frac{2}{3}$ while down type have a negative charge $Q = -\frac{1}{3}$. Each generation includes one up-type quark and one down-type. In the first generation, they are u (up) and d (down), in the second c (charm) and s (strange) and in the third b (bottom) and t (top). In addition to the electric charge, quarks also carry a colour charge, source of the strong field. Colour charged particles have never been observed experimentally as free particles. Combination of colour charged particles can build neutral charge states when combining the three colours together or combining colour and anti colour. Hadrons can be either a combination of a quark and anti quark pair ($q\bar{q}$), called mesons, or as a three quarks states (qqq) called baryons.

Leptons are also arranged into three generations, each of them made of one electrically charged particle and a neutral one, called neutrino. The three charged particles e (electron), μ (muon) and τ (tau) have an electric charge $Q = -1$ and a sizeable mass, while the ν_e (electron neutrino), ν_μ (muon neutrino) and ν_τ (tau neutrino) are electrically neutral and have very little mass. Charged leptons and their associated neutrinos carry the same lepton number. In the classical formulation of the SM, neutrinos were considered massless. However, experimental observation of neutrino oscillation [44, 45, 46] have shown that neutrinos must have a non-vanishing mass value, although very small. Charged leptons interact both electromagnetically and weakly, while neutrinos only interact weakly. Due to this characteristic neutrinos usually pass through solid matter and are very difficult to detect.

In quantum field theory, interactions are mediated by other particles which are called Gauge bosons, which are particles with integer spin value.

The strong force is mediated through gluons, which are massless bosons but contrary to the photons carry a color charge. The introduction of the strong interaction was born from the need to explain the force that keeps together the protons inside nuclei and the quark bound inside hadrons. The postulation of the colour charge was motivated by the need to give an explanation to particles made of three identical quarks being consistent with Fermi-Dirac statistics. A new quantum number, the colour charge, was introduced. It can take three

different values: red (R), green (G) and blue (B). In this way, quarks can carry a colour charge while anti quarks carry an anti-colour charge. The gauge theory which describes the strong interactions between quarks and gluons is called Quantum Chromodynamics (QCD).

The electromagnetic force is mediated by the photon, a massless particle which couples to all electrically charged particles and does not have charge. The $W^\pm$ and Z^0 bosons are carries of the weak force. $W^\pm$ particles have an integer charge and mediates interactions where charge is also transferred, while the Z^0 is electrically neutral and it can only transfer spin, momentum and energy. The SM theoretical framework that describes the electromagnetism and the weak force was introduced by Glashow, Weinberg and Salam [47, 48, 49]. Those forces unify at the electroweak scale into the Electroweak interaction (EW). While the photon only couples to electric charge, the massive $W^\pm$ and Z^0 bosons couple to the weak isospin carried by left-handed particles. Thus in its pure form, the SM theory works with only massless gauge bosons, which is in clear disagreement with the short range property of the weak interaction as well as the measured masses of the W and Z bosons. The solution to this problem is given by the introduction of Spontaneous symmetry breaking (SSB).

The requirement of a symmetry breaking ground state leads to an invariant formulation of the masses of both the electroweak gauge bosons as well as the fermions. This is what is known as the Brout-Englert-Higgs mechanism [50, 51]. As a consequence, an additional massive and scalar boson is predicted to exist, the Higgs boson. In 2012 a new scalar boson was observed by the ATLAS and CMS experiments at CERN. This particle appeared to be in good agreement with the SM prediction [1, 2].

4.1.2 Open questions of the Standard Model

Even though the SM is considered a very successful theory and is currently the best description of the subatomic world, it does not explain everything. There are still a number of inconsistencies for which further extensions of the SM are needed, such as the unification of forces, the dark matter, dark energy and the matter-antimatter asymmetry. The goal of the

HL-LHC is to try to shed light into the questions that challenge the SM.

4.2 Impact of the HGTD in physics analysis

There are three main ways in which the HGTD detector is expected to enhance the physics capabilities of ATLAS by exploiting the new dimension of timing information which is distinct to any other detector measurements.

The first area is the improvement of the physics object reconstruction, such as forward jets and leptons, which are key elements in Vector Boson Fusion (VBF), Vector Boson Scattering (VBS), and lepton based forward-backward asymmetry measurements. Secondly, the use of timing information provided by the HGTD will introduce new features in the analysis of physics data, like the possibility to introduce a track-timing tool. Finally the HGTD detector will provide new capabilities for online and offline luminosity measurements at ATLAS to help achieve the 1% goal of uncertainty on the luminosity for the Higgs precision programme at the HL-LHC.

The primary way in which HGTD can improve the VBF physics event reconstruction is by reducing the impact of the pileup. VBF final states are characterized by two identified jets with a large rapidity gap with most of the time at least one of them in the HGTD acceptance region. This process will be discussed in the next section. In addition, a precise timing information is a completely new feature at hadron colliders experiments. It is expected that, using more precise machine learning algorithms and physics analyses that exploit time information, further improvements will be achieved.

4.2.1 Vector Boson Fusion Higgs production

VBF Higgs boson production is the second largest Higgs production mechanism at the LHC. The cross section measurements of the VBF process $VV \rightarrow H$ followed by the Higgs boson decay into $\tau\tau$, WW and $\gamma\gamma$ will significantly extend the possibility of Higgs boson coupling

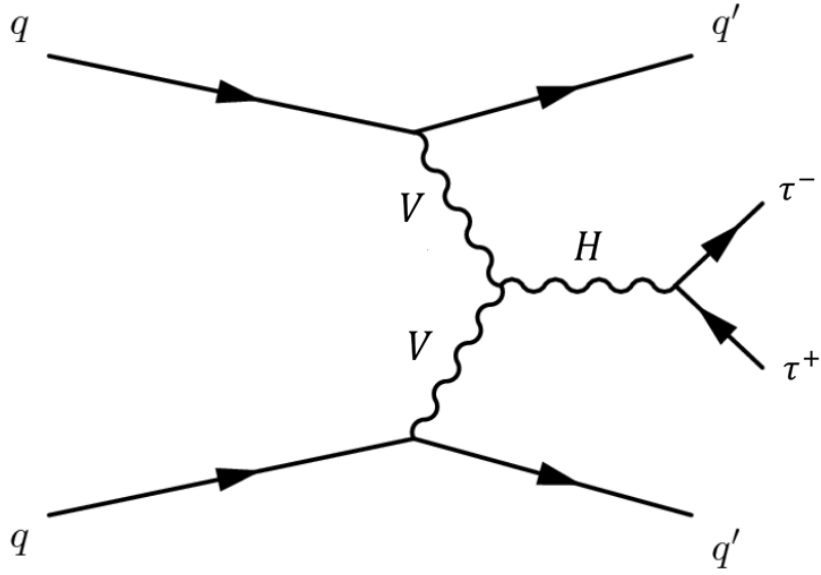


Figure 4.2: Feynman diagram of the VBF $H \rightarrow \tau\tau$ decay process.

measurements. This cross section is the highest one after the gluon-gluon fusion and provides key features that can be exploited at the trigger level or in the offline analysis to separate the signal from the background.

The measurement of the VBF Higgs production is one of the major components of the physics programme at the HL-LHC. In this process, a quark from each of the incoming LHC protons radiates off a heavy vector boson. These bosons interact or “fuse” to produce a particle, in this case a Higgs boson. In Figure 4.2 the Feynman diagram of this process is shown. The main characteristic of a VBF event is the presence of two jets with a large rapidity gap. Most of the time, at least one jet is in the HGTD acceptance region, thus this final state can benefit from the improvement on jet reconstruction and pileup suppression provided by the HGTD.

The final state of this decay can be characterized by two leptons (ll), two hadrons (hh) or a lepton-hadron couple (lh). For the $\tau\tau$ final state, the subject of this study, one of the dominant backgrounds is the QCD $Z \rightarrow \tau\tau + jets$ production, where the final state contains a hard scattered jet plus two additional forward pileup jets. In Figure 4.3 the dominant process for $\tau\tau$ production is shown together with jets originated from pileup. This process can be reduced with the HGTD by identifying the pileup jets. In this situation, timing

information provided from the HGTD can help in overcoming the limitations of the tracking-based pileup jet suppression algorithm in the forward region. Reducing the effect of the pileup and improving the jet transverse momentum reconstruction leads to a better signal to background ratio (S/B).

In the HGTD Technical Design Report [36], the invisible decays of the Higgs produced through VBF was chosen as representative analysis to illustrate the impact of the detector on VBF topologies. For this study of the impact of the HGTD presented in this thesis, the $H \rightarrow \tau\tau$ channel with its main background $Z \rightarrow \tau\tau + jets$ is considered. Unfortunately, the signal sample was not available at the time of this study, which is then performed considering only the effect of the HGTD detector on the background sample.

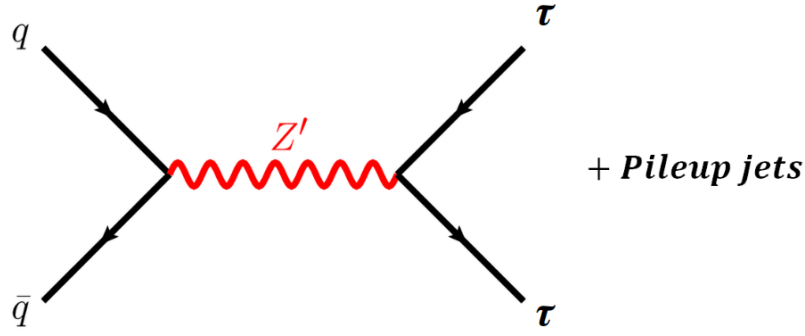


Figure 4.3: Feymann diagram for the dominant background process.

4.2.2 Monte Carlo sample production

The study presented in this thesis was performed using a full simulation based on GEANT4 [52, 53]. The $Z \rightarrow \tau\tau + jets$ sample was simulated with POWHEG-BOX [54, 55, 56] (v1r2856) interfaced with PYTHIA8 [57, 58] (v8.186). The study considers the QCD $Z \rightarrow \tau\tau + jets$ background only. Due to the challenge of Monte Carlo generation at $\sqrt{s} = 200$, the number of events is limited, but this study is intended as a first look into the potential gains that could be achieved in this analysis with the HGTD.

4.2.3 Effect of HGTD in the considered Physics channel

In this study, only three channels for the τ decays are accepted in the final state ($e\mu$, hh and lh) for which the $Z \rightarrow \tau\tau + jets$ background is more important. The cuts listed in Table 4.1 used for the selection of this sample are inspired in Run-2 analysis presented in [59]. Events are required to have at least two jets with $p_T^1 > 40 \text{ GeV}$ and $p_T^2 > 30 \text{ GeV}$, both of them verifying the condition $-4 < |\eta_{1,2}| < 4$. In addition, the two jets are required to have a large rapidity gap $\Delta\eta(j_1, j_2) > 3$. An invariant mass $m_{j_1 j_2} > 400 \text{ GeV}$ and jets in two different hemispheres ($\eta_{j_1} \cdot \eta_{j_2} < 0$) are required. In the following section, four baseline scenarios will be presented.

Existence of a jet	$n_{jets} > 0$
p_T leading jet	$p_{t_{jet1}} > 40 \text{ GeV}$
η leading jet	$-4.0 < \eta_{jet1} < 4.0$
Existence of a second jet	$n_{jets} > 1$
p_T subleading jet	$p_{t_{jet2}} > 30 \text{ GeV}$
η subleading jet	$-4.0 < \eta_{jet2} < 4.0$
Jets rapidity	$ \Delta\eta_{jets} > 3$
Jets invariant mass	$m_{j_1 j_2} > 400 \text{ GeV}$
Jets in two different emisphere	$\eta_{jet1} \cdot \eta_{jet2} < 0$

Table 4.1: Cuts used for the preliminary study presented in this chapter. Those are inspired to the ones in reference [59].

Different baseline scenarios

The selection cutflow explained in the last section has been applied on four different scenarios with different starting conditions. They are considered as a baseline for the study of the cutflow selection. The four scenarios are the following:

- Scenario ALL (A): all available jets are considered without any exception.
- Scenario ITk (B): the ITk detector is included. A cut on the R_{p_T} variable (discussed briefly in Chapter 3) is required at the beginning of the cutflow.

- Scenario ITk + remove all PU (C): the ITk detector is included. In addition, all the pileup jets are rejected using truth information¹.
- Scenario ITk + perfHGTD (D): the ITk detector is included. In addition, all pileup jets are rejected using truth information in the HGTD acceptance region $2.4 < |\eta| < 4.0$.

When the ITk detector is included, an ITk jet tagger requires that for each jet the reconstructed p_T is $R_{p_T} > 0.15$ (which has the effect of removing pileup jets). This variable is defined as in equation (3.3) in Chapter 3 and shown in Figure 4.4 for the simulated sample:

$$R_{p_T} = \frac{\sum_k p_T^{trk_k}(PV_0)}{p_T^{jet}} \quad (4.1)$$

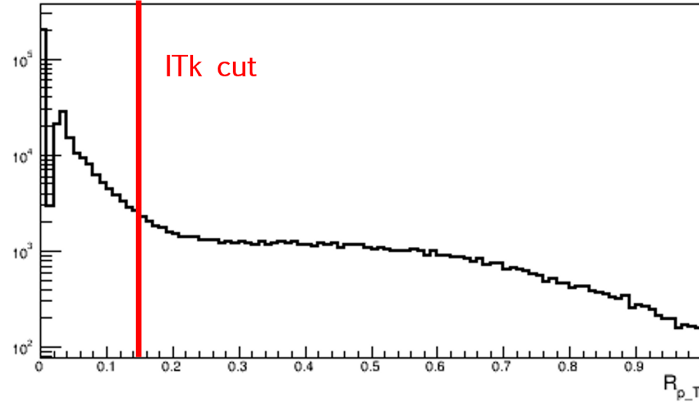


Figure 4.4: Distribution of the R_{p_T} variable for the simulated sample. No cuts are implemented in the plot.

In Table 4.2, the number of entries for each of the four baseline scenarios is shown. It can be seen from the cutflow number of events how the insertion of a perfect HGTD detector ($2.4 < |\eta| < 4.0$), which rejects 100% of the pileup jets in the HGTD acceptance region, reduces the number of entries of a factor ~ 2.8 with respect to the ITk only scenario.

In this section we discussed the effect of an idealized HGTD detector. In the following section

¹The parton level simulated jet as explained already in Chapter 3.

Cut	Scenario A ALL	Scenario B ITk only	Scenario C ITk + no pileup jets	Scenario D ITk + perfHGTD
N_{events}	157762	157762	157762	157762
$n_{jets} > 0$	136177	58263	24045	52049
$p_{T_{jet1}} > 40 \text{ GeV}$	99395	39853	18485	36223
$-4.0 < \eta_{jet1} < 4.0$	96295	39737	18470	36105
$n_{jets} > 1$	81179	14338	4038	10940
$p_{T_{jet2}} > 30 \text{ GeV}$	81179	14338	4038	10940
$-4.0 < \eta_{jet2} < 4.0$	78055	14288	4026	10896
$ \Delta\eta_{jets} > 3$	18844	2534	562	1140
$m_{j1j2} > 400 \text{ GeV}$	8743	1133	263	409
$\eta_{jet1} \cdot \eta_{jet2} < 0$	8546	1104	253	399

Table 4.2: Number of events for the cuts inspired to Run 2 analysis in the four baseline scenarios A, B, C and D. It is visible from the last line of the table how the insertion of a perfect HGTD (scenario D) detector reduces the number of events by a factor of ~ 2.8 with respect to the ITk only scenario (scenario B).

the actual exploitation of the HGTD information will be discussed. This will lead to a reduction of the benefit of the HGTD, but still, for the physics process discussed, HGTD will be shown to provide a potential significant advantage.

Association of time information to reconstructed tracks

The algorithm used to associate the time information to a reconstructed track is based on a progressive extrapolation of tracks to the HGTD surface. First, tracks reconstructed in the ITk are extrapolated to HGTD using the last measurement of the track in ITk as a starting point. With a progressive Kalman filter, tracks are extended to the HGTD surfaces. In each layer of the HGTD, clusters around the extrapolated position of the track are evaluated in order to see if they are compatible with it. Between all the spatially compatible hits, the one with the lower χ^2 is accepted as an extension of the track [36, 60]. This process is iterated in all the HGTD layers, always using the last step information as a starting point of the extension. A cleaning procedure is used to reduce the rate of misassociation of the track extension, helping to reduce the probability of associating a random pile up time to a particle that showered before reaching the sensor surface of HGTD. The track-time is then calculated as the arithmetic mean of the times of the individual associated HGTD hits.

Calculation of vertex time t_0

The time of the primary vertex t_0 is estimated as follow [36]. First, an iterative time-clustering algorithm is used to find clusters of tracks that are within a window in z around the selected hard-scattered vertex in the event and have consistent times. To ensure that the tracks inside a cluster are consistent in time, the track-time of a given track must agree with that of any other track within a window of $3\sigma_t$, where σ_t is the square root sum of track-times errors of the two tracks under consideration. Next, a Boosted Decision Tree (BDT) algorithm is used to identify the most probable hard scattered cluster among the various clusters. After the cluster is chosen, the vertex t_0 is defined as the weighted average time of all the tracks belonging to that cluster:

$$t_0 = \frac{\sum \frac{t_{track}}{\sigma_t^{track}}}{\sum \frac{1}{\sigma_t^{track}}} \quad \text{where} \quad \sigma_t^{track} = \frac{\sigma_t^{hit}}{\sqrt{N_{hits}}} \quad (4.2)$$

Calculation of jet time

The time of the jet [60] is computed with respect to the vertex time t_0 as following:

$$t_{jet} = \sum_{jet} \frac{t_{track} pT_{track}}{\sum_{jet} pT_{track}} - t_0 \quad (4.3)$$

For the sample under study, the time information is provided for the 60% of the jets. The reconstructed time of the jets is then calculated for all the jets in the HGTD acceptance region for which time information is provided. A distribution of the reconstructed vertex t_0 is given in Figure 4.5 (a), while jet time calculated with respect to the internal t_0 is shown in Figure 4.5 (b) for the ITk only scenario at the end of the cutflow. For each event the jet time resolution is calculated as:

$$\sigma_{t_{jet}} = \frac{\sqrt{\sum (\sigma_{t_{track}}^2 \times pT_{track}^2)}}{\sum pT_{track}} \quad (4.4)$$

whose distribution is shown in Figure 4.5 (c). In addition, jets significance has been defined as:

$$\lambda_{jet} = \frac{t_{jet}}{\sigma_{t_{jet}}} \quad (4.5)$$

with its distribution shown in Figure 4.5 (d). New scenarios where cuts on the significance distribution are considered will be presented in the next section, in order to study a more realistic impact of the HGTD.

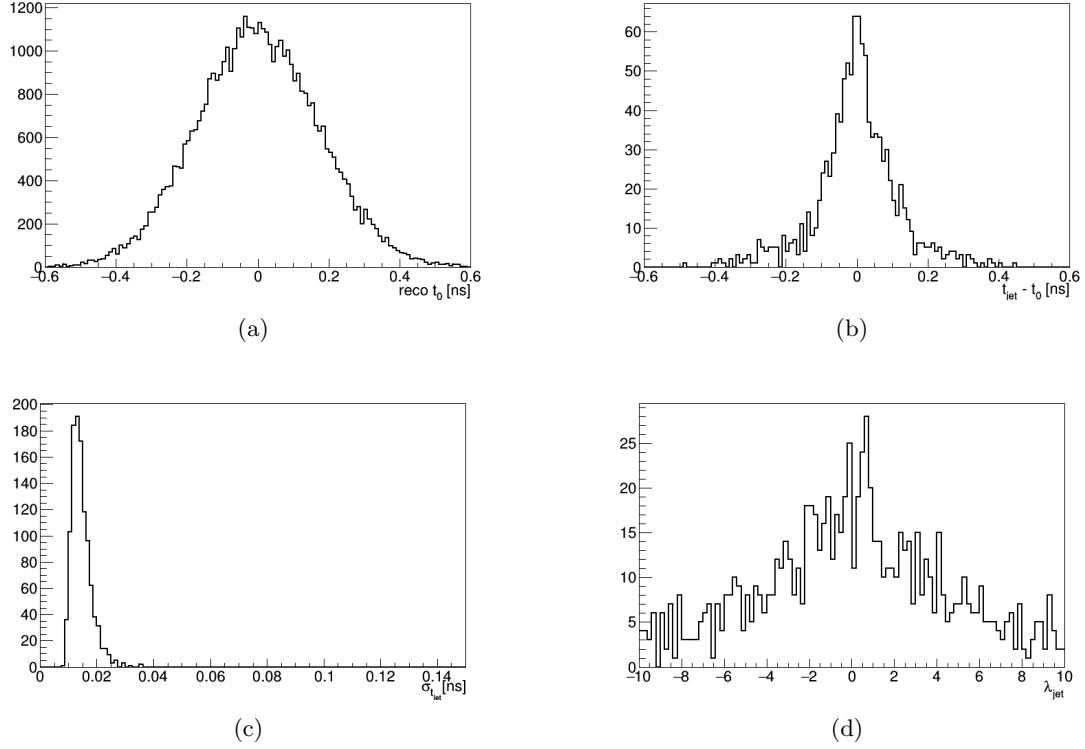


Figure 4.5: Reconstructed vertex t_0 (a), jet time distribution with respect to the vertex time t_0 (b), jet time resolution distribution (c) and jet time significance distribution (d) for the jets at the end of the cutflow in the ITk only scenario.

Jet time information

The ideal case presented in Table 4.2 does not reflect the way the jet time information will be used. Three more realistic scenarios are considered here, for which the time information is used in the jet rejection process. The Scenario B of the previous section is used as a baseline.

The scenarios where time information is realistically considered are the following:

- HGTD1 σ : jets for which the jet time significance is larger than $\pm 1\sigma$ are rejected.
- HGTD1.5 σ : jets for which the jet time significance is larger than $\pm 1.5\sigma$ are rejected.
- HGTD2 σ : jets for which the jet time significance is larger than $\pm 2\sigma$ are rejected.

The corresponding cutflow for these timing scenarios can be seen in Table 4.3, where the cutflow for the ITk only scenario and for the perfect HGTD are also given. The HGTD 1 σ scenario yields a reduction of events of ~ 2.59 with respect to the ITkonly scenario, the HGTD 1.5 σ results in a factor ~ 2.3 and the HGTD 2 σ in ~ 2.05 . In Figure 4.6, the distribution for

Cut	ITk only	Perfect HGTD	HGTD 2 σ	HGTD 1.5 σ	HGTD 1 σ
N_{events}	157762	157762	157762	157762	157762
$n_{jets} > 0$	58263	52049	53160	52599	51964
$p_{T_{jet1}} > 40 \text{ GeV}$	39853	36223	36570	36182	35742
$-4.0 < \eta_{jet1} < 4.0$	39737	36105	36452	36064	35624
$n_{jets} > 1$	14338	10940	11577	11291	10971
$p_{T_{jet2}} > 30 \text{ GeV}$	14338	10940	11577	11291	10971
$-4.0 < \eta_{jet2} < 4.0$	14288	10896	11533	11247	10927
$ \Delta\eta_{jets} > 3$	2534	1140	1453	1343	1230
$m_{j1j2} > 400 \text{ GeV}$	1133	409	553	493	433
$\eta_{jet1} \cdot \eta_{jet2} < 0$	1104	399	537	480	426

Table 4.3: Number of events for the cuts inspired in Run 2 analysis in the three different HGTD timing scenarios, including the ITk only (B) and perfect HGTD. From the last line of the table the reduction of the different timing scenarios can be seen. The HGTD 1 σ scenario reduces the number of events by a factor ~ 2.59 , the HGTD 1.5 σ by ~ 2.3 and the HGTD 2 σ by ~ 2.05 with respect to the ITk only scenario.

both leading (left) and subleading (right) jets both at beginning (top) at the end of the cutflow (bottom) are shown for the ITk only , the perfect HGTD and the HGTD 2 σ scenarios. In these plots it can be seen how much the pileup jets in the forward region are reduced by exploiting the HGTD information.

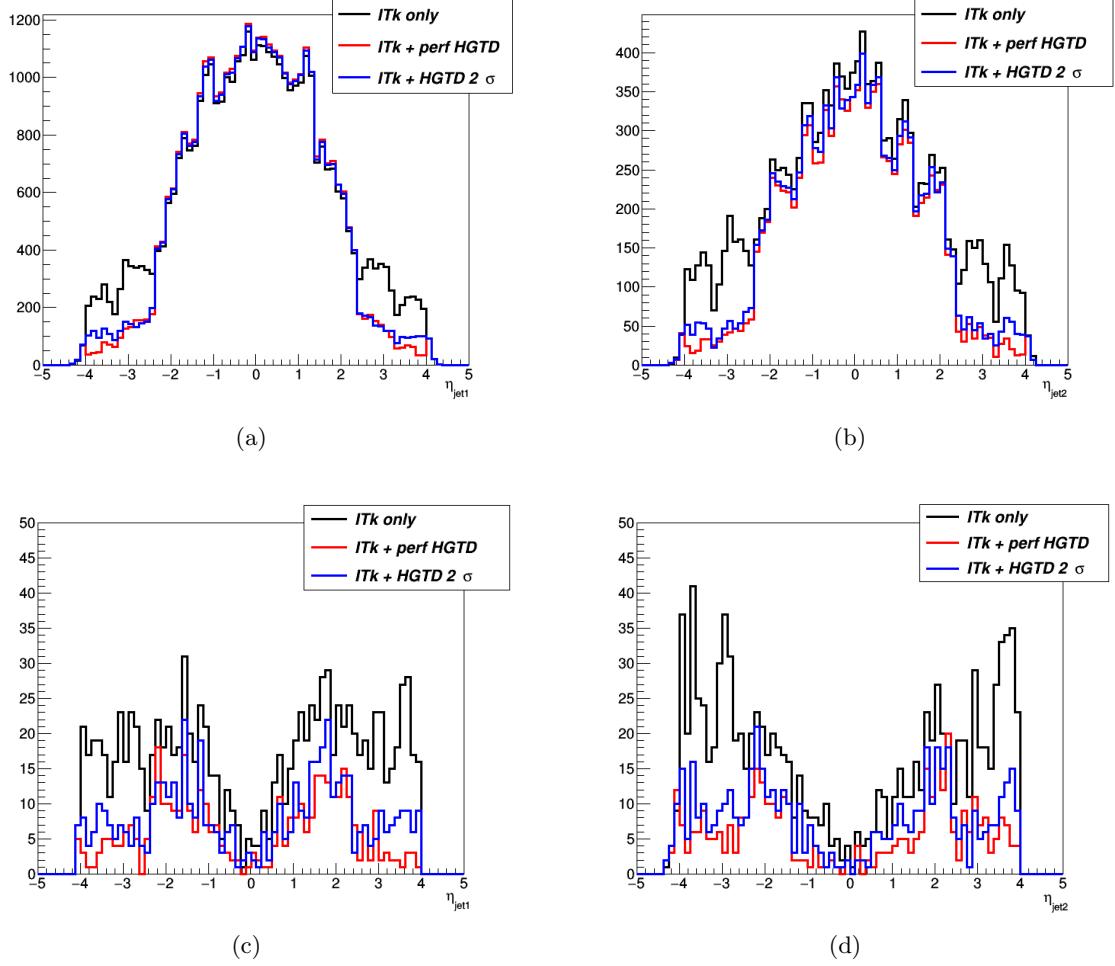


Figure 4.6: η distributions for leading (a) and subleading (b) jets at the beginning of the cutflow and η distributions for leading (c) and subleading (d) jets at the end of the cutflow. The ITk only scenario (black), the perfHGTD (red) and the HGTD 2 σ (blue) scenarios are shown for comparison. It is visible how the insertion of the HGTD detector reduces the number of events in the forward region $2.4 < |\eta| < 4.0$ with respect to the ITk only scenario. The distributions are not normalized.

Conclusions

A simplified VBF jet selection based on full jet reconstruction information has been applied to a QCD $Z \rightarrow \tau\tau + jets$ Monte Carlo sample. The original purpose of the study was VBF $H \rightarrow \tau\tau$, but the results apply to any physics channel in which QCD $Z \rightarrow \tau\tau + jets$ is a dominant background. The ideal performance of HGTD can be checked with truth information and it has been estimated that the background is reduced by ~ 2.8 with respect to the ITk only scenario. The use of timing information has been shown to be very effective in suppressing QCD $Z \rightarrow \tau\tau + jets$ events, with a reduction of ~ 2.05 with respect to the ITk only scenario when discarding jets with time significance greater than two. The very important aspect of the effect of the HGTD on the $H \rightarrow \tau\tau$ signal remains to be studied. Unfortunately, the eventual production of Monte Carlo samples for the $H \rightarrow \tau\tau$ signal channel was not compatible with the timescale of this thesis.

Chapter 5

Sensor Technology: from Solid State Detectors to Low Gain Avalanche Detectors (LGADs)

Solid state detectors have been introduced in the field of experimental particle physics in the 1970s. In the following decades, they became more and more common thanks to their outstanding performances in terms of position resolution and radiation hardness, which are crucial factors for HEP experiments. Nevertheless, gas-based tracking detectors have not been totally replaced by solid state detectors, since their cost makes them more suitable for outer layers of big experiments. This is the case of the LHC, where large volumes have to be covered and time resolution and radiation requirements can be relaxed as the distance from the IP increases.

In the past decades, the scientific community made many progress in the solid state detectors field. To meet the demands of experiments, the manufacturing techniques also improved allowing to produce different thickness wafers and detectors with finer segmentation and increased radiation hardness. At the same time, the progress of ASICs from the electronic industry has been crucial to provide adequate readout systems.

In the first part of this chapter, the fundamental aspects of silicon detectors will be summarized. In the second part, an overview on the LGAD technology, with which the HGTD detector will be instrumented, will be presented.

5.1 Solid State Detectors

In solid state detectors the signal is generated by the current associated to the drift of ionization charge produced by the passing of a charged particle through the sensor. Their characteristics such as high density, fast readout and high segmentation make them suitable for high energy particle detection of collider experiments.

5.1.1 The band model

The fundamental theory behind the solid state detector is the band model of solids. The discrete energy levels of the atoms in which electrons are confined are called bands. Due to the Pauli exclusion principle, each band can host a finite number of electrons. Thus, the lowest energy level are fully filled, while bands above a certain limit will not be occupied. The highest fully filled energetic band is the so called valence band, while the next higher level which is partially filled or empty is the so called conduction band. When this last band is partially filled, the electrons of the material are free to move in the crystalline lattice and the solid is a conductor. Otherwise the energy gap $E_g = V_C - V_V$ between valence and conduction bands defines if the material is a conductor or insulator [61]. The most common semiconductor used in radiation detectors is silicon, for which $E_g \sim 1.2\text{ eV}$, and 3.6 eV are needed to create an electron-hole ($e - h$) pair, as it will be discussed in the next section. Both electrons and holes contribute to the charge carrier concentration inside the material. Electrons can be excited from the valence to the conduction band moving freely in the crystal lattice and leaving vacancies (or holes) in their original position. Holes, move in the crystal lattice as well, acting as positive charges. Through thermal excitation $e - h$ pairs are continuously generated as well as destroyed, since they can recombine. In general, the concentration of electrons in the

conduction band can be calculated with the following equation:

$$n = \int_{E_C}^{\infty} g_e(E) f(E) dE \quad (5.1)$$

with $g_e(E)$ density of states, $f(E)$ the Fermi-Dirac distribution and the integral calculated from the minimum energy level (E_C) to infinity. In a similar way, the concentration of holes can be calculated, this time integrating from zero to the maximum energy level (E_V) in the valence band:

$$p = \int_0^{E_V} g_h(E) f(E) dE \quad (5.2)$$

The Fermi-Dirac distribution used in both calculations is given by:

$$f(E) = \frac{1}{1 + e^{(E-E_F)/k_B T}} \quad (5.3)$$

where k_B is the Boltzmann constant, T is the temperature in Kelvin and E_F is the Fermi energy, which for a semiconductor is placed approximately at the middle of the energy gap:

$$E_F \sim \frac{E_C - E_V}{2} \quad (5.4)$$

It is possible to calculate the density of states for both electrons and holes assuming they are free to move inside the semiconductor but cannot escape from it. This is represented by an infinite potential box which can be written as:

$$g_e(E) = \frac{1}{2\pi} \left(\frac{m_n}{\hbar^2} \right)^{3/2} \sqrt{E - E_C} \quad \text{with } E \leq E_C \quad (5.5)$$

$$g_h(E) = \frac{1}{2\pi} \left(\frac{m_h}{\hbar^2} \right)^{3/2} \sqrt{E_V - E} \quad \text{with } E \geq E_V \quad (5.6)$$

where m_n and m_h are the effective masses of electrons and holes¹ and $\hbar$ is the reduced Planck constant. From the integral of equations 5.1 and 5.2 the electrons and holes concentration

¹For Silicon at $T=300\text{ K}$: $m_n=1.09m_e$ and $m_h=1.15m_e$ with m_e being the mass of the electron.

can be calculated:

$$n = 2 \left(\frac{m_n k_B T}{2\pi \hbar^2} \right)^{3/2} e^{-(E_C - E_F)/(k_B T)} = N_C e^{-(E_C - E_F)/(k_B T)} \quad (5.7)$$

$$p = 2 \left(\frac{m_h k_B T}{2\pi \hbar^2} \right)^{3/2} e^{-(E_F - E_V)/(k_B T)} = N_V e^{-(E_F - E_V)/(k_B T)} \quad (5.8)$$

where N_C and N_V are the effective density of states in the conduction and valence band, respectively. The product of electrons and holes density gives:

$$np = n_i^2 = N_C N_V e^{-E_g/k_B T} \quad (5.9)$$

where n_i is the intrinsic charge carrier concentration². Typical values for n_i in silicon at room temperature are of the order of $1.5 \times 10^{10} \text{ cm}^{-3}$ [62].

5.1.2 Addition of doping materials

The balance between the two charge carries in intrinsic semiconductor can be modified with the addition of a doping material to the pure crystal. The introduction of atoms with one more or one less valence electron creates an excess of electrons or holes. From the silicon band structure point of view, the doping process can consist of introducing an element with more valence electrons (n-type) or more holes (p-type). Elements which are used with silicon are:

- n-type: elements from the group V of the periodic table, such as Phosphorous or Arsenic. These elements introduce an extra electron in the conduction band and are called *donors*.
- p-type: elements from the group III of the periodic table, such as Boron and Gallium. These elements introduce an energy level above the valence band that can be populated by free electrons creating an excess of holes. Due to this reason, they are called *acceptors*.

Acceptors (donors) add an energy level above (below) the valence (conduction) band, which is called E_A (E_D), as shown in Figure 5.1.

²For an “intrinsic” (or un-doped) silicon, the assumption $n = p = n_i$ is made.

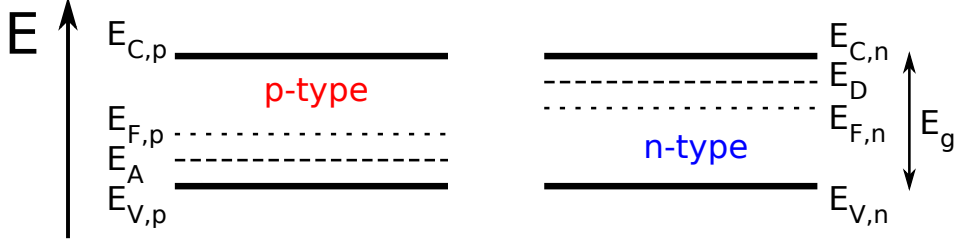


Figure 5.1: Energy levels for p-type (left) and n-type (right) silicon. In the p-type silicon, another energy level E_A slightly above the valence band energy is added, while in n-type silicon an energy level E_D slightly below the conduction band energy is added. The Fermi energy, E_F , is close to the middle of the band gap and shifted towards the energy level introduced by the doping. Scheme taken from [63].

Doped semiconductors remain electrically neutral, since the electric charge of the extra electrons or holes is balanced by the nuclei having one more or less proton than silicon. The sum of positive and negative charges is then equal. If N_A and N_D are the acceptor and donor concentration, it can be written:

$$N_D + p = N_A + n \quad (5.10)$$

In a p-type semiconductor $p \gg n$ and $N_D = 0$. Combining 5.9 with 5.10 the charge carrier density can be written in terms of the dopant concentration as

$$p \simeq N_A \quad \text{and} \quad n \simeq \frac{n_i^2}{N_A} \quad (5.11)$$

On the other hand, in a n-type semiconductor $n \simeq N_D$ and $p \simeq n_i^2/N_D$. This means that in a doped semiconductor the concentration of the majority charge carriers is approximately equal to the dopant concentration. The drift velocity of electrons and holes under the electric field, E , will be:

$$v_{e/h} = \mu_{e/h} E \quad (5.12)$$

where $\mu_{e/h}$ is the mobility of electrons or holes. For a high purity silicon at room temperature, these values are $1350 \text{ cm}^2/\text{Vs}$ and $450 \text{ cm}^2/\text{Vs}$ respectively [62, 64]. The drift velocity reaches a saturation value for large electric field. In an intrinsic semiconductor, electrons and holes have the same density n_i and both contribute to the current density as $J = en_i(\mu_e + \mu_h)E$. The current density can be expressed as $J = E/\rho$ where ρ is the resistivity, which can be

written as

$$\rho = \frac{1}{en_i(\mu_e + \mu_h)} \quad (5.13)$$

In doped semiconductors, the current contribution of the minority charge carriers can be neglected and the charge carrier density can be replaced by the dopant density as in Equation (5.11). Thus, Eq. 5.13 can be written as:

$$\rho_{n-type} = \frac{1}{eN_D\mu_e} \quad (5.14)$$

$$\rho_{p-type} = \frac{1}{eN_A\mu_h} \quad (5.15)$$

Both intrinsic and doped semiconductor have a too large density of free carries in order to be used as particle detectors. Although, by combining semiconductors with opposite doping, a region without free charges can be created and exploited for particle detection. This is the principle of what is called the *p-n* junction, which will be discussed in the following section.

5.1.3 The *p-n* junction

When two semiconductor with opposite doping are in contact, a *p-n* junction is formed. This behaves as a semiconductor diode and ideally it has zero resistance when forward bias is applied and infinite resistance when reverse bias is applied. Due to the difference in carrier concentration at the junction interface, electrons from the n-doped region diffuse to the opposite p-doped region and recombine with the holes. In this way, the semiconductor which was initially neutral become charged because of the charge flow from one side to the other of the junction. The p-doped region acquires a negative charge while the n-doped region acquires a positive one. This creates a region that is free of charge carriers and is called depletion zone. Since the depletion zone is surrounded by donors and acceptors which do not recombine, an electric field is created across the junction, that counterbalances the charge migration pushing away the eventual free charges in this volume. This electric field is characterized by a *built-in voltage* V_{bi} as shown in Figure 5.2.

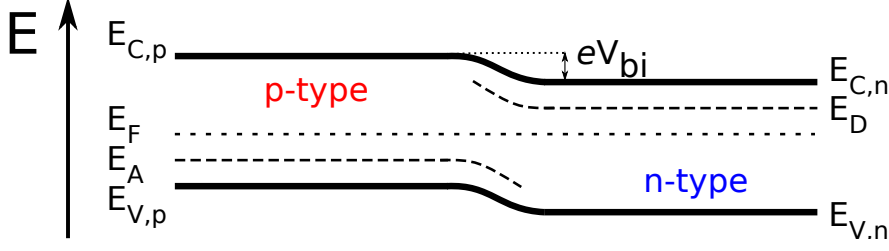


Figure 5.2: Energy levels of a p-n junction. The Fermi energy E_F is at the same level for the p-type and the n-type silicon, thus creating a zone where the conduction and valence bands are bent. This energy shift creates the built-in voltage, V_{bi} , in the central area (depletion zone). Scheme taken from [63].

The *p-n* junction is the base of any semiconductor detector. It generates a region with no free charge that can be altered using different geometries and applying an external bias voltage. Ionizing radiation passing through the depletion zone creates $e - h$ pairs which are separated by the presence of the electric field in the region generating a current which is characteristic of the passing of the particle through the detector.

In principle, the depletion zone can be made thinner or wider by applying direct or reverse bias voltage. Generally, a reverse bias voltage is applied to increase the sensing volume of the detector. In this way, holes in the p-doped region are attracted towards the electrode outside the depletion zone and the same happens for electrons in the n-doped region. Since only the charges which are generated in the depletion zone contribute to the signal, the application of a reverse bias improves the intrinsic performance of the junction as a detector. The width of the depletion zone can be expressed as:

$$d = \sqrt{\frac{2\epsilon}{e} \frac{N_A + N_D}{N_A N_D} V_{bi}} \approx \sqrt{\frac{2\epsilon}{e N_{D/A}} V_{bi}} \quad \text{if } N_A \gg N_D \quad \text{or } N_A \ll N_D \quad (5.16)$$

where ϵ is the dielectric constant, V_{bi} is the applied voltage, e is the electron charge and N_D and N_A the dopant concentrations of donors and acceptors, respectively. In order to increase the depletion zone and to allow detecting particles with larger signals, an additional external reverse bias voltage can be applied. In this way, the depletion zone size can be expressed as:

$$d = \sqrt{\frac{2\epsilon}{e N_{D/A}} (V_{bi} + V_{bias})} \quad (5.17)$$

where V_{bias} is the required voltage to deplete the full thickness of the diode, also called *depletion voltage*. On the other hand, the resistivity of a semiconductor can be expressed as:

$$\rho_{n/p-type} = \frac{1}{eN_{D/A}\mu_{e/h}} \quad (5.18)$$

Equation 5.17 can be expressed in terms of ρ using Eq. 5.18:

$$d = \sqrt{2\mu_{e/h}\epsilon\rho(V_{bi} + V_{bias})} \quad (5.19)$$

Thus, the depletion depth at the same bias voltage is bigger on higher substrate resistivities. The depletion depth is also growing into the less doped region of a semiconductor.

As said, electrons and holes are continuously generated by thermal excitation in a semiconductor. Usually, they recombine between themselves but, if they are generated inside the $p-n$ junction, they drift apart due to the electric field contributing to a current called leakage current. This quantity depends linearly on the depleted volume and increases with $\sqrt{V}$. Its relation with temperature is given by the following equation:

$$I_{leak} \propto T^2 e^{-E_g/2kT} \quad (5.20)$$

meaning that the leakage current is lower at lower temperatures. This is extremely important in the case of irradiated devices, where radiation induced damage in the bulk leads to large leakage currents and consequently to larger noise. In Figure 5.3, the leakage current for a $p-n$ junction is shown: when the reverse bias of the junction increases, the electric field gets stronger and this creates a larger depleted region, improving the performances of the junction as a particle detector. After a value named *breakdown voltage*, V_{bd} , the diode breaks down and starts becoming conductive. This value defines the maximum applicable bias. In the following section, silicon detectors, which are based on the $p-n$ junction explained here, will be described.

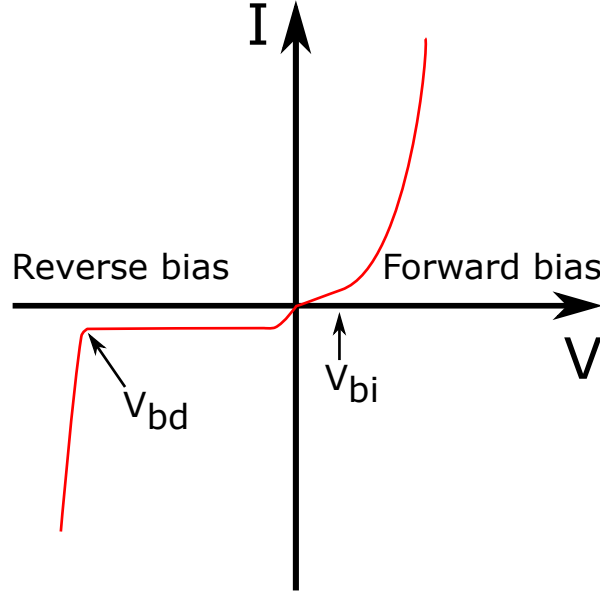


Figure 5.3: Leakage current as a function of the bias voltage for a p-n junction. In reverse bias, the leakage current does not change over a large voltage until the breakdown voltage, V_{bd} , where it rises exponentially. In forward bias, the current rises linearly until the intrinsic in-built voltage, V_{bi} , is overcome. Afterwards, the current rises exponentially. Drawn taken from [63].

5.2 Silicon detectors

As explained in the previous section, the core element of a silicon detector is the reverse biased $p-n$ junction, where $e-h$ pairs are created by ionizing particles passing through the detector and collected by the heavily n and p doped regions that act as electrodes. Usually, heavily n -doped and p -doped regions are called n^+ and p^+ respectively. In Figure 5.4 a sketch of a basic silicon detector with p -type bulk is shown.

What makes silicon detectors common in HEP, beyond their radiation hardness, is the possibility to have highly segmented electrodes. If the detector is left unsegmented, it is considered as a pad diode (as the one shown in Figure 5.4). This is usually used for prototype tests or for applications where segmentation is not required. If the electrode is segmented in parallel strips the detector is called a strip detector. The readout system is then connected to the end of each strip. This kind of detector is usually used to get position information with high resolution in one direction. To have position information in both directions the information

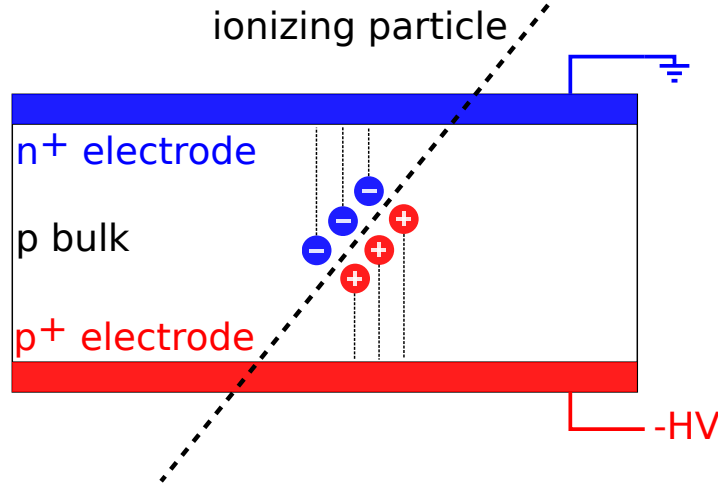


Figure 5.4: Sketch of a n-on-p pad diode with an ionizing particle creating e/h pairs in the bulk that are collected by the electrodes ($n+, p+$). Picture taken from [63].

between two not aligned strips is combined. However, this can lead to an ambiguity on the reconstructed position even with the insertion of a second information from a not aligned strip. This can be solved through pixels detectors, where the electrode is segmented in both directions generating a matrix of pixels. In this way, each pixel has a 2-dimensional (2D) information on the hit position resolving possible ambiguities existing for strips detectors, which is very useful in a particle crowded environment.

The number of electronic channels needed to readout the sensor is much higher in a pixel detector than in a strip one covering the same size. Traditionally, a readout chip is pixel-by-pixel interconnected to a sensor through a process called bump-bonding, making what is called a hybrid detector, as it was shown for the HGTD module in Chapter 3.

5.2.1 Signal generation by charged particles

When charged particles pass through matter, they interact with the atoms of the material losing part of their energy. They can lose energy both interacting with the electrons of the atoms or with their nuclei, being these processes called ionizing or non-ionizing energy loss. The ionizing loss is the responsible of the creation of the $e-h$ pairs, while the non-ionizing one introduces defects in the crystal and is the origin of radiation damage, which will be discussed

in Section 5.2.4 of this chapter.

For relativistic charged particles in the energy range $0.1 \leq \beta\gamma \leq 1000$, the mean rate of the energy loss is described by the Bethe-Bloch equation:

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left(\frac{1}{2} \log \frac{2m_e c \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right) \quad (5.21)$$

where $K = 4\pi N_A r_e^2 m_e c^2$ and N_A is the Avogadro's number, r_e is the classical electron radius and $m_e c^2$ is the rest mass of the electron, Z is the atomic number, A is the atomic mass, I is the mean excitation energy of the medium, T_{max} is the maximum transferable energy in a single collision, $\beta = v/c$, $\gamma = 1/\sqrt{1 - \beta^2}$ is the Lorentz factor and $\delta(\beta\gamma)$ is a correction factor for high energy particles. In Figure 5.5 the energy loss for muons, pions and protons in silicon is shown.

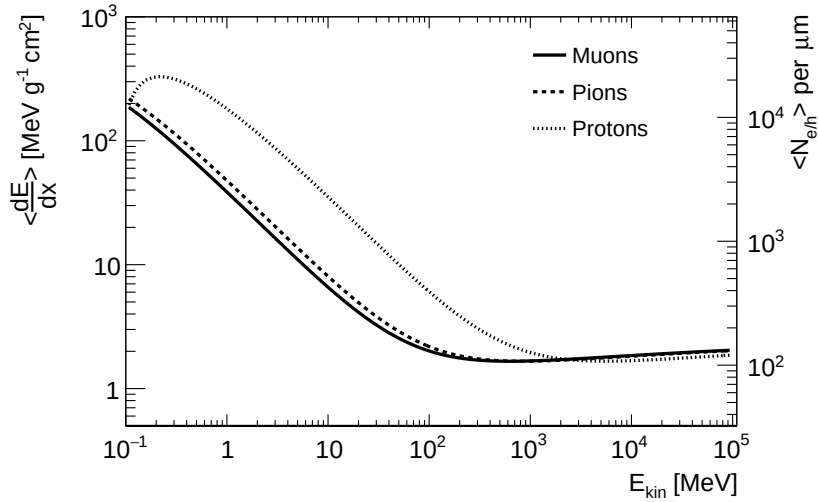


Figure 5.5: Average stopping power for muons, pions and protons in silicon as a function of the kinetic energy. The average number of created electron-hole pairs for micrometer is also shown. Plot adapted from [65].

Equation 5.21 has a minimum for $\beta\gamma \sim 3$ that hardly increases over some order of magnitude. In this way, high momentum particles can still be considered as a mip. For a large momentum range, these particles lose a small fraction of their energy travelling through the material and can be considered as a mip for the entire process. In silicon, a mip has an average stopping

power $\langle \frac{dE}{dx} \rangle = 1.66 \text{ MeV cm}^2/\text{g}$.

The energy loss probability distribution in a thin silicon substrate is described by a Landau distribution. This distribution is asymmetric with a long tail, shifting the mean energy loss to higher values. The most probable energy loss is

$$\Delta_p = \xi \left[\ln \frac{2mc^2\beta^2\gamma^2}{I} + \ln \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right] \quad (5.22)$$

where $\xi = (K/2)/A \rangle z^2(x/\beta^2) \text{ MeV}$ for a detector with a thickness x in g cm^{-2} . The energy loss in a detector is a function of the energy of the passing particle and of the detector thickness, with $\Delta_p \propto a \ln x + b$. The energy deposited by ionization generates a number of $e - h$ pairs proportional to the detector thickness (a mip particle creates $\sim 70\text{-}100$ $e - h$ pairs/ μm) and inversely proportional to the energy needed to create an $e - h$ pair. The distributions of the deposit energy and the Most Probable Value (MPV) scaled to the mean energy loss of a mip in silicon for several thicknesses are shown in Figure 5.6 (a) and (b), respectively.

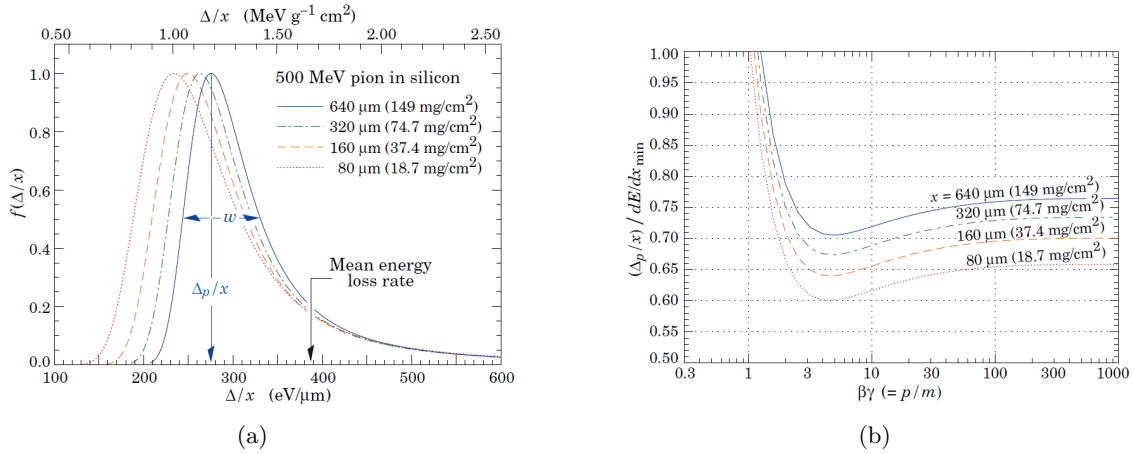


Figure 5.6: (a) Landau distribution of the deposited energy by 500 MeV pions in silicon for different silicon thicknesses. The distributions are normalized to the Most Probable Value of each distribution. (b) Most probable energy loss scaled to the mean energy loss of a mip in silicon for different thicknesses of the silicon substrate. Plots taken from [66].

5.2.2 Signal generation by photons

The interaction of photons in solid state detectors have to be treated in a different way. Photons, differently from charged particles, do not interact along their path but have a probability to be absorbed that depends on the material and on the photon energy. The different processes (see Figure 5.7) are the following:

- *Photoelectric Effect*: the photon is absorbed by an atom which releases an electron whose energy is equal to the energy of the impinging photon minus the ionizing energy. The cross section of this process depends on the atomic number ($\sigma_{pe} \propto Z^n$ with n from 4 to 5), favouring atoms with higher Z . This effect dominates at energy ≤ 100 keV after which it decreases by several orders of magnitude.
- *Compton Scattering*: in the energy range between ~ 100 keV and ~ 10 MeV scattering of a photon with an atomic electron is the dominant process. The final state consists of a lower energy photon and a recoil electron with direction and energy defined by the momentum conservation.
- *Pair Production*: if the photon energy is larger than twice the electron mass (1.022 MeV), e^+/e^- pairs can be created in the interaction of a photon with the material.

5.2.3 Detector Applications

In the HEP community silicon detectors are used for different applications. In particular, the possibility to have segmented electrodes have been exploited to produce position sensitive detector for tracking. In addition, the short charge collection time gives to these detectors a good time resolution when coupled to a suitable readout electronics. In this section, tracking and timing applications will be briefly discussed.

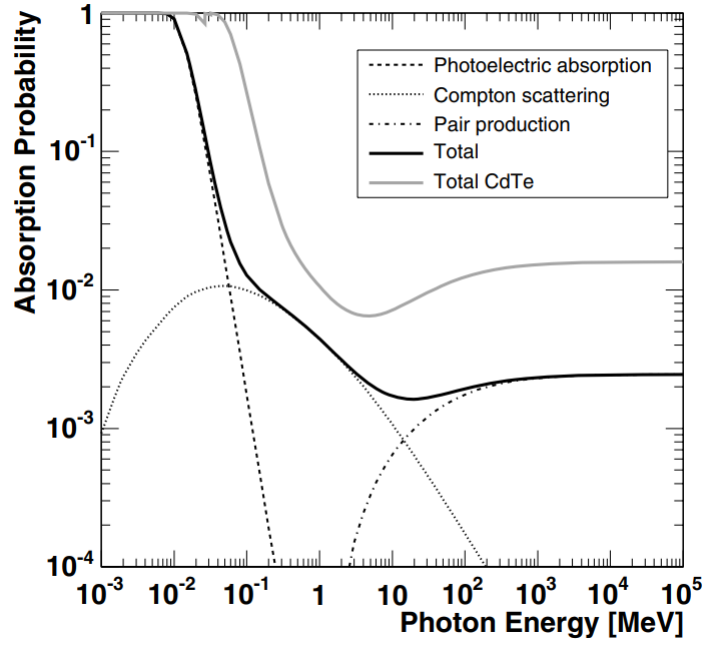


Figure 5.7: Absorption probability of photons in 300 μm silicon as a function of the photon energy. The three contribution from photoelectric effect, compton scattering and pair production are shown. Plot taken from [67].

Tracking applications

Thin devices with an electrode segmentation in the order of tens of micrometers are suitable for tracking applications. The energy deposited by a mip is typically a small fraction of the particle energy, making possible to reconstruct the particle trajectory with several layers of silicon detectors. The ionizing particle will leave a signal in each layer and the position resolution will depend on the electrode segmentation, with better resolution for finer electrodes. Within one pixel it is not possible to know where the particle crossed the detector, thus its position is reconstructed with an uncertainty which depends on the pixel pitch in each direction. The resolution is given by the standard deviation of the uniform distribution $\sigma = \text{pitch}/\sqrt{12}$.

If the particle leaves a signal in more than one pixel, contiguous fired pixels are clustered, and the assigned position depends on the cluster algorithm that is used. Usually, a TOT is recorded by the readout electronics, as a time for which the signal has been larger than the threshold. The TOT is connected with the deposited charge by the particle in the pixel and

can be used to improve the cluster algorithm.

Timing applications

As already introduced, the design of silicon detectors can be optimized in order to build detectors with a good time resolution. The time resolution of a silicon sensor (and its readout electronics) is given by the equation:

$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{Time\ Walk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2 \quad (5.23)$$

where the time walk, jitter and TDC contributions represent the time resolution of the readout electronics (see Eq. 3.5) and have been already discussed in Chapter 3.

The Landau term, σ_{Landau} , is the time resolution of the silicon sensor and takes into account the contribution to the time resolution given by the fluctuation in the density of the generated charge. When a mip passes through the detector, it deposits energy along its path experiencing a number of primary interactions, generating a localized cluster of $e - h$ pairs for each primary interaction. The signal pulse is then given by the sum of each cluster contribution, drifting under the effect of an electric field. The pulse shape depends on the primary cluster distribution. Its fluctuations affect the time resolution of the sensors. When the bias voltage is sufficiently large, the drift velocity of both electrons and hole saturates, thus the duration of the signal scales with the detector thickness. Thus, the Landau term of the time resolution can be reduced decreasing the sensor thickness [68].

In conclusion, a good time resolution for a silicon detector can be achieved (in the order of tens of picosecond), if the Landau term is reduced (minimizing the active thickness of the sensors). In addition, thin devices with charge multiplication further improve the S/t_{rise} ratio with beneficial effects on the jitter and time walk distributions, as explained in Chapter 3. Such devices have been produced based on the Low Gain Avalanche Detector (LGAD) technology in the context of the HGTD detector. The sensors will be discussed in Section 5.3 of this Chapter, and their performances will be presented in Chapter 6.

5.2.4 Radiation damage

Silicon detectors used in HEP experiments are usually exposed to high fluxes of particles (or high level of radiation), thus it is important to understand how the radiation affects the detector performance. Particles penetrating a detector can deposit energy through non-ionizing processes as well as interacting with atoms of the crystal. The resulting radiation damage effects are classified as *bulk* or *surface effects*. Usually, bulk effects are the main contribution on the performance deterioration of silicon sensors, while the surface effects tend to be important for readout electronics. In this section, bulk effects will be described.

When a particle passes through a sensor and deposits energy, if the transferred energy is higher than 25 eV a nucleus can be displaced from its position, producing what is called a bulk defect, and eventually displacing nuclei of neighbouring atoms (cluster defect). This results in a silicon interstitial and a left over vacancy. It can be partially recovered with annealing, but it has a permanent effect which is the introduction of new energy levels that modify the effective doping and can potentially act as generation or recombination centers. The induced damage in the silicon lattice differs from particle type and energy. In a collider experiment such as ATLAS, a wide spectrum of particles of a broad energy range interact with the detectors. An estimation of the radiation induced damage can be obtained through the Non-Ionizing Energy Loss (NIEL) hypothesis [69].

The NIEL hypothesis

The NIEL hypothesis assumes that the damage of any particle at a given fluence, Φ_{eq} , can be calculated by:

$$\phi_{eq} = k\Phi = k \int_{E_{min}}^{E_{max}} \Phi(E) dE \quad (5.24)$$

where k is the hardness factor that scales the displacement damage of each particle and energy to 1 MeV neutron equivalent. The hardness factor can be written as:

$$k = \frac{\int_{E_{min}}^{E_{max}} D(E)\Phi(E)dE}{D(E_n = (1 \text{ MeV})) \int_{E_{min}}^{E_{max}} \Phi(E)dE} \quad (5.25)$$

where the fluence is weighted with the energy dependent displacement damage cross section $D(E)$ (see Figure 5.8) and normalized to the integrated fluence at the damage cross section of the reference particle. Using the NIEL hypothesis, it is then possible to evaluate the

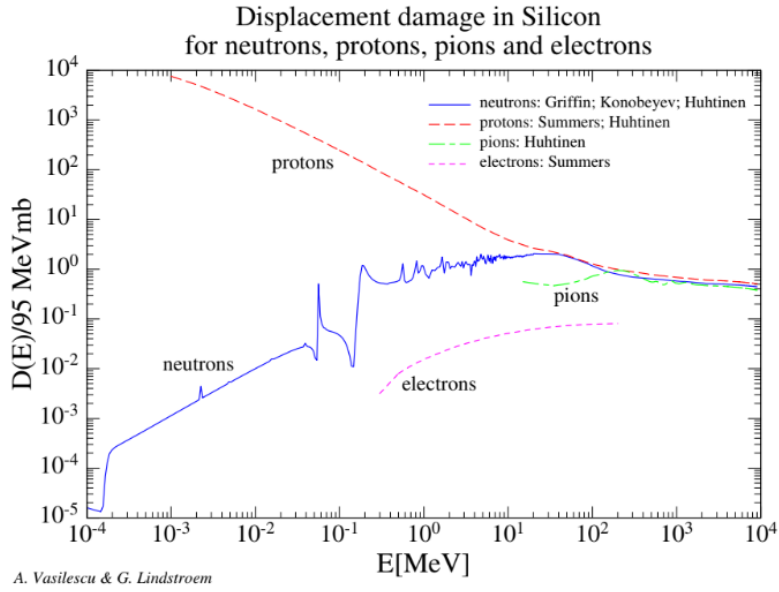


Figure 5.8: Displacement damage cross section $D(E)$ as a function of particle energy for electrons, pions, protons and neutrons, normalized to 1 MeV neutron. Adapted from [70].

1 MeV neutron equivalent fluence on a detector at any point of its lifetime in the experiment. This allows to evaluate the behavior of sensors in the experiment studying the damages on sensors exposed to different fluences (and, in principle, particle types). In this thesis, several irradiation campaigns to study performance of silicon sensors have been carried out with 1 MeV neutrons at the TRIGA reactor at the Jožef Stefan Institute (JSI) in Ljubljana ($k=0.9$). Some sensors were also irradiated with 24 GeV protons in the irradiation facility at the Proton Synchrotron (PS) at CERN ($k=0.7$). From now on, in this thesis all the fluences will be quoted in 1 MeV neutron equivalent.

Doping concentration

In the detector bulk the radiation damage can be described as a change on the effective doping of the sensor. On unirradiated devices, the effective doping of a *p-type* sensor can be described as the difference of the acceptor and donor dopants concentration $N_{eff,0} = N_A - N_D$. After irradiation, the detector irradiated at a fluence Φ presents an effective doping of:

$$N_{eff}(\Phi) = N_{eff,0} - N_c(1 - e^{-c\Phi}) + g_c\Phi \quad (5.26)$$

where N_c and c describe the size and speed of the acceptor removal phenomenon which reduces the doping concentration, and g_c describes the radiation induced acceptor creation in the bulk [71].

Trapping

The charged defects in the bulk can also act as trapping centres for charge carriers. As a consequence, the collected charge, Q , during the drift time is reduced, and can be expressed as a function of the fluence in the following way:

$$Q(\Phi) = Q_0 e^{-t_c/\tau} \quad \text{with} \quad \tau = \beta_t \Phi \quad (5.27)$$

where Q_0 is the initial charge (as the one of an unirradiated device), t_c is the charge collection time and τ is the trapping time, which is proportional to the fluence Φ by a factor. The factor β_t depends on the charge carrier type and on the radiation type, i.e. if it is neutrons or charged hadrons [72]. Even if the trapping time is similar for electrons and holes, trapping is more effective on holes since their collection time is higher than the one of electrons because of the different mobilities. Thus, the hole contribution to the signal will eventually become negligible at high enough fluence.

Leakage current

The bulk damage induced by radiation creates new energy levels in silicon. When these energy levels are created within the band gap, the energy to promote an electron to the conduction band and then acting as a generation centre is also reduced. The effect is an increase of the leakage current, I_{leak} , that is proportional to the fluence and to the depleted volume, V ,:

$$I_{leak}(\Phi) - I_{leak}(0) = \alpha \Phi V \quad (5.28)$$

where α is a proportional factor known as the current-related damage rate. From Figure 5.9, the value for α after an annealing of 80 minutes at 60 °C is 3.99×10^{-17} A/cm [73].

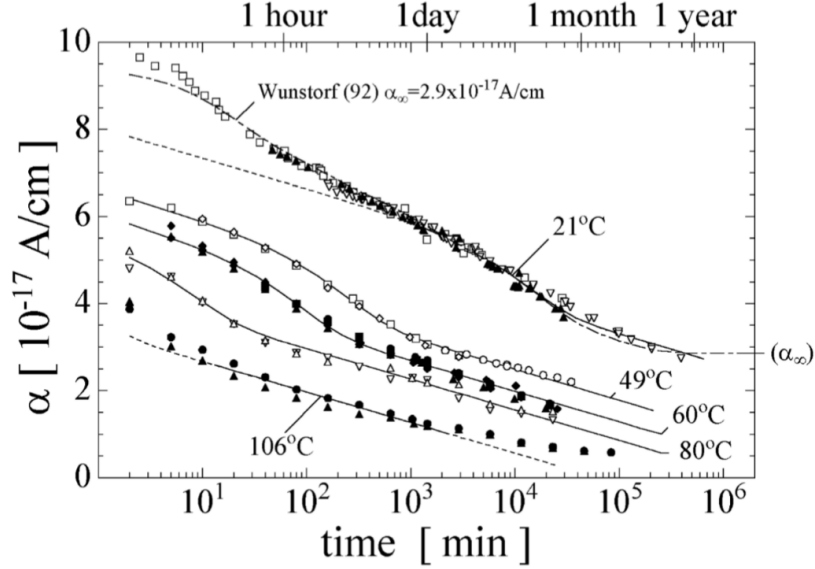


Figure 5.9: Simulation (dashed lines) and measurements (points) of the time evolution of the current-related damage parameter, α , for different annealing temperatures. Plot adapted from [73].

The leakage current in the sensor depends strongly on the operational temperature, as already shown in Equation 5.20. On irradiated devices, a self-heating effect could be present due to the increasing of the leakage current, which generates an increase in the device temperature leading to a *thermal runaway* that can potentially destroy the device. In order to avoid this, irradiated devices can be operated at cold temperatures to compensate the effect of the

increase of the leakage current and the consequent power consumption. In the work presented in this thesis, all the measurements for irradiated devices have been performed at $T = -30\text{ }^{\circ}\text{C}$ ³ for this purpose and to mimic the operational temperature of the HGTD detector (the results are presented in Chapter 6).

Annealing

The bulk defects induced by radiation are not static, but they can move within the crystal. They can react with other defects or impurities and also eventually form new defect structures. This process is called annealing. Its evolution depends on the temperature and can be accelerated by warming up the silicon sensor, or slowed down by cooling it [73]. As shown in Figure 5.9, the annealing is always beneficial on the current-related damage parameter, α , mitigating the increase of the leakage current induced by radiation. On the effective doping concentration, N_{eff} , annealing initially has a beneficial effect, which is given by a reduction of N_{eff} that results in a larger resistance and in a larger depletion depth at the same bias voltage. However, the effect is opposite with a long term reverse annealing where N_{eff} is pushed to larger values, as shown in Figure 5.10. Irradiated silicon sensors are annealed usually for 80 minutes at $60\text{ }^{\circ}\text{C}$ before the rise of the reverse annealing. After that, they are kept at low temperature both during operation and storage.

5.3 Low Gain Avalanche Detectors (LGADs)

The most common detectors with intrinsic charge multiplication are the Avalanche Photodiode (APD), proposed for the first time in the 1950s. An APD is a semiconductor device that uses the photoelectric effect to generate an electric pulse after being illuminated by photons. It consists of a reverse biased p - n junction with an intense electric field. The electrons which are generated can gain enough energy to initiate an avalanche mechanism. APDs can be

³The operating temperature was set to $-20\text{ }^{\circ}\text{C}$ when it was not possible to reach lower temperatures as in TCT setup.

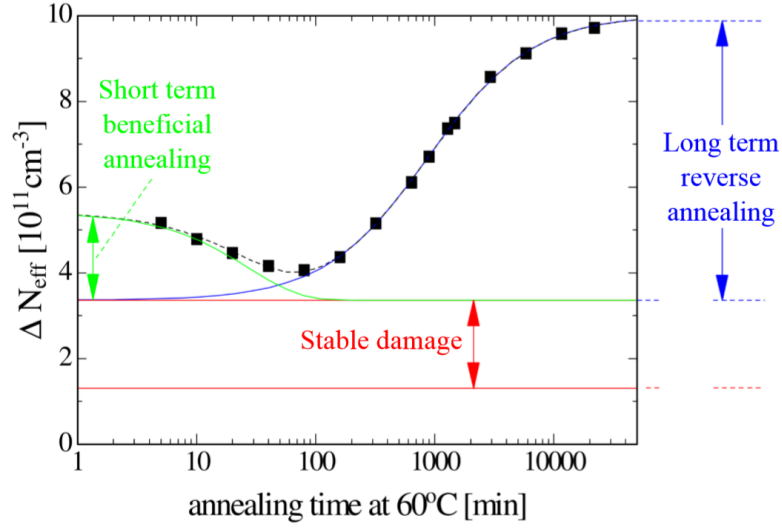


Figure 5.10: Evolution of the radiation induced change in the effective doping concentration ΔN_{eff} with respect to the annealing time at 60 °C for a diode irradiated at a fluence of $1.4 \times 10^{13} \text{ n}_{eq}/\text{cm}^2$. Plot adapted from [73].

operated in linear or Geiger mode. In the first mode, typical gains are of the order of 100 while in the latter mode the gain is typically larger than 1000 and the electric pulse reaches saturation immediately. Their main application are imaging and single photon counting for APDs operated in linear and Geiger mode, respectively. These detectors are optimized to detect photons from infra-red to ultra-violet in a low light environment. In the case of a mip, this generates charge along its trajectory in the full detector thickness, therefore the amount of the primary charge is much larger than in the photon detection case, with about $75 \text{ e} - h$ pairs created per micrometer, as discussed in Section 5.2.

The Low Gain Avalanche Detectors have been initially developed by CNM Barcelona as a potential technology for radiation hard tracking detectors. The idea to have LGAD as radiation hard tracking detectors was born from having charge multiplication already in unirradiated devices counterbalancing the signal degradation induced from radiation damage. For timing applications, the use of detectors with an intrinsic gain enhance the slew rate which results in beneficial effects on the time resolution. Since the detector thickness also affects the timing performance, thin LGAD devices for timing have been developed in the last years. The LGAD technology adapts the design of APD for the detection of mip particles. This tech-

nology targets a gain of 10-20, much lower than the one targeted from APD. The charge multiplication is achieved with the introduction of an extra doped layer of acceptors ($p+$) material, usually Boron, close to the p - n junction. The cross section of a single pad LGAD sensor can be found in Figure 5.11. The resulting profile is characterized by a large increase in the doping concentration in the proximity of the junction, which creates a large electric field. In LGAD sensors, the electric field is divided in two zones: the drift volume, where low values of the electric field are present ($E \sim 30 \text{ V}/\mu\text{m}$), and a thin multiplication zone with few micrometers depth where a very high electric field is present ($E \sim 300 \text{ V}/\mu\text{m}$). In the n-on-p design, the multiplication process is started in the multiplication layer ($p+$) from the electrons drifting towards the $n+$ electrode. To reduce the magnitude of the electric field at the perimeter of each cathode an additional deep $n+$ doping region, known as Junction Termination Extension (JTE), is present [74].

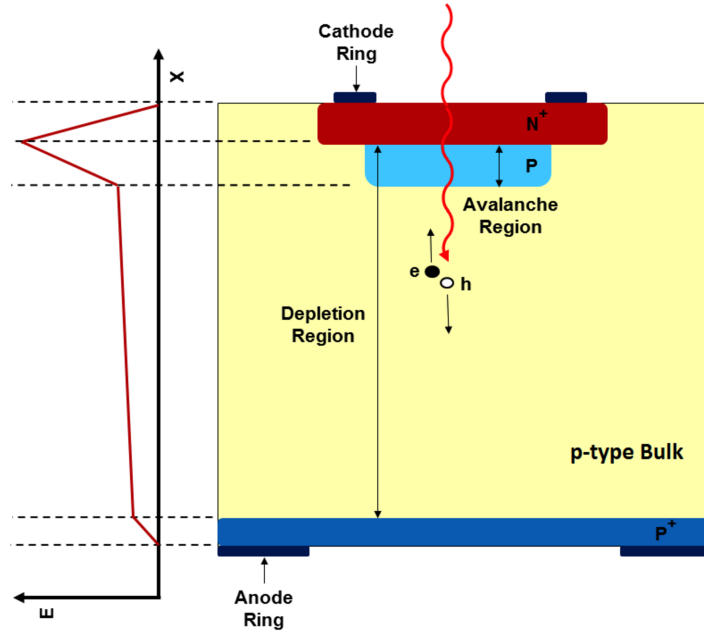


Figure 5.11: Schematic cross section of a single pad LGAD diode. On the left of the figure, the electric field inside the sensor is drawn.

5.3.1 Why low gain?

Silicon detectors with high gain such as APDs or Silicon Photo-Multipliers (SiPM) have the capability to detect single or a few photons. However, high gain levels can bring drawbacks such as the increase of the sensor noise, difficulties in the sensor segmentation and high power consumption. Detection of charged particles instead of photons had the advantage of a much larger initial signal, since a mip creates about 75 $e - h$ pairs per micrometer, allowing the use of detectors with low gain. The LGAD technology offers an interesting possibility for fast detectors in the framework of HEP experiments.

5.3.2 Why thin sensors?

Assuming a fixed value of the gain, the signal steepness depends on the sensor thickness, favouring thin sensors for their faster rising edge (slew rate) which improves the time resolution. In Figure 5.12, the simulated current for a 50 μm -thick LGAD is shown [75]. The initial electrons (red) drift towards the $n+$ electrode, go through the gain layer and generate additional $e - h$ pairs. The gain electrons (violet) are absorbed by the cathode and the gain holes (light blue) drift toward the anode and generate a large current. The gain increases the signal amplitude producing a slew rate following:

$$\frac{di_{Gain}}{dt} \sim \frac{dV}{dt} \propto \frac{G}{d} \quad (5.29)$$

Thus, the slew rate is proportional to the ratio of gain G , over the sensor thickness d . Therefore, thin detectors with high gain provide the best time resolution. Specifically, the maximum signal amplitude is controlled only by the gain value, while signal rise time depends only by the sensor thickness, as shown in Figure 5.13.

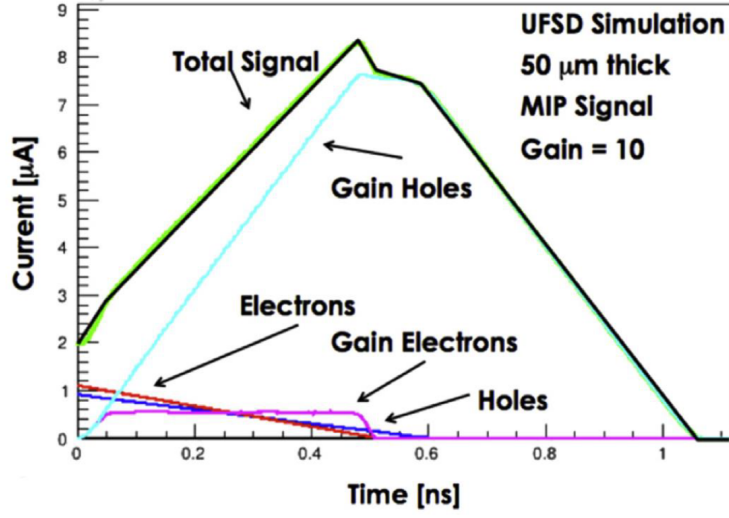


Figure 5.12: Simulated current signal for a 50 μm -thick LGAD detector. Figure taken from [75].

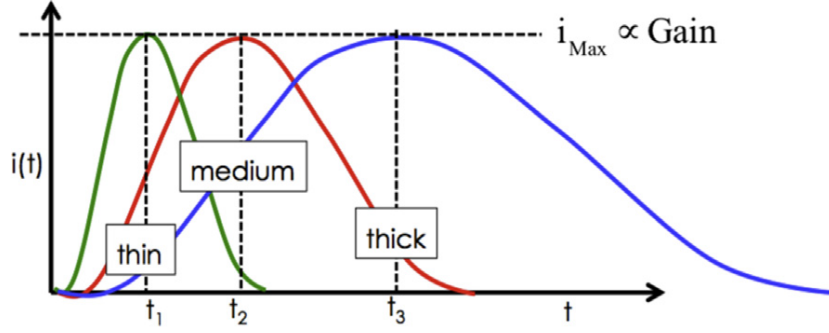


Figure 5.13: Current signal for three different detector thicknesses with the same gain. Figure taken from [75].

5.3.3 Major effects on the time resolution

As mentioned previously, three major effects determine the time resolution. Those are: the time walk from amplitude variations at a fixed threshold discriminator, the jitter from the electronic noise and Landau fluctuations originating from the non-uniform charge deposition along the particle path. As explained in Chapter 3, time walk and jitter depend on the type of readout electronics, both depending on the inverse of the signal slope, dV/dt . Jitter can be minimized by choosing sensors with a high signal-to-noise ratio, while time walk by using reconstruction algorithms such as CFD or TOT corrections. On the other hand, the Landau

contribution is due to the fact that a passing particle deposits its charge along the path inside the sensor in a non-uniform way. This contribution depends on the thickness of the sensor, smaller for thin sensors. As expected from Eq. 3.6 and 3.7 and also from 5.29, the resolution improves with the increase of the gain, which is proportional to the collected charge.

For the HGTD detector, LGAD sensors with an active thickness of 50 μm has been adopted as the best compromise between capacitance and deposited charge, favouring thicker sensors, and signal slope and Landau fluctuation, favouring thinner sensors. Sensors with an active thickness of 30 μm have been also studied by the HGTD community as an option for an improved time resolution but were discarded due to the higher capacitance and higher power dissipation.

5.3.4 LGADs for the HGTD

During the R&D pahse and up to the present time, LGAD sensors have been produced by several manufacturing sites: Hamamatsu Photonics (HPK) in Japan, CNM Barcelona in Spain, Fondazione Bruno Kessler (FBK) in Italy, Micron in United Kingdom, Brookhaven National Laboratory (BNL) in United States, National Nano Device Laboratory (NDL) and Institute of High Energy Physics (IHEP)-Institute of Microelectronics of the Chinese Academy of Sciences (IME) and University of Science and Technology of China (USTC)-IME in China.

As a dopant for the p-type multiplication layer, Boron is typically used. Additional Carbon implantation has been investigated for improved radiation hardness. As a substitute of Boron, Gallium has been studied as well.

In this document, several productions of CNM LGADs have been characterized and their performance will be presented in Chapter 6 including efficiency, charge collection and time resolution, both in beam test and laboratory measurements.

5.3.5 CNM production runs

In this section, a brief presentation of all the production runs for which the performance is shown in Chapter 6 is given.

CNM production run 10478

The CNM LGAD production run 10478 from 2017 consisted of a total of five Boron-doped wafers (with a doping dose of $1.5 \times 10^{13} \text{at/cm}^2$) with 50 μm -thick high resistivity wafer bonded to a 300 μm -thick support. The wafers studied in this thesis are wafer 4 and wafer 5, being the latter carbon enriched in order to study possible advantages in terms of radiation hardness.

The wafer mask contains several single pad square diodes of $1 \times 1 \text{ mm}^2$, $1.3 \times 1.3 \text{ mm}^2$ and $2 \times 2 \text{ mm}^2$, 2×2 , 3×3 and 8×8 matrices of different pixels size and 2×1 arrays with different spacing. For wafer 4 sensors, an opening in the metallization on the ohmic side was introduced in order to perform laser measurements, since the junction side (top) is metallized. From this production run, a set of $1 \times 1 \text{ mm}^2$ single pad sensors has been used for measurements with a radioactive source and, in case of wafer 4 sensors, also with a laser.

CNM production run 10924

The CNM LGAD production run 10924 from 2017 consisted of seven Gallium-doped 50 μm -thick Si-on-Si high resistivity wafers with different implantation doses. A set of $1 \times 1 \text{ mm}^2$ single pad sensors from wafer 6 (with a doping dose of $6 \times 10^{13} \text{at/cm}^2$) has been electrically characterized and measured with charged particle beam, radioactive source and laser.

CNM production run 12914

The CNM LGAD production run 12914 from 2020 consisted of a total of four Boron-doped Si-on-Si wafers with 50 μm -thick high resistivity wafers with an implant dose of 1.8×10^{13}

atoms/cm². The wafer mask contains several single pad square diodes of $1 \times 1 \text{ mm}^2$, $1.3 \times 1.3 \text{ mm}^2$ and, 2×2 and 5×5 matrices of different pixel sizes with different values of inter pad distances. The different values for the inter pad distances are achieved modifying the width of the JTE, while the distance between them remains the same.

In this document, a set of $1.3 \times 1.3 \text{ mm}^2$ single-pads has been measured with a radioactive source in the laboratory to study the charge collection and time resolution while a set of 2×2 arrays with $1.3 \times 1.3 \text{ mm}^2$ pads has been measured with laser to study the behavior of the inter pad distance at different fluences.

CNM production run 13002

The CNM LGAD production run 13002 from 2021 consisted of four Boron-doped wafers with different implantation doses. These are 50 μm -thick wafers on 525 μm low-resistivity epitaxial wafer substrate. The wafer mask contains only single-pad sensors with pad sizes of $1.3 \times 1.3 \text{ mm}^2$ and $3 \times 3 \text{ mm}^2$. In this thesis, a set of single-pad sensors from the highest doped wafer (with a dose of $2.0 \times 10^{13} \text{ atoms/cm}^2$) of a size $1.3 \times 1.3 \text{ mm}^2$ were measured with a radioactive source and a laser.

Chapter 6

Performance studies of CNM LGAD sensors before and after irradiation

The main objective of this thesis is to evaluate the performance of the CNM LGAD sensors. This work was carried out at various research centres: the laboratories at IFAE and CNM (Barcelona) and at the test beam facilities at DESY and CERN. Four different CNM LGAD productions were characterized to analyze if the CNM sensors fulfill the requirements for the HGTD detector (shown in Table 3.1). In order to improve radiation hardness of LGADs, different doping materials and wafer technologies were considered. The studies presented here aim to assess key properties such as time resolution, collected charge, and hit efficiency before and after irradiation.

The different experimental setups are described in Section 6.1, while the investigation of the four production runs follows.

Section 6.2 is dedicated to the description of CNM LGAD runs on Si-on-Si wafers from 2017 with different doping materials. For single pad sensors, the electrical characterization and

stability measurements are presented. Performance results with a Sr90 radioactive source, using TCT and from test beams are also shown.

Section 6.3 describes a more recent CNM LGAD boron-doped Si-on-Si wafer run from 2019 with higher doping dose than the previous one. For single pad sensors, the electrical characterization and stability measurements are presented. Performance results with a Sr90 radioactive source and using TCT are shown. A set of 2×2 LGAD arrays will be characterized using the TCT to study the behavior of the inter pad effective distance evolution with irradiation.

Finally, in Section 6.4, results from LGAD sensors produced in epitaxial wafers from 2020 will be shown. The full electrical characterization and stability measurements are presented for single pad sensors. Measurements with a Sr90 radioactive source are presented and the results are compared with those from the Si-on-Si devices.

6.1 Experimental Setups

This section describes the setups that have been used to perform the different set of measurements presented later in this chapter. First of all, the laboratory setup where the electrical characterization of sensors was performed is presented. Secondly, the laboratory setups where measurements with a Sr90 radioactive source and measurements with a laser are performed are discussed. Finally, the system used to study the samples with charged particle beams is described.

6.1.1 Electrical characterization setup

The electrical characterization is the first step to study the sensors in order to determine the gain layer depletion voltage (V_{gl}), the fully depletion voltage (V_{fd}) and the breakdown voltage (V_{bd}) of the sensors. Current-Voltage (IV) and Capacitance-Voltage (CV) measurements are performed at the CNM laboratory on a probe station both at room and cold temperatures. In Figure 6.1, an image of the CNM probe station setup is shown. The sensor backside (ohmic)

is grounded through the probe station's chuck and the sensors are biased from the topside (junction side) with positive voltage. High voltage is applied to the pad and the guard ring through two needles each of them connected to a sourcemeter. The setup is controlled by software on the laboratory PC. The setup can be run at cold temperature thanks to a cold chuck and a temperature control system connected to it.

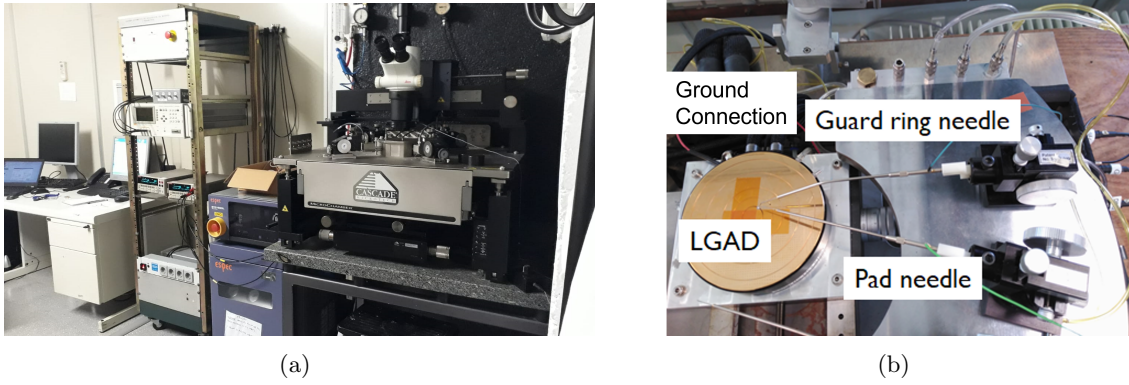


Figure 6.1: (a) Probe station setup in the CNM laboratory used for electrical characterization. From left to right, the PC used to run the software to acquire data, the power supplies, the temperature control system and the probe station. (b) View on the sensor with needle connections.

6.1.2 Setup for measurements with Sr90 β source

The LGAD response to mip was studied using 2 MeV electrons from a Sr90 radioactive source, which is encapsulated in a plastic container and mounted on a 3D-printed support. Two LGAD sensors are assembled on 10 cm $\times$ 10 cm read-out boards, developed at the University of California Santa Cruz (UCSC) [76], using a double-sided conductive tape, see Figure 6.2. The LGAD front-side metal pad layer was coupled to the input of an on-board transimpedance first-stage amplifier via multiple wirebonds to reduce the inductance, while the guard ring was grounded. For further amplification, an external second-stage amplifier¹ with a gain of 10 and 2 GHz bandwidth is used. The board is equipped with an input for the power (low voltage) of the first stage amplifier, an input for the high voltage to bias the sensor, an input

¹MiniCircuits 2 GHz bandwidth second stage amplifier.

for calibration purposes (not used in these measurements) and an output which is connected to an external second-stage amplifier.

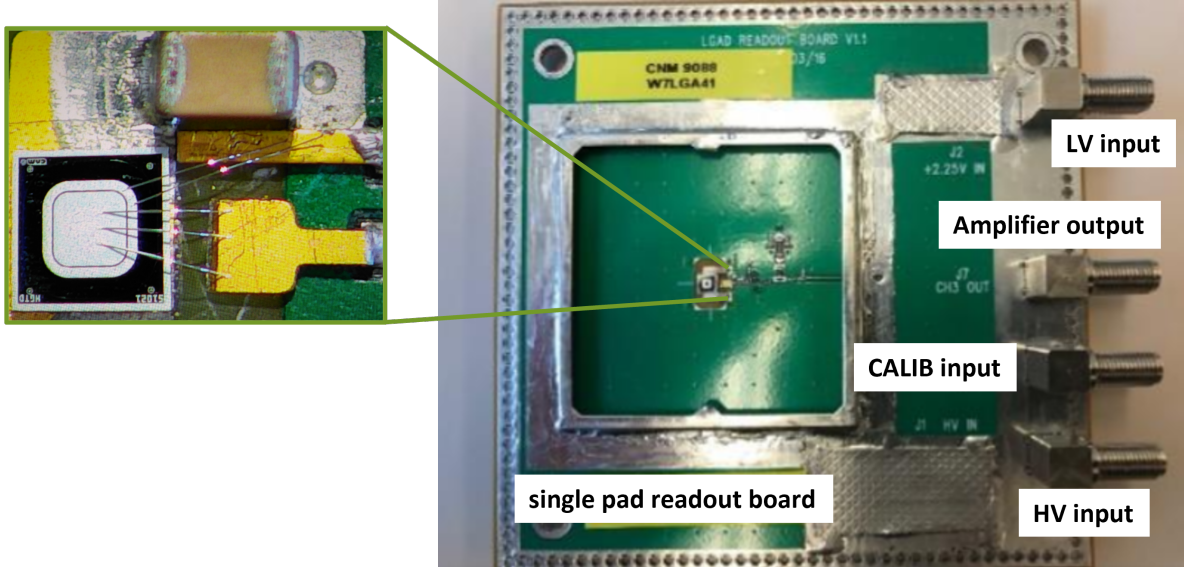


Figure 6.2: Picture of a single-channel board used for measurements with a radioactive source. On the left, a zoom on the sensor is shown: the pad is connected to the readout line with three wire-bonds while the guard ring is grounded with two wires. The sensor is biased from the backside (ohmic) with a negative voltage.

Two readout boards are mounted back-to-back on an aluminium L-shaped support frame and are aligned with respect to the source beam axis, mounted on a second base plate, as it is shown in Figure 6.3 (right). One of the two devices is a sensor with a well known performance², which has been calibrated in the past. From now on, we will refer to this sensor as reference sensor. The second sensor, which is under study, will be referred as Device Under Test (DUT). The system is operated inside a climate chamber³ at -30°C . To avoid condensation on the sensor surface dry air is provided to the internal side of the climate chamber. The bias voltage to the sensor is supplied by a sourcemeter⁴, while a low voltage supply⁵ provides a 2.25 V needed for the first amplification stage of the signal (on the board), and a 12 V needed for the external second stage amplifier. The output of the second stage

²Sensor S1022 from production run 10478 wafer 4.

³Climate chamber model Votsch VT4002.

⁴Keithley 2410 1100 V SourceMeter.

⁵Rohde & Swartz HMP4040 Programmable power supply 384 W.

amplifier is connected to an oscilloscope⁶ which runs the acquisition software (see Appendix B for detailed information). Part of the experimental setup (oscilloscope, climate chamber and low voltage power supply) is shown in Figure 6.3 (left).

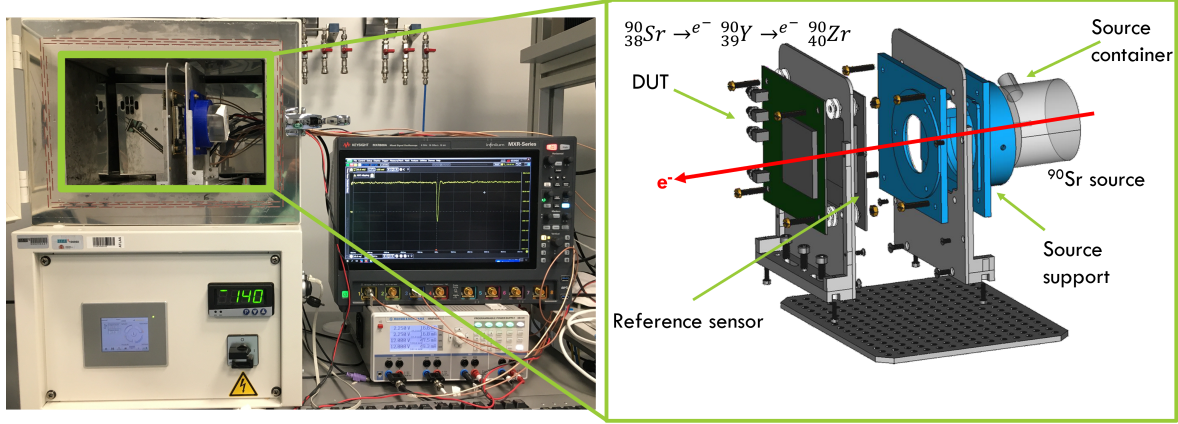


Figure 6.3: Setup for the measurements with the Sr90 source. On the left picture, the climate chamber, low voltage power supply and oscilloscope are visible. The reference sensor and the DUT are mounted back-to-back on a metal support together with a second support holding the radioactive source. On the oscilloscope screen a typical LGAD signal is shown. Two high voltage power supply (not shown in the picture) are used to bias the sensors.

Waveform data were analyzed using the LGADUtils framework [77], an analysis software which has been developed at IFAE, for which a brief description will be given in Appendix C. First, the oscilloscope ASCII data were converted into a ROOT ntuple containing the raw information for both the DUT and the reference sensor. The second step is the determination of the pulse polarity, the maximum and the minimum on the pulse, and the start and stop of the signal. As a third step, the noise and pedestal of the signal were computed and the pedestal value is then subtracted for each waveform in an event-by-event basis. The last step is the computation of several waveform properties. More about how the computation of some properties of the waveform is done can be found in Appendix C. As the charge collection and time resolution are the main properties which are studied using this setup, the analysis computation is described below. Events are collected when both reference and DUT sensors register a signal higher than a set threshold (10 mV) (logic AND). This cut is equivalent to $\sim 5\sigma_{noise}$, being the noise level generally smaller than 2 mV for all the sensors. A brief

⁶Oscilloscope model from Keysight DSO9404A.

explanation of the trigger used for data acquisition is given in Appendix B.

The setup described in this section is also used for stability measurements, to calculate the rate of self triggers (also called auto-triggering) of the sensors without an external source of particles. This is an intrinsic property of sensors with gain, which present spurious events at high enough bias voltages. These events are thermally generated and are random in nature and present waveforms which are identical to real signals generated by impinging particles. The onset of auto-triggering regime appears before the breakdown voltage and limits the operating voltage of the sensor. These measurements are performed at -30°C in order to define the operating voltage range for DUTs for data taking with the Sr90 radioactive source at the same temperature. The time between consecutive auto-triggering events when there is no external source was studied using an oscilloscope⁷. Signals larger than 10 mV are acquired. The auto-triggering rate is defined as the inverse of this time difference, and it is calculated for each bias voltage by the acquisition software. More details on the calculation are given in Appendix B

Collected charge calculation

For each event, the charge of the sensor is computed for each sensor as the integral of the waveform signal around the peak divided by the transimpedance of the board and the gain of the voltage amplifier. A charge distribution for each bias voltage point is built. An example of this distribution is shown in Figure 6.4 for a DUT⁸. An iterative fit process is used to define the best number of bins and interval for the distribution and fit parameter with the lowest χ^2 . More about the fit optimization can be found in [77]. The charge distribution is fitted using a Landau-Gauss convoluted function. The collected charge is defined as the MPV of the fit function and the standard deviation, σ , is considered as the error of the charge.

⁷Oscilloscope model from Keysight DSO9404A.

⁸Carbon S1038 irradiated at 10^{14} n_{eq}/cm² and operated at 220 V.

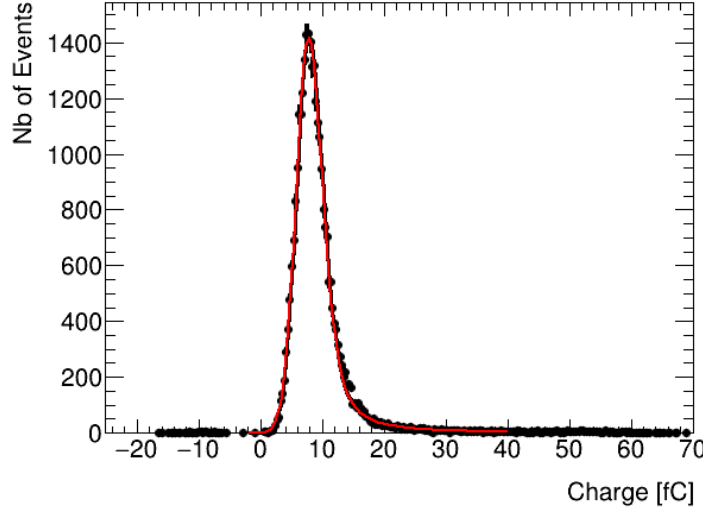


Figure 6.4: Charge distribution for a DUT (carbon enriched sensor W5S1038 irradiated at 10^{14} n_{eq}/cm^2 at 220 V) at -30 °C. The distribution is fitted with a Landau-Gauss convoluted function and its MPV parameter corresponds to the charge at a given bias voltage.

Time resolution calculation

The time resolution is calculated from the distribution of the difference between the TOA of the reference sensor and that of the DUT as it will be explained below. The LGADUtils software determines the TOA of the recorded waveforms for each event using the CFD method. This method defines the TOA as the time when the signal crosses a constant fraction of its maximum amplitude. This fraction will be called f_{CFD} , and is calculated in steps of 5% of the signal maximum amplitude.

For each sensor, at a given bias voltage, the time resolution is obtained from the time difference distribution using all the CFD fractions combinations, and it is defined as the standard deviation of a Gauss function fit. Using this CFD optimization procedure, the lowest time resolution is found. The optimal CFD fraction is 15-25% for unirradiated sensors and 40-70% for irradiated sensors [78]. For unirradiated sensors, the dominant contribution is given by the Landau term because of the fluctuations in charge deposition while, for irradiated ones, jitter is the dominant effect because of the lower $\frac{S}{N}$ ratio in the waveform signal.

The reference sensor was calibrated in the past to determine its time resolution [78] which

was found to be 35.7 ps for an optimal $f_{CFD} = 0.15$ at -30°C . The time resolution of the reference sensor at different temperatures and voltages are listed in Table 6.1.

Temperature [$^\circ\text{C}$]	Voltage [V]	Time resolution [ps]	f_{CFD}
-10	100	30.9	0.15
-20	90	33.2	0.15
-30	80	35.7	0.15

Table 6.1: Time resolution obtained for the reference LGAD sensor at different temperatures during calibration measurements presented in [78].

The time resolution of the DUT is determined using the time difference between the TOA of the reference sensor for a $f_{CFD} = 0.15$ and the TOA of the DUT at several CFD fractions. Each distribution is fitted with a Gaussian function, see Figure 6.5.

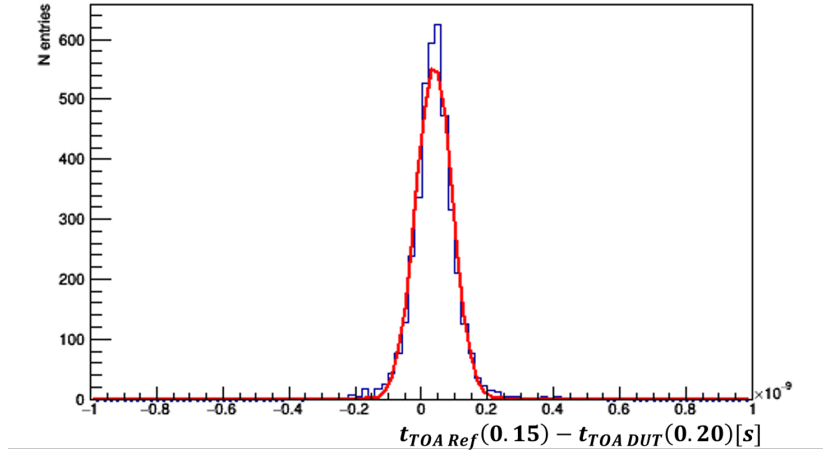


Figure 6.5: Distribution of the difference between the TOA of the reference LGAD sensor and of the DUT at -30°C of a given bias voltage and a CFD percentage of 15% for the reference and 20% for the DUT.

The time resolution of the DUT is obtained from the relation:

$$\sigma_{DUT_{f_{CFD_i}}} = \sqrt{\sigma_{DUT_i}^2 - \sigma_{refLGAD_{f_{CFD}=0.15}}^2} \quad (6.1)$$

where σ_i is the sigma of the Gaussian fit function of the distribution on Figure 6.5.

6.1.3 Transient Current Technique setup

The Transient Current Technique (TCT) [79, 80] consists of measuring time-resolved current waveforms induced by the drift of charges inside a sensor. The current is proportional to the number of charges, to their drift velocity and to the weighting field of the readout electrode. Different detector properties can be determined from the analysis of recorded waveforms, such as the charge collection, the gain and the inter pad distance for LGAD arrays. The TCT allows to perform measurements with good position resolution ($\sim 10\,\mu\text{m}$). A pulsed laser source⁹ mimics the behavior of charged particles by illuminating the sensor with a large number of photons in a short time interval. An InfraRed (IR) laser is used because its absorption length in silicon is of the order of mm, much larger than the detector thickness (μm). In this way, it can simulate the passing of a charged particle. Note, however, that the total charge deposited by the laser pulse is much larger than the charge corresponding to a mip. The TCT setup consists of:

- two laser sources, Red (660 nm) and Infrared (1064 nm)
- an optical system to focus the laser beam
- a current amplifier¹⁰
- a waveform digitizer¹¹
- a set of movable stages that allows to move the sensor on the perpendicular plane with respect to the laser beam and along the beam axis
- a Peltier element and controller to regulate operational temperature of the DUT
- a dry air filter to avoid condensation for measurements at low temperature

TCT measurements were performed at -20°C in a dry environment. It was not possible to achieve lower temperatures due to the cooling system. The IR laser illuminates the center of

⁹Pulsed laser from Particulars, fibre coupled laser FC.

¹⁰Cividec broadband amplifier, 2 GHz, 20 dB.

¹¹A DRS oscilloscope [81].

the back of the DUT to avoid possible edge effects. In Figure 6.6, a picture of the TCT setup with its components is shown. More detailed information about the TCT setup available at the IFAE laboratory can be found in Appendix A. This setup is used to perform gain measurement on single pad sensors and to estimate the inter pad distance for 2×2 LGAD arrays.

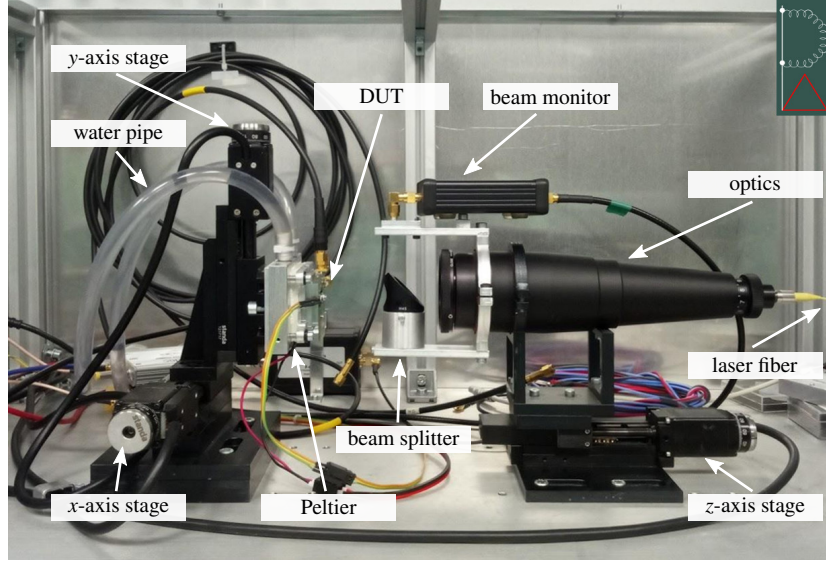


Figure 6.6: Transient Current Technique setup at IFAE.

Setup configuration for gain measurements

A sketch of this configuration is shown in Figure 6.7 (a). The sensor is located in a metal box mounted on the x-y movable stage as shown in Figure 6.7 (b). In this case, the DUT is biased from the topside while the backside (ohmic) is grounded. The pad and the guard ring (GR) of the sensor are wire-bonded to two different connectors and connected to the high voltage source (see Figure 6.7 (a)). The connector on the left side of the metal box is not used and is not connected to the sensor. The pad is biased through a Bias-T element which sends the output signal of the sensor to the Cividec amplifier and then to the data acquisition (DAQ) system. The metal box presents a circular opening for the laser beam to hit the back of the sensor surface which has an opening in the metal layer allowing these kind of measurements.

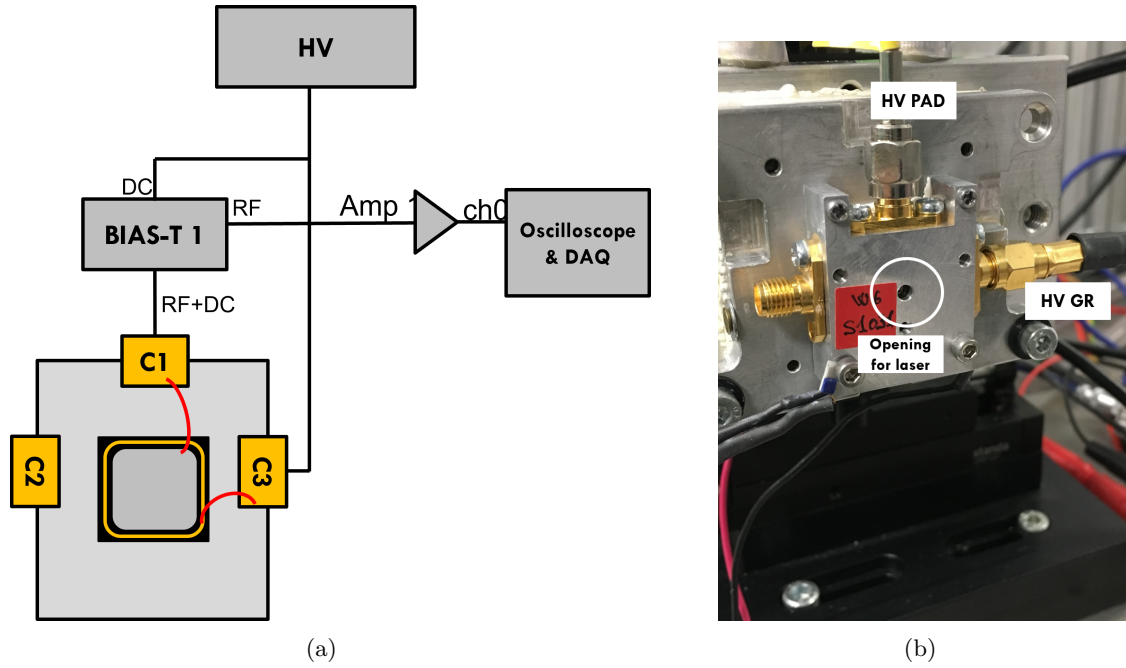


Figure 6.7: Sketch of the setup used for gain measurements (a) and a picture of the metal box in which the sensor is located, mounted on the x-y movable stage (b).

Setup configuration for inter pad distance measurements

A sketch of the setup is shown in Figure 6.8. As for the previous setup shown for gain measurements, the sensor is located in a metal box mounted on the x-y movable stage. The backside (ohmic) of the sensor is grounded and the four pads and GR of the 2×2 array are biased from the topside with the same high voltage source. Two of the four pads, named PAD A and PAD B, are wire bonded to two connectors C1 and C2, while the other two pads and the GR are connected to connector C3 and are not read out by the oscilloscope. Pads A and B are biased through two Bias-T elements which send the signal output to the Cividec amplifier and then to the DAQ system. The sensor is centered with respect to the opening in the metal box to allow the illumination of the laser in the central region between the two pads.

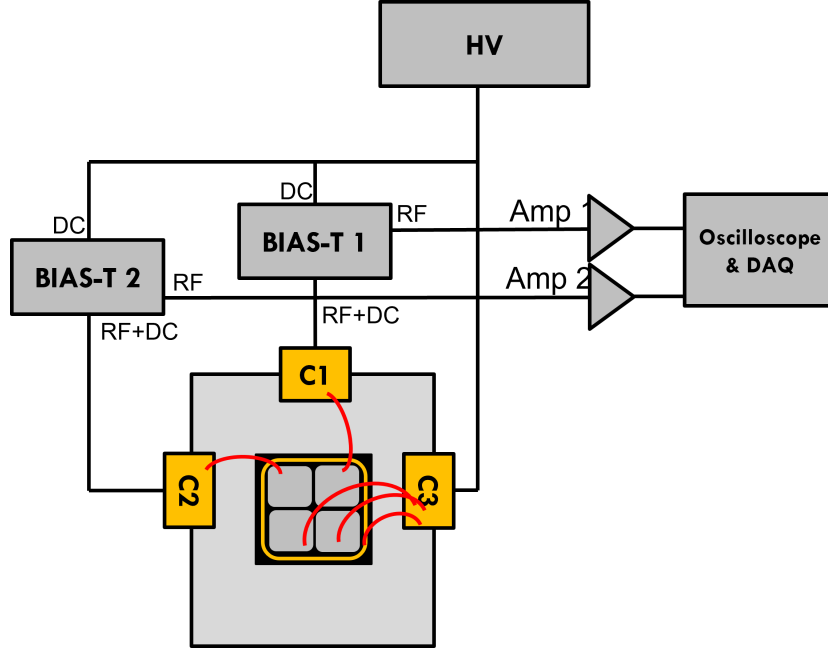


Figure 6.8: Sketch of the setup used for inter pad distance measurements of 2×2 arrays. The connections for pads and guard ring are shown.

6.1.4 Test beam setup

Several test beam campaigns were conducted both at CERN Super Proton Synchrotron (SPS)[82, 83] H6A line using a 120 GeV pion beam and at DESY TB 22 [84] line using a 5 GeV electron beam. The two setups are similar, with the only difference that at DESY only three DUTs could be tested in order to reduce the multiple scattering. A picture of the test beam setup at DESY TB22 is shown in Figure 6.9. A more detailed description of the setup and its components is given in [85].

Position dependent measurements were performed using a EUDET-type telescope [86] consisting of two arms, each of them made of three MIMOSA pixel planes of $10.6 \times 21.2 \text{ mm}^2$, providing particle track information with a resolution of a few micrometers. DUTs were assembled on the UCSC boards shown in Figure 6.2 and placed in the space between the two arms of the telescope on a movable stage¹² as shown in Figure 6.9. The tracking information allows to reconstruct the trajectory of particles and to identify the specific position where the

¹²Stage system from Physik Instrumente (PI).

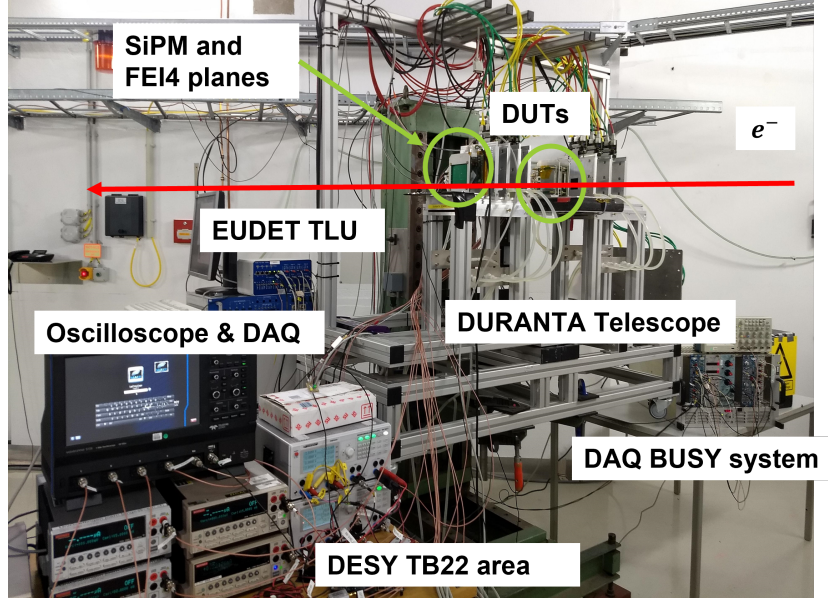


Figure 6.9: Picture of the test beam setup at DESY TB 22 area with its components. The direction of electron beam is shown by the red arrow. A detailed description of all the components and of its performances can be found in reference [85].

DUT has been hit.

Data acquisition and trigger scheme

Signals from DUTs were registered by a four-channel oscilloscope (first three channels for DUTs and a fourth channel for a time reference signal coming from a SiPM assembly) [85]. The trigger and DAQ architecture is shown in Figure 6.10. A ROI of about $3\text{ mm} \times 3\text{ mm}$ on a FE-I4 plane that contained the projected area of the LGADs and SiPM was defined. The downstream intersecting scintillator in the oscilloscope, the HitOr signal from the FE-I4 plane and the oscilloscope auxiliary output were the input to the EUDET Trigger Logic Unit (TLU) [87]. When the oscilloscope is triggered by the EXT signal coming from the TLU, it emits a TTL pulse that is sent back to the TLU module for synchronization of the telescope and FE-I4 DAQ system. Two independent data streams were recorded, one containing particle position information from the telescope and the FE-I4 and a second one containing waveform signals from the DUTs registered by the oscilloscope. These were merged offline for further analysis.

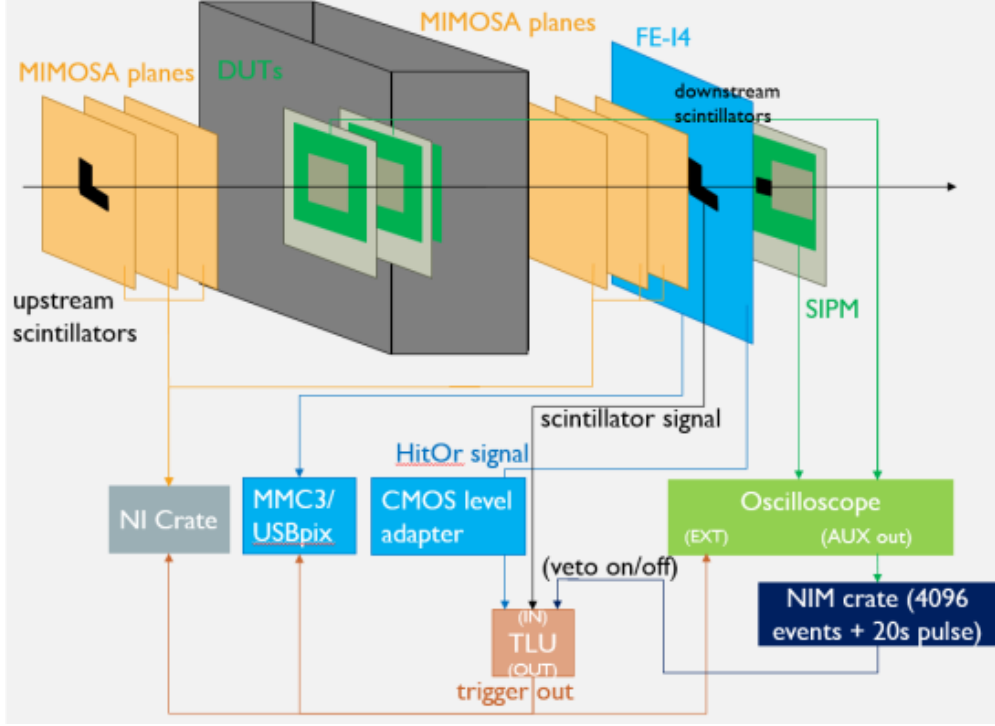


Figure 6.10: DAQ and trigger scheme for test beam measurements. More information can be found in reference [85].

Data analysis approach

Native data from the telescope containing the track information were reconstructed with EU-Telescope software [88, 89] using a General Broken Line (GBL) algorithm to take into account the scattering of the 5 GeV electron beam. Similarly to data measured with Sr90 radioactive source, DUT waveforms are analyzed with LGADUtils framework. The two outputs ROOT ntuples, provided by the conversion of oscilloscope data and by the track reconstruction, are merged into a single file for user offline analysis. This setup is used to perform measurements of collected charge, time resolution and hit reconstruction efficiency.

6.2 Investigation of CNM LGAD productions with boron, boron plus carbon and gallium doping material on Si-on-Si wafers

In the past years, several doping materials have been explored by CNM for LGAD sensors. In 2017, 50 μm -thick LGAD with boron¹³, boron plus carbon¹⁴ (with a doping dose of 1.5×10^{13} at/cm²), and gallium¹⁵ (with a doping dose of 6×10^{13} at/cm²), [90, 91] have been produced on high resistivity Si-on-Si wafers in order to explore possible radiation improvements. The charge collection and time resolution of a set of single-pad $1 \times 1 \text{ mm}^2$ devices have been studied at cold temperatures for both neutron and proton irradiation. A complete overview of the laboratory results are presented in [78].

In this thesis, the sensor fluence will be indicated in units of $\text{n}_{eq}/\text{cm}^2$ with the notation $1\text{e}14 \text{ n (p)}$ corresponding to $10^{14} \text{ n}_{eq}/\text{cm}^2$, and similarly for the other fluence values, where n or p indicates if the device was proton- or neutron-irradiated. Sensors have been irradiated with neutrons¹⁶ and protons¹⁷ up to a fluence of $10^{15} \text{ n}_{eq}/\text{cm}^2$.

6.2.1 Electrical characterization

Sensors were characterized on a probe station before irradiation at room temperature by the CNM group. The IV and CV curves are shown for some sensors in Figure 6.11 for boron-doped, in Figure 6.12 for carbon-enriched and in Figure 6.13 for gallium-doped LGAD sensors. For boron-doped LGADs from wafer 4 the gain layer depletion voltage is $V_{gl} \sim 40 \text{ V}$ and the breakdown voltage $V_{bd} \sim 130 \text{ V}$ to 140 V , for carbon-enriched sensors $V_{gl} \sim 40 \text{ V}$ and $V_{bd} \sim 120 \text{ V}$ to 140 V and for gallium-doped devices $V_{gl} \sim 35 \text{ V}$ to 40 V and $V_{bd} \sim 140 \text{ V}$. In particular, gallium-doped sensors present a high leakage current, as can be seen from Figure 6.13 (a). The sensors, once depleted, are close to the breakdown, having less room to operate in a safe way with respect to boron and boron plus carbon sensors. Gallium devices present

¹³Production run 10478 Wafer 4.

¹⁴Production run 10478 Wafer 5.

¹⁵Production run 10924 Wafer 6.

¹⁶Irradiation performed with 1 MeV neutrons in the TRIGA reactor in Ljubljana, Slovenia.

¹⁷Irradiation performed with 24 GeV at CERN PS, Geneva, Switzerland.

also a high variation in the gain layer depletion voltage, as shown in Figure 6.13 (b). This is explained by the fact that gallium penetrates less than boron in silicon because of the heavier atoms, and it diffuses faster than boron during the annealing process. This indicates also a not optimal process of gallium implantation in silicon for these sensors. This defect was not investigated further and the reason of the high leakage current was not understood.

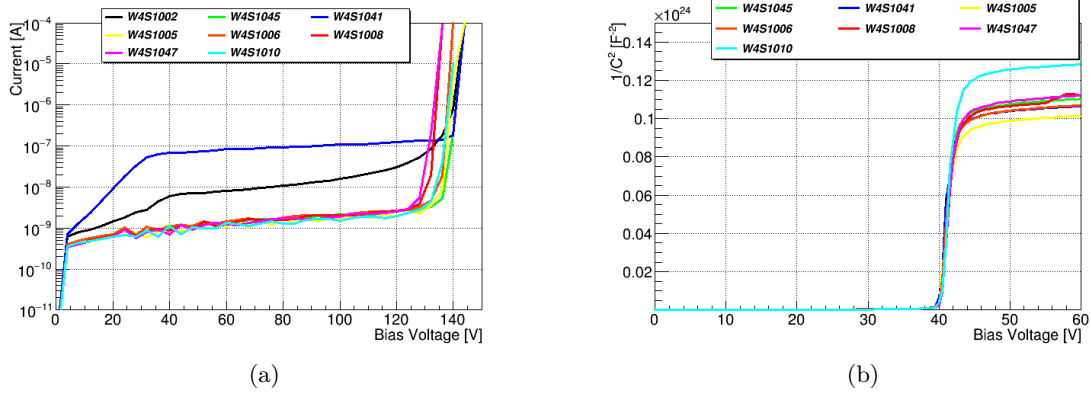


Figure 6.11: IV (a) and CV (b) curves at room temperature before irradiation for boron-doped LGADs on Si-on-Si wafers.

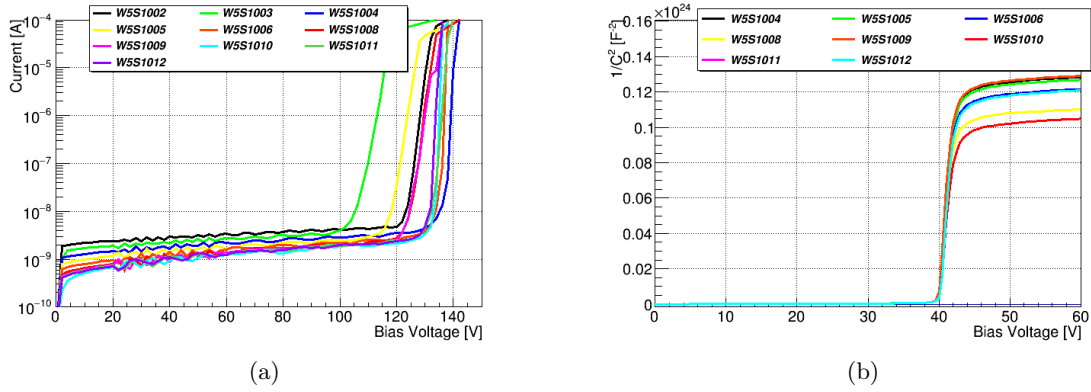


Figure 6.12: IV (a) and CV (b) curves at room temperature before irradiation for boron plus carbon LGADs on Si-on-Si wafers.

A list of the measured sensors with their characteristics is given in Table 6.2. After irradiation, the IV behavior of these sensors at different fluences has been studied at -30°C on a probe station and it is shown in Figure 6.14 for all the three doping materials. As expected, the breakdown voltage V_{bd} increases for irradiated sensors with respect to the unirradiated

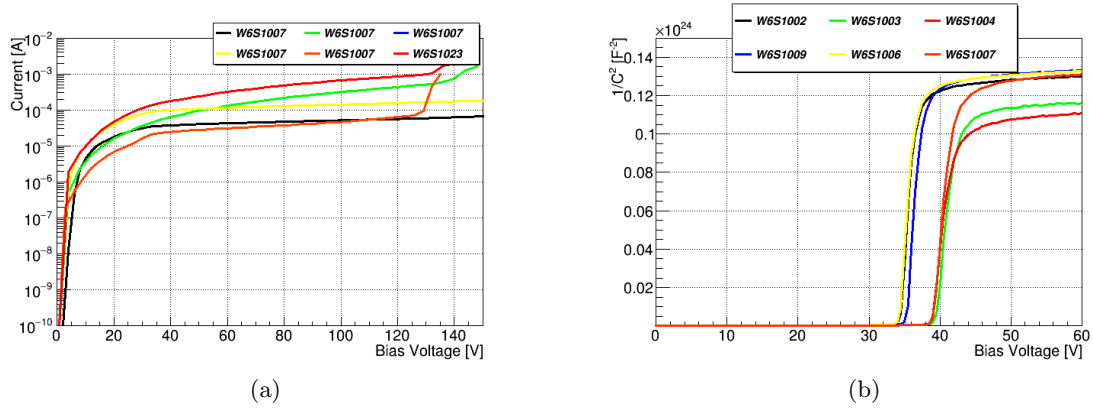


Figure 6.13: IV (a) and CV (b) curves at room temperature before irradiation for gallium-doped LGADs on Si-on-Si wafers.

devices up to 680 V. For the unirradiated sensors, the breakdown voltage V_{bd} decreases to ~ 120 V for the boron-doped sensor, to ~ 90 V for the boron plus carbon sensor and to ~ 100 V for the gallium-doped sensor.

Run	Wafer	Sensor	Dopant	Fluence [n_{eq}/cm^2]	Type	Size [mm^2]
10478	W4	S1022	boron	unirradiated	-	1×1
10478	W4	S1095	boron	1×10^{14}	neutron	1×1
10478	W4	S1067	boron	1×10^{14}	proton	1×1
10478	W4	S1016	boron	6×10^{14}	neutron	1×1
10478	W4	S1064	boron	6×10^{14}	proton	1×1
10478	W4	S1068	boron	1×10^{15}	neutron	1×1
10478	W5	S1021	boron + C	unirradiated	-	1×1
10478	W5	S1038	boron + C	1×10^{14}	neutron	1×1
10478	W5	S1005	boron + C	1×10^{14}	proton	1×1
10478	W5	S1008	boron + C	6×10^{14}	neutron	1×1
10478	W5	S1076	boron + C	6×10^{14}	proton	1×1
10478	W5	S1009	boron + C	1×10^{15}	neutron	1×1
10924	W6	S1021	gallium	unirradiated	-	1×1
10924	W6	S1007	gallium	1×10^{14}	neutron	1×1
10924	W6	S1023	gallium	1×10^{14}	proton	1×1
10924	W6	S1012	gallium	6×10^{14}	neutron	1×1
10924	W6	S1036	gallium	6×10^{14}	proton	1×1
10924	W6	S1023	gallium	1×10^{15}	neutron	1×1

Table 6.2: List of boron, boron plus carbon and gallium sensors on Si-on-Si wafers used for Sr90 measurements.

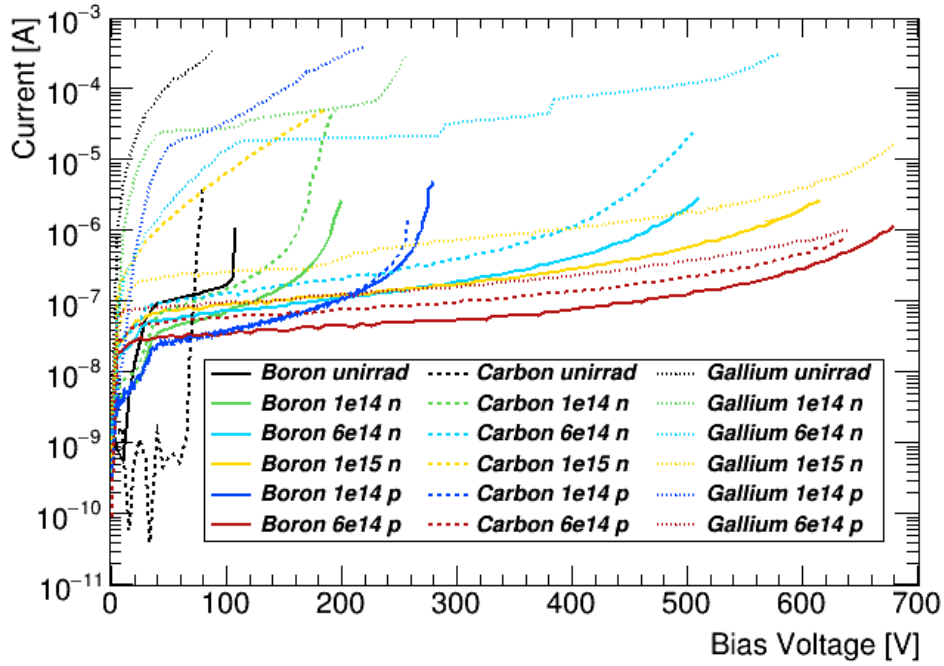


Figure 6.14: IV curves measured on probe station at -30°C for boron, boron plus carbon and gallium doped sensors.

The gain layer depletion voltage varies with fluence, due to the dopant loss in the silicon, following the relation:

$$V_{gl} = V_{gl,0} \times e^{-(C\Phi_{eq})} \quad (6.2)$$

where $V_{gl,0}$ is the depletion voltage for the unirradiated sensor, Φ_{eq} is the fluence and C is the acceptor removal coefficient. For these sensors, the acceptor removal coefficient C was found to be $C_{boron} = 9.69 \times 10^{-16}$ for boron-doped sensors, $C_{boron+carbon} = 9.33 \times 10^{-16}$ for boron plus carbon sensors and $C_{gallium} = 8.25 \times 10^{-16}$ for gallium-doped sensors [92].

6.2.2 Stability measurements

As introduced in the previous section, it is important to study the rate of self triggers to define the operational range of the sensor. The rate of self triggers for these sensors is shown in Figure 6.15 as a function of the bias voltage for different neutron and proton fluences. As shown, no self trigger is present for the unirradiated devices in their operational range. boron

plus carbon devices start autotriggering before than boron ones, while gallium devices start autotriggering at higher voltages.

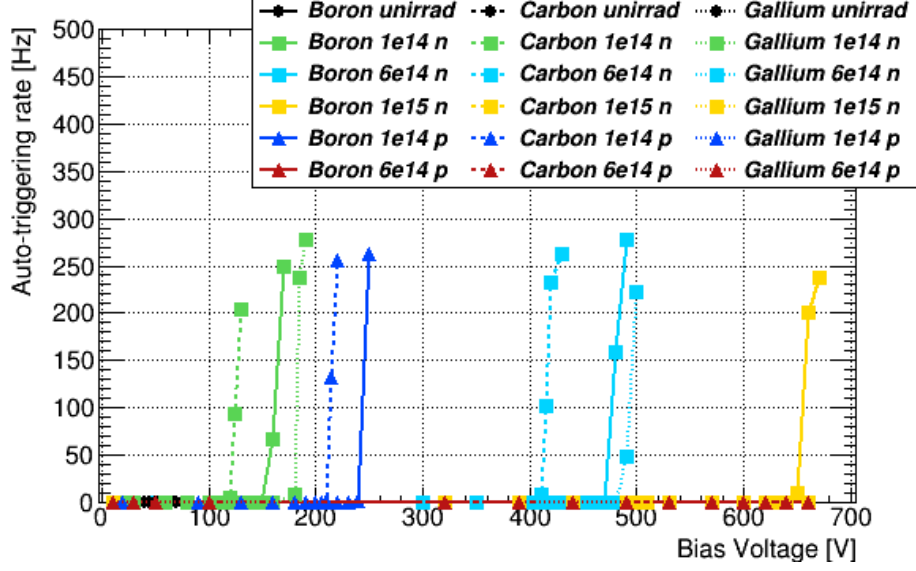
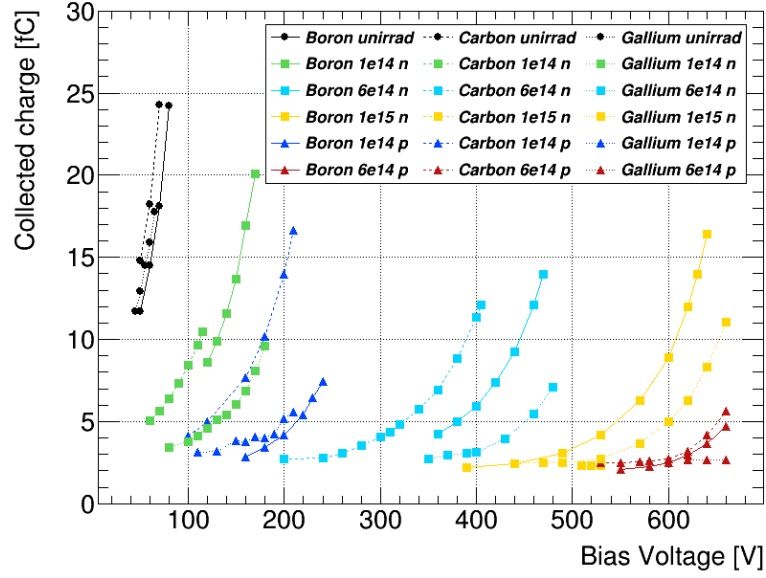


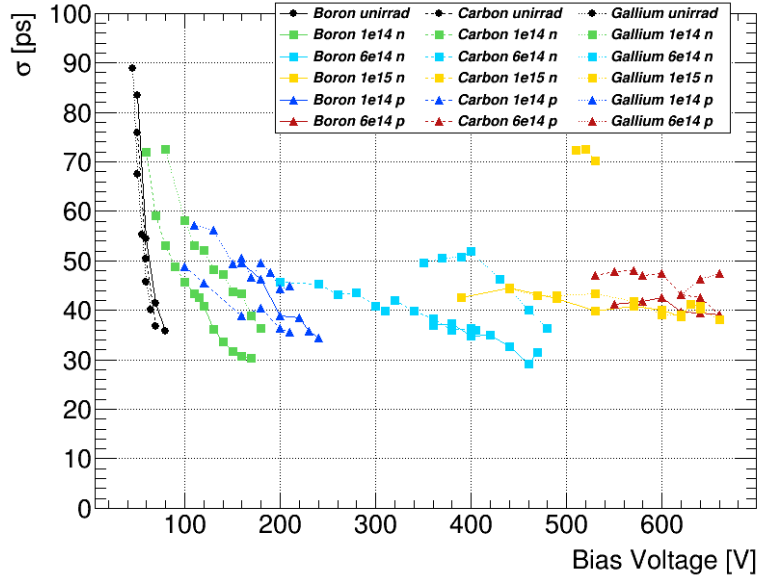
Figure 6.15: Rate of self triggers on sensors doped with boron, boron plus carbon and gallium on Si-on-Si wafers at -30°C .

6.2.3 Measurements with Sr90 radioactive source

Collected charge and time resolution were studied as a function of the bias voltage with a Sr90 radioactive source setup. Figure 6.16 shows the collected charge (a) and time resolution (b) results from boron, boron plus carbon and gallium devices. boron plus carbon sensors have a larger charge collection than boron and gallium devices at the same bias voltage. These results indicate that carbon enrichment helps maintaining a larger gain after irradiation compared to the other dopants. A time resolution better than 50 ps for both unirradiated and irradiated sensors is achieved. boron and boron plus carbon sensors show similar performances in time resolution, while gallium devices achieve a worse time resolution due to the higher leakage current. All the three LGAD types meet the HGTD requirements up to $10^{15} \text{ n}_{eq}/\text{cm}^2$ despite the high voltages needed at higher fluences.



(a)



(b)

Figure 6.16: Collected charge (a) and time resolution (b) before and after irradiation measured with Sr90 source for sensors doped with boron, boron plus carbon and gallium. All the measurements are taken at -30° in a dry environment.

6.2.4 TCT measurements

In this section, gain measurements of a set of single-pad boron and gallium-doped sensors using TCT are presented. Carbon-enriched devices were not measured because they were metallized on the backside, with no possibility to illuminate the device. The sensors used for these measurements are listed in Table 6.3. Unirradiated pin diode does not present any multiplication layer and, consequently, does not have charge multiplication (gain = 1). It will be used for the calculation of the gain of the other sensors.

Run	Wafer	Sensor	Dopant	Fluence [n_{eq}/cm^2]	Type	Size [mm^2]
10478	W4	S1022	boron	unirradiated	-	1×1
10478	W4	S1067	boron	1×10^{14}	proton	1×1
10478	W4	S1095	boron	1×10^{14}	neutron	1×1
10478	W4	S1016	boron	6×10^{14}	neutron	1×1
10478	W4	S1068	boron	1×10^{15}	neutron	1×1
10924	W6	S1041	gallium	unirradiated	-	1×1
10924	W6	S1044	gallium	1×10^{14}	proton	1×1
10924	W6	S1007	gallium	1×10^{14}	neutron	1×1
10924	W6	S1012	gallium	6×10^{14}	neutron	1×1
10924	W6	S1039P	-	Unirradiate Pin Diode	-	1×1

Table 6.3: List of the boron and gallium sensors on Si-on-Si wafers used for gain measurements.

The signal induced by the laser pulses was acquired. At each bias voltage an average of 300 waveforms was collected. The laser pulse width was set at 60%¹⁸ with a pulse frequency of 200 Hz [93]. An example of the recorded waveforms at different bias voltages for an unirradiated LGAD sensor is shown in Figure 6.17.

The collected charge of each sensor is determined at each bias voltage from the integral of the waveform around the peak, in the range 12 ns to 24 ns (see Figure 6.17). The gain is calculated by:

$$G_i = \frac{Q_i}{\langle Q_{PIN} \rangle} \quad (6.3)$$

where Q_i is the charge collected by the sensor and $\langle Q_{PIN} \rangle$ is the average collected charge

¹⁸The minimum pulse width for this system is 350 ps and the maximum is 4000 ps, where the minimum value corresponds to a pulse width of 100% and the smallest intensity.

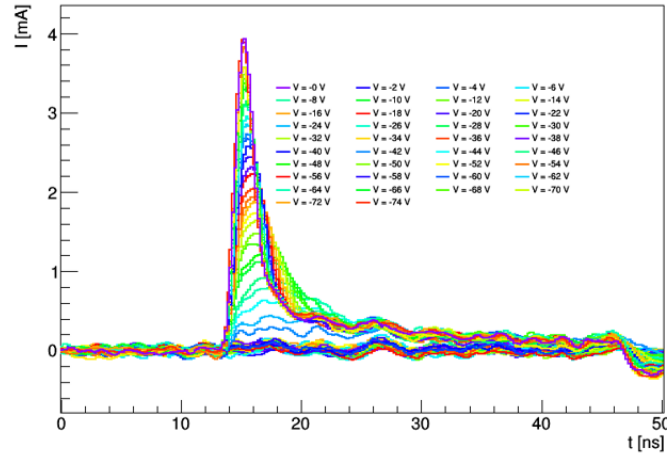


Figure 6.17: Example of recorded waveforms at different bias voltages for the unirradiated boron-doped LGAD sensor (W4S1022).

of the pin diode at each bias voltage. Gain results, presented also in [78], for the different LGADs are shown in Figure 6.18, where continuous lines correspond to boron sensors and dashed lines correspond to gallium devices. Boron LGADs show a higher gain at the same bias voltage with respect to gallium. Moreover, proton irradiation presents a higher damage with respect to neutrons at the same fluence.

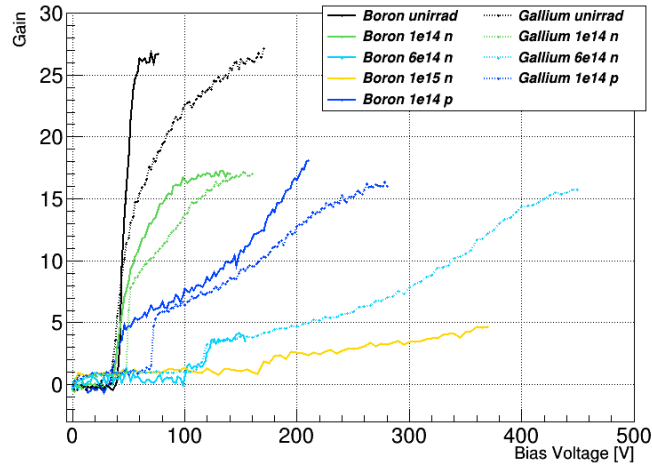


Figure 6.18: Gain as a function of the bias voltage for boron (continuous line) and gallium (dashed line) doped sensors.

Results for gallium-doped LGAD irradiated at a fluence of 10^{15} neq/cm^2 are not shown since

the sensor went to irreversible breakdown during the ramp up of the bias voltage.

6.2.5 Performance in beam test

The CNM LGAD sensors were tested with particle beams by the HGTD community, together with sensors from other vendors. The results presented here corresponds to a gallium-doped device irradiated with neutrons at a fluence of $3 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. The data were collected during the year 2019 at DESY TB 22 with 5 GeV electrons. The setup as described in Section 6.1, used dry ice for cooling the temperature down to -30°C , which was monitored with a PT100 temperature sensor.

In Figure 6.19, the hit efficiency of the gallium-doped sensor irradiated at a fluence of $3 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ is shown as a function of the bias voltage. Hit reconstruction efficiency is computed as the number of reconstructed tracks corresponding to a hit on the LGAD with a waveform peak higher than 10 mV, $n_{tracks \text{ with signal} > 10 \text{ mV}}$, (which correspond to a collected charge of $\sim 1.5 \text{ fC}$) divided by the total number of reconstructed tracks, n_{tracks} , for single track events, following the relation:

$$\epsilon = \frac{n_{tracks \text{ with signal} > 10 \text{ mV}}}{n_{tracks}} \quad (6.4)$$

The 10 mV threshold has been chosen since it corresponds to $\sim 5\sigma$ over the noise (with a noise level of 2 mV for all the bias voltages). The efficiency is computed in the central $0.5 \times 0.5 \text{ mm}^2$ area of the sensor to avoid edge effects. For bias voltage higher than 680 V, efficiency is higher than 95%.

For the highest bias voltage, 740 V, the hit efficiency as a function of the charge cut has been studied. This was done in order to understand what will be the effect of the ALTIROC discriminator. In this case, the hit efficiency is calculated as the number of reconstructed tracks associated to a hit in the sensor with a collected charge higher than a Q_{cut} , $n_{tracks(Q > Q_{cut})}$, divided by the total number of reconstructed tracks associated to a hit in the sensor, n_{tracks} ,

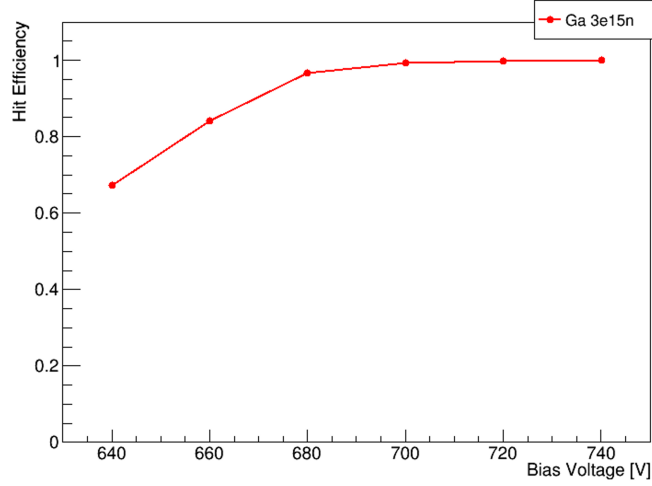


Figure 6.19: Hit efficiency as a function of the bias voltage for the gallium-doped LGAD irradiated at $3 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$.

following the relation:

$$\epsilon = \frac{n_{tracks}(Q > Q_{cut})}{n_{tracks}} \quad (6.5)$$

Figure 6.20 shows the hit efficiency at 740 V for the gallium doped sensor as a function of the charge cut. The efficiency is higher than 99% till a charge cut of 2 fC and drops to 75% for a charge cut of 5 fC. For other irradiated CNM LGADs measured during the 2019 beam test campaign, it was not possible to achieve a reasonable value of the hit efficiency because the bias voltage was not high enough (collected charge $\sim 2 \text{ fC}$). Thus, results for these sensors are not reported in this thesis. During test beam campaigns, some devices were experiencing an irreversible breakdown when operated at high voltages under particle beam. This effect, eventually, was known as Single Event Burnout (SEB) which will be explained in Section 6.5.

For this gallium-doped sensor, 2D efficiency maps were produced with different charge cuts. In Figure 6.21 the efficiency as a function of the reconstructed particle position is shown for a bias voltage of 740 V. The cut of 2 fC (equivalent to a signal above 15 mV) was applied because it is the minimum threshold target for the ALTIROC chip. In the central $0.5 \times 0.5 \text{ mm}^2$ area, the average efficiency is 99.74% with the 2 fC cut, see Figure 6.21 (a), whereas the edges of the

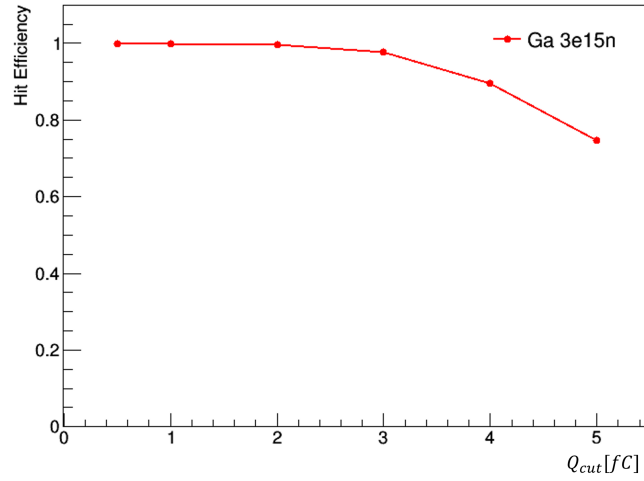


Figure 6.20: Hit efficiency as a function of the charge cut for the gallium-doped LGAD irradiated at $3 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$, operated at 740 V. The MPV for the collected charge at this bias voltage is 5.3 fC.

sensor are less efficient. Since for an optimal ALTIROC performance, 4 fC collected charge is required, a second map requiring tracks associated to signal with more than 4 fC collected charge has been produced, see Figure 6.21 (b). In this case, the average efficiency in the central $0.5 \times 0.5 \text{ mm}^2$ area is 89.56%. The blurred edges in both figures are determined by the movement of the cooling box containing the DUTs due to the evaporation of the dry ice.

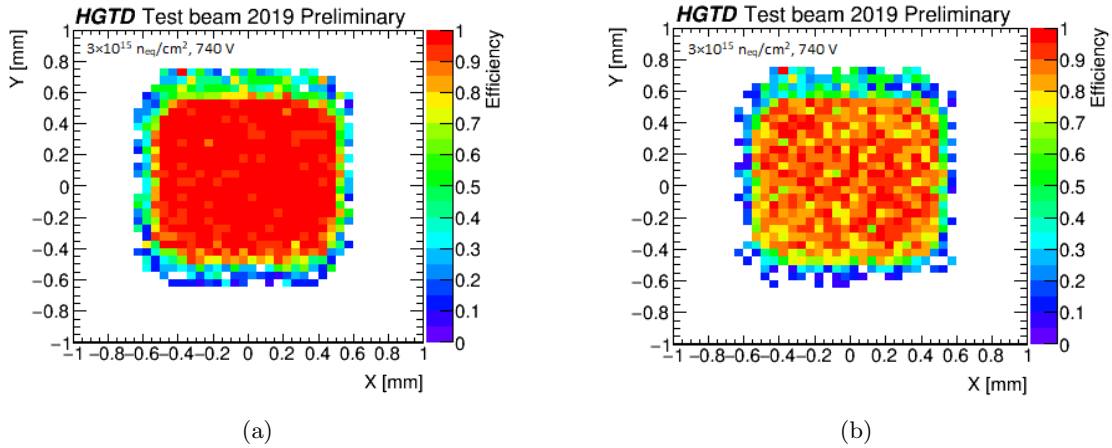


Figure 6.21: 2D efficiency map for the gallium-doped LGAD irradiated at $3 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ at 740 V for signals with more than 2 fC collected charge (a) and signals with more than 4 fC collected charge (b).

Results for collected charge and time resolution as a function of the bias voltage are shown in Figure 6.22 (a) and (b). The sensor reaches the 4 fC requirement for an optimal ALTIROC performance, in particular it collects 5.3 fC at 740 V. The time resolution has been computed as explained in Section 6.1. Since for irradiated sensors the dominant effect to the time resolution is the noise, a CFD fraction at the 50% is used for the time resolution calculation. The time resolution was found to be 48.7 ps at 740 V, where the contribution from the reference sensor was already subtracted.

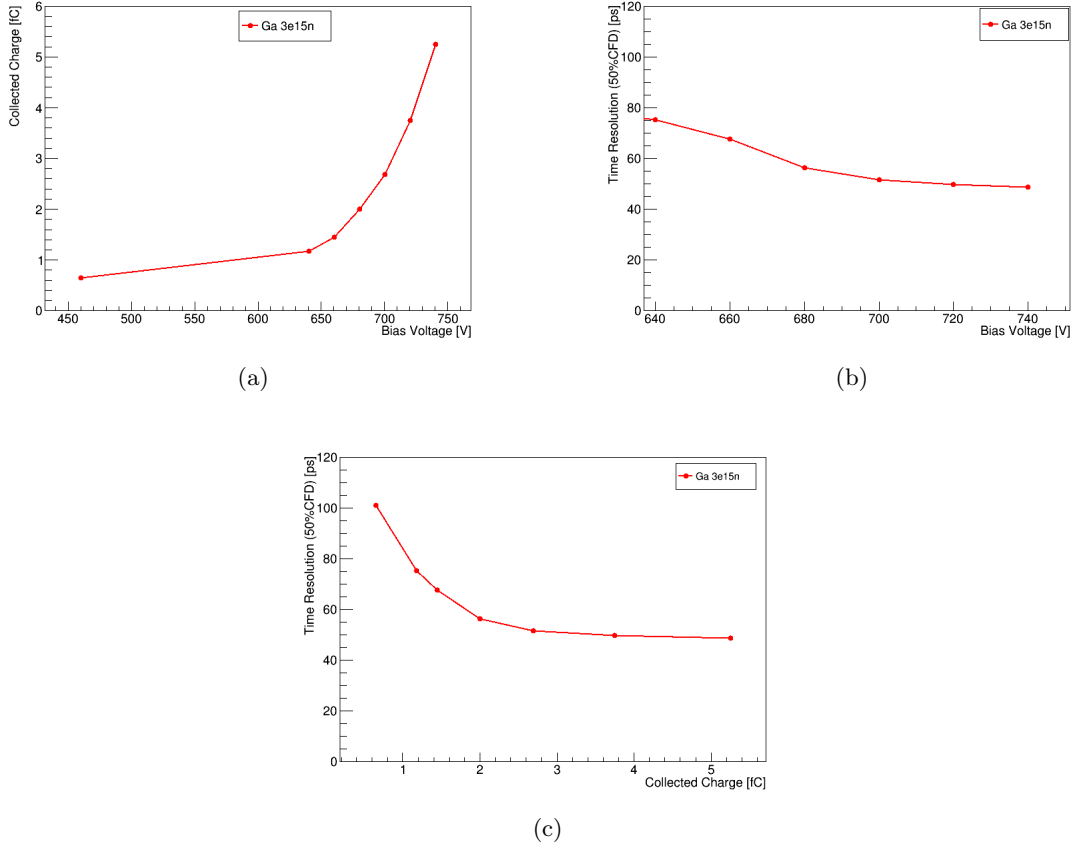


Figure 6.22: Charge collection and time resolution of the gallium doped sensor irradiated at $3 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. Collected charge as a function of bias voltage (a), time resolution as a function of the bias voltage (b) and time resolution as a function of the collected charge (c) are shown.

Figure 6.22 (c) shows the behavior of time resolution as a function of the collected charge. This sensor meets then the HGTD timing requirements of 70 ps at the end of the HL-LHC, even though it went to irreversible breakdown during data taking at 740 V. However, this

research line was not pursue since the replacement of boron by gallium does not show clear benefits, considering also laboratory results, where gallium devices show 20% less gain than boron doped sensors.

6.2.6 Conclusions

As shown from laboratory results with Sr90 radioactive sources, boron and boron plus carbon devices perform similarly in terms of time resolution and charge collection before and after irradiation. Carbon-enriched devices collect more charge at the same bias voltage, diminishing the effect of gain reduction after irradiation with respect to boron sensors. However, boron plus carbon start auto-triggering earlier in voltage than other implants, which makes these devices not operable at higher voltages. Thus, the determining factor for carbon is stability, and not radiation hardness. However, in this first run with carbon, the implantation process was not optimal, mainly because it was done early in the run, and subsequent steps in the production diffused the carbon away from the multiplication layer. Thus, the benefits from carbon are not clear compared to later productions of carbonated devices from other manufacturers [94]. Boron-doped devices present a higher gain with respect to the gallium-doped sensors at the same bias voltage. It was also observed that proton irradiation results in a higher damage with respect to the neutron one at the same fluence.

From beam test data, results from the 2019 campaign were presented. A full study of both CNM and HPK LGAD sensors can be found in [85] where results from 2018 and 2019 campaign carried both at CERN and DESY are presented. A gallium-doped sensor irradiated at $3 \times 10^{15} n_{eq}/cm^2$ meets the HGTD requirements in terms of charge collection, time resolution and hit efficiency despite the high bias voltage needed. A full study on this sensor can be found also in [95]. However, the replacement of boron by gallium does not show clear benefits. Thus, considering also results from laboratory measurements, where gallium devices present 20% less gain with respect to the boron sensors, this line was not pursued further. Between 2017 and 2020 ten test beam campaigns carried out both at CERN (2017 and 2018) and DESY (2019 and 2020) were devoted to study LGAD sensors and their properties. About the 20% of

the total number of sensors died through an irreversible breakdown, called SEB. Several beam test campaigns were carried out during 2021 and 2022, devoted to the study of the mortality problem. It was determined that sensors with carbon implanted in the multiplication layer can avoid the SEB effect. This will be discussed further in 6.5.

6.3 Characterization of highly boron-doped LGAD sensors on Si-on-Si wafer from CNM production run 12916

These LGAD sensors¹⁹ were produced with a 50 μm active area in a high resistivity Si-on-Si wafer with a boron doping dose of 1.8×10^{13} atoms/cm² which is higher than the one for sensors discussed Section 6.2. The sensors have been irradiated with neutrons²⁰ up to a fluence of 2.5×10^{15} n_{eq}/cm². For a set of 1.3×1.3 mm² single-pad sensors, the electrical characterization before and after irradiation (IV and CV curves) and stability measurements is discussed first. The charge collection and time resolution measured with Sr90 radioactive source setup will be shown. Finally, the inter pad distance of 2×2 arrays with 1.3×1.3 mm² pads is presented.

6.3.1 Electrical characterization

Initially, these devices were electrically characterized before irradiation by the CNM group on a probe station at 20 °C in a dry environment. The leakage current was studied as a function of the bias voltage, in order to determine the depletion and breakdown voltages. Figure 6.23 shows the IV (a) and CV (b) curves before irradiation. For all the samples, the gain layer depletion voltage is $V_{gl} \sim 38$ V, the fully depletion voltage is $V_{fd} \sim 42$ V and the breakdown voltage is $V_{bd} \sim 85$ V.

After neutron irradiation, the IV on a probe station at -30 °C in a dry environment was measured as a part of this thesis. The IV curves are shown in Figure 6.24. The tested sensors

¹⁹CNM production run 12916, named AIDA2020v2.

²⁰Irradiation performed with 1 MeV neutrons in the TRIGA reactor in Ljubljana, Slovenia.

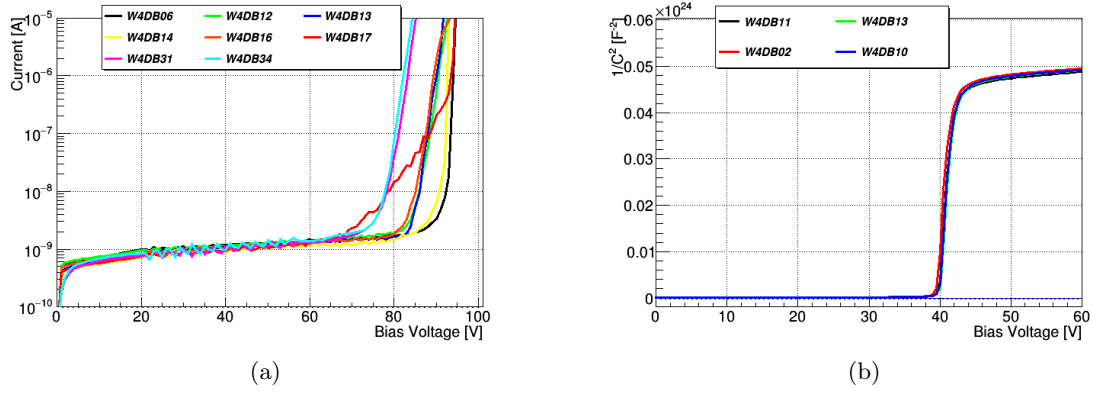


Figure 6.23: IV (a) and CV (b) curves of the unirradiated Si-on-Si LGAD sensors at room temperature. As shown in the plots, for those sensors $V_{gl} \sim 38$ V, $V_{fd} \sim 42$ V and $V_{bd} \sim 85$ V. Adapted from [96].

are listed in Table 6.4, including their fluences and breakdown voltages.

Run	Wafer	Sensor	Dopant	Fluence [n_{eq}/cm^2]	Type	Size [mm^2]	V_{bd} [V]
12916	W1	DB07	boron	unirradiated	-	1.3×1.3	~ 50
12916	W1	DB08	boron	1×10^{14}	neutron	1.3×1.3	~ 140
12916	W1	DB04	boron	6×10^{14}	neutron	1.3×1.3	~ 500
12916	W1	DB05	boron	6×10^{14}	neutron	1.3×1.3	~ 500
12916	W1	DB06	boron	1×10^{15}	neutron	1.3×1.3	~ 640
12916	W1	DB03	boron	1×10^{15}	neutron	1.3×1.3	~ 640
12916	W1	DB33	boron	2.5×10^{15}	neutron	1.3×1.3	~ 720
12916	W1	DB28	boron	2.5×10^{15}	neutron	1.3×1.3	~ 720

Table 6.4: List of sensors from CNM production run 12916 irradiated with neutrons.

As shown in Figure 6.24, the breakdown voltage of irradiated sensors increased with respect to the unirradiated devices, being the ones at high fluences operated up to 700 V. For the unirradiated sensor, the V_{bd} decreases from ~ 85 V at room temperature to ~ 50 V at -30°C . The reduction of V_{bd} with lower temperatures is expected. Due to the reduction of the temperature, vibration of atoms increase and this increase the mean free path for electrons. Thus, the breakdown voltage V_{bd} reduces with a reduction of temperature. The low V_{bd} at -30°C and its consequences will be discussed further in the next sections.

The gain layer depletion voltage varies with fluence, due to the loss of boron in silicon. The lower is the acceptor removal coefficient, the more resistant the sensor is to acceptor removal

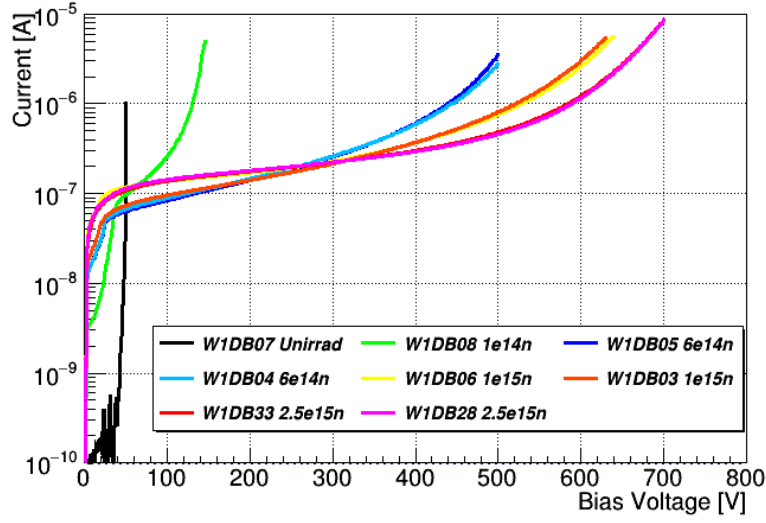


Figure 6.24: IV curves for Si-on-Si LGAD sensors before and after irradiation at $-30\text{ }^{\circ}\text{C}$.

(maintain the gain after irradiation). The V_{gl} does not depend on the temperature, then for unirradiated devices the value is taken from the CV measurements at room temperature shown in Figure 6.23 (b). Since the CVs were not measured at $-30\text{ }^{\circ}\text{C}$, the depletion voltages have been determined from the IVs using a derivative method [97]. It consists of studying the $\frac{dI}{dV}$ as a function of the bias voltage. Around the V_{gl} , the $\frac{dI}{dV}$ curve shows a peak that is then fitted with a Gaussian function, where the V_{gl} is defined as the mean value of the fit. An example of this procedure is shown in Figure 6.25 for the neutron irradiated sensor at fluence $10^{14}\text{ n}_{eq}/\text{cm}^2$.

The behavior of the V_{gl} values as a function of the fluence is shown in Figure 6.26. The acceptor removal coefficient, C , can be determined using the following fitting function [92]:

$$f(\Phi_{eq}) = e^{A+C\cdot\Phi_{eq}} \quad (6.6)$$

where Φ_{eq} is the fluence and A is a constant. The slope of the function corresponds to the so called acceptor removal factor $C_{AIDA} = 7.26 \times 10^{-16}$.

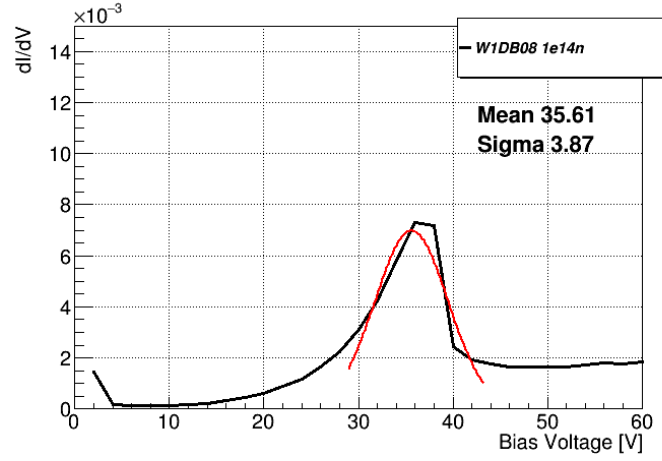


Figure 6.25: The figure shows an example of dI/dV as a function of the bias voltage for the sensor irradiated with neutron at fluence $10^{14} \text{ n}_{eq}/\text{cm}^2$. The distribution is fitted with a Gauss function and the mean value of the fit is identified as the gain layer depletion voltage, V_{gl} .

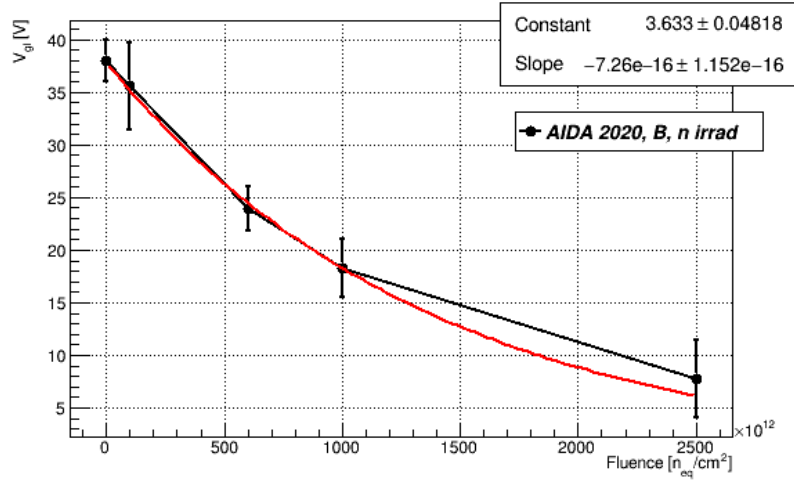


Figure 6.26: Gain layer depletion voltage as a function of the fluence for the Si-on-Si LGAD sensors at -30°C . The experimental data is fitted using Equation 6.6.

6.3.2 Stability measurements

Before studying the performance of the LGAD sensors with a radioactive source, the determination of the operating voltage points is done by measuring the rate of self triggers as a function of the bias voltage.

For these measurements, a threshold at 10 mV is set on the oscilloscope channel where the

DUT is connected. This threshold corresponds to $5\sigma_{noise}$, where the noise mean value is ~ 2 mV. In Figure 6.27, the mean value of noise distribution during data taking with a Sr90 source is shown as a function of the bias voltage. The noise level is around 2 mV for almost all the bias voltages used apart some for which a high rate of self triggers was registered and the sensor started to be unstable for which a noise level of ~ 5 mV is present (see light blue lines in the plot corresponding to the sensors irradiated at $6 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$).

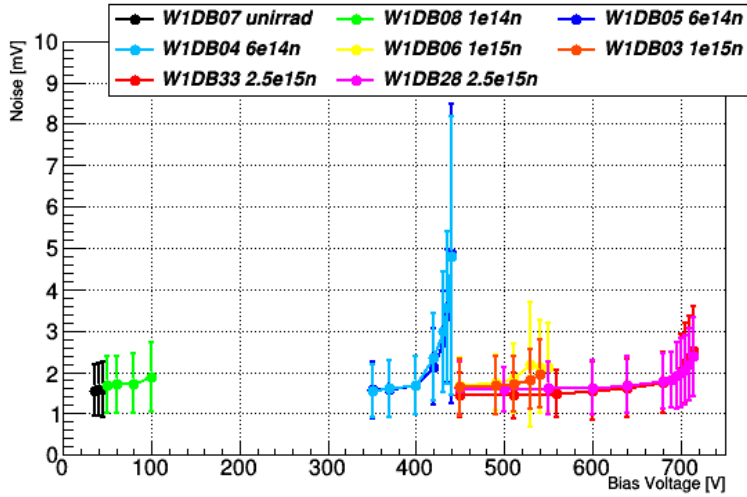


Figure 6.27: Mean noise as a function of the bias voltage at -30°C for the Si-on-Si LGAD sensors. The noise is calculated using data from data taking with a Sr90 radioactive source using points between the 10% and the 90% before the signal peak.

Since the waveforms generated by auto-triggering events are identical to real signals, it is critical to measure this rate as a function of the bias voltage. An acceptable operating voltage point is defined as an auto-triggering rate lower than 1 kHz. This limit comes from the average rate of data expected to be recorded in ATLAS. An excessive self-triggering would increase the dead time of the HGTD detector hindering its operation. In Figure 6.28, the auto-triggering for the set of sensors listed in Table 6.4 as a function of the bias voltage is shown. The unirradiated sensor presents a high auto-triggering rate of 7 kHz at 45 V, which severely limits the operational range of the device before irradiation, since as mentioned earlier, the full depletion is 42 V. This affects the sensor timing performance, as will be shown in the next section. However, after irradiation the operational range is extended since the gain is reduced

and the operating point can be pushed closer to the breakdown value.

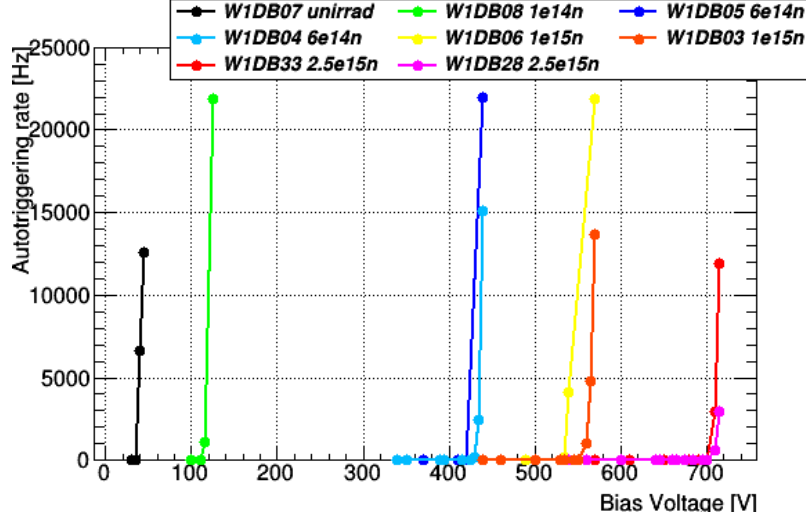


Figure 6.28: Rate of self triggers for Si-on-Si LGAD sensors as a function of the bias voltage at -30°C .

6.3.3 Measurements with Sr90 radioactive source

The performance with β particles is presented in this section. The collected charge as a function of the bias voltage is shown in Figure 6.29, where the charge distribution at each bias voltage is fitted with a Landau-Gauss convoluted function, where the MPV of the fit is taken as collected charge and the σ of the fit as its error. A big error corresponds to a wide charge distribution, as it is present in some of the last points of the irradiated sensors at fluence $6 \times 10^{14} \text{ n}_{eq}\text{cm}^2$ and $10^{15} \text{ n}_{eq}\text{cm}^2$. Sensors irradiated to the highest fluence reach the HGTD target of 4fC^{21} for bias voltages higher than 680 V .

The time resolution as a function of the bias voltage is shown in Figure 6.30. All the irradiated sensors reach a time resolution below 40 ps up to the highest fluence value, meeting the HGTD requirements of 70 ps per hit at the end of the HL-LHC lifetime. However, as introduced in Section 6.3.2, the unirradiated sensor performance suffers from the small operational range between V_{fd} and V_{bd} values, and consequently from the high rate of self triggers at those bias

²¹The 4fC low limit is given by the HGTD sensor and electronics requirements, see Chapter 3.

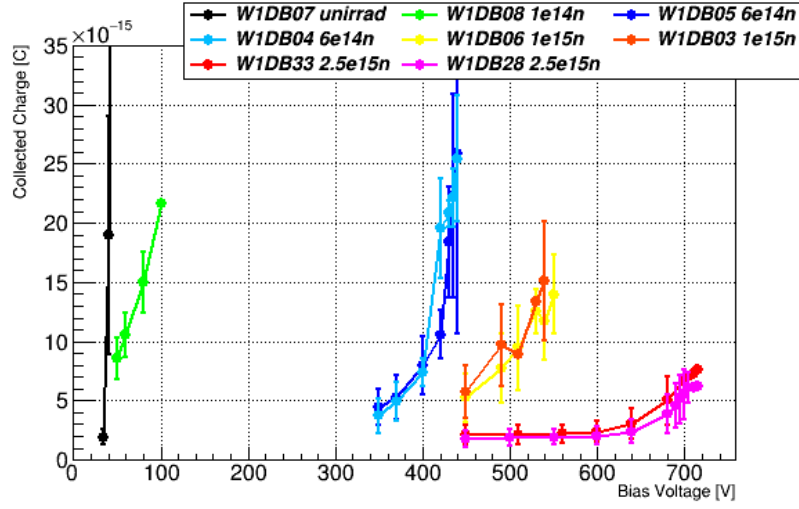


Figure 6.29: Collected charge as a function of the bias voltage for Si-on-Si LGAD sensors before and after irradiation at -30°C .

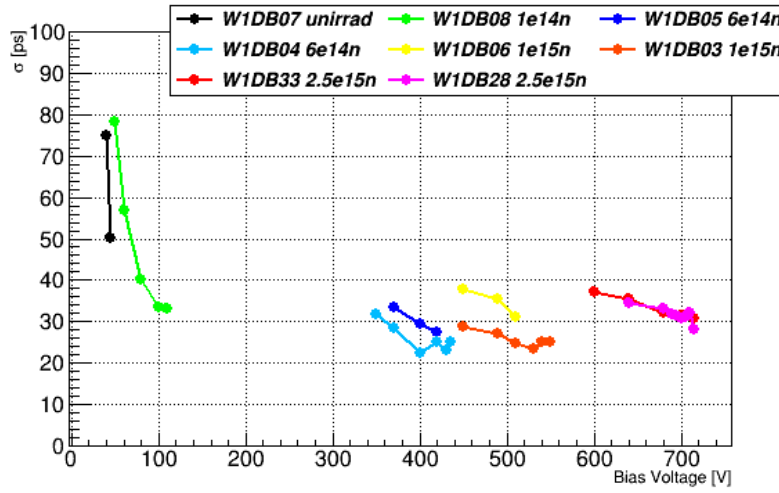


Figure 6.30: Time resolution as a function of the bias voltage for Si-on-Si LGAD sensors before and after irradiation at -30°C .

voltages. Performance before irradiation for these Si-on-Si sensors are marginal due to this restricted operational voltage range. The time resolution as a function of the collected charge for irradiated sensors is shown in Figure 6.31. From this plot, it can be seen that a minimum value of 4 fC for the collected charge and a value lower than 70 ps for the time resolution can be obtained for all the irradiated sensors up to a fluence of $2.5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$.

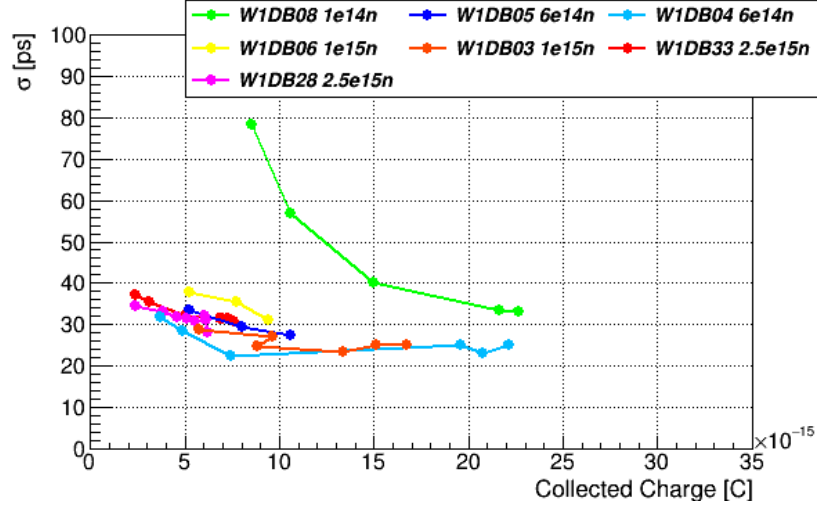


Figure 6.31: Time resolution as a function of the collected charge for Si-on-Si LGAD sensors before and after irradiation.

6.3.4 Inter pad distance of 2×2 LGAD arrays

In this section, measurements of the inter pad distance of a set of 2×2 LGAD arrays after irradiation as a function of the bias voltage is presented. The studies sensors are listed in Table 6.5. They have been irradiated with neutrons²² up to fluences of $2.5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$.

First, sensors were electrically characterized on a probe station at the CNM laboratory at -20°C in a dry environment to identify the operating range for each sensor. This temperature is the same as the one to be used in TCT setup. IV curves are shown in Figure 6.32. For each sensor, the IV is done biasing the four pads and the guard ring from the junction side of the sensor while its ohmic side is grounded.

²²Irradiation performed with 1 MeV neutrons in the TRIGA reactor in Ljubljana, Slovenia.

Run	Wafer	Sensor	Dopant	Fluence [n_{eq}/cm^2]	Type	Pad Size [mm^2]	Nominal IP gap [μm]
12916	W1	A242	boron	1×10^{14}	neutron	1.3×1.3	57
12916	W1	A236	boron	6×10^{14}	neutron	1.3×1.3	57
12916	W1	A237	boron	1×10^{15}	neutron	1.3×1.3	57
12916	W1	A239	boron	2.5×10^{15}	neutron	1.3×1.3	57

Table 6.5: List of the 2×2 LGAD arrays used for inter pad distance measurements. The nominal value of the inter pad distance is also reported.

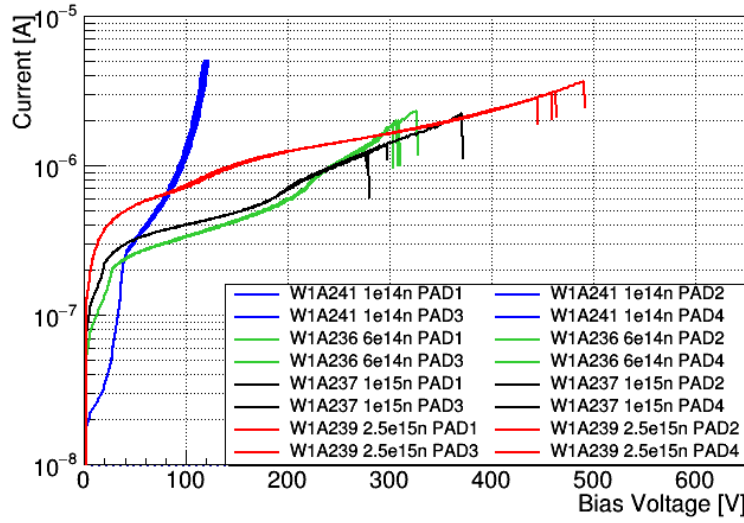


Figure 6.32: IV curves of 2×2 LGAD arrays at -20°C on probe station in a dry environment. For each sensor the four pad curves are shown.

The TCT measurements were performed at -20°C in a dry environment. As explained in Section 6.1.3, the cooling system does not allow to have stable operation at -30°C . The IR laser was illuminating the backside of the sensor through the opening in the metal layer and an area of $0.5 \text{ mm} \times 0.5 \text{ mm}$ between pads A and B was scanned with $10 \mu\text{m}$ steps in both x-and y-directions. In Figure 6.33, a sketch of an LGAD array and the area for the x-y scan is shown. An average of 1000 waveforms was recorded for each x-y position. The laser pulse was set at 60%²³ with a pulse frequency of 200 Hz.

As explained in Section 6.2.4, the collected charge for each x-y position of the scan is obtained by integrating the waveform around the peak. A 2D map of the x-y scanned area is built for

²³The minimum pulse width for this system is 350 ps and the maximum is 4000 ps, where the minimum value corresponds to a pulse width of 100% and the smallest intensity.

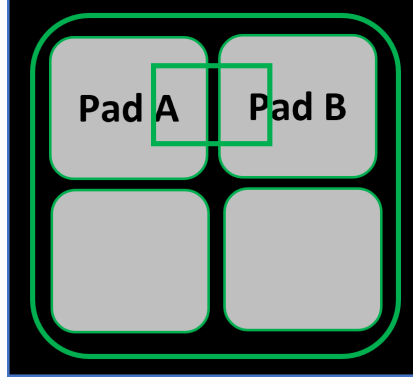


Figure 6.33: Sketch of the x-y scanned area for inter pad distance measurements.

each pad output, see Figure 6.34 for the PAD B output, with the collected charge in color scale expressed in arbitrary units (AU). The negative value of charge shown in the region of PAD A is due to the discharging of the PAD B capacitor [98].

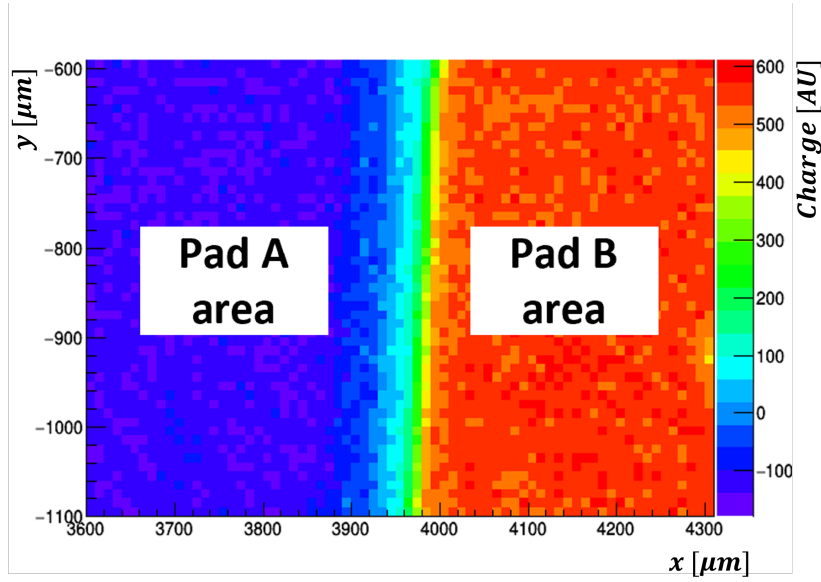


Figure 6.34: 2D map of the scanned x-y area with IR laser only for PAD B output. The color scale shows the collected charge in AU.

The projection of the 2D map for each of the pad is fitted with a (reverse) error function:

$$f = p_3 + p_2 \cdot \frac{(1 \pm \text{Erf}(\frac{x-p_0}{p_1}))}{2} \quad (6.7)$$

where p_3 is the baseline, p_2 is the amplitude, p_1 is the sigma and p_0 is the x position at the

50% of the height of the fit function. A pad projection with a fit can be seen in Figure 6.35, where the projection of the two pads are plotted together with their corresponding fitting functions and parameters.

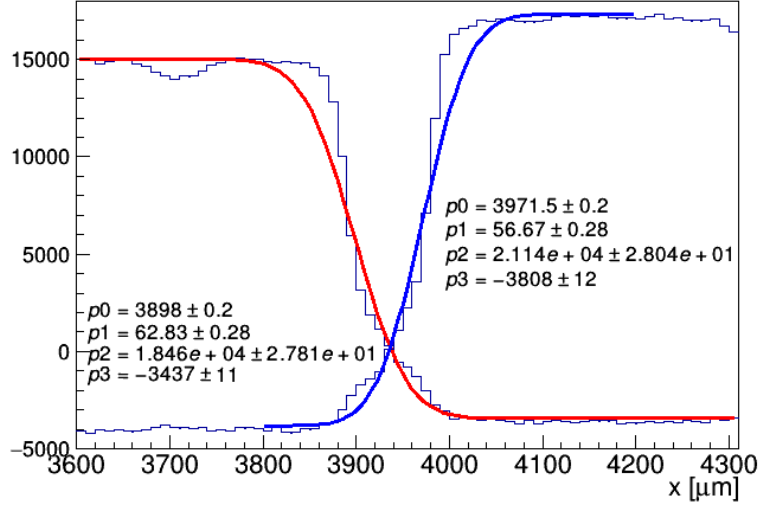


Figure 6.35: 2D map projection of the two pads with the fitting functions.

For each sensor and each bias voltage, the inter pad distance can be estimated as the difference between the p_0 parameter of the two pads, following the relation:

$$IP_{DISTANCE} = |p_{0(PADA)} - p_{0(PADB)}| \quad (6.8)$$

The nominal inter pad distance, that is the distance defined in the LGAD design, is 57 μm . The behavior of the measured inter pad distance is shown in Figure 6.36, for sensors irradiated from $10^{14} \text{ n}_{eq}/\text{cm}^2$ to $2.5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. Results from the unirradiated device are not reported here since their early breakdown voltage did not allow to run the TCT measurements in stable conditions. From the figure two different behaviors are seen. At low fluences (green line), part of the carriers generated underneath the gain layer drift to the JTE and don't produce charge multiplication. The effect, translated into an higher inter pad distance, is reduced as the bias voltage is increased. However, the effect of the JTE is reduced at higher fluences. At the same time, at higher fluences some multiplication is achieved by carriers drifting to the JTE

area and smaller inter pad distances are measured at higher voltages (blue, yellow and red lines). This behavior was also observed on LGADs from other vendors [99] and verified by simulations.

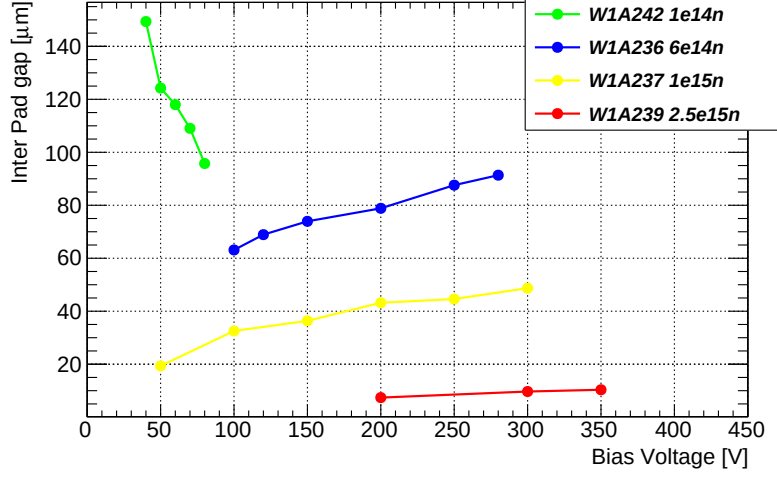


Figure 6.36: Inter pad distance as a function of the bias voltage for Si-on-Si irradiated LGAD sensors at -20°C .

6.3.5 Conclusions

Measurements of Si-on-Si single-pad LGAD sensors with a Sr90 radioactive source show that the target minimum charge of 4 fC for HGTD and a time resolution lower than 70 ps can be achieved up to $2.5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ for bias voltage higher than 680 V. However, unirradiated devices show marginal timing performances due to the restricted operational voltage range at cold temperature. In order to study if LGAD performances before irradiation can be improved maintaining the performance after irradiation, a set of sensor on low-resistivity epitaxial wafers have been investigated. Results for these devices are shown in the next section.

For the 2×2 LGAD arrays, the inter pad distance has been studied as a function of the bias voltage up to $2.5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. As shown, the behavior differentiates between low and high fluences, for which the value of the inter pad distance tends to the nominal value. These results are in agreement with simulation studies [99].

6.4 Characterization of LGAD sensors on low-resistivity epitaxial wafers from CNM production run 13002

These 50 μm -thick LGAD sensors²⁴ were produced on a 525 μm -thick low-resistivity²⁵ epitaxial substrate with a boron doping dose of 1.9, 1.95 and 2.0×10^{13} atoms/ cm^2 . LGAD sensors on low-resistivity epitaxial wafers have been irradiated with neutrons²⁶ up to a fluence of 10^{16} n_{eq}/ cm^2 . For a set of 1.3×1.3 mm² single-pad sensors, the electrical characterization before and after irradiation (IV and CV curves) and stability measurements are presented. Then, charge collection and time resolution measured with a Sr90 radioactive source setup are also shown. In addition, TCT measurements for gain and time resolution performed by the CNM group are also reported.

6.4.1 Electrical characterization before and after irradiation

Initially, these devices were electrically characterized before irradiation by the CNM group on a probe station at 20 °C in a dry environment. Sensors were biased from the junction side with positive voltage and the ohmic side of the sensors was grounded. The unirradiated sensors which have been characterized are listed in Table 6.6. Three wafers have been produced with different implantation doses, as indicated. Two sensors from each wafer were characterized in order to study the V_{gl} , V_{fd} and V_{bd} voltages and IV and CV curves are shown in Figure 6.37 (a) and (b), respectively. For all the wafers, $V_{gl} \sim 30$ V and $V_{fd} \sim 35$ V, while the V_{bd} varies from ~ 420 V for the wafer with the highest multiplication layer dopand dose (W4) to ~ 500 V for the wafer with the lowest dose (W2).

Sensors from wafer 4 listed in Table 6.7 were irradiated with neutrons²⁷ are shown in Figure 6.38. These measurements were performed at -30 °C.

²⁴CNM production run 13002.

²⁵The wafer resistivity is 200 Ω cm.

²⁶Irradiation performed with 1 MeV neutrons in the TRIGA reactor in Ljubljana, Slovenia.

²⁷Irradiation performed with 1 MeV neutrons in the TRIGA reactor in Ljubljana, Slovenia.

Run	Wafer	Sensor	Dopant	Dose [at/cm ²]	Size [mm ²]	V _{bd} [V]
13002	W2	N18-6	boron	1.9×10 ¹³	1.3 × 1.3	~500
13002	W2	N18-8	boron	1.9×10 ¹³	1.3 × 1.3	~500
13002	W3	N09-7	boron	1.95×10 ¹³	1.3 × 1.3	~480
13002	W3	N09-4	boron	1.95×10 ¹³	1.3 × 1.3	~480
13002	W4	N09-1	boron	2.0×10 ¹³	1.3 × 1.3	~420
13002	W4	N09-2	boron	2.0×10 ¹³	1.3 × 1.3	~420

Table 6.6: List of sensors from CNM production run 13002 electrically characterized before irradiation at room temperature.

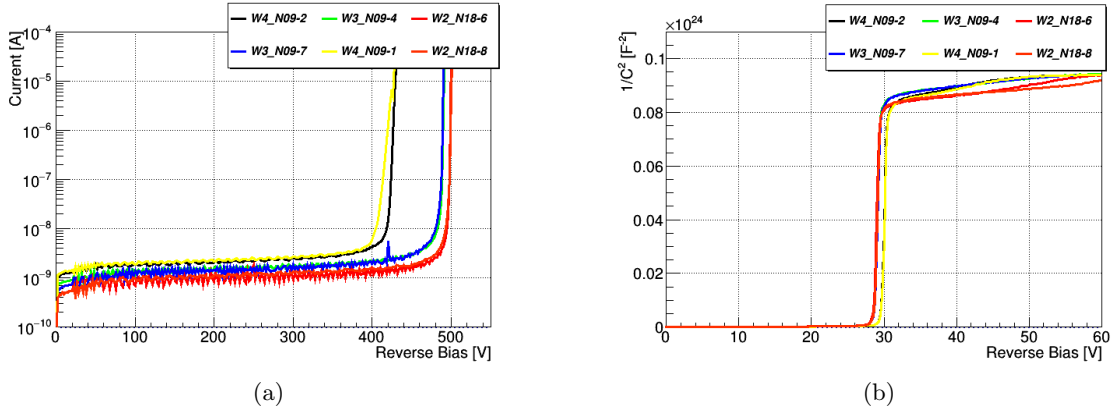


Figure 6.37: IV (a) and CV (b) curves of the unirradiated LGAD sensors on low-resistivity epitaxial wafer at room temperature.

Run	Wafer	Sensor	Dopant	Fluence [n _{eq} /cm ²]	Type	Size [mm ²]	V _{bd} [V]
13002	W4	N09-2	boron	unirradiated	-	1.3 × 1.3	~420 V
13002	W4	N09-4	boron	1×10 ¹⁴	neutron	1.3 × 1.3	~500
13002	W4	N18-1	boron	5×10 ¹⁴	neutron	1.3 × 1.3	>700
13002	W4	N18-2	boron	8×10 ¹⁴	neutron	1.3 × 1.3	>700
13002	W4	N09-3	boron	1×10 ¹⁵	neutron	1.3 × 1.3	>700
13002	W4	N18-3	boron	2×10 ¹⁵	neutron	1.3 × 1.3	>700
13002	W4	N09-6	boron	5×10 ¹⁵	neutron	1.3 × 1.3	>700
13002	W4	N09-5	boron	1×10 ¹⁶	neutron	1.3 × 1.3	>700

Table 6.7: List of sensors from CNM production run 13002 irradiated with neutrons and studied with Sr90 radioactive source at -30 °C.

The acceptor removal factor has been calculated from the behavior of the V_{gl} with the fluence, as shown in Figure 6.39. As explained in Section 6.3.2, the V_{gl} value for the unirradiated sensor were extracted from the CV measurements at room temperature, while the V_{gl} values for the irradiated sensors were extracted from the behavior of the $\frac{dI}{dV}$ as a function of voltage. Note

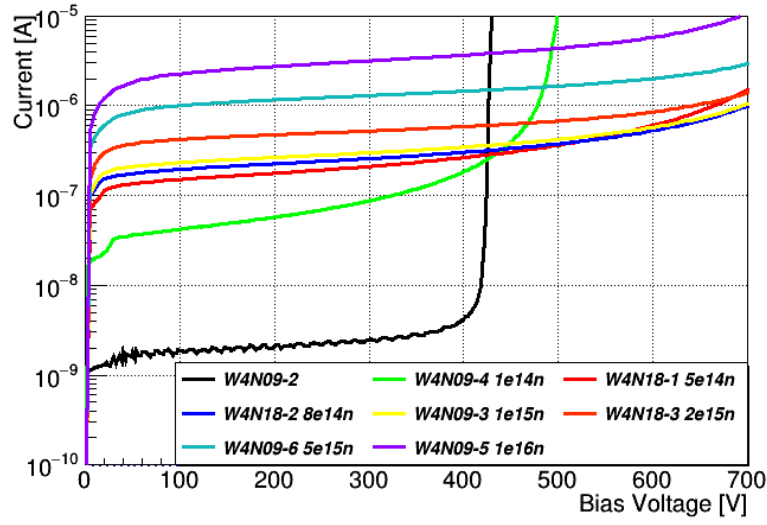


Figure 6.38: IV curves for LGAD sensors on low-resistivity epitaxial wafer before and after irradiation performed at -30°C on probe station.

that for sensors irradiated at fluences higher than $10^{15} \text{ n}_{eq}/\text{cm}^2$, it was not possible to identify the V_{gl} values since no bump was visible in $\frac{dI}{dV}$. The data points are fitted using equation 6.6, and the acceptor removal factor for the sensors on low-resistivity epitaxial wafers is found to be $C_{EPI} = 8.533 \times 10^{-16}$. This value is larger than the one calculated for Si-on-Si sensors, showing that these sensors are more sensitive to the loss of the gain with irradiation with respect to the previous ones.

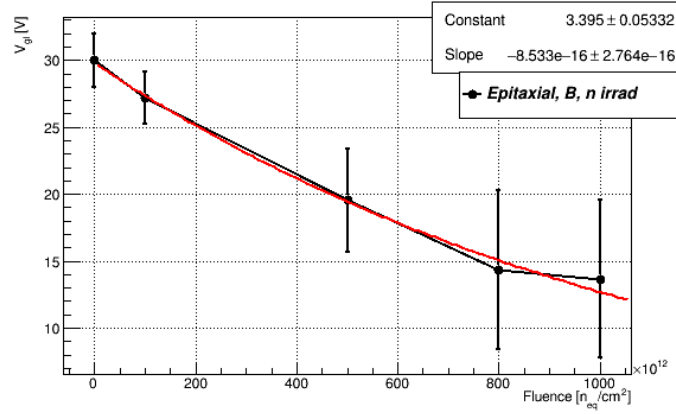


Figure 6.39: Gain layer depletion voltage as a function of the fluence for the LGAD sensors on low-resistivity epitaxial wafers.

6.4.2 Stability measurements

The rate of self triggers was studied with no external source as a function of the bias voltage for the sensors listed in Table 6.7. Results for auto-triggering measurements are shown in Figure 6.40, where a rate of triggers over 1 kHz is shown only for the unirradiated and the irradiated sensors at 10^{14} n_{eq}/cm². For the irradiated sensors at higher fluences, no auto-triggering was observed. This can be explained by the fact that these sensors were operated at relatively low bias voltages compared to the breakdown values. For safety, measurements were not performed at voltage values higher than 770 V. A threshold of 10 mV was used in these measurements. As can be seen in Figure 6.41, this is well above the noise (<2 mV) of the sensors for all the bias voltages used for data taking with a Sr90 radioactive source.

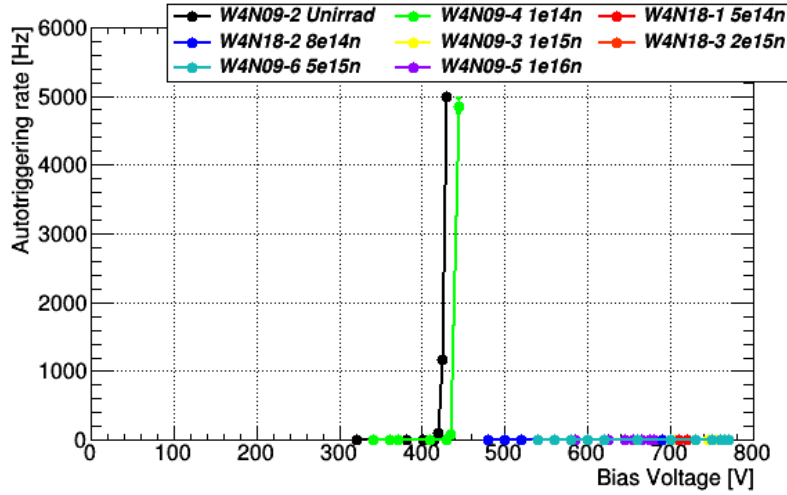


Figure 6.40: Rate of fake triggers as a function of the bias voltage for the LGAD sensors on low resistivity epitaxial wafers before and after irradiation at -30°C .

6.4.3 Measurements with Sr90 radioactive source

Measurements with Sr90 source were performed at -30°C in a dry environment. Results will be compared with those obtained for Si-on-Si sensors presented in Section 6.3. Collected charge for the sensors has been computed as explained in Section 6.1.2. Figure 6.42 shows the collected charge as a function of the bias voltage for LGAD sensors on low-resistivity

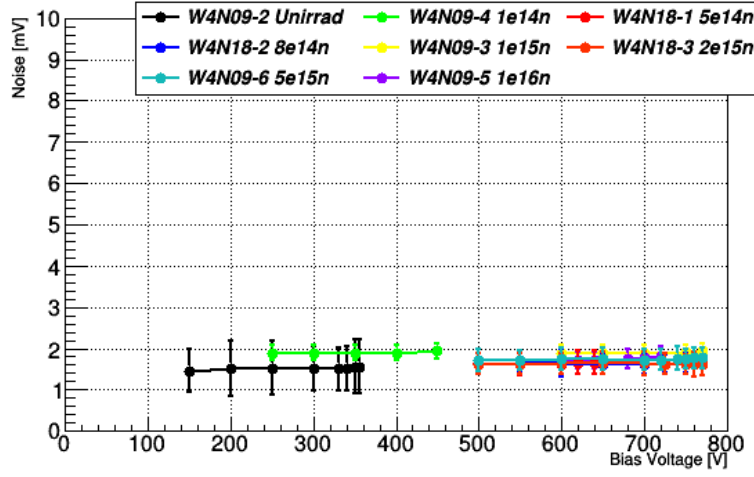


Figure 6.41: Noise as a function of the bias voltage for the LGAD sensors on low resistivity epitaxial wafers before and after irradiation at $-30\text{ }^{\circ}\text{C}$.

epitaxial wafers. The sensor irradiated at the highest fluence ($10^{16}\text{ n}_{eq}/\text{cm}^2$) does not show any gain up to 720 V, but its high leakage current (see Figure 6.38) prevented safely reaching higher voltages. The sensor irradiated at $10^{15}\text{ n}_{eq}/\text{cm}^2$ reaches a collected charge of 4 fC for bias voltages higher than 700 V. These sensors present less gain and collected charge than the Si-on-Si LGAD sensors. This is in agreement with the $\frac{dI}{dV}$ behavior shown in the previous section.

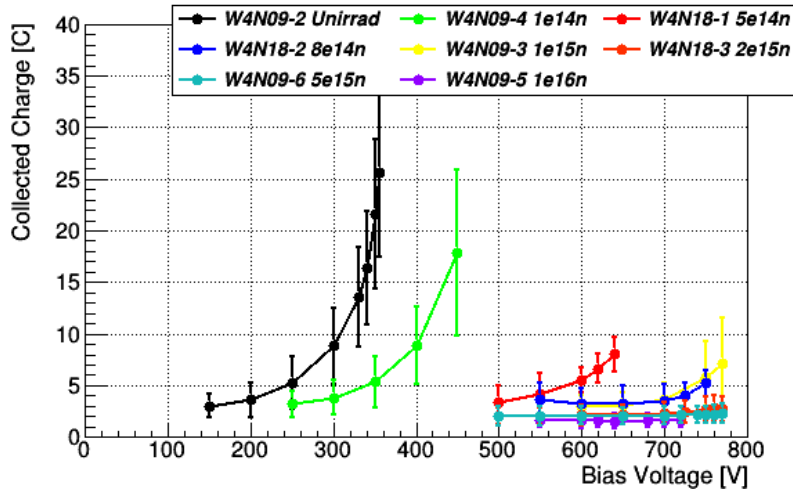


Figure 6.42: Collected charge as a function of the bias voltage for unirradiated and irradiated LGAD sensors on low-resistivity epitaxial wafers at $-30\text{ }^{\circ}\text{C}$.

The time resolution is computed as explained in Section 6.1.2, using as reference the same sensor. The optimal time resolution obtained with the CFD optimization algorithm is shown in Figure 6.43 as a function of the bias voltage. The time resolution of unirradiated and irradiated sensors feature values below 50 ps.

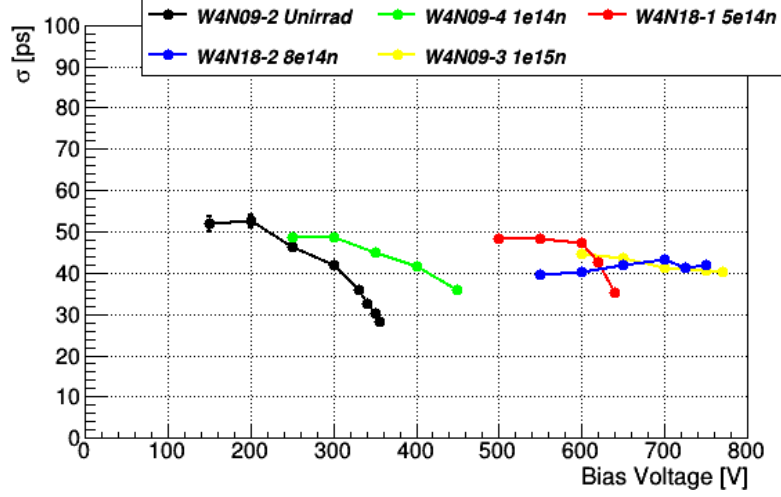


Figure 6.43: Time resolution as a function of the bias voltage for unirradiated and irradiated LGAD sensors on low-resistivity epitaxial wafers at -30°C .

6.4.4 Conclusions and comparison of results with Si-on-Si sensors

Measurements with Sr-90 source of LGAD sensors produced on low-resistivity epitaxial wafers show that the target collected charge of 4 fC can be achieved up to $10^{15} \text{ n}_{eq}/\text{cm}^2$ at 750 V, and they feature a time resolution below 50 ps. Comparing these results with the ones obtained for Si-on-Si LGAD sensors showed in Section 6.3, the Si-on-Si sensors show better performance at the same bias voltage for each fluence. In Figure 6.44, the charge collection as a function of the bias voltage is plotted for both Si-on-Si (continuous line) and epitaxial (dashed line) sensors irradiated at $10^{14} \text{ n}_{eq}/\text{cm}^2$ and $10^{15} \text{ n}_{eq}/\text{cm}^2$. From the curves, it is clear that sensors produced on low resistivity epitaxial wafer need a larger bias voltage with respect to the Si-on-Si devices to achieve the same collected charge for the same fluence. This can be explained by the difference of the wafer resistivity, since the low-resistivity of $200 \Omega \text{ cm}$ of the epitaxial wafers requires a higher bias voltage to be operated, differently to the high-resistivity wafer

of the Si-on-Si technology. On the other hand, Si-on-Si devices show marginal performances before irradiation due to the restricted operational voltage range. However, both productions present a high acceptor removal factor, which requires to push the sensor to very high voltages after irradiation to meet the HGTD requirements.

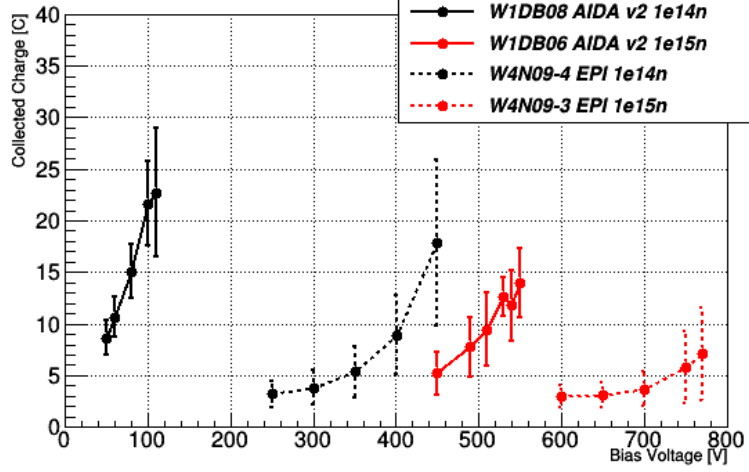


Figure 6.44: Charge collection as a function of the bias voltage for the sensors irradiated at $10^{14}n_{eq}/cm^2$ and $10^{15}n_{eq}/cm^2$ for LGAD produced both on Si-on-Si (continuous line) and low resistivity epitaxial wafer (dashed line).

6.5 Outlook

In this chapter, the performance of several CNM LGAD production runs have been presented using different experimental setups. Key properties like the collected charge, time resolution, gain and inter pad distance have been investigated. CNM LGADs with boron, gallium and boron plus carbon doping were initially studied. The results show that carbon enrichment in LGAD sensors improves the radiation hardness of the sensors with a lower effect of gain reduction due to irradiation. Carbonated LGAD sensors collect more charge with respect to the boron doped LGADs at the same bias voltage. However, sensors from this first production with carbon started auto-triggering earlier in voltage than only boron sensors, not showing clear benefits with respect to carbonated sensors from other manufacturers. The gallium

research line has not been pursued since the replacement of boron does not show clear benefits from results for testbeam, TCT and Sr90 measurements.

Secondly, results from the AIDA2020v2 boron-doped Si-on-Si sensors have been shown. These sensors reach the HGTD target collected charge of 4 fC and a time resolution of 35 ps for bias voltages higher than 680 V at a fluence of $2.5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. However, the early breakdown voltage limits the performance of the device before irradiation. In any case, the acceptor removal factor is relatively high and the gain loss with irradiation is not optimal compared to other sensors from other vendors (such for carbonated LGAD sensors from FBK and IME [94]).

A way for CNM to investigate possible improvements on the Si-on-Si technology shown in Section 6.3 would be to decrease the dose of boron doping, using an intermediate value between the one of the AIDAv2 production run 12916 and the old production run 10478 (shown in Section 6.2). This would avoid the problem of the high rate of self triggers for the unirradiated sensors, and consequently allow a more stable operation at cold temperatures. In addition, carbon enrichment on this technology together with the optimization of the doping process would help lowering the bias voltage required to meet the HGTD requirements by reaching a better acceptor removal factor.

Lastly, it was interesting to study LGAD sensors produced on low-resistivity epitaxial wafers for its lower cost with respect to the Si-on-Si ones and wafer availability. Those sensors could yield good results, but their low-resistivity ($200 \Omega \text{ cm}$) requires a higher voltage to be operated in order to maintain the performance. Results for LGAD sensors produced on low resistivity epitaxial wafers are shown for measurements with Sr90 radioactive source, but the large operational range of epitaxial LGADs compared to that of the Si-on-Si LGADs does not show clear benefits. The target collected charge and time resolution can be reached only at 700 V of a fluence of $10^{15} \text{ n}_{eq}/\text{cm}^2$, after which no more gain is visible. A new production of LGAD sensors from CNM produced on low-resistivity epitaxial wafers with carbon implantation in a few wafer has been irradiated with neutrons and is being tested to study eventual improvements on carbon implantation on this wafer technology. First

tests on unirradiated devices shows that carbonated epitaxial LGAD sensors requires a lower voltage to achieve the required collected charge compared to the one presented in this thesis. First tests conducted in Ljubljana for irradiated sensors show an acceptor removal factor of $C_{CarbonatedEPI} = 4.9 \times 10^{-16}$ which is clearly in the correct direction, but not yet as good as the one for IME devices, for which $C_{IME} \sim 1 \times 10^{-16}$ [100] (CNM sensors are still short of carbon).

The HGTD community decided to use carbon enriched LGAD sensors to instrument the HGTD detector, since the presence of carbon reduces the operational voltage at high fluence to meet the HGTD requirements for charge collected and time resolution, avoiding the failures caused by particles at very high electric field, called SEB.

Single Event Burnout failure investigation

The SEB is a process through which the sensor dies with a typical burn mark pattern in the presence of an high electric field ($E > 12 \text{ V}/\mu\text{m}$). This conditions appears only in test beams, where measurements are more problematic, even for sensors which were performing in the lab with Sr-90 sources till 700 V. The hypothesis for the death is that the electric field collapses in the presence of high concentration of free carries. There is a large charge deposition (step 1 in Figure 6.45) in few μm (which is not possible with laboratory measurements) and a large carries density leads the field to collapse (step 2 in Figure 6.45). Once this happens, the high voltage is brought closer to the pad leading a very high field strength and to avalanche breakdown that causes a full discharge of the sensor (step 3 in Figure 6.45). A single particle is responsible for the death of the sensor, with a star shaped crater (see Figure 6.46) appearing in correspondence of the passing particle on the sensor surface if enough energy is stored (step 4 in Figure 6.45).

Figure 6.47 shows how the particle responsible for sensor death is identified, and the corresponding mark on the sensors surface. The problem was not related to any specific producer or test beam facility, since it was observed both in HPK and CNM LGADs and for both DESY

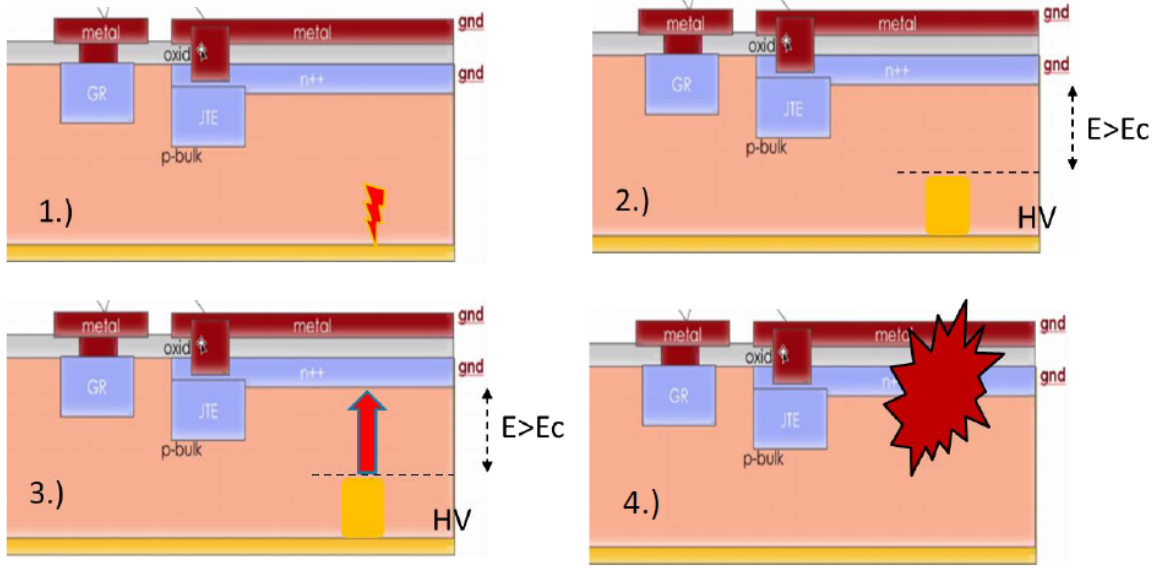
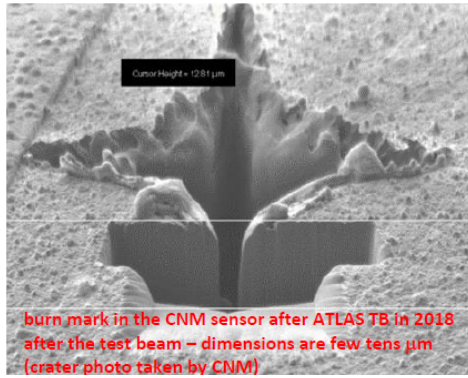
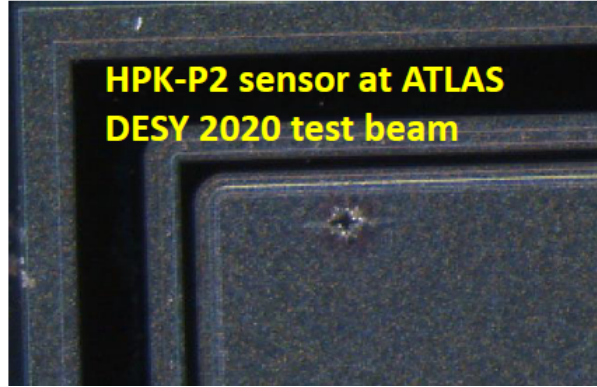


Figure 6.45: Sketch of the steps described for the hypothesis of the Single Event Burnout.

and SPS test beams. During the last years, as common effort between ATLAS, CMS and the RD50 collaborations, the SEB process has been systematically studied. From these studies, it has been seen that craters were appearing at different places over the sensor surface and after that the device was in short and not operational anymore. Through test beam campaigns dedicated to the study of the SEB, it has been understood that the thickness of the sensors can have an effect, with a critical region defined for an electric field $> 12 \text{ V}/\mu\text{m}$ (see Figure 6.48). However, this does not depend from the fluence, the gain or the bulk damage. The presence of carbon in the gain layer helps to avoid this failure since a lower voltage is required ($\sim 550 \text{ V}$) for the sensor to meet the HGTD requirements for charge and time resolution.



(a)



(b)

Figure 6.46: Single Event Burnout marks for a (a) CNM sensor after a test beam with 120 GeV pions at CERN, and for a (b) HPK sensor after a testbeam with 5 GeV at DESY [94].

ATLAS HGTD Preliminary

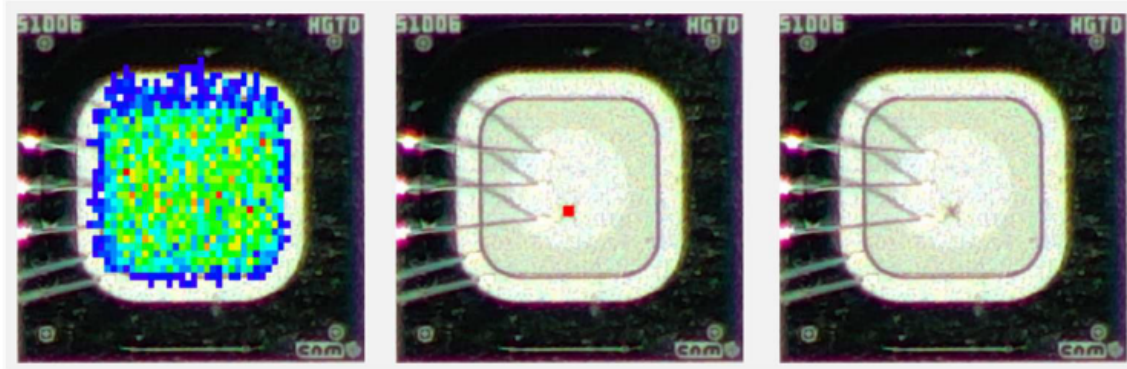


Figure 6.47: On the left, 2D map of reconstructed tracks in correspondence of the sensor surface. At the center the last event recorded for the sensor with the track responsible for the sensor death and on the right a picture of the sensor with the star-shaped crater in correspondence of the particle responsible for the death [101].

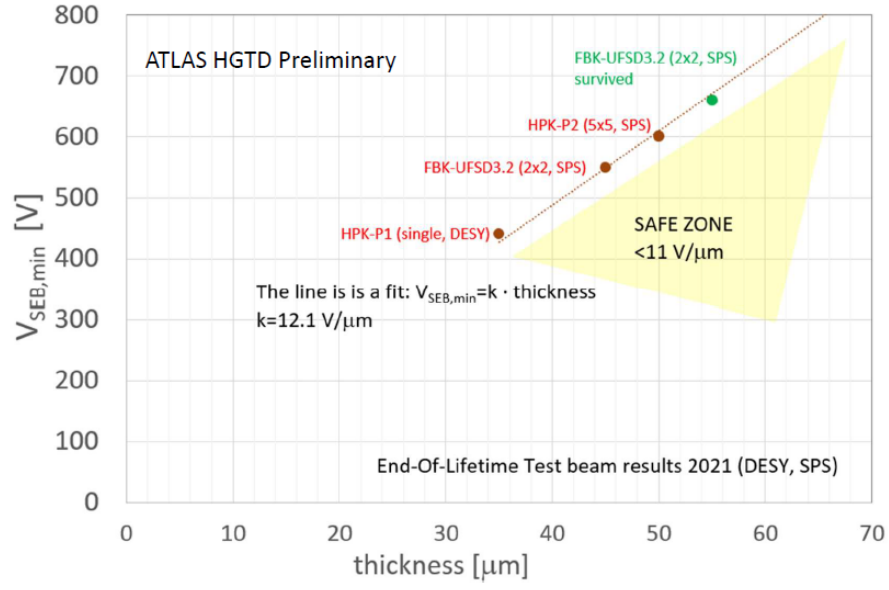


Figure 6.48: Single Event Burnout voltage dependence on sensor thickness. The minimum V_{SEB} at which SEB was observed after several 10^6 particles/pad for each thickness in 2021 HGTD End-Of-Lifetime test beams is shown. About 80 sensors (single-pad, 2×2 , 5×5 arrays) were tested. Note that 55 μm -thick device survived at indicated voltage. The line fit to the points results in critical average electric field of 12.1 V/ μm where SEB occur. The safe zone of 11 V/ μm where no SEB was ever observed is indicated in yellow [101].

Conclusions and Outlook

The HL-LHC presents a challenge to the ATLAS and CMS experiments due to the increase in radiation damage and pileup. ATLAS is upgrading its detectors to more radiation hard technologies to face the high luminosity era. The new tracker, the ITk, is expected to maintain, or improve, the performance of the detector despite the luminosity increase. However, in the forward region the expected position resolution of the tracker is not enough to disentangle the pileup tracks from the ones originating in the primary vertex. Thus, ATLAS will install the HGTD in the $2.4 < |\eta| < 4.0$ region that will provide 30 ps to 50 ps track time resolution. The HGTD is based on LGAD sensors. The first productions of LGAD sensors towards the HGTD at CNM were fully characterized in the context of this thesis.

The timing information provided by the HGTD will be used mainly to identify pileup tracks (which originate at a different time window). This feature of HGTD will improve the overall physics performance of ATLAS. In this thesis, the impact of the HGTD in the identification of the process $H \rightarrow \tau\tau$ was studied. The main background of this signal is $Z \rightarrow \tau\tau + jets$. Since a Monte Carlo sample of the signal ($H \rightarrow \tau\tau$) is not available, the effect on the background suppression was studied comparing the impact of the “ITk only” scenario versus the pileup suppression using HGTD. The time information of a jet is obtained from the time of the tracks in the jet and if the clustered time is sufficiently different ($\pm 1.5\sigma$ away) from the event t_0 (time of the hard scattered) then the jet is tagged as pileup. This process results in the removal of about 2.4 more pileup tracks than using the ITk information alone. Of course, it is important to know the detrimental effect that this may have on the hard-scattered tracks.

For this, the Monte Carlo simulation of the signal is needed.

The core of this thesis is the study of the LGAD sensors produced at CNM. The LGAD technology was originally developed for tracking at CNM and later identified as a potential solution for timing in HEP. The LGAD sensors rely on a multiplication layer that provide low (~ 10) gain which results in an enhanced timing performance. However, early on, one of the problems that was identified was the fact that the multiplication layer would degrade after irradiation, though the acceptor removal effects that affects the p-type multiplication layer. In order to maintain the multiplication layer after irradiation different doping materials were investigated.

In this thesis the first set of devices produced in 2017 at CNM on 100 mm Si-on-Si wafers with different dopants and materials in the multiplication layer (boron, boron plus carbon and gallium) were fully investigated before and after irradiation with protons and neutrons. Laboratory measurements with a Sr90 source show that boron and boron plus carbon sensors perform similarly in terms of charge collection and time resolution before and after irradiation. At the same bias voltage, carbon-infused devices tend to collect more charge, diminishing the effect of the gain reduction after irradiation with respect to the boron devices. However, they start to auto-trigger earlier in voltage and are not operable at high voltages. TCT results show that gallium devices collect less charge than boron sensors at the same bias voltage, and that the proton irradiation results in a larger reduction of the multiplication layer compared to irradiation with neutrons. Gallium LGAD sensors were irradiated up to $3 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. Though the sensor could reach the HGTD target collected charge, a very high voltage was needed (about 700 V). Furthermore, gallium devices have 20% less gain than boron sensors. Thus, gallium devices were not further investigated. Results from TCT and measurements with a Sr90 radioactive source are in agreement. However, the LGAD boron-doped devices required a large bias voltage to operate after irradiation.

In 2019, LGADs on Si-on-Si wafers with Boron in the multiplication layer were produced at CNM. In order to improve the performance with respect to the previous production, the multiplication layer doping dose was increased. This resulted in sensors with low breakdown

voltage before irradiation at cold temperature, in which the timing performance was poor (~ 50 ps) because of this. However, after irradiation the sensor did provide the HGTD target charge at 680 V. This voltage is, nevertheless, too high to ensure good sensor operation with high energy particles due to the discharge through the bulk that destroys the device (“single event burnout”).

TCT measurements were carried on the 2019 2×2 LGAD arrays in order to study the behavior of the inter-pad distance with respect to the fluence and bias voltage. A set of sensors irradiated at different fluences from 10^{14} n_{eq}/cm^2 to 2.5×10^{15} n_{eq}/cm^2 were measured with an IR laser and the behavior of the inter pad distance was studied. Results show two different behaviors. At low fluences, part of the carries which are generated underneath the gain layer drift to the JTE and don’t produce charge multiplication. The effect is translated into a larger inter pad distance, which is reduced with the increasing of the bias voltage. At high fluences, the effect is the opposite: some multiplication is achieved by the carriers drifting to the JTE and smaller distances are measured. These results are compatible with those from other vendors and are verified by simulation.

The last production included in this thesis is from 2020. The LGADs were fabricated in a 150 mm epitaxial wafers (which are less expensive than Si-on-Si). The sensors showed insufficient gain even before irradiation. The timing measurements using Sr90 sources showed that a time resolution of about 40 ps could be achieved at 750 V for devices irradiated up to 10^{15} n_{eq}/cm^2 . This is far from the needed performance by HGTD.

In summary, though CNM is the original developer of the LGAD technology, the various CNM sensors included in this thesis fail to satisfy the HGTD requirements in terms of time resolution at moderate bias voltage after irradiation (to avoid irreversible damage when operated under realistic conditions). While CNM was also the first site to produce boron plus carbon sensors, they showed only marginal improvements compared to boron-only devices. Other fabrication sites (like FBK and IHEP-IME) produced LGADs with boron plus carbon that showed large improve results over the boron-only devices meaning they provided the charge required by HGTD at a moderate bias voltage (~ 500 V). Their acceptor removal constant is $C \sim 1 - 2 \times$

10^{16} . The poor results of the first carbon infused sensors from CNM is now understood. The carbon was infused early on the wafer during the sensor production and it is very likely that it diffused deeper into the bulk, away from the multiplication layer. CNM recently produced another batch of LGAD sensors on 150 mm epitaxial wafers with boron plus carbon that are being tested. The acceptor removal factor, which was $C_{AIDA} = 7.26 \times 10^{-16}$ for sensors on Si-on-Si wafers presented in Section 6.3 and $C_{EPI} = 8.533 \times 10^{-16}$ for sensors on epitaxial wafers presented in Section 6.4, improved to $C_{CarbonatedEPI} = 4.9 \times 10^{-16}$ for carbon enriched sensors on epitaxial wafers. However, the target for the HGTD is about $\sim 1 - 2 \times 10^{-16}$ [100].

In the coming year, a new production of CNM LGAD sensors on Si-on-Si high-resistivity wafers will be produced. It will consist of ten wafers all with carbon enrichment in different doses, but the gain layer characteristics are still to be defined. This production run will benefit from all the lesson learned during the past years especially in the carbon implantation process.

Appendix A

Transient Current Technique

In the high energy physics community the characterization of sensors is usually carried out through radioactive source and test beams measurements. The first one has the advantage that can be carried out in the laboratory in a table-top set up, but the low-energy radiation is emitted in a large angle, and even if it is collimated does not provide a good position resolution. The second one has the advantage of providing a good position resolution for mip when combined with a telescope for track reconstruction. Although, this kind of measurement can be performed for a limited time and in a limited number of facilities.

The TCT consists in the measurement of time-resolved current waveforms induced by the drift of charges inside a sensor. The current is proportional to the number of charges, their drift velocity and the weighting field of the readout electrode following the Shockley-Ramo theorem:

$$i(t) = q \vec{v}_{drift} \cdot \vec{E}_W \quad (\text{A.1})$$

where q is the moving charge, $\vec{v}_{drift}$ is the free electrons drift velocity and $\vec{E}_W$ is the weighting field of the readout electrode. From the analysis of the recorded waveforms, different detector properties can be extracted.

The Transient Current Technique (TCT) gives the opportunity to perform measurements with good position resolution ($\leq 10 \mu\text{m}$). The signal is generated by low energy photons which do

not ionize along their path, in contrast to what happens with charged particles, but penetrate the sensors until they are eventually absorbed. The probability of photons to be absorbed is related to the detector material and photon wavelength. To mimic the behaviour of charged particles the pulsed laser is used to illuminate the sensor with a large number of photons in a short time interval. The TCT setup available at the IFAE Pixel group laboratory is shown in Figure A.1. The minimal TCT setup consists of a laser source, an optical system to focus the laser beam, a current amplifier and a waveform digitizer.

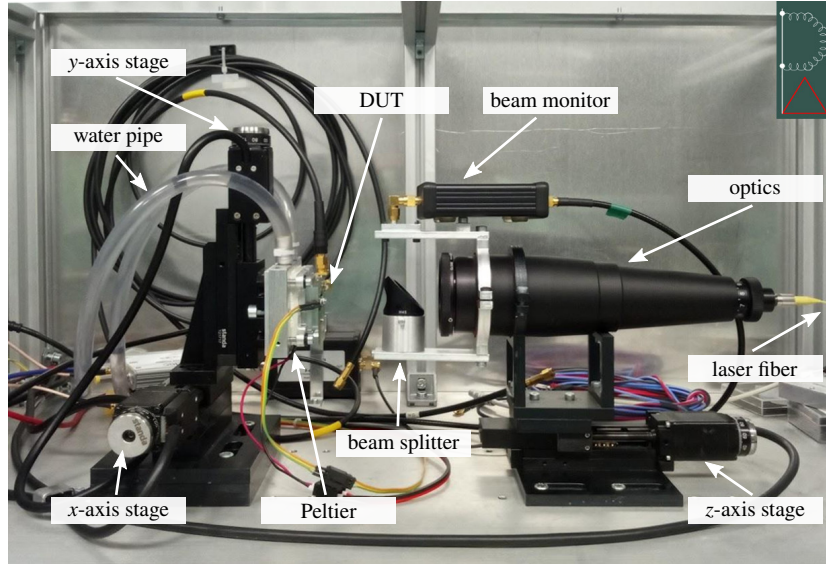


Figure A.1: Transient current technique setup at IFAE.

Laser Sources

Two different laser sources are available at IFAE. An IR source with a wavelength of 1064 nm and a red one with a wavelength of 660 nm. The absorption depth, that is the distance after which the number of photons is reduced by a factor $1/e$, in silicon is about 1 mm for the IR light and about $3\mu\text{m}$ for red light [102].

The red laser creates electron-hole pairs only on the proximity of the surface behaving as an α -particle that is immediately stopped. On the other hand, the IR laser can be compared to a mip. Since the typical thickness of the silicon detectors used as DUT is between 50 and

300 μm , the intensity drop within the detector can be neglected, being the ionization uniform along the full thickness.

The duration and repetition rate of the laser pulses can be adjusted through a control software. The repetition rate is usually set to 500 Hz, while the duration is set to the minimum achievable value of 440 ps. The laser intensity is set through a Digital to Analog Converter (DAC) parameter called “pulse width”. The intensity is larger when the pulse width is lower. At the start up, this value is set to 2%, while for data acquisition should be larger than 60%.

The laser source is coupled with an optical fiber that is plugged into an optical system providing a beam spot of 8-10 μm . The laser sources also provide an electric signal synchronous to the laser pulse to trigger the readout system.

Amplifiers

Two pairs of broadband current amplifiers optimized for TCT measurements are available at IFAE. A pair of Particulars AM-02 amplifiers [79] with a gain of 53 dB and a bandwidth of 2 GHz with a low band cutoff frequency of 10 kHz and a pair of CIVIDEC C2-TCT amplifiers [103] operating in the same frequency band with a gain of 40 dB. The current input/output ratio can be obtained through the formula $G_{db} = 20 \log_{10}(I_{Out}/I_{In})$, resulting in an amplification factor of 100 for the CIVIDEC amplifiers and about 450 for the Particulars. Usually, the CIVIDEC amplifiers are preferred because of the lower noise.

Bias-T

The Bias-T element gives the possibility to connect an amplifier to the high voltage contact of the detector. It decouples the high voltage needed to bias the detector from the low voltage input of the amplifier. It is an essential part of any TCT system where both contacts, grounded and high voltage one, are read at the same time. Particulars Bias-T offers wide bandwidth with almost no pulse distortion and can tolerate high voltages of up to 2 kV (depending on

its version). Biasing a detector through Bias-T is many cases the only option. In particular, when the setup requires the backside of the detector to be connected to ground.

Waveform Digitizer

After being amplified the signals are digitized to be recorded in the DAQ PC. The digitizer used is a 4-channel DRS4 Evaluation Board [81] with 700 MHz analog bandwidth, a sampling rate of 5 GSPS for a 200 ns sampling depth. The fourth channel is usually connected to the laser head output signal synchronous to the laser pulse that is used for triggering purpose.

Movable Stages

Three single axis Standa motorized translational stages [104] allow to remotely control the DUT and the focus position. The focusing lens system is mounted on one of the stages, with the stage moving axis aligned with the laser beam direction in order to move forward or backward the focus position. The other two stages are mounted orthogonally to each other and to the beam axis. They hold the mounting plate that hosts the DUT and the Peltier element. The stages have a position resolution better than 1 μm , so that the pointing resolution of the TCT setup is given by the laser spot focus size.

Cooling System

As mentioned, the DUT can be cooled through a Peltier element placed on the backside of the mounting plate. The Peltier has a cooling power of 40 W, able to cool down at temperatures about 40 °C lower than the ambient. To operate the sensor at low temperature dry air is flushed into the TCT box to ensure the dew point temperature is lower than the coldest part of the setup. The cooling system is completed by a circulating water chiller used to cool down the warm side of the Peltier element.

Data Acquisition System

The Particulars scanning TCT is provided of two LabView software programs that allow to control the different components of the setup and store the digitized data. A laser controller is dedicated to the control of the laser source, switching it on and off, and adjusting the laser properties, such as beam intensity, pulse duration and repetition rate. The DAQ software is used to control the other elements of the setup: the three movable stages, the waveform digitizer and up to two power supplies. The only component that is not controlled remotely is the Peltier element that have to be set manually.

The DAQ system can control different models of movable stages, waveform digitizers and power supplies. In the IFAE TCT setup these are the Standa stages, DRS4 evaluation board and a Keithley 2100 high voltage power supply.

The signal-over-noise ratio is usually low and an average of about 100 waveforms is performed to suppress the stochastic noise and enhance the signal. In Figure A.3, an example of a single waveform (a) compared with the average of 100 waveforms (b) is shown. For highly irradiated devices, usually an higher number to compute the average is chosen.

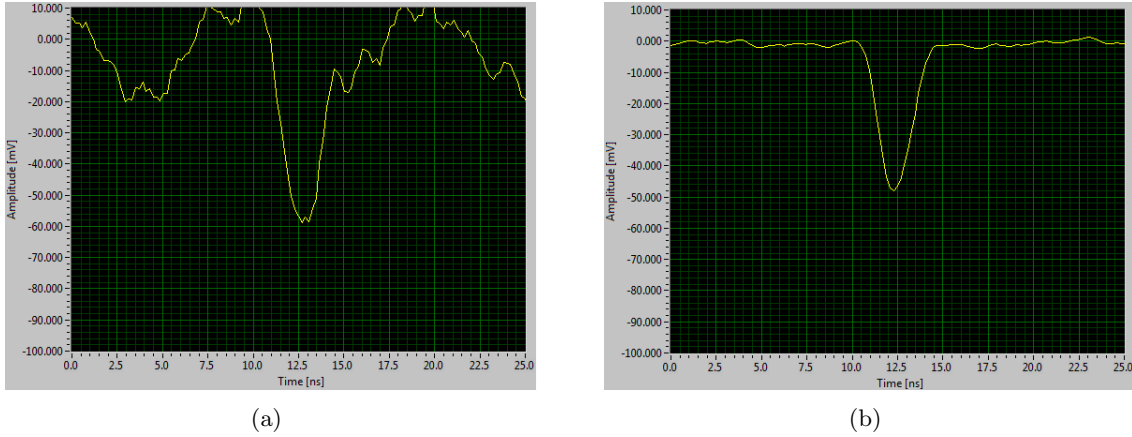


Figure A.2: TCT signal over a 50 μm -thick PIN diode illuminated with IR laser pulses. A single waveform (a) and an average of 100 waveforms (b) are shown.

The system can be set to perform scans over any of the stages and power supplies. For each voltage and position value, a waveform for each of the enables channel of the DRS4 is stored,

together with the current variation read by the power supply at each bias voltage.

Scanning TCT operations

The DUT can be mounted in several ways with the help of specific supports: facing the beam with the top surface (Top-TCT), with the backside (Back-TCT) or with the edge (Edge-TCT). With each of the listed configuration different sensor properties can be investigated. For example, with red light charges are generated close to the illuminated surface, this means that only the charges collected by the electrode at the opposite side contribute to the signal. By using Top or Back-TCT configurations it can be chosen to study the contribution of holes and electrons separately. Edge-TCT is usually used to study the evolution of the depletion depth since shooting the laser from a lateral side of the sensor all the charges are generated at the same distance from the surface, if this is larger than the depletion depth the charges will not contribute to the signal.

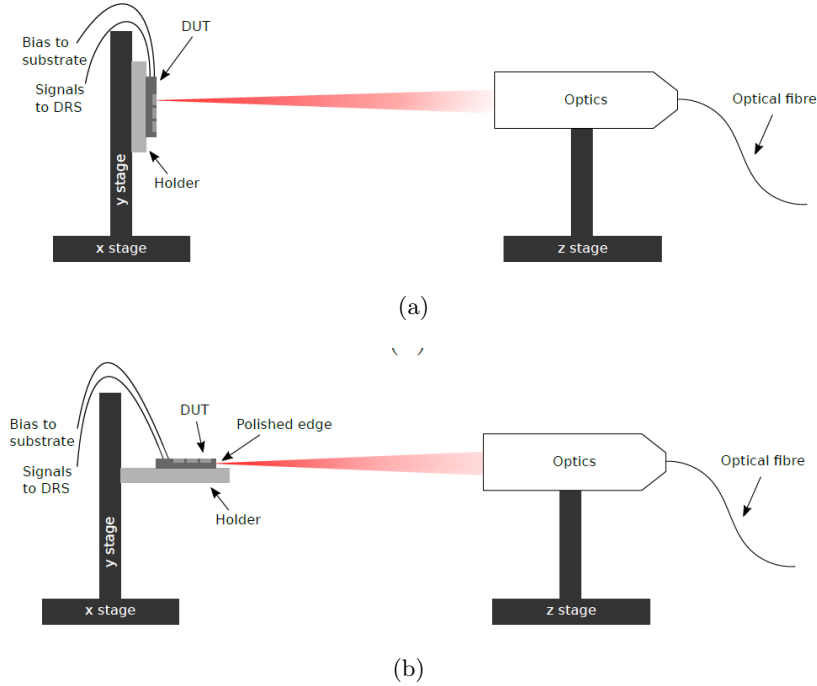


Figure A.3: Sketch of the Top- (a) and Edge- (b) TCT setup configurations.

In this thesis the IFAE TCT setup has been used to perform gain and inter pad distance mea-

surements with Back-TCT configuration on CNM LGAD sensors before and after irradiation as shown in Sections 6.2.4 and 6.3.4 respectively.

Appendix B

Setup and Data Acquisition software for measurements with a radioactive source

In this appendix, an overview of the setup and the Timing Control Automation Software (TiCAS) DAQ system for Sr90 source measurements will be given.

One of the most common ways in the high energy physics community is to use a radioactive source for testing the response of sensors to particles in the laboratory. The main two properties under study with this setup are the collected charge and the time resolution at different bias voltages.

The setup for measurements with a Sr90 source at the IFAE laboratory, as shown in Figure B.1, is made of:

- a low voltage power supply ¹
- two high voltage power supplies ²

¹Rohde & Swartz HMP4040 Programmable power supply 384 W

²Keithley 2410 1100 V Sourcemeter

- a climate chamber ³
- an oscilloscope ⁴

The setup is controlled through a LabView software which allows to control all the setup components remotely, with the only exception of the dry air, that have to be open and close manually. As shown in Figure B.1, the DUT and the reference sensor are mounted back-to-back on a metal support where the source container can also be placed.

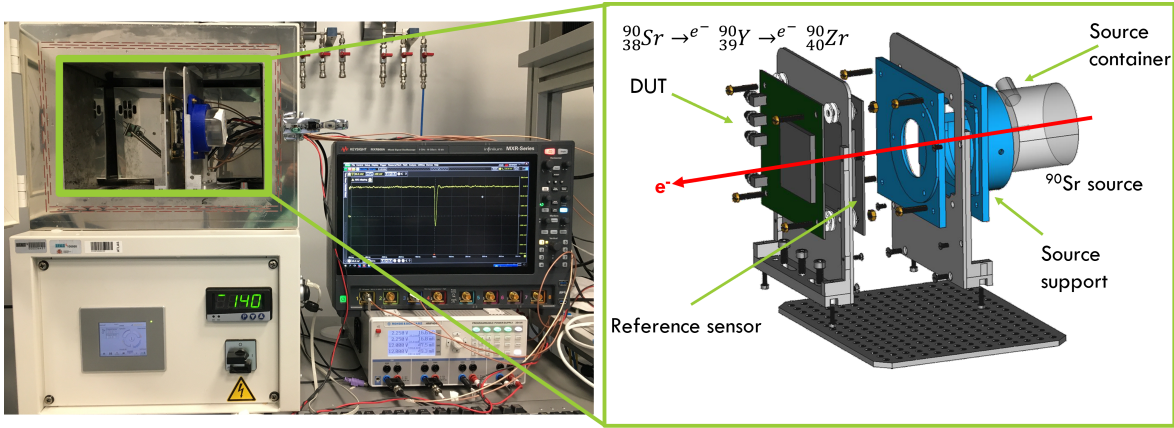


Figure B.1: Setup for the measurements with the Sr90 source. On the left picture the climate chamber, low voltage power supply and oscilloscope are visible. The reference sensor and the DUT are mounted back-to-back on a metal support together with a second support holding the radioactive source. On the oscilloscope screen a typical LGAD signal is shown. Two high voltage power supply (not shown in the picture) are used to bias the sensors.

Data Acquisition System

A first panel, shown in Figure B.2 (a), controls the low voltage power supply and the climate chamber. The 2.25 V for the board is provided together with the 12 V needed for the second-stage amplifiers (external to the readout board). Different types of power supplies and climate chamber are compatible with this DAQ system.

In Figure B.2 (b) the high voltage panel is shown. Also for this feature, several high voltage sources can be used. The compliance level for the current can be set for each of the two

³VOTSCH VT 4002

⁴Keysight model DSO9404A

sources, as well as the desired bias voltage and the number of steps. At the bottom of the panel a preview of the voltage and current behaviors with respect to the time is shown.

The oscilloscope dedicated panel is shown in Figure B.2 (c). Several settings for each of the four oscilloscope channels can be changed, such as the vertical range and offset and the coupling. In the bottom part, it includes a trigger panel which can be enabled in coincidence or edge trigger mode. The first is used for coincidence measurements between two sensors with a radioactive source to study properties such as charge collection and time resolution. The latter is used for measurements of the self triggers without an external source of particle for only one sensor at time. In the case of coincidence trigger the threshold, the channels which contributes to the trigger and the logic state can be settled. For the edge trigger, once a channel is chosen, is possible to set the threshold, the edge and the coupling. In the last Figure B.2 (d) the preview panel of the scope is visible with the noise signals coming from two sensors, in the plot referred as Reference and DUT.

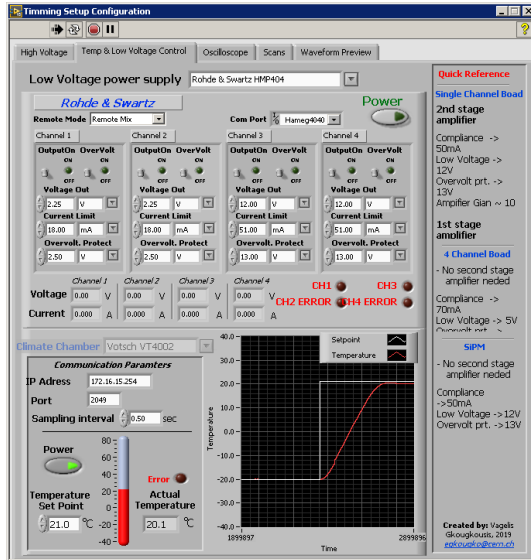
Scan DAQ panel

The DAQ system described here is completed by a scan panel that allows to perform measurements of the self trigger without an external source of particles, see Figure B.3 (a), or coincidence measurements between the DUT and reference sensors, See Figure B.3 (b).

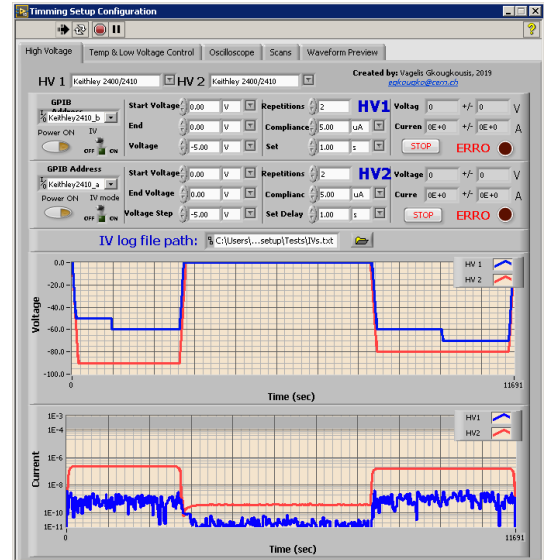
To perform auto-triggering measurements, a maximum value for the DUT sensor bias voltage is given. This corresponds to the HV 1 of Figure B.2 (b). In the oscilloscope panel, the edge trigger is enabled and the required information that are oscilloscope channel, threshold and slope are settled. In the auto-triggering panel, the temperatures at which one wants to perform measurements is settled and the information will be automatically given to the climate chamber control panel of Figure B.2 (a). Once press START, the low voltage is turned on and the temperature starts to go down to the desired one. Once the temperature is stable, the high voltage on the sensor is turned on at a value below the maximum and the number of self triggers at each bias voltage starts to be counted. If no self triggers are registered

after 2 minutes the bias voltage is raised and next data point will be collected. If less than 500 self triggers events are registered after 2 minutes, the system continues counting till a maximum of 15 minutes, after which the bias voltage will be raised in any case. Results from this measurements will be shown in the dedicated area at the bottom of the panel as can be seen from Figure B.3 and stored in a .txt file.

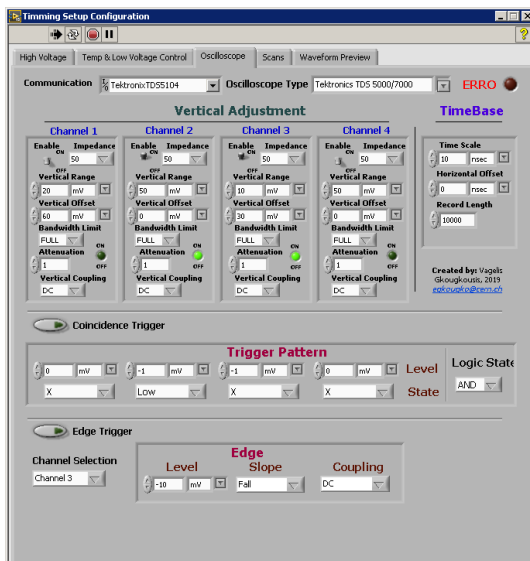
To perform coincidence measurements with a Sr-90 source, the top panel evidenced in Figure B.3 (b) is used. As before, the temperatures at which one wants to perform the measurements are given and information will be automatically given to the climate chamber. For each temperature, a line will appear where the bias voltage values for the DUT and reference sensors can be listed. Usually, 5000 events per bias voltage point are stored. This number can be set in the left side of the panel. Both the overall and the current point progress are shown on the right side of the panel. Eventually, error messages will be stored in the dedicated box. Once press START, the low voltage is turned on and the cooling system starts working till the desired temperature. After the temperature is stable, high voltage will be automatically turned on for both sensors and then coincidence starts to be registered. Waveforms data are stored as ASCII files for each of the devices in folders divided for each temperature and each bias voltage. These can be converted to ROOT ntuples and then analyzed with the LGADUtils [77] framework described in Appendix C.



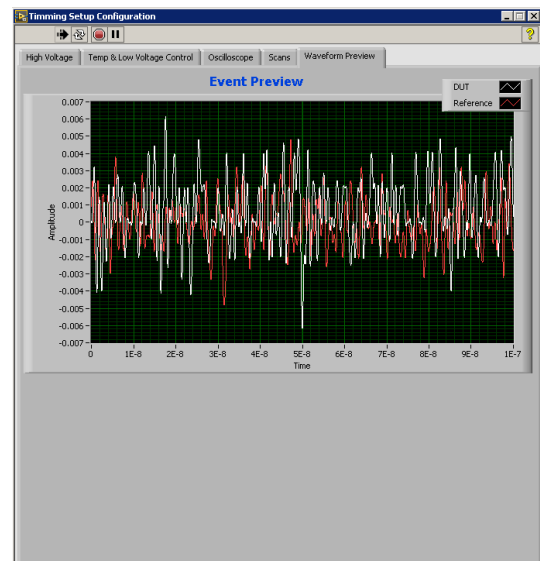
(a)



(b)

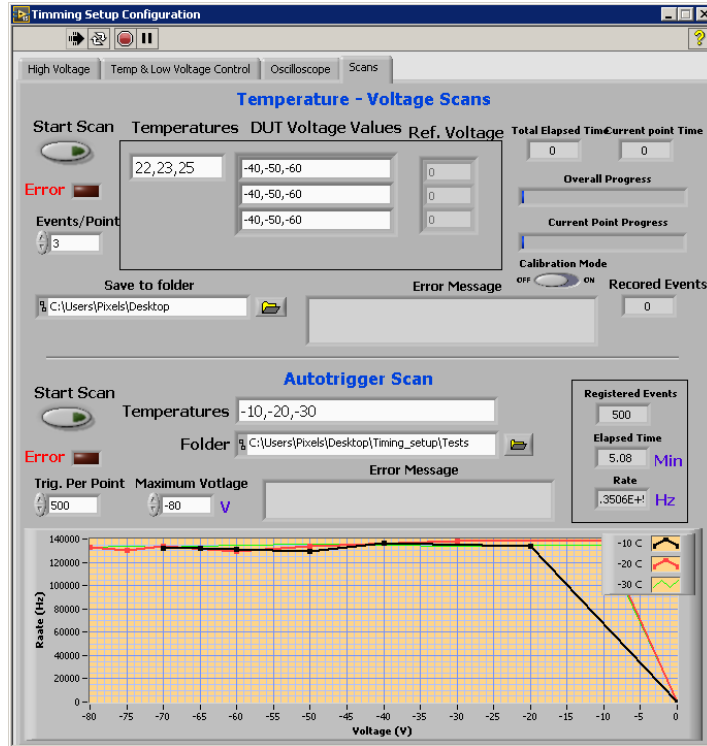


(c)

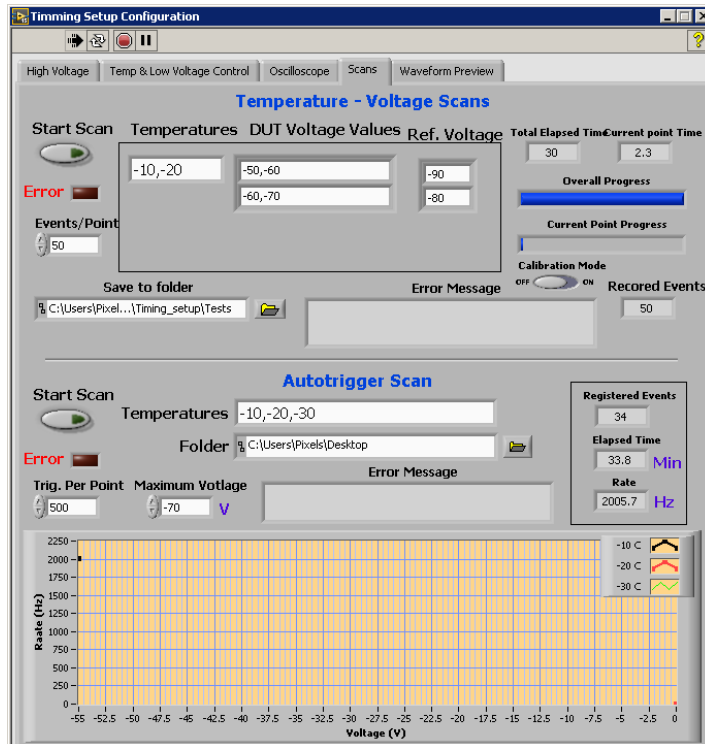


(d)

Figure B.2: Data acquisition low voltage and temperature panel (a), high voltage panel (b), oscilloscope panel (c) and an example of oscilloscope preview (d).



(a)



(b)

Figure B.3: Scan panel where auto-triggering (a) and coincidence (b) measurement settings.

Appendix C

LGADUtils framework for data analysis

In this appendix, an overview of the LGADUtils framework [77] will be given. This framework has been developed at IFAE by the ATLAS Pixel group and has been used in the work presented in this document for data analysis of Sr-90 radioactive source and beam test measurements. LGADUtils is a waveform data analysis framework written in C++, which can be used for both laboratory and test beam measurements. This framework has been developed together with the data acquisition software TiCAS, explained in Appendix B.

Oscilloscope ASCII (laboratory) or binary (test beam) files are converted into a ROOT ntuple containing the waveform information stored event-by-event for each of the channels where a DUT is connected (for laboratory measurements usually two). Then, in a second step, the data are analyzed and information for each channel, such as collected charge, rise time and other properties and all the histograms are saved into a ROOT ntuple.

Logic structure

The logical structure is organized in four main classes with dedicated header and implementation files, plus one wrapper class handling user interaction:

- **LGADUtils** is a class containing the basic framework function and infrastructure
- **LGADRun** is dedicated to the multi DUT operations, computing of the CFD maps and timing resolution calculation
- **DUTChannel** is used to calculate mean pulse shape and its properties for the entire run
- **WaveForm** calculates properties for each waveform and is responsible of time walk correction
- **LGADBase** is the wrapper to handle user input-output and pass arguments

A schematic view of the logic is given in Figure C.1. In addition, a **LGADSel** selector class with auto-set 64 channel support is given. This is a wrapper for setting pointers, branch address, understanding how many active channels are present and doing the necessary mapping. In this class, all required pointers and branches are stored for the several instruments and cases. This is necessary since this framework can be used for both laboratory and test beam data (different cases) and with different types of oscilloscope for waveform acquisition (different instruments). The instrument number is given in the user interface when launching data analysis and LGADSel will automatically detect the appropriate conversion function.

Waveform class

The WaveForm class is the core of the framework. In this class, all the waveform properties are computed on an event-by-event basis.

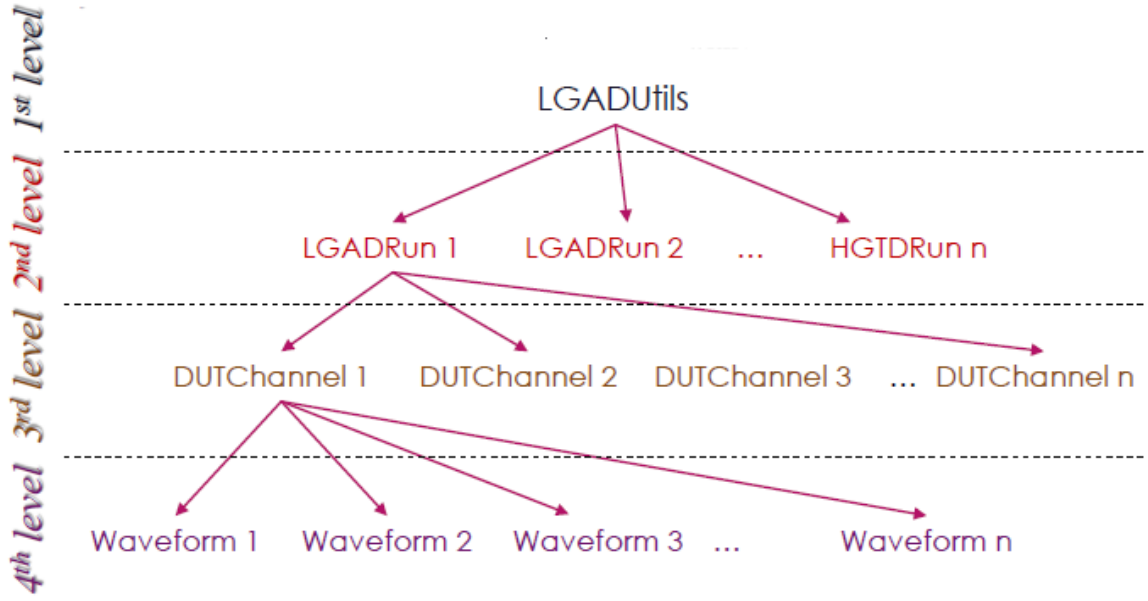


Figure C.1: Logic structure of the LGADUtils framework.

First, the polarity of the pulse is determined and its start and stop points are found. In a second step, it is important to determine if the waveform under study is a noise signal or if the pulse is within the acquisition window. In order to determine the pulse polarity, the first and second derivative are calculated for each waveform. For the first derivative, the zero crossing point is found and at this point the sign of the second derivative is determined. If this sign is negative, the zero crossing point is a local maximum, otherwise is a local minimum. This means in the first case there is a positive pulse, in the latter a negative.

Subsequently, the noise and the pedestal level have to be determined. For their calculation, only points before the pulse are used, in this case from the 10% to the 90% of the points preceding the pulse. A distribution is built and fitted with a Gaussian function. The noise is then defined as the σ value of the Gaussian fit and the pedestal as the mean value.

After that, the pedestal level is subtracted from the waveform and, in case of negative polarity, the pulse is inverted in order to have a positive pulse. After inversion, start and stop points are recalculated together with the minimum and maximum values of the pulse.

From the positive pulse now, as explained in Section 6.1.2, the charge is computed for each pulse as the integral of the pulse between the start and stop points, as it is shown by the red area in Figure C.2. A distribution for the calculated values of all the pulses is made and will be fitted with a Landau-Gauss convoluted function at the end of the analysis.

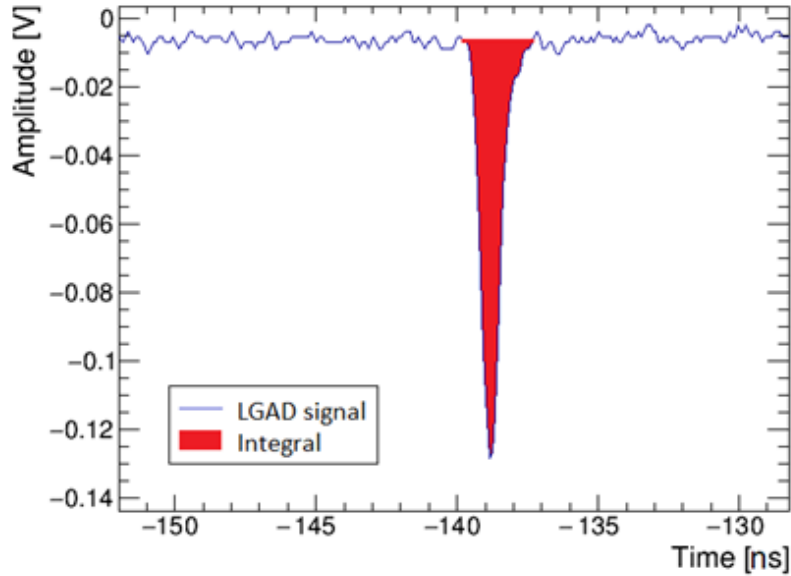


Figure C.2: Example of a signal waveform with the area used for charge calculation evidenced in red.

In a similar way, always on a event-by-event basis, the rise time and the CFD time are computed. The rise time is computed as the time the pulse needs to go from its 10% to the 90% of its maximum value, while the CFD time is calculated every 5% from the 5% to the 95% of the maximum value of the pulse. The CFD time will be used to compute the time resolution as explained in Section 6.1.2.

DUT channel class

The class logic is divided in four steps:

- **Initialize:** all the class variables are initialized to a default value and vectors are cleared
- **Append:** each new waveform is added to the channels. Waveform calculations are

Quantity	Applied Fit Type
min, max voltage	Gauss X Landau
start, stop, min, max indices	Gauss
Noise/Pedestal	Gauss
Min, Max, Rise and Trigger time	Gauss
Charge, dV/dT, Jitter, FFT	Gauss X Landau

Table C.1: List of the applied fits type for the waveform properties calculated with the LGADUtils framework.

added and, in case of some of them failing, only successful results are added leaving the unsuccessful results to the default values

- **Update:** channel properties are updated and recalculated
- **Print:** all the information are printed. This is the step where the information are printed as terminal output or can be saved into a file

To calculate the channel properties a Fit method is used. This method generates a value for each property by fitting the histogram with an appropriate distribution. At the moment of the Update, this apply the corresponding fit to each of the histogram to extract the expected value of the property. In Table C.1, the different channel quantities with the applied fit type are listed.

LGADRun class

This class contains the main functions and the execution order. It is organized as follows:

- **Begin:** initialization of all variable and pointers, histograms declaration
- **Slave Begin:** eventual loading of additional libraries
- **Notify** definition of channel number and instruments. Channel and waveform objects are created. Called every time a new file is opened
- **Process:** Called at every event. Recovers variables, generates waveform and append to channel

- **Slave Terminate:** Update channel properties, print terminal output, time resolution calculation, CFD maps
- **Terminate:** General plotting, saving

Optimization for test beam analysis

This framework was born in the beginning to analyze laboratory data where only oscilloscope data were recorded as ASCII file. In the past three years, this has been also optimized for test beam data, where both binary and ASCII files were saved by the oscilloscope. A new conversion function for test beam data has been developed to be able to decode the raw waveform data and generate a ROOT ntuple. In a second step, it was necessary to merge waveform data together with track information recorded by a telescope and reconstructed using EUTelescope[88, 89] framework. Then, a merging function has been developed which matches event-by-event the track with waveform information. This last function is a fundamental step for the generation of the efficiency maps which have been shown in Chapter 6.

List of abbreviation and acronyms

AFP ATLAS Forward Proton

ALFA Absolute Luminosity For ATLAS

ALICE A Large Ion Collider Experiment

ALTIROC ATLAS LGAD Time Read Out Chip

APD Avalanche Photodiode

ASIC Application-Specific Integrated Circuit

ATLAS A Toroidal LHC ApparatuS

AU arbitrary units

BDT Boosted Decision Tree

BNL Brookhaven National Laboratory

BSM Beyond the Standard Model

CERN Conseil Européen pour la Recherche Nucleaire

CFD Constant Fraction Discriminator

CMS Compact Muon Solenoid

CNM Centro Nacional de Microelectronica

CSC Cathode-Strip Chambers

DAC Digital to Analog Converter

DAQ data acquisition

DESY Deutsches Elektronen-Synchrotron

DUT Device Under Test

ECAL Electromagnetic CALorimeter

EMEC ElectroMagnetic End-Cap

EOC End Of Column

EW Electroweak interaction

FBK Fondazione Bruno Kessler

FCAL Forward Calorimeter

GBL General Broken Line

GR guard ring

IFAE Institut de Física d'Altes Energies

IHEP Institute of High Energy Physics

IME Institute of Microelectronics of the Chinese Academy of Sciences

HPK Hamamatsu Photonics

LHC Large Hadron Collider

LHCb Large Hadron Collider beauty

HCAL Hadronic CALorimeter

HEC End-Cap

HEP High Energy Physics

HGTD High Granularity Timing Detector

HL-LHC High Luminosity LHC

IBL Insertable B-Layer

ID Inner Detector

IP Interaction Point

IR InfraRed

ITk Inner Tracker

JSI Jožef Stefan Institute

JTE Junction Termination Extension

LAr Liquid Argon

LGAD Low Gain Avalanche Detector

LUCID LUminality Cherenkov Integrating Detector

MDT Monitored Drift Tube

MBTS Minimum-Bias Trigger Scintillator

mip *minimum ionizing particle*

MPV Most Probable Value

NDL National Nano Device Laboratory

NIEL Non-Ionizing Energy Loss

PS Proton Synchrotron

QCD Quantum ChromoDynamics

ROI Region of Interest

RPC Resistive Plate Chambers

SCT SemiConductor Tracker

SEB Single Event Burnout

SiPM Silicon Photo-Multipliers

SiT Silicon Tracker

SM Standard Model

SPS Super Proton Synchrotron

SSB Spontaneous symmetry breaking

TCT Transient Current Technique

TDC Time-to-Digital Converter

TGC Thin Gap Chambers

TiCAS Timing Control Automation Software

TileCal Tile Calorimeter

TLU Trigger Logic Unit

TOA Time Of Arrival

TOE Time Of End

TOF Time Of Flight

TOT Time Over Threshold

TRT Transition Radiation Tracker

TZ pseudo-transimpedance configuration

UCSC University of California Santa Cruz

USTC University of Science and Technology of China

VBF Vector Boson Fusion

VBS Vector Boson Scattering

VPA voltage sensitive preamplifier

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Education

- 2017–2022 **PhD in Physics**, *Institut de Fisica d'Altes Energies (IFAE)*, UAB Campus, Barcelona, Low Gain Avalanche Detectors for the ATLAS High Granularity Timing Detector. Thesis director: S. Grinstein, L. Castillo García and M. del Pilar Casado Lechuga
- Jul–Sept 2017 **Summer Intern**, *Fermi National Accelerator Laboratory*, Chicago, USA, Characterization of straw tubes for the Mu2e gas chamber. Supervisor: M. Kargiantoulakis
- 2013–2017 **Master Degree in Physics**, *Università degli Studi di Napoli "Federico II"*, Naples, Italy, Performance studies of resistive pad MicroMegas prototype for high rate applications. Thesis director: M. Alviggi and C. Di Donato
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Research activities

- since 2017 **Member of the ATLAS Collaboration.**
- Oct 2017–2022 **PhD candidate in Physics**, *Institut de Fisica d'Altes Energies*, UAB Campus, Barcelona, Main supervisor: S. Grinstein.
End date - July 11th, 2022
- Qualification task for ATLAS authorship:
 - Study of the performance of the Silicon Tracker of the ATLAS Forward Proton Detector
 - Participation in detector installation in the LHC tunnel and in several testbeams, calibration of sensors in the lab both at IFAE and CERN
 - Analysis of the results from LHC data taking for 2016 and 2017, presented in a conference with a poster and published in *Proceeding of Science (Pos (LHCP18) 031)*
 - Deep involvement in test beams: preparation, setup, data taking, shifts, data analysis
 - Preliminary Monte Carlo study of the effect of the HGTD detector effect in pile-up suppression for the process $Z \rightarrow \tau\tau + jets$ as the main background of the process $H \rightarrow \tau\tau$
 - Mentoring of bachelor and master students

- Complete characterization of LGADs sensors for High Granularity Timing Detector:
 - Electrical characterization before and after irradiation
 - Stability studies to define the operational voltages for data taking
 - Preparation and use of a ^{90}Sr setup to measure the collected charge and time resolution of un-irradiated and irradiated single pad sensors and contribution to the development of the data analysis framework
 - Use of Transient-Current-Technique (TCT) setup for gain, collected charge and inter pad gap measurements for 2×2 LGAD arrays as a function of fluence and bias voltage
 - Oral communication skills expressed in regular presentation in regular presentations in ATLAS (HGTD groups) and in various conferences and workshops
 - Regular report to collaboration meetings
- Jul–Sept 2017 **Summer Intern**, *Fermi National Accelerator Laboratory*, Chicago, USA, Supervisor: M. Kargiantoulakis.
- Characterization of Mu2e Tracker's straw tubes
 - Study of the time resolution and energy spectrum (both data taking and analysis)
 - A comparison between differences on the signal obtained with ^{90}Sr and ^{55}Fe has been carried out
 - Study on the best way to connect preamplifiers to straw tubes in order to save time
 - A preliminary analysis of crosstalk between neighbouring channels to study different approaches that could be used to reduce it
- Oct 2016–Jul 2017 **Master Thesis student**, *Università degli Studi di Napoli "Federico II" and CERN*, Supervisors: M. Alviggi and C. Di Donato.
- Full characterization of a new prototype of MicroMegas gas detector with resistive pads readout developed in the RD51 collaboration at CERN
 - Participation in test beam data taking at CERN with muon and pion beams
 - Study of collected charge, spatial resolution at different beam angle incidence and efficiency of the detector as a function of the bias voltage
 - Measurements with ^{55}Fe radioactive source of the transparency and gain have been carried out at CERN RD51 laboratory
 - Analysis of all the results
 - Regular report to group meetings
- May–Oct 2013 **Bachelor Thesis student**, *Università degli Studi di Napoli "Federico II"*, Napoli, Italy, Supervisors: M. Alviggi and C. Di Donato.
- Full characterization of a MicroMegas detector for the ATLAS muon detector upgrade, developed by RD51 collaboration at CERN
 - MBT0 and R20 prototypes were characterized with cosmic rays in University of Naples's laboratory. Properties studied as a function of voltage, using two different gas mixtures of Argon and CO_2 .
 - A study was performed to characterize clusters has the aim to use the MicroMegas as μ -TPC (Micro -Time Proportional Chamber). This work is a preliminary step for the study of clusters needed to perform a tracking inside the detector.

Publications

Main author

- 2 **Overview of CNM LGAD results: Boron Si-on-Si and epitaxial wafers**, *Proceeding of the 12TH International Conference on Position Sensitive Detectors (PSD12)*, Under review by JINST.

In this paper a full comparison between Si-on-Si and Low Resistivity Epitaxial wafers LGAD sensors will be given, comparin results for MIPs and laser measurements before and after irradiation

- 1 **ATLAS Forward Proton Detector**, *Proceeding of Science*, PoS (LHCP2018) 031.
The purpose of the AFP detector is to measure proton scattered at very small angles. In 2017 AFP participated in the ATLAS high-luminosity data taking. This paper presents the AFP detector and its performances during 2016 and 2017.

Direct contribution

- 9 **Performance in beam tests of irradiated Low Gain Avalanche Detectors for the ATLAS High Granularity Timing Detector**, Under review by JINST.

This paper presents results obtained with data recorded during HGTD test beams campaign during 2018 and 2019 both at CERN and DESY. Collected charge, time resolution, efficiency and charge uniformity are presented for CNM and HPK LGAD sensors.

- 8 **Characterization of Irradiated Boron, Carbon-Enriched and Gallium Si-on-Si Wafer Low Gain Avalanche Detectors**, *Proceeding of Workshop on pico-second timing detector for physics*, Instruments 2022, 6(1), 2.

In this paper, a full characterization of Boron, Carbon-enriched and Gallium doped LGAD sensors has been tested with Sr-90 radioactive source. Results for charge collection and time resolution are presented for different levels of irradiation

- 7 **A High-Granularity Timing Detector for the Phase-II upgrade of the ATLAS Calorimeter system: detector concept, description, R&D and beam test results**, *Proceeding of INSTR2020*, 2020 JINST 15 C09047.

In this paper, HGTD detector is presented and results from the R&D campaign for LGADs sensors are shown.

- 6 **Beam test results of NDL Low Gain Avalanche Detectors (LGAD)**, *Proceeding of HST12*, NIM A, Volume 978, November 2020, 164956.

This paper reports on beam test results for two proto-types LGADs (BV60 and BV170) developed for the HGTD and manufactured by the Institute of High Energy Physics (IHEP) of Chinese Academy of Sciences (CAS) collaborated with Novel Device Laboratory (NDL) of the Beijing Normal University.

- 5 **Radiation Campaign of HPK Prototype LGAD sensors for the High Granularity Timing Detector (HGTD)**, *Proceeding of HST12*, NIM A, Volume 979, November 2020, 164382.

Results of HPK LGADs sensors irradiated up to $3 \times 10^{15} n_{eq}/cm^2$ for collected charge and time resolution are presented.

- 4 **First characterization of 3D pixel detectors irradiated at extreme fluences**, *Proceeding of HST12*, NIM A, Volume 979, November 2020, 164458.

In this paper, 3D strip and pad detectors irradiated with neutrons up to a fluence of $3 \times 10^{17} n_{eq}/cm^2$ (1 MeV neutron equivalent) are characterised for the first time: the charge collection measurements with Transient Current Technique (TCT) are carried out at several voltages and the results are reported.

- 3 **Layout and Performance of HPK Prototype LGAD Sensors for the High-Granularity Timing Detector**, *Proceeding of HST12*, NIM A, Volume 980, November 2020, 164379.

The layout and performance of the various versions of LGAD prototypes produced by Hamamatsu (HPK) have been studied by the ATLAS Collaboration. The breakdown voltages, depletion voltages, inter-pad gaps, collected charge as well as the time resolution have been measured and the production yield of large size sensors has been evaluated.

- 2 **Performance of a Front End prototype ASIC for picosecond precision time measurements with LGAD sensors**, *2020 JINST 15 P07007*, Vol 15, July 2020.

This paper presents the results on the first prototype of a front-end ASIC, named ALTIROC0, which contains the analog stages (preamplifier and discriminator) of the read-out chip. The combined performance of the ASIC and the LGAD sensor, which was measured during a beam test campaign in October 2018 with pions of 120 GeV energy at the CERN SPS, is around 40 ps for all measured modules. All tested modules show good efficiency and time resolution uniformity.

- 1 **Small-pad resistive micromegas for operation at very high rates**, *TIPP 2017*, Proceedings of International Conference on Technology and Instrumentation in Particle Physics 2017., Springer Proceedings in Physics, vol 213. Pages 138–142.

A first prototype of Micromegas detector with readout and resistive pads connected by resistors embedded in an insulating layer, has been constructed at CERN and first performance studies are presented.

I am the author of 75 publications, a full list can be obtained in this link:
<https://inspirehep.net/authors/1633990>.

Conferences, schools and workshop

Talks

- 14 October 2021 **ATLAS Collaboration Week "Towards Run 3"**, CERN, Low Gain Avalanche Detector for the ATLAS High Granularity Timing Detector.
- 12-17 September 2021 **The 12th International Conference on Position Sensitive Detectors**, Birmingham, United Kingdom, Overview of CNM LGAD results with B, Ga and C diffused Si-on-Si and epitaxial wafers.
- 27-31 January 2020 **8th Beam Telescope and Test Beam Workshop**, Tbilisi, Georgia, A High-Granularity Timing Detector for the Phase-II upgrade of the ATLAS Calorimeter system: beam test results.
- 14–15 March 2018 **ATLAS Forward Physics and Detector workshop**, CERN, Geneva, The Silicon Tracker of the ATLAS Forward Proton Detector.

Posters

- 13-17 May 2019 **6th EIRO Forum School of Instrumentation**, ESA, Noordwijk, The Netherlands, Low Gain Avalanche Detectors for ATLAS High Granularity Timing Detector.
- 4–9 June 2018 **The Sixth Annual Large Hadron Collider Physics conference (LHCP 2018)**, Bologna, Italy, ATLAS Forward Proton detector.
- 28 February 2018 **LHCC session**, CERN, Geneva, AFP - ATLAS Forward Proton detector.

Other

- 1 July 2021 **ATLAS Collaboration week, Phase II + NSW Upgrade Session.**
Convener of the session

Outreach

- Feb 2022 **Dia de la dona i la ciencia**, *Outreach Talk for 100fiques BIST event.*
Agrupació Escolar Anselm Clave, Mollet Del Valles, Barcelona
- Feb 2021 **Dia de la dona i la ciencia**, *From Universe to particle physics.*
Escola Sant Gervasi Cooperativa. Mollet del valles, Barcelona
- Jan 2020 **Bojos per la Física (Beam Line for Schools)**, *Fast timing pixel detectors for High Energy Physics Experiments.*
IFAE Barcelona
- Sept 2019 **Matè de la Recerca**, *CERN and LHC: exploring the energy frontier.*
Escola Pia Mataró. Mataró (Barcelona)
- Feb 2019 **Dia de la dona i la ciencia**, *CERN and LHC: exploring the energy frontier.*
Institut Ramon Barbat i Miracle. Tarragona
- May 2017 **Futuro remoto.**
Città della Scienza. Napoli

Software skills

- Programming **C/C++**, *Good knowledge.*
python, *Basic.*
- Editors **MS Office**, **L^AT_EX**.
- Data analysis **ROOT**.
- Other **Windows**, **Linux**.

Languages

- Italian **Native**
- English **Professional Proficiency** *Level B2 certificate from Cambridge University in July 2017*
- Spanish **Professional Proficiency** *Level C1 certificate by Instituto Cervantes in December 2020*

Academic experiences

- 2020-2022 **Italian speaking training for spanish people**, *Barcelona, Spain.*
- 2019-2022 **University and high school support**, *Barcelona, Spain.*
- 2013-2017 **University support near three students**, *Napoli, Italy.*
- 2009-2015 **High school support with several students**, *Napoli, Italy.*

Work experience

- 2014-2018 **Employee in a bakery.**
- 2009-2011 **Appearance in TV series.**