

Faculté des sciences

Performance of the silicon modules of the CMS tracker for HL-LHC

Mémoire présenté en vue de l'obtention du grade académique de
Master [120] en sciences physiques

Auteur : Noémie Déplechin

Promoteur : Christophe Delaere

Lecteurs : Eduardo Cortina Gil et Vincent Lemaitre

École de Physique

Année académique 2024-2025

Acknowledgements

I start my acknowledgements with my supervisor, Christophe Delaere, who proposed this really exciting project. I am grateful for all the time he spent with me sharing his knowledge about the CMS tracker, for his support, for letting me be part of his team and for giving me the opportunity to travel to Hamburg.

I also want to thank my two readers, Eduardo Cortina Gil and Vincent Lemaitre, for their involvement in my master's thesis. Eduardo for letting me use his microscope, but also for learning me so many things about particle detectors during his courses. And Vincent for his numerous advice on how to make my master's thesis more pleasant to read.

This year, I joined the team working on the integration of the future CMS tracker in Louvain-la-Neuve, composed of Jerome de Favereau, Paul Malek, Semra Turkcapar and Majid Hussain. I want to express my gratitude to all of them for their warm welcome, for the time they spent explaining all the details about the tracker and for their help to run tests related to my master's thesis. I want to thank Nicolas Szilasi, Laurent Bruniaux and Raphaël Indot for their explanations from a more technical perspective. I also thank Quentin de Smedt for moving the spiders out of my office and for his help in understanding the functioning of the electronic chips. Finally, I thank Khalil El Achi for his help with the radioactive sources.

I really enjoyed my master at UCLouvain, and I want to thank all the teachers for sharing their passion about particle physics and especially particle detectors. I also thank Carinne Mertens for her kind help with administrative tasks.

I also want to thank all the physicists from Hamburg, Lyon and Aachen I met during the exercises for their kindness, especially the Hamburg team for their warm welcome and all the tips they shared with us. I also thank Martin Delcourt for sharing his work with me.

And last but not least, I thank my parents and my brother for their constant support during the last five years. I am deeply grateful for the nice environment they offered me so that I could focus on my studies.

Contents

Acknowledgements	i
Acronyms	iv
1 Introduction	1
2 The CMS Phase-2 Upgrade	3
2.1 The High Luminosity-LHC	3
2.2 The Compact Muon Solenoid detector	5
2.2.1 CMS coordinate system	7
2.3 The CMS Phase-2 Tracker Upgrade	8
3 Modules of the Outer Tracker Upgrade	9
3.1 Silicon to track particles	9
3.1.1 Silicon sensors	9
3.1.2 Charged particle-matter interaction	13
3.1.3 Working principle of a silicon tracking device	13
3.1.4 Noise in silicon sensors	15
3.1.5 Estimation of the signal generated by a crossing particle	16
3.2 2S and PS modules	16
3.2.1 Description of the modules	16
3.2.2 Positions of the modules	18
3.2.3 Connections between the sensors and the chips	19
3.2.4 L1 trigger	20
3.2.5 Electronic chips of the modules	21
3.3 Quick and full tests	23
3.3.1 Alignment procedures	24
3.3.2 Noise measurements	27
3.3.3 Steps only present in full tests	30
3.3.4 The Analyzer of Test Outputs	31
4 Setups in Louvain-la-Neuve	33
4.1 Reception room	33
4.2 Clean room	35
4.2.1 Burn-in setup	36
4.2.2 Cold box setup	37

5	Training for future module integration	38
5.1	Integration exercise	38
5.2	Double-disk assembly exercise	39
6	Results about one module	41
6.1	Comparison of noise between two setups	41
6.2	Temperature cycles	44
6.3	Noise in a PS module	50
7	Results from the integration exercise	52
7.1	Temperatures of the modules	53
7.2	Noise in the modules	54
8	Conclusion	56
A	Additional plots for section 6.2	58

Acronyms

2S Two Strip

AMC Advanced Mezzanine Card

ASIC Application-Specific Integrated Circuit

ATCA Advanced Telecommunications Computing Architecture

CBC CMS Binary Chip

CERN European Organization for Nuclear Research

CFRP Carbon Fiber Reinforced Polymer

CIC Concentrator Integrated Circuit

CMS Compact Muon Solenoid

DESY Deutsches Elektronen-Synchrotron

ECAL Electromagnetic CALorimeter

ENC Equivalent Noise Charge

ESD-safe ElectroStatic Discharge safe

EYETS Extended Year-End Technical Stop

FPGA Field-Programmable Gate Array

GIPHT Graphical user Interface for PHase 2 Tracker objects

HCAL Hadron CALorimeter

HL-LHC High-Luminosity LHC

L1 Level-1

LHC Large Hadron Collider

LINAC LINear ACcelerator

lpGBT low power Giga Bit Transceiver

MARTA Monoblock Approach for a Refrigeration Technical Application

MicroTCA Micro Telecommunications Computing Architecture

MIP Minimum Ionizing Particle

MPA Macro Pixel ASIC

OTSDAQ Off The Shelf Data AcQuisition software

Ph2_ACF CMS Tracker Phase2 Acquisition & Control Framework

POTATO CMS Phase 2 Outer Tracker Analyzer of Test Outputs

PS Pixel Strip

SCR Space Charge Region

SPS Super Proton Synchrotron

SSA Short Strip ASIC

TEDD Tracker Endcap made of Double-Disks

VTRx+ Versatile TRansceiver plus

Chapter 1

Introduction

The Large Hadron Collider (LHC), the most powerful particle accelerator, will be upgraded to reach higher luminosities. The detectors around its collision points also need to be upgraded to fully exploit the interesting events that will be produced. The Compact Muon Solenoid (CMS) will be upgraded for 2030, when higher luminosities will be achieved. One endcap of its outer tracker will be integrated in Louvain-la-Neuve, and it is in this context that my master's thesis has come together.

The CMS tracker is composed of silicon modules, some composed of Two Strip (2S) sensors and others containing one macro-Pixel and one Strip sensor (PS). Two prototype modules, one of each type, are in Louvain-la-Neuve, and my first goal consisted in understanding the various tests that we can run on these modules to check that they work as expected. I had a closer look on the noise measurements, to see how the noise changes depending on the setup, on the temperature and on the strip length. I also participated in an exercise consisting of the integration of twelve silicon sensors on large half-disks that assembled together form a Tracker Endcap made of Double-Disks (TEDD). After this exercise, I analyzed the cooling and the noise of modules placed on the half-disk structure.

Chapter 2 describes the context: why we need to upgrade the LHC, how it is done, and the impact it has on the CMS tracker. A description of the whole detector is also given.

In the beginning of Chapter 3, we explain in detail how silicon is able to track the crossing of charged particles, with also a description of the noise sources in a silicon sensor and the estimation of the signal left by a crossing particle. The different types of modules used in the CMS tracker and the corresponding electronic chips are described, and the future positions of modules in the tracker are also given. In the new detector, data from the tracker will be used for the Level-1 trigger, and there is an explanation of how it is handled. This Chapter ends with a summary of the different procedures we can run on modules to check if they are working as expected.

The rooms used by the Louvain-la-Neuve tracker team, the reception room and the clean room, are presented in Chapter 4, along with the equipment we use to test and integrate modules.

The integration of the future tracker is only starting in Louvain-la-Neuve, for the moment exercises are organized to practice for the future integration. Colleagues from Lyon and Hamburg joined us to practise together the integration of twelve modules on a half-disk structure. In March, I had the opportunity to travel to Hamburg to participate in a double-disk assembly exercise. In Chapter 5, I describe what was done during these two exercises.

There are two different parts in the results. In Chapter 6, noise measurements are made on individual prototype modules. We compare the noise between two setups, also at different temperatures, and between PS and 2S modules. In Chapter 7, temperature and noise measurements from the integration exercise are given, so several modules at a time placed on a half-disk structure.

Finally, the conclusion summarizes the results and outlines what lies ahead, and the appendix contains additional result plots.

Chapter 2

The CMS Phase-2 Upgrade

This chapter introduces the Large Hadron Collider and why it will soon be upgraded to reach higher luminosities in the particle collisions. The Compact Muon Solenoid detector is also described, with some improvements that are planned for the future tracker to survive and give valuable information from events with increased luminosity.

2.1 The High Luminosity-LHC

The CERN (from the French acronym "Conseil Européen pour la Recherche Nucléaire") was founded in 1952 with the goal to create a leading fundamental physics research organization in Europe. In those days, physicists were trying to understand what was happening inside of atoms. Nowadays, physicists are studying the interactions between subatomic particles. Between 1998 and 2008, scientists built the Large Hadron Collider (LHC) [1], the world's largest and most powerful particle accelerator, reaching 13.6 TeV of centre-of-mass energy. The LHC is mostly used to collide protons, but one month per year it is dedicated to lead-lead and proton-lead collisions.

Figure 2.1 is a representation of all the accelerators in operation at CERN. The largest accelerator is the LHC, with a circumference of 27 km. Before their injection into the LHC, protons have already been accelerated thanks to a chain of less powerful accelerators, starting with LINAC 3 (LINear ACcelerator 3). The final step for the beams before entering the LHC is the Super Proton Synchrotron (SPS) where they reach 450 GeV. There are four interaction points at the LHC, each of them surrounded by a particle detector, and one of them is the Compact Muon Solenoid (CMS) [2].

The LHC, in combination with detectors surrounding the beam collision points, successfully led to the discovery of the Higgs boson in 2012. But that is not the end of the story, there are still a lot of processes that physicists can not precisely explain due to a lack of data and analysis of this data. For instance, the Higgs boson trilinear self-coupling is not measured precisely yet, it appears in the case of Higgs boson pair production with for instance the interaction shown in figure 2.2. The trilinear coupling is related to the third derivative of the Higgs potential at its minimum, thus by measuring the trilinear coupling we could probe the Higgs field potential.

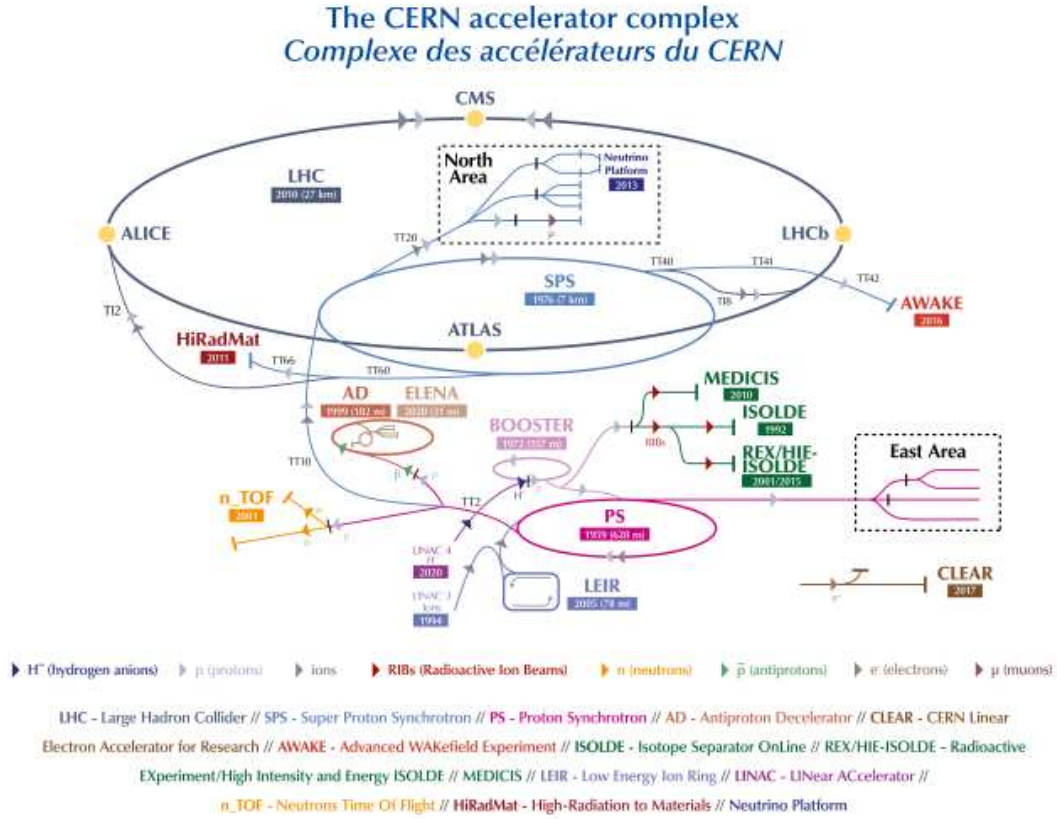


Figure 2.1: An overview of all accelerators in operation at CERN [3].

We could understand its shape, and determine if it has the typical "mexican hat" shape predicted by the standard model or a more complex structure. By measuring the Higgs boson pair production we can probe the Higgs boson trilinear coupling, but the pair production has a cross section about 1000 times smaller than the one for single Higgs boson production, therefore a large dataset is needed. We described this example because the Higgs bosons can decay into bottom quarks. These quarks have a sufficient lifetime to travel some distance before decaying. Therefore, the b-jets are displaced from where the bottom quarks were formed. The identification of b-jets requires precision silicon trackers, such as the CMS tracker which is the focus of this thesis.

To perform precision measurements of the standard model, like the studies of

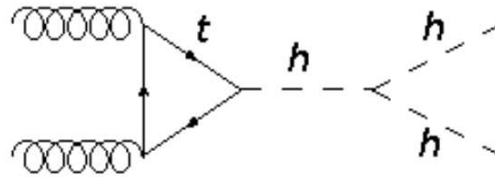


Figure 2.2: One of the Feynman diagrams for the gluon fusion Higgs boson pair production [4].

Higgs boson properties, and beyond the standard model with new physics, the LHC will be upgraded into the High-Luminosity LHC (HL-LHC) [5] to enable instantaneous luminosities largely exceeding the current performance. Figure 2.3 is a plan of the LHC, on which we can see that the upgrade for HL-LHC is scheduled to be ready in 2030. We can also observe that the luminosity is increasing over the years.

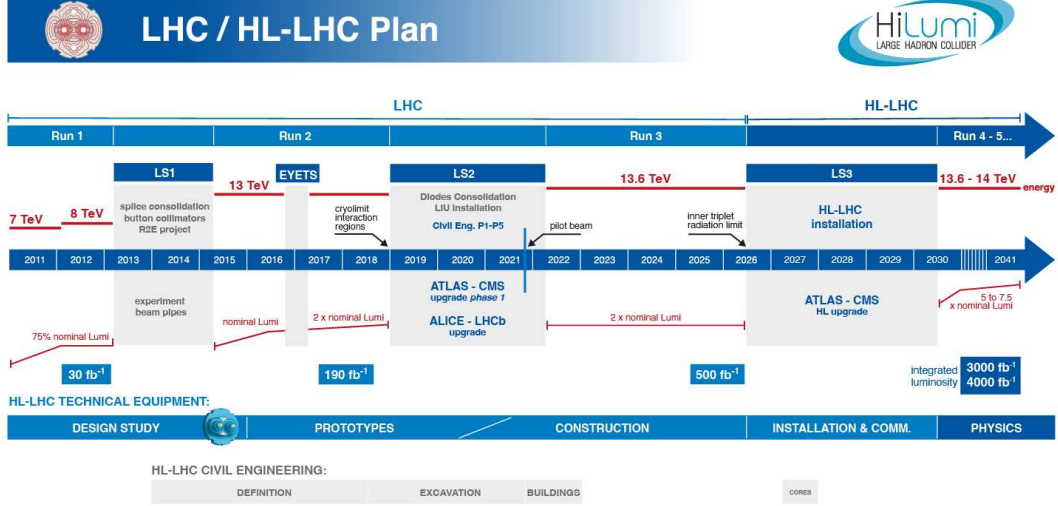


Figure 2.3: The LHC and HL-LHC upgrade plans [6].

The luminosity in the case of a collider is computed using the following formula [7]:

$$L = n \frac{N_1 N_2}{A} f \quad (2.1)$$

where N_1 and N_2 are the numbers of particles in the n colliding bunches, A is the cross-sectional area of the beam and $f = 1/T$ is the frequency with T the time to make one turn of the ring. The most important upgrade to increase the luminosity is the replacement of the quadrupole magnets in the insertion regions. The more radiation tolerant new magnets will provide a higher magnetic field strength and have a larger aperture. They will reduce the cross-sectional area of the beams, leading to a luminosity increase that we can understand with equation 2.1. The HL-LHC will reach instantaneous peak luminosities of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with centre-of-mass energy of 14 TeV and a bunch spacing of 25 ns.

2.2 The Compact Muon Solenoid detector

CMS stands for Compact Muon Solenoid, compact because the detector has a diameter of 15 m, is 21 m long and weighs 14 000 tons, muon because it detects those particles very accurately, and solenoid because it has a very powerful solenoid magnet of 6 m internal diameter producing a magnetic field of 3.8 T.

The CMS detector contains several layers located around one LHC interaction point, like a cylindrical onion, as represented in figure 2.4. Each layer is designed to

obtain specific types of information from the crossing particles, so that in the end we have a precise idea about all the particles that were created at the collision and their energies.

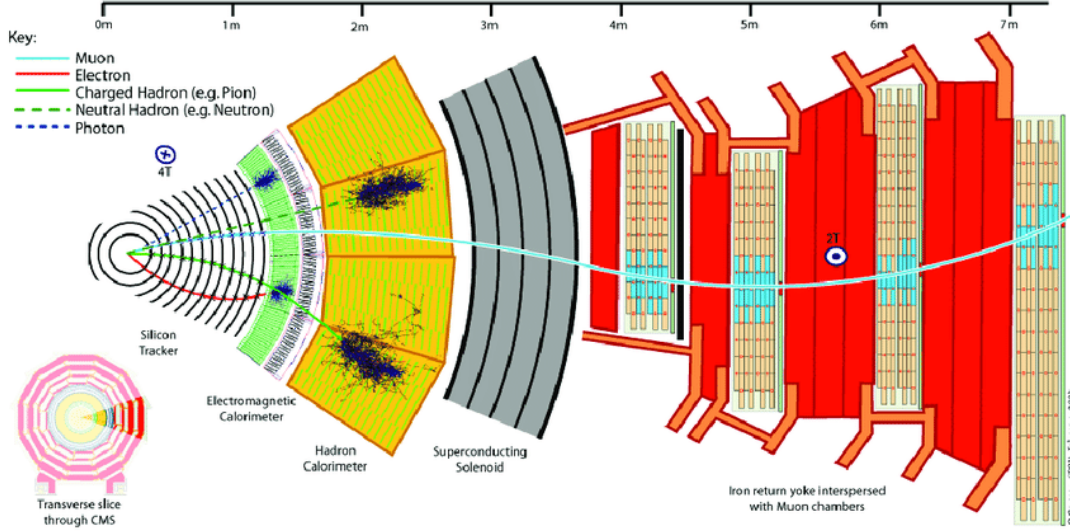


Figure 2.4: Transverse slice view through the CMS detector [8].

The first layer in contact with particles from the collision is the silicon tracker. It is made of pixel and strip sensors that detect the crossing of charged particles to determine their trajectories with $10\ \mu\text{m}$ accuracy. It is also able to compute the transverse momentum of particles with the bending of their tracks in the magnetic field. More detailed explanations about the tracker are provided in Chapter 3.

There are two different calorimeters in CMS, and they are designed to find a particle's position, energy and arrival time. They are made of high-density materials where incident primary particles induce a shower, leaving low-energy photons in a scintillating material. The addition of the energies of the photons corresponds to the energy deposited by the incoming particle. The readout is done by photodetectors that convert the light into an electrical signal and amplifies it. The Electromagnetic CALorimeter (ECAL) is a homogeneous detector, it is made of only one material for energy degradation and signal generation, lead tungstate crystal, an extremely dense but highly transparent material. Electrons and photons create an electromagnetic shower through bremsstrahlung and electron-positron pair creation in the scintillation calorimeter. After the ECAL, particles that were not stopped reach the Hadron CALorimeter (HCAL). It is a sampling calorimeter, meaning that it is made of alternating layers of absorber and active medium for signal generation. The absorbing material is dense and hadrons (for example protons, neutrons, pions and kaons) interact in it to give showers. Hadrons have inelastic interactions with nuclei in the medium, leading to pions that can have further inelastic collisions or decay, but there are also nuclear processes, electromagnetic showers and even non-visible energy such as nuclear binding energies. The HCAL is larger than the ECAL because hadronic showers have longer longitudinal and transverse sizes.

Muons are not stopped by the calorimeters, and muons chambers are located in

the outer part of the experiment where muons are the only particles likely to produce a clear signal. Four different types of detector are used: drift tubes, cathode strip chambers, resistive plate chambers and gas electron multiplier chambers. The four detectors are gaseous, and the crossing of muons ionizes the gas, producing free electrons. The amplification and collection of electrons depend on the type of muon chamber. A particle track is measured by fitting a curve on the generated signals in the four muon stations, and it gives access to the muon momenta.

It is not possible to store data from all the collisions happening in the middle of CMS at 40 MHz. A first selection is done by an electronic system, the Level-1 (L1) Trigger, to reduce the rate at which data needs to be stored to 100 kHz. Currently, data from the calorimeters and the muon chambers is used to look for signs of interesting physics, keeping interactions with highly energetic particles or unusual combinations for instance. Finer filtering is performed by a software trigger called the High-Level Trigger that synchronizes information from the different parts of the detector to recreate the entire event.

During the Extended Year-End Technical Stop (EYETS) in 2016/2017, the original pixel detector was replaced by the CMS Phase-1 pixel detector [9]. The original pixel detector suffered from inefficiencies in the readout chip at high rates, because the instantaneous luminosity exceeded the original design value. The inner pixel detector was designed in order to be easily removed and reinstalled in CMS without removing the beam pipe, which makes it possible to replace degraded parts during regular shutdowns.

2.2.1 CMS coordinate system

A short description of the CMS coordinate system is given to introduce the relevant variables that will be used afterwards. Figure 2.5 shows the important coordinates, with CMS represented as the light red cylinder and the beam direction along the z axis. The origin is centred at the interaction point in the middle of the experiment. The x axis points towards the centre of the LHC, and the y axis points vertically upwards. In the x - y plane, r is the radial coordinate. η is the pseudorapidity, defined as $\eta = -\ln(\tan(\theta/2))$, with θ the polar angle measured from the z axis.

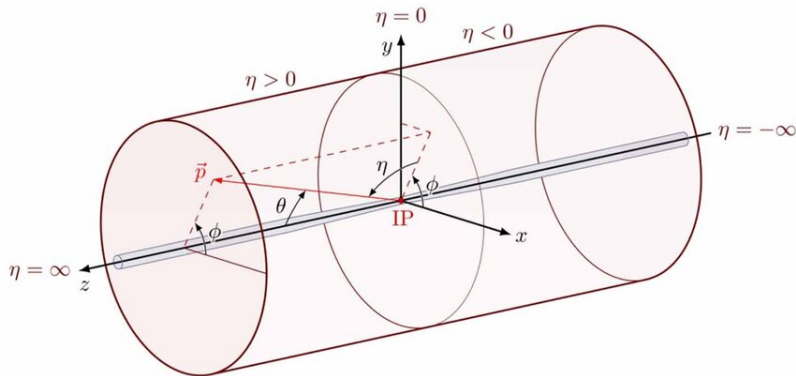


Figure 2.5: The CMS coordinate system [10].

2.3 The CMS Phase-2 Tracker Upgrade

The detectors around the beam crossing points of the LHC also need to be upgraded, and the whole CMS detector will be upgraded during the Long Shutdown 3 between 2026 and 2030 to exploit the increase in luminosity provided by the HL-LHC. This is referred to as the CMS Phase-2 Upgrade [11], and one team at UCLouvain is assembling one endcap of the new outer tracker for CMS that will be sent to CERN by March 2028. The Inner Tracker, where the radius is smaller than 20 cm (and smaller than 30 cm when located more than 1.6 m away from the interaction point in the beam direction), will consist of silicon pixel modules. The Outer Tracker will contain silicon strip and macro-pixel sensors. The tracker improvements are described in this section.

The higher luminosity in the LHC means that pileup will increase, up to 200 collisions per bunch crossing are expected on average. This leads to an increase of particle density that will be handled in the following ways:

- Several materials and thicknesses were investigated to obtain a tracker with sufficient radiation tolerance.
- The granularity is increased in order to keep the occupancy below the per cent level in the Outer Tracker, so that the tracking performance stays efficient.
- An increased bandwidth is needed to accommodate the higher data rates.
- The CMS trigger will work with a longer latency and a higher output rate to ease the selection of interesting events. Furthermore, the tracker will provide information about tracks with a transverse momentum higher than a certain threshold directly to the L1 trigger.

A few other improvements will be introduced:

- Reduced material in the tracking volume will improve the performance of the tracker but also of the calorimeters leading to a better overall event reconstruction.
- The design of the upgraded tracker will enable efficient and fast track finding, as well as improved two-track separation.
- The acceptance of the tracker in the forward region will be extended to provide an efficient tracking up to $|\eta| = 4$.

Chapter 3

Modules of the Outer Tracker Upgrade

This chapter summarizes all the concepts needed to understand how the silicon sensors used for the CMS tracker upgrade work and how they are tested before their integration. The first section explains how pn-junctions work and the interactions of charged particles with matter, to understand how silicon tracking devices operate. The noise sources are described and an estimation of the signal left by a crossing particle is computed. The second section describes the modules used for the future tracker, explains where they are located, how the sensor is connected to the chips, the working of the L1 trigger and the electronic chips. The different types of test that are available to determine the quality of a module are described in the last section, with a focus on the noise measurements, and also an overview of the Analyzer of Test Outputs.

3.1 Silicon to track particles

This section starts with basic principles to explain how silicon is able to detect the crossing of charged particles. Most of the explanations are based on the book of F. Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics* [12].

3.1.1 Silicon sensors

Silicon is a semiconductor, it behaves like an insulator at low temperatures and is conductive at higher temperatures. Since 1960, silicon is used in particle detectors, and since the late 1980s it is used in strip and pixel detectors close to the primary interaction point. One main advantage of silicon sensor is its very good energy resolution, one electron-hole pair is created when only 3.6 eV is transmitted to the medium by a crossing particle.

The sensors used in the CMS tracker are made of silicon so it is interesting to understand how the crossing of a charged particle leads to a signal that we can analyze. Given that silicon is a semiconductor, there is a band gap in its energy band structure. This band gap is of 1.12 eV. At low temperature, all the electrons lie in the valence band (see figure 3.1), but as the temperature increases, electrons are thermally excited and can go from the valence band to the conduction band where

they become mobile.

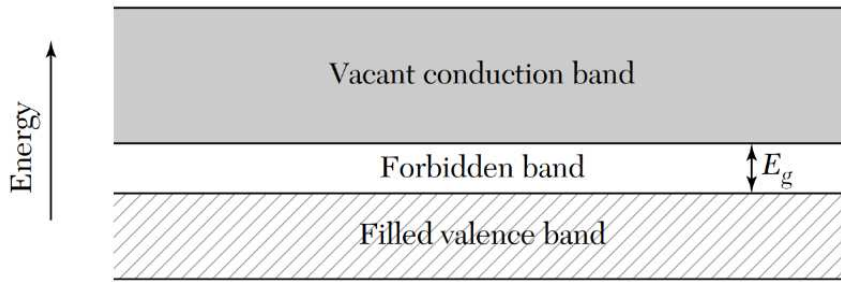


Figure 3.1: Band scheme in a semiconductor. At 0 K the conductivity is zero because all states in the valence band are filled and all states in the conduction band are vacant [13].

To better understand the explanations, we need to introduce the Fermi level, which corresponds to the energy where exactly half of the available levels are occupied. It is located in the middle of the band gap for intrinsic (without impurities) silicon.

By doping the material, we can add additional states in the band gap, and this increases the probability to excite electrons and holes thus the conductivity of silicon can vary. Doped silicon is referred to as extrinsic. Silicon has four valence electrons, and we can obtain an "n-type" silicon by adding material containing five valence electrons (for instance arsenic). The doping with arsenic and the corresponding band scheme is shown in figure 3.2. The introduction of arsenic leads to an excess of electrons that can not bond because only four are needed to bond with the surrounding silicon atoms, thus there are loosely bound electrons added to the valence band. A donor level is then formed just under the conduction band and the quasi-free electrons can easily be excited into the conduction band.

"p-type" silicon can be obtained by incorporating materials with only three va-

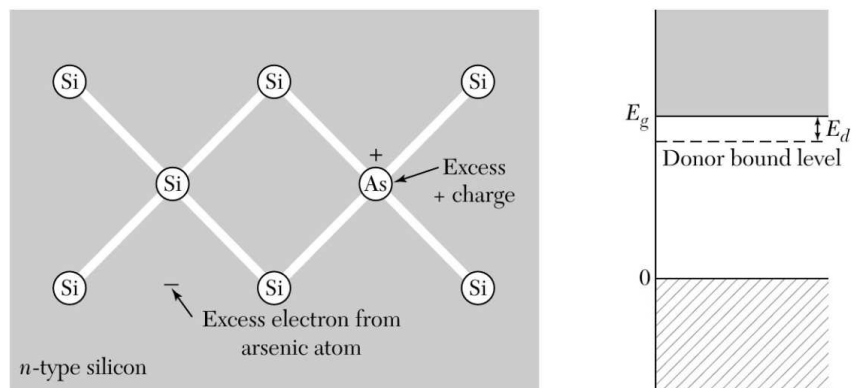


Figure 3.2: The addition of arsenic into silicon to obtain n-type silicon. On the left there is an atomic representation, and on the right the band scheme with the new level created close to the conduction band [13].

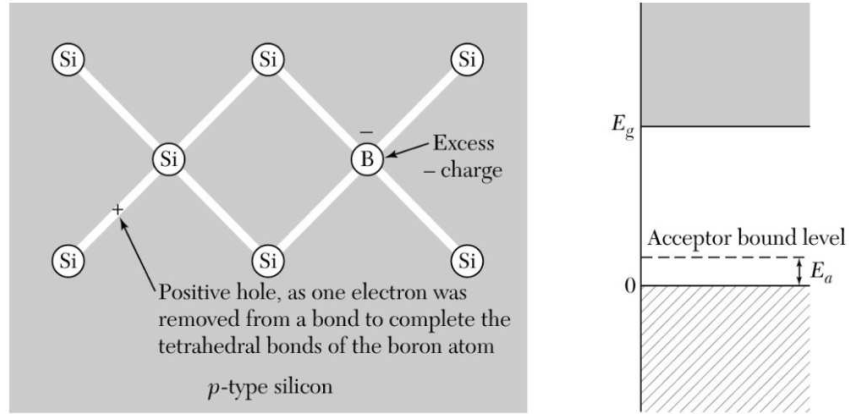


Figure 3.3: The addition of boron into silicon to obtain p-type silicon. On the left there is an atomic representation, and on the right the band scheme with the new level created close to the valence band [13].

lence electrons (for instance boron, see figure 3.3). In this case, some silicon bonds are incomplete due to the deficit of electrons. An acceptor level is formed just on top of the valence band, and it attracts electrons from nearby silicon atoms. This leads to an excess of holes (the vacancy created in the valence band when an electron absorbs enough energy to enter the conduction band, treated like positively charged particles) as majority charge carriers.

In an intrinsic silicon substrate with a typical size for high-energy particle detection, there are around 10^9 free charge carriers. An ionising particle will only generate in the order of 10^4 electrons, thus its signal would be lost in the amount of free charge carriers. The goal is now to reduce the number of free charge carriers. A first option is to cool down to very low temperatures, but for large detector applications it is not practical. A better option consists in depleting the semiconductor volume by using p-type and n-type silicon in a reverse-biased pn-junction configuration.

Figure 3.4 is a representation of the evolution of the different states in a n-type and p-type silicon when they are placed next to each other. In the beginning, the n-type and p-type silicon are not in contact. In the n-doped part, the majority charge carriers are electrons, and in the p-type holes are the dominant carriers. When the two parts are in contact, the strong concentration gradient between the charge carriers at the interface leads to a diffusion current. It consists of electrons moving from the n-doped region to the p-doped region, and holes going in the opposite direction. Electrons and holes will then recombine so a zone without free charges is created at the interface, it is the depletion zone that acts as an insulator. Even if there are no more free charge carriers, the ionized atomic cores are still present and they create an electric field that prevents further diffusion, and when the field is strong enough to stop the diffusion of holes and electrons, a dynamic equilibrium is created. This stable state is represented in the last frame of figure 3.4, with in the middle the Space Charge Region (SCR), and the Fermi level constant everywhere.

In our case, we want to have the largest SCR as possible, because charges created in the non-depleted zones recombine and are not detected. By applying an external

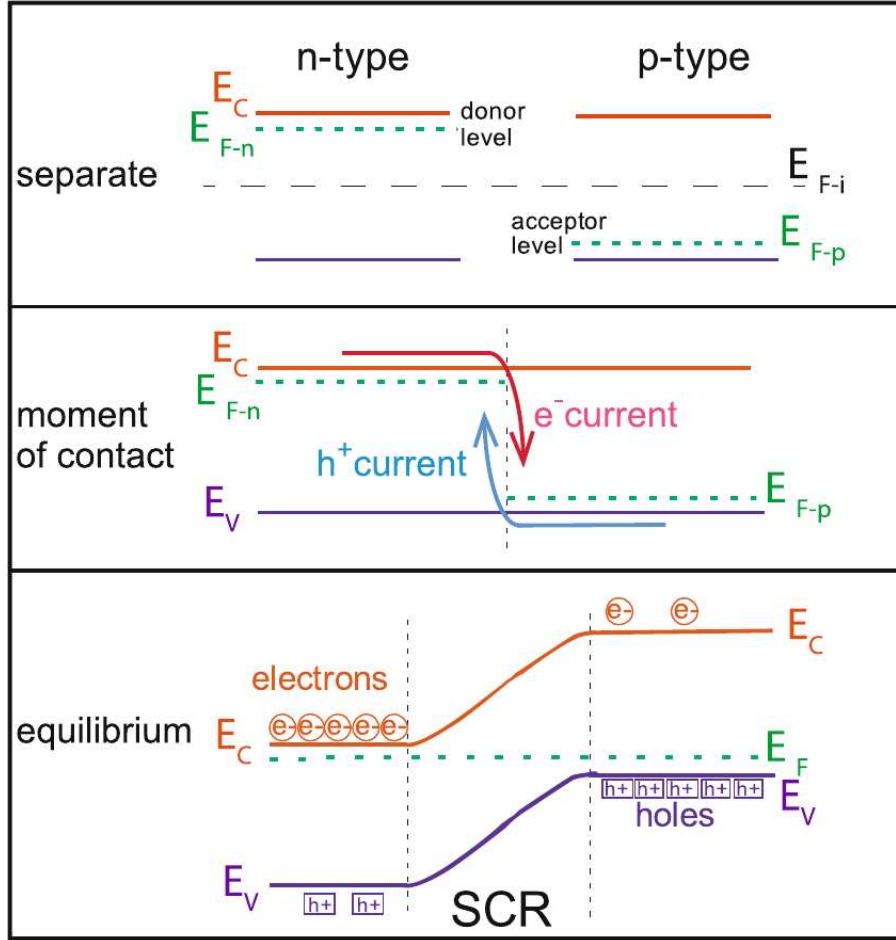


Figure 3.4: Behavior of p-type and n-type silicon when brought into contact. The limits to the conduction band are shown in orange, and in purple for the valence band. The dark dashed line in the first frame represents where the Fermi level is in an intrinsic sensor. The green dashed lines are the Fermi levels for the two doped sides [12].

voltage in reverse bias mode to the pn-junction, we can increase the potential barrier of the junction and increase the depletion width. V_{FD} defines the voltage that fully depletes the junction, and usually the operation voltage V_{bias} is set higher than V_{FD} to run over-depleted. This high bias disturbs the equilibrium of the junction and an electric field pushes the thermally generated electron-hole pairs in the SCR out of the depletion region. This leads to an undesired reverse current, called leakage current.

The surface of silicon strip sensors contains layers of high-doped silicon strips, an insulation layer of silicon dioxide (SiO_2) and on top metal strips that ensure the connection to the readout electronics. The Si to SiO_2 affinity allows to have a capacitive coupling between the diode and the metal, so that the three layers on top of the sensor form an integrated capacitor. The sensor is thus AC-coupled to the electronic chips. Pure silicon would chemically react to anything, and the thin layer of silicon dioxide acts as a protection. The different layers are visible in figure 3.6.

If silicon sensors are stored in places with high relative humidity levels ($> 30\%$),

their leakage current could increase. That is because silicon is hygroscopic, meaning that it absorbs water molecules from the surrounding environment. Water molecules can thus reach the bulk of the sensor, where they add unwanted impurities, leading to an increase of the leakage current because new levels are created in the band gap. To prevent this from happening, modules are stored in dry cabinets and tests stations are flushed with dry air. Fortunately, this is not an irreversible phenomenon and the water molecules can diffuse out of the sensor if it is kept in dry air for a long period.

3.1.2 Charged particle-matter interaction

When charged particles cross a medium, for instance silicon, they transfer kinetic energy to atomic electrons through Coulomb scattering. Electrons are then freed from the atom if enough energy is received, leading to the creation of an electron-hole pair. This scattering process is called ionization, and dominates over radiation for all particles other than electrons and positrons at all but the highest energies. We can compute the average energy loss of a charged particle in a medium, $\frac{dE}{dx}$, with the Bethe formula [12]:

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \cdot \frac{Z}{A} \cdot \frac{1}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} \right) - \beta^2 - \frac{\delta(\gamma)}{2} \right] \quad (3.1)$$

with z the charge of the incident particle, $T_{\max}$ the maximum kinetic energy that can be transmitted to a free electron in one single collision, I the mean excitation energy, Z the atomic number, A the atomic mass, N_A the Avogadro's number, m_e the electron mass, c the speed of light, r_e the classical electron radius, δ the density effect correction, $\beta = v/c$ with v the speed of the incident particle and $\gamma = \frac{1}{\sqrt{1-\beta^2}}$.

To extract useful information from this formula we can visualize it in figure 3.5. The most interesting point is the minimum at approximately $\beta\gamma = 3$, it corresponds to the minimum energy a particle can deposit in a medium, and to be able to detect the crossing of particles of that energy, called Minimum Ionizing Particles (MIPs), we need to keep the noise well below this energy. The Bethe formula works for $0.1 < \beta\gamma < 1000$ because it only accounts for energy losses due to ionization and excitation of bound electrons (leading to the emission of low-energy photons after the de-excitation of the atom). Below $\beta\gamma = 0.1$, the electrons can not be considered as stationary anymore, and for $\beta\gamma > 1000$, the radiative corrections can no longer be ignored.

3.1.3 Working principle of a silicon tracking device

In the previous sections, we saw how pn-junctions work and how a charged particle interacts with silicon. We will now put the two concepts together to understand how crossing particles are detected by silicon. Figure 3.6 is a view of what happens in a silicon strip detector when a particle goes through. The n-in-p polarity will be used for sensors in the outer tracker, because highly irradiated p-in-n sensors have in their noise distributions a significant non-Gaussian contribution. Non-Gaussian noise distributions have longer tails producing fake hits that can not be eliminated with a 5 sigma threshold. Therefore, it is difficult to suppress noise with a non-Gaussian component while keeping a high efficiency in the detection of crossing

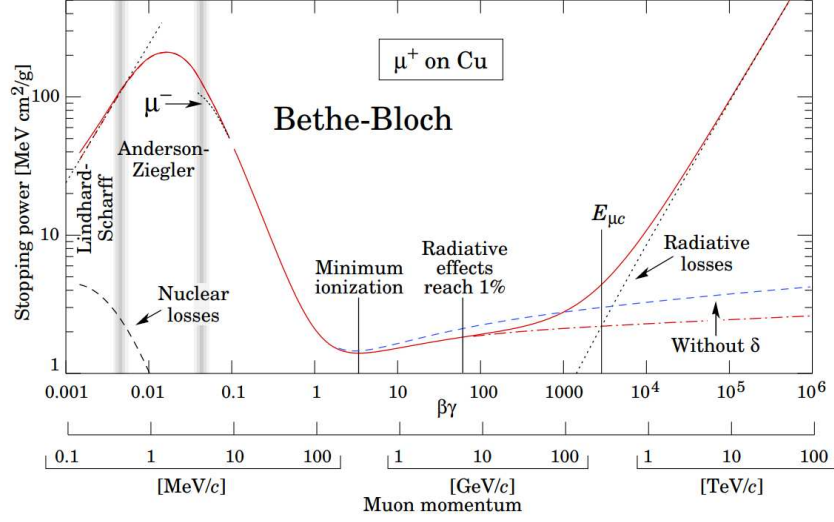


Figure 3.5: The stopping power $\langle dE/dX \rangle$ of copper for traversing muons depending on the muon momentum. The plot includes the corrections to the Bethe formula at low and high energies [14].

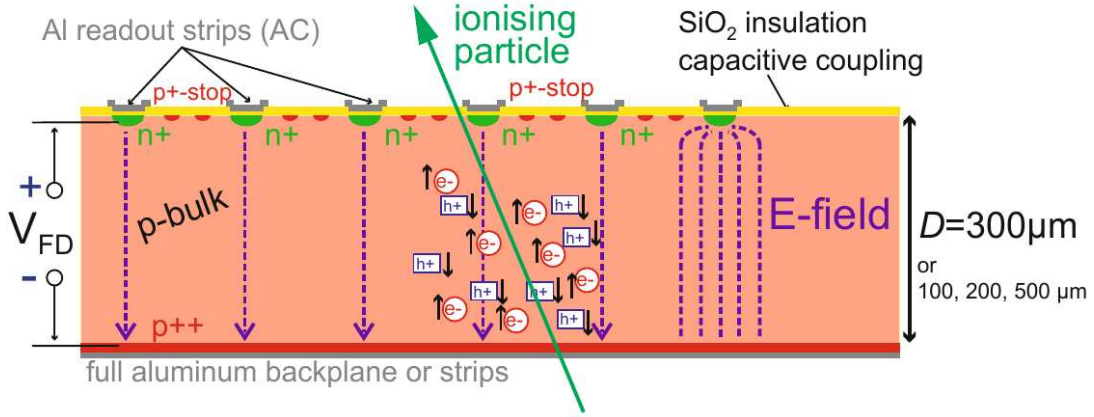


Figure 3.6: Working principle of an n-in-p AC-coupled silicon strip detector. The thickness, D , is equal to $200 \mu\text{m}$ for the modules of the CMS phase-2 upgrade [12].

particles. The silicon sensor is composed of a fully depleted p-doped slice, with on top n+ doped strips and at the bottom a p++ backplane. The + refers to the amount of doping, the bulk has the lowest doping, the n+ strips have a higher doping, and the p++ backplane has the highest doping concentration.

When an ionizing particle penetrates the sensors, electrons and holes are generated. The electrons drift along the electric field created by the bias voltage to the n+ strips, and holes drift to the p++ backplane. The electrons induced on the strips are capacitively coupled (AC) to the aluminium readout strips. The strips are wire-bonded with a direct connection (DC) to the chips responsible for the amplification and shaping of the signal. On the right of the p-bulk, we can see the electric field and notice that it concentrates on the strips. In reality, it is not when electrons reach the electrodes that we have a signal. The signal starts when the electrons and holes are moving, because the induced current in the strips is due to changes of the

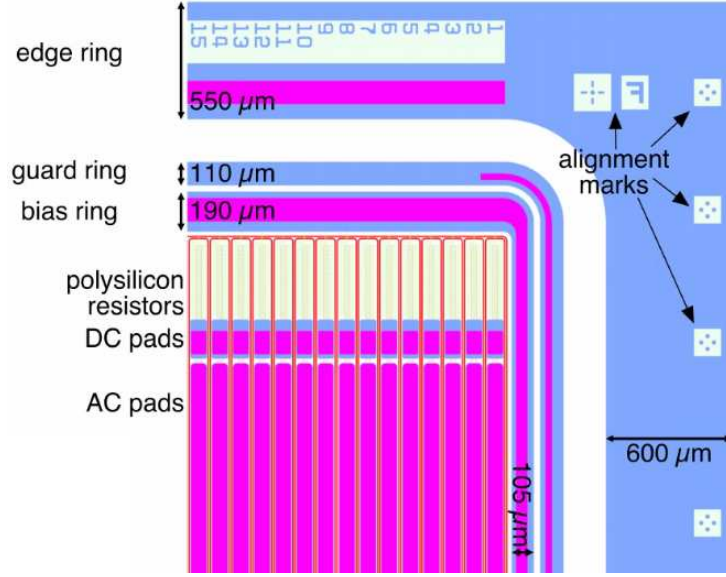


Figure 3.7: Representation of a corner of the strip sensor in a PS module to highlight the three rings [15].

electrostatic flux lines. This mechanism is described by the Shockley-Ramo theorem, and more details can be found in F. Hartmann’s book on page 27 [12]. The high mobilities in silicon result in collection times below 10 ns for sensors of several 100 μm thickness. To prevent the accumulation of electrons on the n+ strips, p+ implants surround the strips to dissipate the electrons and thus isolate the readout strips. The distance between two strips is called the pitch, and is it an important parameter in the detection of a particle position because it puts a limit on the resolution. When an event generates signal in one strip, the track position is given by the strip number.

Three rings surround the silicon sensors: bias, guard and edge rings, and they are represented in figure 3.7. The bias voltage is applied via the bias ring and the backplane. The bias ring is connected to all bias resistors to provide the ground potential to all the strips and the negative high potential is applied at the backplane. The bias ring distributes the ground potential to each strip in order to ensure a homogeneous potential. Another ring surrounds the active area of a sensor: the guard ring. It guarantees a defined homogeneous potential for all strips, including the edge ones, to minimize edge effects. These rings are made of aluminium and located on top of the strips. There is also a highly doped p++ implant at the periphery, called the edge ring. When the silicon wafers are cut, energy levels can appear in the forbidden gap at the edges of the sensor. They lead to leakage currents that we can suppress by avoiding high fields inside the cracked region. The p++ implant has the same polarity as the backplane and fixes the potential on top of the edge of the sensor. This implant is covered with aluminium containing alignment marks.

3.1.4 Noise in silicon sensors

Sources of statistical electron and hole fluctuations exist even when the sensor is fully depleted, and they cause noise in the detector. The goal is to minimize the

noise to better detect the signal. Four elements have an impact on the noise, and their contributions sum up quadratically.

The most significant noise source is caused by the load capacitance C_d . Its Equivalent Noise Charge (ENC), so the number of electrons contributing to this source of noise, can be computed in the following way [12]:

$$ENC = a + b.C_d \quad (3.2)$$

with a and b constants fixed by the preamplifier parameters. The load capacitance is proportional to the strip length, so one way to decrease this source of noise is to use shorter strips.

Leakage current leads to shot noise, another noise source that we want to keep as low as possible. The resistances that apply the bias voltage lead to parallel thermal noise that we can decrease by choosing higher resistances. And the metal strip resistances are the sources of serial thermal noise that can be reduced with smaller resistances. These three noise sources also depend on temperature, and noise is reduced at lower temperatures.

3.1.5 Estimation of the signal generated by a crossing particle

If we want to detect the crossing of a particle, we need to keep the noise well below the energy deposited by a MIP. The average energy loss for a MIP is around 390 eV per μm . By taking into account that each 3.6 eV deposited in the medium lead to one electron-hole pair, we have 108 pairs created per μm . And since the sensors used for the CMS tracker are 200 μm thick, the crossing of a MIP will generate 21 700 electron-hole pairs. During our noise measurements, we will check that noise is small enough so that the tracker is able to detect particles.

3.2 2S and PS modules

This section summarizes the important concepts about silicon modules needed to understand the results of the master's thesis. More details can be found in the Technical Design Report of the Phase-2 Upgrade of the CMS Tracker [15].

3.2.1 Description of the modules

Two versions of modules were realized for the outer tracker: modules with 2 Strip sensors (2S modules) and modules with a Strip and a macro-Pixel sensor (PS modules). Figure 3.8 is a picture containing a production 2S module and a production PS module. During the first part of the master thesis, we did not have access to final modules, so the first results were obtained with prototypes modules.

Each 2S module contains two identical strip sensors with a $10 \times 10 \text{ cm}^2$ size. The sensors are on top of each other, so only the top one is visible in picture 3.8. The sensors are all 200 μm thick. There are two variants of 2S modules, with the spacing between the two sensors equal to 1.8 mm or 4.0 mm thanks to different

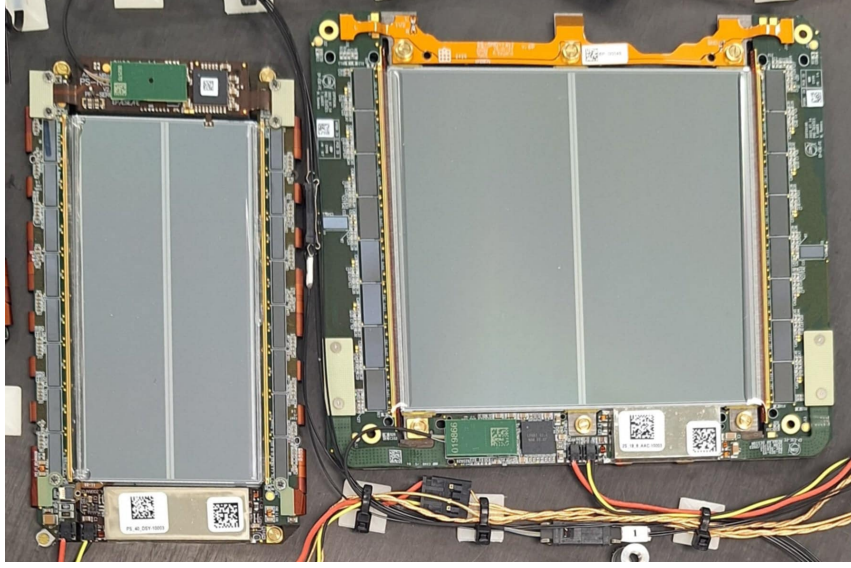


Figure 3.8: Picture of one PS module (on the left) and one 2S module (on the right).

shapes of spacers. The sensors have different spacings to optimize the transverse momentum filtering for the L1 trigger in different regions of the detector. The strips in the 2S modules are about 5 cm long, and their location and direction are shown in figure 3.9. There are 4064 strips in the whole module. The strip pitch is of $90\ \mu\text{m}$. There are four hybrids around a 2S module, one on each side. We call hybrid a flexible printed circuit board surrounding the silicon sensor, it hosts the electronic chips of the module and their connections. The lower one on figure 3.8 is the service hybrid that contains power and data transmission chips, on each side of the sensor there are front-end hybrids hosting front-end chips that amplify and process the sensor signal, and on top there is the ground balancer. Given that the chip used to generate the correct voltage to the module is not in the middle of the service hybrid, the length of the wires is not the same between the two sides of the module. This leads to different voltages that could equalize themselves with current flowing through the sensor. The ground balancer is used to prevent this current from going through the module by deviating it in a wire on the ground balancer hybrid. One difference between prototypes and productions 2S modules is that the prototypes do not have a ground balancer to redirect current out of the sensor, contributing to a higher noise. The left and right parts of a 2S module are defined with the service hybrid at the bottom of the image, like in figure 3.8.

In PS modules, the active areas that correspond to the sensors have $10 \times 5\ \text{cm}^2$ sizes, so half of the surface of a 2S sensor. A sketch on a PS module is shown in figure 3.10. The PS modules also have a strip sensor, but the strips are only 2.4 cm long and have a pitch of $100\ \mu\text{m}$, and there are in total 1920 strips. The second sensor below is segmented into macro-pixels of $1.5\ \text{mm} \times 100\ \mu\text{m}$, leading to a total of 30 720 macro-pixels. The main difference between a macro-pixel sensor and a strip sensor is that the strips on the pixel sensor have a smaller length (here $1.5\ \text{mm}$), and since strips cover the whole sensor, data also needs to be read out from the central region. To be able to connect all the small strips to the corresponding readout chip,

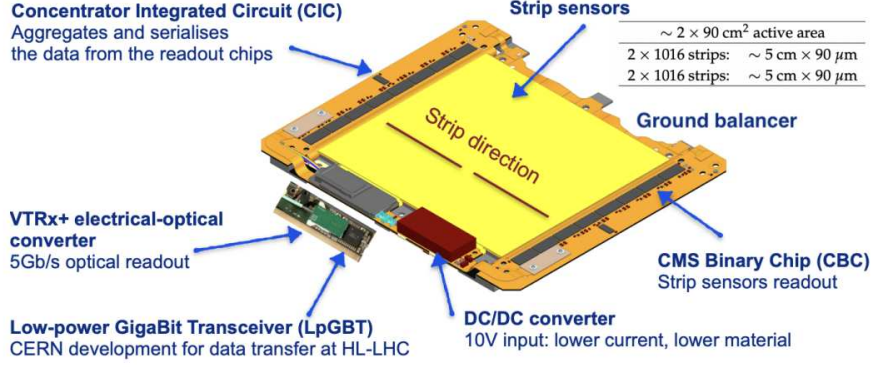


Figure 3.9: Labeled sketch of a 2S module [16].

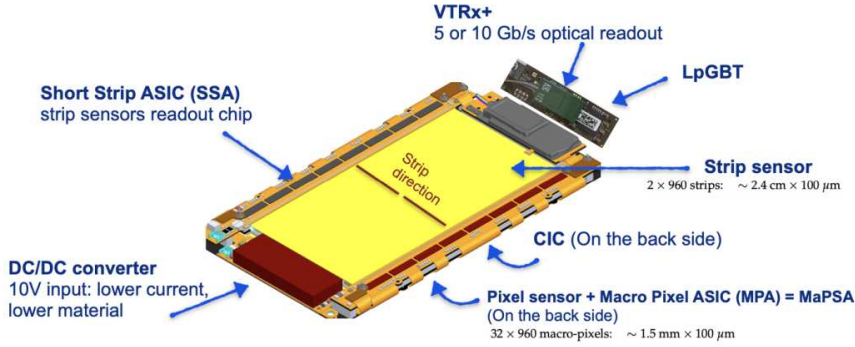


Figure 3.10: Labeled sketch of a PS module [16].

the chips are placed parallel to the sensor and are directly connected via bumps to the strips. PS modules are built with three different sensor separations: 1.6 mm, 2.6 mm, and 4.0 mm. For the tracker endcap double-disks, so the part built in Louvain-la-Neuve, only 4.0 mm variants are used. When PS modules are in the inner part of the detector, they can transfer data at 10 Gb/s, but there also exist modules that operate at 5 Gb/s. Given that the PS module has half of the width of the 2S, it has two service hybrids, one for powering (on the left of figure 3.10) and the other for data transfer, called the readout hybrid (on the right of the same figure).

3.2.2 Positions of the modules

Figure 3.11 is a sketch of the CMS Phase-2 tracker. The axis labels were described with the CMS coordinate system in section 2.2.1. The tracker endcap double-disks 1 (TEDD1) have a smaller inner radius and are equipped with 15 rings of modules, whereas the TEDD2 only contain modules in rings 4 to 15, to leave room for the insertion of the central part of the inner tracker. Therefore, dees for the TEDD1 support 161 modules, and those for TEDD2 only 141 modules. A picture of a double-disk without integrated modules is given in figure 5.2 on page 40.

It appears clearly in figure 3.11 that the PS modules are located in the inner part, with $r < 60 \text{ cm}$. This allows to keep the occupancy at acceptable levels, even in the higher track density closer to the interaction, because the PS strips are

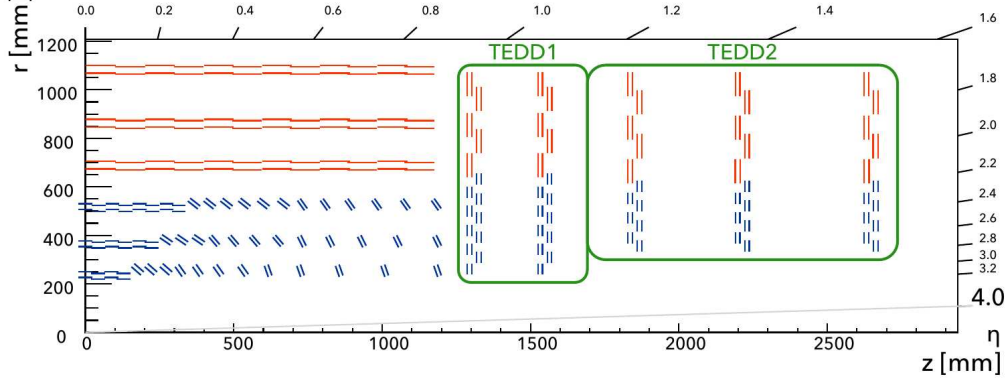


Figure 3.11: Layout of one quarter of the outer tracker in r - z view. The interaction point is in position (0,0). Blue (red) lines represent PS (2S) modules. The Tracker Endcap Double-Disks are encircled in green [17].

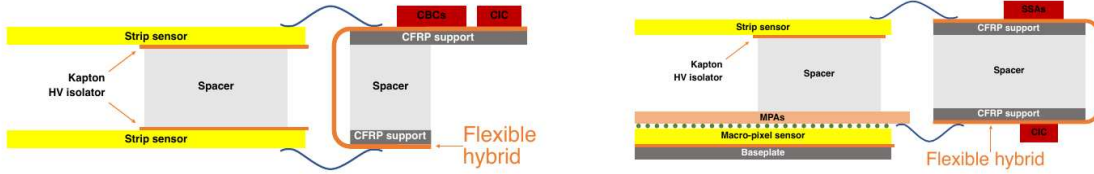


Figure 3.12: Sketches of the front-end hybrid folded assembly and connectivity for the 2S module on the left and PS module on the right [15].

shorter. The reduced size of the PS modules was also chosen so that the surface of the pixelated sensor could be covered with two rows of readout chips (the MPAs that are described in section 3.2.5).

3.2.3 Connections between the sensors and the chips

Figure 3.12 represents the inside of modules to understand how the strips and pixels are connected to the corresponding electronic chips, and figure 3.13 is a picture showing the connections on a 2S module. The front-end hybrids are flexible and laminated onto Carbon Fiber Reinforced Polymer (CFRP) supports for stiffness. This allows to minimize the length of the wirebonds going to the hybrids. For the 2S module, we recognize the two layers of sensor, and they are wire bonded directly to the front-end hybrid. The bottom layer is connected to the lower part of the hybrid, and the flexible hybrid transmits data to the CBCs (the chips that determine if a detected charge is a hit or not, see section 3.2.5). All the chips are bump-bonded onto the hybrids. The spacers maintain the desired gap between the two sensors but they also remove the heat with their high thermal conductivity. The advantage of using Kapton between the sensor and the spacer is that Kapton can resist to very high voltages and remains stable from -269 to $+400$ °C. In the PS module, the strip sensor is connected in the same way as in the 2S module. The pixels are directly connected to the readout chips through bumps, and there are wirebonds from these chips to the hybrids. To limit the heating, the module is built on a baseplate to benefit from a large-surface cooling. This baseplate is placed on the deck on top of carbon foams blocks into which the cooling pipe is glued.

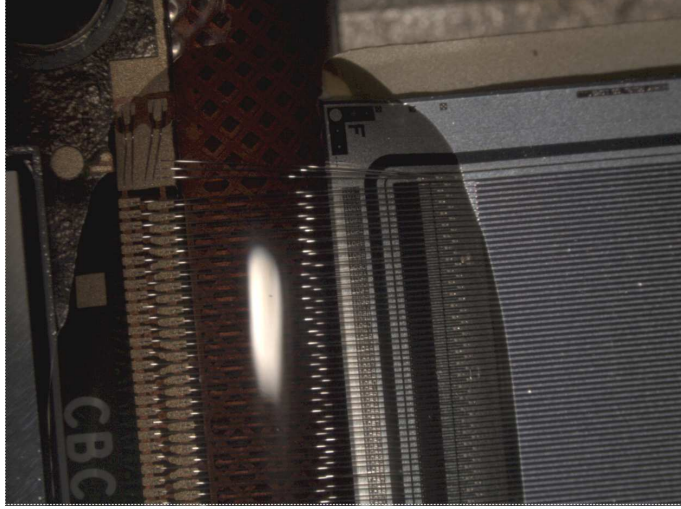


Figure 3.13: Picture of the top left corner of the 2S prototype module taken with the Leica digital microscope [18].

3.2.4 L1 trigger

As already mentioned in section 2.3, data from the tracker will be used by the Level-1 trigger to improve the trigger decision. For instance, the transverse momentum (p_T) resolution of objects will have a better resolution at L1. It will also contribute to the mitigation of the higher pileup caused by the increase of luminosity. The plan is to have the L1 trigger rate at 750 kHz and a latency of $12.8 \mu\text{s}$. The tracker needs to be able to send out a selection of information at each bunch crossing, thus each 25 ns, so at a rate of 40 MHz. Data reduction is achieved in the electronic chips on the modules, they can reject signals from particles below a certain p_T threshold. To know the p_T of a particle, we can look at its track curvature, because the tracks from charged particles are bent in the transverse plane by the 3.8 T field of the CMS solenoid magnet. The following equation [19] links the radius of the helix traced by the charged particle (R) to the p_T of this particle in a solenoid magnetic field (B):

$$p_T[\text{GeV}/c] = 0.3 \times B[\text{T}] \times R[\text{m}] \quad (3.3)$$

We can see in figure 3.14 two tracks left by charged particles in a module. The particle on the right has a lower p_T because its track is more bent. The chips correlate the signals in the two sensors and only select hit pairs compatible with particles having a p_T higher than roughly 2 GeV. The hit in the second sensor for the right particle is not in the acceptance window that defines particles with $p_T > 2 \text{ GeV}$, so it does not lead to an accepted stub. The acceptance window can be tuned by modifying settings in the readout chips. This is useful because the same p_T corresponds to a larger acceptance window at larger radii for a given spacing between the sensor. The sensor spacing also plays a role, indeed in the endcaps a larger spacing is needed to achieve the same discriminating power as in the barrel (located closer to the interaction point). This is why modules with different spacings exist. The on-detector filtering reduces the data volume by a factor of 10 to 100. The stubs are then sent to the off-detector L1 tracking system that reconstructs tracks to take decisions.

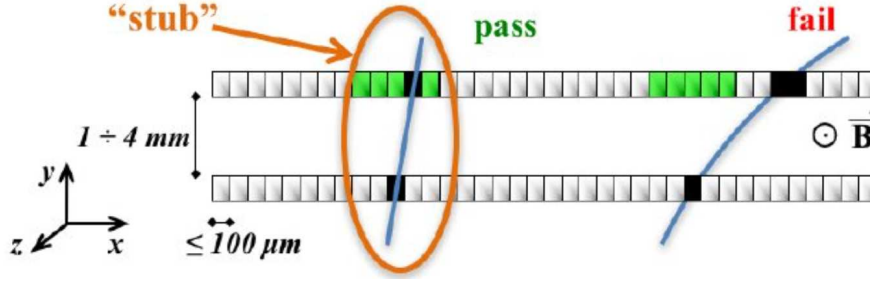


Figure 3.14: Illustration of the stub concept, the two horizontal lines depict the two silicon sensors in a module, and the squares on it represent the pitch. The blue lines show the tracks of particles, and in dark the strips in which they leave a signal. The channels in green represent the acceptance window to define an accepted stub.[15]

3.2.5 Electronic chips of the modules

Besides the sensor, a module is also composed of several radiation tolerant electronic chips that process the data from all the channels to send it through a single optical link. The readout electronics need to satisfy low power consumption constraints, while being able to handle high data rates and the L1 trigger [20]. The electronic system is fully digital, with the exception of the analogue front-end chips. The different chips are briefly presented in this section, starting with the electronics on 2S modules.

The location of the chips on the hybrids surrounding the sensor is represented in figure 3.9, and figure 3.15 is a diagram of the 2S module electronics, containing the chips and their connections.

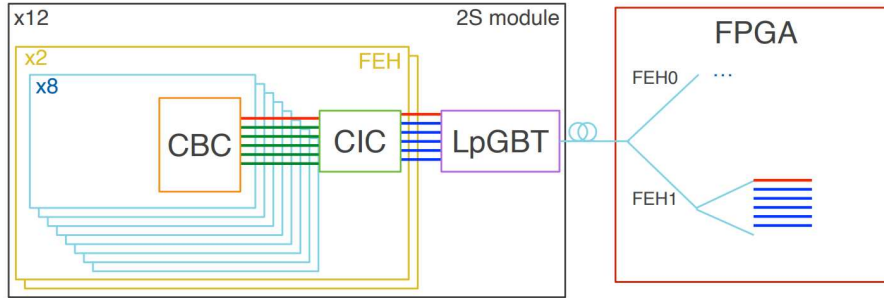


Figure 3.15: Diagram of the front-end electronic on a 2S module and the back-end electronic with the FPGA [21].

The first chip in contact with the silicon strip sensor of a 2S module is the CMS Binary Chip (CBC) [22]. It converts the charge generated by ionising events within the strips into a ‘hit’ or ‘no hit’ binary value for each of the strips. This chip can store the interaction data of up to 512 events, to give the external system some time to decide which interaction was interesting and should be kept. This time is called trigger latency and is equal to $12.8 \mu\text{s}$. One readout chip looks at 254 strips, half from the top and half from the bottom sensor. There are eight readout chips per front-end hybrid, so 16 CBCs per 2S module.

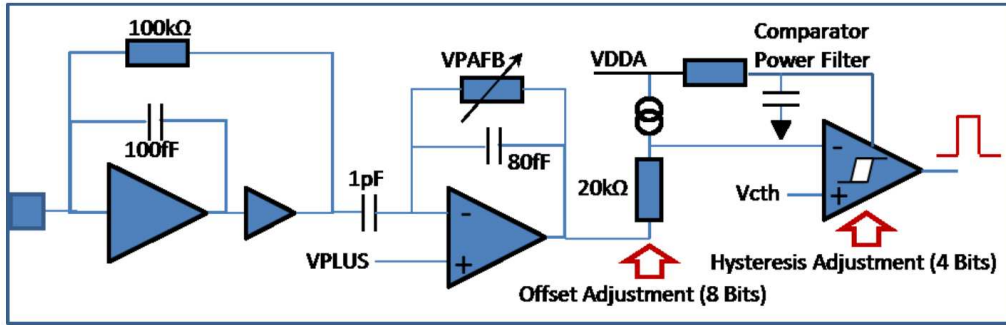


Figure 3.16: CBC analogue front-end connected to the end of each strip [22].

One CBC front-end channel is represented in figure 3.16. Each input on the left is bonded to a different strip on the sensor to read out the electrons generated by an ionizing event. The incoming signal is thus negative. The circuit then amplifies the incoming charges through a pre-amplifier and a post-amplifier. Each post-amplifier has a programmable "offset adjustment" used to compensate for any mismatch between amplifiers and comparators thresholds of different strips. At the end of the chain, there is an inverting comparator that detects if a signal is lower than a threshold (V_{cth}), and for as long as the signal stays below it, produces a digital "1" output. V_{cth} is the same for the whole strip readout chip and usually the average between the 16 CBCs is used to fix one value of V_{cth} per module.

Information from the eight strip readout chips on the same front-end hybrid is then sent to a Concentrator Integrated Circuit (CIC) [23] that buffers, aggregates and formats the data. There is one concentrator chip per front-end hybrid, so two on a module, and each CBC sends data through six differential lines to the concentrator (see figure 3.15). Five lines contain the stub data for the L1 trigger, and the last one sends the sensor's full raw data when a L1 trigger is received. The concentrator chip works at high input (320 MHz) and output data rates. There are 48 differential lines coming in and seven differential lines going out. The CIC is mostly a digital chip but it contains twelve analog blocks that align the phases to sample properly the incoming digital data stream.

The low power Giga Bit Transceiver (lpGBT) [24] is an Application-Specific Integrated Circuit (ASIC) used to implement multipurpose high speed bidirectional optical link. It is located on the service hybrid, next to the Versatile TRansceiver plus (VTRx+), an optoelectronic transceiver converting all data leaving the module into an optical signal, and data coming into the module into electrical signal. There is one single optical link (two fibers) between the module and the back-end electronics, and it is used simultaneously for data readout, trigger data, timing, experiment control and monitoring. When information is sent out of the module, the lpGBT acts as a serializer. This transceiver is also able to check the environment and parameters of the module, for instance it contains a temperature sensor.

The last chip on the 2S module is the DC-DC converter [25]. The power required by the front-end chips is defined as $P = U.I$, thus we can increase the voltage U to transport less current I from the power supply to the module while still sending

the same power. The converter then transforms the input voltage (10 V) to the voltages required by the front-end electronics and optoelectronics (between 1 V and 2.55 V). Given that the Ohmic power losses are proportional to I^2 , this allows to minimize the losses in the supply cables and therefore store the power supplies in rooms shielded from radiation.

Besides the electronic chips on the modules, we need an FC7 Advanced Mezzanine Card (AMC) [26] to manage the data acquisition and the control of the front-end chips. This card is connected to modules through the optical link. It hosts a Field-Programmable Gate Array (FPGA) which performs various digital functions using configurable logic gates. When the tracker is installed in CMS, the FC7 cards will be replaced by larger crates of the Advanced Telecommunications Computing Architecture (ATCA) specification that can contain a larger number of electronic chips.

By comparing the diagram of the electronics on 2S (figure 3.15) and PS (figure 3.17) modules, we see that the front-end chips are different for the two types of modules. In a PS module, the readout is performed by 16 Short Strip ASICs (SSAs) for the strip sensor and 16 Macro Pixel ASICs (MPAs) for the pixel one [15]. Besides from this, the PS modules have two concentrators, one transceiver (with the corresponding VTRx+) and one converter just like for the 2S module. The concentrator is adapted to the CBCs and the MPAs, and it can switch between the two modules types via a simple configuration change.

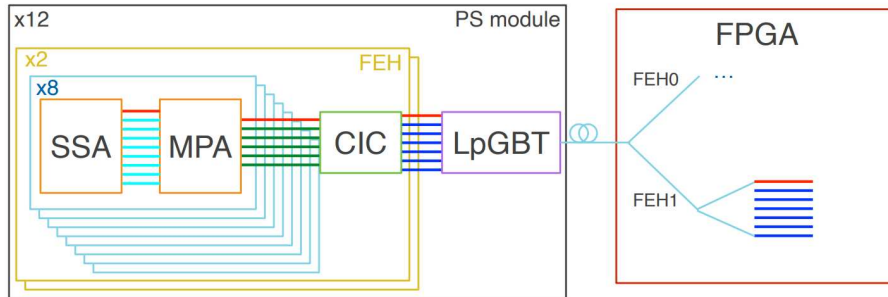


Figure 3.17: Diagram of the front-end electronic on a PS module and the back-end electronic with the FPGA [21].

The 16 SSAs are located on the front-end hybrids and they process the signals from the strips to send sparsified data to the corresponding pixel readout chip. The 16 MPAs are bump bonded to the macro-pixel sensor, each of them to 1888 pixels. This pixel readout chip also filters the hits, and then it looks for correlations between the top strip sensor and the bottom pixel sensor to build stubs for the L1 trigger.

3.3 Quick and full tests

The outer tracker developers created two different tests that can be run easily to check if a module is working properly, the name of the program is CMS Tracker Phase2 Acquisition & Control Framework (Ph2_ACF) [27, 28, 29]. The two tests

consist of a collection of elementary procedures, some are required and others optional. The first test is called a quick test, it lasts around 1 minute for a 2S module, and 3 min for a PS, and it contains essential tests that tell if there is a big issue in the module. The second type of test is a full test, it takes longer than a quick test, around 14 min for a 2S module, and 32 min for a PS, because it runs all the tests from a quick test, but also additional checks. The full test is there to understand where issues come from. In this section, we will briefly go through the different parts of these tests. We will start with the alignment procedures and the noise measurements, present in the two tests, and then analyze the tests that are only in the full test.

3.3.1 Alignment procedures

Quick and full tests start with the following steps, and the user can look at the results files that summarize the outputs of each step. All the plots come from a full test on a 2S module prototype in the reception setup.

- **Configuration:** The first step is the configuration of all the chips on the module, and simply consists in the loading of default values into various registers.
- **TuneLpGBTVref:** Meaningful values of a reference voltage are tested in the transceiver chip and the best value is loaded.
- **VTRxLightYieldScan:** This checks that we are able to modify the optical power of the optoelectronic transceiver. The bias and modulation of optical output are modified, and if an extra attenuation appears, or if the power stays constant when a parameter is changing, it is an indication that something is wrong with the VTRx+.
- **LpGBTEyeOpeningTest:** Figure 3.18 represents the eye diagram of the incoming data at the lpGBT that we measured during a test, and the purpose of this procedure is to decide which delay gives the best received signal. Figure 3.19 represents the theoretical sum of received signal over time, and we see the transitions between digital 1 and 0. This is a good signal because the transitions are sharp. In the case of lower slopes, there are less delays that can be chosen for alignment, and it may lead to communication issues. To compute the eye diagram, we sample the incoming signal in time and we pick a voltage threshold, we then check if the received voltage is above or below this threshold. If it is above it, we will be able to differentiate the 1 from the 0, and it adds a count to the eye. On the eye diagram, we have a high count rate when the receiver is able to differentiate 0 from 1, and we have low count rates in the transitions regions. If a delay of 90 ps was chosen on the eye, we would not be able to understand the signal, because it corresponds to transitions in the signal. From the eye-diagram, a delay of 250 ps, so in the middle of the yellow eye, would ensure a robust connection. The eye-diagram depends on the power supply voltage, the temperate, the transmission medium and is sensitive to saturation effects. This scan allows to verify the quality of the data transmission, and to check the quality of the eye diagram over time. It could indicate that the optical link is not optimal and that we should clean the connectors for instance.

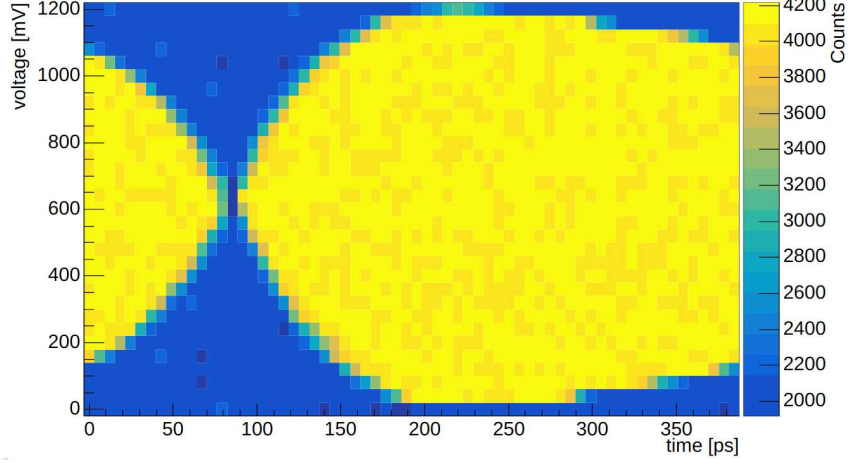


Figure 3.18: Eye opening scan of the 2S prototype module, without lpGBT attenuation. The higher count rates are in yellow.

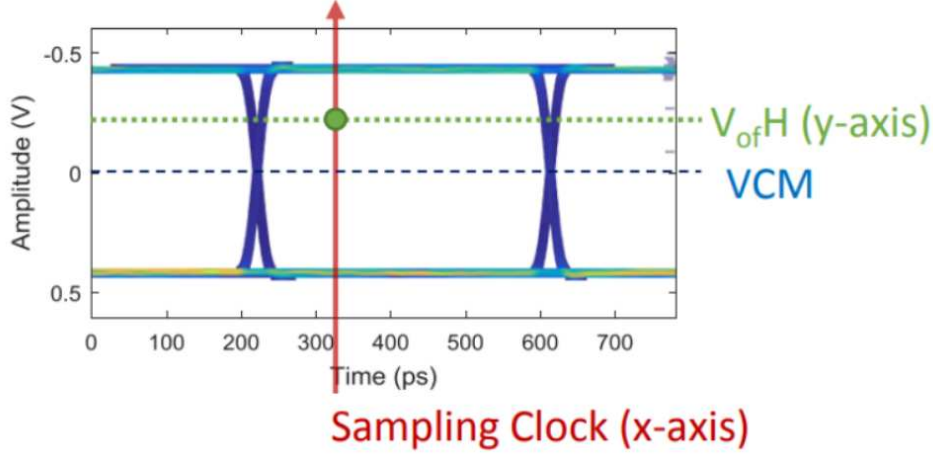


Figure 3.19: Sum of received signals at the transceiver, with the transitions between digital 0 and 1 at 220 and 610 ps [24].

The following steps are about the alignment of the chips' receiver circuits to incoming signals from the neighbouring chips to ensure a good communication.

- **AlignLpGBTinputs:** On figures 3.15 and 3.17, we can see that the input lines of the transceiver (lpGBT) come from the two concentrators (CICs). The goal here is to find the best sampling phase for each input line of the transceiver so that it can properly decode the inputs from the concentrators. The CIC sends 100 patterns to the transceiver that looks for the best phase to sample this data. The chosen phases are represented in figure 3.20. Up to three different phases could be used for each line during this test, but if all the 14 phases were chosen during the alignment, then the transceiver could not decide on a phase and something is wrong. Phase 15 is an error code. Given that the two chips are on different hybrids, the first thing to check if the plot is not as expected is the connections between the hybrids. In the end, the best phase for each line is picked as the one the most often chosen. It is not because three phases could be chosen for one line that using only one will give errors, the best phase

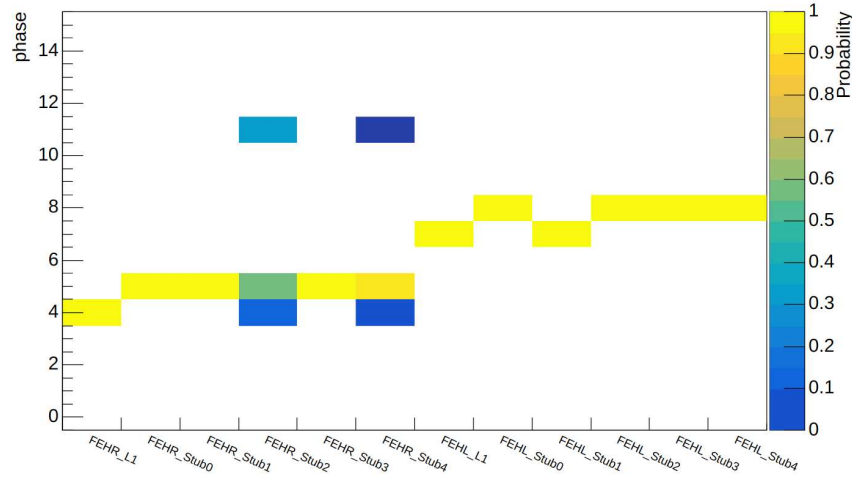


Figure 3.20: Transceiver input phases distribution for patterns sent by the concentrators. The x-axis represents the 12 lines coming into the transceiver. FEHR is the right front-end hybrid, FEHL the left one, stub lines are used for the L1 trigger and the L1 line sends data from the whole interaction.

will be efficient to read all the incoming data. For instance, for FEHR_Stub2, phase 5 is the best one.

- **AlignBoardDataWord:** The FC7 board needs to know which bit is the first one in a pattern coming from the concentrators in order to understand the messages. Thus the concentrators send patterns to the board through all the CIC-to-lpGBT lines, and the board finds out the bitslips (so finds the beginning of the word) for each line.
- **VerifyBoardDataWord:** Check that the patterns sent by the concentrator are well received by the board. A first plot describes the number of tested bits for the different lines: 10^6 bits for the L1 line, and 10^8 for the stub lines because they have a shorter processing time (pattern matching is done directly in the firmware). We also have access to the error rate to confirm that the communication between the concentrator and the board is stable.
- **AlignStubPackage:** The purpose is to determine the delay the board needs to use to read the stub lines, and the same delay needs to work for the two hybrids.
- **CICphaseAlignment:** We now focus on the lines between the readout chips and the concentrator. The different steps are done in the two front-end hybrids at the same time. The readout chips send 100 patterns to the concentrators that search for the best alignment phase. To control this step we receive three plots: the efficiency of the alignment, the frequency at which each phase was chosen and the best phase.
- **CICwordAlignment:** The concentrator needs to find the start of the words from the CBC (MPA in the case of a PS module) stub lines. The concentrator knows what to expect and aligns itself to the beginning of patterns sent by the readout chips.

- **VerifyCICdataWord**: We test the quality of the connections between the readout and the concentrator chips by sending specific patterns from the readout chips and checking that we receive the expected bits in the FC7 board. 10^5 bits are sent through the L1 line and 10^7 through the stubs lines. To validate this step we have access to the error rate.
- **VerifyMPASSAdataWord** (only for PS modules): To confirm that information from the strip readout chip arrives to the pixel readout chip, the strip readout chip sends patterns to the pixel readout strip that verifies that it matches with what was expected.
- **RingOscillatorTest** (only for PS modules): Count the number of oscillations of the ring oscillators during a fixed amount of time in the strip and pixel readout chips. The frequency of oscillation depends on temperature, power and radiation damage, so this measurement might indicate a bad power distribution for instance. Limits are defined to know when the frequency is not in the expected range for a good module.

3.3.2 Noise measurements

The noise in the module is computed during quick and full tests. It is an important measurement that can point to issues in the module, like for instance a bad grounding, or a bad connection between a strip and the front-end hybrid, but it is also important that the noise stays low enough so that we can detect the signal left by a crossing particle. The noise measured in a module also depends on the setup that was used. When noise measurements will be run on a dee and later in the tracker, they will give an indication about how well the module is cooled and connected to the ground. Therefore, noise will be a parameter of the whole system performance.

To measure the noise, we put the module in a dedicated setup and run a firmware that will go through the following steps. In this procedure, we want to analyze the noise that is always present in the module, there is no actual signal and we just detect "hits" due to noise above a certain threshold. The occupancy is computed as the amount of hits in a strip divided by the number of events, 1000 events in our case. 0% occupancy means that there was no signal, and at 100% all the events are detected.

- **PedestalEqualization**: This procedure determines the V_{cth} and then the channel offsets that achieve a 56 % occupancy at pedestal. The two parameters are represented in figure 3.16 and were described in section 3.2.5. Firstly, a scan of V_{cth} is performed, measuring the channel occupancy at each step, in order to find the threshold that achieves a 56 % occupancy at pedestal for each readout chip. The average of the 16 measured V_{cth} is then computed and set as the V_{cth} value for all the readout chips in a module. The CBC comparators at each strip are not exactly identical after construction, but we can compensate it with an offset that can increase or decrease a bit the signal so that the target occupancy is obtained in each channel. This is done in a second step, with V_{cth} fixed at the average, and the offset of each channel that is tuned so that

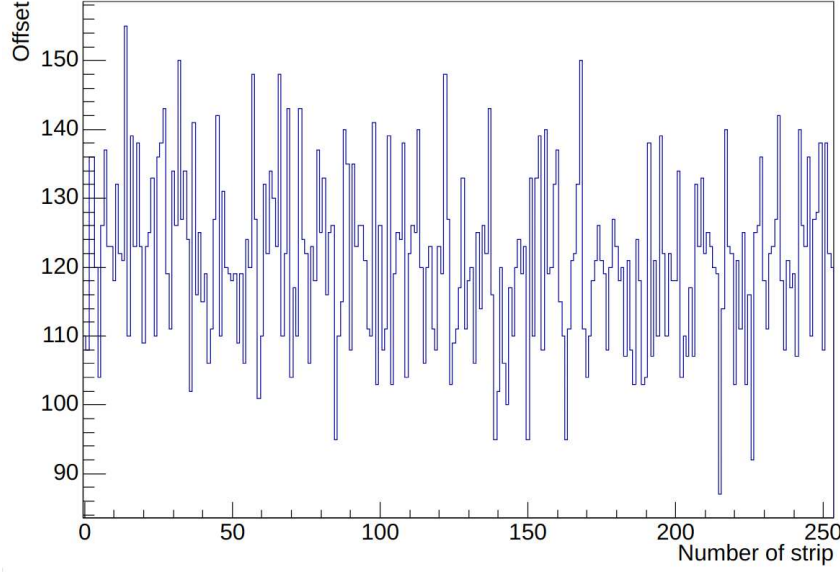


Figure 3.21: Illustration of the offsets chosen by the PedestalEqualization step for the second CBC on the left front-end hybrid of the 2S prototype module. Each 254 strips (127 on the bottom sensor with even numbers and 127 on the top sensor with odd numbers) have a different offset.

each channel comes as close as possible to the 56 % occupancy at pedestal. Figure 3.21 represents the offsets that were chosen.

- **PedeNoise:** We can now compute the noise. A scan of the occupancy in a strip is completed for various V_{cth} in figure 3.22. As a reminder, V_{cth} is a threshold voltage that can be modified in the electronic chain of the CBC (figure 3.16), and it is compared to the amplified signal to decide if the signal was a hit or not. The comparator at the end of the chain is an inverting comparator, so there is a hit when the signal is smaller than V_{cth} . A fit of the measurements is done using an error function (i.e. an s-curve). The standard deviation of the fit is defined as the noise in the strip. So a sharp s-curve corresponds to a low noise. Figure 3.23 is a plot obtained during a quick test run on the 2S prototype module. It contains the s-curves for all the strips connected to the second readout chip on the left hybrid. Each column represents a strip, and the colours tell the occupancy of a given strip for a certain voltage. In the ROOT files we receive at the end of a test, we have also access to the plot containing the measurements made to obtain the s-curve for each strip, with the corresponding fit. This allows to check if the fit is correct in the case of incoherent noise values.
- Finally, to validate the noise computations, it is checked that the noise is suppressed from the measurements by taking events with the V_{cth} of all CBCs fixed 5 sigma away from the pedestal and checking that the occupancy is low enough. If the noise was purely Gaussian, we would expect a number of hits in the order of 10^{-7} times the number of events. During the data taking of CMS, the noise will be discarded in the tracker approximately in the same way, but the threshold will be computed in order to achieve the best compromise between occupancy and efficiency.

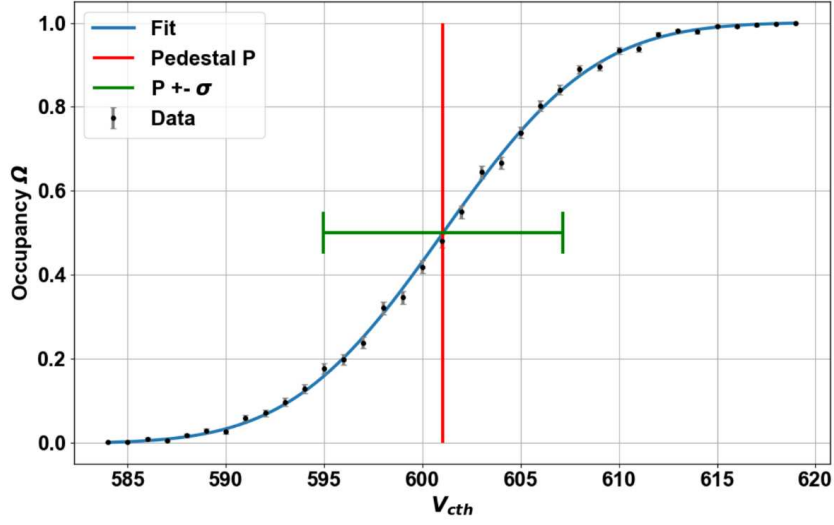


Figure 3.22: Evolution of the occupancy in a strip Ω as the threshold voltage V_{cth} changes. The black dots are the measurements with errors, the pedestal is shown in red, a fit of the values is computed in blue to obtain the standard deviation (σ) represented in green. The standard deviation of this s-curve is defined as the noise [30].

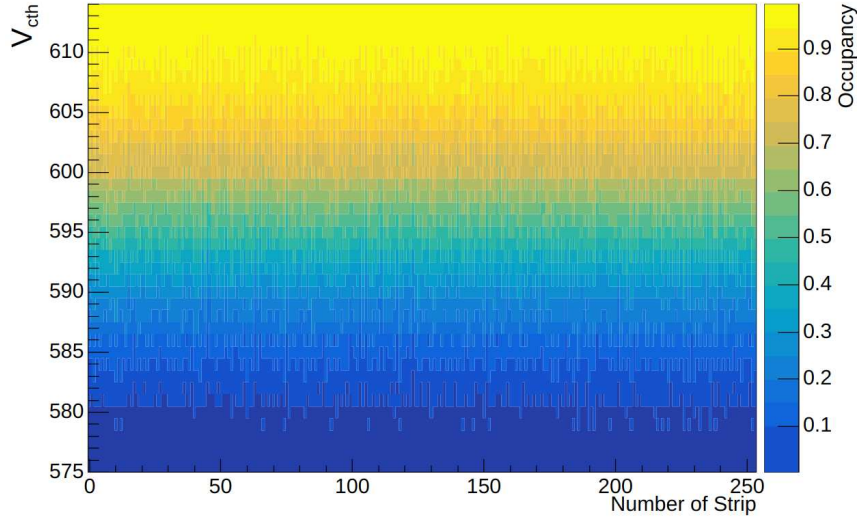


Figure 3.23: S-curves obtained during a quick test on the 2S prototype module. The occupancies are given for the 254 strips in the second CBC of the left hybrid for the interesting range of V_{cth} .

3.3.3 Steps only present in full tests

- **PSADCCalibration** (only for PS modules): The strip and pixel readout chips contain analog-to-digital converters and their parameters are optimized.
- **InjectionDelayOptimization**: We look for the best delay from charge injection to buffer readout in the readout chips. The best delay corresponds to the highest signal for a fixed amplitude of the calibration pulse. For this procedure, the readout chip sends a pulse to itself and we observe how it propagates to determine the best delay.
- **InjectionOccupancyScan**: In this case too, the readout chip generates pulses, but this time the amplitude of the pulse changes to check that we will be able to detect the crossing of particles. In the first case, no pulse is injected and the occupancy should be at 0 %. But when the amplitude of the pulse corresponds to half of a MIP, 100 % occupancy is expected. Of course, when the amplitude is larger than a half MIP, we also want a 100 % occupancy. This allows to find not effective or very noisy strips.
- **CMNoise**: Common Mode Noise refers to a variation of the signal affecting groups of channels in a coherent way, caused by noise on the supply voltage for instance. In figure 3.24, we look at the clear correlation between the number of hits in events in the top and bottom sensors, but a lot of other parts are also compared during the test. The correlation between the two sensors was expected because they share a common ground. Figure 3.24 was obtained in the "occupancy driven" case, where the thresholds are set to have an occupancy of 56 %. Other measurements are made with the thresholds set at 3 sigma from the pedestal, and these focus on the right tail of the noise distribution.
- **Electric chain validation**: This procedure analyzes whether other phases than the best one are able to sample incoming data in case the best phase does not work anymore. The phase is manually changed and we check if the chip is able to read correctly the patterns. This outputs two plots, the number of tested bits and the error rates for the different phases. The larger the number of neighbouring phases that work, the better. This measure is conducted for different values of current in the lines. This electric chain validation is done from the concentrator to the transceiver, from the strip to the pixel readout chip and between the strip readout chips on PS modules.
- **AlignLpGBTinputsForBypass**: When we perform an electric chain validation between the readout chip and the concentrator, we are not able to know in which stub line an error occurred because the concentrator processed the data before it could reach the board. To find this information, we put the concentrator in bypass mode, meaning that it just forwards the incoming data to the transceiver without processing it. We can only do it for groups of four incoming lines at a time. The transceiver is not aligned to data coming from the readout chip with the concentrator in bypass mode, so a manual scan of the transceiver phase is performed to find the best phase. Once this phase is found, the transceiver can send data from the readout chip to the board,

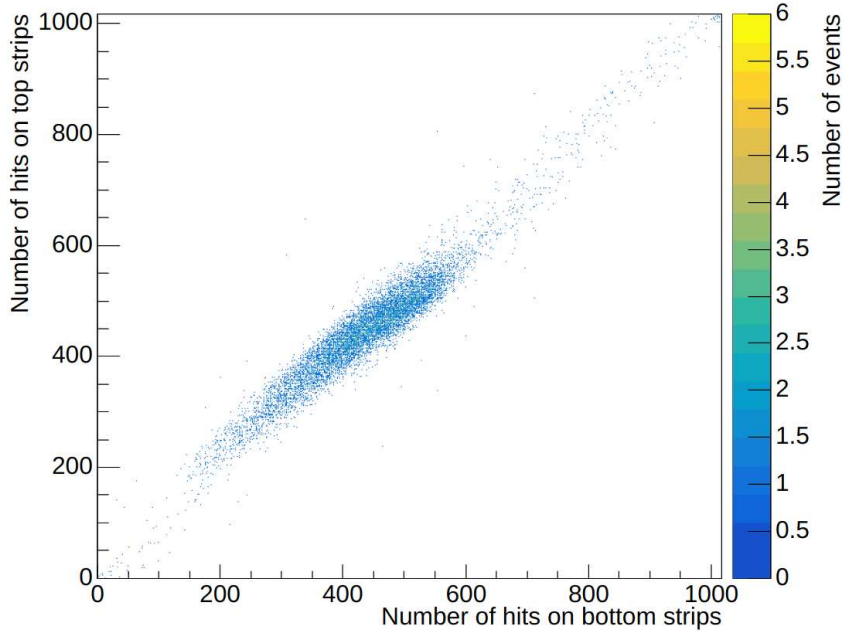


Figure 3.24: Analysis of the common mode noise by the correlation of the number of hits per event between the top and bottom sensors on the right side of the module.

and the electric chain validation from the readout chip to the concentrator is performed.

- **BitErrorRateTest:** This procedure checks the stability of the link between the transceiver and the board. They both generate pseudo-random bits in the same pattern, and we check in the board that the bits received from the transceiver match with what was expected. Each incoming line to the transceiver is tested individually so we know which line has an issue. Once again we receive two plots: the number of tested bits and the error rate. Up to five flipped bits can be corrected, so even if we see no error some bits might still have been corrupted during the transmission. Therefore, we also need to check the number of flipped bits to confirm that the connection is stable.
- **RegisterTester:** For this last test, we write and read several registers in the front-end chips, and we look at the matching efficiency for each chip. If the efficiency is not equal to 100%, it could be caused by a bad connection between the front-end and the service hybrid.

3.3.4 The Analyzer of Test Outputs

The CMS Phase 2 Outer Tracker Analyzer of Test Outputs (POTATO) [31] is a graphical user interface developed to analyze the ROOT files created by quick and full tests (Ph2_ACF). In the end of the analysis, it will grade a module and put the results in the Database. This Database stores information about all the pieces needed to build the tracker, for instance where they are located, and also which tests have been run on modules and the corresponding results. To grade a module, the Analyzer will look at the current-voltage curve, the mean of the noise and its outliers, and the number of unusable channels among others. The interface will be

really useful to handle the large amount of modules that will be tested, because even a quick test outputs a lot of files, making it difficult to quickly determine whether a module has issues. It will also provide consistency in quality control between the different production and integration centres.

Chapter 4

Setups in Louvain-la-Neuve

This chapter describes the two rooms and the equipment used by the CMS tracker upgrade team in Louvain-la-Neuve to test the silicon modules and to integrate them on the double-disks that will form the tracker endcap.

4.1 Reception room

When new modules arrive in Louvain-la-Neuve, they come in big boxes, such as the one on top of the cupboard in figure 4.1a. The transport boxes are designed to absorb shocks and are air-tight to control the humidity inside during transport. The cupboards are flushed with dry air, and we can control the flux in order to keep the humidity low in the cupboard, and that is important because we want to keep the humidity low around the modules. Figure 4.1b is a picture of the trolley we use to take the modules from one room to the other. The big black boxes are made of ElectroStatic Discharge safe (ESD-safe) materials that are conductive to reduce static electricity and protect the modules. The same kind of material is used on the desks where modules are put. On top of the trolley, we can see a tray (also ESD-safe) used to store the modules in the cupboard and to maintain the modules during the transport in the trolley. There are humidity and temperature sensors in the room but also in the cupboards to verify that the humidity is low enough.

Reception test

The reception lab is used to test the modules when they arrive. A picture of the test bench is given in figure 4.2. On the left, we see the FC7 card [26] used for the CMS data acquisition and system control. Next to it there is the Iseg high voltage power supply [32] and the Rohde&Schwarz low voltage power supply [33]. The grey suitcase is the KIT test box [34] in which modules are placed to be tested. The test station is the same in all integration sites to ensure equal testing conditions. In the box, the module is connected through an optical fiber to the FC7, it is also plugged into the power supplies and is flushed with dry air.

The whole setup can be controlled by the Graphical user Interface for PHase 2 Tracker objects (GIPHT) [34]. It allows to run quick and full tests, current-voltage curves, and also to upload the results in the database.



(a)



(b)

Figure 4.1: Furniture in the reception room, with on the left a cupboard flushed with dry air and on the right a trolley to transport the modules.

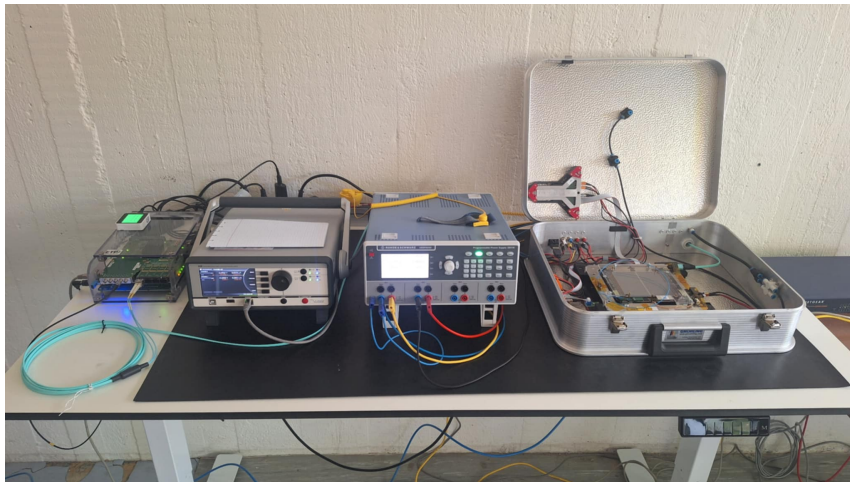
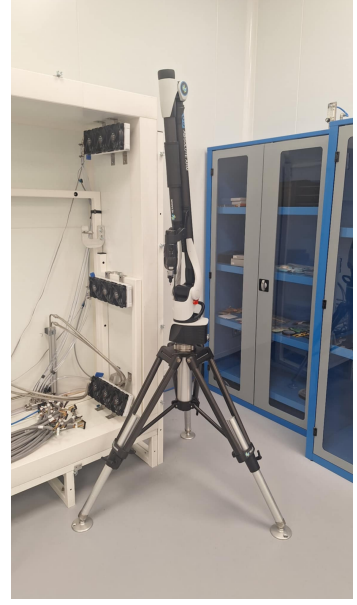


Figure 4.2: The outer tracker module test bench in the reception room to test the incoming modules. From left to right, there is the FC7, the high voltage and low voltage power supplies and the KIT box where we put the module. In this case, a 2S module is ready to be tested (when the suitcase will be closed).



(a)



(b)

Figure 4.3: The double-disk assembly structure and the Hexagon metrology arm in the clean room.

4.2 Clean room

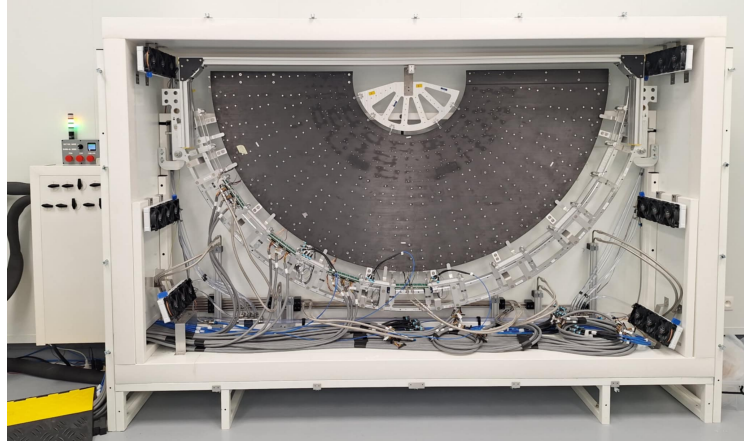
A dedicated ISO 7 clean room was built in the Marc de Hemptinne (SC01) building for the integration of modules on the dees. Before entering the clean room, we go through a changing room to put on clean shoes, a lab coat and a hairnet. There is also a small technical room, with inside the large devices needed for module testing and integration. There is an air drying unit [35] that sends dry air to the burn-in and cold box (we will describe these setups below), the CAEN high and low voltage power supply [36, 37, 38], the optical fibers connections to a Micro Telecommunications Computing Architecture (MicroTCA) crate containing five FC7 boards (one for the burn-in and four for the cold box), the Monoblock Approach for a Refrigeration Technical Application (MARTA) CO₂ cooling system [39] and the Julabo refrigerated circulator [40]. The clean room is equipped with an air conditioning that keeps the temperature and the humidity at reasonable levels. It was observed that the humidity was sometimes quite high, so a dehumidifier might be added in the room during the integration of modules.

Figure 4.3a is a picture of the double-disk assembly structure taking most of the space in the clean room. Between the two large frames, a dee is placed horizontally for the integration of modules. To precisely locate the dee in its arcframe, and later to assemble dees together, a metrology arm is needed. The Hexagon metrology arm [41], shown in figure 4.3b, has precisions around 10 μm with probes and 25 μm if we scan with the laser.

There are two separate setups in the clean room to run tests at cold temperatures, the burn-in and the cold box.



(a)



(b)

Figure 4.4: The two setups in the clean room to test the performance of the modules. On the left, the burn-in box to test modules individually, and on the right the cold box to test the modules once they are integrated on a dee.

4.2.1 Burn-in setup

This first setup is the burn-in, represented in figure 4.4a. It consists in a commercial fridge turned into a silicon modules test setup able to reach $-35\text{ }^{\circ}\text{C}$ thanks to the Julabo refrigerated circulator. A metal shelf is located inside, so that up to ten modules can be tested. The electrical and optical services connected to the modules come from the corresponding devices in the technical room. The goal of the burn-in fridge is to stress the different components of the module by changing their temperature, to detect potential failures.

The burn-in setup is connected to a better ground than the reception setup. Firstly, there are two different power supplies for the reception tests, one for the high voltage and the other for the low voltage, but for the burn-in setup there is only the CAEN power supply that is less noisy. Besides from having a better power supply, the burn-in setup also has a dedicated electrical panel in the clean room. This panel gives access to a more stable ground because it is directly connected to the ground of the building. Additionally, the metal rack in which the module is placed acts like a small Faraday cage. But the clean room in itself is also well electrically isolated because the walls are made of three layers: metal, insulating material and again metal, so the clean room is also a kind of Faraday cage. There are still sources of noise, like the ventilation in the roof, and through the ground.

Off The Shelf Data Acquisition Software

The Off The Shelf Data Acquisition software (OTSDAQ) is able to handle the temperature in the burn-in setup and to start tests when the wanted temperatures are achieved. The user can fix two temperatures, a low and a higher one. In the

beginning of the run, a small calibration is done and a current-voltage curve is taken. The following steps are part of a loop that is followed a certain amount of time, for instance in the experiment with the 2S module prototype described in section 6.2, the loop is taken two times. In the loop a quick test is run at the high temperature, then the chiller decreases the temperature, and when the low one is achieved a quick test is also done. After repeating these two steps a certain amount of times, the temperature remains low to take a full test of the module, and finally the temperature goes high again for one last quick test.

Even if it is not its main objective, the burn-in gives precious information about the impact of temperature on the noise in the sensor (see section 6.2). But this kind of test takes a lot of time to be completed: going from 20 °C to -35 °C takes 90 minutes, and going the other way around 60 minutes. In order to go twice in the loop with the given temperatures, we had to let the software run during 6 hours.

4.2.2 Cold box setup

The previously explained setups look at the modules individually. The cold box is large enough for a whole half-disk support structure, called a dee, to be put inside, as shown in figure 4.4b. When a dee is integrated with modules, the cold box setup allows to check that the modules were not damaged during the previous operations, and that the grounding is correct. It also allows us to have an insight about the influence of the surrounding modules on the noise in a sensor for instance. Through temperature measurements, we can check that the thermal interface between the modules and the dee is working properly.

Testing all the modules at the same time would require large power supply, cooling and data acquisition systems that are not necessary for the integration centers. The tests will thus be done by sectors corresponding to maximum two cooling loops, and that is why these tests are called sector tests. The cold box will be cooled to -35 °C, using the liquid CO₂ from the MARTA in the cooling loops of the dee, and the silicon oil from the Julabo that will cool the environment with the help of fans. As usual, dry air will be flushed in the box. In addition to the usual temperature and humidity sensors to monitor the environment, there are also CO₂ sensors to detect leaks from the cooling loops.

Chapter 5

Training for future module integration

During my master thesis, I had the opportunity to take part in two exercises to prepare the future integration of the CMS outer tracker. In this chapter, I will quickly describe what we did and what I learned.

5.1 Integration exercise

When modules arrive in Louvain-la-Neuve, they undergo a quick reception test and then they are ready to be integrated on dees. Dees have an outer diameter of 2.196 m and are made of a sandwich structure with on top and bottom CFRP, and inside the CO₂ cooling pipes. The positioning inserts for the 2S and PS modules are placed on the dee during its construction.

The goal during the exercise was to place six 2S and six PS modules on a dee to verify that the tools and procedures work as expected. Colleagues from Lyon and Hamburg joined us because they will also integrate modules for the outer tracker. Thanks to their presence, we were able to share knowledge and discuss the issues we encountered during integration.

The big steps to integrate a module are:

- Remove the module from its transport plate.
- Only for PS modules: apply the thermal interface material where the module will be placed to ensure a good thermal contact.
- Place the module at its correct location on the positioning inserts. This step requires a lot of care because the module comes with a power wire and an optical fiber that are detached, and they can not touch the modules in the surrounding because they could damage them.
- Insert the screws, they hold the module and provide cooling.
- Connection of the power cable and the optical fiber to the patch panels located at the dee periphery.

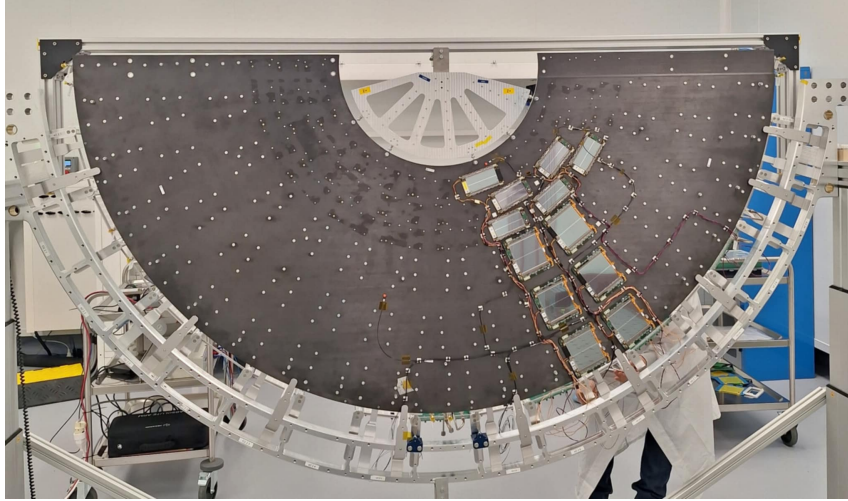


Figure 5.1: The dee with the twelve integrated modules during the exercise in Louvain-la-Neuve.

- To ensure the continuity of the electrical chain we apply voltage to the module and we measure the current.
- Check that we can communicate with the module by reading the unique identification number of the transceiver chip (lpGBT). To confirm the quality of the optical chain, we measure the light yield.

Figure 5.1 is a picture of the twelve integrated module on the dee during the exercise. A zoomed-in view of two modules with their connections is represented in figure 3.8 on page 17. The next step consisted in putting the dee in the cold box to perform full tests on all the modules.

5.2 Double-disk assembly exercise

Once a dee is fully integrated with modules and that the tests in the cold box were successful, this half-disk is ready for assembly. We went in Hambourg, at the Deutsches Elektronen-SYNchrotron (DESY), for three days with colleagues to learn how to assemble four dees to form one double-disk.

For the exercise, we worked with dees without modules to practise the different steps without the additional difficulty of having modules and wires in our way. We started by assembling two dees to form one disk using a structure similar to the one in Louvain-la-Neuve represented in figure 4.3a on page 35. When two disks were done, we assembled them to create one double-disk, that is shown in figure 5.2. During the different assembly steps, we used the metrology arm to know if two pieces were perfectly aligned. If it was not the case yet, the measurements were telling us in which direction we needed to move the dee to obtain a proper alignment.

The different steps already required a lot of care, for instance due to the cooling pipes outlets that could be damaged if we pushed on them without noticing. A similar exercise is planned during the summer in Louvain-la-Neuve, to practise again

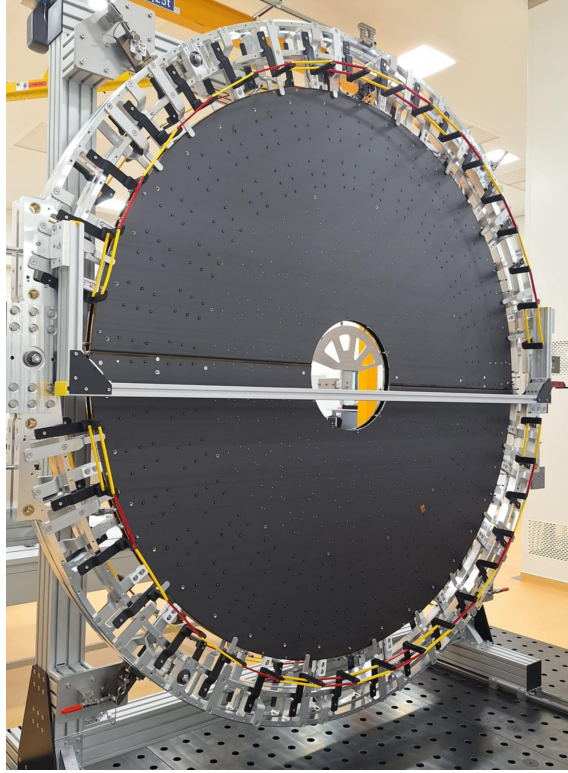


Figure 5.2: The double-disk that we assembled at DESY. In the central region, we can notice the hidden dee.

the assembly before having to do it with modules on it, but also to get used to the structure in Louvain-la-Neuve.

In the end, five double-disks will be assembled in Louvain-la-Neuve to form one outer tracker endcap, that will be sent to CERN for the integration in CMS. That represents 5 960 modules in total.

Chapter 6

Results about one module

In this first chapter regarding the results, we will analyze measurements made on only one module at a time, with a clear focus on noise measurements. The tests were run before the arrival of final modules, so with prototype versions of the modules. With the 2S module, we compared the noise between two setups, and then we examined the impact of temperature on the noise. With the PS module, we observed if the length of the strips has an impact on the noise.

6.1 Comparison of noise between two setups

On the same day we tested the 2S module prototype in the reception setup and right after in the burn-in setup located in the clean room. The goal is to understand whether the setup has an influence on the noise in the module. The two setups were kept at room temperature.

Firstly, the noise can be plotted for each of the 4064 strips in a 2S module. As a reminder, the noise is defined as the sigma of the s-curve obtained by changing a threshold voltage, and therefore modifying the occupancy in the strip. Noise has components from the sensor and from the readout chips. Figure 6.1 represents the noise for each strip in the four different regions of the module. The left and right sides of a module are defined with the service hybrid at the bottom, as in figure 3.8 on page 17. We can already observe that the noise is on average lower in the burn-in setup, and that is because the burn-in fridge has a better grounding than the reception setup (see section 4.2.1). We can also note that the more noisy strips are on the ends of the sensors. For the left hybrid top sensor, it is possible to see the different trends in the strips noise that are caused by the eight different readout chips (CBCs). The noise fluctuations caused by the electronics are small compared to the total noise.

On figure 6.1 all the plots have the same range of noise values to ease the interpretation, but the right hybrid top sensor has extreme values that are out of the usual range, and figure 6.2 represents them. There are a few outliers on the ends of the sensor with higher noise values, but that is the case for all sensors. What is more unusual is that the third strip has a very low noise of 368 electrons in the reception setup and 402 electrons in the burn-in setup. One cause of this low noise could be that the wirebond between the strip on the sensor and the front-end hybrid

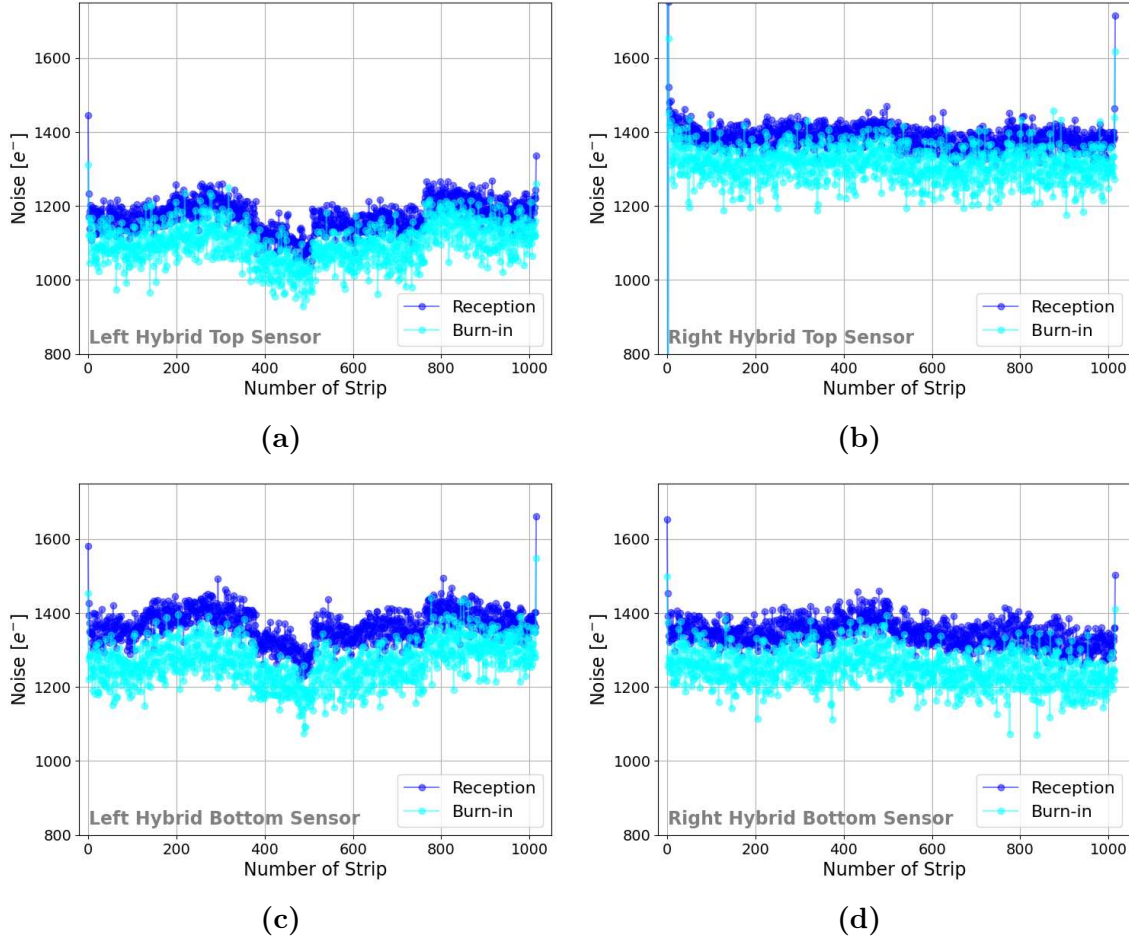


Figure 6.1: Comparison of the noise for each strip of the 2S module in the reception and burn-in setups. Strips 0 are the ones close to the service hybrid. The left (right) plots correspond to strips that are read out by the left (right) service hybrid so the left (right) part of the sensor and the two top (bottom) plots are showing the noise in the top (bottom) sensor.

is not well connected. To confirm this hypothesis, we looked at the module with the help of the Leica digital microscope [18]. Figure 6.3a is a picture of the wire connection on the strips and figure 6.3b the corresponding connection on the front-end hybrid at the low right corner of the top sensor. Strip 3 is easy to find because it is the third strip starting from the bottom. The wire and the connections seem to be correct. There are also bump connections under the readout chip on the front-end hybrid that we can not check because they are hidden by the chip (see figure 3.12 on page 19). This bump connection could be the cause of the observed low noise.

To have a more global view, we plotted the histograms of the noise for the four different regions of the sensor in the reception (figure 6.4a) and in the burn-in (figure 6.4b) setups. Each colour corresponds to a different part of the module, the mean is computed based on the noise values of all the strips but the standard deviation is computed without outliers. We made this choice because the standard deviation with outliers was not representative of the width of the observed distributions so we

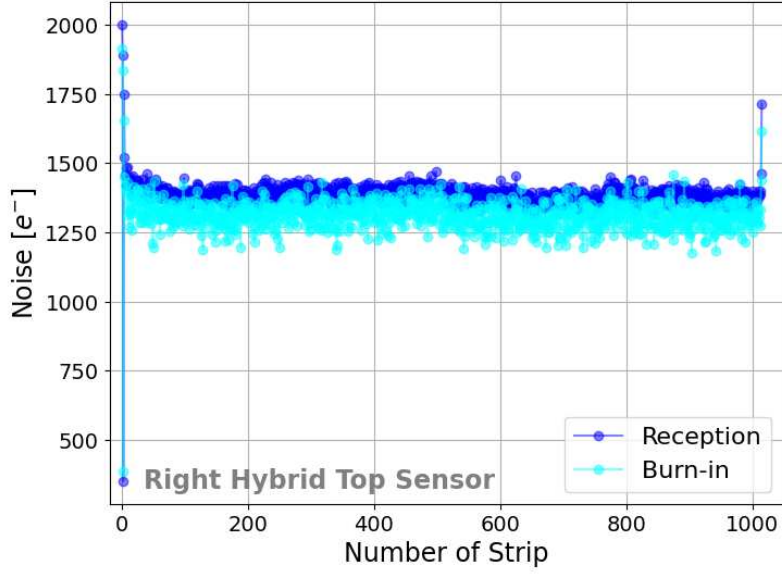
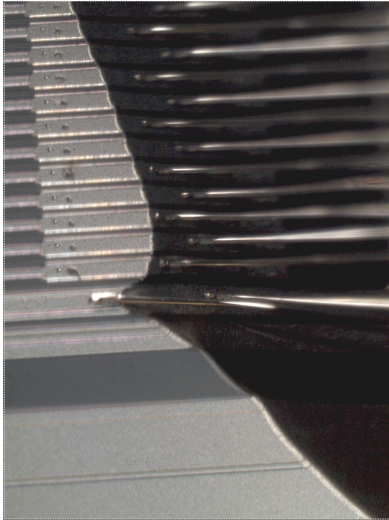


Figure 6.2: Comparison of the noise for each strip of the 2S module right hybrid top sensor in the reception and burn-in setup. In this case, the range of noise values is larger to show all the outliers.



(a)



(b)

Figure 6.3: Pictures of the lower right corner of the 2S module obtained with the microscope. The left picture shows the connections of the wires to the strips, and the right picture represents how the other ends of the wires are connected to the front-end hybrid. We are interested in the third wirebond starting from the bottom.

could not easily interpret it. Outliers are values outside of the following range [42]:

$$[Q_1 - 1.5(Q_3 - Q_1), Q_3 + 1.5(Q_3 - Q_1)] \quad (6.1)$$

with Q_1 and Q_3 the lower and upper quartiles, as a reminder the lowest 25% of data are below Q_1 and 75% of data are below Q_3 .

Figure 6.4 confirms that the noise is lower in the burn-in setup, from around 100 electrons. The order in increasing noise between the different parts of the module stays the same for the two setups, and the shifts between the two setups are the same, so the variations in noise between the different parts are intrinsic to the sensor and are not caused by the test setup. The top left sensor has constantly a lower noise, but we expect the final modules to have an even lower noise, around 950 electrons at ambient temperature. We can notice that the standard deviation is higher in the burn-in fridge, which means that noise is more spread between the different strips on the same part of the module.

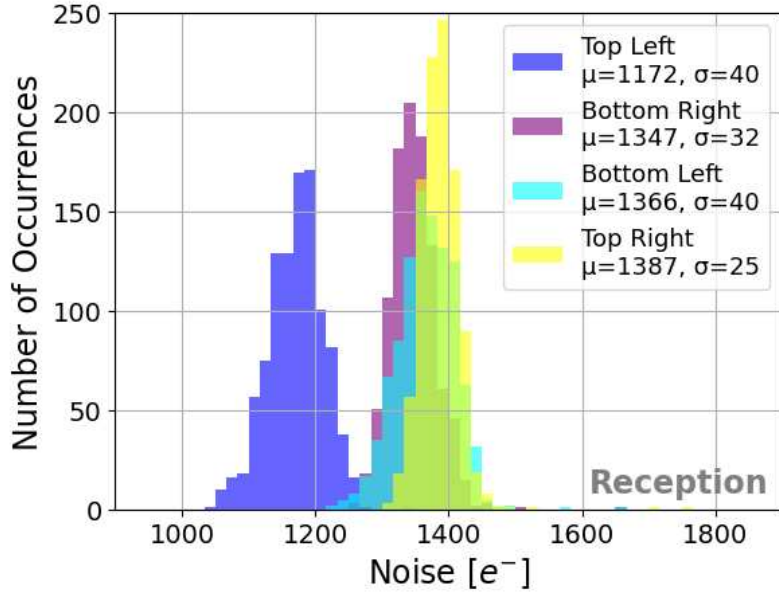
Finally, we put all the important values in the same plot in figure 6.5. We can again clearly observe the shift in noise between the setups, with a lower noise in the burn-in fridge because its ground is better. We can also see that most of the lower noise outliers are close together, but the outliers due to higher noise are more spread.

Even in the reception setup, and even on the more noisy strips on the ends of the sensors, the noise is more than ten times smaller than the signal we expect a MIP to generate in the sensor. As a reminder, we expect at least 21 700 electron-hole pairs as signal (see section 3.1.5 on page 16).

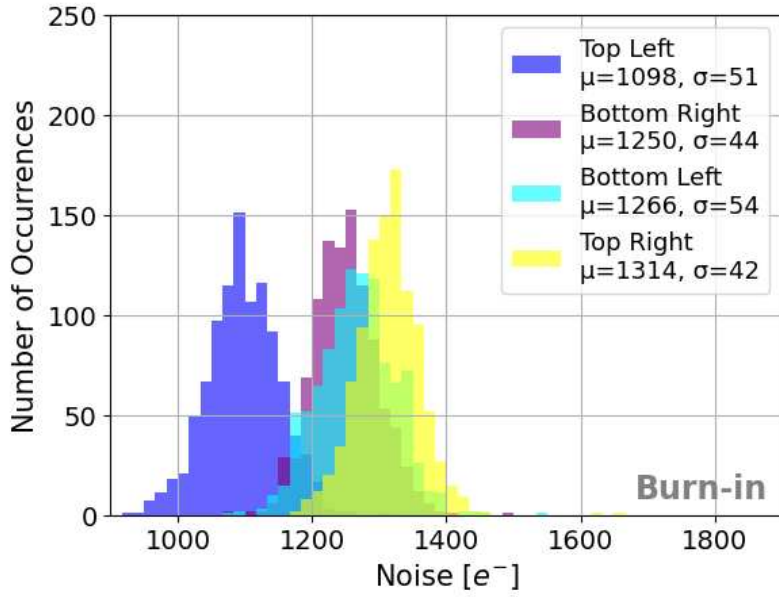
6.2 Temperature cycles

In the burn-in setup, we can run the software that handles temperature cycles and starts tests when the wanted temperatures are achieved (OTSDAQ). A description of the operations was given in section 4.2.1 on page 36. In this experiment, the low temperature was set to -35 °C and the higher one to 20 °C. The tests were run on the 2S prototype module.

The first information we checked is the temperature of the module during the whole experiment, to check that the two cycles in temperature were correctly followed. Figure 6.6 is a representation of the temperature of the lpGBT during the tests. The higher temperature is around 35 °C and the lower one around -15 °C, there is a shift of 15 °C at high temperature and 20 °C at low temperature compared to the temperatures we asked to the software. This is completely normal because the reference temperature for the chiller, corresponding to the one we asked, is taken by a temperature sensor on the metal frame holding the module. However, we have access to the "sensor temperature" measured by a temperature sensor located on the silicon sensor, and read out by the lpGBT transceiver chip. This temperature is higher because the surrounding electronic chips emit heat. The second time the fridge reaches -35 °C, the module stays for a longer time at this temperature because a quick test and a full test are run. The jumps in temperature measured by the



(a)



(b)

Figure 6.4: Comparison of the noise in the reception (top) and burn-in (bottom plot) setups. The different colours refer to the four different parts of the module. μ is the mean and σ is the standard deviation, and they are both given in number of electrons.

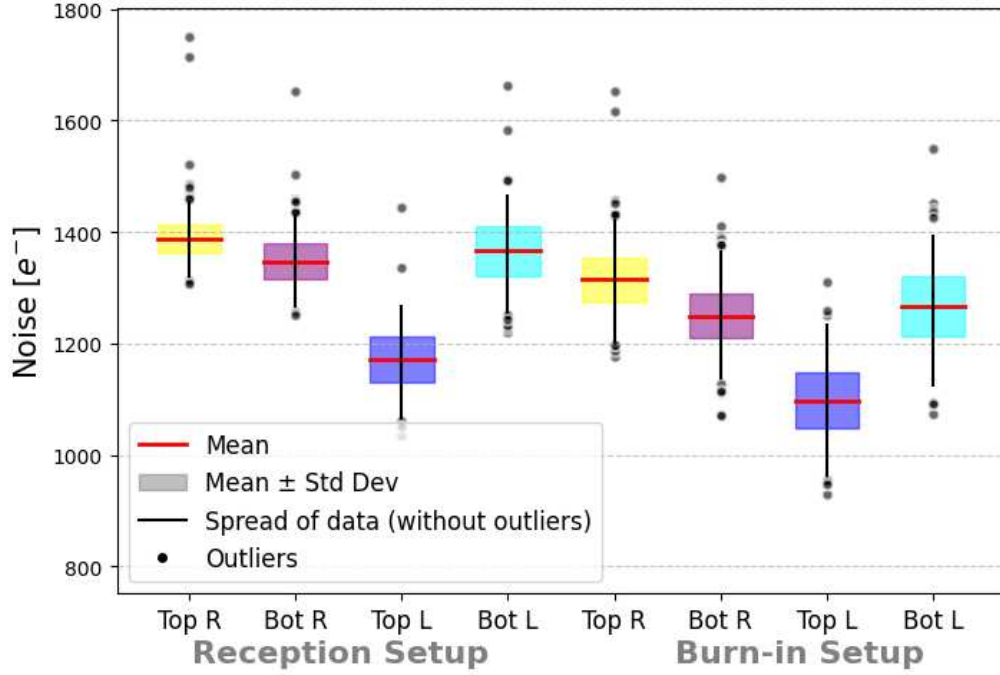


Figure 6.5: Candlestick chart that summarizes the mean noise, its standard deviation, the spreads of most of the data and the outliers for the different parts of the module in the two setups. The spread of most of the data is the whole data without outliers, it corresponds to the range defined in equation 6.1. Each side corresponds to one setup, and each column contains the information about one part of the sensor, with Bot. standing for bottom sensor, L for left and R for right part.

lpGBT are happening at the same time as jumps in the low voltage current measured by the power supply (represented in figure 6.7). These jumps in low current are caused by changes in the conditions around the sensor in the beginning of tests. The steps in temperature around the jumps give a lower bound on the resolution of the temperature sensor.

We will now look at the distributions of noise during the different tests run at different temperatures. Each test has a different label, and they are defined in table 6.1. The first quick test at 20 °C is referenced as "0", then the labels are given in the order of appearance of a test, thus the following quick test at -35 °C is called "1", and so on until the final quick test at 20 °C referenced as "5".

Figure 6.8 represents the significant values of noise as candlesticks obtained during the tests taken at different temperatures, with one plot per part of the module. The plots contain a lot of information, but we can easily notice that, for the whole module, the means of the noise distributions are always lower at -35 °C (tests 1, 3 and 4) than at 20 °C. The shift between the means for the two temperatures is always higher than 100 electrons. We can also observe that the different parts of the sensor keep almost the same sequence between the tests. For instance, in tests 0, 1 and 4, the order in increasing noise of the different parts stays the same: top left, bottom right, bottom left and top right. The results also seem consistent with the values obtained for the comparison between the two setups (section 6.1), with

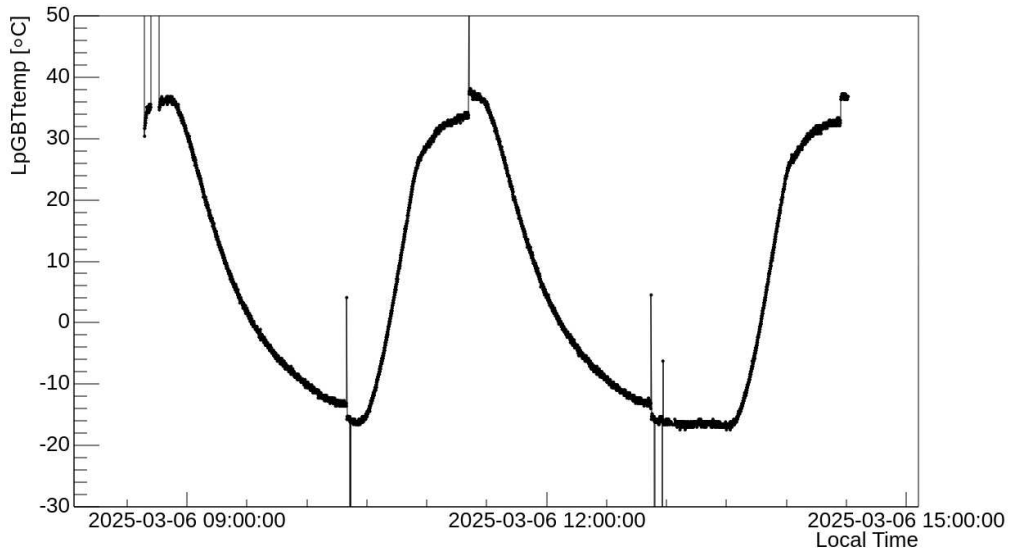


Figure 6.6: Evolution in time of the temperature measured by the lpGBT during the two temperature cycles.

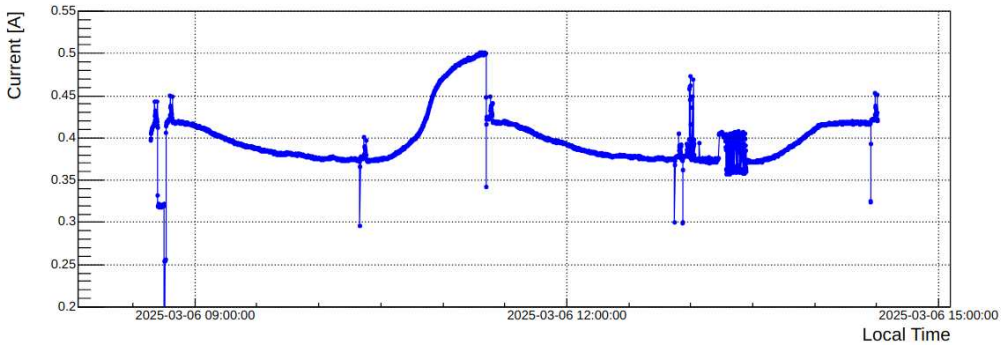


Figure 6.7: Current consumed by the module during the whole experiment. This is measured by the CAEN low voltage power supply.

Name of the test	Temperature	Type of test
0	20°C	Quick
1	-35°C	Quick
2	20°C	Quick
3	-35°C	Quick
4	-35°C	Full
5	20°C	Quick

Table 6.1: Explanation of the names of the tests, with the corresponding temperatures and types of test. The first test in time is named "0" and the last one is the "5".

the left side of the top sensor constantly having a lower mean noise than the other parts of the module. The noise distributions for the four parts of the module are plotted in the appendix, see figure A.1. And figure A.2, also in the appendix, gives a global view of the noise during the whole experiment.

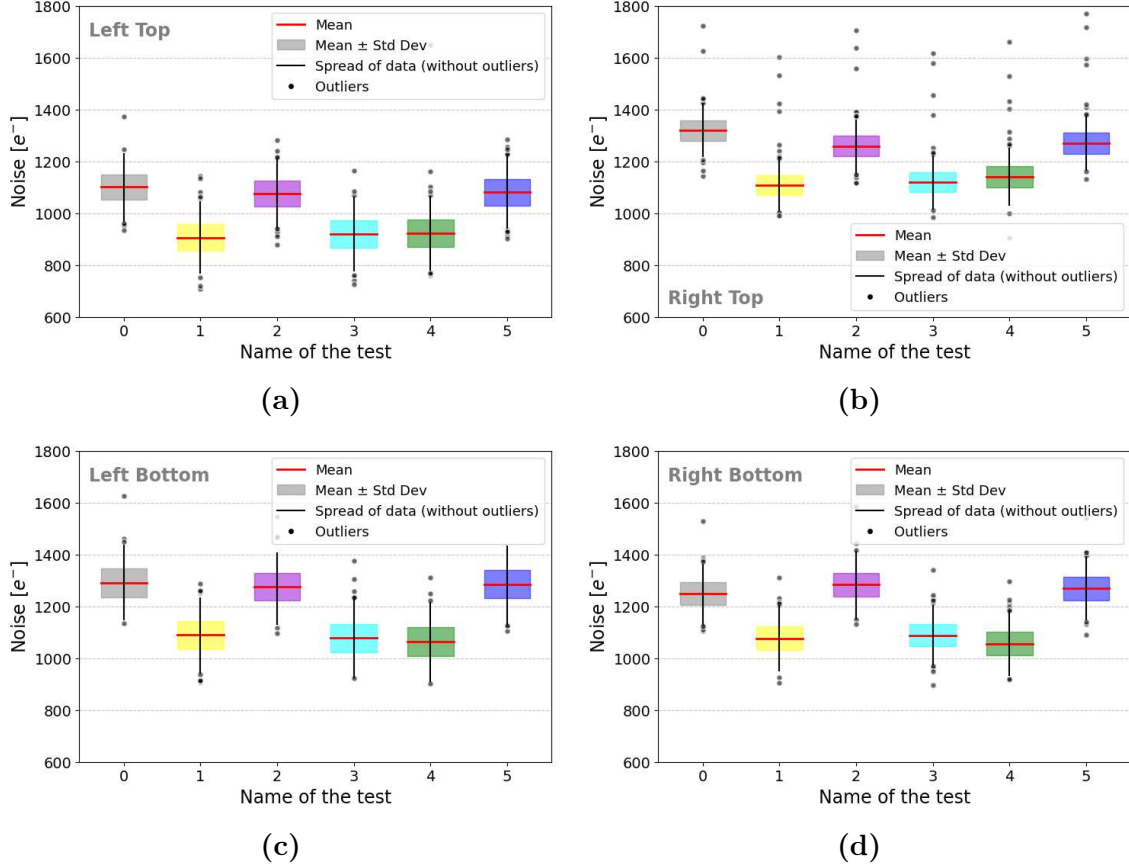


Figure 6.8: Comparison of the noise mean values, standard deviations, spreads without outliers and the outliers for the different parts of the 2S module during the six different tests at different temperatures. The left (right) plots correspond to strips that are read out by the left (right) service hybrid so the left (right) part of the sensor and the two top (bottom) plots are showing the noise in the top (bottom) sensor.

We noticed that the noise is higher in test 0 than in test 2, for three different parts of the module, it is only lower in the right bottom case. We tried to see if this could be linked to a larger leakage current, so we plotted it in figure 6.9. We can recognize the cycles in temperature with a higher leakage current at 20 °C. At higher temperature, the electrons have more kinetic energy, so they can more easily move in the conduction band, and their movements are detected as leakage current. But we can observe that the leakage current is higher during the second test at high temperature, so there is no clear correlation between the slightly higher noise for most of the module in test 0 and the leakage current.

We will now look at the noise values for the strips at the ends of the sensors to see if they correspond to the outliers or if another part of the module is responsible.

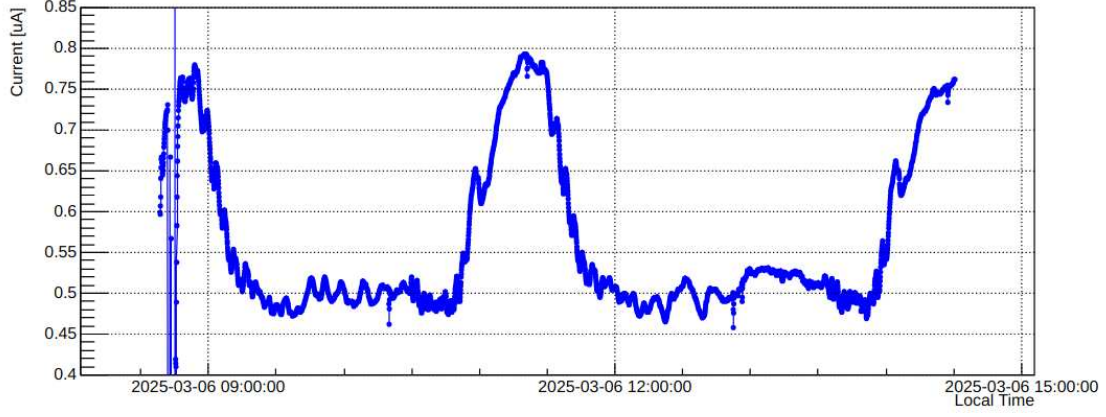


Figure 6.9: High voltage current measured by the power supply during the whole experiment. It represents the leakage current in the module.

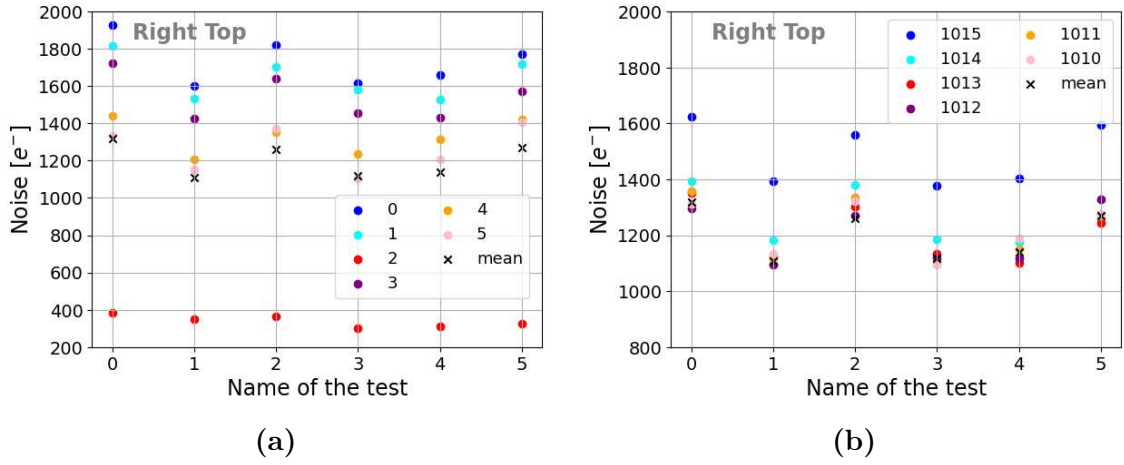


Figure 6.10: Noise in strips on the ends of the right side of the top sensor during the cycles in temperature. The left plot represents the strips close to the service hybrid, with strip 0 the closest strip to the hybrid, strip 1 the next one and so on. The right plot contains the strips further away from the service hybrid, with strip 1015 at the end. The mean is computed on the 1016 strips of the right top part of the module.

The upper noise outliers in the right top part of the module are more spread (see figure 6.8), thus we plotted the noise values at the ends of this part of the sensor in figure 6.10. We can observe that the noise in the end strips also depends on the temperature and has a higher value at 20 °C. We also recognize the third strip on the side of the service hybrid (in red) with the atypical low noise. The strip at the end has almost always the highest noise. By comparing the outliers in figure 6.8b with figure 6.10, we have the confirmation that the strips at the ends of the sensor are responsible for the outliers. The same plots for the other parts of the module are displayed in figures A.3 and A.4 of the appendix.

6.3 Noise in a PS module

We looked at the noise distributions in the PS prototype module to check that shorter strips lead to a lower noise, as we would expect given that the most significant noise source depends on the load capacitance that is proportional to the strip length. All the details were given in section 3.1.4 that describes the different noise sources in silicon sensors.

We placed the PS prototype module in the reception setup and we started a full test. The noise measurements in PS modules follow the same logic as for the 2S modules, but some implementation details differ. Figure 6.11 shows the noise distributions in the two sensors: the strip sensor on top and the pixel sensor below. The distributions are normalized in order to see values from the strip sensor, because there are 30 720 macro-pixels and only 1920 strips in a PS module. In PS modules, the left and right side are defined with the readout hybrid in the bottom, so not like in figure 3.8 on page 17, and strip 0 is the closest to the readout hybrid.

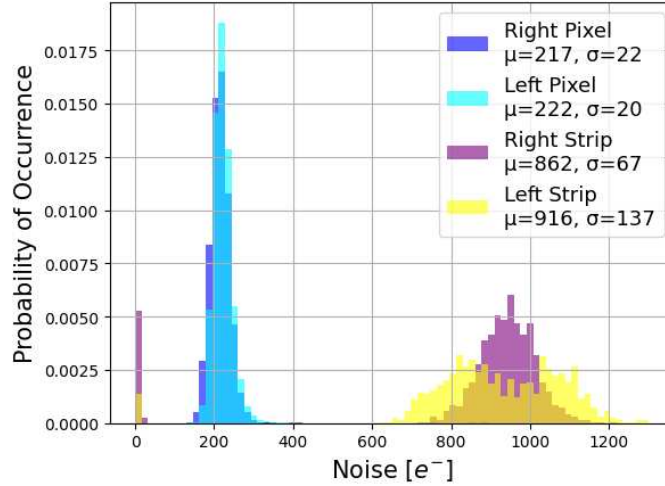


Figure 6.11: Normalized noise distributions for the four parts in the PS prototype module.

The wide noise distributions for the strips can be understood by looking at the noise values per strip, represented in figure 6.12. The noise is constantly increasing as the strips are further away from the readout hybrid, especially for the left hybrid. This is caused by the voltage drop along the readout hybrid. The noise is even larger for strips close to the service hybrid due to the proximity to the DC-DC converter. A lot of strips have unusual noise due to an unexpected behaviour of the occupancy during the threshold scan, and the program was not able to fit the measurements with an s-curve.

In the 2S module, the 5 cm long strips have a noise around 1300 electrons in the reception setup, and in the PS module, the strips are 2.4 cm long and the noise is 900 electrons, and the 0.15 cm long macro-pixels have an average noise of 200 electrons. We can thus confirm that shorter strips have a lower noise for the prototype modules, but the length of the strip is not the only parameter influencing

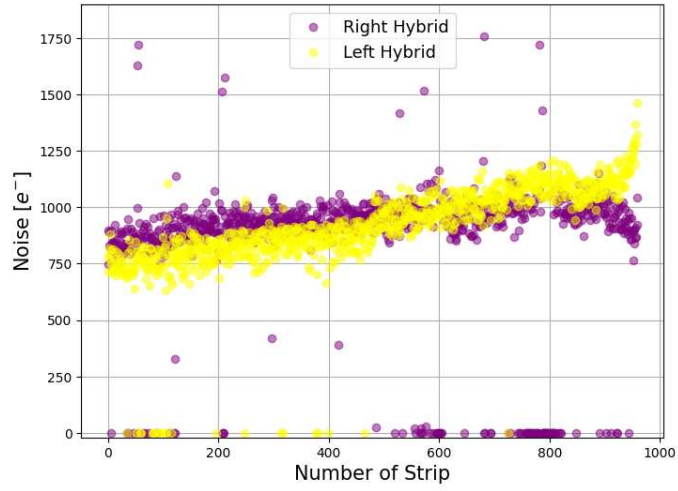


Figure 6.12: Noise per strip for the strip sensor in the PS prototype module during a full test in the reception setup. Strips 0 are on the side of the readout hybrid.

the noise in a silicon sensor. The three readout chips (CBC, SSA and MPA) also differ and have different impacts on the noise.

Chapter 7

Results from the integration exercise

During the integration exercise (described in section 5.1), twelve modules were placed on a dee. This was a nice opportunity to check that the modules were efficiently cooled in the cold box and that their noise level was satisfactory. We were not able to run full tests on all the modules, mainly due to firmware issues. The six modules that gave us meaningful results are labelled in figure 7.1.



Figure 7.1: Zoomed-in view of figure 5.1 with a label on the working modules on the dee. Modules 0 and 1 are PS modules, and the four others with labels are 2S modules.

When the dee is in the cold box, we can modify its temperature with the MARTA CO₂ cooling pipes that run through the dee and the Julabo silicon oil that passes behind the fans to modify the air temperature around the dee. We took measurements at two different configurations, one warm and one cold. In the warm case, Julabo was set to 15 °C and MARTA to 13 °C. In the cold case, Julabo to -20 °C and MARTA to -34 °C.

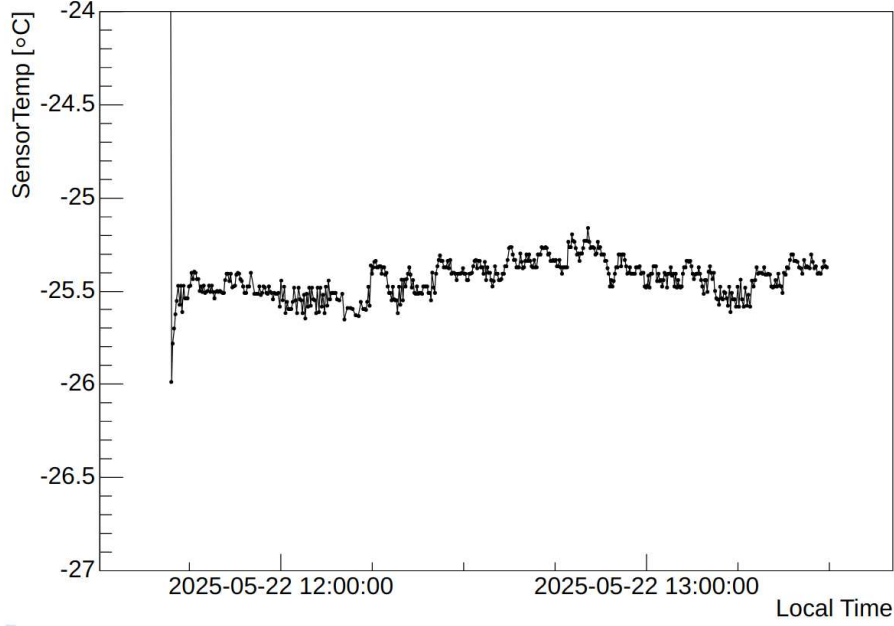


Figure 7.2: Sensor temperature for module 3 during a full test in cold conditions.

7.1 Temperatures of the modules

In the first step, we checked that the modules were at the expected temperatures in the warm and cold configurations. We obtained the temperatures measured by the sensor located next to the silicon sensor for the four working 2S modules. Figure 7.2 represents the temperature of the module labelled 3 in cold conditions. The four 2S modules have the same temperature behaviour. The first very high value is not significant, it appears when the full test starts. When computing the average temperature, this value was discarded. The temperature is slightly rising at the beginning of the test, when the chips are powered on. After that, the temperature oscillates but stays between -25.1°C and -25.7°C , so we can confirm that the temperature was stable during the test.

The average temperatures during the full test for the four 2S modules are given in table 7.1. The temperatures are less than 1°C apart in the two configurations, which means that the dee is uniformly cooled in the integrated sector. In cold conditions, the sensor temperatures are around -25°C , indicating that the cold box is efficiently able to cool down the modules. The CO_2 cooling has a clear impact because at cold temperature the modules are cooler than the environment fixed at -20°C by the Julabo.

Label	Average cold temp. [$^{\circ}\text{C}$]	Average warm temp. [$^{\circ}\text{C}$]
2	-24.8	15.9
3	-25.4	15.2
4	-25.1	15.8
5	-25.0	15.2

Table 7.1: Temperature measurements for the working 2S modules.

We analyzed the temperatures measured by sensors in the pixel readout chips of PS modules during the warm and cold conditions. We observed high variations between the temperatures in the two conditions, confirming that the two PS modules were cooled in the cold box. But the PS temperature sensors are not calibrated and thermal interface material was not applied to glue the PS modules to the dee, so further analysis on the cooling of the PS modules is needed.

7.2 Noise in the modules

We checked the noise values of the 2S modules during the full tests in the cold box. In our previous experiments, we noted that the two sensors in a module have the same noise behaviours. Therefore, for this part of the results, we only looked at the left side of the bottom sensor in the four modules.

The four modules were firstly tested in the reception room, to have an idea about their noise without the potential impact of using the new cold box setup. The important noise distribution parameters are given in figure 7.3. It is clear that the noise is lower in production modules than in the prototype 2S used in Chapter 6. The four modules have usual noise behaviours.

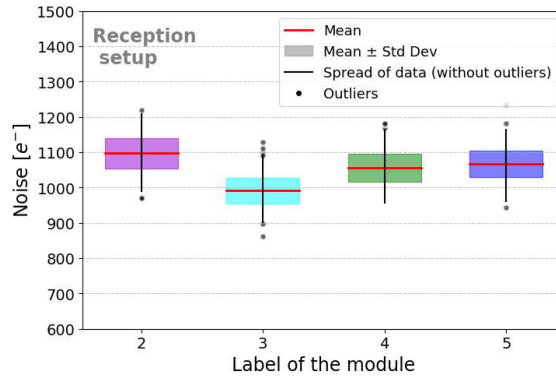


Figure 7.3: The noise mean values, standard deviations, spreads without outliers and the outliers for the left bottom parts of the 2S modules during a quick tests in the reception setup.

Figure 7.4 contains all the useful information about the noise in the four integrated 2S modules in the cold box in the two temperature configurations. As expected, the noise is lower in cold conditions. There are no extreme outliers. The noise in the warm conditions on the dee is lower than the one measured in the reception setup. In the reception suitcase, the temperature was around 22 °C, and in the cold box the modules were at 15 °C, so the lower temperature in the cold box could have a small impact on the noise. We already explained in section 4.2.1 on page 36 that the clean room (where the cold box is) has a better ground connection than the reception room. On the dee, modules are connected to the ground through the power wires. But they are attached to the dee with inserts that have a low ohmic connection to the cooling pipes that are on ground potential, and all the inserts of one sector are short-circuited. This ensures a very good ground for the modules.

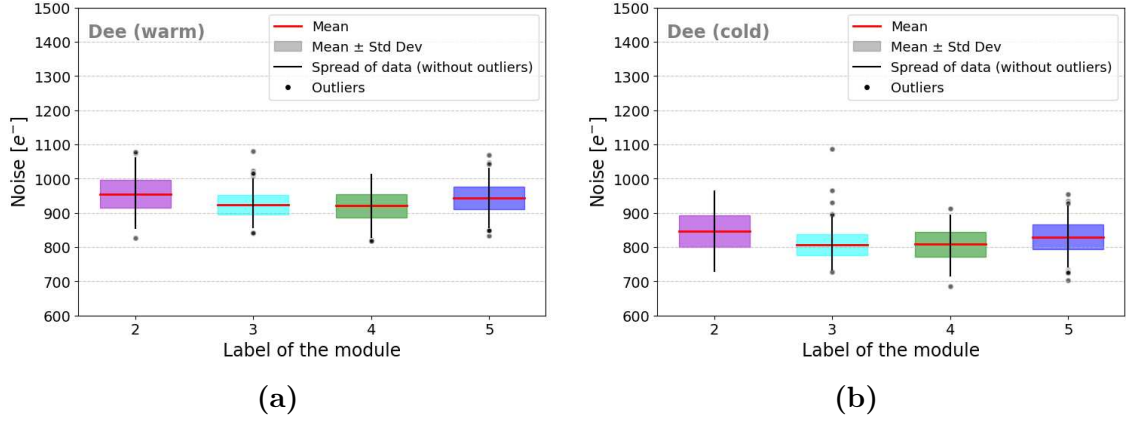


Figure 7.4: The noise mean values, standard deviations, spreads without outliers and the outliers for the left bottom parts of the 2S modules during full tests in the cold box on the dee. The left (right) plot correspond to warm (cold) conditions.

We think that the better grounding on the dee is the most important factor to the lower noise.

When modules are integrated on the dee, they are placed close to each other, sometimes at less than one centimetre from their neighbours. The presence of powered on modules, each with a clock and high voltage, in the vicinity of a module could increase its noise. Further studies are needed to see if this has a noticeable impact on the noise.

The predicted signal left by a crossing MIP in one tracker silicon sensor is around 21 000 electron-hole pairs. So even when a threshold is set at 5 sigma from the noise pedestal, we should not loose any signal.

A lot of other measurements could have been done with the production modules, but they had to return to integration and production centers for different types of tests and for training personnel at these sites.

Chapter 8

Conclusion

My master's thesis is about the performance of the silicon modules of the CMS tracker for HL-LHC. We started with a description of the context leading to the upgrade of the CMS detector, and the improvements it implies on its silicon tracker. The tracking of particles with silicon was then explained, first in the general case, and then for the CMS tracker modules that were described in details. We looked at the important procedures to qualify these modules, as well as the setups used to run the test. We described two exercises that prepare us for the future, one about the integration of modules and a second where we assembled a double-disk for the tracker endcap.

The first results concern the performance of individual prototype modules. With the 2S module, we compared the module noise between the reception and the burn-in setups. We also compared the noise in this module at different temperatures. By looking at the noise in a PS module, we observed the impact of the length of the strip on the noise. In the second part of the results, we analyzed the modules as they were integrated on the dee. We checked that they were efficiently cooled in the cold box, and we checked their noise levels.

A lot of noise measurements were performed, and in all of them the noise was smaller than the predicted signal a charged particle would generate in the sensor. The noise measurements on the dee are especially encouraging for the efficiency of the future CMS tracker.

Regarding the tests on individual modules, further measurements can be performed, especially with PS modules and production modules. We saw that modules have a higher noise in the reception setup, we could try to provide a more stable ground to this room to obtain a better idea about the modules' performance as they arrive in Louvain-la-Neuve. We could also try to improve the firmwares, to make them more autonomous and faster when we run module tests. Given that the real integration should start in September, detailed analysis of the noise and grounding on the dee are needed to check that everything works as expected, because once modules are integrated on the dee it will be harder to modify the dee if we discover failures in the design.

The future steps for the tracker team in Louvain-la-Neuve are quite clear: in-

tegrate modules on the dees, until 5 double-disks are obtained, and then assemble the tracker in CMS at CERN. Performance measurements, like the ones described in this master's thesis, will be useful during all these steps, to check the quality of modules before their integration on the dee for instance, or to understand if some issues appear when they are integrated. Even when CMS will be fully integrated and analyze the protons collisions generated by the HL-LHC, the knowledge of the noise behaviour will be valuable to understand unexpected behaviours of some sensors and to obtain the best possible data.

Appendix A

Additional plots for section 6.2

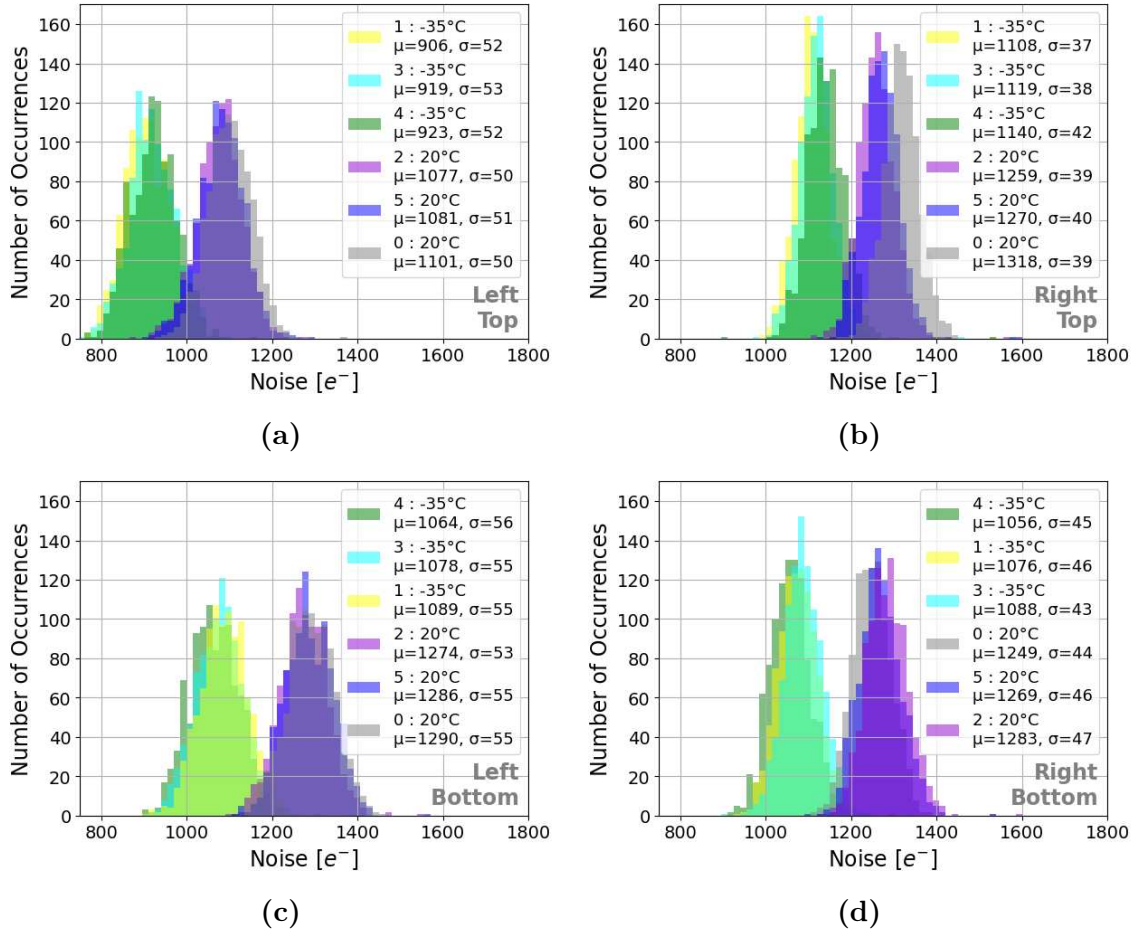


Figure A.1: Comparison of the noise histograms for the different parts of the 2S module during the six different tests at different temperatures. The left (right) plots correspond to strips that are read out by the left (right) service hybrid so the left (right) part of the sensor and the two top (bottom) plots are showing the noise in the top (bottom) sensor. μ is the mean and σ is the standard deviation, and they are both given in number of electrons.

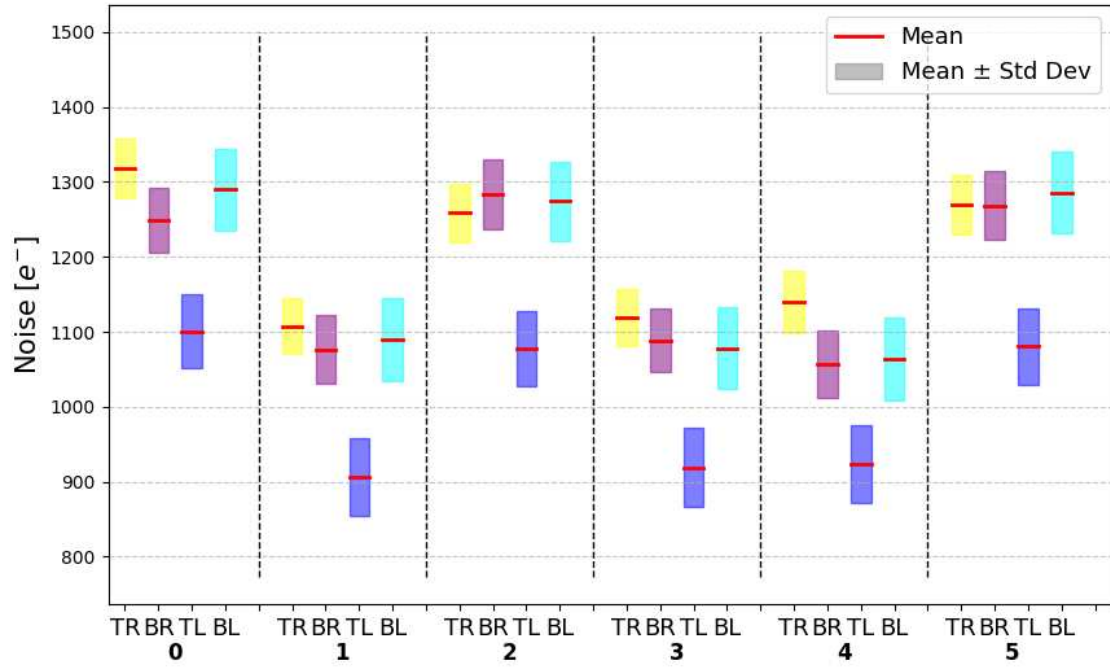
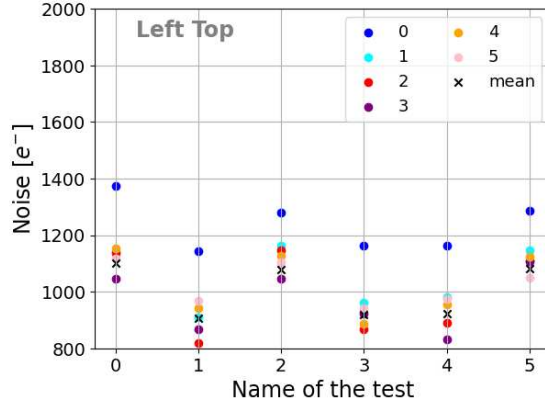
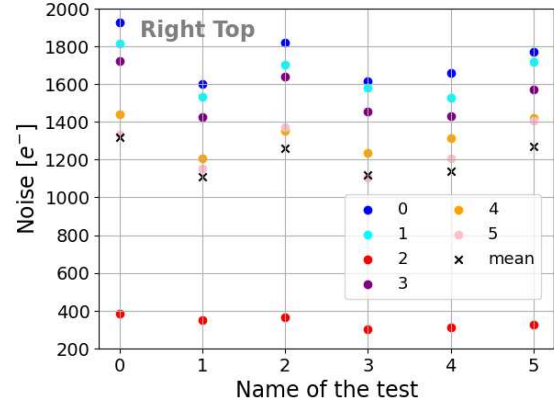


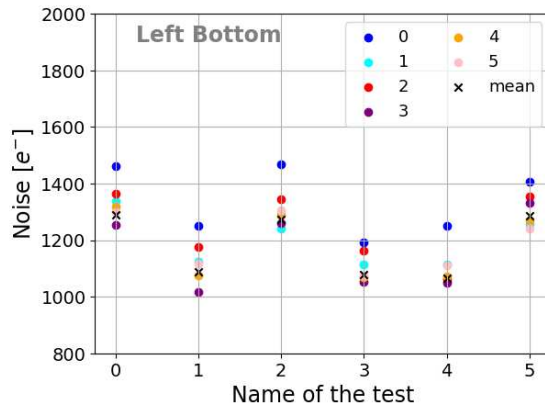
Figure A.2: Mean and standard deviation (computed without outliers) of the noise during the cycles in temperature. The numbers below on the x-axis correspond to the names of the tests, and on top of it is indicated the part of the module, with B standing for bottom, T for top sensor, and L for left and R for right hybrid. This plot confirms what was already discussed, with the fact that the module has a lower noise at -35 °C.



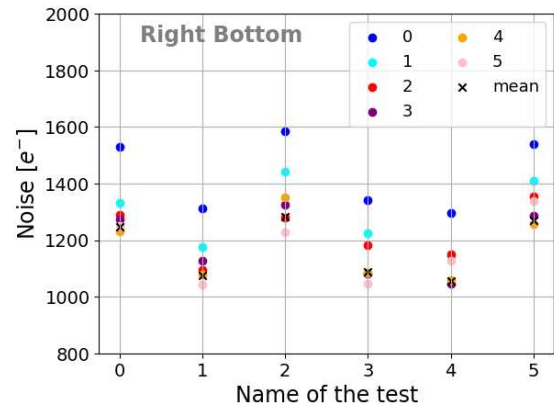
(a)



(b)

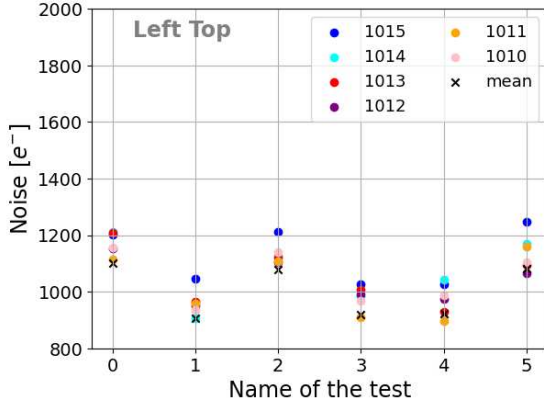


(c)

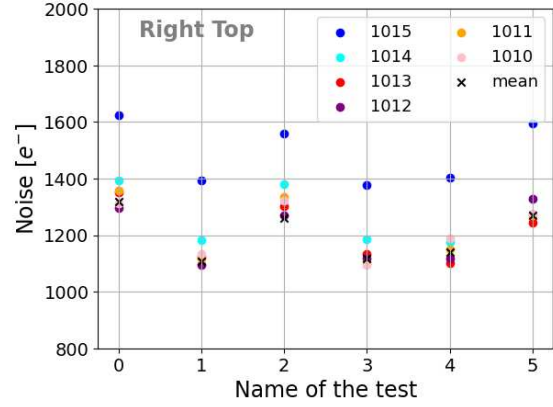


(d)

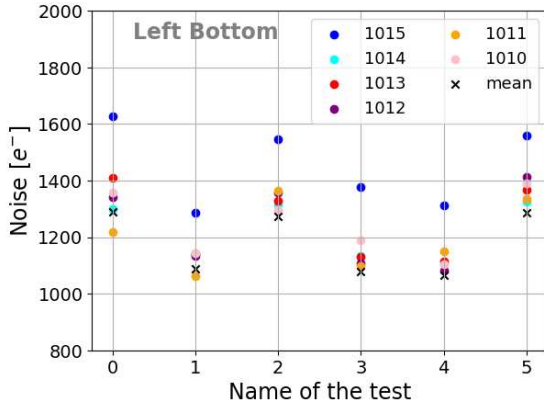
Figure A.3: Noise in the strips on the side of the service hybrid, with strip 0 the closest strip to the hybrid, strip 1 the next one and so on. The mean is computed on the 1016 strips of the part under consideration of the sensor. The right top plot has a wider range of noise values to see all the values.



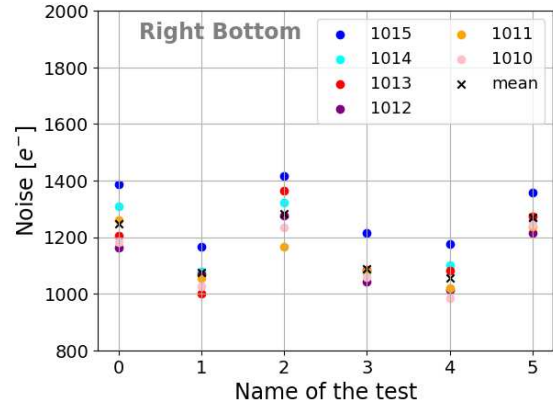
(a)



(b)



(c)



(d)

Figure A.4: Noise in the strips on the opposite side of the service hybrid, with strip 1015 the farthest strip from the hybrid, strip 1014 the next one a bit closer to the hybrid and so on. The mean is computed on the 1016 strips of the part under consideration of the sensor.

Bibliography

- [1] L. Evans and P. Bryant. “LHC Machine”. In: *Journal of Instrumentation* 3.08 (Aug. 2008), S08001. DOI: [10.1088/1748-0221/3/08/S08001](https://doi.org/10.1088/1748-0221/3/08/S08001). URL: <https://dx.doi.org/10.1088/1748-0221/3/08/S08001>.
- [2] CMS Collaboration. “The CMS experiment at the CERN LHC. The Compact Muon Solenoid experiment”. In: *JINST* 3 (2008), S08004. DOI: [10.1088/1748-0221/3/08/S08004](https://cds.cern.ch/record/1129810). URL: <https://cds.cern.ch/record/1129810>.
- [3] F. Landua. “The CERN accelerator complex layout in 2022. Complexe des accélérateurs du CERN en janvier 2022”. In: (2022). General Photo. URL: <https://cds.cern.ch/record/2813716>.
- [4] D. Contardo et al. *Technical Proposal for the Phase-II Upgrade of the Compact Muon Solenoid*. Tech. rep. Geneva, 2015. DOI: [10.17181/CERN.VU8I.D59J](https://cds.cern.ch/record/2020886). URL: <https://cds.cern.ch/record/2020886>.
- [5] I. Béjar Alonso et al. *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*. CERN Yellow Reports: Monographs. Geneva: CERN, 2020. DOI: [10.23731/CYRM-2020-0010](https://cds.cern.ch/record/2749422). URL: <https://cds.cern.ch/record/2749422>.
- [6] *HL-LHC : Project Schedule*. Jan. 2012. URL: <https://project-hl-lhc-industry.web.cern.ch/content/project-schedule>.
- [7] B. Martin. *Nuclear and Particle Physics, an introduction*. Wiley, 2006.
- [8] D. d’Enterria et al. “CMS Physics: Technical Design Report v.2: Addendum on High Density QCD with Heavy Ions”. In: (Jan. 2007).
- [9] A. Dominguez et al. *CMS Technical Design Report for the Pixel Detector Upgrade*. Tech. rep. 2012. URL: <https://cds.cern.ch/record/1481838>.
- [10] L. Anzalone et al. “Triggering dark showers with conditional dual auto-encoders”. In: *Mach. Learn.: Sci. Technol.* (2024). DOI: [10.1088/2632-2153/ad652b](https://doi.org/10.1088/2632-2153/ad652b).
- [11] D. Contardo et al. *Technical Proposal for the Phase-II Upgrade of the CMS Detector*. Tech. rep. Geneva, 2015. DOI: [10.17181/CERN.VU8I.D59J](https://cds.cern.ch/record/2020886). URL: <https://cds.cern.ch/record/2020886>.
- [12] F. Hartmann. *Evolution of Silicon Sensor Technology in Particle Physics, Second Edition*. Springer, 2017.
- [13] C. Kittel. *Introduction to Solid State Physics, Eighth Edition*. John Wiley & Sons, Inc, 2004.
- [14] S. Stapnes. *Instrumentation for high-energy physics*. University of Oslo, Norway.

- [15] CMS Collaboration. *The Phase-2 Upgrade of the CMS Tracker, Technical Design Report*. 1 July 2017.
- [16] I. Zoi. “Design and construction of the Outer Tracker for the CMS Phase-2 Upgrade”. In: 4March 2025. URL: https://cds.cern.ch/record/2930434/files/CR2025_081.pdf.
- [17] G. Baldinelli, S. Bhattacharya, ... A. Zuber⁴. *The Tracker End-Cap Double Disks (TEDD) of the CMS Phase 2 Outer Tracker*. 12/10/2021.
- [18] Leica. *S8 APO Unique Greenough Stereo Microscope with Apochromatic Optics*. URL: <https://www.leica-microsystems.com/products/light-microscopes/stereo-microscopes/p/leica-s8-apo/downloads/>.
- [19] G. Bruno. *LPHYS2233: Experimental methods in Fundamental Physics*.
- [20] S. Scarfi et al. “A System-Verilog Verification Environment for the CIC Data Concentrator ASIC of the CMS Outer Tracker Phase-2 Upgrades”. In: June 2019, p. 097. DOI: [10.22323/1.343.0097](https://doi.org/10.22323/1.343.0097).
- [21] F. Ravera. *Plots for PS alignment quality*. OT system tests meeting, Production QA SW group. Mar. 2024. URL: https://indico.cern.ch/event/1392905/contributions/5864544/attachments/2824591/4933766/FRavera_2024_03_21.pdf.
- [22] M. Prydderch. *CBC3.1 User Manual*. ASIC Design Group. July 2019.
- [23] S. Viret. *CIC2.1 technical specification*. Institut de Physique des 2 Infinis (FR), CERN. Feb. 2024.
- [24] *lpGBT Documentation*. lpGBT Design Team. Aug. 2024.
- [25] L. Feld. *Powering for Future Detectors: DC-DC Converters for the CMS Tracker Upgrade*. 1/10/2011. URL: https://cds.cern.ch/record/1395434/files/CR2011_201.pdf.
- [26] M. Pesaresi et al. “The FC7 AMC for generic DAQ & control applications in CMS”. In: *JINST* 10.03 (2015), p. C03036. DOI: [10.1088/1748-0221/10/03/C03036](https://doi.org/10.1088/1748-0221/10/03/C03036).
- [27] *Configuration and Calibration of a 2S/PS Module*. URL: <https://codimd.web.cern.ch/onQ0giHeSIKREqPRWRgRJw#Configuration-and-Calibration-of-a-2SPS-Module>.
- [28] F. Ravera. *OT Ph2_ACFschool–2Smodules*. 28/04/25. URL: <https://indico.cern.ch/event/1540157/>.
- [29] F. Ravera. *OT Ph2_ACFschool – PSmodules*. 29/04/25. URL: <https://indico.cern.ch/event/1540158/>.
- [30] J. Terörde. *Investigations on Common Mode Noise in Outer Tracker 2S modules*. 17.10.2024 (RWTH Aachen University).
- [31] S. Baradia. *The CMS Phase 2 Outer Tracker Analyzer of Test Outputs - POTATO!* DOI: [10.2172/2406075](https://doi.org/10.2172/2406075). URL: <https://inspirehep.net/literature/2807619>.
- [32] Iseg. *SHR Switchable High Precision AC/DC Desktop High Voltage Power Supply (22 60)*. URL: <https://iseg-hv.com/en/products/detail/SHR>.

- [33] R&S. *HMP (4040) Power Supply Series*. URL: <https://befr.rs-online.com/web/p/bench-power-supplies/1742920>.
- [34] S. Maier. *Manual, OT Module Test Bench and Readout GUI (GIPHT)*.
- [35] Donaldson. *Ultracac HED/ALD/MSD 0005-0035 Adsorption Dryer (MSD 0025)*. URL: www.donaldson.com.
- [36] CAEN. *SY4527 Universal Multichannel Power Supply System*. URL: <https://www.caen.it/products/sy4527/>.
- [37] CAEN. *A7435 12/24 Channel, 3.5 kV, 3.5/0,35 mA (9W) Common Floating Return Dual Range Boards*. URL: <https://www.caen.it/products/a7435/>.
- [38] CAEN. *A251x Series 50W LV Boards User Manual*. URL: <https://www.caen.it/?downloadfile=9163>.
- [39] T. Olchawski. *MARTA Monoblock Approach for a Refrigeration Technical Application*. URL: <https://repozytorium.biblos.pk.edu.pl/resources/25031>.
- [40] Julabo. *FP52-SL Ultra-Low Refrigerated / Heating Circulator*. URL: <https://julabo.us/wp-content/uploads/2023/07/JULABO-FP52-SL-9352752N-US.pdf>.
- [41] Hexagon. *Absolute Arm User Manual (2m with 7 axes)*. 2021.
- [42] *Outlier detection with Tukey's fences*. URL: https://en.wikipedia.org/wiki/Outlier#Tukey's_fences.

Some of the codes used to generate the results plots were developed with the assistance of ChatGPT (chat.openai.com).

UNIVERSITE CATHOLIQUE DE LOUVAIN

Faculté des sciences

Place des sciences, 2 bte L6.06.01, 1348 Louvain-la-Neuve, Belgique | www.uclouvain.be/sc

