

UNIVERSITY OF CAMERINO



SCHOOL OF SCIENCE AND TECHNOLOGY

Master Degree in Physics (class LM-17)

Particle physics and solid-state Si detectors:
HL-LHC from strip sensor to the first bent MAPS

Master Thesis in Applied Particle Physics

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ACADEMIC YEAR (2020-2021)



Scientific environment

The following research, a result of multiple work experiences done by the candidate in the field of solid-state silicon detectors, was performed across several facilities. The author spent most of his research time at the Fermi National Accelerator Laboratory, (FNAL) in the United States, and at the European Organization for Nuclear Research (CERN) in Switzerland. The work concerned the use of silicon detectors in particle physics in the context of the High luminosity Large Hadron Collider (HL-LHC) and it was done across two collaborations: the Compact Muon Solenoid (CMS) collaboration and the A Large Ion Collider Experiment (ALICE) collaboration.

In the CMS collaboration, I had the opportunity to take part in two projects. First, in the context of the CERN summer student program, working with hybrid pixel technology applied to a radiation monitoring system. Precisely R&D for the implementation of an innovative compact setup aiming slow neutrons measurements. Then in an Internship at the Fermi National Accelerator Laboratory I worked with silicon strips sensors. The work was on the data acquisition (DAQ) software for the CMS Phase II tracker, a fundamental step in integrating the control and readout of Strip-Strip (2S) modules into the Off-The-Shelf DAQ (OTSDAQ) framework developed by the group.

The CERN Technical Student Program gave me the opportunity to take part in an additional experience, this time in the ALICE collaboration. The project, like the previous ones, was in the field of solid state silicon detectors, working on the first bent monolithic active pixel sensors. All the projects were challenging, the scientific environment was a key factor for the R&D results. With different grades, these results are crucial for the completion of the HL-LHC which is planned to be operational in 2028.



Acknowledgments

This thesis was made possible by the opportunities that all student programs and related institutes provided to the candidate. I would like to thank all the people involved in the organization of the technical and summer student programs and the correspondent institutes CERN and FNAL. A special thanks goes also to my home institute, UNICAM, which gave me the necessary support to participate in the mentioned programs. The scientific environment, the fact of being in a large scientific community, was crucial. It helped me to develop knowledge in a variety of subjects with the assistance of many experts. I also want to mention that, aside from the work and from obtaining sound advice, I also established good friendships with many colleagues.

From my first experience, I would like to express the depth of my gratitude to my CERN-CMS supervisor Dr. Arkady Lokhovitskiy for his guidance, support, and continuous encouragement. I also want to thank the group leader, Anne Evelyn Dabrowski, and for his support, Srinidhi Bheesette, a PhD student from the University of Canterbury. Concerning the experience at Fermilab, it is my pleasure to express my gratitude to Dr. Fabio Ravera, a great mentor and amazing expert in the HEP field. Also, I would like to extend my appreciation to Anadi Canepa, the head of the Fermilab CMS Department, and Lorenzo Up-egger. In my last experience, CERN-ALICE, I was supervised by Dr. Magnus Mager I am grateful for the his assistance, also I had great help in the laboratory from Lukas Lautner, Alperen Yuncu and Francesca Carnesecchi. A very special thanks go to Prof. Stefania Beolè the project leader of the ALICE ITS that also helped me in the revision of this work, and Dr. Antonello di Mauro the team leader of EP-AID-DT Group.

I would finally like to express my acknowledgement to my UNICAM supervisor, Prof. Nicola Pinto, for his support throughout all of these experiences and his role in the revision of this thesis work. The most important thanks goes to my family, to all the friends I encountered on this journey, and in general, all the people that helped me to believe in myself, to never give up, and support my success during my studies.

Abstract

From their beginnings in the 1980s to the present days, solid-state silicon detectors have played a crucial role in particle physics and, in particular, in the field of particle tracking devices. Over the years, different sensor types have been developed. Nowadays, cutting-edge technologies are strip sensors, hybrid pixels, and monolithic active pixels sensors (MAPS).

All of these technologies will be used in the upcoming High Luminosity Large Hadron Collider (HL-LHC), a challenging LHC upgrade project designed to increase the current luminosity of the collider. The goal is to provide an integrated luminosity of 3000 fb^{-1} in 12 years, a tenfold increase over the nominal design value of the LHC in its original configuration.

This work addresses all the mentioned solid state silicon detector technologies with an historical perspective, going from strips to one of the latest forward-thinking developments, i.e., bent MAPS. For each technology, a R&D project is shown in the context of the HL-LHC. The remarkable outgoing results from these R&D projects are: the characterization of a first strip detector prototype that will be used for the High Luminosity CMS Tracker; the first slow neutron measurement with Medipix3RX technology in the CMS cavern; and finally, the investigation of the first curved solid-state silicon detector, i.e., bent MAPS chips.

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This prefatory chapter first recalls the history of the Standard Model and CERN's achievements and contributions to the model. Then it discusses how the accelerator complex at CERN accelerates and collides protons. The general mechanisms of particle detection that several experiments at CERN employ are addressed along with a full description of the fundamental components of HEP detectors. The last part is devoted to describing, in brief, the phase 2 of the LHC, which boasts an increase in the integrated luminosity of a factor of 10.

1.1 History of the Standard Model

SINCE the beginning of classical civilization humans have tried to understand the behavior of the natural world and the basic constituents of matter. Beginning at the start of the 6th century BC, ancient Greek philosophers such as Democritus and Epicurus were the first to formulate ideas regarding the atom and elementary particles [17]. It wasn't until the 19th century that scientists, Proust and Dalton, proved the laws of definite and multiple proportions in which a chemical element was found to have fixed ratios of elements based on their weight, no matter the source [3][53]. This suggested that each chemical element is made up of tiny particles of consistent weight. Subsequently, other developments in the understanding of the constituents of matter were made by Mendeleev, who built what is now known as the chemical table of elements that arranged the 65, known at that time, elements in a logical way. The beginning of particle physics is dated to 1897 when J.J. Thomson discover the electron, e^- , in Cambridge at the Cavendish Laboratory. The electron is the lightest particle in the atom and the first observed subatomic fundamental particle. In Manchester, Ernest Rutherford, a student of Thomson, and his



Figure 1.1:
Democritus [145]

colleague Hans Geiger studied how the electron fit into the atom. They did this by scattering a beam of alpha particles produced from the decay of radioactive elements off of a gold foil. The study of this scattering process resulted in the discovery of the nucleus, and subsequently the basic structure of the atom. By 1932 Rutherford and his colleague, James Chadwick, had found that nuclei are made up of two basic particles: one of them positively charged, the proton, and the other electrically neutral, the neutron. At the time, the basic building blocks of all known matter appeared to be fully understood.

However, there were still phenomena that couldn't be explained in terms of only these three particles. For example, the process of beta decay appeared to violate energy conservation in the form of 'missing energy' that was hypothesized by Pauli to be attributed to a new sub-atomic particle, the electron neutrino. In addition, the existence of other sub-atomic particles like Yukawa's meson and Dirac's positron, e^+ , were also hypothesized. In the early 20th century the most common way to produce a beam of particles was using radioactive materials. However, in 1912 Austrian physicist Victor Hess [139] detected penetrating radiation arriving from outer space called cosmic rays. This was the first evidence of a natural high-energy particles source. Since this discovery, physicists started to think about how to produce similar radiation in the laboratory, marking the beginning of a new era: the era of particle physics accelerators.

Advancements in detector technologies, along with the construction of the first accelerator facilities and the study of cosmic rays allowed for the discovery of many new particles that collectively came to be known as the "particle zoo". Among the new discoveries were several of the fundamental particles that we know today: the muon, μ^- , discovered in 1937 by Anderson, and the electron and muon neutrinos, ν_e and ν_μ , discovered in 1956 and 1962 respectively. Through deep inelastic scattering experiments that took place in 1968 at SLAC, the strange quark, s , the up quark, u , and the down quark, d , were detected. These discoveries completed the first generation of elementary particles. Scientists were then faced with the task of organizing these newly discovered particles based on their fundamental properties in the hopes that ultimately a grand unified theory would be able to explain our universe. The first attempt at a theory such as this, was by Murray Gell-Mann with the Eightfold way that led to the Quark model [7]. Between the years 1974 and 2000 the picture became more clear due to the discovery of the second and third generations of the fundamental particles. In 1974 physicists at SLAC and BNL independently discovered the charm quark, c , and in 1976 they also discovered the tau lepton, τ . One year later the Fermilab E288 experiment, team led by Leon M. Lederman [126] discovered the bottom, also known as the beauty, quark b . The discovery of the

most massive fundamental particle, the top quark t , was more difficult. It was not until 1995 that at Fermilab the Tevatron, a protons and antiprotons collider with center-of-mass energy $\sqrt{s} = 1.96 \text{ TeV}$, had enough energy to discovery the top quark. Two experiments CDF [39] and DØ (DZero) [24] provide the data that proved the existence of the top quark. Finally, in 2000 the experiment DONUT discovered the tau neutrino, ν_τ [115]. All the standard model constituents of matter and, the mediators of the interactions between them, except from the Higgs, were then observed. The mediators are: the photon γ , which mediates the electromagnetic interaction, the gluon, which mediates the strong interaction, and the $W^\pm$ and Z^0 bosons, which mediate the weak interaction.

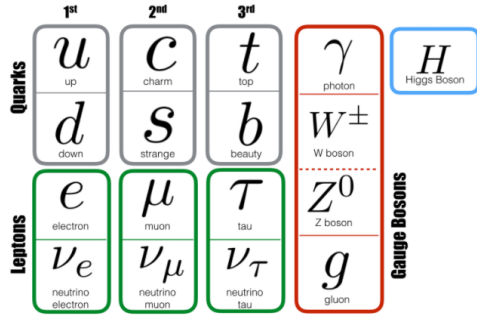


Figure 1.2: The elementary particles of the Standard Model. [165]

The photons concept is based on Planck's law that suggests the quantized nature of light, and was also described by Einstein (1905) in his explanation of the photoelectric effect. The gluon was discovered much later in 1979 at DESY. The strong interaction binds quarks together, and interestingly becomes weaker as the distance between two quarks is decreased. The weak force bosons are the only force carriers with mass. These particles were first observed at CERN, and for their work leading the discovery, Carlo

Rubbia and Simon van der Meer received the Nobel Prize in 1984. There is now only one fundamental interaction that we have not discussed, gravity. This interaction is not included in the standard model and the existence of a mediator for this force, the graviton, has not yet been proved to exist [147].

The last piece to complete the puzzle of the Standard Model was the Higgs boson. The Higgs field is fundamental in the theory of spontaneous symmetry breaking, and gives mass to all other fundamental particles. In 2012 CERN announced that CMS [37] and the ATLAS [22] collaborations had detected the Higgs using data from collisions at the LHC. The weighted CMS results for the data, signal and background models for the diphoton mass distribution is shown on the left of figure 1.3. The colored bands represent the one and two sigma uncertainty bands on the background estimate [37]. The ATLAS result for the observed and expected p_0 values as a function of the Higgs mass for a combination of channels is shown in the right side of figure 1.3. Where p_0 is the probability that the background can produce a fluctuation greater than or equal to the

excess observed in the data, and the combination of channels include: the decay of the higgs into two photons $H \rightarrow \gamma\gamma$, into two Z bosons giving four leptons $H \rightarrow ZZ^{(*)} \rightarrow 4l$ and into two Z bosons giving two leptons and two neutrinos $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ [22]. The cut out in the bottom right corner of the ATLAS plot is the low energy portion of the full spectrum which serves to highlight the excess of events and their significance.

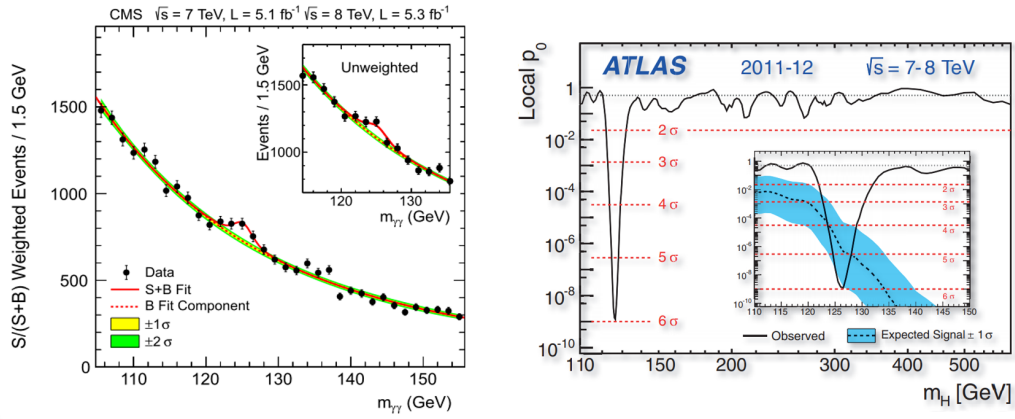


Figure 1.3: On the left: The weighted CMS results for the data, signal and background models as a function of the mass of two photons from the decay of the Higgs. On the right: The ATLAS result for p_0 as a function of the Higgs mass for the full and low energy parts of the spectrum, 1σ indicates that the results might be random fluctuations in the data, 3σ represents an observation, and a 5σ results is a discovery [130] [179].

1.2 CERN mission and achievements

As mentioned before, the turning point in particle physics was marked by the construction of accelerator facilities that allowed scientists to produce high energy particles in the laboratory in order to study the constituents of matter and their behaviors. In this framework, CERN has and will play, at least for the next fifty years, a crucial role in the advancement of physics. The acronym, CERN, literally stands for Conseil Européen pour la Recherche Nucléaire, but today the center is commonly known as The European Organization for Nuclear Research. From its founding in 1954 until now, the principles and values of the first council have not changed. CERN's internal structure is divided into directorates, and while the main part of the physicists remain employed by their national institutes, they use the tools that the organization offers. The laboratory's location at the Swiss-French border just outside of Geneva, is an excellent exam-

ple of science unconstrained by a national border. In fact, during the cold war CERN was one of the few places in the world where western and soviet scientists worked side by side. Their collaborative work contributed to the spread of peace around Europe [178]. CERN's mission is to push the frontiers of technology through international collaboration to advance human knowledge for the benefit of all [177]. In the last 67 years of activity, a plethora of milestone discoveries and technological achievements marked CERN as one of the most prestigious and respected international organizations. These discoveries include that of the $W^\pm$ and Z^0 bosons, the invention of the World-Wide Web, and several innovations in the field of hadron therapy, medical imaging and pixel detector technology. Today, Medipix3 is one the latest innovations in pixel technology from CERN, more details are presented in chapter four. Medipix has allowed for many innovations including an X-ray color technique that will allow doctors to see inside the human body with unprecedented accuracy via 3D images that provide high contrast and good detail at a low dose of x-ray exposition to the patient [35]. Other contributions that CERN has facilitated, include those in the fields of education and open science via the development of complex simulation software, advancements in robotic and information technology [129], the implementation of the LHC computing grid and, last but not least, the discovery of the Higgs Boson, a milestone discovery in particle physics and the last piece of the Standard model.

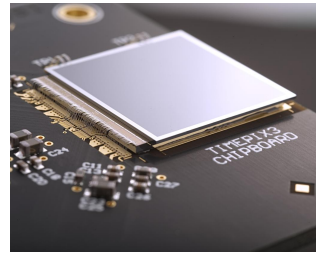


Figure 1.4: Medipix technology is an example of an advancement in pixel detector technology that has applications in medical imaging, education, space dosimetry and material analysis.[180]

Successful modern particle physics facilities are characterized by pioneering technology in the following three fields: accelerators, detectors, and data analysis. In order to make new discoveries, particles need to be accelerated at higher and higher energies. This requires advancements in accelerator technology. Advancements in detector technology is necessary to properly and precisely detect these particles and store the useful data. Solid state detectors play an important role in this field and will be widely discussed in this thesis. Lastly, data analysis, within the development of new hardware and software tools that allow physicists to identify the physical processes that took place in particle collisions, allow scientists to test theoretical predictions and discover new phenomena.

1.3 The LHC Accelerator

CERN is the home of the Large Hadron Collider (LHC), the world's largest and most powerful particle accelerator that is 27 km in circumference and is located 100 meters underground on the French-Swiss border. The LHC itself serves to collide particles together and is designed to run at a maximum collision energy of 14 TeV. CERN is actually comprised of several accelerators that are crucial in the particles journey. CERN scientists study many different particles and also heavy ions collisions, however in this section the focus will be on proton-proton collisions.

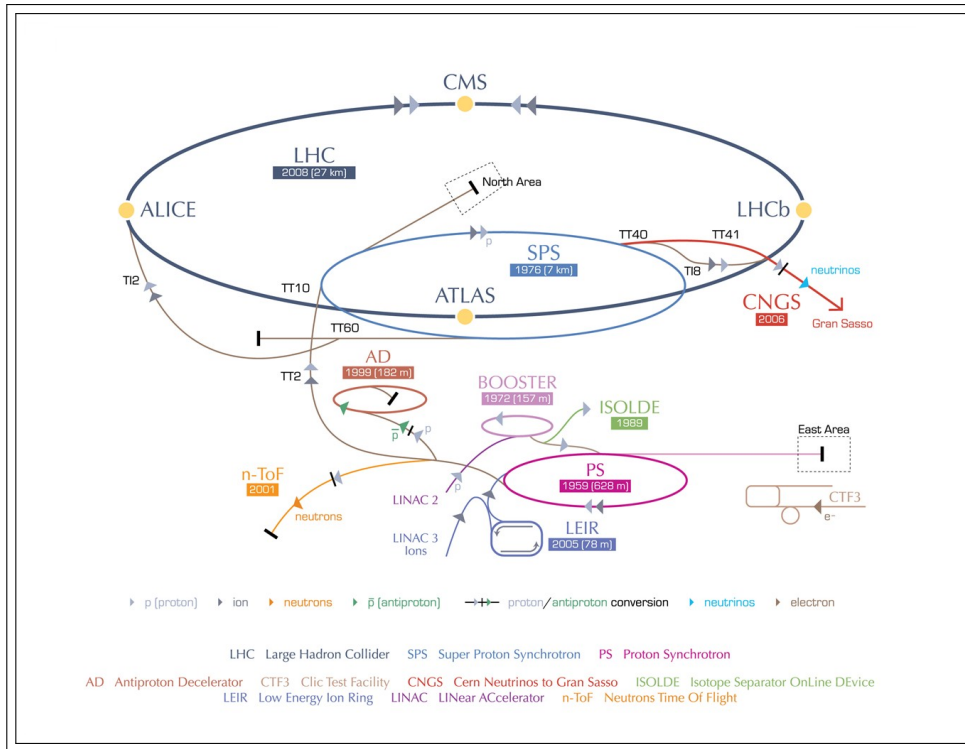


Figure 1.5: The CERN accelerator complex [158].

Accelerators injection chain The journey of colliding protons at the LHC, to exploit the basic constituents of matter and their interactions, starts from a bottle of hydrogen. The proton source is a hydrogen gas that, by an electric field, is stripped of its electrons in a device called the duoplasmatron. The resulting protons are then injected into a linear accelerator, the LINAC2 that under alternating electric fields accelerates the protons to 50 MeV using radio frequency cavities. The proton beam is then injected into the first synchrotron the PSB

(Proton Synchrotron Booster) which is composed of four superimposed rings of 25 meters in radius, and accelerates protons to 1.4 GeV. An experiment called ISOLDE uses protons directly from the PSB to make radioactive beams of nuclei. The PSB then transfers the protons to the PS (Proton Synchrotron) which is 628 meters in circumference and accelerates the protons to 25 GeV. The protons here reach 99.9% of the speed of light. At this speed the energy added to the proton cannot increase the protons velocity, so is instead manifested as an increase in the mass of the protons [135]. The PS was the first synchrotron at CERN, beginning its operation in 1959 [4] [102].

The PS also has the ability to split the proton beam into bunches and squeezes the protons in each bunch closer together. The bunch spacing of 25 ns that is necessary for the Super Proton Synchrotron (SPS) is generated in the PS, the bunches are partitioned using a method of longitudinal splitting that splits one bunch into two or three bunches (double or triple splitting) for the SPS beam in the following way: 6 PSB bunches (2 batches of 3 bunches each) are injected into 6 out of the 7 PS buckets, thus leaving a void for the PS extraction kicker. These bunches are then split into three via the triple splitting process producing 18 bunches. These bunches are then split again into four bunches ("Quadruple" splitting, or double splitting twice) producing 72 bunches and 12 empty buckets in the PS [31]. The journey of protons does not end yet, and the beam energy is still further increased in the SPS, the second largest accelerator at CERN measuring 7 kilometers in circumference. In the 1980's the SPS operated as a proton-antiproton collider and facilitated the discovery of the $W^\pm$ and Z^0 bosons. The SPS still uses conventional magnets and can accelerate particles up to 450 GeV. Finally, the protons are injected into the LHC and split into two proton beams that travel in opposite directions around the ring in separate vacuum tubes. Using super conducting magnets the protons are directed around the ring and accelerated to 7 TeV where they are made to collide at several different points along the ring [4] [102].

There are four experiments located at each collision point: CMS, ATLAS, ALICE and LHCb. CMS and ATLAS are general purpose detectors. This means they investigate a wide range of physics, from that of the Higgs boson to that of extra dimensions and particles that could make up dark matter. ALICE is dedicated to studying quark gluon plasma in the hopes that this research will reveal more information about the early universe just after the Big Bang. Finally, LHCb is dedicated to studying the properties of the bottom quark in order to explain the apparent matter antimatter disparity in our universe [127].

1.4 Particles Interaction with Matter

At this point, in our pathway along the LHC machine, the protons have been accelerated, $\sqrt{s} = 14\text{TeV}$, and have been made to collide at several crossing points. Even though 100,000 million protons per beam are squeezed down to about the width of a human hair, 64 microns, given the nominal beam current there are around 28 collisions per bunch crossing (pileup $\langle\text{PU}\rangle \approx 28$) [170]. This means that most protons do not interact with each other and carry on around the ring. In fact, the proton beams are kept circulating for hours [167]. It is interesting to note that the bunches of protons intersect every 25 ns, this means that in one second around 700 million collisions occur. In order to study these collisions, the particles involved have to interact with ordinary matter to be detected and identified. One way a particle can interact with matter is via the elec-

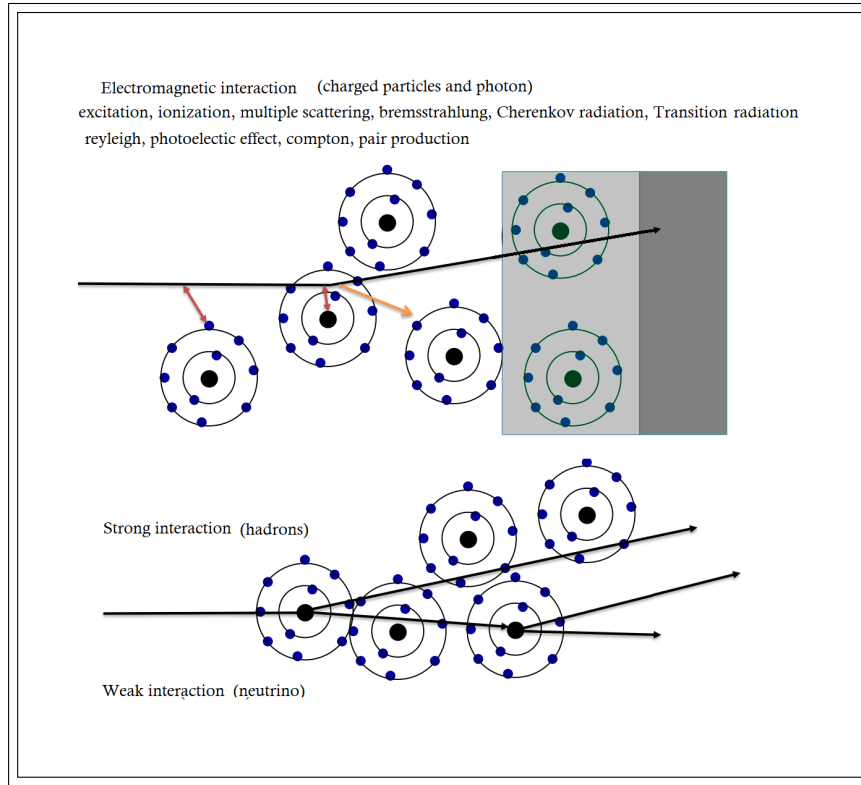


Figure 1.6: Summary of the possible fundamental interactions of particles with ordinary matter and the correlated particles and phenomena [122][4].

tromagnetic interaction. Charged particles and photons are involved in process such as: excitation, ionization, multiple scattering, bremsstrahlung radiation, Cherenkov radiation, transition radiation, annihilation, Rayleigh scattering, the

photoelectric effect, Compton scattering and pair production. Another way particles can interact with matter is via the nuclei of the atoms that make up the matter. Particles can interact with the nucleus via the strong interaction if the incident particles is a hadron or by the weak interaction if it is a neutrino [4]. This work will not explore in detail particles interactions with matter, the focus will be on the mechanisms used in the detection of high energy particles, which have long enough lifetimes to be detected in high energy physics detectors with traditional configurations. Surprisingly, out of all the known particles, elementary and composite particles (such as mesons and hadrons), very few have sufficient lifetimes, τ , and cross sections to leave a signal in a physical detector. These particles, by far the most frequently detected ones, are summarized in the table 1.2. Their difference in mass, charge and interaction is the key to their identification [123]. Particles that do not leave a characteristic track in the detector are measured through known kinematic relations and decay products that can be seen as an excess above background.

Particle	Mass	$c\tau$	Interaction
$e^\pm$	0.511 MeV	∞	EM
$\mu^\pm$	105,7 MeV	658,6 m	
γ	0 Mev	∞	
$\pi^\pm (u\bar{d}, d\bar{u})$	139.6 MeV	7,8 m	EM, strong
$K^\pm (u\bar{s}, \bar{u}s)$	493.7 MeV	3.7 m	
$P^\pm (uud)(\bar{u}\bar{u}\bar{d})$	938.3 MeV	∞	
$K^0 (d\bar{s}, s\bar{d})$	497.7 MeV	15,5 m 2.7 cm	Strong
$n (udd)$	939.6 MeV	$2655 \cdot 10^8 km$	
Bottom and charm quarks also leave very short tracks before decaying.			

Table 1.1: The 8 particles able to leave signals in a typical high energy physics detector. Their corresponded mass, decay length and type of interaction is shown [123] [50].

A complete overview of the physical phenomena involved in the detection of this 8 particles will be given. The description divided the phenomena in terms of radiation involved. The word radiation is defined as: "...the emission or transmission of energy in the form of waves or particles through space or through a material medium" [181]. This section will cover charged radiation, neutral radiation and hadron radiation. Hadrons are discussed at the end of this section for two reasons. The first is because hadrons can be either charged particles or neutral particles, so they can be detected using several methods. The second reason is because it is simpler to introduce the direct detection of particles first, and then discuss the detection of particles from the products of the primary interactions, where their detection requires destructive processes (the particle has to decay to be detected).

1.4.1 Charged Radiation

As a charged particle travels through a medium, it interacts with the atoms of the surrounding material via the Coulomb force. The energy transfer to the particle in each atomic interaction is relatively small, so the particle needs to undergo a large number of interactions before it can come to a stop. Two classes of interactions can be defined: collisions with the orbital electrons which ionizes the material via the Coulomb interaction, and radiative interactions where the incoming particle interacts with the external field of the nuclei of the surrounding material, this phenomena is known as Bremsstrahlung [16].

Ionization ($p^\pm K^\pm \pi^\pm \mu^\pm e^\pm$) Collisions with atomic electrons create electron-hole pairs along their path. Due to the ionization process the particles lose energy. The energy loss per unit length is described by the Bethe-Bloch formula. The following Bethe-Bloch formula, equation 1.4.1, gives the mean rate of energy loss (stopping power) of a heavy charged particle. For a light particle like an electron or positron, a modified equation is used [96].

$$-\left\langle \frac{dE}{dx} \right\rangle = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln \left(\frac{2m_e c^2 \beta^2 \gamma^2}{I^2} W_{\max} \right) - 2\beta^2 - \delta(\beta\gamma) - \frac{C}{Z} \right] \quad (1.4.1)$$

Fundamental constants			
r_e	classical radius of electron	m_e	mass of electron
N_a	Avogadro's number	c	speed of light
Absorber medium		Incident particle	
I	mean ionization potential	z	charge of incident particle
Z	atomic number of absorber	β	$\beta = v/c$ of incident particle
A	atomic weight of absorber	γ	$\gamma = (1 - \beta^2)^{-1/2}$
ρ	density of absorber	$W_{\max}$	max. energy transfer in one collision
δ	density correction		
C	shell correction		

Table 1.2: Table of the constants and variables involved in the Bethe–Bloch formula with quantum mechanic corrections [101].

It is possible to see equation's 1.4.1 dependence on the energy loss as a function of the velocity of the particle if we divide equation 1.4.1 by the density of the material and plot (see figure 1.7) it as a function of the $\beta\gamma$ factor. If the particle is slow, it has more time to interact with the material causing higher energy loss. As the velocity increases the energy loss decreases. In principle it should saturate at speed close to c , arriving at the Fermi plateau. The only reason why

it increases again is because the maximum amount of energy available to the particle increases so more energy is transferred. This is a small effect indeed, as the graph is in the log base two scale. Is clear that the amount of energy a particle can transfer is dependent on the velocity of the particle, but not on the mass. However, if equation 1.4.1 is plotted as a function of momentum, the curve will look different for each particle type, because $\vec{p} = \gamma m_0 \vec{v}$. If one can measure the momentum of the particle and the energy loss, the particle can be identified using the graph 1.7 [122].

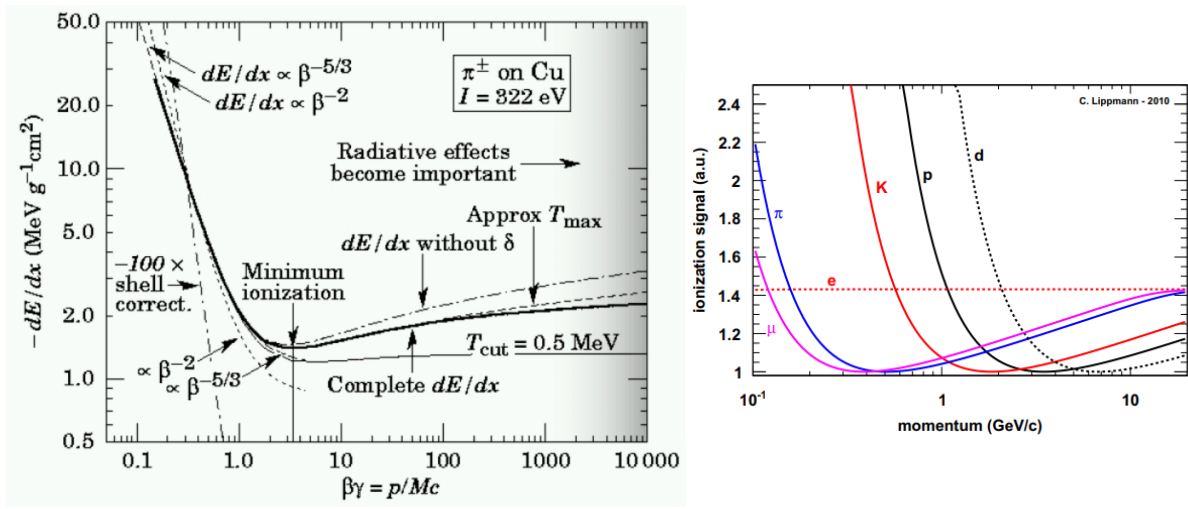


Figure 1.7: On the left: Energy Loss for Pions in Copper normalized to the material density. The density of the copper is 8.94 g/cm^3 a Minimal Ionising Particle (MIP) loss $\approx 13 \text{ MeV/cm}$ [101]. On the right: Ionization signal as a function of particle momentum for a number of known charged particles. Charged particles can be easily identified, in particular at low momentum [60].

Bremsstrahlung ($e^\pm \mu^\pm$) When a light charged particle traverses matter, it can loose energy in two ways: via ionization/excitation of the atoms, as discussed previously, and via radiative interactions with nuclei. The electric field of a nucleus can change the direction of the incoming particles. The consequence of this is to accelerate or decelerate the incoming particles as they pass near a nucleus, causing them to radiate photon, and lose some energy. This process is called Bremsstrahlung, in german, literally 'braking radiation'. The most common particles that can be detected via Bremsstrahlung are the electron and positron with energy above 20 eV. Also, highly energetic muons, $E > 1\text{TeV}$, radiate via Bremsstrahlung. Nowadays, muons are not detected via this effect, however, future higher energy colliders will have to take into account this process [4] [122].

1.4.2 Neutral Radiation

Neutral radiation, unlike charged particles, are always detected from interactions secondary products. Particles such as: photons, neutrons and neutrinos can be included in this category. In high energy physics photons are produced from fast electrons interacting with matter and neutrons are produced from matters interaction with heavy charged particles. In both cases a destructive process is involved, the particle's energy is converted to a detectable signal and the particles products are stopped in a block of matter. A brief overview of photon and neutrino detection principles are given in the following section, and neutron detection is discussed in detail in chapter four, where the CMS neutron radiation monitoring is described.

Photon γ The photon is a neutral particle and has no mass, for these reasons photon detection may seem difficult to achieve. Photons, however, can be detected in a variety of ways because it is the carrier of the electromagnetic force. In contrast with charged particles, when interacting with electrons or nuclei photons always change their energy and direction or even disappear [9]. Photons traveling through ordinary matter, as is shown in the following figure 1.4.2, can interact via the following processes: photon-electron and photon-nucleus interactions.

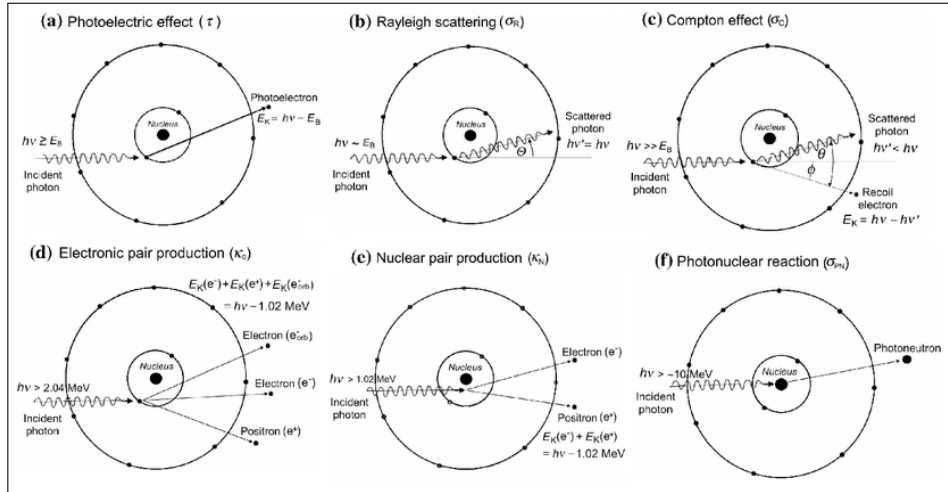


Figure 1.8: The pictures from a) to d) show photon-electron interactions: photoelectric effect, Rayleigh scattering, Compton scattering and electron pair production. The photon-nuclear interactions are shown in e) and f): nuclear pair production and the photonuclear reaction respectively [15].

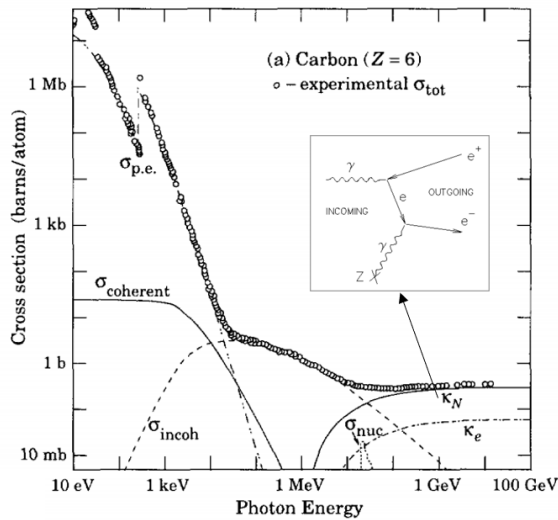
- Photon-electron interactions:

- *Photoelectric effect* = the incident photon is absorbed which leads to the emission of a free electron. This effect occurs if the photon energy exceeds the binding energy of the atomic shell.
- *Rayleigh scattering or Coherent scattering* = the resulting photon changes direction, but has the same energy as the incident photon.
- *Compton scattering or Incoherent scattering* = the photon collides with an electron and the resulting photon changes direction and has a lower energy than the incident photon. The excess of energy is transferred to the electron.
- *Electron pair production* = a positron and an electron are produced spontaneously when a photon interacts with an electron.

- Photon-nuclear interaction:

- *Nuclear pair production* = a positron and an electron are produced spontaneously when a photon interacts with a nucleus.
- *Photonuclear process* = the nucleus absorbs the photon, and in most cases emits a neutron.

The strength of each phenomena is dependent on the energy of the incoming photon, an overview is given in the following graph. In high energy physics pair production is the most important process [59][16].



$\sigma_{\text{p.e.}}$ = Atomic photoeffect

σ_{Coherent} = Coherent scattering
 (Rayleigh scattering)

σ_{Incoh} = Incoherent scattering
 (Compton scattering)

κ_n = Pair production, nuclear field

κ_e = Pair production, electron field

σ_{nuc} = Photonuclear process

Figure 1.9: Total photon cross section in carbon as a function of the photon energy, showing the contributions of all processes involved. For pair production the corresponding Feynman diagram is given [138] [49],

Neutrino ν Even if particles do not interact with the surrounding matter they can still be identified. An example of one such particle is the neutrino. Neutrinos do interact with matter through the weak force by a charged-current or a neutral-current interaction, but the interaction is very weak [9]. The corresponding cross section is so small that extremely massive and large detectors are necessary to measure the secondary charged particles with reasonable efficiency [89]. The actual signature of a neutrino detection is an event that was found, via kinematic relations and statistics, to have missing momentum.

1.4.3 Hadron Radiation

Hadrons travelling in a medium interact with nuclei via the strong force [59]. Indeed, the fact that these particles interact through the strong force defines them as hadrons. Hadrons are composed of quarks and include mesons, which are made of quark-antiquark pairs, and baryons, that are composed of three quarks [164]. Hadron-Nucleus (hA) reactions or Hadron-Nucleon (hN) interactions can occur, and in both cases the collisions can be elastic or inelastic [100].

Elastic collisions ($p^\pm n K^\pm K^0 \pi^\pm$) Elastic collisions do not change the internal structure of the hadron and nucleus/nucleon involved, but part of the incoming particles energy is transferred to the target deflecting it.

Inelastic collisions ($p^\pm n K^\pm K^0 \pi^\pm$) Collisions are considered inelastic if the internal structure of the target nucleus/nucleon or the projectile, the hadron, is changed and new particles are produced, inelastic reactions usually have an energy threshold below which the reaction cannot occur [100] [59].

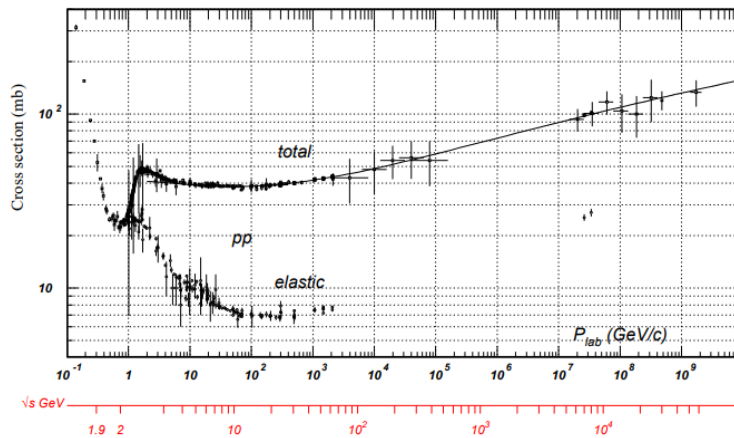


Figure 1.10: Proton-Proton (pp) collisions, elastic and total cross section as function of the energy in the centre mass reference frame and the lab one [84].

1.5 Particle Detectors

"Just as hunters can identify animals, and might understand what happened from the tracks in the snow, physicists identify subatomic particles and reconstruct the involved phenomena from the traces that particles leave in detectors" [128]



Figure 1.11: Lynx and hare tracks in fresh snow.

After the concise description of the main processes occurring in the particle-matter interaction, given in the previous chapter, it's possible to describe how collisions, the related particles and corresponded measurable quantities like momentum and energy can be detected. Large particle physics detectors, such as, CMS ATLAS ALICE and LHCb, are based on six core components: tracking devices, magnet system, calorimeters, particle-identification system, trigger data acquisition (TDAQ), and the monitoring instrumentations.

Tracking devices ($p^\pm K^\pm \pi^\pm \mu^\pm e^\pm$)[§] are based on the well-discussed ionization process and are used to reveal efficiently and with very high precision the trajectories of all electrically charged particles coming from collisions.

The Magnets system ($p^\pm K^\pm \pi^\pm \mu^\pm e^\pm$)[§] implemented by large solenoid magnets aims to provide a large magnetic field in order bend the charged particles coming from the interaction point. Charged particles moving in a magnetic field experience the Lorentz force, undergoing a change in their trajectory (circular). The following scalar relation can be written: $qv_t B = mv_t^2/R$. Knowing the magnetic field and the curvature of the particle path, the transverse momentum can be calculated $p_t = qRB$. Furthermore, the presence of a magnetic field allows positively and negatively charged particles to be distinguished, they will be bent in opposite directions.

[§]Particles detected/influenced by the device

Calorimeters ($e^\pm \gamma p^\pm n K^\pm K^0 \pi^\pm$)[§] are based on the shower physics processes, i.e., multiple hadron inelastic collisions, bremsstrahlung, and pair production. Their main function is to measure the energy of particles, such as hadrons, photons, electrons, and positrons. The particles are fully absorbed and their energy is transformed into a measurable quantity. To accomplish this task, absorbing high-density material layers (e.g. Pb or Cu) are spaced apart from an active detector, such as Si detectors, scintillators, or liquid Argon detectors [128].

The Particle-identification system ($e^\pm \gamma p^\pm n K^\pm K^0 \pi^\pm \mu^\pm$)[§] in conventional detectors (CMS, ATLAS, etc.) may be hidden in the structure of the detector itself. Except for the magnet system, which can be placed differently. Starting from the collision and pointing outward, there is first a silicon-based tracking system, then an electromagnetic calorimeter (ECAL), a hadronic calorimeter (HCAL), and finally a muon tracking system. As can be seen in the figure 1.12, photons and electrons are seen in the ECAL, but only electrons leave a track in the silicon tracker. The neutrons are seen in the HCAL but not in the track and so forth. This system works extremely well. Nevertheless, some studies require finer particle identification. In such cases, the overall structure is partially changed and special detectors are used for particle identification [128] [143].

The TDAQ is the Trigger and Data Acquisition system. The trigger system is responsible for the real-time selection of the subset data to be recorded. The Data Acquisition (DAQ) system collects data from detectors, convert into digital, and then save data into a mass storage for offline analysis. At collider experiments, the two systems, i.e., trigger and DAQ, are closely linked, and often the overall unit is called TDAQ.

Monitoring instrumentation in HEP experiments is of fundamental relevance. Measuring and monitoring several parameters connected to beam conditions, the number of collisions, and the resultant amount of radiation released in the detectors is crucial for the operational work of the detectors, the safety of the personnel, and also to determine the aging of the detectors. These tasks are done using the detectors data itself and integrating specialized devices.

[§]Particles detected/identified by the device/system

1.5.1 The Compact Muon Solenoid (CMS)

The Compact Muon Solenoid (CMS) is a cylindrical detector that is 21.6 m long, has a diameter of 14.6 m and a total weight of 12500 tonnes. While it was designed to ultimately detect the Higgs boson, CMS is a general purpose detector and the physics goals of CMS are far reaching. For example, physicists use data collected from the detector to look for evidence of super symmetric particles and to reconcile the matter-antimatter asymmetry in our universe. The CMS detector consists of several different sub-detectors working together to detect the position and momentum of particles such as, muons, electrons, photons and particle jets over a large energy range (0.9 13 TeV) of proton collisions. The CMS collaboration counts over 4,000 people, from over 206 scientific institutes and 47 countries [27] [30].

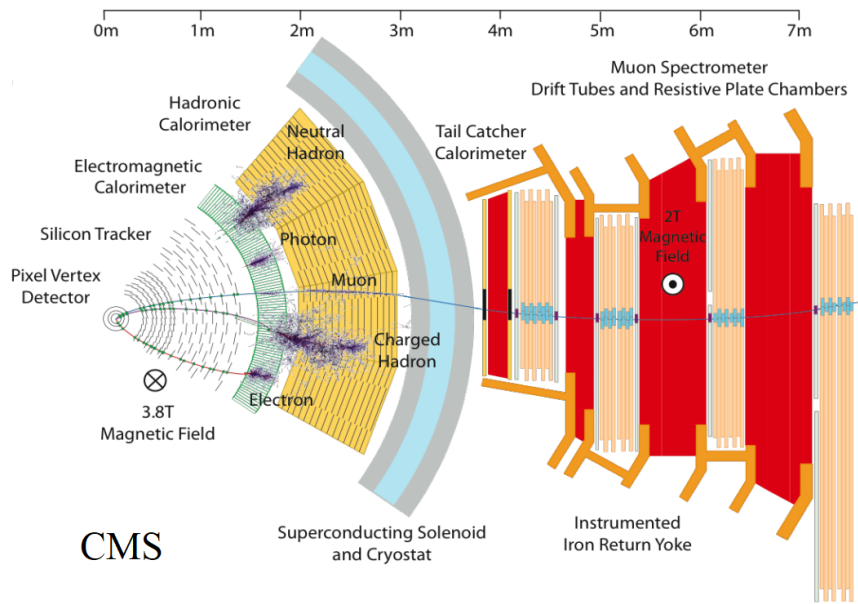


Figure 1.12: One slice of the Compact Muon Solenoid (CMS) detector, with a schematic depicting the particle-identification approach. A muon originating at the interaction point is deflected by the central solenoidal magnet. Once it crosses the centre of the magnet, its curvature reverses, and the muon continues its path through the detector. The muon's backbending is readily evident in the outer magnetic spectrometer [8] [97].

As concerns the particle detectors, the CMS (see figure 1.12) is equipped with a silicon tracker of pixel and strip sensors, two calorimeters, the Electromagnetic Calorimeter (ECAL), made of 75848 lead tungstate, and the Hadronic Calorimeter (HCAL), made of 75848 lead tungstate, and the Hadronic Calorimeter.

ter (HCAL), made of repeating layers of dense absorber and layers of plastic scintillator[141], the superconducting solenoid magnet, providing a 3.8T magnetic field and, finally, the muon spectrometer with its 1400 muon chambers. The overall CMS's operational work is carried out by all of these sub-detectors in unison [93].

1.5.2 A Large Ion Collider Experiment (ALICE)

The ALICE (A Large Ion Collider Experiment) detector, with a total weight of 10000 tonnes, is 26 m long, 16 m high, and 16 m wide. ALICE was designed for studying nucleus–nucleus collisions, to investigate the properties of strongly interacting matter, and the Quark-Gluon-Plasma (QGP). Already, by the first design (figure 1.13) of the detector, it was readily evident that the detector structure is unusual, a mix of a cylindric collider geometry and a fix-target one. Another distinguishing characteristic of the detector is its excellent particle-identification system (PID). In the years the ALICE detector evolved and the ALICE collaboration has grown, nowadays consists of more than 1000 scientists representing over 100 physics institutes and 30 countries [46][151].

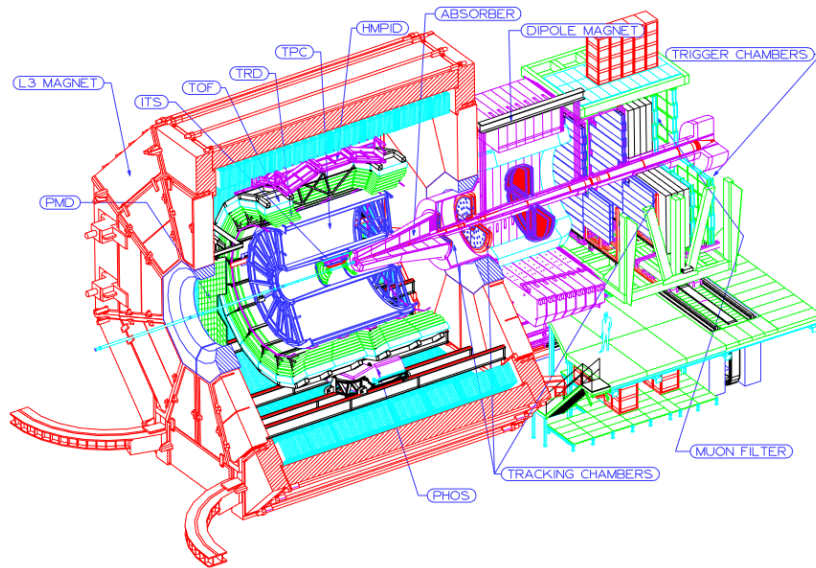


Figure 1.13: Longitudinal view of the first design of ALICE detector [46].

As mentioned, ALICE has a mixed geometry, so its sub-detectors can be categorized into two classes: the central-barrel region detectors and the forward region detectors. To the central-barrel detectors class belong the Inner Tracking System (ITS), the Time Projection Chamber (TPC), the Transition Radia-

tion Detector (TRD), the Time Of Flight (TOF) detector, the ElectroMagnetic Calorimeter (EMCal), the Di-Jet Calorimeter (DCal), the PHOTon Spectrometer (PHOS), the Charged-Particle Veto (CPV), the High-Momentum Particle Identification Detector (HMPID), and the ALICE COsmic Ray DETector (ACORDE). To the central-barrel detectors class belong the Muon Forward Tracker (MFT), Muon Spectrometer (Muon Chamber (MCH) and Muon Trigger (MTR), the ALICE Diractive detector (AD), the Zero Degree Calorimeter (ZDC) the Photon Multiplicity Detector (PMD), the Forward Multiplicity Detector (FMD), The Fast Interaction Trigger(FIT)(include FT0, FV0, FDD detectors) [137] [23] [134].

1.6 Towards High Luminosity LHC

The forthcoming phase of the large hadron collider, development referred as the LHC Phase II Upgrade, aims to push the accelerator technology beyond its present limits, and implement a massive upgrade of all the present LHC detectors to build what is called the High-Luminosity Large Hadron Collider (HL-LHC) [82]. Three key parameters have to be explained in this context: energy, luminosity (instantaneous and integrated), and pile-up. The energy, in this case, is the central-mass energy of the collisions, and the value will not change. The HL-LHC, similarly to the LHC, is designed to run at a maximum collision energy of $\sqrt{s} = 14$ TeV. The main parameters that will be improved are the instantaneous luminosity, L , and, as a result, the integrated luminosity, L_I . They can be expressed by the following equations:

$$L = \frac{\gamma n_b N^2 f_{\text{rev}}}{\beta^* \epsilon_n 4\pi} R \quad R = 1 / \sqrt{1 + \frac{\theta_c \sigma_z}{2\sigma}} \quad L_I \equiv \int_{\Delta t} L dt \quad (1.6.1)$$

In the equations above: γ is the proton beam energy in unit of rest mass; n_b is the number of bunches per beam colliding at the Interaction Point (IP) at LHC for 25 ns bunch spacing is 2808 (nominal LHC value); N is the bunch population ($N_{\text{nominal 25 ns}}: 1.15 \times 10^{11}$ p); f_{rev} is the revolution frequency (11.2 kHz); β^* is the value of the beta function (focal length) at the collision point (nominal design 0.55 m); ϵ_n is the transverse normalized emittance (nominal design: 3.75 μm); R is a luminosity geometrical reduction factor from the crossing angle; θ_c is the full crossing angle between colliding beam (285 μrad as nominal design); and σ, σ_z are the transverse and longitudinal root mean square sizes, respectively (nominally 16.7 μm and 7.55 cm, respectively); Δt is the operating time in collision mode [29] [82]. Summarising, the instantaneous luminosity quantify the number of potential collisions per unit area per second, and the

integrated luminosity the total number of events recorded. The last parameter to exploits is then the pile-up number. As mentioned earlier the beam in particle-physics accelerators is spitted in bunches, so the collisions occur when the bunches traveling in opposite directions let the accelerated particles to interact in "hard scattering" events. The pile-up number (conventionally indicate with $\langle \text{PU} \rangle$ or $\langle \mu \rangle$) is defined as the average number of particle interactions per bunch-crossing [166] [171]. One of the goal of the HL-LHC is to achieve an integrated luminosity of 3000fb^{-1} (10 times more the LHC initial configuration) in 12 years of operation. This means that each general purpose detector, i.e., CMS and ATLAS, has to increase its instantaneous luminosity, and, consequently, the pileup number will also increase. Ultimately, the instantaneous luminosity has to be $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and the average pile-up value 200. On the right side of figure 1.14 is displayed a simulated event with $\langle \text{PU} \rangle = 200$. The HL-LHC is expected to be operational in 2028, and the amount of data generated will for example allow for greater precision in Higgs boson coupling measurements [133] (see figure ref 1.14 right side) and may reveal information about dark matter and the existence of SUSY particles.

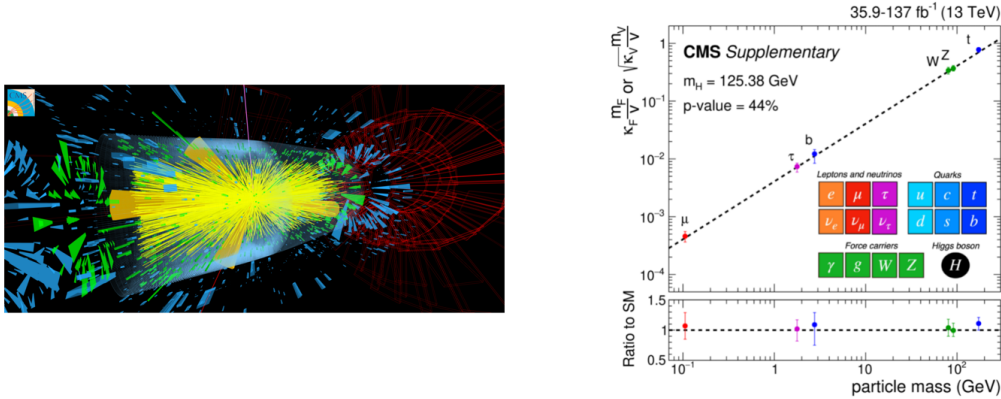


Figure 1.14: On the left: an illustration of VBF (Vector boson fusion) H in 200 p-p collisions [160]. On the right: reduced coupling strength scale factors for fermions and weak bosons, compared to their corresponding predictions from the Standard Model. The corresponding error bars represent 68% confidence intervals for the measured parameters [133].

In the HL-LHC context, important detector parameters to be improved are rate capabilities, spatial resolution, and the enhancement of the radiation monitoring systems. This thesis work will address these challenging goals through the discussion of R&D projects for the solid state silicon detectors used in the HL-LHC.

2 Solid State detectors

The purpose of this chapter is to introduce solid-state detectors, explain why silicon is the most commonly used material, and illustrate the basic principles of signal formation and signal processing.

“There are two kinds of scientific revolutions ... those driven by new tools and those driven by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained ... In almost every branch of science there has been a preponderance of tool-driven revolutions.”

Freeman Dyson [5]

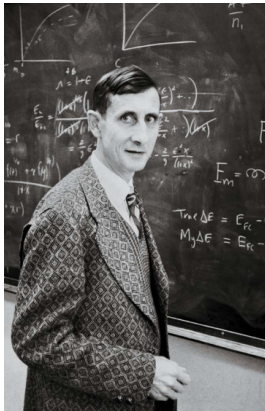


Figure 2.1: Freeman Dyson [44].

Tools, as highlighted by Freeman in his book, *Imagined Worlds*, are one of the key components in leading new directions in science, hence opening the door to new discoveries. Based on the interaction and then the physical phenomena involved, a variety of tools exist in particle physics. These tools are known as particle detectors. A wide explication of particle physics detection processes and the correspondent detectors was done in the previous chapter.

Solid-state detector technology is nowadays one of the most important in high-energy physics. R&D studies in the field already suggest great, unprecedented results and will most probably soon lead to new tools.

Ionization based detectors Among high-energy particle detectors, those used to detect charged particles through the ionization process play an important role. Charge particles passing through the matter leave behind excited atoms and electric charges (figure 2.2 a). Excited atoms lead to the emission of photons; photon detectors such as photomultipliers or semiconductor photon detectors are, in this case, used [124]. Instead, the electric charges that are left behind are the result of the ionization process and are known as charge carriers. Ionization based detectors can be sub-classified into: gas detectors (cloud chambers, wire chambers, drift chambers, time projection chambers), liquid detectors (bubble chambers, liquid Argon time projection chambers) and solid state detectors.

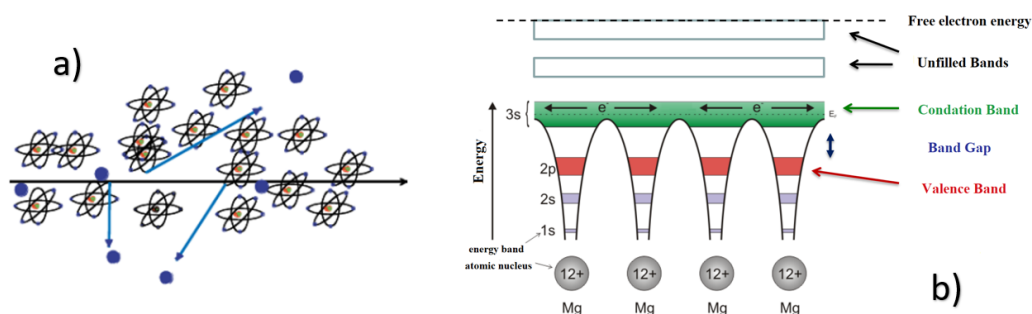


Figure 2.2: On the left a) A charged particle traversing the matter; on the right b) Crystal energy bands model with potentials, using as example solid magnesium [124]

As it can be easily deduced from the name, the general process is common to all of ionization based detectors. The main distinction is that in gases and liquids the charge carriers are electrons and ions, in solid state detectors electrons and holes [12]. The arrangement of molecules in gaseous substances, and liquid is not so close or fixed. The liberated charges are relatively free to move between the gas atoms. In solid, specifically in crystals is not the case, the molecules are much strong and compact arranged. Quantum mechanics proved that the electrons are in energy bands, and the charge carriers tend to move into the orbitals of neighboring atoms (figure 2.2 b) [124] [176]. The arrangement of the electrons in the energy bands determine the macroscopic electrical behavior of the substance, and in particular if the material act as an electrical conductor, semiconductor or insulator.

2.0.1 Semiconductors and Silicon detectors

Semiconductors are the base of solid state detectors. Three fundamental notions can clarify the definition of a semiconductor: resistivity, microscopic behavior of materials at different temperatures, and as mentioned energy bands.

Insulators	· ·	resistivity 10^{14} to $10^{22} \Omega\text{cm}$
Semiconductors	· ·	resistivity 10^{-2} to $10^9 \Omega\text{cm}$
Conductors	· ·	resistivity of the order $10^{-5} \Omega\text{cm}$

A semiconductor at ambient temperature have a resistivity in the range of 10^{-2} to $10^9 \Omega\text{cm}$. The macroscopic electric conductive behavior is between a insulator and a conductor [21]. Figures 2.2 b and 2.3 show a much deep explanation of the phenomena. Semiconductors have a unique band structure, electrons in lowest energy bands are close to the nucleus and stay with their atoms. At temperature $T = 0^\circ\text{K}$ the valence band is filled and conduction band is empty, the material behave as a insulator. However, the difference in energy between the valence and conduction bands, the E_{gap} , is small compared to an insulators.

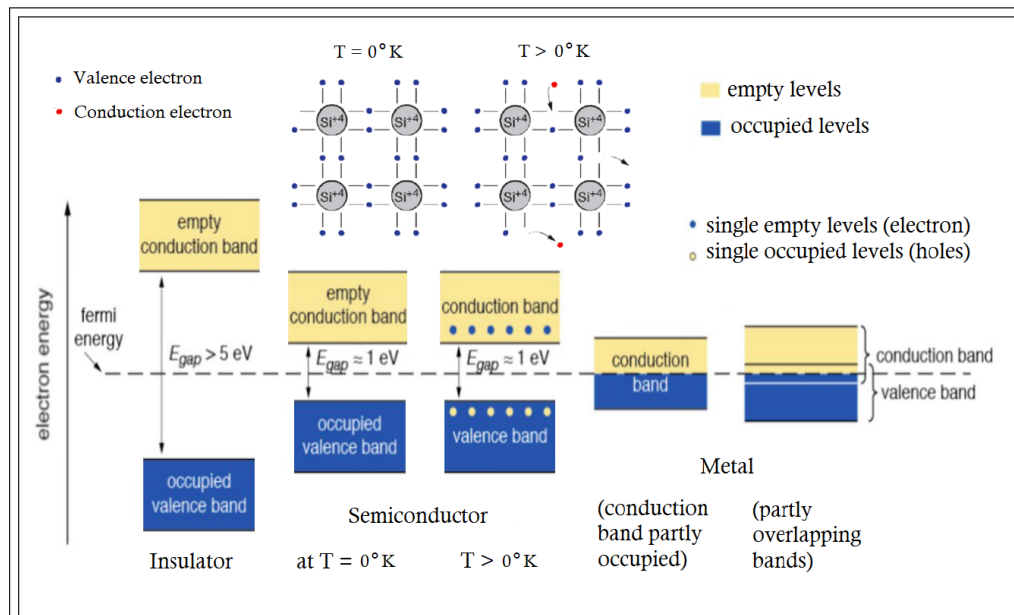


Figure 2.3: Illustration of a two-dimensional silicon lattice displaying the behavior of the material at different temperatures, as well as band structures for electrical insulators, semiconductors, and metals [173].

Therefore, if an amount of energy greater than band gap energy is given to one of the electrons in the valence band, a jump of the electron into the conduction band will occur, and a hole will be left in the valence band [124]. The extra energy, given to electrons in the valence bands, that make the possibility of the "jump", and consequently the possibility to the material to behave as a conductor comes from either thermal excitation or from the passage of a charged particle. Also electrically charged particles can transfer some of their energy to electrons propelling them into the conduction band, this can seem superfluous but is actually one of the most important process in detector physics.

Silicon's supremacy Silicon is the second most abundant element in the earth. Of all the semiconductor detectors, silicon detectors are the most frequently used. Several are the reasons that explain silicon's supremacy over semiconductors such as Germanium, GaAs, SiC, and also diamond. The use of silicon, over the last 68 years (in 1954 was implemented the first silicon based

transistor), accomplished a tremendous growth in the microelectronics industry due to wide commercial applications. This implies that today silicon detector production is based on well known industrial technology. Silicon also has good mechanical properties; it can be easily shaped into small dimensions; it has enough rigidity to allow thin self-supporting structures, and it can be operated at room temperature [98]. Concerning particles-silicon interaction, it is known that particles in silicon have a long mean free path (MFP), and indeed, silicon has a sufficient collection charge efficiency. The band gap of silicon is 1.12 eV (figure 2.4) and the average energy required to produce an electron/hole pair is very low 3.6 eV (the energy left goes to phonon excitations) [10]. High carrier yield a better energy resolution and high signal. High specific density 2.33 g/cm^3 allow silicon to have high specific energy

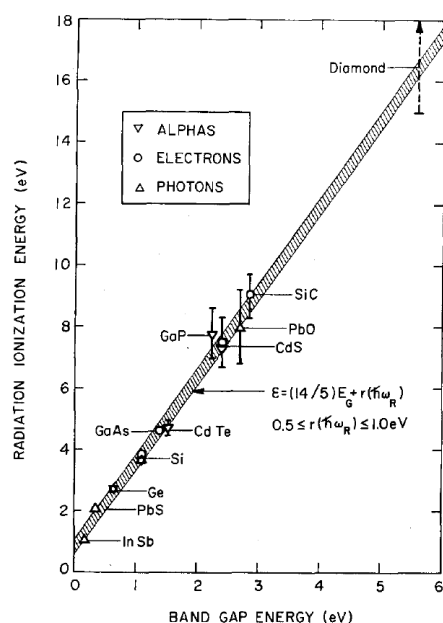


Figure 2.4: Average amount of incident radiation energy consumed per generated electron-hole pair, as a function of the energy band gap [54].

loss dE/dx (M.I.P.) $\approx 3.8 \text{ MeV/cm}$ (about $108 \text{ e-h}/\mu\text{m}$ in average). Thinner detectors can be manufactured with the resultant improvement in spatial resolution.

Moderate atomic number $Z=14$ and high carrier mobility $\mu_e=1450 \text{ cm}^2/\text{Vs}$, $\mu_h=450 \text{ cm}^2/\text{Vs}$ give respectably low multiple scattering, and fast charge collection ($<10 \text{ ns}$) [117]. Silicon has a crystalline structure and is radiation hard. Diamond is usually referred to have a better radiation hardness compared to silicon [26], and can be a good competitor for high-intensity collider experiments. On the other hand, diamond have a large band gap which yields a low signal, and moreover seams to be significantly effected from polarization with a significant radiation induced signal degradation [153]. Diamond is also expensive to manufacture and therefore not suitable for large detectors.

2.0.2 Temperature, Doping, and the P-N junction

Temperature's impact on semiconductors In a detector, the process of electron/hole production, as mentioned several times, can be due to the passage of a charged particle but can also be a consequence of the thermal condition. Electrons are fermions, hence they obey to the Pauli exclusion principle and the Fermi-Dirac statistic. The probability of finding an electron in a state with energy E can be expressed by the Fermi-Dirac distribution function (2.0.1). The distribution clearly shows the contribution of the temperature T and also the importance of the Fermi energy level E_F .

$$f(E, T) = \frac{1}{e^{(E-E_F)/kT} + 1} \quad (2.0.1)$$

E_F = Fermi energy

T = Temperature of the system

k = Boltzmann constant

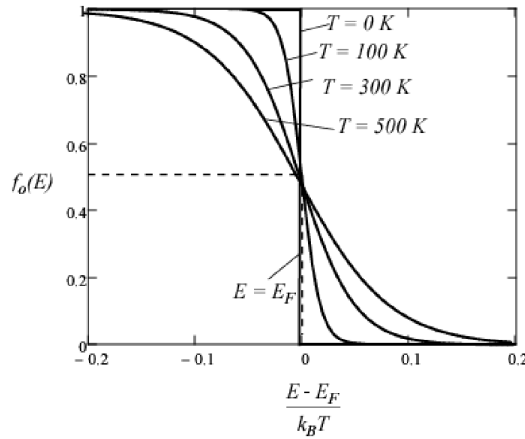


Figure 2.5: The Fermi-Dirac distribution at different temperatures [157] .

As the temperature rises, the distribution changes from a sharp step function to a much smoother curve, as shown in figure 2.5. When the temperature increases, the probability of finding an electron at an energy level above the Fermi

energy level is no longer zero and, furthermore, increases with the temperature. Electrons excited by higher temperatures go into the conduction band, leaving holes in the valence band. The process is reversible, and electrons from the conduction band may recombine with the holes in the valence band. Excitation and recombination of charge carriers per given temperature reach an equilibrium. In silicon with not impurities (intrinsic silicon), the carrier density for electrons n_e and for holes n_h is the same. The 2.0.2 relation shows how the intrinsic carrier concentration n_i changes with the temperature T [173], the energy gap is written as E_g , and k is the Boltzmann constant.

$$n_e = n_h = n_i \quad n_i \propto T^{\frac{3}{2}} \cdot \exp\left(-\frac{E_g}{2kT}\right) \quad (2.0.2)$$

In pure silicon at room temperature ($T \approx 300$ °K) the intrinsic carrier concentration n_i is equal to $1.45 \cdot 10^{10} \text{ cm}^{-3}$. Silicon crystal has about 10^{22} atoms per cm^3 , this means that about one in 10^{12} silicon atoms is ionized. For a silicon detection layer with a thickness $d=300 \text{ } \mu\text{m}$ and an area $A = 1 \text{ cm}^2$, the number of thermal created e-h+ pairs (noise), is equal to:

$$\text{noise} = n_i \cdot d \cdot A \approx 4.35 \cdot 10^8 e^- h^+ \text{ pairs} \quad (2.0.3)$$

Taking into account the same silicon detection layer and that the mean energy loss per flight path of a minimum ionised particle (MIP) is $dE/dx = 3.87 \text{ MeV/cm}$ (proton in silicon). The created e-h+ pairs by the minimum ionised particle are:

$$\frac{dE/dx \cdot d}{I_0} = \frac{3.87 \cdot 10^6 \text{ eV/cm} \cdot 0.03 \text{ cm}}{3.62 \text{ eV}} \approx 3.2 \cdot 10^4 e^- h^+ \text{ pairs} \quad (2.0.4)$$

The number of thermally generated electron/hole pairs is four orders of magnitude larger than the signal from the minimum ionizing particle [117]. The silicon detection layer has to be cooled or the number of free charge carriers must be decreased using other techniques.

Doping silicon and the p-n junction The key point is the following: the probability of finding an electron in a state with energy E , as shown in 2.0.1 relies on the Fermi level, which itself is affected by the semiconductor impurities, and can then be shifted. Impurities are added into the semiconductor material ("doped") to have specific regions of the material be p-type, having more holes than electrons, or n-type, having more free electrons than holes (top left figure 2.6). The addition of acceptor atoms (p-type doping) causes the Fermi level to move toward the valence band. The addition of donor (n-type doping)

does move the Fermi level towards the conduction band [173]. The n-type region and p-type region are then joined together and the so-called p-n junction is built. This is useful because at the junctions of these regions a depletion zone is formed (figure 2.6 (a) left). The depletion zone is a zone between the p-type and n-type regions that has no charge carriers because the electrons from the n-type region move to fill the holes in the p-type region creating neutral atoms in the p-type region and leaving behind neutral atoms in the n-type region. In other words, due to the fact that the Fermi level E_F at equilibrium must be constant, the conduction band E_C and the valence band E_V has to curve at the junction, as shown in figure 2.6 (a) right.

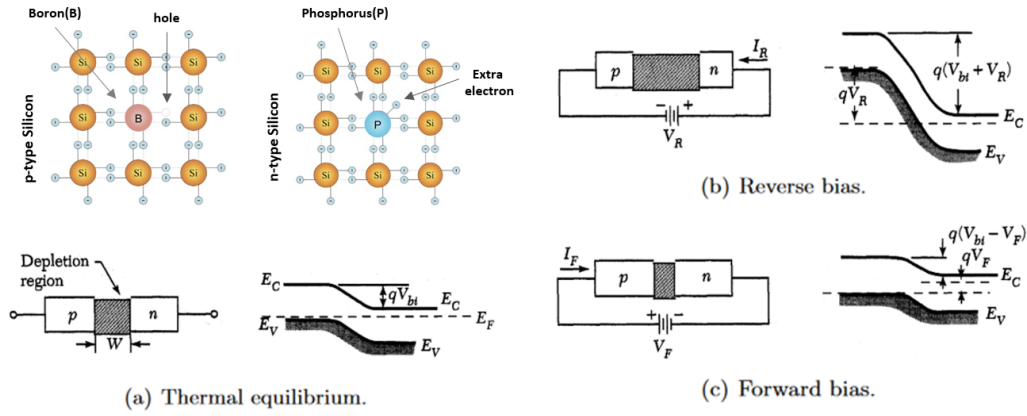


Figure 2.6: On the top left: insertion of p-type dopant (boron) and n-type dopant (phosphorus) into the silicon crystal lattice. On the bottom left, and top and bottom right: P-N junction with the depletion region and the band diagram at a) thermal equilibrium, with b) reverse bias, and with c) forward bias [85] [173].

The variation of the difference between the E_C , E_V and E_F causes the drift of the electrons to the n-type region, and the holes in the p-type region. This creates, at equilibrium, the so-called built-in potential V_{bi} [173].

$$\begin{aligned} N_a &= \text{doping concentration of acceptors} \\ N_d &= \text{doping concentration of donors} \end{aligned} \quad V_{bi} = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2} \quad (2.0.5)$$

By placing electrodes on either side of the regions and applying a reverse bias voltage, V_R , across the junction, the depletion zone can be extended [124]. The opposite, the reduction of the depletion region, occurs if a forward bias voltage, V_F , is applied. These effects, with a schematic representation of the

p-n junction configurations ((b) reverse and (c) forward bias), and their correspondent band diagrams, can be seen on the left of the figure 2.6 .

The Poisson equation 2.0.3 describes the electrostatic potential $V(x)$ [10]. Doing a first integration $\mathcal{E}(x)$ can be determined. By integrating twice the following two important relations (2.0.8, 2.0.9) can be found.

$$\frac{d^2 V}{dx^2} = \frac{-\rho(x)}{\epsilon_s} \quad \rho(x) = \mp e N_{a/d} \quad (2.0.6)$$

$$\mathcal{E}(x) = -\frac{q N_a}{\epsilon_s} (x - x_p) \quad x_p \leq x \leq 0 \quad \mathcal{E}(x) = \frac{q N_d}{\epsilon_s} (x_n - x) \quad 0 \leq x \leq x_n \quad (2.0.7)$$

ϵ_s is the semiconductor permittivity. N_a and N_d are the doping concentrations (n-type, p-type). P side of the depletion layer correspond to $x_p \leq x \leq 0$ and the N-side of the depletion layer to $0 \leq x \leq x_n$. The electric field must be continuous than equating the two equations for the electric field at $x=0$ yields $N_a x_p = N_d x_n$. The depletion zone is defined as: $W_{dep} = x_n - x_p$ and N is the lighter doping concentration. C_{dep} is the depletion-layer capacitance and A is the area [11] [76] .

$$W_{dep} = \sqrt{\frac{2\epsilon_s (V_{bi} + V_R)}{qN}} = \sqrt{\frac{2\epsilon_s \times \text{potential barrier}}{qN}} \Rightarrow V \propto W^2 \quad (2.0.8)$$

$$\frac{1}{C_{dep}^2} = \frac{W_{dep}^2}{A^2 \epsilon_s^2} = \frac{2(V_{bi} + V_R)}{qN \epsilon_s A^2} \Rightarrow C \propto V^{-\frac{1}{2}} \quad (2.0.9)$$

This means that as the bias across the silicon is increased, so is the depletion zone, while the capacitance of the silicon decreases [76]. The journey thought the constituent principles of silicon detectors is not complete. Up to now it is possible to conclude the following: intrinsic silicon can not be used as detection layer because the presence of thermal noise, a doping technique and the creation of the p-n junction is used to form a depletion region that is enhanced by an electric field. At this point, when a charged particle passes through the depletion zone, the particle will ionize the surrounding atoms and the newly created electron-hole pairs along the particle path through the material (track) will move to the electrodes, under the influence of the applied electric field. The movement of the charge carries induce the correspondent charge for read-out [124]. The explication of this final stage has to be addressed. In the next

paragraph, a brief description of the motion of the charge carriers, the corresponding induced signal, and the succeeding signal processes will be given.

2.0.3 Moving charges, Induced Signal, and Signal Processing

Motion of the charge carriers As already mention, the charge carriers in gases are electrons and ions, and in solids electrons and holes. In both cases, the Boltzmann transport equation is able to describe the motion of the charge carriers in dependence on the external field E . Equation 2.0.10 is refereed as the transport equation with the relaxation time approximation. The approximation implies that the deviation from the equilibrium distribution f_0 (the Fermi-Dirac distribution 2.0.1) is small, so the field is weak enough that the equilibrium state is not significantly disturbed [12]. The non-equilibrium distribution function f describes the probability of finding a particle at position $\vec{r}$, with momentum $\vec{k}$ and at time t [162].

$$f(\vec{r}, \vec{k}, t) \quad \frac{\partial f}{\partial t} = -\frac{\vec{F}_{\text{ext}}}{\hbar} \cdot \nabla_{\vec{k}} f - \vec{v} \cdot \nabla_{\vec{r}} f - \frac{f - f_0}{\tau} \quad (2.0.10)$$

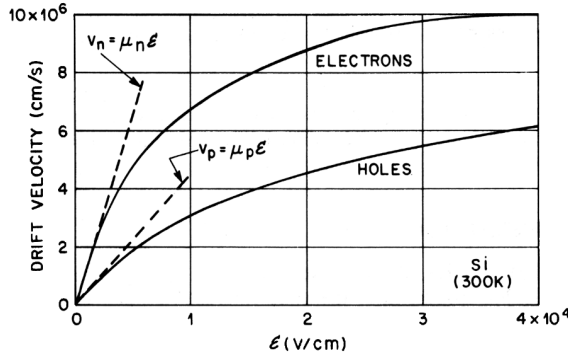
Three terms can be easily recognised. The fist one is the drift term, is due to the influence of the driving force that will change the electrons momentum. In our case the force is given by the applied external electric field. The second term is due to the diffusion of electrons, carriers will flow into and out of any volume element around r [19]. The last term represents the dissipative forces, the interaction of the charge carriers with the semiconductor crystal. It is called collision term and represent the scattering events that return the system to equilibrium if the external force is removed [155]. The τ is the time constant that the system requires to return to its equilibrium [12].

On the basis of the transport equation, the macroscopic observables of the ordered and the unordered concentration-difference based motion of the charge carriers, i.e., drift and diffusion, can be determined as collective properties of the correspondents distributions [12]. The Drift-Diffusion equations for electrons J_n and holes J_p are shown in 2.0.11.

$$J_n = q(n\mu_n\vec{E} + D_n\vec{\nabla}_r n) \quad J_p = q(p\mu_p\vec{E} - D_p\vec{\nabla}_r p) \quad (2.0.11)$$

n and p correspond to the charge carrier densities. μ_n, μ_p the mobilities of the electrons and holes. $D_{n,p}$ depends on the semiconductor material and are the diffusion coefficients for electrons and holes, respectively.

Drift time and the induced signal The previous results show the importance of the drift and diffusion processes. Focusing on the drift of electrons and holes in silicon detectors, it is also important to evaluate the drift time. The knowledge of the time when the charge carriers reach the electrodes is useful to better understand the collection charge process and if this influences the rise of the signal current in the front-end electronics. Considering a $300\mu\text{m}$ thick silicon detector layer at room temperature $T = 300^\circ\text{K}$, that the charge carriers mobility values are approximately $\mu_n \approx 1450 \text{ cm}^2/\text{Vs}$ $\mu_p \approx 450 \text{ cm}^2/\text{Vs}$ and a typical value for E is $2.5\text{kV}/\text{cm}$, the drift time for electrons t_n is 9 ns and for holes t_p 27 ns [119] (equation 2.0.12).



$$\vec{v}_{n,p} = \mu_{n,p} \cdot \vec{E} \quad \mu_{n,p} = \frac{e\tau_{n,p}}{m_{n,p}}$$

$$t_{n,p} = \frac{d}{v_{n,p}} \quad (2.0.12)$$

Figure 2.7: On the right: drift velocity in silicon at room temperature as function of the electric field. On the left several equations regarding the charge carriers are shown: drift velocity $\vec{v}_{n,p}$, carries mobility $\mu_{n,p}$, and drift time $t_{n,p}$. The $\tau_{n,p}$ is the mean free time between collisions, and $m_{n,p}$ the effective mass for electrons and holes [107].

Therefore, the drift time for electrons and holes in silicon differ. The electrons reach the associated electrode much earlier. The effect can also be seen in the above graph, 2.7. The graph also shows that the evaluated drift velocity equation for the electrons/holes holds for a small electric field. Much more generally, the process is described by the empirical drift velocity $\mathbf{v}_{e,h}$ relation (2.0.13)[154].

$$\mathbf{v}_e = \frac{\mu_e E}{\left[1 + \left(\frac{\mu_e E}{\mathbf{v}_{e,sat}}\right)^{\beta_e}\right]^{1/\beta_e}} \quad \mathbf{v}_h = \frac{\mu_h E}{\left[1 + \left(\frac{\mu_h E}{\mathbf{v}_{h,sat}}\right)^{\beta_h}\right]^{1/\beta_h}} \quad (2.0.13)$$

The $\mu_{e,h}$ is the low field mobility for electrons and holes, and $\mathbf{v}_{e,h,sat}$ the corresponded saturation drift velocity, which is attained at high fields in silicon. The exponent β , which can differ for electrons β_e and holes β_h , typically lies between one and two [20].

As soon as the charge carriers are generated by an traversing particle, they start to move. The velocity is $\mathbf{v} = \sum_i \mathbf{v}_{i,e} + \sum_i \mathbf{v}_{i,h}$ [154]. It is usually thought that the generated signal is due to the collection of charges by the electrodes. In a real detector where the electrodes are not infinitesimal thin, the previous statement is not correct [125]. Indeed, as illustrated in figure 2.8, the generated signal current begins as soon as the charge carriers move. When the charge carriers reach the electrodes, the signal does stop. This is because the measured signal is an induced signal generated by the motion of the charge carriers. The Shockley–Ramo theorem is usually used to quantify the induced, charge Q (2.0.14) and current i (2.0.15) on the electrode by the moving charge q [51].

$$Q = -q\varphi_w(\mathbf{x}) \quad (2.0.14)$$

$$i = q\mathbf{v} \cdot \mathbf{E}_w(\mathbf{x}) \quad (2.0.15)$$

φ_w = weighting potential
 $\mathbf{E}_w$ = weighting field

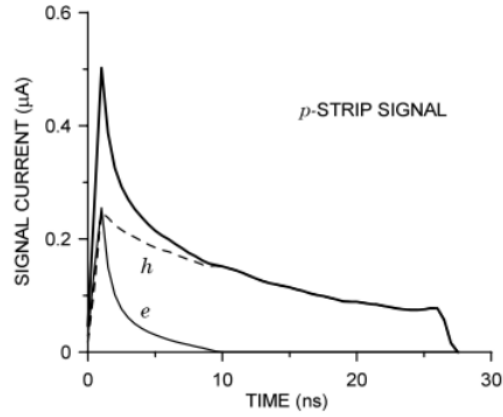


Figure 2.8: Strip detector signals current for an n-bulk device with 60 V depletion voltage operated at a bias voltage of 90 V. Integrated the signal current of course it is possible to know the total charge [20] [51].

The Shockley–Ramo theorem assumes that the electric field propagates instantaneously and also does not take into account possible magnetic effects. The weighting potential φ_w is the potential at the charge's instantaneous position $\mathbf{x}$, when all charges are removed, the electrode k is to unity potential and all others electrodes are grounded [154]. The weighting potential is found by solving the Poisson equation with the mentioned boundary condition. The weighting field depends only on the geometry and defines how the charge motion couples to the electrodes [20]. It is uniquely determined with the following relation $\mathbf{E}_w = -\nabla\varphi_w(\mathbf{x})$ [51].

As just described, the incident radiation interacts with the sensor and a current signal is induced on the electrode, which in the case of the solid state silicon detector can be a strip or a pixel. From now on, other steps are needed to convert

this analog signal into a digital one in such a way that the given information can be easily handled. The next paragraph aims to give a brief explanation of the basic Front-end signal processing functions.

Front-end basics of signal processing The acquisition of the short signal induced by the passage of radiation through the detector and the extraction of the useful information is attained by the analog and digital front-end electronics with the detector's signal processing system [1]. A readout design of semiconductor detectors is typically driven by several factors, including high-speed operation, low power consumption, low-noise performance, and also the system's efficiency in operating in a high radiation intensity environment. All of this has to be addressed taking into account the main priorities of the detector purpose: amplitude or timing of the output pulse, the minimum detectable signal, the and event rate [75]. A unique general solution for the optimization of all parameters do not exist, however a typical structure for the readout can be presented. A simple schematic representation of the front-end basic signal processing functions is shown in Figure 2.9. The functions are the following: preamplification, pulse shaping, and the analog-to-digital conversion of the data.

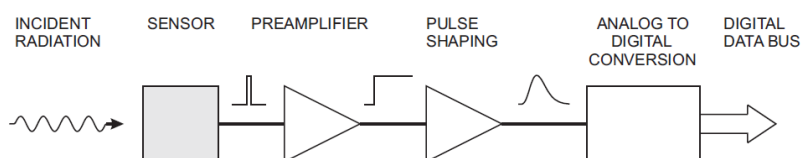


Figure 2.9: Front-end detector signal processing diagram: the radiation is absorbed in the detector sensor and generates a signal; the low-level signal is integrated in a preamplifier and sent to the pulse shaping; finally with the analog to digital system the signal is digitized. [75].

Preamplification: a preamplifier is required because the signal charge in a typical high-energy tracking detector is fairly weak (around 4 fC). The preamplifier can be seen as an ideal integrator that detects an input charge burst $Q \delta(t)$ [87]. The preamplifier has to be designed and optimized to deal with the statistical fluctuations and noise that usually can come up from different sources. It is mounted as close as possible to the electrode, this because the signal-to-noise ratio depends on the total capacitance in parallel with the input, i.e. the sensor capacitance, that as before highlight decreases as the bias voltage increasing, and also by the input capacitance of the amplifier [20].

Pulse shaping: the signal produced by the preamplifier has to be shaped, i.e., the amplitude (further amplification) and timing of the signal have to be adapted to the requirements of the predefined desired output signal. The pulse shaping system is a filter that aims to limit the signal's duration and optimize the signal-to-noise ratio taking care of the frequency response. Semiconductor detectors in HEP require a very high rate. Typically, many pulses one after the other have to be detected, so the signal's duration has to be modulated in a way to avoid pile-up. As the well known double-hit effect prove a signal with a large pulse width might interfere with the subsequent pulses and will give a wrong interpretation of the data in the next digitization process [20].

In the design of both the preamplifier and the pulse shaper, an important parameter to be taken into account is the Equivalent Noise Charge (ENC). It quantifies the overall noise at the input of the preamplifier-pulse-shaper unit. It comes from different sources, as illustrated in the equivalent circuit for noise analysis displayed in figure

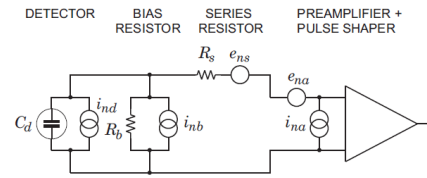


Figure 2.10: Equivalent circuit for noise analysis of detector [65].

2.10. The detector is represented by the capacitance C_d with the bias voltage applied through R_b . The resistance R_s indicates all the resistances in the input path. In the figure 2.10, i_{nd} is the sensor leakage current noise (shot noise), i_{nb} the shunt resistor noise (thermal noise), e_{ns} the series resistor voltage noise (thermal noise). i_{na} and e_{na} are the amplifier voltage and current equivalent-noise, this include thermal, shot, and flicker noise contributions [114] [75] [14].

Analog to digital conversion: the digitization of the data is usually the last step in the analog signal processing chain. The shaped pulse is converted into a digital signal through an ADC system. The conversion is used to analyze and store the relevant information contained in the signal. The typical methods used are the following: digital ramp ADC, successive approximation ADC, tracking ADC, Wilkinson ADC, flash ADC, hybrid ADCs. Generally speaking, analogue-to-digital conversion systems are often based on comparators, and increasing speed implies a decrease in the resultant resolution [1] [20].

3 Strips and the CMS 2S module

This chapter focus on the strip technology and the CMS tracker Upgrade project. A primarily characterization of 2S module first prototypes is exhibit with the IV curves current-temperature dependence measurements and CMS binary chip 3 (CBC3) calibrations.

3.1 Micro-strips sensor

Even though, silicon detectors technology originated about 60 years ago, at that time microelectronics was in its early stages, no silicon based large-scale detectors were used in particle physics [52]. Around the mid-70s physicists were struggling to find a device able to identify and measure short-living particles with lifetimes in the order of 10^{-13} s ($c\tau$ 30 μm), investigations on silicon detectors started [33] [79]. The first silicon based detector for particle physics it was a micro-strip device. It was developed in 1980, and a modified version using the planar technology was installed in the NA11 experiment at CERN in 1983. Micro-strips sensors part of the solid-state silicon detector family are characterise to have a collection of strip-shaped implants that serve as the charge collecting electrodes, an illustrations is shown in figure 3.6. In the previous chapters: general description of detection principles, properties and basic signal processing concepts of silicon detectors were exploit. From the early beginning until now, silicon strip detectors as all the other types of silicon detectors saw tremendous growth as a result of: semiconductor exponentially growing industry, the miniaturization processes, resultant development of Application Specific Integrated Circuits (ASIC), in-

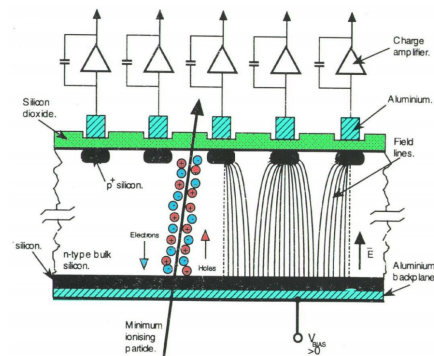


Figure 3.1: microstrip sensor [86]

crease of the computing power and also the advancements in interconnecting techniques i.e micro bonding [57]. Silicon strip detectors are today used in a variety of experiments, e.g. ATLAS, BaBar, CMS, LHCb, PHENIX, not only in the high- energy physics, but also in astroparticle physics (AMS, GLAST), medical physics and X- ray imaging. They evolved, played, and will still continue to play an important role in particle detecting systems in the coming decades [28].

3.2 CMS Tracker Upgrade project

The forthcoming HL-CMS tracker, set to become operational in 2028, it will make an extensive use of silicon strips based detectors. This decision is motivated by a number of factors: strips sensors are based on simple well known and tested technology, they well fit for large-area fabrication [28], and per unit area are relatively cheap compered with similar technologies, hence are ideal for large tracking systems, such as, the new CMS tracker. In figure 3.2 one-quarter schematic, in the $r - z$ view, of the proposed tracker is shown.

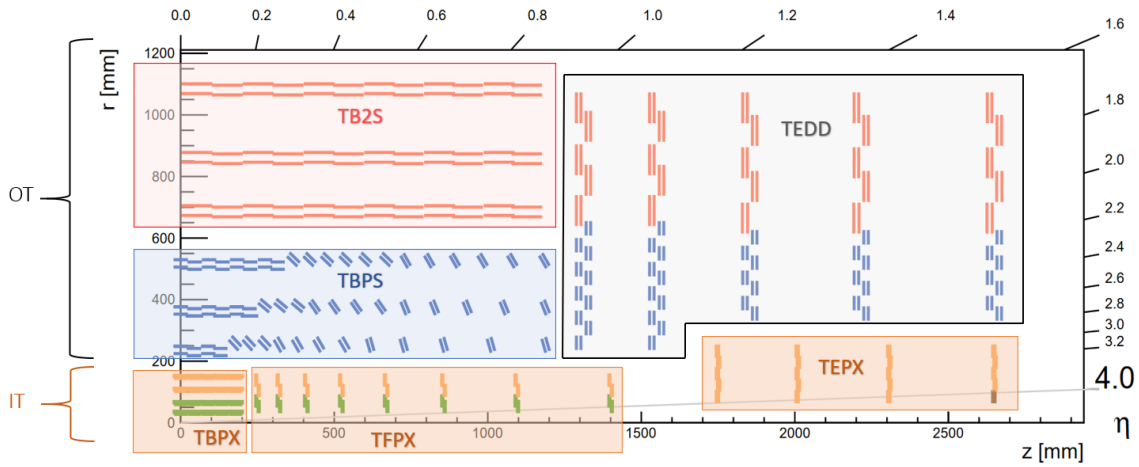


Figure 3.2: One-quarter schematic, $r - z$ view, of the tracking system. The inner tracker (IT) 1x2 and 2x2 readout chips modules, and Outer Tracker (OT) PS and 2S modules are respectively drawn in green, yellow, blue and read. In addition, all tracker sub-sectors TBPX, TFPX, TEPX, TB2S, TBPS, and TEDD are shown [58].

In order to build the new CMS tracker, the existing one has to be entirely dis-mounted. As mentioned in paragraph 1.6 the HL-LHC will significantly increase the instantaneous peak luminosity; the design parameters of the exist-

ing detector do not match the new requirements, radiation tolerance, granularity, and rate capability have to be improved. Moreover, due to the harsh HL-LHC data taking conditions, it is critical for the Outer Tracker to provide online trigger information in order to guarantee high physics performance. The new tracker, as illustrated in 3.2 will be made up of an Inner Tracker (IT) composed of silicon pixel sensors and an Outer Tracker (OT) comprised of and hybrid design with macro-pixels and strips. All the tracker sections have a cooling system that allowed the sensors to operate below -20°C and, as a result, enhance detection efficiency [61] [41].

3.2.1 Hardware

The Inner Tracker aims to improve tracking capabilities, in particular vertexing performance and provide coverage up to a pseudorapidity of $\eta \approx 4$. The task has to be carried out in an environment characterized by the most intense detector's particle fluxes. The IT as shown in the following figure 3.3 is subdivided in three subsections TBPX, TFPX, TEPX. The TEPX, in addition to the tracking work performs background and luminosity measurements [58] [36].

- TBPX · · tracker barrel pixel detector (barrel with 4 layers)
- TFPX · · tracker forward pixel detector (8 small double-discs)
- TEPX · · tracker end cap pixel detector (4 large double-discs)

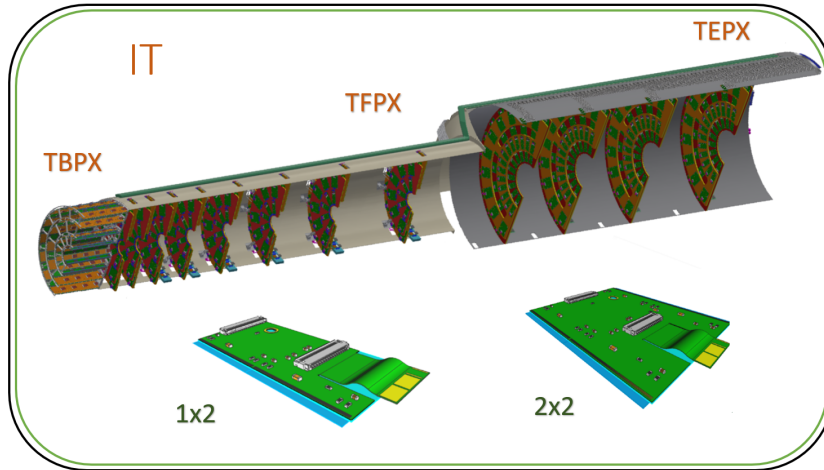


Figure 3.3: One quarter of the Inner Tracker (IT), with the TBPX ladders and the TFPX, TEPX dees inside their mechanical supporting structures [41]. Also a sketch of the IT 1x2 ($1.8 \times 4.4 \text{ cm}^2$) and 2x2 ($3.7 \times 4.4 \text{ cm}^2$) pixel modules are shown [64].

The inner tracker will cover a surface $S \approx 4.9m^2$ composed of hybrid pixels modules with two or four (1x2, 2x2) readout chips (ROC chips) for a total of two billion channels. High granularity will be attained through tiny pitch pixel cells with either a rectangular, $25 \times 100 \mu m^2$, or a square, $50 \times 50 \mu m^2$, layout [64].

The Outer Tracker as well aims to improve the tracking capability, howbeit also will perform a first selection of interesting events with a stub-based system (other details are described in the next paragraph). The OT as shown in picture 3.4 is subdivided into three subsections named TB2S, TBPS, and TEDD. These sectors of the tracker will make extensive use of the strip-strip (2S) and the macro-pixel strip (PS) modules (3.4) this as already outlined, it is because they are today the most well fit technology for a so large system.

- TB2S · · tracker barrel with 2S modules (372 ladders, with 12 modules)
- TBPS · · tracker barrel with PS modules (3 layers with flat-tilted sections)
- TEDD · · tracker endcap double-discs (10 double-disc, 5 for each endcap)

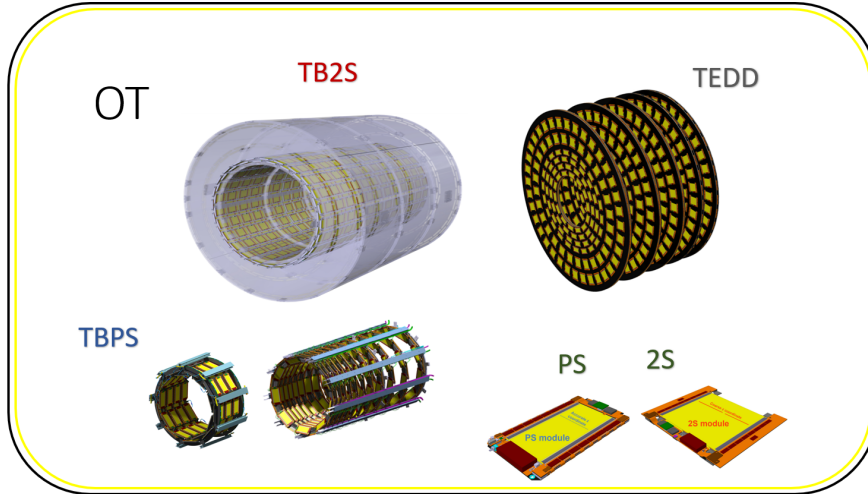


Figure 3.4: Innermost layer of TB2S, TEDD unit , TBPS layer 1 with the central flat section and tilted section. The PS and 2S modules are also shown [41].

The complete outer tracker with 7680 strip-strip and 5616 pixel-strip modules covers a large surface, $S \approx 190m^2$, with about a total of 213 million readout channels [41]. The 2S module design and the electronic front-end readout system will be discussed in detail in the following paragraphs.

pT tracks and the 2S module FE-BE The new CMS tracker has to implement trigger capability to process the enormous amount of data that will be delivered by the high luminosity LHC. In the HEP-LHC context, it is possible to identify interesting events just looking at charged particles with medium or high momentum, $p_T > 2$ GeV. To still maintain good efficiency for the electroweak physics, but also to get a remarkable data volume reduction this has to be handled by the trigger decision system. The CMS Phase II Outer Tracker will identify hits coming from high momentum tracks, p_T , with the so called:

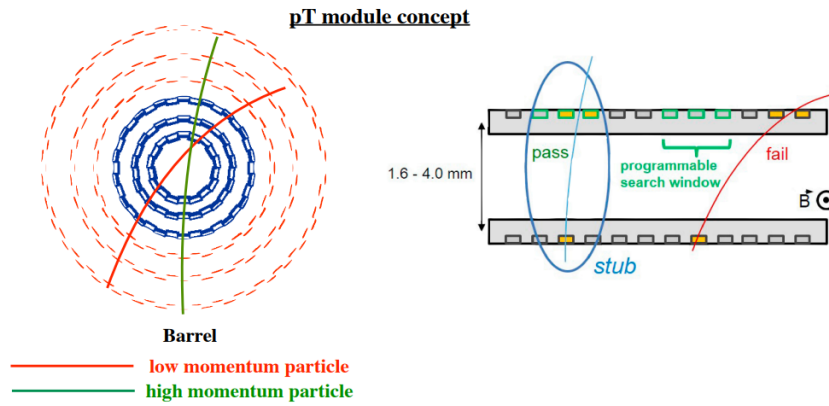


Figure 3.5: Cross section of the outer tracker barrel (x-y), and the outer tracker module with the pT principle discrimination system [163] [72] .

stubs technique or trigger primitives system [72] [63]. As shown in figure 3.5 the goal is archived spacing two silicon sensors with a small gap, and one ASIC that correlating the data from both sensors selecting stubs. A stub corresponds to a particle whit small curvature hence with high momentum, the stub can be also tuned whit a programmable research window. Both the PS and the 2S modules implement the trigger primitives system. The 2S module (3.6) is made of two silicon strip sensors (n-type strips in p-type silicon substrate) AC-coupled [25] [105] stacked on top of each other and spaced whit a distance of 1.8 mm or 4 mm. The distance depend on the tracker region where the module will be installed [113]. Each module includes 2032 strips of 5 cm length and 90 μm pitch, also hosts the two front-end hybrid (FEH) and the service hybrid (SEH). In the FEH are placed the concentrator ASIC made of 16 CBC3 (CMS Binary Chip 3) and two CIC (concentrator integrated circuit), the chips are implemented correspondingly in 130 nm and

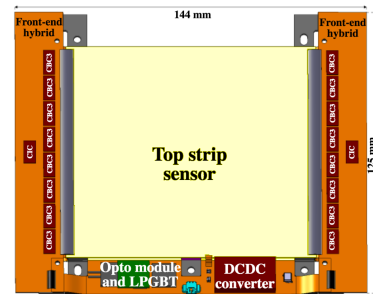


Figure 3.6: The 2S module [56].

64 nm CMOS (Complementary metal-oxide-semiconductor) technology [80] [112]. In the SEH are placed the lpGBT (low-power Gigabit Transceiver), the VTRx+ optical link, and the power distribution system with the - converters and the high voltage distribution circuitry [58].

The 2S FE-BE (Front-End - Back-End) data flow (figure 3.7) is the following: each CBC read out 256 strip channels, 127 of the top sensor and 127 channels of the bottom sensor, executes hit correlations and per bunch crossing send the data to the the CIC [83]. Two data stream from each of the 8 connected CBCs are managed by the CIC: the trigger data stream, that contain information useful to form a trigger decision, and the raw data that passed the Level 1 trigger [111]. The CIC then aggregates the digital data formatting it into data packets, and finally sends them to the service hybrid. In the SEH the data of the full module, from both the left and right FEHs, are merged and sent via a single optical fibre to the back-end system [106].

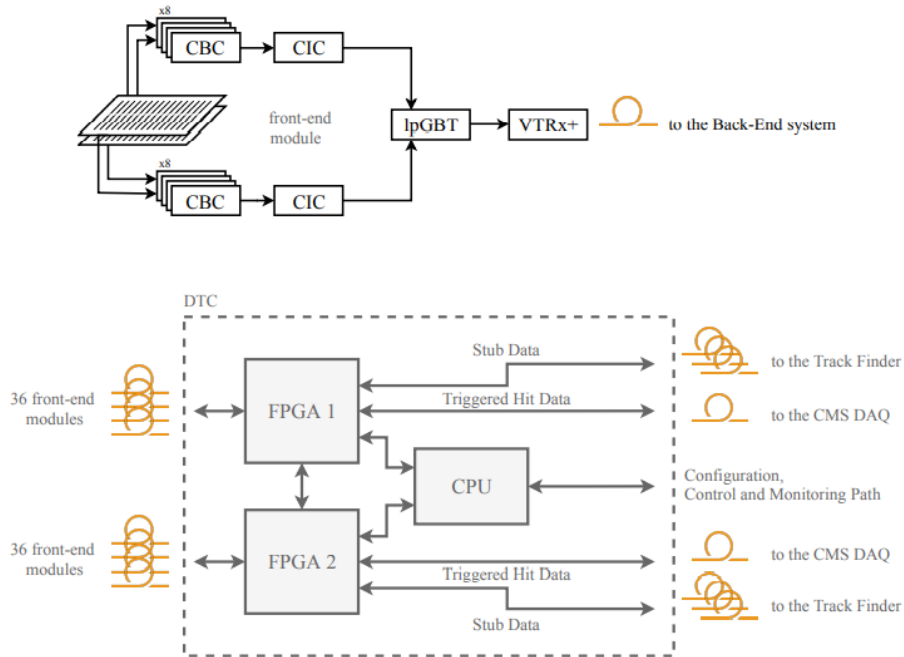


Figure 3.7: Sketch of the data flow for the 2S module front and back-end [150].

The back-end board, based on two FPGAs and a System on Chip (SoC), receive the data from 72 modules, and work as a DAQ, Trigger and Control (DTC) system. The two FPGA perform the data formatting and aggregation, then stub data pre-processing, and with a latency in the order of microseconds continuously send the data stream to the Track Finding (TG). The FPGA also decode

the L1 (Level-1) data readout on the way to the central CMS DAQ. The SoC equipped with a multi-core CPU with a clock speed in the order of few GHz and tens of GB storage is responsible for the configuration, control and monitoring of the front-end modules and the DTC board itself [172] [150].

3.2.2 Software

The tracker, as already described, is a large apparatus. Like the other CMS sub-detectors, it requires an overall-software approach to effectively perform its tasks alongside the much more general CMS TDAQ system. The CMS Tracker Phase2 Acquisition & Control Framework (PH2_ACF) developed by the CMS Tracker DAQ group will help for this purpose. Indeed, it is designed not just for prototyping but also for the production and final detector operation stages.

The PH2_ACF main goal is to fulfill the needs of all the different front-ends of the Phase II CMS Tracker. The fact that the PH2_ACF is built on an overall-software approach implies that all the non-chip-related utilities can be written and optimized once for all, and then the newly CMS tracker software will be easy to be maintained. The PH2_ACF run on a CERN CentOS 7 (CC7) operating system (OS) and is implemented in C++ 1y (gcc > 4.8). The software is divided into two parts: the so-called middleware (see figure 3.8), which contains the low-level utilities such as reading and writing from chip and board, sending commands such as triggers, reset, setting channel injection, receiving and decoding data, and the calibration procedure. All the calibrations that need to optimize a specific HL-CMS tracking detector have to follow the calibration procedure. The software use the μ HAL library (version 2.7.1) in order to communicate whit the IPbus of the firmware. μ HAL to be fulling working needs the pugixml

XML processing library and the boost library. The Linux machine is then physically connected by an Ethernet wire to a board containing the SoC and the DTC. The software also uses CMake > 2.8 and ROOT 6.10 [175]. ROOT is the open-source data analysis framework used by the HEP community in this case is used

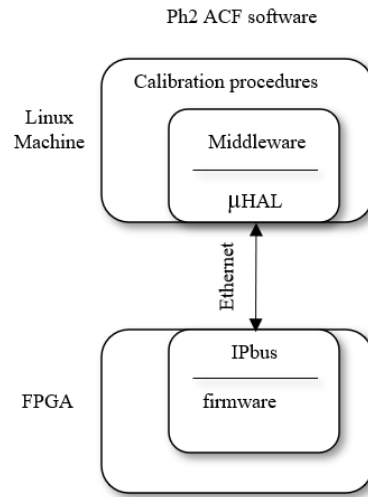


Figure 3.8: High level overview of the _ACF [172].

to make histograms with the data received by the modules. As highlighted in section 1.6, HL-LHC will enhance the luminosity of the collider, and all the detectors will have to improve their rate capabilities. The HL-CMS tracker has to ship from its 2.2 billion readout channels an enormous amount of useful data within the 25ns bunch crossing interval. To tackle this problem the discussed trigger primitives system is used and for the calibrations the SoC solution is implemented. The calibrations run on the SoC and are made ROOT-independent to make them lighter. The data quality monitoring (DQM) system is implemented on a separate Linux machine where the SoC shipped data is received and the ROOT histograms can be constructed. To manage the corresponded data the software use a tensor-containers architecture that follow in parallel the tracker hardware structure. As shown in figure 3.9 the tensor-container has as the first items the detector with IT and OT, then each of them contain the correspondent Beboard back-ends where are attached the OpticalGroups and so on.... until the readoutchips that in the case of the 2S module are the CBCs.

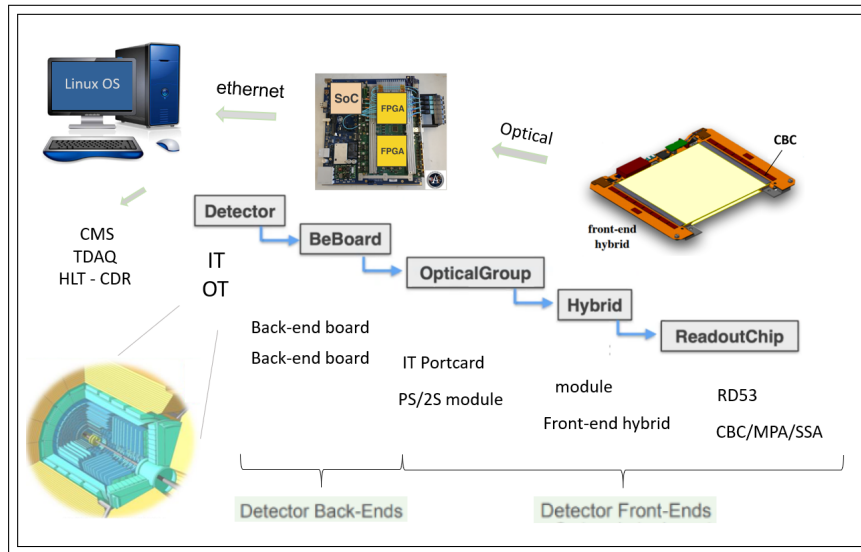


Figure 3.9: Overall schematic of the data flow. The data from the 2S module is sent to the DTC (Data Trigger and control) back-end board that with its SoC (system on chip) and FPGAs that ships correspondingly the data to the data quality monitoring (DQM) system that is based on ROOT and the CMS TDAQ. The different description classes implemented in the software are also shown [172] [163].

3.3 2S Module measurements

The measurements that will be presented in this section were made by the author of this thesis at the Fermi National Accelerator Laboratory (Fermilab) under the young interns program at Fermilab (figure 3.10) [159]. The work is in the context of the CMS-US collaboration for the Phase 2 upgrades, planned for the HL-LHC. The Fermilab outer tracker group is responsible in the assembly and test of 1250 PS modules and 1000 2S modules [148], and also in the development of the discussed Tracker Phase2 Acquisition Control Framework PH2_ACF.

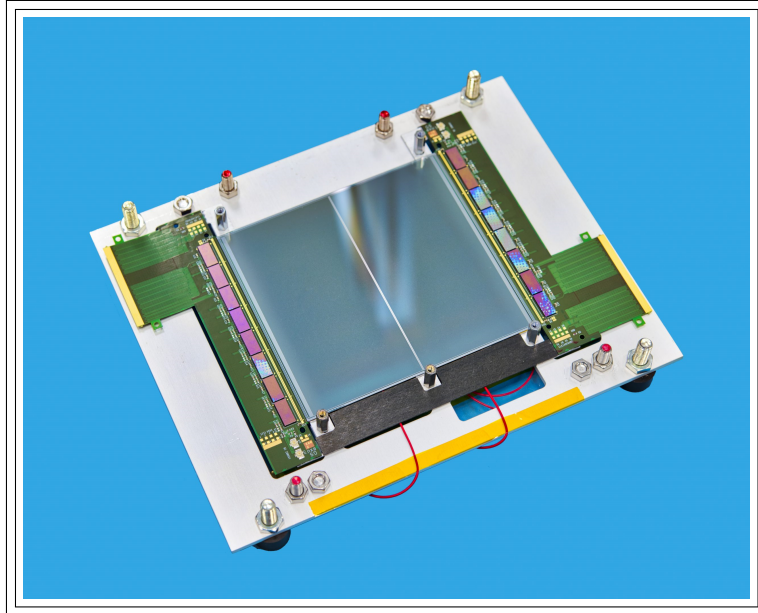


Figure 3.10: Example of a two silicon strip module, 2S, assembled at the Fermi National Accelerator Laboratory (Photo: Reidar Hahn) [156].

The work also concerns both areas: hardware tests on the 2S module first stage prototypes and software developments. A first study is on the temperature variation induced effects of the 2S mini module and 2S first module prototypes. The effort then concentrated on the CMS Phase II tracker's DAQ software with the CMS binary chip three CBC3 calibrations. This work is crucial for the integration the control and readout of 2S modules into the Fermilab Computing Division's OtSDAQ developed framework [159].

3.3.1 Current-Temperature Dependence

The CMS outer tracker's operating temperature will be $-35\text{ }^{\circ}\text{C}$. This will allow to run the detector event, after the large radiation dose accumulated at the end of its lifetime. The thermal conditions as exploited in chapter 2 influence the number of the free charge carriers, or much more precisely, in the reverse bias configuration, the number of the minority carriers, which cause the leakage current. The response of the tracker modules at different temperatures is an important assessment to confirm the operational parameters of the detector. The main issues that the change in temperature can cause concern the mentioned increase in the leakage current, the noise, and also the induction of mechanical stress on the device that, as a consequence, can interfere with the standard operations of the detector. The setup used to study and quantify the temperature-related effects is the following:

- 2S mini module 3-1, first stage prototype 2S module
- TestEquity temperature chamber model 140
- Keithley 2410 Source Measure Unit SMU

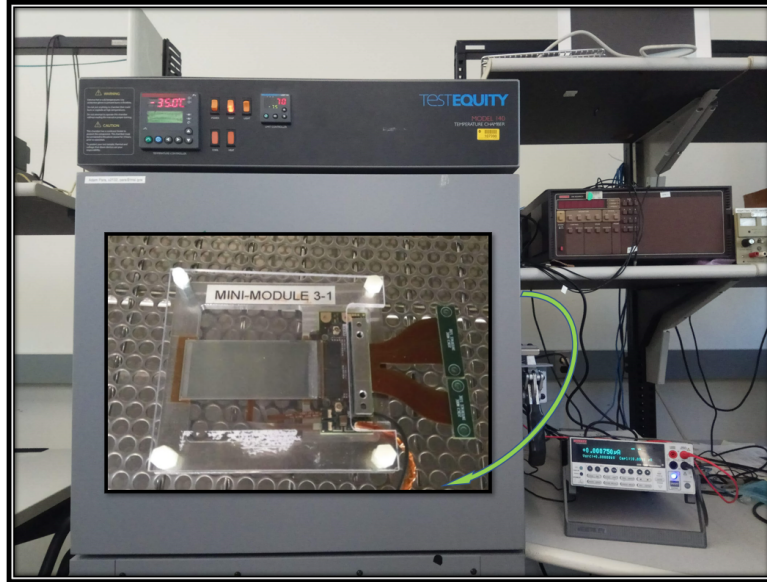


Figure 3.11: 2S module prototypes current-temperature dependence test setup. A 2S mini-module to test, inserted into the climatic chamber, is visible in the central part of the photo.

The device under test (DuT) is placed inside in the environmental chamber, the

chamber allow the control of the temperature in a wide range -73°C to $+175^{\circ}\text{C}$. The test is performed in the range -35°C to $+23^{\circ}\text{C}$, the humidity is maintained at 1 % with a continuous N_2 flux, figure 3.11 illustrate the overall setup. The first DuT is a 2S mini module and consists of two small strips sensors arranged on top of each other, each with 254 strips of 5 cm length and $90\mu\text{m}$ wide. The total active area is about 23 cm^2 .

The test consists of several IV (current-voltage) curve measurements performed at different temperatures. The measured leakage currents are normalized with respect to the active surface of the DuT, obtaining the corresponding current densities (see figure 3.13). The first two measurements were made at room temperature, $T = 23^{\circ}\text{C}$, and the results show that the test is reliable; indeed, the two curves coincide. Then, slowly, the temperature chamber was set in order to cool down the detector under test, and with several steps, the current density–voltage curve, JV, was performed for several temperatures until the final detector operational temperature was reached at -32°C . At the end, a final measurement was again made at room temperature.

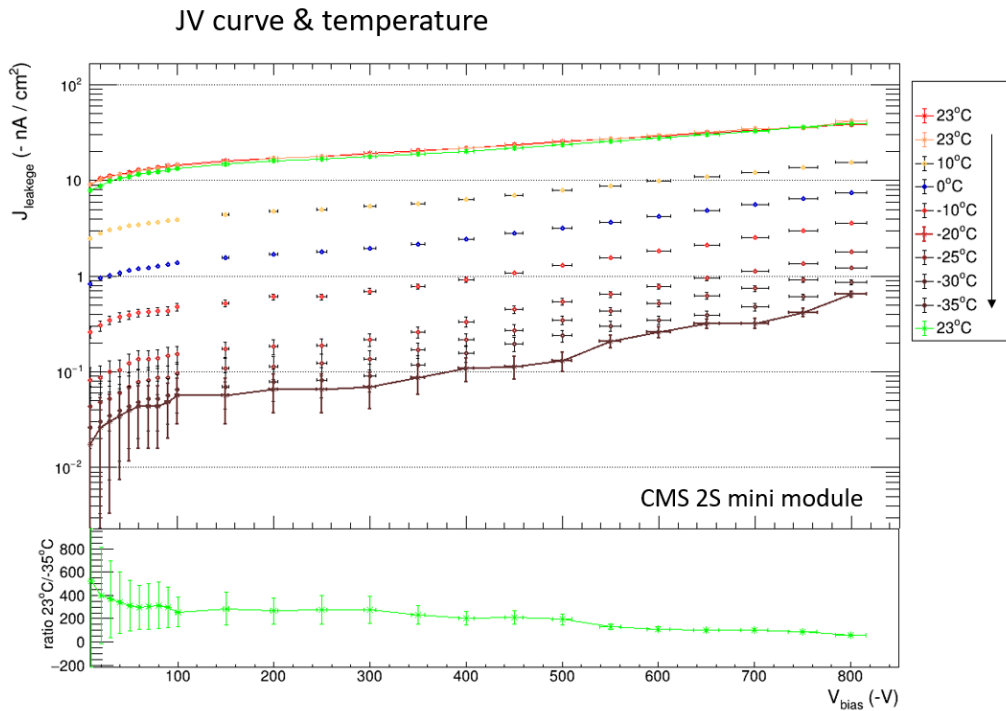


Figure 3.12: 2S mini module JV curves evaluated at given temperature starting from ambient temperature 23°C to the most probable operational temperature of the device -35°C . The ratio between the 23°C and -35°C curve is also shown in a bottom graph.

These measurements clearly show a remarkable decrease on the leakage current when the 2S-mini module is cooled down. For instance, the ratio of the current densities at 23°C and -35 °C at the operational reverse bias voltage $V_{bias} = -300$ V, has a value of 300. Within the error the final measurement, $T = 23^\circ\text{C}$, coincides with the initial measurements done at the same temperature. This means that the DuT was not damaged in the test. It is worthwhile noticing that the device's functionality was unaffected by the temperature-mechanical stress imposed on the DuT. The full test was repeated with a full-size 2S module first prototype (active area = 180 cm^2). In this case, it was detected a decrease in the leakage current at lower temperatures less pronounced than in the previous case. One of the most likely explanations is that the module was not fully thermalized when the measurements were taken, or that this first 2S module prototype was affected by manufacturing defects. This last hypothesis find a confirm in the rapid increase of the current at 300V, which is not expected from an high quality silicon sensor.

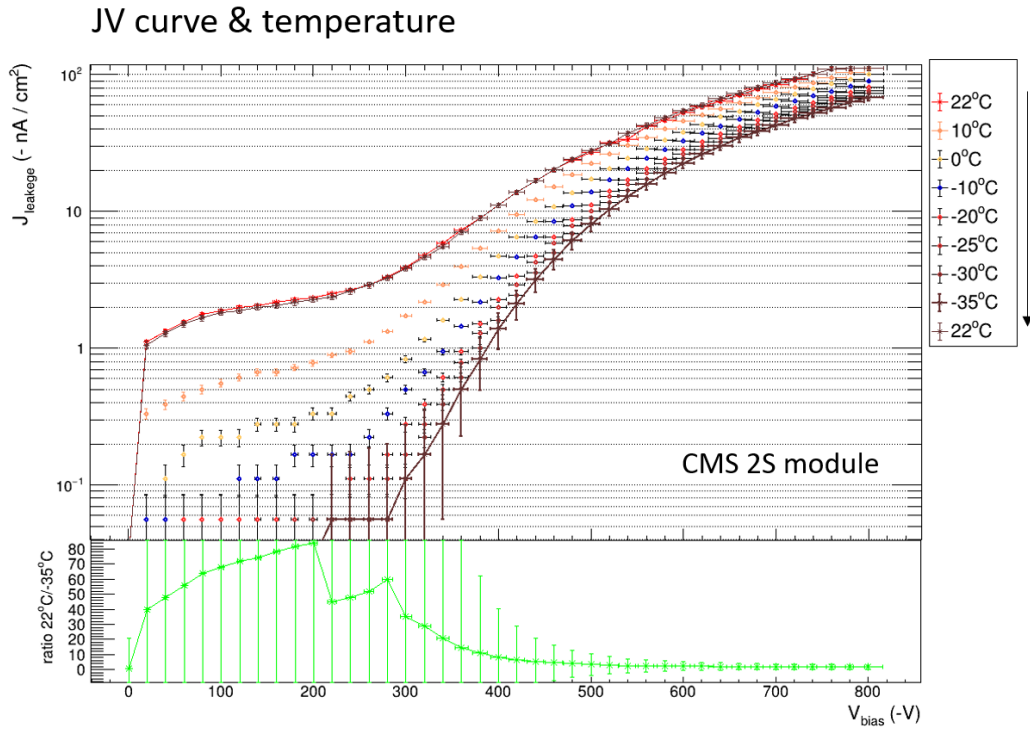


Figure 3.13: 2S module J-V curves measured at several fixed temperatures from ambient temperature 23°C down to -35 °C. The J ratio between the 23°C and -35 °C curve is also shown in the bottom graph.

3.3.2 CBC3 Calibrations

As already mentioned, one of the requirement of the new software, i.e. PH2_ACF, is to decouple the ROOT utilities from the core operations of the CBC3 calibrations of given sensor. The calibrations are performed by the system on chip and the data, that needs to follow the detector's hierarchy, is stored in an object called `DetectorDataContainer`. Then through the TCP-IP protocol, the data is sent to another Linux machine, where the data quality minoring (DQM) system can read the data from the `DetectorDataContainer` and fill the correspondent ROOT histograms. The work then focused on this purpose, and different calibrations were performed. In this thesis, the 2S module CBC3 fundamental calibration, i.e. pedestal equalization, will be briefly addressed, and then the focus will be on Signal-Scan and Pulse-shape calibration measurements. The experimental setup utilized is the following:

Front end:

- 2S mini module silicon detector
- Front-end adapter board

Back end:

- uDTC (uTCA Detector Trigger and Control back-end board)
- Tektronix PS2520G low voltage power Supply for the Front-ends
- Keithley 2410 high voltage power supply for the 2S sensors

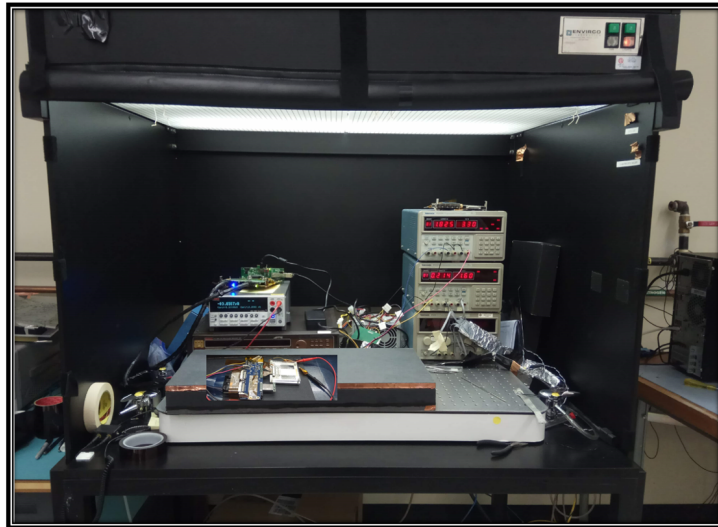


Figure 3.14: Sidet 2S mini module setup for CBC3 calibrations

Pedestal equalization: the first basic CBC3 calibration that all the modules has to run before to be operational is the pedestal equalization. The CBC3 has channel-to-channel variation of the pedestals with respect to the comparator threshold due to fabrication tolerances. To ensure a uniform distribution of pedestals across one chip, this calibration procedure equalizes the distance of the pedestals from the comparator threshold. A key concept in this discussion is the s-curve of a given strip. Injecting several time a given charge to a strip, i.e. sending a given number of triggers the s-curve allows to measure the strip efficiency at given threshold V_{cth} (see top right figure 3.15). The pedestal of a strip is the V_{cth} value corresponding to 50% occupancy (mean of the differentiate s-curve). The noise is measured as the standard deviation of the derivative of the S-curve.

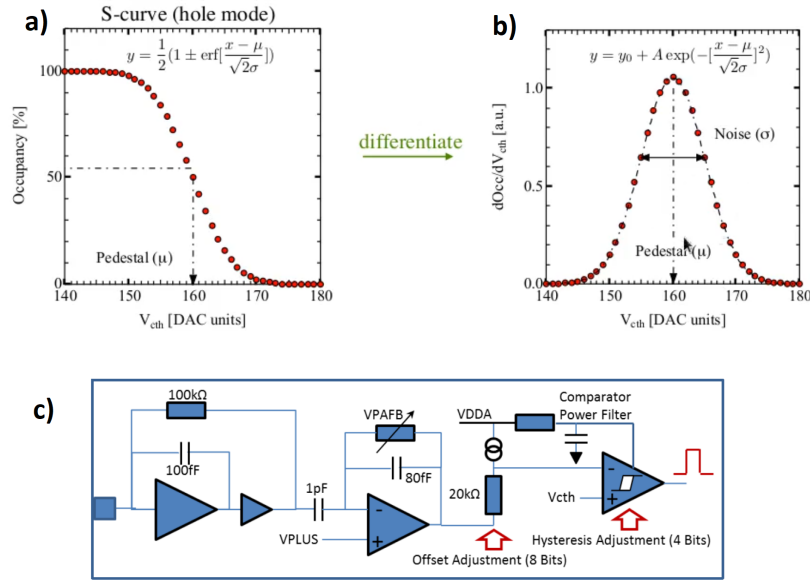


Figure 3.15: a) S-curve in the hole mode. b) S-curve's differentiated function showing the pedestal and the noise of a strip. c) CBC3 Analogue Front-End [110].

SignalScan: the test provides signal information about the top and bottom sensor, then the number and size of the clusters at given threshold. The signal scan test injects the charge to all strip and counts the number of the strips hit at different thresholds. Odd (127 strips) and Even (127 strips) correspondent to the top and bottom sensor strips and are counted separately. The strip cluster distribution is also evaluated. A cluster is a group of neighboring strips that are

hit simultaneously.

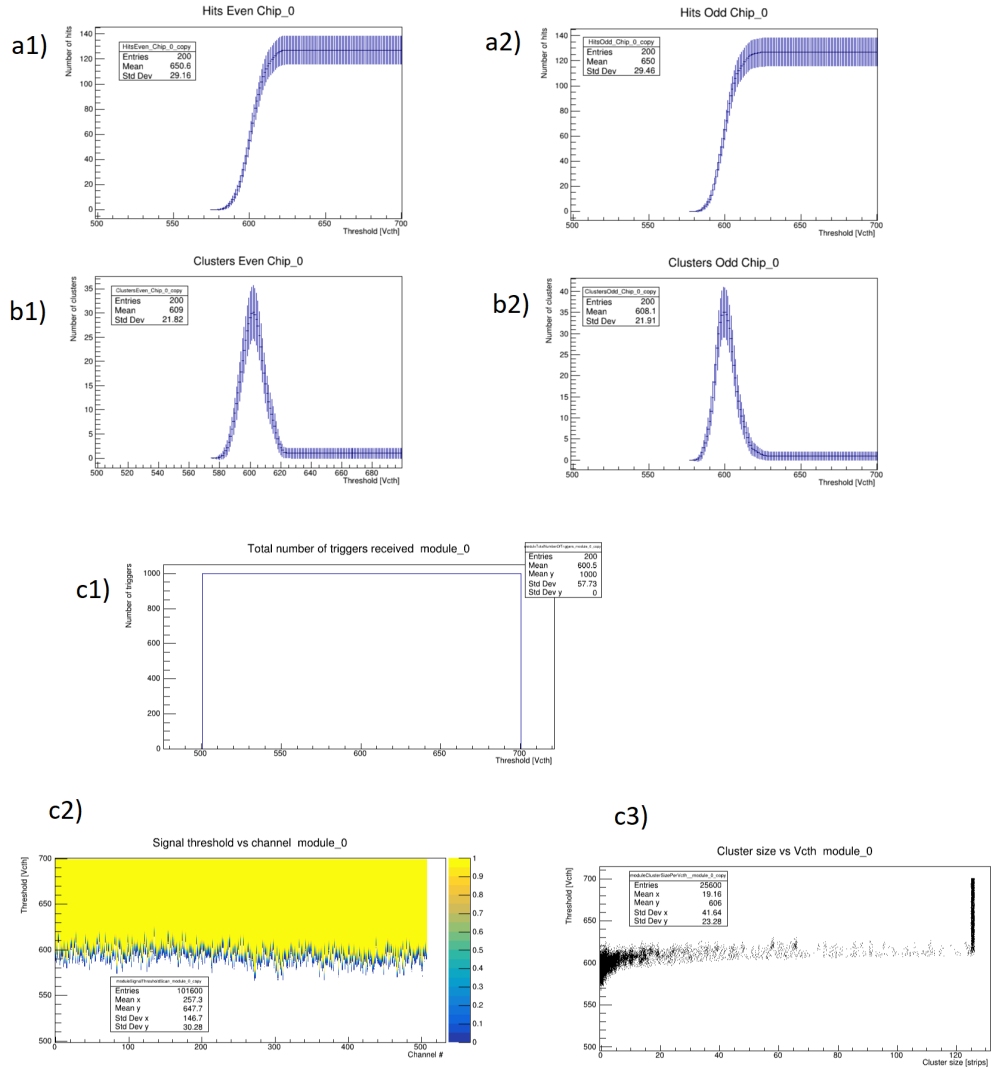


Figure 3.16: Number of hits (a), and clusters(b) as function of the threshold for even (a1,b1) and odd strips (a2, b2). The plots are normalised respect the number of triggers. (c1) The signal efficiency for each channel as a function of the threshold (scaled values range 0-1). (c2) and the cluster size (c3) of the overall mini module are also shown.

The same measurements are also performed after the run of the pedestal equalization on the module. As expected, all the measurements show that the chip

tuning of the pedestals correctly shrinks the distributions around the global value of the threshold, which was set to 600.

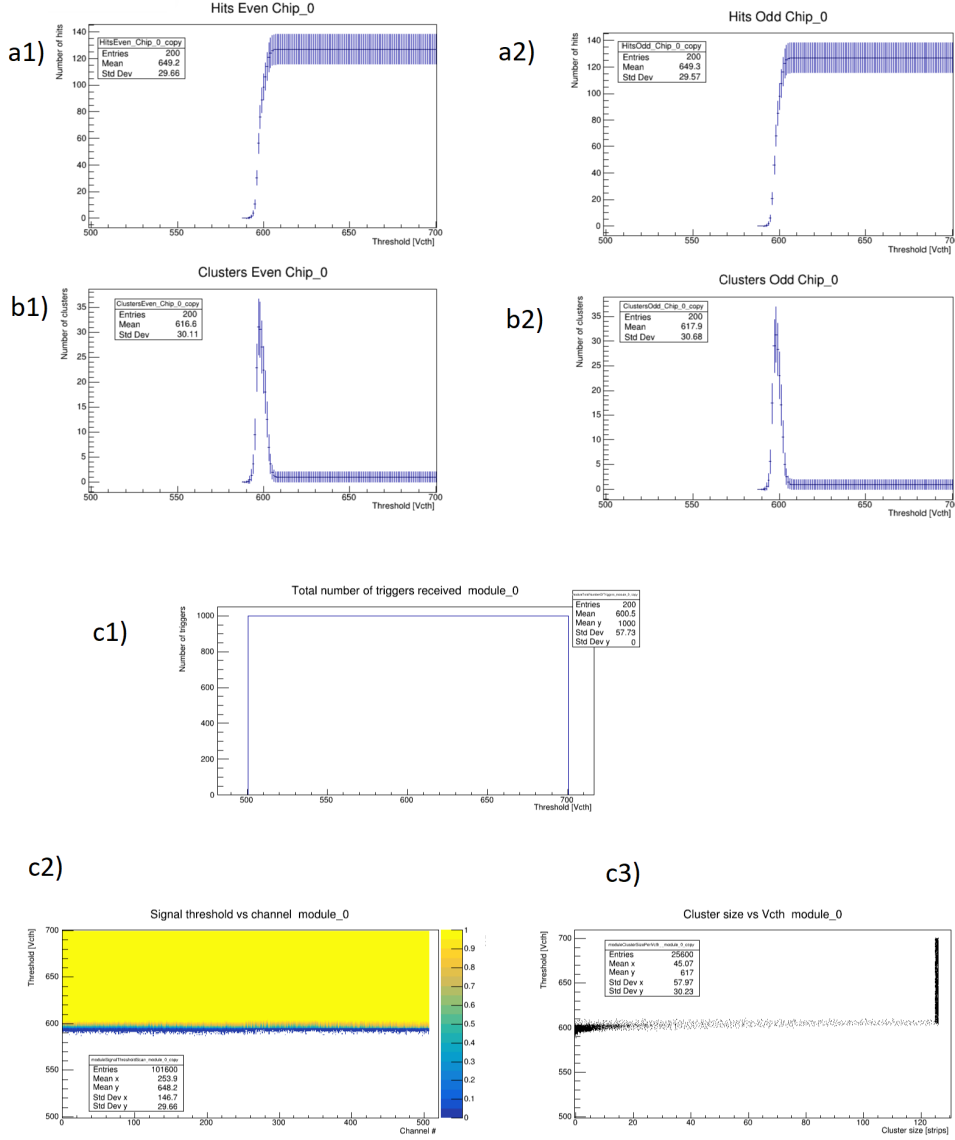


Figure 3.17: Number of hits (a), and clusters(b) as function of the threshold for even (a1,b1) and odd strips (a2, b2). The plots are normalised respect the number of triggers. (c1) The signal efficiency for each channel as a function of the threshold (scaled values range 0-1). (c2) and the cluster size (c3) of the overall mini module are also shown. The measurements are performed after the pedestal equalization calibration.

Pulse shape: the test with the injection of a given charge in the preamplifier, that simulate a given minimum ionizing particle (MIP) passing through the detector (see appendix I.1), shows the shape of the signal after the pulse shaping stage. Each point in the measured is extracted from the measurement of the pedestal as a function of the delay of the charge injection. Since this last one allows to set at maximum a 25 ns delay, the trigger latency (see appendix I.2) was changed during the measurement in order to scan a the full pulse shape (325 ns). In order to perform the pulse shape measurement shown in the figure, the conversion from injected charge and MIP was extracted using the test pulse calibration procedure and it was required to find the latency at which the signal was recorded in the CBC buffers. Both the two calibration results are shown in appendix I. From the measurement, It was possible to extract the response of the CBC analog circuit as a function of different values of collected charges.

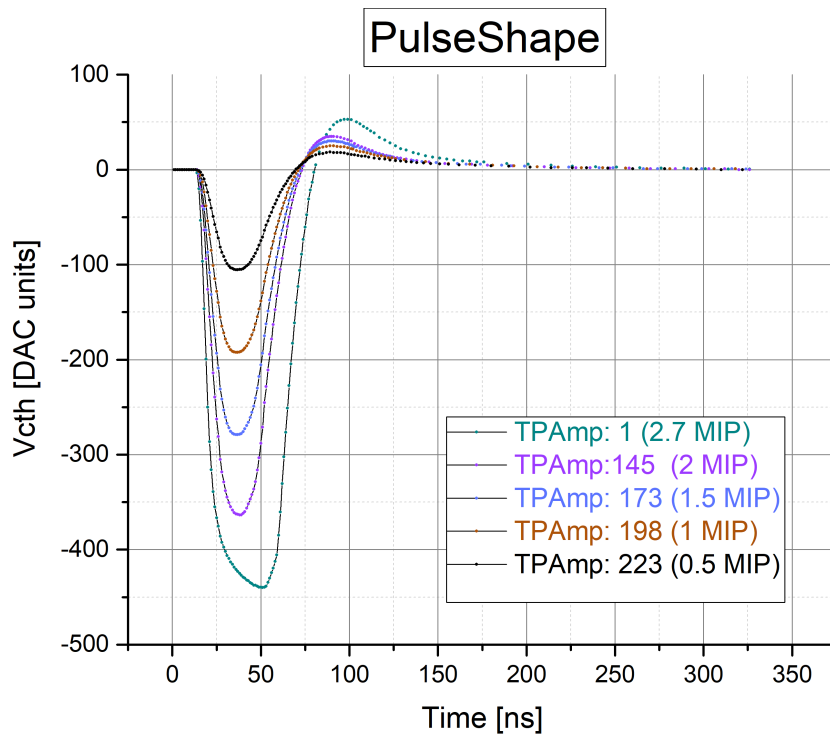


Figure 3.18: Pulse shapes for different values of externally injected charge. The values chosen for the TPAmplitude correspond to the signal given from different MIP.

4

Hibrid Pixels and the CMS Medipix3RX neutron cameras

This chapter focuses on a promising technique, hybrid pixel technology, and its use in a forthcoming CMS neutron detector. The device aims to operate in the typical mixed radiation fields of modern HEP experiments. The full process is discussed: coating of the lithium-fluoride conversion layer, equalization with the working test procedure, calibration, and finally the measurement in the CMS cavern.

4.1 Hybrid pixel technology

Along with the rising complexity of strip detectors, i.e., micro-strips and double-sided strip devices, the need for a pixel device in particle physics emerged simultaneously, or likely even before the actual commissioning of the first strip sensor. The first strip sensor for particle physics, as already mentioned was developed in 1980, while a pixel technology with the Charge-Coupled Device (CCD) sensor was invented by Boyle and Smith in 1969 [45] for digital imaging purpose. At that time pixels devices were not suitable for particle physics application. First developed in 1984, the most common configuration used today is the hybrid pixel configuration (figure 4.1). In hybrid devices the sensor and the readout are fabricated independently, and then coupled by bump connections. It was in 1992 that the pixel technology reached maturity with a first hybrid pixel sensor used in the heavy ion experiments employing the CERN Omega spectrometer [18]. In the same years, a fundamental issue whit the employing of strips as a

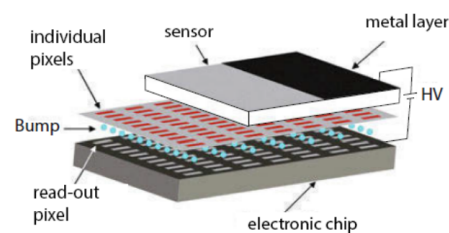


Figure 4.1: Hybrid pixel detector [86]

collection electrodes arise and the pixel detectors slowly gain popularity. In the tracking system, to measure both x and y coordinates of the traversing particle, the double-sided strip configuration can be used. In these devices, the two array electrodes are located on opposite sides of the sensor layer and are typically perpendicular to each other. Thus, when a single particle crosses the detector, two electrodes are hit, indicating the x and y position of the particle. If two particles cross the detector at the same time, the collected charge can be assigned to four separate spots on the detector's surface. For n simultaneous particles, n^2 points are reconstructed, and $n^2 - n$ is the number of the so-called ghost hits obtained by this detector architecture [172].

Pixel-based technology is not affected by this issue, and it has evolved over the years, to replace the strip technology in many fields. Despite the high manufacturing costs per unit area, hybrid pixel sensors are widely used nowadays, sometimes also for large tracker systems. This is because they are one of the best solutions in terms of spacial resolution and space-point information. They have low sensor input capacitance and, hence, low noise, high rate capabilities and radiation hardness [28]. Due to the various advantages of hybrid pixel sensors have been considered also for application in radiation monitoring systems and, in particular, for neutron detection. In order to better understand potentials, advantages and disadvantages of using hybrid pixel technology for neutron detection purposes, the next section provides a brief overview of neutron interactions, classification, and conventional detection methods.

4.2 Neutron Detection

Neutrons are composed of one up and two down quarks, belong to the family of hadrons, and are usually bound together in the atomic nucleus. Neutrons have spin $1/2$, and indeed, they follow the Fermi-Dirac statistic. The mass of a neutron is $939.57 \text{ MeV}/c^2$ (or $1.674927471 \cdot 10^{-27} \text{ kg}$), which is slightly greater than the mass of the proton but nearly 1839 times greater than the mass of the electron. Overall, they make up more than half of all the visible matter in our universe [169].

Interaction As already mentioned, neutrons are neutral particles, so they do not undergo Coulomb interactions and can not be directly detected. Outside the nucleus, neutrons are unstable. A free neutron decays through the weak interaction into a proton, electron, and anti-neutrino with a mean lifetime of about 877 seconds [47]. In this lifetime, they are able to travel long distances in matter. Being composed of quarks, neutrons can interact through the strong

force with atomic nuclei. Neutrons interact with atomic nuclei and, due to their magnetic moment, can also interact with magnetic fields from unpaired electrons. Neutron detection relies mainly on neutron interactions with various nuclei. This process initiates the release of one or more charged particles that produce an electric signal subsequently processed by the readout system. Depending on the nucleus and the energy of the incoming neutron a scattering or an absorption process can occur. Various neutron interaction are shown in figure 4.2.

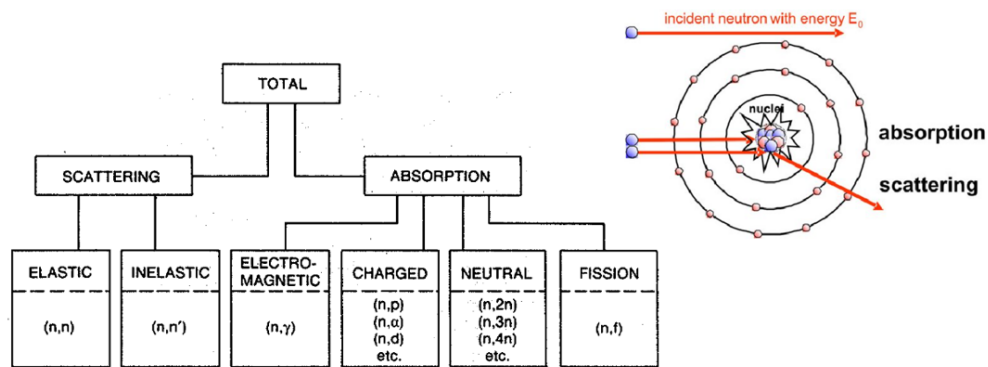


Figure 4.2: Interactions of neutrons with matter. Basic neutron atomic-nuclei processes are illustrated in a schematic representation. In the parenthesis, the first and the second letters separated by commas represent the incoming and outgoing particles, respectively [69] [77].

a) In scattering processes, the incoming neutron collide with the nucleus then change his initial direction. In elastic scattering events, the nucleus remains in its ground state, the neutron and the nucleus change directions, and their total energy is conserved. In inelastic scattering events, the incoming neutrons and nucleus also change direction, but part of the momentum-energy of the incoming neutron causes the nucleus to go into an excited state, and then the excitation energy is released with the emission of γ [48] [13].

b) Absorption processes imply that the incoming neutron is taken by the nucleus and then the emission of nuclear products occur. A first option can be the emission of electromagnetic radiation, i.e., γ radiation, also known as radiative neutron capture. Absorption can also imply the emission of other charged particles, such as protons, deuterons, and alpha particles, or the nucleus might also rid itself of excess neutrons. [69]. The neutron capture followed by emission of a charged or neutral particles are usually refereed as transmutation or transfer reactions [48] [169]. Fragmentation processes, such as, fission and spallation, can be included in a final class. In nuclear fission, neutrons interact

with nuclei and split them into lighter nuclei. Other neutrons are created in the reaction, causing a chain effect. In spallation, high-energy neutrons interact with a heavy nucleus and cause the emission of a large number of hadrons or other types of fragments [9].

Classification The classification of neutrons follows historical naming and their kinetic energy. The main reason is that the magnitude of the probability of neutron-matter interaction, i.e., cross section, is strongly dependent on the energy of the incoming neutron (see figures 4.3) [70]. Neutrons can be described classically as particles, but they also have wave behavior, as clearly described by the de Broglie relation: $\lambda = h/mv$ where λ is wavelength, h is Planck's constant, and m is the mass of the particle moving at velocity v . The following equations, 4.2.1, 4.2.2, show the relations among energy E [meV], wavelength $[\text{\AA}]$, and velocity [m/s]. The linked classification for free neutrons is shown in the subsequent table [168] [169].

$$E = \frac{mv^2}{2} = \frac{h^2}{2m\lambda^2} \implies E[\text{MeV}] = \frac{81.82}{(\lambda[\text{\AA}])^2} \quad (4.2.1)$$

$$\lambda[\text{\AA}] = \frac{9.045}{\sqrt{E[\text{MeV}]}} \quad v[\text{ m/s}] = 437\sqrt{E[\text{MeV}]} = \frac{3956}{\lambda[\text{\AA}]} \quad (4.2.2)$$

Neutrons	Energy range	Wavelength $[\text{\AA}]$	Velocity [m/s]
Cold	0 eV - 0.025 eV	≥ 57	≤ 69
Thermal	0.025	57.2	69
Epithermal	0.025 eV - 0.4 eV	57.2 – 14.3	69 – 276
Cadmium	0.4 eV - 0.5 eV	14.3 – 12.8	276 – 309
Epicadmium	0.5 eV - 1 eV	12.8 – 9.04	309 – 437
Slow	1 eV - 10 eV	9.04 – 2.86	437 – 1381
Resonance	10 eV - 300 eV	2.86 – 0.52	1381 – 7569
Intermediate	300 eV - 1 MeV	0.52 – 0.286	7569 – 13819
Fast	1 MeV - 20 MeV	0.286 – 0.064	13819 – 61801
Relativistic	> 20 MeV	≤ 0.064	≥ 61801

In most of the contexts, this narrow distinction between neutron energies is not used. This is because typical neutron detectors are not capable to do such tight discrimination. In this thesis, neutrons are classified into the following neutron energy groups:

Slow neutrons (0.025 eV – 1 keV) Fast neutrons (1 keV – 100 MeV)

Detection The interaction of neutrons with matter occurs mainly with the atomic nuclei and can produce charged particles or electromagnetic radiation. This is the main point that can be retrieved from the previous sections, and it is also the key point for neutron detection devices. A neutron detector must contain a substance having sufficient cross section with the incoming neutrons in order to efficiently convert the neutron radiation to charged particles or electromagnetic radiation. Then a conventional direct particle detector is used to reveal the products of the first interaction. Substances and neutron-nuclear reactions employed in neutron detectors, based on transfer reactions and radiative neutron capture, can be seen below (figure 4.3).

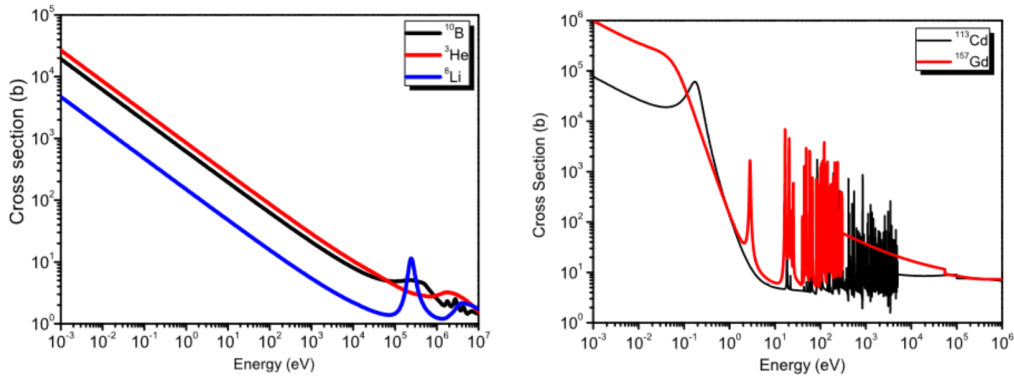
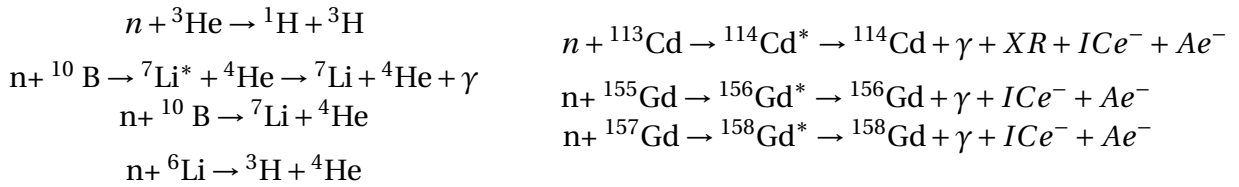


Figure 4.3: On the left: Transfer reactions and correspondent cross sections graphs of ${}^{10}\text{B}$, ${}^3\text{He}$, and ${}^6\text{Li}$ in the neutron energy range up to 10^7eV . On the right: cross sections of radiative neutron capture reaction of ${}^{113}\text{Cd}$ and ${}^{157}\text{Gd}$ [67].

The products of the first interaction, i.e., charged particles and γ , are measured with conventional devices such as: gaseous detector, scintillation detector and semiconductor detector. One of the traditional most used neutron device is the ${}^3\text{He}$ gas filled detector. In this case, the ${}^3\text{He}$ itself acts as the material for neutron conversion and also for counting, so there is no need to add another substance to help measure the products of the interaction. The main issue is that ${}^3\text{He}$ has a natural abundance of roughly 0.000137 percent, and production, in different ways, is extremely expensive. Substance, such as ${}^{113}\text{Cd}$ and ${}^{157}\text{Gd}$, employ the radiative neutron capture process as neutron detection

principle. In this case, the main issue is the discrimination of the signal created by the neutrons from the γ background. Continuous research activities in this field are then carried out. The prospect of employing a semiconductor hybrid pixel detector in conjunction with the use ^6Li as a material for neutron conversion is a more recent option, and a very compact, durable, and relatively cheap solution. The next part of this thesis will address the most recent developments made in the field by the CMS-Medipix New Zealand group.

4.3 Medipix3RX radiation monitoring system

As discussed at the beginning of this chapter, the hybrid pixel technology was first used at CERN in 1992. However, it has quickly become very attractive also in other fields. It was in this context that the Medipix collaboration was founded with the goal of transferring this expertise to the medical field. In the last 30 years, the Medipix devices and all the microelectronics related technologies undergone an increase on complexity and a fast evolution. In 2005, a Medipix3 chip in 130 nm CMOS technology was manufactured. The device has a wide range of applications and unique features. On several occasions, the collaboration went in the opposite direction, and the Medipix devices were used by HEP experimenters ([2]).

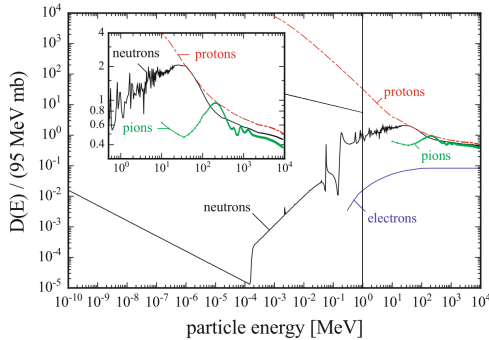


Figure 4.4: $D(E)$ function for neutrons, protons, pions and electrons [45].

several particles in the high energy range still give their contribution. However, of all the radiation sources, such as charged particles, photons, and neutrons, these last, as neutral particles, have the greatest penetrating capacity. In the HEP experiments, neutrons are one of the primary components of the ambi-

This is also the case of a promising CMS radiation monitoring system that is indeed based on the Medipix3RX* ASIC [142]. Monitoring the radiations level, i.e., the flux of the various particles in the CMS cavern, is crucial since radiation damages the components of the detectors and also is important for personnel safety actions. Silicon is used in the manufacture of the majority of electronic devices. Displacement damage functions $D(E)$ for silicon are shown in the figure 4.4, and it can be seen that sev-

*Medical pixel detector, third generation, Rafa Xavi

ent radiation environment, and neutron interactions are the main source of radiation damage to instruments [92]. The current CMS radiation monitoring system is versatile and uses multiple instruments, systems, and detectors. For simulation, FLUKA and MARS software are used. The neutron detection is performed by the HF radiation monitors (HFRadmon). They are positioned in the vicinity of the CMS hadronic forward calorimeter and perform long-term monitoring of neutron flux to estimate degradation of HF fibers, electronics, s, and other components, as well as provide an extra independent luminosity measurement. The RAMSES, Radiation Monitoring System for the Environment and Safety, is used to provide continuous real-time radiation measurements to ensure the safety of all exposed personnel [120]. This uses Environmental Pressurized Ionization Chambers (EPIC) sensitive to photons and muons ($\approx 0.1\mu\text{Sv/h}$), and Environmental Rem-Counters (ERC), BF3 based and sensitive to neutrons ($< 0.005\mu\text{Sv/h}$) [90]. Other complementary radiation monitoring systems, devices, and techniques are the RadMons system, which is a network of the LHC radiation monitors; the use of residual radiation measurements in shutdown periods; the benchmarking with other CMS data; and the employment of devices, such as enriched scintillators with silicon photomultipliers (SiPM) and passive monitors [95].

Besides the fundamental operational devices and complementary radiation monitoring systems, R&D projects are also conducted. TheMedipix3RX radiation monitoring system developed in 2018 falls in this category. Medipix technology, with the possible implementation of image recognition, machine learning techniques, and the introduction of a conversion layer on the silicon sensor, potentially enables the identification of different types of charged particles and also neutral particles such as neutrons. Events taken in 2018 from Medipix cameras installed in the CMS cavern prove that even charge particle emitting delta electrons and showers event can be clearly seen 4.5.

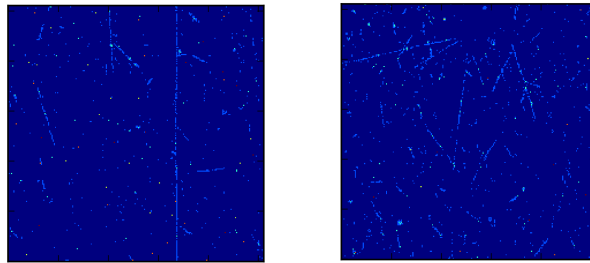


Figure 4.5: Example of very interesting Medipix event observed by the author of this thesis work. On the left: charge particle emitting delta electrons along its track. On the right: hadronic shower event.

These data are clearly interesting, and studies to better classify the measured particle events will continue. The first commission of the system, however, due to the importance of measuring the slow and fast neutron fluxes, focused on the implementation of Medipix neutron cameras.

Medipix neutron cameras In the implementation of the neutron cameras the Medipix3RX chip (figure 4.6 left) is used. This is a silicon hybrid pixel device (see section 4.1) which form a matrix of 256x256 pixels, each with a size of 55x55 μm . As illustrated in the graph below (figure 4.6 right), silicon itself cannot be used to detect neutrons because it does not have sufficient cross section with the incoming neutrons, and also from his low-probability neutron nuclear reactions, i.e, $^{28}\text{Si}(n, p)^{28}\text{Al}$ and $^{28}\text{Si}(n, \alpha)^{25}\text{Mg}$ (fast neutron region) does not produce uniquely identifiable tracks. The slow and fast neutron detection relies on the coupling of the silicon-based Medipix device with the implementation of neutron conversion layers. The two transfer reactions used are the following:

Slow neutrons (0.025 eV – 1 keV)

Fast neutrons (1 keV – 100 MeV)

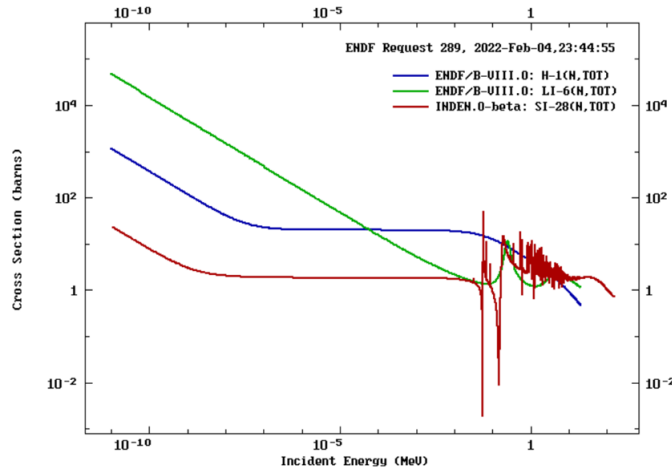
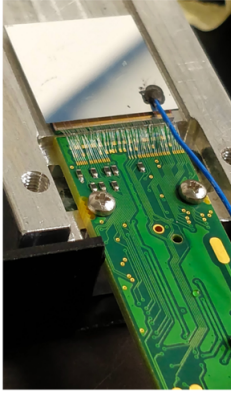
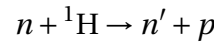
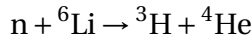


Figure 4.6: On the left: photo of a Medipix3RX chip. On the right: total cross section for silicon, ${}^6\text{Li}$ and ${}^1\text{H}$ as function of the incident neutron energy [146].

The cross section of ${}^6\text{Li}$ for slow neutrons is remarkable. The lithium fluoride is used to build the neutron conversion layer that is placed on the Medipix sensor. More details can be found in the next section. For fast neutrons ($E > 1 \text{ keV}$), polypropylene $(\text{C}_3\text{H}_6)_n$ was chosen as the material for the conversion layer. The energy transfer is more efficient for light elements as ${}^1\text{H}$. So although the hydrogen scattering cross section decreases towards higher neutron energy, the

probability of escape of the recoil proton increases, as it has a longer range (see [42]) The recoil protons deposit their energy in the Medipix device and produce very characteristic, recognizable comet-shaped tracks.

The fast and slow neutron sensors are contained in a single enclosure (4.7 top right image). As shown in the table below and in the lower part of the figure 4.7, the Medipix3RX neutron camera system consists of seven stations positioned at different locations. Each station has two Medipix3RX cameras. The idea is to cover the most important regions in the CMS cavern that should be affected by a higher neutron flux. Most of the cameras are positioned along the beam line.

Name	Location	X[m]	Y[m]	Z[m]
BHTOP	[1] Blockhouse top	0	3.6	22.80
X3FOR	[2] X3 forward	0	9.5	14.36
HFTOP	[3] HF platform	0	2.2	14.0
HFX3	[4] HF electronics rack	3.35	2.9	13.5
YE4TOP	[5] Top of YE4 tower	0	7.5	10.71
X4FOR	[6] X4 forward region handrail	0	17.3	7.0
X3IP	[7] Cavern wall at level with IP	13.5	0	0

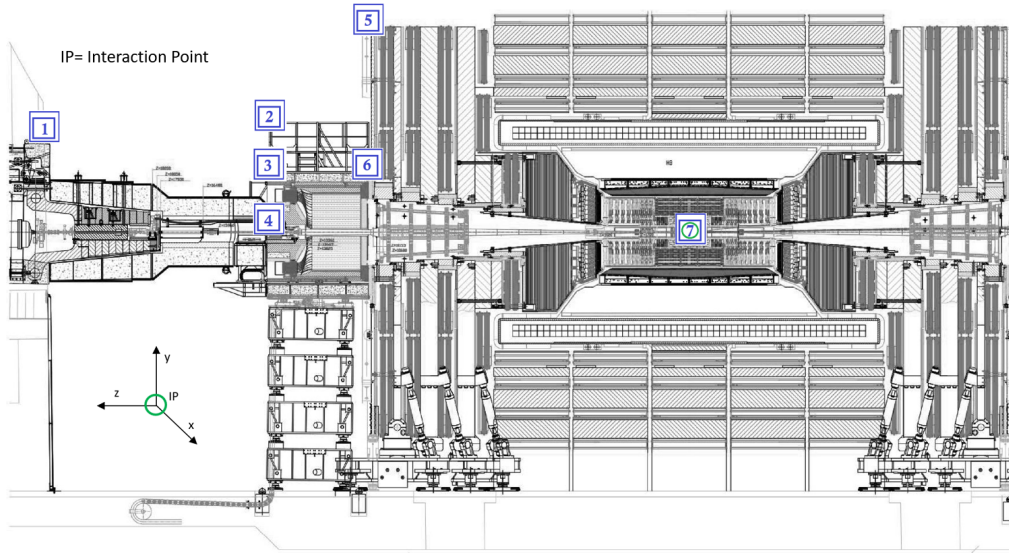
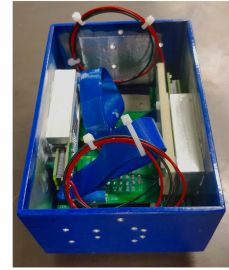


Figure 4.7: On the top left: table resuming the position of the Medipix3RX neutron stations. On the top right: first fully assembled detector box with two Medipix3RX chips. On the bottom: layout of the CMS Medipix3RX radiation monitoring system [88].

4.4 Development of the SN-Medipix3RX camera

One of the developments made to build the Slow Neutrons Medipix3RX (SN-Medipix3RX) camera was the design of the lithium fluoride conversion layer (figure 4.8). This must be designed and fabricated to efficiently generate the products of the nuclear transfer reaction mentioned earlier so that the Medipix sensor can register the signal. The sensor must also have enough uncovered area to be able to perform background measurements. In this context, an important parameter is the thickness of the layer. The design is based on FLUKA simulations [88], which clearly shows that the thickness of the ${}^6\text{Li}$ layer should be $200\text{ }\mu\text{m}$ to maximise the average energy deposited in the sensor. The exposed area available for background measurements is set to be about 25% of the chip's sensitive area. The precise architecture is shown in figure 4.8. To build and fix the conversion layer on the top of the Medipix sensor a chemical solution was prepared. The solution is composed of 70% of Lithium Fluoride LiF powder, (LiF has 7.4 % of Li-6) 20% of distilled water and 10 % of polyvinyl acetate glue. This solution was applied to the top of the sensor with a small brush, making sure to not touch the wire-bonding area and spreading the solution evenly. The final step was to wait for drying and then carefully buff it with a stiffer brush to smooth the surface and achieve the exact shape and thickness of the desired coating. The final step before starting the testing procedure is to bond the high voltage wire to the metallization layer with a silver epoxy resin that must cure at 80°C for 3 hours [116].

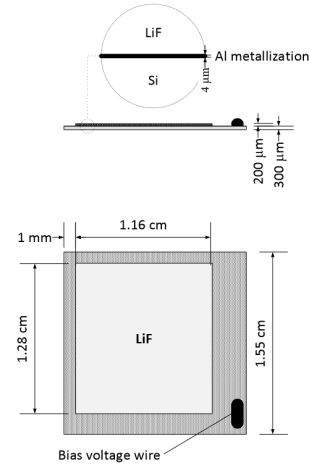


Figure 4.8: Layout of the SN-Medipix3RX sensor

Functionality Tests and Calibration The subsequent step in the development of the slow neutron Medipix3RX camera was to fully test and calibrate the built device. Functionality tests were performed at the TIF, the CMS Tracker Integration Facility, in the BRIL's laboratory space. The standard Medipix functionality tests, such as the digital test, DAC scan, equalization, and conversion layer masking (figure 4.9) were performed mainly using the official Medipix software, i.e., MARS (Medipix All Resolution System). More details about the exact setup

and output data can be found in the report written by the author of this thesis as part of the final documentation of the summer student experience [116]. The most important result to highlight is that all the assembled chips successfully passed the tests. The expected results were obtained. Focusing on the alpha particles test, the obtained data frame (figure 4.9) shows that the uncounted part of the sensor works and is still sensitive to charged particles, in this case to the alpha particles coming from the Americium-241 decay ${}^{241}_{95}\text{Am} \xrightarrow{432.2\text{y}} {}^{237}_{93}\text{Np} + {}^4_2\alpha^{2+} + \gamma 59.5409\text{keV}$.

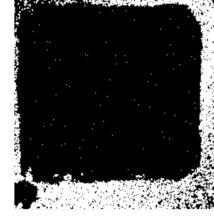


Figure 4.9: Alpha source mask test.

The first attempt to check the device's functionality was made with the reference source of slow neutrons at the Czech Metrology Institute in Prague. The setup is shown in 4.10. The Am-Be and Pu-Be radionuclide decays act as the neutron sources, and the surrounding graphite pile as the moderator. The SN-Medipix3RX camera is located at the center as in the photo 4.10. At the central position (194cm from the setup reference point) the neutron flux is $\phi_R = (291.3 \pm 8.7)\text{E}+02 \text{ cm}^{-2} \text{ s}^{-1}$. After several trials and measurements (see [116]) the setting to cut the gamma background and detect the slow neutrons from the ${}^6\text{Li}$ transfer reaction previously explained were found. The data acquisition for the calibration of the slow neutrons cameras was accomplished.

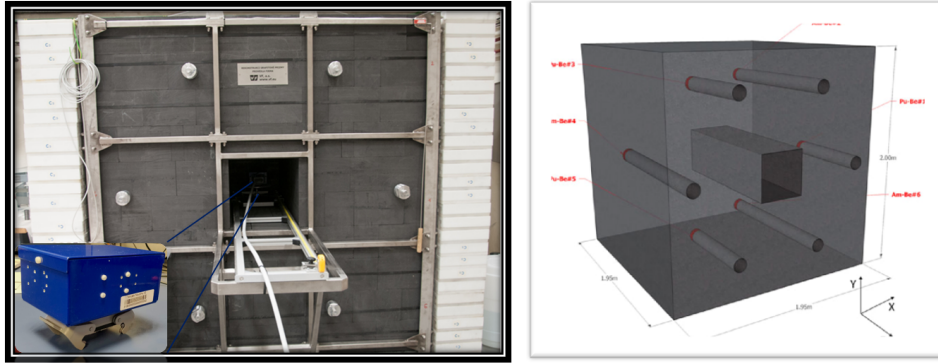


Figure 4.10: Image and model of calibration setup. The slow neutron camera is positioned in the center of the moderator, i.e., a graphite pile, and the radioactive neutron sources are arranged as shown in the model on the left. [71].

Subsequently, the development of an image processing algorithm able to distinguish the neutron signal from the remaining background let the final calibration coefficients of two SN-Medipix3RX cameras be retrieved (see table 4.11).

Calibration coefficients				
Fuse	0 × 440c1161		0x440c11e9	
Active area [cm ²]	1.23		1.10	
Counter	0	1	0	1
ϕ_M [cm ⁻² s ⁻¹]	32.9 ± 7.2	13.8 ± 4.1	13.3 ± 4.8	11.1 ± 4.4
k	884 ± 196	2098 ± 634	2183 ± 789	2611 ± 1035

Figure 4.11: Calibration coefficients for slow neutron Medipix3RX cameras. The sum of all slow neutrons detection gives the active region of the slow neutron chip. The reference neutron flux can then be used to derive the calibration coefficients for both camera counters.

CMS slow neutron flux measurement After passing the testing and the calibration step, the slow neutron cameras were installed in the CMS cavern to start taking data and be operational. The first CMS commission of the slow neutron detection through silicon hybrid pixel technology, i.e., the SN-Medipix3RX sensor, was successfully completed. The cameras started taking data on October 16, 2018. In the following figure 4.12(left side), as an example, is given the data taken on October 17 from 06:30:54 to 18:09:58 by the camera (shutter time 130s DAC=100) installed in the X3IP station. The measurement shows that the camera, with the developed image processing software, is able to provide the slow neutron flux. The experimental data, even though seem to show lower values, within the experimental errors, agreement is found with the slow neutron flux simulated by the FLUKA software. Further studies will be necessary to better tune the working parameters of the device and suppress the noise.

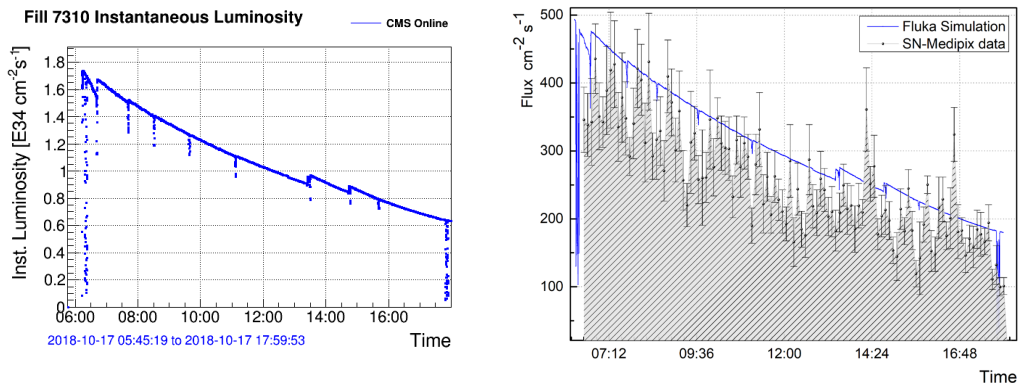


Figure 4.12: On the left: CMS Instantaneous luminosity on October 17 2018 fill number 7310. On the right: Slow neutron flux measured at X3IP with the SN-Medipix3RX camera and the expected slow neutron flux simulated with the FLUKA software.

5 Monolithic Active Pixels sensors and the ALICE ITS3

This chapter addresses one of the latest developments in the field of silicon detectors, the monolithic active pixel sensors (MAPS). It presents a characterization of the first curved MAPS. The work carried out by the author of this thesis includes mechanical and electrical tests.

5.1 Monolithic Active Pixels sensor

The need for higher performance detectors in particle physics has been driving research and development activities in the field of solid-state silicon detectors from its beginning. The strip technology specifically in a high-multiplicity region, viz., that close to the interaction point, as already mentioned, is not suitable because of the ghost hits issue [68].

Pixels and not strips have to be connected to a separate readout electronics channel. The increasing popularity of the bump-bonding technology has caused a progressive replacement of the strip sensor technology with the with the hybrid pixel one in many applications. Today, research and development activities continue to push furthermore the boundaries of the mechanical and electrical design of sensors and the overall architecture of particle tracking systems. Despite the initial idea dates

back in 1989 [74] and the first large scale implementation in HEP field was in the HFT (Heavy Flavor Tracker) of the STAR experiment, MAPS (Monolithic Active Pixel Sensors) figure 5.11, which integrate the sensor pixel matrix and readout into a single piece of silicon, are only now becoming one of the most forward-thinking sensor technologies in the solid-state silicon device family. The fea-

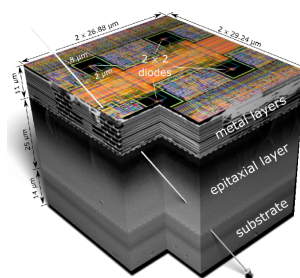


Figure 5.1: Monolithic active pixels sensor [91].

tures of this technology are: lower power consumption, smaller pixel size, high integration, good performance in terms of signal to noise ratio, detection efficiency, radiation hardness, and an intermediate cost system [99]. However, the real interesting development that makes them, up to now, unique is their ability to be bent, i.e., the possible implementation of a Curved Monolithic Active Pixel Sensor (CMAPS). The following sections will briefly address the physics performance expected by the implementation of such technology in the ALICE tracking system and then the measurements made by the author of this thesis on a first prototype CMAPS-based mini-device.

5.2 ALICE ITS3 and bent MAPS

5.2.1 Physics Motivation

As mentioned in chapter 3, the first silicon detector investigation began around the mid-70s and reflected the need of physicists to identify and measure short-living particles, such as particles containing the charm quark. The main requirement was to have a detector with spatial resolution better than $10\text{ }\mu\text{m}$ [33]. Today, the main basic concept of improving the spatial resolution for the identification and measurement of short-living particles has not changed. However, study of heavy-flavour physics requires improvements of other important parameters of the detector system as well [132]. The next generation of detectors has to provide a spatial resolution of less than $5\text{ }\mu\text{m}$, high stiffness and stability, a low material budget $x/X_0 < 0.1\%$ per layer, high efficiency, optimal tracking and vertex capability. In ALICE, the current solution of this challenging plan is faced with the construction of a new Inner barrel for the Tracker System (ITS), the ITS3. The planned new vertex system is based on a truly cylindrical ultra-thin ($20\text{ }\mu\text{m}$ to $40\text{ }\mu\text{m}$) wafer-scale sensors [62], with even lower material budget $x/X_0 < 0.05\%$ per layer, and the innermost layer is planned to be located at 18 mm from the interaction point [38]. This then will necessitate the development of a curved silicon sensor, and MAPS was chosen as the best possible candidate. The major measurements that will benefit from these outstanding improvements in this detector performance are the measurement of low-momentum charm and beauty hadrons and the measurements of low-mass dielectrons. Measurement of Λ_c production (figure 5.3) would give important information on the charm quark thermalisation and hadronisation in the Quark-Gluon Plasma. Other measurement that will benefit of the ITS3 design and then also be uniquely accessible by AL-

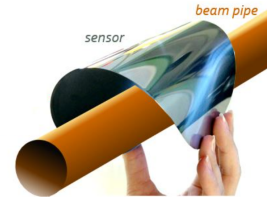


Figure 5.2: Image of a curved silicon wafer [132].

ICE are the following: improvement of the statistical significance for the beauty baryon Λ_b , this because $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$, possible detection of light nuclear states with charm, i.e. the c-deuteron, and c-triton, further insight to charm quark hadronisation across colliding system due to charm-strange baryons detection, elliptic flow of D_s mesons, B_s mesons via non-prompt D_s , charm jets and charm correlations [109].

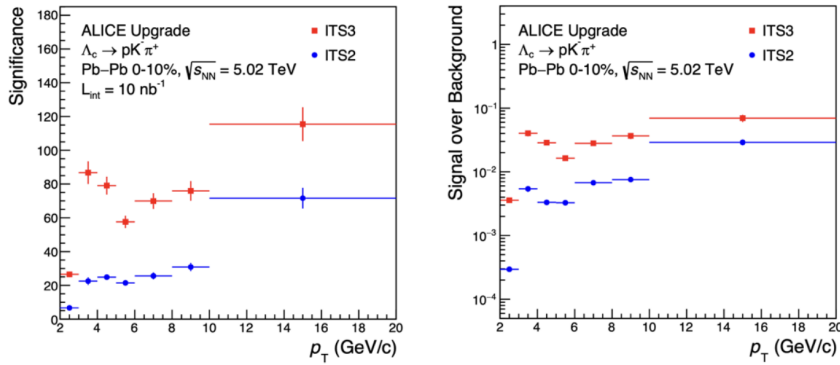


Figure 5.3: Simulated performance of the ITS2 and the ITS3 for $\Lambda_c^+ \rightarrow pK^- \pi^+$ in central Pb – Pb collisions. On the left the statistical significance and on the right S/B ratio as a function of p_T [62][109] .

5.3 Characterization of first bent MAPS chips

As mentioned in the introduction of this chapter, mechanical and electrical test of CMAPS chip is the work that the author of this thesis has carried out. The idea is to understand how mechanical stress of the MAPS can cause issues to the device functionality or induce changes in the electrical operational parameters of the device.

5.3.1 Mechanical tests

The mechanical characterization starts with a bending test on flat MAPS chips. The experimental setup comprise the following components: MAPS chip T968874-05A7 and T968874-01D3 with dimension 60x15 mm and thicknesses of 40 μm and 30 μm respectively, load cell TCA CTCA2K5 with nominal load of 2kg and a sensitivity of 5 mN, motorized linear stage Zaber T-LSR300A, adjustable basis to set the 3 bending points, digital micrometer Mitutoyo IP 65 with accuracy of 1 μm (range 0-25mm), and raspberry Pi Camera for remote control and possible computer vision complementary data. The first tasks of the work have been the

The screenshot displays the Alice ITS3 tests software interface, which is used for data acquisition and analysis in the ALICE experiment. The interface is divided into several panels:

- File Explorer (Top Left):** Shows the file system structure, including folders like 'data' and 'logs'. The 'data' folder is expanded, showing files such as 'Tsc_20_03_20', 'AMC.txt', and 'Tsc_20_03_20'. The 'logs' folder is also expanded, showing files like 'log_20_03_20', 'log_20_03_20', and 'log_20_03_20'.
- Camera View (Bottom Left):** A live video feed from a camera, showing a white, cone-shaped object (likely a detector component) in the center of a circular frame.
- BENDING STRENGTH TEST (Top Right):** A control panel for the bending strength test. It includes a 'Back to Home' button, a 'Home position' field set to 170000, a 'Set position' field set to 170000, and a 'Set x max' field set to 170000. It also has a 'Set x min' field set to 170000, a 'Set x step' field set to 100, and a 'Start test' button. The 'Max force measurable' is set to 1800, and the 'Measure the force' is set to 10.0 mN. The 'Measure the position' is set to 170.0 mm.
- BENDING STRENGTH TEST (Bottom Right):** A graph showing the bending strength test results. The x-axis is 'Displacement (mm)' ranging from 169 to 176. The y-axis is 'Force (mN)' ranging from 0 to 600. The graph shows a curve that starts at approximately 170.5 mm and 10 mN, remains relatively flat until about 172.5 mm, and then rises sharply to about 550 mN at 175.5 mm.

Slight initial curvature The first sample bending measurements were carried out on a 40 μm and a 30 μm thick flat MAPS chips. For both MAPS chips, measurements were carried out, taking into account the face-up and face-down configuration. Data were analysed by ROOT, the HEP open-source data analysis framework [175]. The results can be seen in figures 5.5 and 5.6. In the face-up (face-down) configuration the silicon sensor surface is pointing up (down) in other words the readout ASIC surface normal vector is pointing in the same (opposite) direction of the external applied force. The figure 5.5 show the behavior of the 40 μm thick MAPS chip. As it can be easily seen also from the two

fits, the curves evidence a displacement shift. This means that the chip is not flat, as previously assumed, but has a very small curvature (see figure 5.5 top right corner), while an FDw-FUp displacement of $ds = (0.28 \pm 0.01)\text{mm}$. Had the chip been perfectly flat, the starting positions would have been the same.

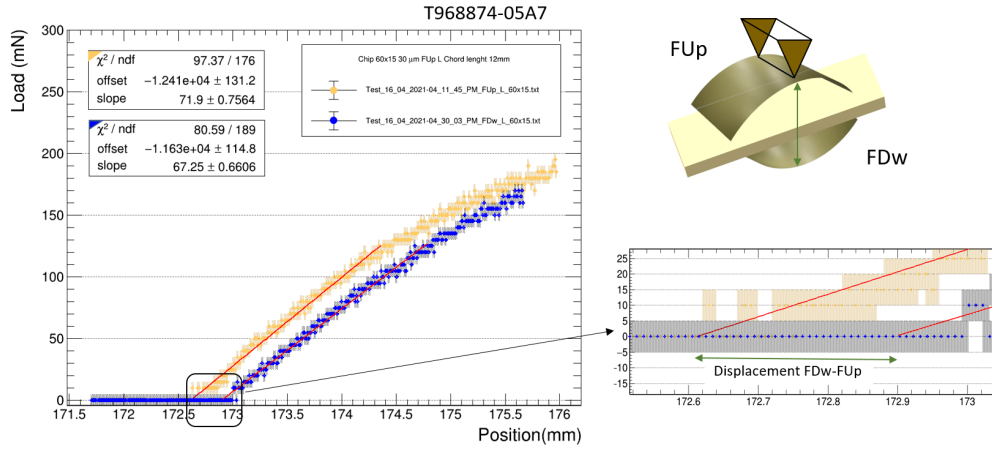


Figure 5.5: Three-point bending test on the MAPS chip 968874-05A7. Force exerted on the load cell by the chip as a function of the position in the face-up (orange) and face-down (blue) configuration. The chord length is set to 18 mm and the chip has a thickness of 40 μm . The red lines are least squares fitting to the experimental points. A picture and the a magnification of the initial region of plot is also shown to highlight the FDw-FUp displacement.

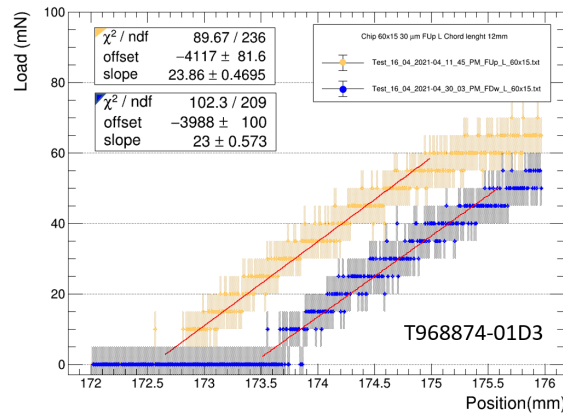


Figure 5.6: Three-point bending test on the MAPS chip T968874-01D3. Force exerted on the load cell by the chip as a function of the position in the face-up (orange) and face-down (blue) configuration. The chord length is set to 18 mm and the chip has a thickness of 30 μm . Red lines are least squares fitting to the experimental point.

It is also worthwhile noting the behavior of the chip at the end of the linear (elastic) region. In the face-up configuration, the non linear (plastic) behavior seems to occur at a lower displacement. Moreover, the data points of the two curves on the far right of the graphs are not parallel and have convergent behavior. A similar behavior is shown by 30 μm thick MAPS chip (figure 5.5) Also in this case the slight initial curvature had been detected, and appear enhanced with respect to the 40 μm thick chip, indeed, this time the FDw-FUp displacement is greater $ds=(0.88 \pm 0.01)\text{mm}$.

Three-point bending chip thickness dependency test The previous measurements proved that MAPS chips are not perfectly flat and, from the beginning, assume a slight curved shape. The main tasks now are to test to what extent these sensors can be curved without breaking, evaluate their elastic and plastic behavior, and also how the breaking point is related to the thickness of the chips. The three-point bending test is performed with chips of different thicknesses: 100 μm , 50 μm , 40 μm , and 30 μm . The already mentioned setup is used and the load and position are read out by the correspondent transducers. First results for each chip are shown in plots and to calculate the three-point bending displacement (D), fits in the correspondent linear regions are performed (see Appendix II.3). Subsequently, plots of flexural stress σ_f as a function of the flexural strain ϵ_f can be made (figure 5.8). For the flexural distinctive physical quantities, the following equations are used:

$$\sigma_f = \frac{3PL}{2bd^2} \quad \epsilon_f = \frac{6Dd}{L^2} \quad E_f = \frac{\sigma_f}{\epsilon_f} = \frac{L^3 m}{4bd^3}$$

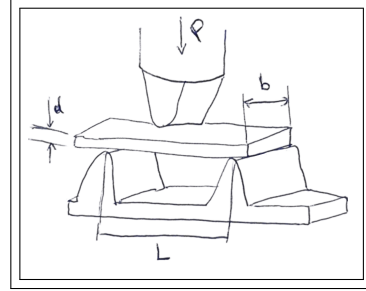


Figure 5.7: Schematic representation of the three-point bending test.

The force exerted on the chip (Load) is expressed as P, the support span whit L, and b and d are the width and thickness of the DuT (see figure 5.11), respectively. E_f is the flexural Modulus of elasticity, and represents the ratio of flexural stress to corresponding strain of the material within the linear elastic region. It is an important parameter because it describes the rigidity of a material, or in other words, the resistance of the material to being bent. Stiff materials have a high modulus and ductile materials demonstrate a low flexural(bending) modulus [43]. The coefficient m is the slope of the load deflection curve, i.e. P/D, in the initial straight-line region [131]. Several information can be extracted from the

measures plotted in the figure 5.8. The first two curves, the violet and the black one, aim at representing the chip classes of 100μ and $50\mu\text{m}$ thick, respectively, and have a clear linear behavior, i.e., the chips behave elastically. At a certain point, the value for flexural stress drops to zero. This means that the chip has reached its breaking point and is then broken. The blue and the yellow correspond to a 40μ and $30\mu\text{m}$ thick chips. In this case the initial linear-elastic behavior is still present but the non linear-plastic one also becomes visible. In the thinning process just the silicon sensor layer is thinned and this means that the metal layer as well as the thickness decrease start playing a increasing contribution on the overall mechanical behavior of MAPS chips. The rise of the plastic region indicates that, from that point, the chip starts to be permanently deformed. If the external force is removed, the chip will not return to its initial state because it is microscopically mechanically damaged.

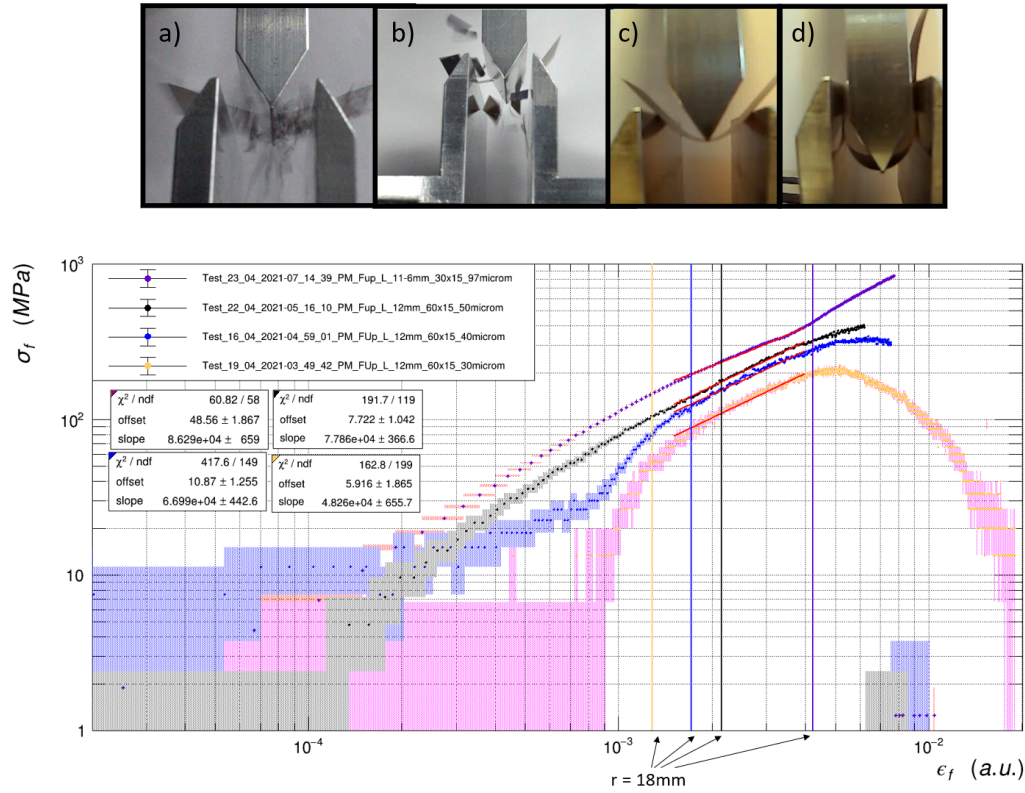


Figure 5.8: On the top: three-point bending test scenarios for chip thickness classes of a) $100\mu\text{m}$, b) $50\mu\text{m}$, c) $40\mu\text{m}$, and d) $30\mu\text{m}$. On the bottom: Flexural stress σ_f versus flexural strain ϵ_f graphs. The slopes of the fits in the linear regions represent the flexural modulus of elasticity of the given chip. It is clear that as the thickness decreases, so does the flexural modulus.

It is also important to underline that for the thinner chip ($30\mu\text{m}$) there is no breaking point since the chip has not undertaken any rupture (see top figure 5.8 d)), and then MAPS chips of that thickness became truly flexible sensors. The flexibility and the fact that the rigidity of the sensor decreases according to the thickness value can be seen deduced by the flexural modulus, i.e. the slope values of the performed fits in the linear regions. At the top of figure 5.8 several photos are shown to illustrate how the chips break. The $100\mu\text{m}$ (a)) thick chip, breaks into a myriad of pieces with a sudden breaking point. In the case of the $50\mu\text{m}$ chip, the behavior is similar, but the chip pieces have a greater dimension. The $40\mu\text{m}$ thick chip, c), broke into two pieces, and the breaking occurred along a straight line at the middle point of the 3-point bending setup. Finally, the $30\mu\text{m}$ thick chip d), as already seen from the data, did not break at all and remained stacked on the setup. Focusing again on the plots, knowing the radius-displacement relation and the previously presented flexural strain equation, it is possible to locate the corresponding 18 mm ITS3 radii on the plot. In all thickness scenarios, even the smaller ITS3 radius is in the linear region, and except for the 100mm chip, it is also far away from the breaking point, or however far away from the plastic region.

5.3.2 Electric tests

The next step on the study of bent MAPS was the analyses of the electrical parameter in the flat and the bent configuration. As reported above, all MAPS chips show in reality a small initial curvature. Then in this context, the attribute flat will be given to a chip assuming the presence of this slight initial curvature. The prepared two experimental setups can be seen in figure 5.9, and are composed of the following elements:

Flat MAPS setup:

- FS DAQ board-125
- ALPIDE3 Carrier Board with mounted $50\mu\text{m}$ thick MAPS thickness
- Flat MAPS chip T968879W23TA4

Bent MAPS setup:

- FS DAQ board-126
- ALPIDE3 adapter Board-200020 -ALPIDE3 I-board 14
- 24mm radius bent MAPS chip T854936W09R31 (thickness $50\mu\text{m}$)

Both setups are located in the darkroom of the ITS3 laboratory, use the official ALPIDE DAQ software, the programmable power supply HMP4040 ROHDE & SCHWARZ with a developed HMP4040 software and a Lemo FFS 0 resistor. The

reverse bias voltage for the measurements was set to 0V. The development of the $50\mu\text{m}$ thick bent chip was done by the ITS3 collaboration, starting with a flat chip that, by means of a precise bending machine, was placed on a cylindrical support with a radius of 24mm. The chip is then held by an on-purpose developed plastic holder. The chip did not undertake mechanical break in the process and then was connected electrically through wire bonding. The full setup includes the I-Board, the ALPIDE3 adapter Board, and the FS DAQ board. The electrical investigation done by the author of this thesis on flat and bent chips started with standard tests, such as power on/off, FIFO test, DAC scan, Digital and Analog Scan aiming at investigating the basic performance of the device. For the two configurations, the flat and the bent one, all of these tests were successfully performed. The bent monolithic active pixel sensor appears to be fully functional. In these tests non significant differences were found among the two configurations. This is the reason why in this work they will not be presented. Instead the focus of the last part will be on the threshold scan test, the temperature dependency and the difference seen in the threshold map of flat and bent MAPS chips.

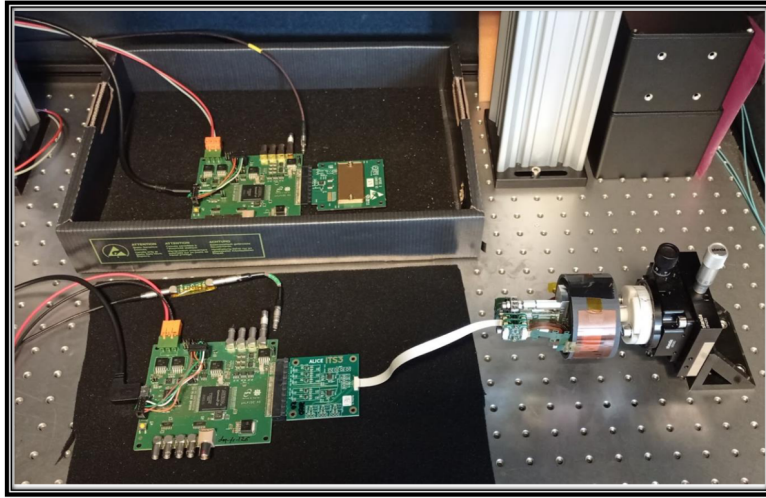


Figure 5.9: Overall experimental setup located in the darkroom of the ITS3 laboratory that was prepared to test the electric behavior of flat and bent MAPS.

The threshold scan is performed with a given a number of triggers on each pixel. Then the data are analysed and fitted with an S-curve function (see section 3.3.2) for each pixel. For each pixel the so called pedestal corresponds to the threshold value where the pixel responded 50 % of the times. Taking into account all the Pedestals of the pixels the threshold distribution of the chip is then built and the mean and the standard deviation of the distribution give the

threshold of the chip, and the noise respectively. The threshold scan give also the threshold map i.e. the two dimensional distribution of the thresholds of the chip. The plot in figure 5.10 resumes the output of several threshold scan measurements taken at 30-minute intervals. The chip temperature is measured by the on-board DAC chip sensor and an external sensor placed in the vicinity of the chip. As it can be clearly seen, the ambient temperature and the chip temperature follow the same curve and are shifted about by 3.8°C. This threshold-temperature dependency measurement is important because it proves that the threshold value of the chip is tightly inversely correlated with the external temperature as well as with the temperature of the chip itself. This measurement has been shown because the temperature of the chip seems to be an import parameter in this context. In fact, the temperature distribution on the chip can play an important role when comparing MAPS chips in the flat and bent configuration.

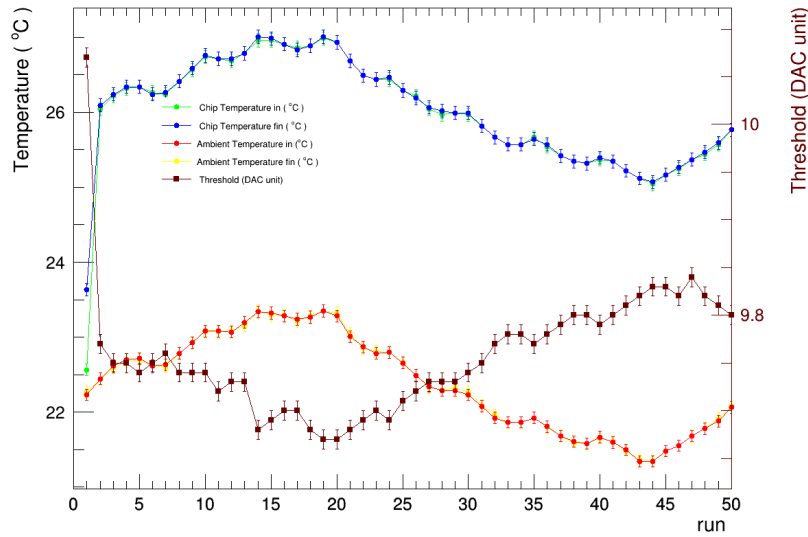


Figure 5.10: The brown curve (right y axis) show the trend of the chip threshold value as a function of the performed run. Each run take about 1 minute and the time interval between runs is about 30 minutes. The green (yellow) and blue (red) curves show the measured ambient (chip) temperature before and after the measurement, respectively. The measurements are performed in the darkroom of the ITS3 laboratory.

The investigation then continues with a thresholdmap measurement of a flat MAPS chip, i.e. chip T968879W23TA4. The result can be seen in figure 5.12 a). The threshold is normalised to the surface integral of the distribution and then scaled in the range 0-1. The projection along the x direction is also displayed. It is worthwhile noting that pads on the chip can be clearly distinguished, the threshold assume an higher value on the correspondence of

their position. Another interesting effect visible also in the x projection plot, is that, at the central region the chip has high values of threshold. One of the options can be that the fact that the chip has a slight initial curvature in some way influences the thresholdmap of the chip. However, more clear evidence (see figure 5.11) is that this is due to the temperature distribution of the chip, more precisely how the heat is generated and it is dissipated in the chip. The data transmitter which at highest data rate consumes about 70 mW on its own (the matrix itself is 6 mW/cm^2), is located in the center so it really creates a hot spot on the chip [118]. The thresholdmap was also performed with a MAPS chip (T854936W09R31) in the $r = 24 \text{ mm}$ bent configuration (figure 5.12 b)). In this case, the data show the superposition of two effects: the first one is the already mentioned hot spot effect at the center of the chip, and the second one is the higher values for the threshold at the edge of the chip in the y direction. The mechanical stress seems to not affect the overall thresholdmap of the chip, and these edge effects are due to the heat dissipation in the regions where the plastic holders are located.

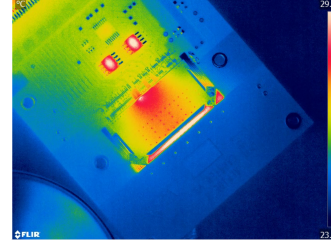


Figure 5.11: Flat MAPS temperature distribution [118].

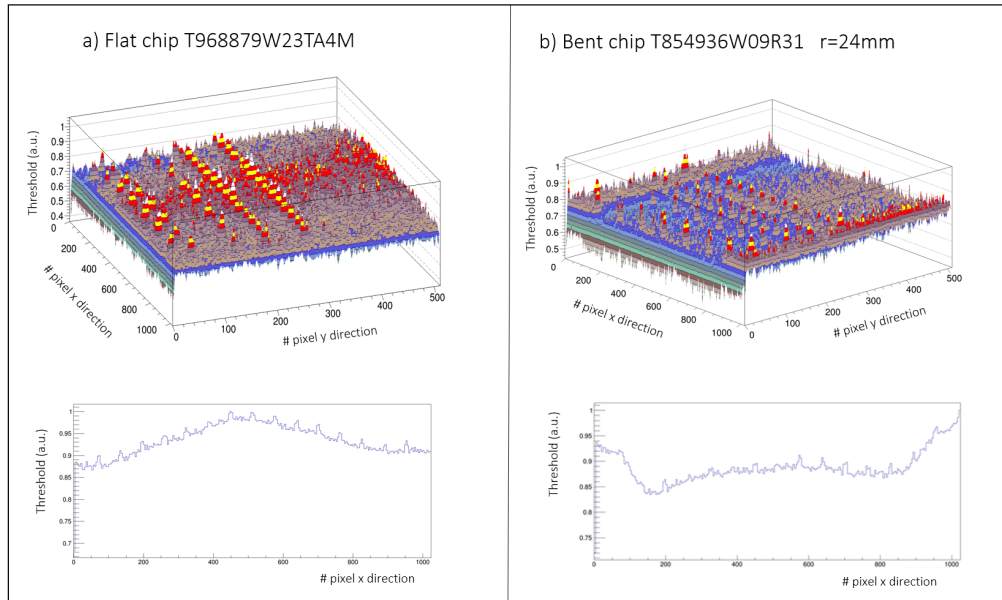


Figure 5.12: a) Thresholdmap of a MAPS in the flat configuration, the projection along the x direction is also shown b) Thresholdmap of a MAPS in the $r=24\text{mm}$ bent configuration, the projection along the x direction is also shown.

6 Conclusions

Frontier physics requirements guide frontier detector design. The evolution of silicon sensors has progressed alongside, and now frontier technologies are being considered to build high-performance detectors for HL-LHC. Fundamental operational parameters such as rate capability and spatial resolution of all HL-LHC detectors must be improved in this context, and their radiation monitoring systems must often be upgraded as well. The aim of this work was to go through the current solid state silicon detector technologies and present examples of how these operational parameters will be improved.

Concerning strip sensors and rate capabilities, the new CMS tracker goal will be reached with the implementation of the hardware trigger primitives system, and a remarkable role will also be played by the Phase2 Acquisition Control Framework. The reported temperature dependent electrical characterization and CBC3 calibrations for the 2S module first prototypes show reference values for the leakage density current and also that the PH2_ACF, with the developed calibration procedure aiming to decouple the ROOT utilities from the core calibration functions, it can be successfully implemented for prototyping and also for the production and final detector operation stages.

Concerning hybrid pixel sensors and the introduction of a possible new radiation monitoring system in CMS, at the LHC Run 2, the prototype neutron cameras based on the Medipix3RX readout chip were installed in the experimental cavern to collect slow neutron flux data during collisions. The area with a high contribution of slow neutrons in the ambient radiation was selected. To convert track count to neutron flux, the monitors were calibrated with a reference thermal neutron source. The first commission of the slow neutron Medipix3RX camera showed that the system can provide accurate measurements of slow neutron flux in the CMS cavern.

Finally, to further improve pixel sensors spatial resolution, the possible implementation of a curved MAPS in the ITS3 has been addressed. Mechanical and electrical tests demonstrated that the implementation is possible, even with the $50\mu\text{m}$ thick chips. The measurements also demonstrate the slight initial curvature present in the assumed flat chips, the threshold temperature dependency and the different behaviors in terms of heat dissipation and, consequently, thresholdmap for flat and bent MAPS chips.

Appendix

I Supplementary CBC3 calibrations

I.1 Latency Scan measurement

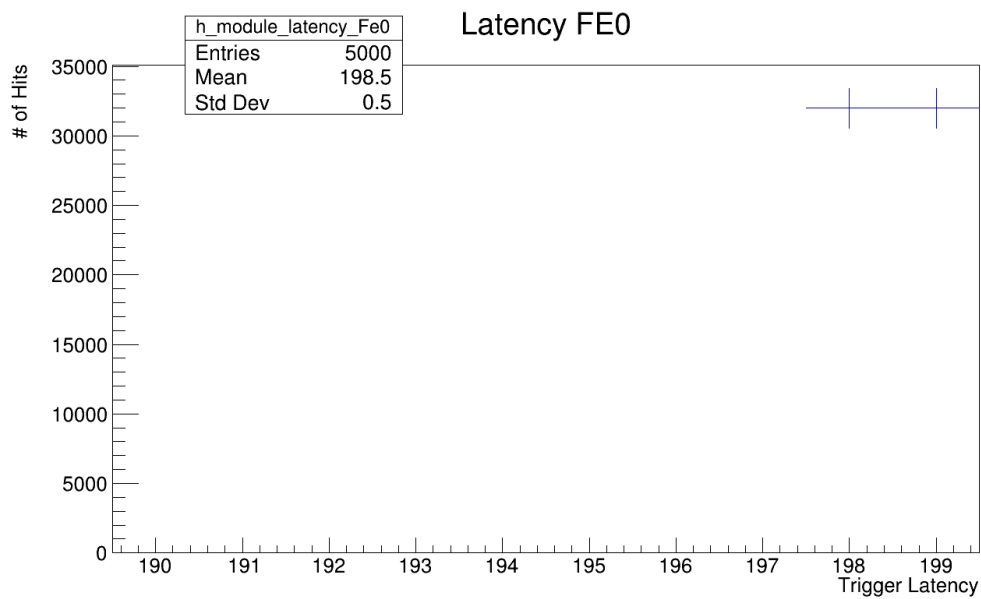


Figure 6.1: Histogram of the latency scan test. To find the trigger latency, a full scan of the possible latencies is performed. In the test pulse mode, the correct trigger latency can be determined by using an external signal to simulate the source, then setting a sensible threshold and counting the number of hits as a function of latency.

I.2 Test Pulse calibration

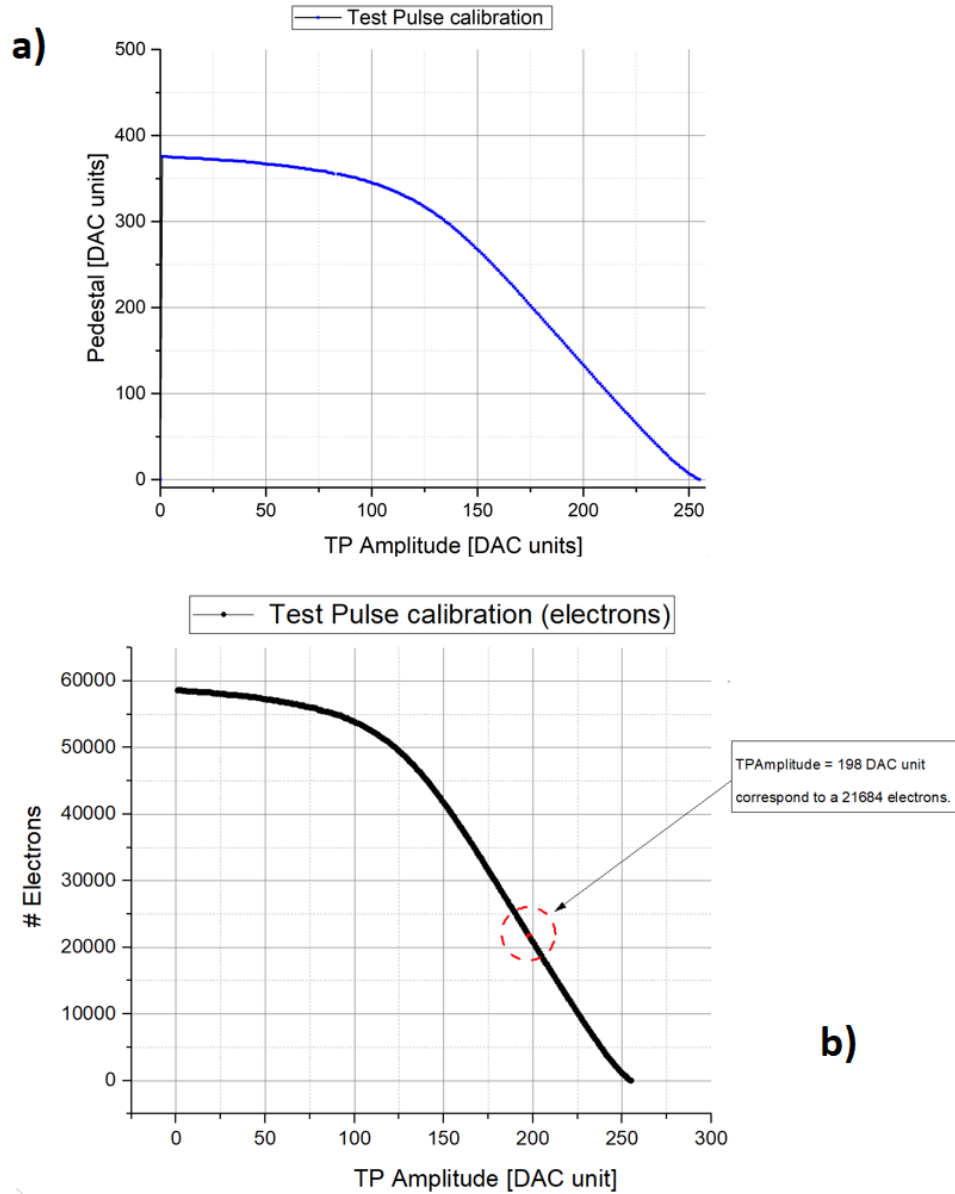


Figure 6.2: a) Test Pulse (TP) Calibration calibration measures the dependency of the pedestal as function of the pulse amplitude. b) The conversion from pedestal value to electrons was measured by the CMS collaboration to be $156 \text{ e}^- / \text{DAC}$. An input of 21750 electrons corresponds to the MIP signal expected for a silicon thickness of $290 \mu\text{m}$ ($75 \text{ electrons}/\mu\text{m}$).

II Supplementary CMAPS measurements

II.1 First trial measurements

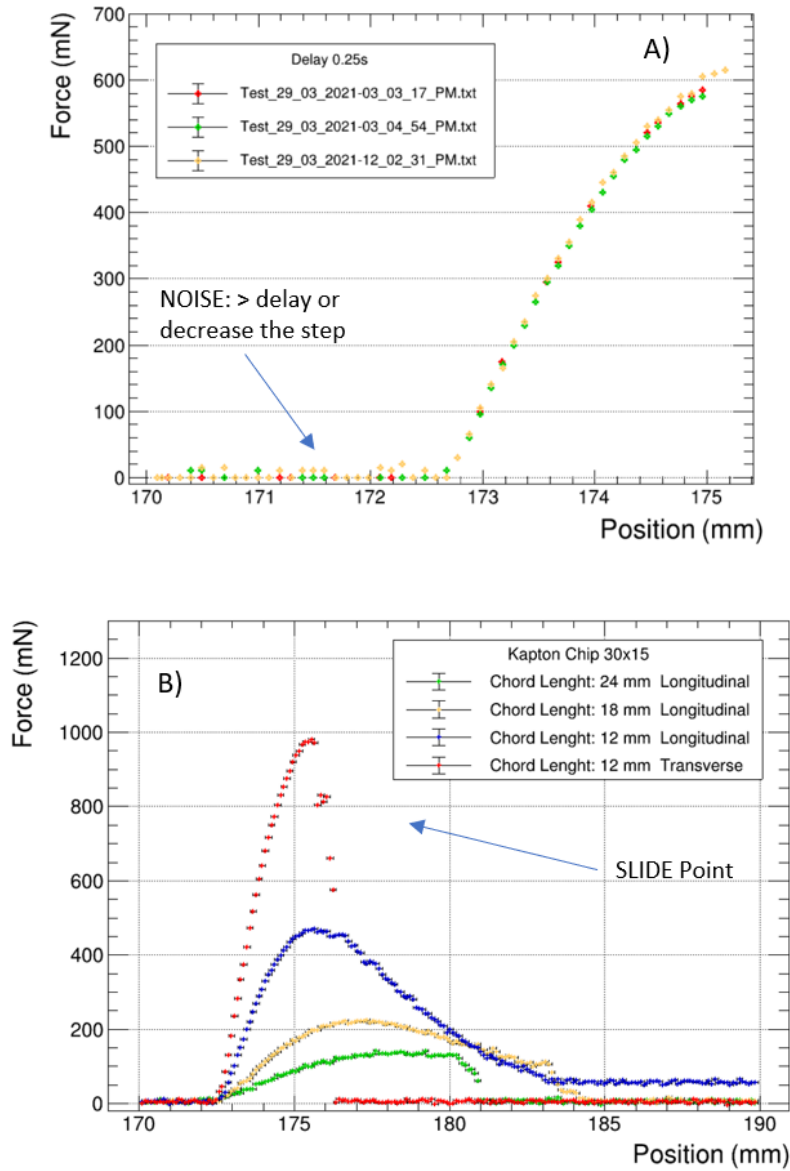


Figure 6.3: A) Three point bending setup kapton delay tests. To suppress the noise coming from the linear stage fine steps are used. B) The three point bending kapton test at various chord lengths and the longitudinal and the transverse configuration.

II.2 Misalignment measurements

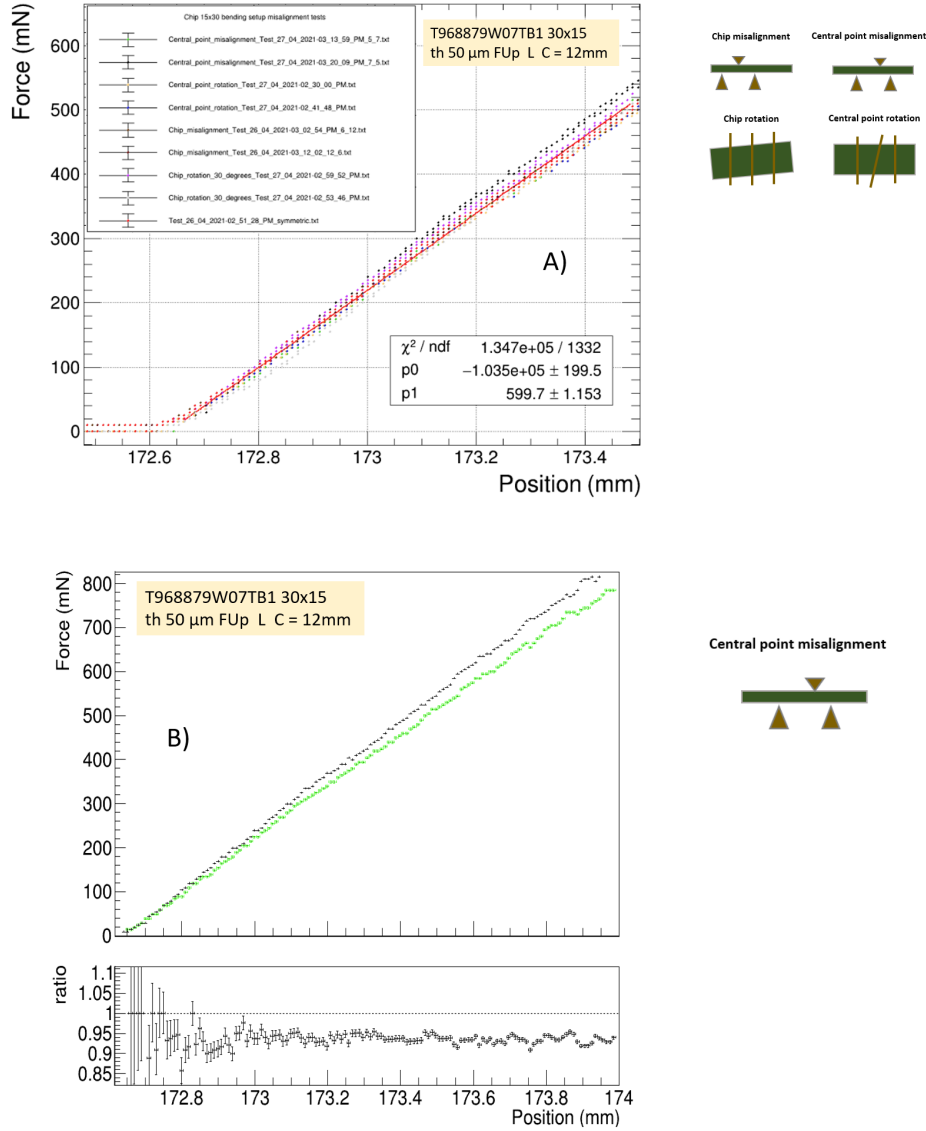


Figure 6.4: A) Three point bending measurements with large misalignment: 1 mm central point misalignment (5_7 mm and 7_5 mm), central point rotation 60°, 3mm chip misalignment (6_12 mm and 12_6 mm), chip rotation 30° B) The plot shows the biggest misalignment error that actually came from the central point misalignment. Even though the measurement was done with a large misalignment, the error is $\approx 5\%$.

II.3 Three point bending, thickness plots

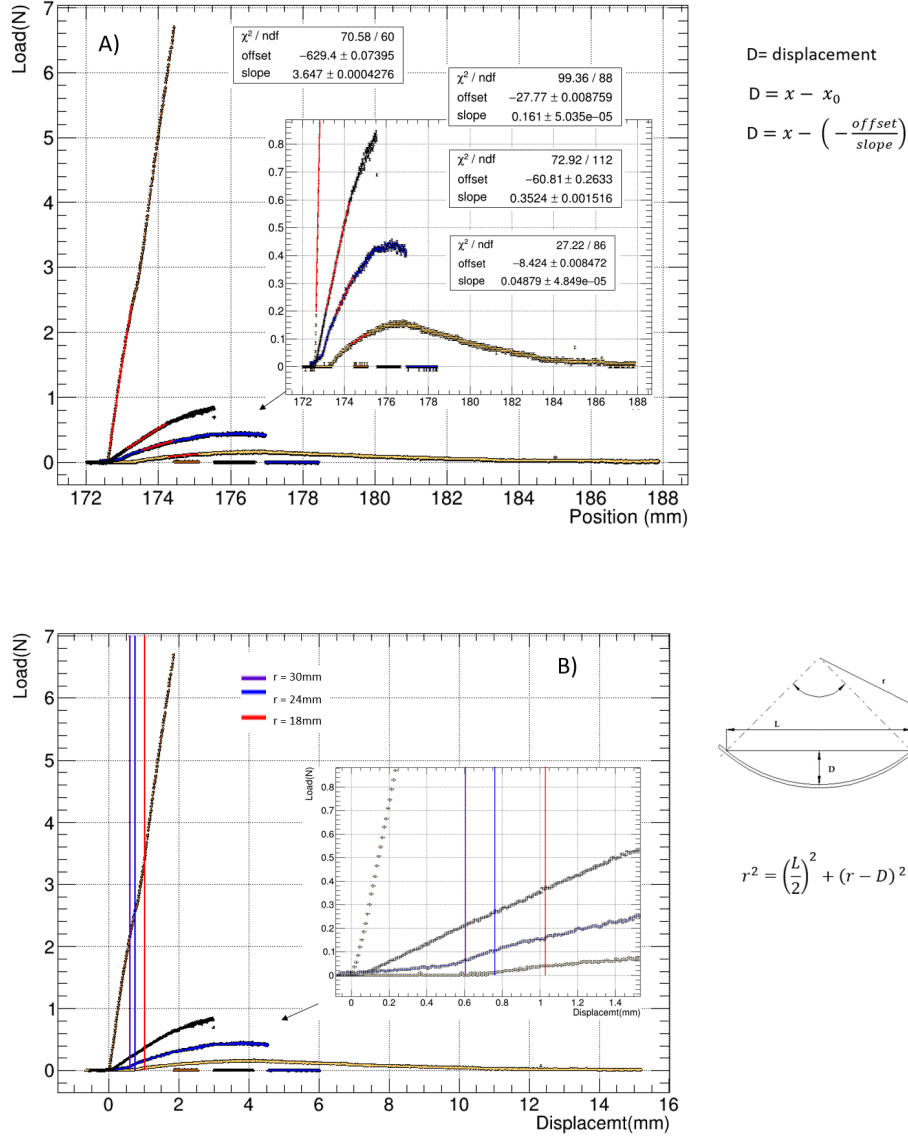


Figure 6.5: A) Three point bending measurements with various chips of thicknesses of $30 \mu\text{m}$ (yellow), $40 \mu\text{m}$ (blue), $50 \mu\text{m}$ (black), $100 \mu\text{m}$ (orange). B) Previous measurements are displayed as a function of the evaluated displacement. The straight lines localize the planned ITS3 radii (30mm violet, 24 mm blue, 18mm red) in the displacement axis (see relation on the left). The radii are located in the linear elastic region in all cases, however in the case of chip of $100 \mu\text{m}$ the 18mm radius is too near to the breaking point of the chip.

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Acronyms

- 2S** Strip-Strip module, two strip sensor. 1, 36, 37, 39–41, 43–48, 76, 85, 86
- ACF** Acquisition & Control Framework. 42, 44, 48, 76, 85
- ACORDE** ALICE COsmic Ray DEtector. 21
- AD** ALICE Diractive detector. 21
- ADC** Analog to Digital Converter. 35
- AID-DT** ALICE Detector Systems Group-Detector Technologies. 3
- ALICE** A Large Ion Collider Experiment. 1–3, 9, 17, 20, 65
- AMS** Alpha Magnetic Spectrometer. 37
- ASIC** Application Specific Integrated Circuits. 36, 40, 58, 68
- ATLAS** A Toroidal LHC ApparatuS. 5, 6, 9, 17, 18, 22, 37, 83
- BE** Back-End. 41
- BNL** Brookhaven National Laboratory. 4
- BRIL** Beam Radiation, Instrumentation, and Luminosity. 62
- CBC** CMS binary chip. 36, 40, 41, 43, 44, 48, 49, 52
- CBC3** CMS binary chip Three. 1, 48, 49, 76, 86
- CCD** Charge-Coupled Device. 53
- CDF** Collider Detector at Fermilab. 5
- CERN** Conseil Européen pour la Recherche Nucléaire. 1, 3, 5–9, 36, 42, 53, 58, 83
- CIC** Concentrator Integrated Circuit. 40, 41

- CMAPS** Curved Monolithic Active Pixel Sensor. 66, 67
- CMOS** Complementary Metal Oxide Semiconductor. 41, 58
- CMS** The Compact Muon Solenoid. 1, 3, 5, 6, 9, 17–20, 22, 36, 37, 40, 42–45, 53, 58, 59, 61, 62, 64, 76, 83, 84, 86, 87
- CMS-US** Compact Muon Solenoid - United States. 44
- CPU** Central Processing Unit. 42
- CPV** Charged-Particle Veto. 21
- DAC** Digital to Analog Converter. 62, 73, 74
- DAQ** Data Acquisition system. 18, 41, 42, 44, 72, 73
- DCal** Di-Jet Calorimeter. 21
- DESY** Deutsches Elektronen-Synchrotron. 5
- DONUT** Direct observation of the nu tau. 5
- DQM** Data Quality Monitoring. 43, 48, 86
- DTC** Data Trigger and control. 41–43, 86
- DuT** Device under Test. 45–47, 70
- DZero** Detector at the Tevatron collision point D0. 5
- EM** Electromagnetic. 11
- EMCal** ElectroMagnetic Calorimeter. 21
- ENC** Equivalent Noise Charge. 35
- EP** Experimental Physics department. 3
- EPIC** Environmental Pressurized Ionization Chambers. 59
- ERC** Environmental Rem-Counters. 59
- FDD** Forward Diffraction Detector. 21
- FE** Front-End. 41

- FEH** Front-End Hybrid. 40, 41
- FIT** The Fast Interaction Trigger. 21
- FLUKA** FLUktuierende KAskade. 59, 62, 64, 87
- FMD** Forward Multiplicity Detector. 21
- FNAL** Fermi National Accelerator Laboratory. 3
- FPGA** Field Programmable Gate Array. 41, 43, 86
- FT0** Fast Trigger T0. 21
- FV0** Fast Trigger V0. 21
- GLAST** Gamma-ray Large Area Telescope. 37
- GUI** Graphical User Interface. 68, 88
- HCAL** Electromagnetic calorimeter. 18, 19
- HCAL** Hadronic calorimeter. 18, 20
- HEP** High Energy Physics. 3, 18, 35, 40, 42, 53, 58, 65, 68
- HFT** Heavy Flavor Tracker. 65
- HL** High Luminosity. 37, 42–44, 76
- HL-LHC** High Luminosity Large Hadron Collider. 21, 22, 37, 38
- HMPID** High-Momentum Particle Identification Detector. 21
- ISOLDE** Isotope mass Separator On-Line facility. 9
- IT** Inner Tracker. 37, 38, 43, 85
- ITS** The Inner Tracking System. 2, 3, 20, 65–67, 72–74, 87, 88
- ITS3** The Inner Tracking System three. 66, 77
- L1** Level-1 trigger. 42
- LHC** Large Hadron Collider. 1, 3, 5, 7–10, 21, 22, 40, 43, 44, 59, 76
- LHCb** Large Hadron Collider beauty. 9, 17, 37

- LINAC2** Linear Accelerator 2. 8
- lpGBT** low-power Gigabit Transceiver. 41
- MAPS** Monolithic Active Pixel Sensors. 2, 65–75, 77, 88
- MARS** MAGIC analysis and reconstruction software. 59, 62
- MCH** Muon Chamber. 21
- Medipix** Medical pixels detector. 58–62, 87
- Medipix3RX** Medical pixels detector, third generation, Rafa Xavi. 1, 53, 58–62, 64, 76, 87
- MFT** Muon Forward Tracker. 21
- MIP** Minimal Ionising Particle. 13, 52, 83, 86
- MTR** Muon Trigger. 21
- OS** Operating System. 42
- OT** Outer Tracker. 37–39, 43, 85
- OtSDAQ** Off the Shelf Data Acquisition system. 44
- PH2** Phase 2. 42, 44, 48, 76
- PHENIX** Pioneering High Energy Nuclear Interaction eXperiment. 37
- PHOS** PHOton Spectrometer. 21
- PID** Particle-identification system. 20
- PMD** Photon Multiplicity Detector. 21
- PS** Proton Synchrotron (Chaper 1), Pixel Strip (Chapter 3). 9, 37, 39, 40, 44, 85
- PSB** Proton Synchrotron Booster. 8, 9
- pT** High Transverse momentum (p) particles. 40, 85
- PU** Pileup. 10, 22
- QGP** Quark-Gluon-Plasma. 20

- ROC** ReadOut chips. 39
- SEH** Service Hybrid. 40, 41
- SiPM** Scintillators with silicon Photo-Multipliers. 59
- SLAC** Stanford Linear Accelerator Center. 4
- SMU** Source Measure Unit. 45
- SN-Medipix3RX** Slow Neutrons Medipix3RX. 2, 62–64, 87
- SoC** System on Chip. 41–43, 86
- SPS** Super Proton Synchrotron. 9
- SUSY** Super Symmetry. 22
- TB2S** Tracker Barrel with 2S modules. 37, 39, 85
- TBPS** Tracker Barrel with PS modules. 37, 39, 85
- TBPX** Tracker Barrel PiXel detector. 37, 38, 85
- TCP-IP** Transmission Control Protocol-Internet Protocol. 48
- TDAQ** Trigger and Data Acquisition system. 17, 18, 42, 43, 86
- TEDD** Tracker Endcap Double-Discs. 37, 39, 85
- TEPX** Tracker End cap PiXel detector. 37, 38, 85
- TFPX** Tracker Forward PiXel detector. 37, 38, 85
- TG** Track Finding. 41
- TIF** Tracker Integration Facility. 62
- TOF** Time Of Flight Detector. 21
- TPC** Time Projection Chamber. 20
- TRD** Transition Radiation Detector. 21
- UNICAM** Università degli Studi di Camerino. 3
- VBF** Vector Boson Fusion. 22, 84

VTRx+ Versatile Link Plus Transceiver. 41

XML Extensible Markup Language. 42

ZDC Zero Degree Calorimeter. 21