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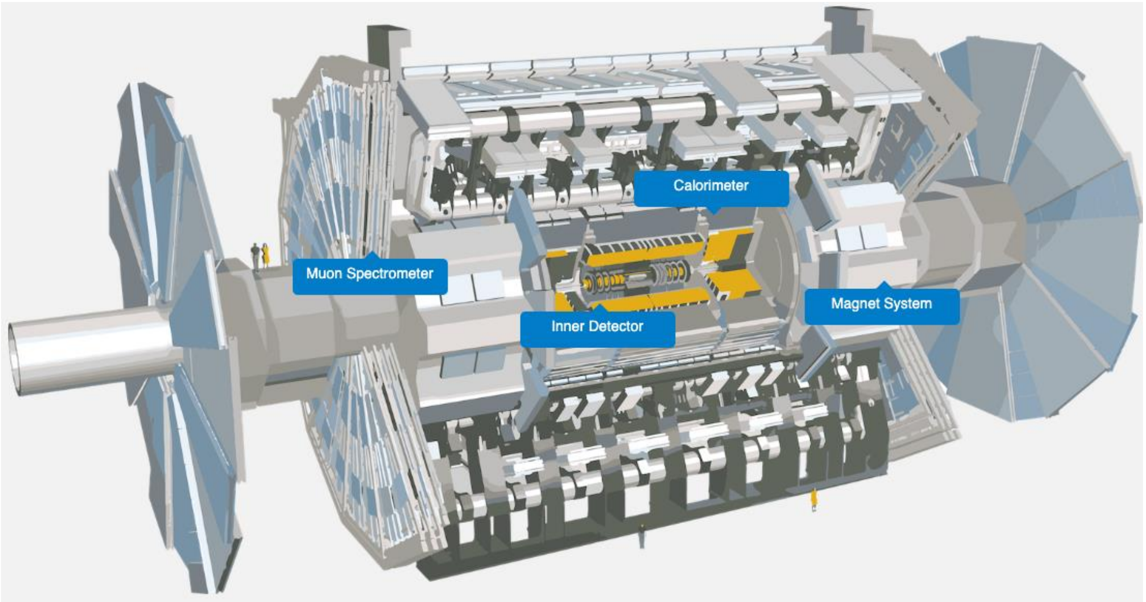
THE EUROPEAN CENTER FOR NUCLEAR RESEARCH (CERN) - GENÈVE

Quality Control Setup and Characterization of Silicon Pixel Detector Loaded Modules for the Inner Tracker of the ATLAS Experiment for HL-LHC.



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Internship done at CERN from 14th March to 31st August 2024

Dedication

To my dear parents

Said Achaq, Fouzia Harta, No word can express my gratitude to you, your sacrifices and your unconditional support will forever be etched in my heart.

To my sisters

Salma and Fatima Zahra.
Your love, your help, and your trust has been great support,
May this work be the expression of all my affection.

To all these people I dedicate this modest work for their support throughout my journey.

Acknowledgment

This project would not have been possible without the support of many people, who offered guidance, help, and encouragement.

First and foremost, I acknowledge the educational team of the embedded systems engineering department at “**EVERING Institute - Bordeaux University**” for stepping up to ensure the students are getting enough knowledge to face labor market challenges.

I am indebted to my supervisor, **Pr. REUNGOAT David**, professor at Bordeaux University, for his continued guidance, his valuable assistance, and his support with full encouragement and enthusiasm.

I am extremely thankful to my technical supervisor **Dr. EL JARRARI Hassnae,** a scientific researcher at the European Organization for Nuclear Research for allowing me to be part of the Experimental physics – Detectors department in one of the world’s largest and most respected centers for scientific research as well as for her valuable inputs and suggestions throughout this project.

My sincere recognition also goes to all members of the electronics section especially **Dr. KUEHN Susanne, and Dr. PACIFICO Nicola** for their unfailing support and continuous encouragement.

Most importantly, I am grateful for **my family’s** unconditional, unequivocal, and loving support.

Abstract

Physicists and engineers at CERN use the world's largest and most complex scientific instruments to study the basic constituents of matter – fundamental particles. Subatomic particles are made to collide together at close to the speed of light. The process gives us clues about how the particles interact and provides insights into the fundamental laws of nature.
The purpose is to advance the boundaries of human knowledge by delving into the smallest building blocks of our universe.

The instruments used at CERN are purpose-built particle accelerators and detectors. Accelerators boost beams of particles to high energies before the beams are made to collide with each other or with stationary targets. Detectors observe and record the results of these collisions.

Nowadays, The European Organization for Nuclear Research (CERN) is in the process of developing the technologies required to upgrade their state-of-the-art particle accelerator, the Large Hadron Collider (LHC). This upgraded machine, known as the High Luminosity Large Hadron Collider (HL-LHC) aims to increase the number of particle collisions (formally referred to as luminosity) by a factor of 10 to increase the number of observations of rare particle phenomena. While the actual installation is expected to commence in 2027, the various engineering sections at CERN are already diligently working towards this milestone.

One aspect of this upgrade involves the upgrade of the ATLAS detector system. In fact, The ATLAS detector at the Large Hadron Collider is undergoing a major upgrade with the construction of a new silicon Inner Tracker (ITk) that will operate at High Luminosity. This silicon tracking detector plays a crucial role in reconstructing tracks of charged particles. The ITk's pixel detector, located closest to the collision point, will comprise of approximately 10,000 pixel modules loaded onto carbon cooling structures. These loaded quad modules consist of four front-end chips, the silicon sensor, wire-bond protection, and are assembled onto thermal conductive support structures. The EP-ADE-TK section at CERN is working on a replacement of the Inner Detector with the new Inner Tracker.

- Keywords: LHC, HL-LHC, ATLAS, ITK.

Résumé

Les physiciens et ingénieurs du CERN utilisent les instruments scientifiques les plus grands et les plus complexes au monde pour étudier les constituants de base de la matière – les particules fondamentales. Les particules subatomiques sont amenées à entrer en collision à une vitesse proche de la vitesse de la lumière. Le processus nous donne des indices sur la façon dont les particules interagissent et donne un aperçu des lois fondamentales de la nature. L'objectif est de repousser les limites de la connaissance humaine en fouillant dans les plus petits éléments constitutifs de notre univers.

Les instruments utilisés au CERN sont des accélérateurs et des détecteurs de particules spécialement conçus. Les accélérateurs accélèrent les faisceaux de particules à des énergies élevées avant que les faisceaux ne soient amenés à entrer en collision les uns avec les autres ou avec des cibles fixes. Les détecteurs observent et enregistrent les résultats de ces collisions.

Aujourd'hui, l'Organisation Européenne pour la Recherche Nucléaire (CERN) est en train de développer les technologies nécessaires pour moderniser son accélérateur de particules de pointe, le Large Hadron Collider (LHC). Cette machine améliorée, connue sous le nom de High Luminosity LHC.
Le collisionneur de hadrons (HL-LHC) vise à augmenter le nombre de collisions de particules (formellement appelée luminosité) d'un facteur de 10 dans le but d'augmenter le nombre des observations de phénomènes de particules rares. Vu que l'installation proprement dite devrait débutera en 2027, les différentes sections d'ingénierie du CERN travaillent déjà avec diligence vers cette modernisation.

Un aspect de cette mise à niveau concerne la modernisation du système de détection ATLAS. En effet, le détecteur ATLAS au LHC subit une importante mise à jour avec la construction d'un nouveau traceur interne en silicium (ITk) qui fonctionnera à haute luminosité. Ce détecteur de trajectoires en silicium joue un rôle crucial dans la reconstruction des trajectoires des particules chargées. Le détecteur à pixels de l'ITk, situé le plus près du point de collision, sera composé d'environ 10 000 modules à pixels montés sur des structures de refroidissement en carbone. Ces modules quadruples chargés sont constitués de quatre puces frontales, du capteur en silicium, de la protection des fils de connexion, et sont assemblés sur des structures de support thermo conductrices. La section EP-ADE-TK du CERN travaille sur le remplacement du détecteur interne par le nouveau traceur interne.

- Keywords: LHC, HL-LHC, ATLAS, ITK.

List of abbreviations

ATLAS	A Toroidal LHC Apparatus
ALICE	A Large Ion Collider Experiment
CERN	European Organization for Nuclear Research
CMS	The Compact Muon Solenoid
FPGA	Field-programmable gate array
HL-LHC	High Luminosity Large Hadron Collider
LHCb	LHC-beauty
LHC	Large Hadron Collider
PCB	Printed circuit board
QPS	Quench protection system
SPI	Serial Peripheral Interface
EP-ADE-TK	Experimental Physics - Detectors, Tracker department
ITK	Inner Tracker
ID	Inner Detector
OB	Outer Barrel

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Chapter I:

Introduction to the host organization

1. CERN history

At an intergovernmental meeting of UNESCO in Paris in December 1951, the first resolution concerning the establishment of a European Council for Nuclear Research (in French Conseil Européen pour la Recherche Nucléaire) was adopted.

Two months later, an agreement was signed establishing the provisional Council – the acronym CERN was born.

Established by 12 European governments in 1952. During these early years, the council worked at the University of Copenhagen under the direction of Niels Bohr before moving to its present site in Geneva. The acronym was retained for the new laboratory after the provisional council was dissolved, even though the name changed to the current Organisation Européenne pour la Recherche Nucléaire (European Organization for Nuclear Research) in 1954. According to Lew Kowarski, a former director of CERN, when the name was changed, the abbreviation could have become the awkward OERN, and Werner Heisenberg said that this could "still be CERN even if the name is [not]".

At the sixth session of the CERN Council, which took place in Paris from 29 June – 1 July 1953, the convention establishing the organization was signed, subject to ratification, by 12 states. The convention was gradually ratified by the 12 founding Member States: Belgium, Denmark, France, the Federal Republic of Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, the United Kingdom, and Yugoslavia.
Founded in 1954, the CERN laboratory sits astride the Franco-Swiss border near Geneva. It was one of Europe's first joint ventures and now has 23 member states.
Today, our understanding of matter goes much deeper than the nucleus, and CERN's main area of research is particle physics. Because of this, the laboratory operated by CERN is often referred to as the European Laboratory for Particle Physics.
CERN's first president was Sir Benjamin Lockspeiser. Edoardo Amaldi was the general secretary of CERN at its early stages when operations were still provisional, while the first Director-General (1954) was Felix Bloch.

2. Mission

CERN's primary mission is to provide the infrastructure to scientists to help to uncover what the universe is made of and how it works. A unique range of particle accelerator facilities are built and developed for research to advance the boundaries of human knowledge with important applications in other fields like medical imaging.

CERN primary missions are:

- Provide a unique range of particle accelerator facilities that enable research at the forefront of human knowledge.
- Perform world-class research in fundamental physics.

- Unite people from all over the world to push the frontiers of science and technology, for the benefit of all [1].

3. CERN governance

CERN's governance is structured to ensure effective management and oversight of the organization’s scientific endeavors, financial resources, and international
The CERN Council is the highest authority of the Organization and has responsibility for all-

Figure 1: Council meeting in December 2019 (Image: CERN) Council

important decisions. It controls CERN’s activities in scientific, technical, and administrative matters. It approves programs of activity, adopts the budgets, and reviews expenditure. The Council is assisted by the Scientific Policy Committee and the Finance Committee. The Director-General, appointed by the Council, manages and runs the Laboratory through a structure of departments.
CERN is run by 23 Member States, each of which has two official delegates to the CERN Council. One represents his or her government’s administration; the other represents national scientific interests. Each Member State has a single vote and most decisions require a simple majority, although in practice the Council aims for a consensus as close as possible to unanimity [1].

- Scientific Policy Committee

The Scientific Policy Committee evaluates the scientific merit of activities proposed by physicists and makes recommendations on CERN's scientific program. Its members are scientists elected by their colleagues on the committee and appointed by the Council based on scientific eminence without reference to nationality. Some members are also elected from the Non-Member States [1].

Figure 2: Scientific Policy Committee

- Finance Committee

The Finance Committee is composed of representatives from national administrations and deals with all issues related to financial contributions by the Member States and the Organization's budget and expenditure [1].

Figure 3: Finance Committee meeting in December 2019 (Image: CERN)

- Directorate

Tableau 1: Directorate of CERN

Director-General Appointed by Council, usually, for five years, the Director-General manages CERN. A directorate assists the Director-General, who proposes its members to Council. The Director-General reports directly to the Council, and can also propose any adjustment deemed necessary to meet the evolving needs of the research program.	**Fabiola Gianotti**

Director for Finance and Human Resources	**Raphaël Bello**
Director for Accelerators and Technology	**Mike Lamont**
Director for Research and Computing	**Joachim Mnich**
Director for International Relations	**Charlotte Warakaulle**

- Heads of departments

Tableau 2: Heads of departments of CERN

Site and Civil Engineering	Mar Capeans
Engineering	Katy Foraz
Theoretical physics	Gian Francesco Giudice
Accelerator systems	Brennan Goddard
Information technology	Enrica Porcari
Technology	José Miguel Jiménez
Beams	Rhodri Jones
Experimental physics	Manfred Krammer
Industry, Procurement and knowledge transfer	Christopher Hartley
Human resources	James Purvis
Finance and administrative Process	Florian Sonnemann

4. Member States

CERN has 23 member states. Belgium, Denmark, France, the Federal Republic of Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland) 1953
The United Kingdom and Yugoslavia (1954), Austria (1959), Spain (1961-1969) (re-joined 1983), Portugal (1985), Finland (1991), Poland (1991), Czechoslovak Republic (1992), Hungary (1992),Bulgaria (1999), Israel (2014), Romania (2016) and Serbia (2019).

The Czech Republic and Slovak Republic re-joined CERN after their mutual independence in (1993). Yugoslavia left CERN in (1961). Member States have special duties and privileges. They contribute to the capital and operating costs of CERN's programs and are represented in the Council, responsible for all important decisions about the Organization and its activities. Cyprus, Estonia, and Slovenia are Associate Member States in the pre-stage to Membership. Croatia, India, Latvia, Lithuania, Pakistan, Turkey, and Ukraine are Associate Member States.

Japan, and the United States of America hold Observer status with respect to the LHC, while the United States of America also holds Observer status with respect to the HL-LHC.

Over 600 institutes and universities around the world use CERN's facilities. Funding agencies from both Member and Non-Member States are responsible for the financing, construction, and operation of the experiments on which they collaborate. CERN spends much of its budget on building machines such as the Large Hadron Collider and it only partially contributes to the cost of the experiments [1].

5. People at CERN

Cooperation between nations, universities, and scientists is the driving force behind CERN's research.
As of 2017, more than 17 500 people from around the world work together to push the limits of knowledge. CERN's staff members, numbering around 2500, take part in the design, construction, and operation of the research infrastructure. They also contribute to the preparation and operation of the experiments, as well as to the analysis of the data gathered for a vast community of users, comprising over 12 200 scientists of 110 nationalities, from institutes in more than 70 countries.

6. Key achievements

LHC (The Large Hadron Collider).

Particle detectors – ATLAS, CMS, ALICE , and LHCb.

The discovery of Brout-Englert-Higgs mechanism

- The birth of the web
- Antimatter

Chapter II:

LHC and ATLAS experiment

1. LHC

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator. It first started up on 10 September 2008 and remains the latest addition to CERN's accelerator complex. The LHC consists of a 27-kilometer ring of superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way.
The beams inside the LHC are made to collide at four locations around the accelerator ring, corresponding to the positions of four particle detectors – ATLAS, CMS, ALICE , and LHCb.

Along the LHC tunnel, the four experiments ATLAS, CMS, ALICE, and LHCb are set up. While ATLAS and CMS are multipurpose detectors and used for a wide range of searches for new physics and for precision measurements at the highest possible energies, ALICE is designed for heavy-ion collisions and studies of the quark-gluon plasma and LHCb for specific measurements on the decay of B-mesons.

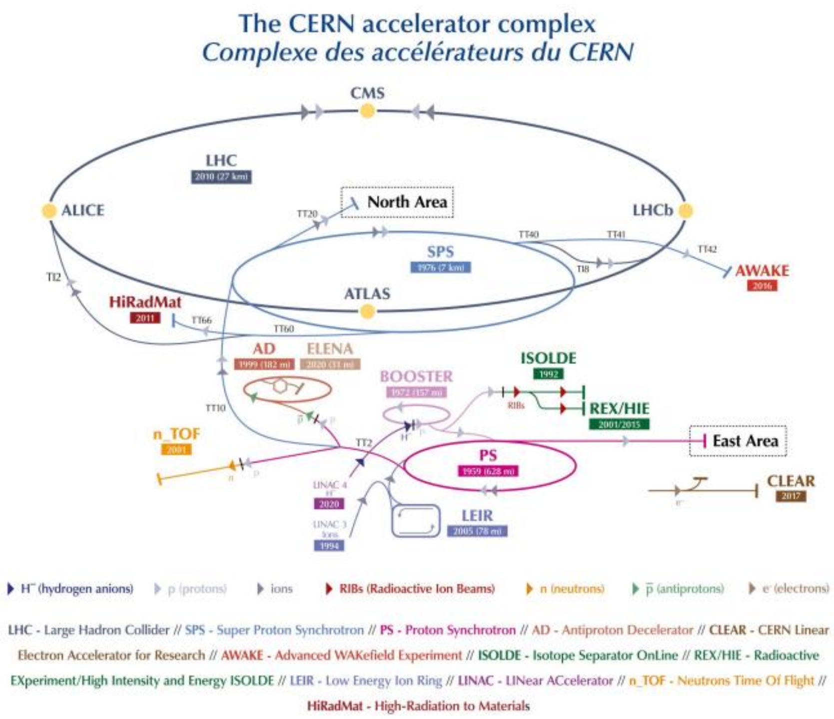


Figure 4: CERN accelerator complex with the pre-accelerator stages of the lhc. Protonproton collisions start in linac4, go to the booster, the ps and the sps.

2. ATLAS detector

The ATLAS Detector has a total length of 44 m, a height and width of 25 m and weighs approximately 7000 t, which is about as much as the Eiffel Tower. Particles can be measured and identified via their interactions with matter. The structure of the detector is hence chosen to be onion-like with multiple layers of different detectors and magnetic systems. It features three main detector systems: the Inner Detector (ID) to obtain tracking information, the Calorimeters for energy measurement and the muon system for muon tracking, as shown in Figure 5. All detector components aim for a large acceptance in pseudorapidity with almost full azimuthal angle coverage. Electrical signals returned from the recorded collisions in these detector systems are processed to reconstruct the physics objects passing the detector. The physics performance of ATLAS experiment highlights the discovery potential for new physics regarding especially the Higgs sector or SUSY particles and precision measurements of heavy quarks and gauge bosons.

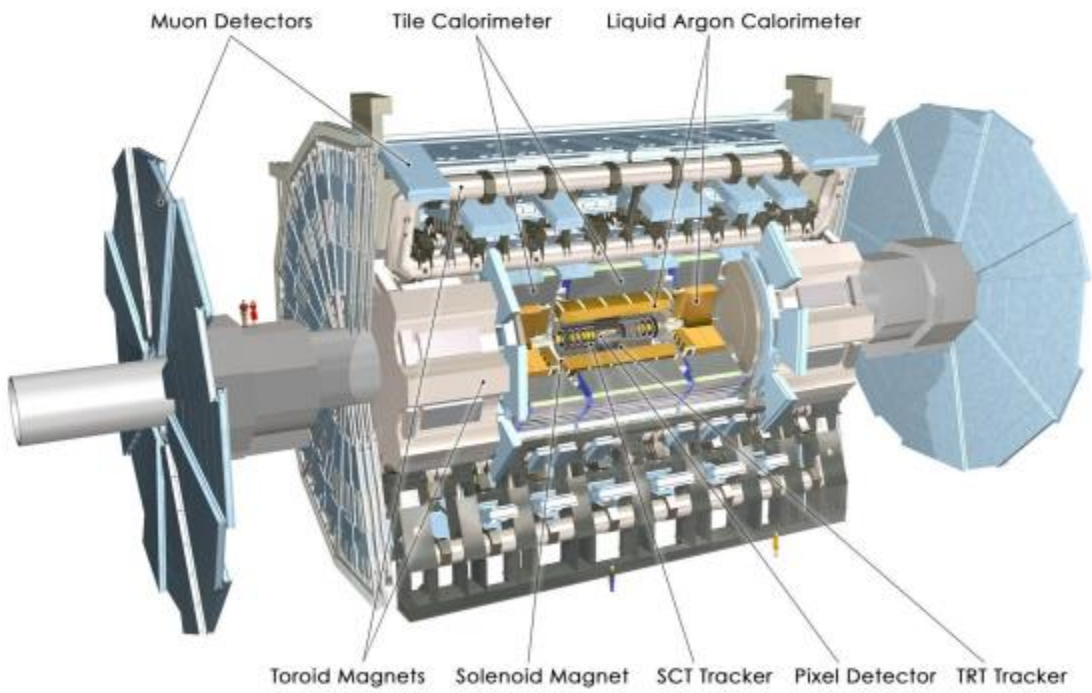


Figure 5: Schematics of the atlas Detector with humans shown for scale. ATLAS

3. Tracking System

The purpose of the Inner Detector, which is the closest to the interaction point is efficient tracking and vertex detection for charge-momentum measurements. It is 7 m long and 2.3 m wide and consists of three sub-systems, the semiconductor pixel Detector, the Semiconductor Tracker (SCT), which has several layers of silicon microstrip detectors and around these the Transition Radiation Tracker (TRT), a gaseous detector, for pattern recognition, momentum and vertex measurements is installed. Figure 6 shows the layout of the ID which is enclosed in a longitudinal magnetic field of 2 T, provided by a superconducting solenoid, which bends the charged particles' trajectories and allows the electric charge identification of the particles. Apart from that, the transverse momentum of the particle is obtained from the radius of curvature r and the magnetic field strength B(T) to be $p_T(GeV) = 0.3B(T)r(m)$

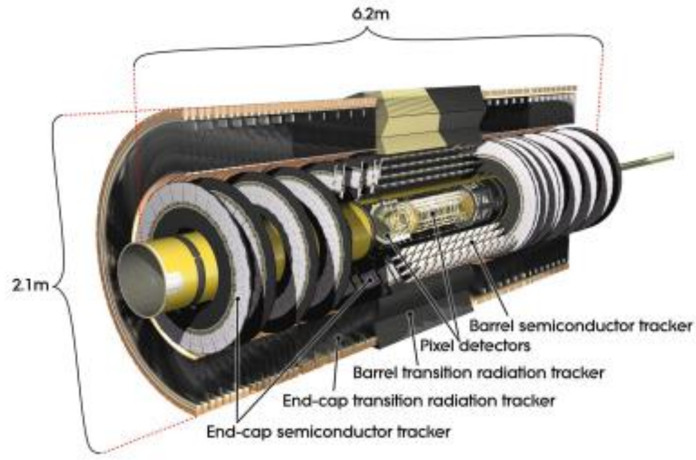


Figure 6: Schematics of the Inner Detector. ATLAS Experiment © 2021 CERN.

4. Pixel Detector

The pixel Detector was built in two stages. There were three layers of pixel modules in two different structures during Run 1. There are barrel shaped layers in the central section and three end-cap disks in the forward direction. The modules are hybrid pixel modules, which means that planar silicon sensors with 47232 pixels are bump bonded to sixteen readout chips with 2880 pixels each. The distances between the pixels, the pixel pitch of the sensor, is (400 × 50) µm2 and the sensor thickness is (256 ± 3) µm to offer high granularity for tracking and small material budget closest to the interaction point. Figure 7 shows the three-pixel layers in the middle of the ID and the three end-cap discs on both sides.

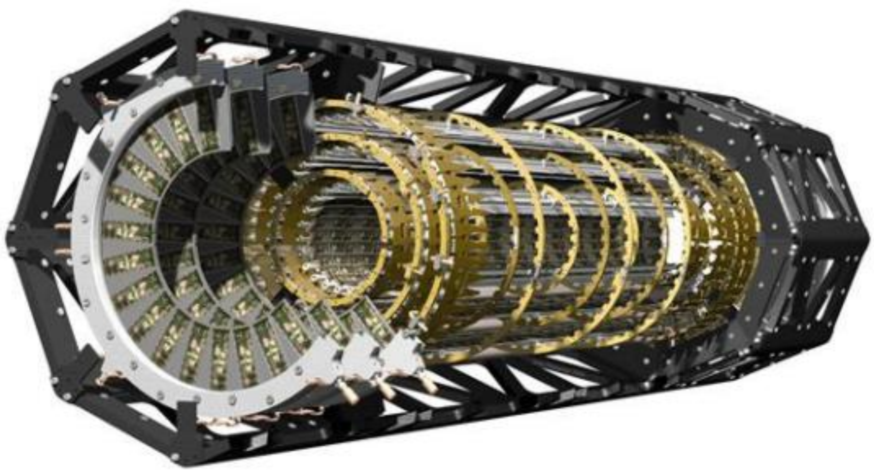


Figure 7: Schematics of the pixel Detector. Modules on the barrel staves and the

5. The LHC and ATLAS experiment Upgrades

In order to increase the physics reach and tackle the open questions, both, the LHC and the ATLAS Detector undergo upgrades. The upgrades are performed in different steps and parts of the upgrades have already taken place in the past years during the periods of shutdown. The LHC operation can be divided in three different periods. There is the yearly shutdown from December till March where small issues can be solved, then a daily fill status of the machine, with approximately 20 h of beam and then every few years long shutdowns which make upgrades of the machine and the detectors possible. In the first long shutdown, the energy as well as the luminosity of the LHC have been ramped up from 8 to 13 TeV. Accordingly, the ID was upgraded to withstand the new run conditions. The second long shutdown from December 2018 onwards ended in early 2022, initiating Run 3 with higher energy of 13.6 TeV. Several accelerator upgrades, including the replacement of the former proton linear accelerator linac2 with linac4, result in a twice as high beam brightness and intensity. The brightness of a beam describes the phase space density of the protons in the beam and the intensity, the number of protons or ions per bunch. During the current Run 3 the LHC is operated at twice the design luminosity. Concerning ATLAS, the Small Wheels, parts of the forward muon tracking system, have been replaced with the New Small Wheels. With higher luminosity, improved tracking and trigger performance are required to suppress background, several updates are ongoing to tackle this as well.

6. The High Luminosity-LHC

The High-Luminosity Large Hadron Collider (HL-LHC) project aims to crank up the performance of the LHC in order to increase the potential for discoveries. The objective is to increase luminosity by a factor of 10 beyond the LHC's design value.
Luminosity is an important indicator of the performance of an accelerator: it is proportional to the number of collisions that occur in a given amount of time. The higher the luminosity, the more data the experiments can gather to allow them to observe rare processes.
The High-Luminosity LHC, which should be operational from the end of 2029, will allow physicists to study known mechanisms in greater details, such as the Higgs boson, and observe rare new phenomena that might reveal in these experimental conditions. For example, the High- Luminosity LHC will produce at least 15 million Higgs bosons per year, compared to around three million from the LHC in 2017.
The High-Luminosity LHC project was announced as the top priority of the European Strategy for Particle Physics in 2013.

7. HL-LHC ATLAS Upgrade: The Inner Tracker

The innermost layers of the pixel detectors (see figure 8) fastused in the large experiments to find the vertices and the trajectories of the particles are exposed to high radiation levels near the interaction point. Therefore, new pixel sensor technologies are required to withstand these harsh environments and deliver accurate physics results.

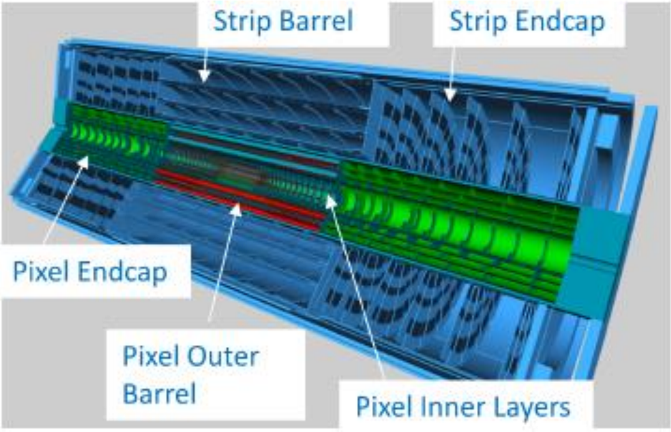


Figure 8: ATLAS ITK

The pixel Detector will be separated from the Strip Detector by a Pixel Support Tube and consists of five layers of pixel modules and a forward region with different sensor technologies. Due to the high radiation in the innermost layers, the inner two layers are replaceable and housed in the Inner Support Tube (ist) for easier access. About 10000 modules will be implemented in the barrel layers and end-cap rings on each side.

The ITK modules are required to be fast, highly granular and radiation hard. With smaller pixel pitches of (50×50) μm^2 or (25×100) μm^2 compared to the ID ((400×50) μm^2) the granularity is enlarged. This is necessary to minimize pile-up and accurately resolve tracks within boosted jets that have narrow tracks. Simulations predict a maximum channel occupancy of 0.16% in the innermost layer. However, with more pixels, more channels need to be read out. As parallel powering is not feasible, the readout chips are powered in so-called serial power chains. This saves space but also limits multiple scattering.

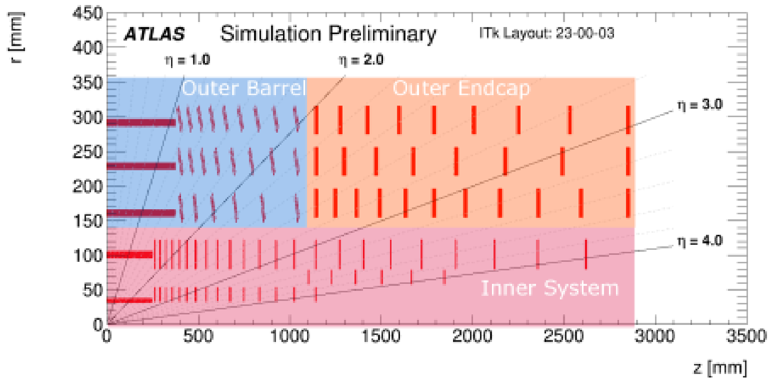


Figure 9: Different pixel Detector regions in the ITK

8. Hybrid Pixel Detectors for the ITK

Pixel detectors can be realized on the one hand as hybrid pixel detectors and on the other as monolithic pixel detectors. Monolithic pixel detectors have active and passive parts integrated on the same Application-Specific Integrated Circuit (ASIC) silicon chip so that the signal created in the passive part from passing particles is directly transformed and read out in the active part. **Hybrid pixel detectors** on the contrary, are made from two different silicon chips, where the sensor chip is passive and an active readout chip is bump bonded to the sensor pixels, pixel by pixel. The main purpose of a pixel detector, the detection of particle tracks with high spatial resolution, is obtained by its segmentation in pixels - on the sensors and respectively on the readout chip. For the ATLAS Pixel Detector and the ITK, hybrid pixel modules will be used across multiple layers, enabling the measurement of passing particles' trajectories.

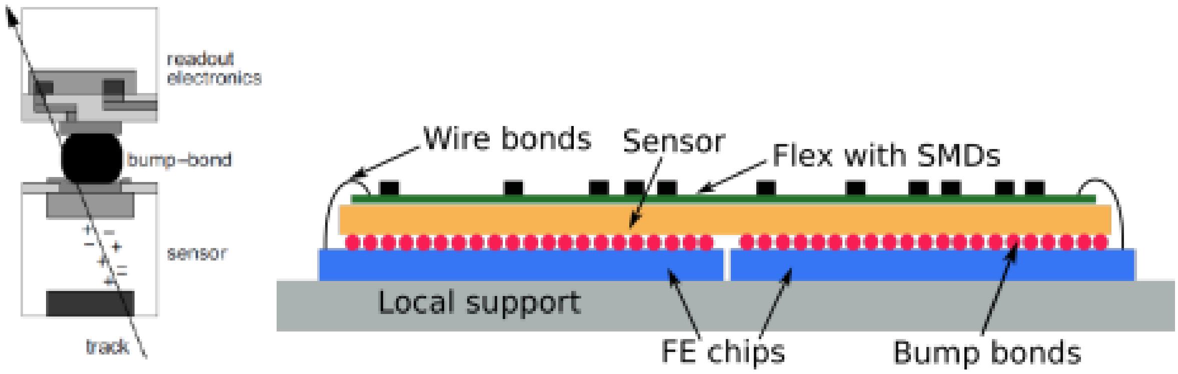


Figure 10: Left: A single pixel of a hybrid pixel detector with the active sensor volume where a passing particle creates an electron-hole pair and the bump bond connection to the readout chip [95]. Right: A pixel module with its components: sensor, readout chips and flex. The module is wire bonded and on a local support.

In Figure 10, one can see on the left a single pixel cell with a bump bond in between the bare sensor and the readout chip. The different doping which defines a pixel is indicated with different shades of grey. The bump bond is conductive material, either indium or tin-silver. On the right, a detector module with all of its components is shown. Additionally to the components in the figure on the left, the flex with its wire bond connections to the readout chips is shown. Also, the local support, a mechanical structure each module is connected to, is displayed.

The readout chips path comprises an analog and a digital part. The analog part consists of an amplifier and a threshold discriminator which generate a pulse with a pulse length proportional to the charge signal. As every pixel has its own readout but all pixels need to be comparable, the discriminator thresholds and the return to baseline of the amplifier need to be adjusted to equalise the pixel response. The digital part measures the pulse width. The processed data is passed to a buffer which is shared between several pixels. Also, in order to achieve the high bandwidth required in the detector, parallel readout is needed.

Chapter III:

Presentation of the Project

1) Project context and objective

The ITk (Inner Tracker) Pixel Detector is a critical component of the ATLAS detector upgrade at CERN, designed to enhance the performance of particle detection at the Large Hadron Collider (LHC). The pixel detector comprises approximately 10,000 pixel modules, each mounted onto carbon cooling structures for optimal thermal management.

The loaded quad modules, which are key elements of the pixel detector, include four front-end chips, a silicon sensor, and wire-bond protection. These modules are assembled onto thermally conductive support structures and undergo a rigorous series of inspections and tests to ensure their mechanical, visual, and electrical integrity.

A dedicated setup at CERN will be used to test the electrical properties of these loaded quad modules. Consequently, it is necessary to install, connect, and commission the testing setup. The goal of this project is to develop and operationalize this new setup, thereby enhancing the overall quality assurance process for the ITk pixel detector.

2) Gantt Diagram

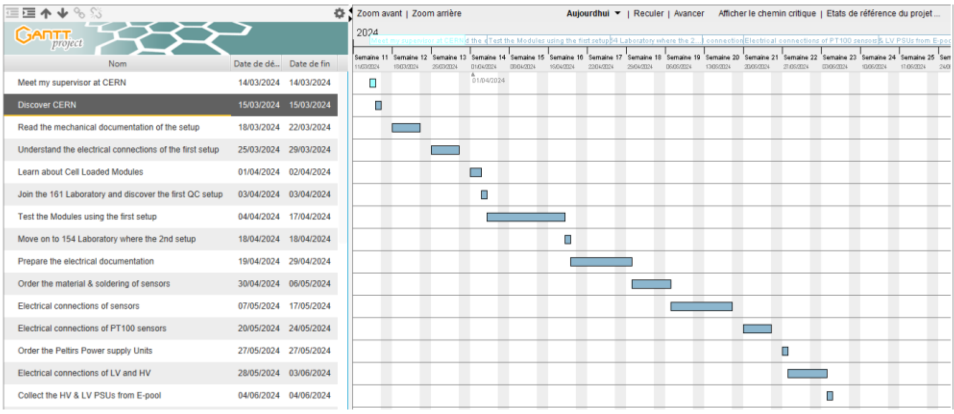


Figure 11: Diagram de Gantt (first part)

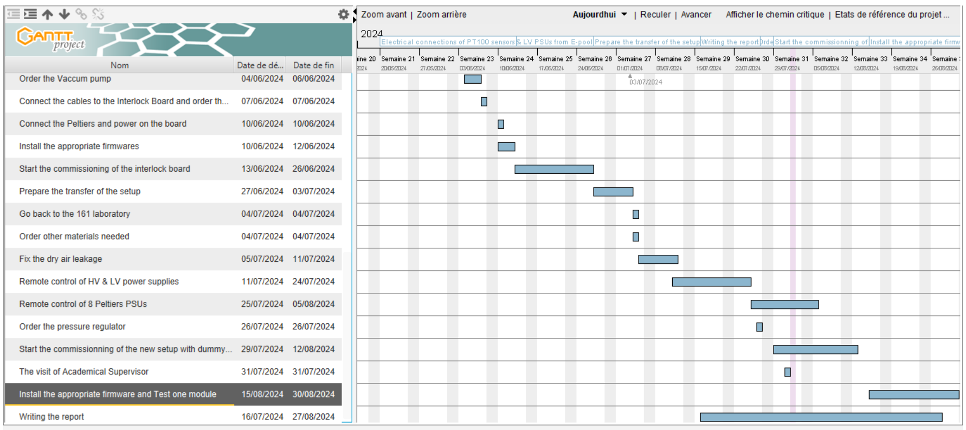


Figure 12: Diagram de Gantt (second part)

3) FAST (Function Analysis Systems Technique)

The FAST approach is a systematic method for analyzing and improving a project by breaking it down into functions, understanding their relationships, and optimizing them.

Application of the FAST approach to my project on commissioning a quality control setup for the ITk Pixel Detector and testing of modules performance.

- *Define the Project Scope and Objectives:*

  Objective: Commission and operationalize a testing setup for the electrical properties of loaded quad modules in the ITk Pixel Detector, ensuring enhanced quality assurance and reliable performance evaluation.

- *Identify the Functions:*

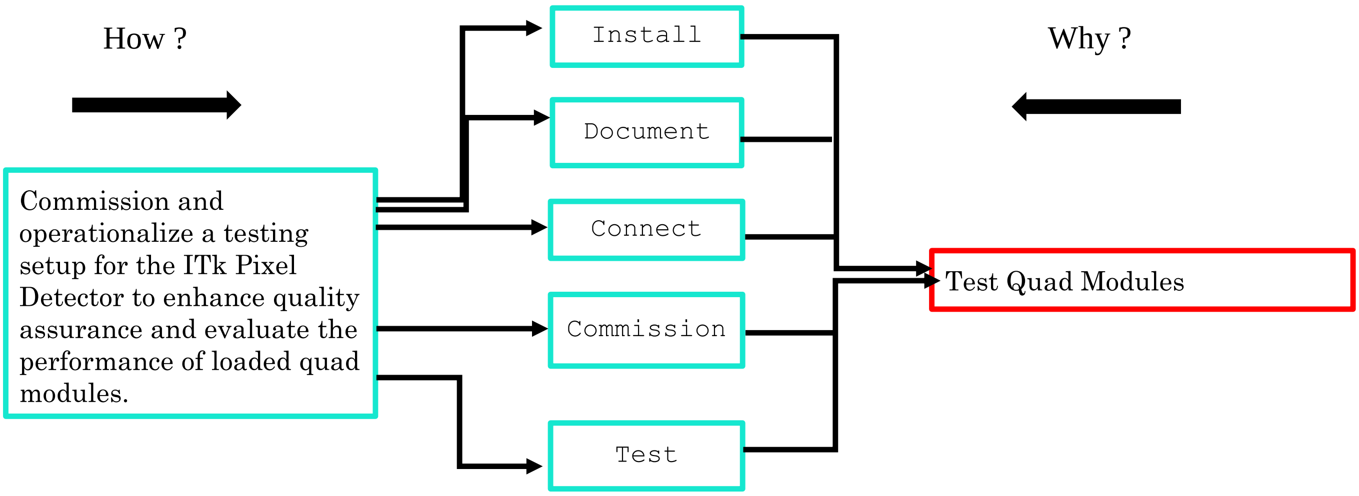
➢ **Primary Function:** Test Quad Modules: Ensure that the electrical properties and overall performance of loaded quad modules meet the required standards.

➢ **Secondary Functions:**

- **Install Setup:** Assemble and connect the necessary equipment.
- **Document Process**: Write documentations for future reference.
- **Connect Setup:** Integrate the electronic board developed at CERN.
- **Commission Setup:** Qualify the setup for accurate testing.
- **Conduct Tests:** Perform quality control tests on the modules.
- **Evaluate Performance:** Assess the performance of the modules based on test results.

- *Develop a FAST Diagram:*

  The FAST diagram helps visualize the relationships between the functions.



Chapter IV:

Hardware installation of the Quality Control setup and Software tests

1) Technical procedure to assemble the electronic part of the setup

To assemble the different components connected to the board developed for the interlocking and monitoring of the QC setup for ATLAS ITk Outer Barrel Cells, I had to write a completed technical documentation for reference. (For details, see annex).

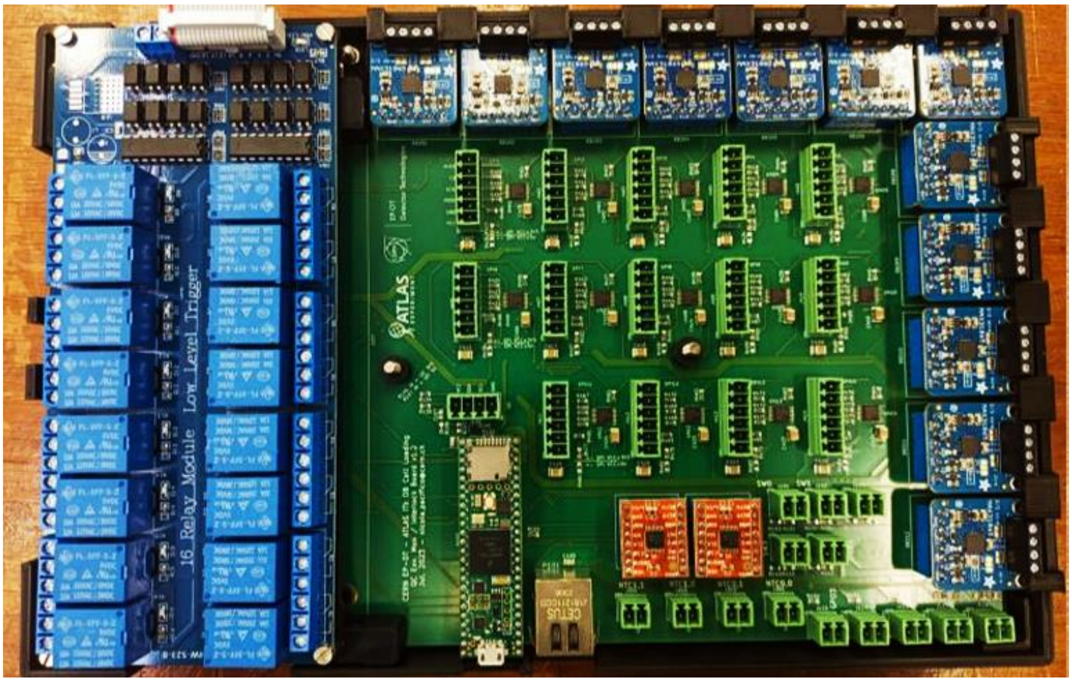


Figure 13: Interlock board with temperature sensors installed

- Wiring of SPI sensors (humidity and light sensors)

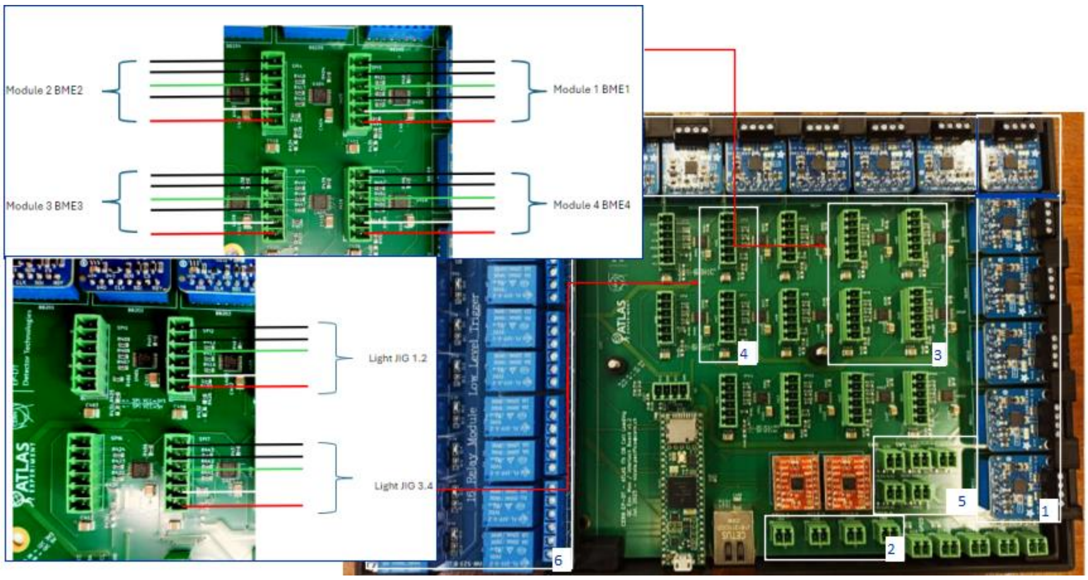


Figure 14: Wiring of humidity and light sensors

- Wiring of the switches and relay board

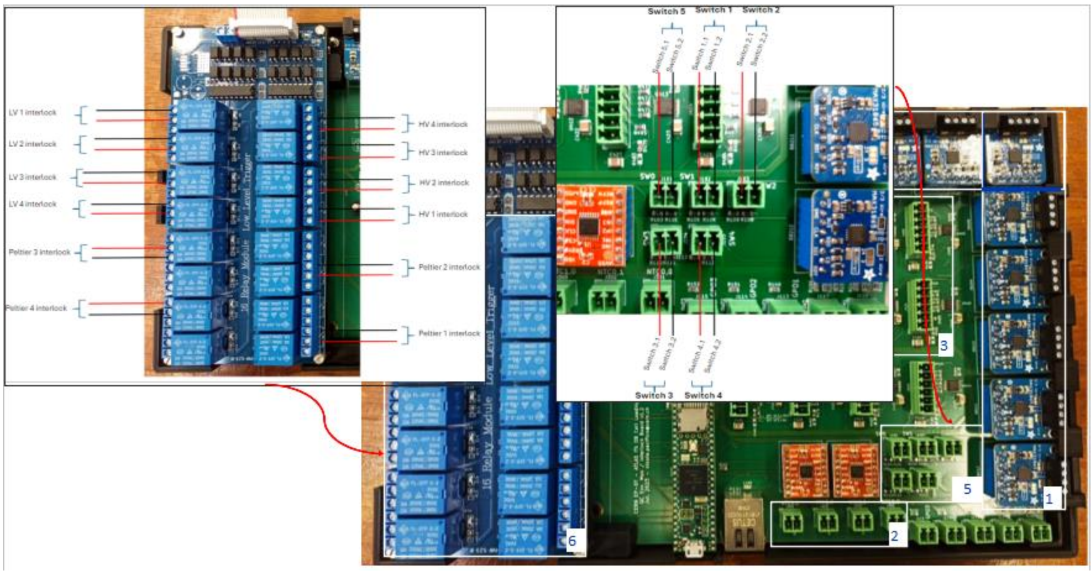


Figure 15: Wiring of switches connected to the covers of the setup and wiring of the relay that is connected to the different power supplies

2) Setup Installation

Preparation was required for some of the components. Cabling is as well was required to connect the inputs of the boards to the sensors and power supplies in the QC setup.
In this part, I had to assemble the necessary components for the quality control setup following the technical procedure that I had written. First, the setup should have multiple sensors installed inside, light and humidity sensors as well as temperature sensors. These sensors will be connected later to the electronic board developed previously at CERN.

Soldering of the different sensors:

The temperature sensors represent a key element of the setup, they are used to control the temperature of the four jigs of the setup. In total, the setup contains 12 temperature sensors.

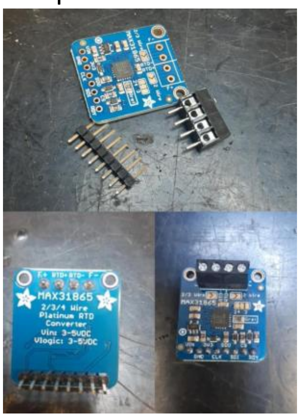


Figure 16: Temperature sensors

Figure 17: Humidity sensor

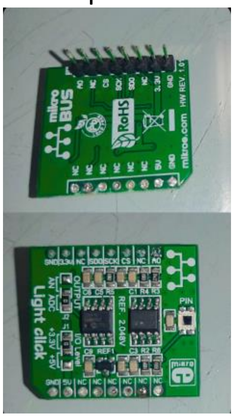


Figure 18: Light sensor

Installing sensors inside the box

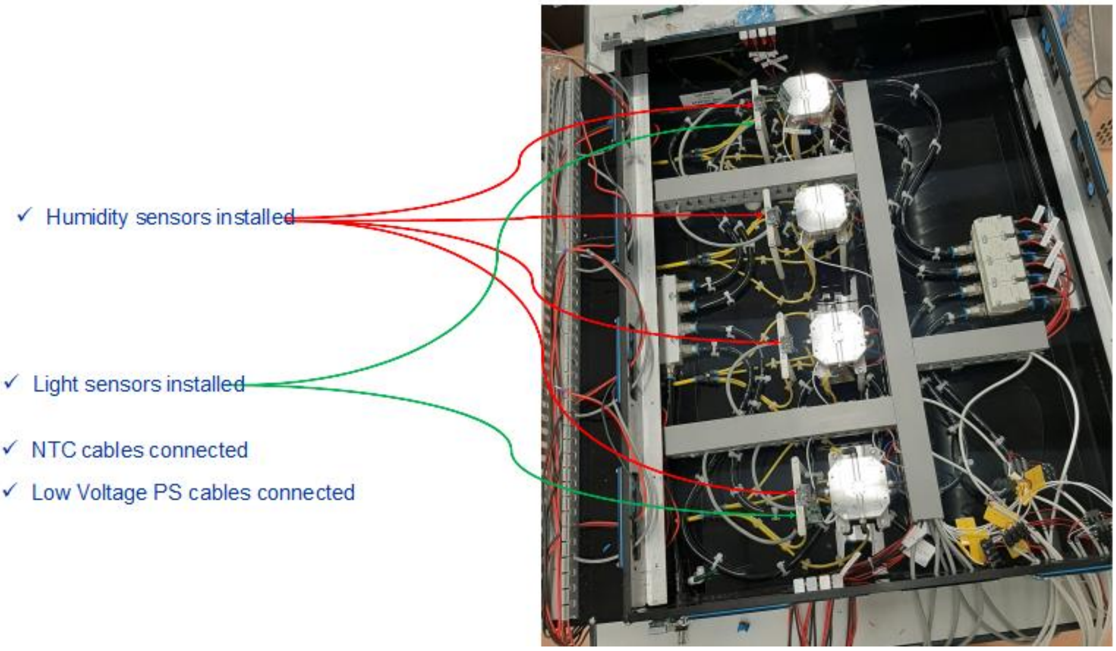


Figure 19: Humidity and light sensors installed inside the QC box

Installing sensors on the electronic board and connecting the cables coming from inside the setup

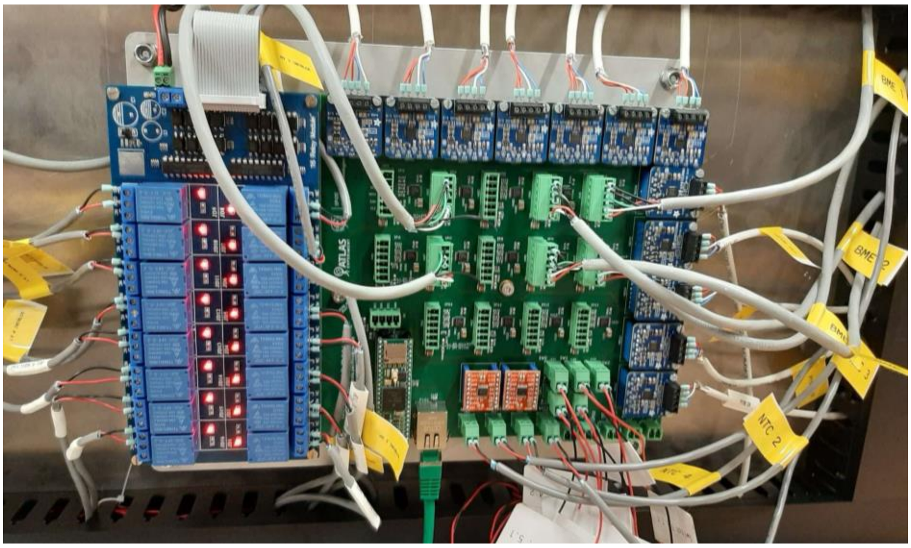


Figure 20: Temperature sensors installed and wired as well as LV and HV power supply cables

The next step was the electrical connections of the setup and powering of the electronic board. To do this, I had to prepare the appropriate electrical diagram.

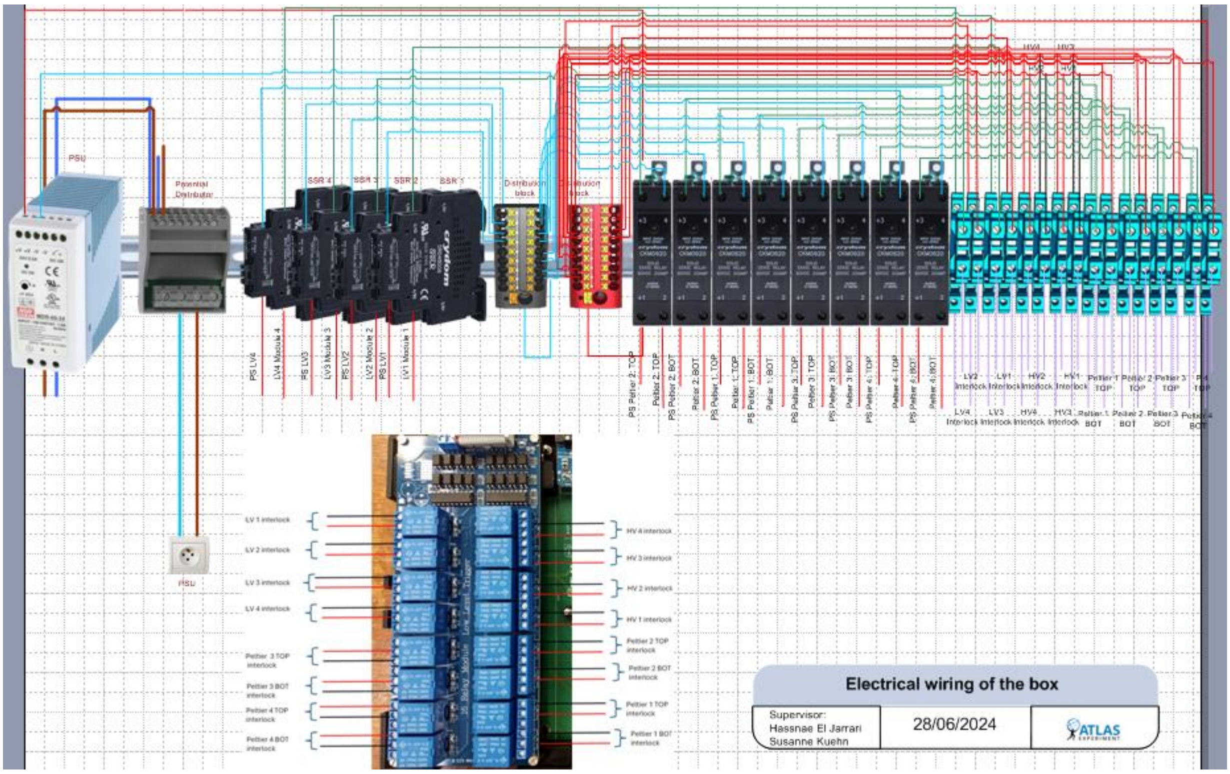


Figure 21: Electrical diagram ready to be implemented

After preparation of all the necessary materials for implementation of the diagram, I started the cabling of the different components. (See figure 22)

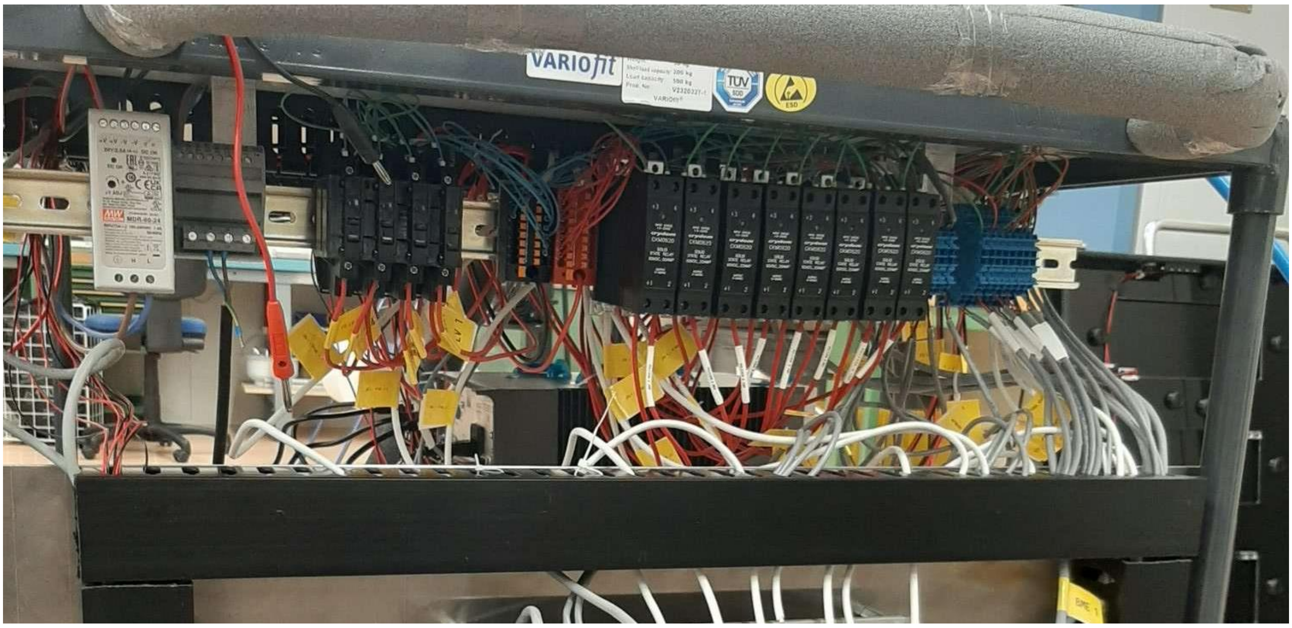


Figure 22: Implementation of the electrical diagram

The next phase consisted of collecting the power supplies necessary for the powering of the modules.

Figure 23: Preparation of Low voltage, High voltage, and Peltiers power supplies

Afterward, I installed the cooling system and other necessary infrastructure to maintain operational conditions during testing. Eventually, the installation of the setup and the connection of different parts was completed.

3) System Integration and Connection

At this level, I Integrated the testing setup with the existing CERN infrastructure, ensuring compatibility with existing systems and protocols. Then, I connected the setup to the data acquisition systems for real-time monitoring and analysis of test results. Afterwards, I had to implement necessary software and hardware interfaces to facilitate communication between the setup and CERN's central InfluxDB Database. (See annex)

4) Commissioning of the Quality Control Setup

- *Commissioning of the Interlock board*

After establishing the communication between the interlock board and the different parts (electronic components, electrical components…). I started the commissioning of the Interlock board system using the QC-Interlock software that was developed at CERN. This test bench aims at protecting modules during tests. It is made of a controller box which is the interlock board mentioned before, connected to a set of sensors and detectors, to collect bench monitoring data in real time, power supplies and other bench control instruments, to shut them OFF if a dangerous condition is met, a PC that runs the interlock GUI application, to display live data, configure the interlock box, reset interlocks, store monitoring data to InfluxDB database.

Figure 24: Site Qualification of the interlock board

The first part of the commissioning consists of conducting a series of warm and cold tests to validate the accuracy and reliability of the interlock board system.

- Test of left light sensors

At this level, I applied a source of light inside the box and I was testing if the interlock board will be triggered.

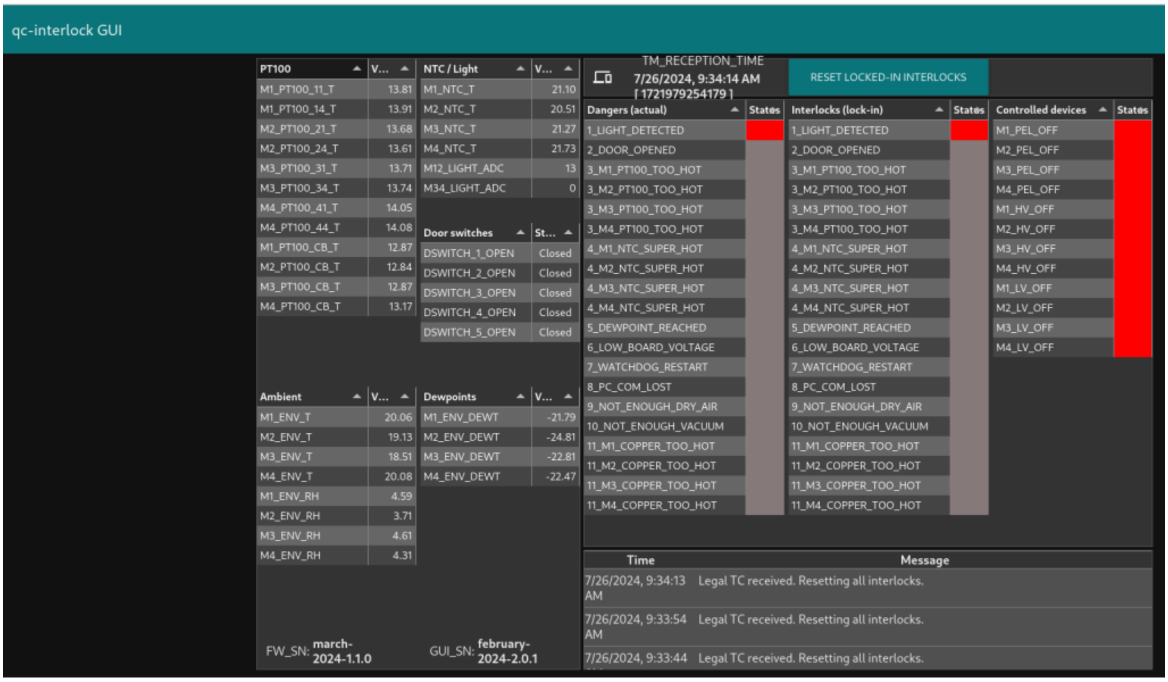


Figure 25: Interlock board triggered due to light detected inside the box

As a result, the power supplies were turned OFF to protect the modules. (See other tests in annex).

Description of setup

The QC setup is composed of 1 Low Voltage power supply, 4 High Voltage power supplies, 8 peltiers power supplies, chiller, Pump for vacuum, data boards, and power boards.

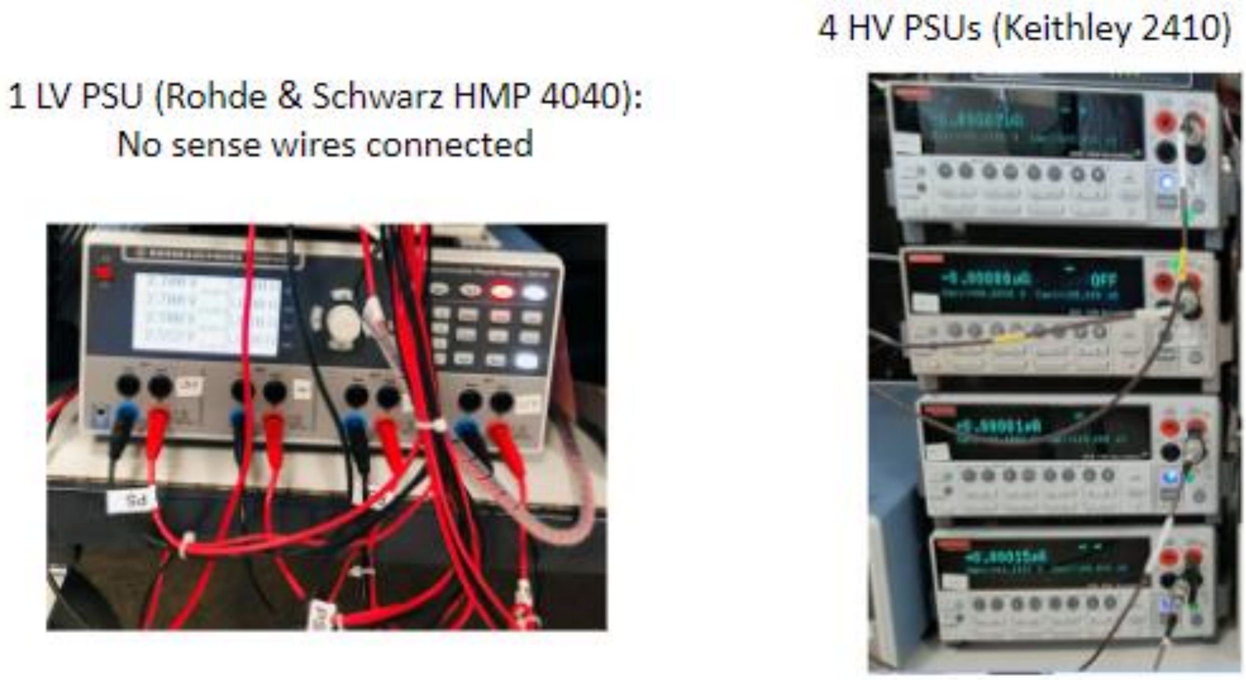


Figure 26: HV and LV power supply

- Cooling System

Figure30: Pump for vaccum

Figure 31: Chiller

Figure 32: 8 peltier PSUs (RND 320 – KWR103): Each jig has two (top and bottom)

- Vacuum and dry-air:

A vacuum pump is used to provide vacuum to the box and delivered to the 4 jigs for cell holding. A system provides the dry air to the box mainly for humidity reduction and to possibly flush each jig individually (a switch can be used to select vacuum, dry air or nothing)
Dew point is always monitored in 4 locations.

- Grounding scheme:

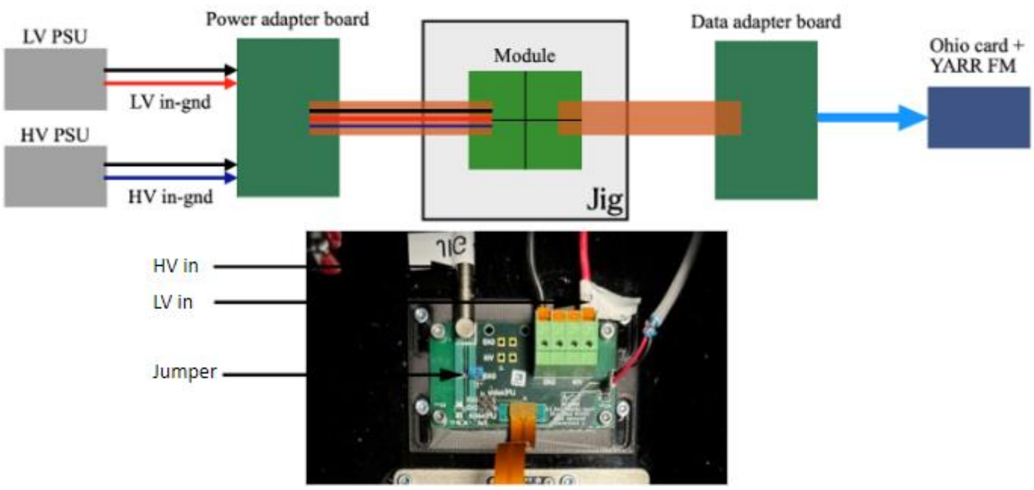


Figure 33: Grounding scheme

- ***Commissioning of the setup using a dummy cell:***

After validation of the appropriate work of the interlock board, I started the commissioning of the setup using a dummy cell. At this point, I tried to see the performance of the different power supplies and their response while using a dummy cell, and I established a baseline metrics with different values (Temperature of the jigs, humidity value, dew point, temperature of cupper block…) for future quality control assessments. (See annex)

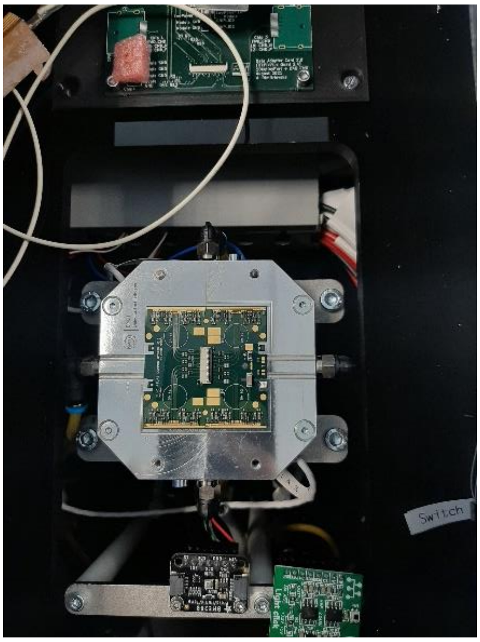


Figure 27: Dummy cell installed

- Cover switch test

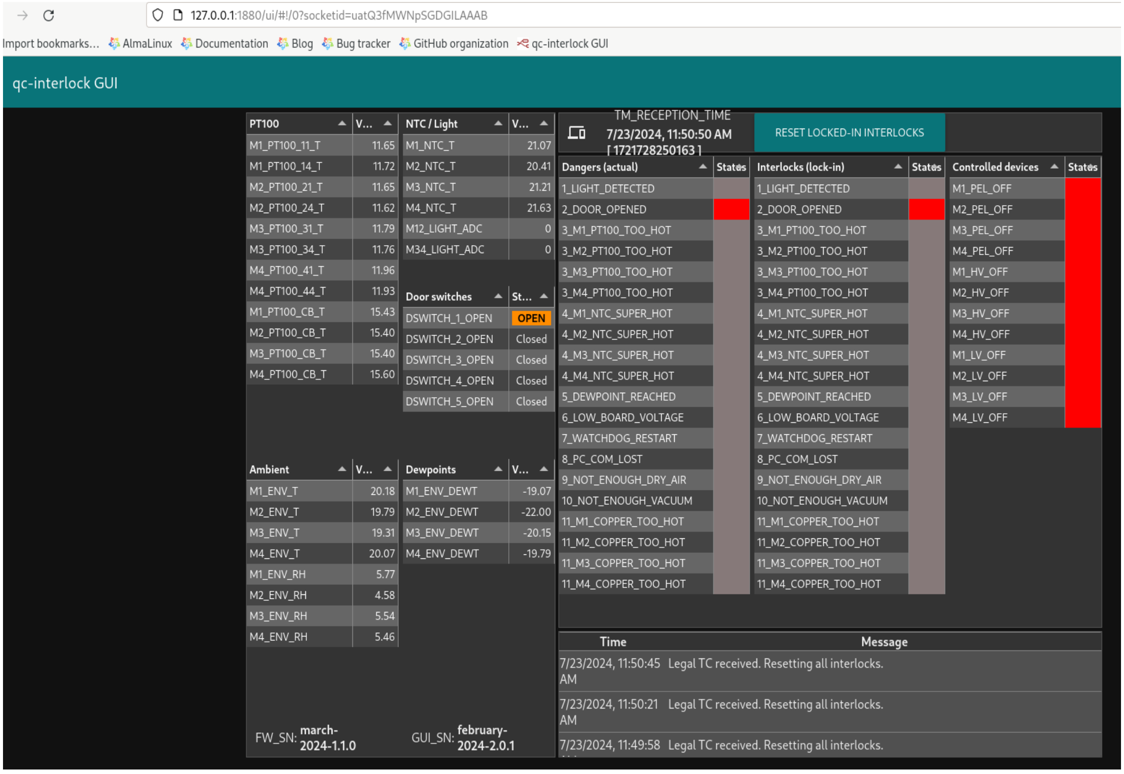


Figure 28: Interlock board triggered after detection of cover one been open

- ## *Commissioning of the setup using a Digital Quad module:*

At this point, I performed the initial quality control tests on a digital loaded quad module using the newly commissioned setup.

The module is handled with gloves at all time. Using temporary pigtails the module is installed in its carrier in loaded cell setup to perform minimum health tests.

Figure 29: Digital loaded quad module

- Electrical tests

The set-up used has 4 jigs. The results obtained in each location with the same digital module are presented here.

Each scan run with the YARR includes an efuses check of each enabled FE chip. It is performed at the beginning of the scan.

- ✓ Digital scan result for four jig positions

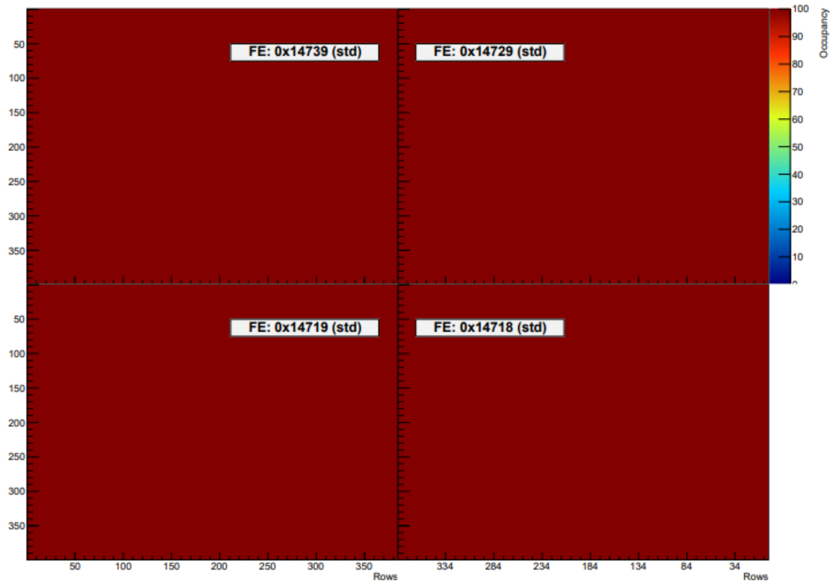


Figure 30: Digital scan

- ✓ Analog scan result for four jig positions

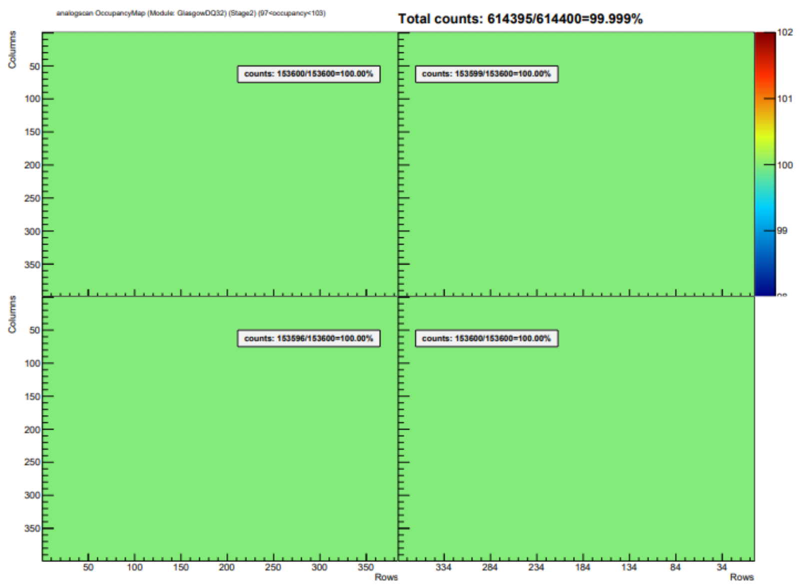


Figure 31: Analog scan

✓ Threshold Scan results

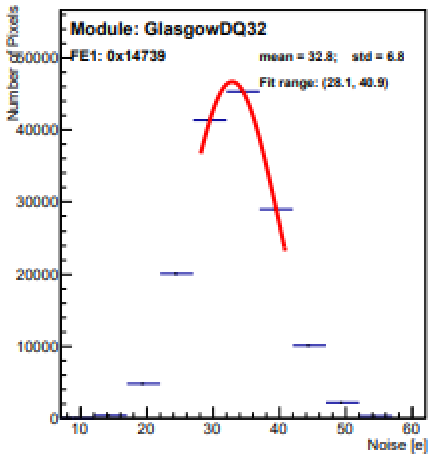


Figure 32: Threshold scan FE1

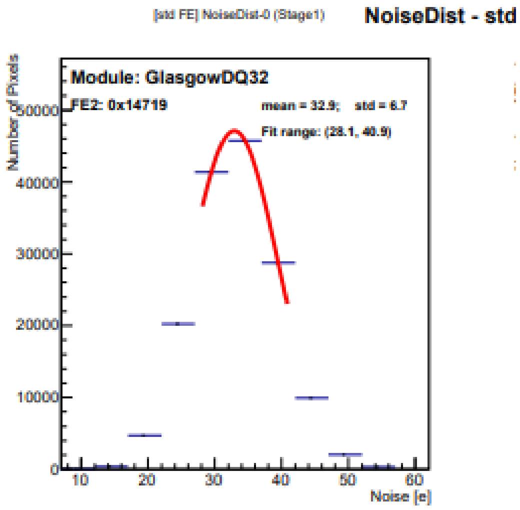


Figure 33: Threshold scan FE2

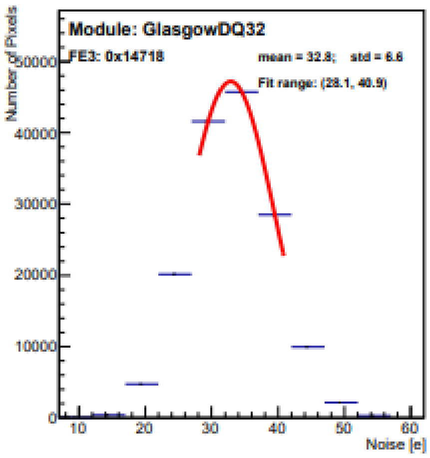


Figure 34: Threshold scan FE3

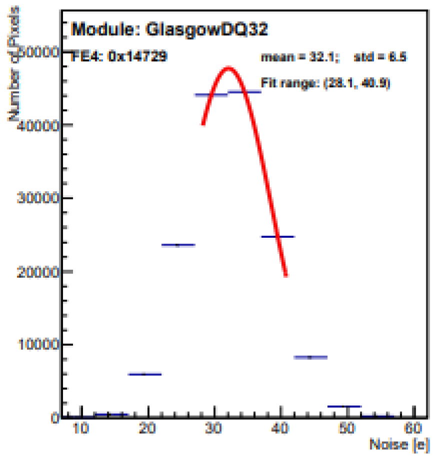


Figure 35: Threshold scan FE4

SUMMARY

The ITk (Inner Tracker) Pixel Detector is a crucial part of the ATLAS detector upgrade at CERN, aimed at enhancing particle detection at the Large Hadron Collider (LHC). The detector consists of around 10,000 pixel modules, with quad modules integrating four front-end chips and a silicon sensor. These modules are rigorously tested to ensure their mechanical, visual, and electrical integrity.

This project focuses on developing and commissioning a new quality control (QC) setup to test the electrical properties of the quad modules. The setup involves assembling components, connecting sensors, installing a cooling system, and integrating it with CERN's data acquisition and monitoring infrastructure. After assembling the necessary hardware and software, the setup is commissioned, beginning with the interlock board system that ensures module safety during testing by automatically shutting off power in dangerous conditions.

The commissioning process included tests with light sensors, which successfully triggered the interlock system, ensuring module protection. Subsequent tests involved validating the setup with a dummy cell and establishing baseline metrics like temperature and humidity for future assessments. The setup was further tested with a Digital Quad module to ensure reliable operation, conducting various electrical tests and scans to assess the module's performance across different jig positions.

I learned valuable skills throughout this project, including the detailed assembly and commissioning of sophisticated testing equipment, as well as integrating hardware and software systems with existing infrastructure. I gained hands-on experience in setting up and operating quality control systems, including conducting both warm and cold tests to validate the accuracy and reliability of interlock systems. Additionally, I developed expertise in establishing baseline metrics for future quality control and executing electrical tests on digital quad modules to assess performance across various conditions. This experience deepened my understanding of high-precision testing environments and the critical role of quality assurance in complex particle detection systems.

In summary, the project aims to ensure the proper functioning of the QC setup to guarantee the performance and safety of the ITk Pixel Detector modules.

ANNEX

Technical Procedure

Table of Contents

Figure 36: Technical procedure documented

Tableau 3: The interlock and monitoring board kit provided to the cell QC site

Quantity	Item description
1	Board
1	Teensy 4.1 microcontroller with headers
12	PT100 Module (MAX31865)
2	NTC Boards (ADS1220)
1	Spool 2 conductors cable
1	Spool 6 conductors cable
14	6 way screw terminal
14	2 way screw terminal
3	12 way crimp terminal
1	4 way screw terminal
1	Relay board
1	Relay board adapter
1	Flat cable assembly
1	Power supply

Figure 37: The considered parts of wiring the interlock board

Tableau 4: Connection map for the humidity sensor

BME280 connection map	
Breakboard	**Interlock**
VIN	VCC
3V0	-
GND	GND
SCK	SCK
SDO	MISO
SDI	MOSI
CS	CS

Tableau 5: Connection map for the light sensor

LightClick connection map	
Breakboard	**Interlock**
GND	GND
3.3v	VCC
SDO	MISO
SCK	SCK
CS	CS
-	MOSI

Hardware components:

Figure 38: Master controller of the interlock system (Teensy 4.1)

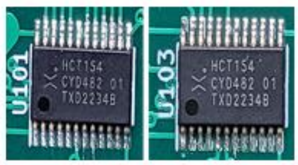
ADS1220 (ADCs for NTC readout)	
MAX31865 (ADCs for PT100 readout)	
Adafruit BME280 (Humidity, Temperature and Pressure readouts)	
Mikroe1424 (light readout)	

Figure 39:Sensors breakout boards

SRD(T73) 16 ch relay board

Figure 40: Relays breakout board

HCT154 (Decoder/demultiplexer)
Used to Chip Select the active device among multiple SPI peripherals by means of a smaller set of Teensy DO lines.
Previously "DM74154"



MCP23S18 (DO expander chip)
Used to control the 16 primary output relays by means of a smaller set of Teensy DO lines.

Figure 41: Main board components

System integration

Figure 42: Program for communication test

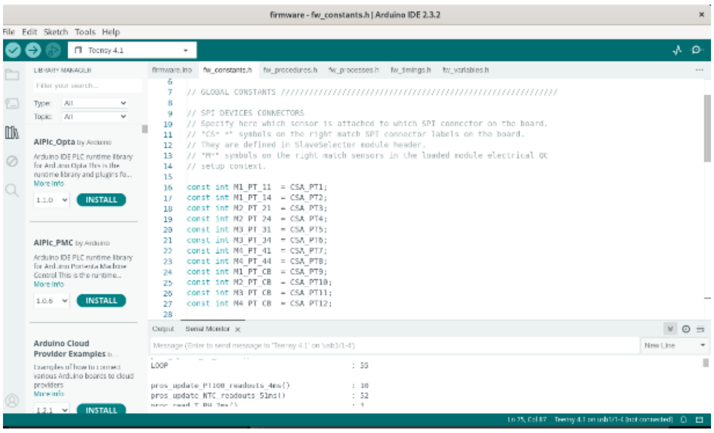


Figure 43: System integration

Commissioning of the Interlock board


Figure 44: Preparation of the setup for tests

- NTC tests:

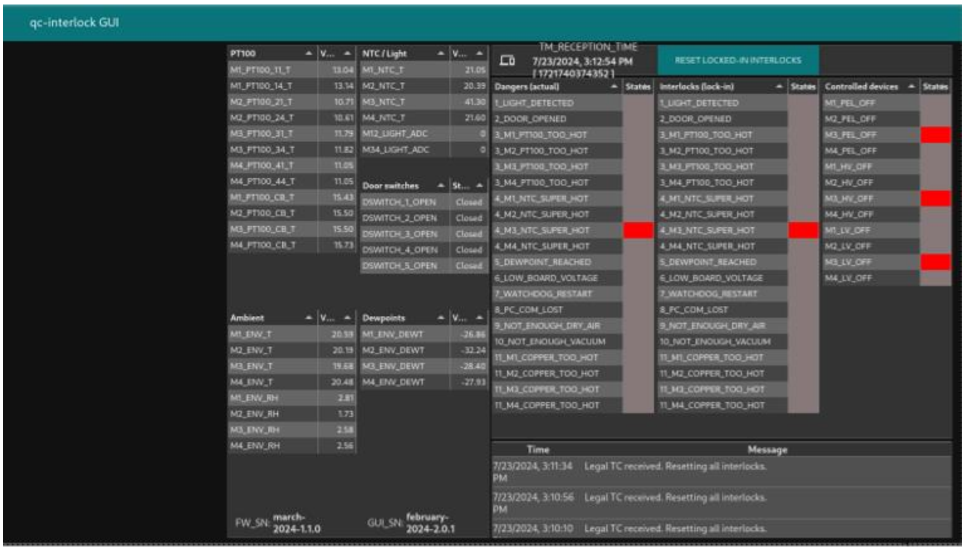


Figure 45: Interlock board triggered due to high NTC temperature

Figure 46: NTC 3 Interlock Propagation

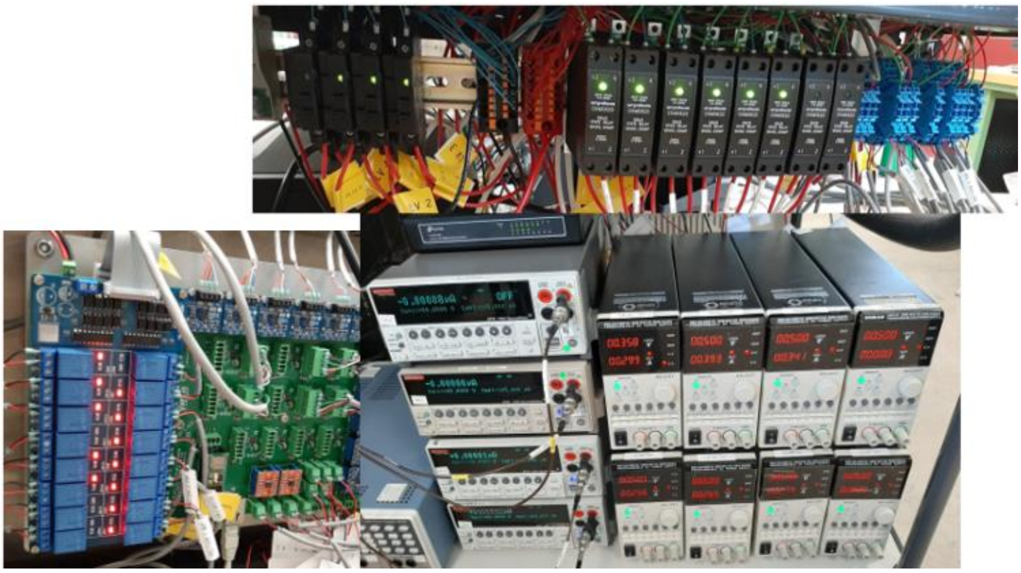


Figure 47: NTC 4 Interlock Propagation

- Low Voltage tests :

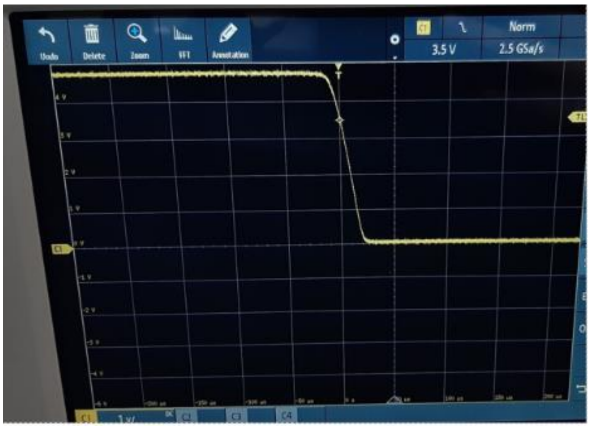


Figure 48: Low voltage of Jig 1 after the interlock has been triggered

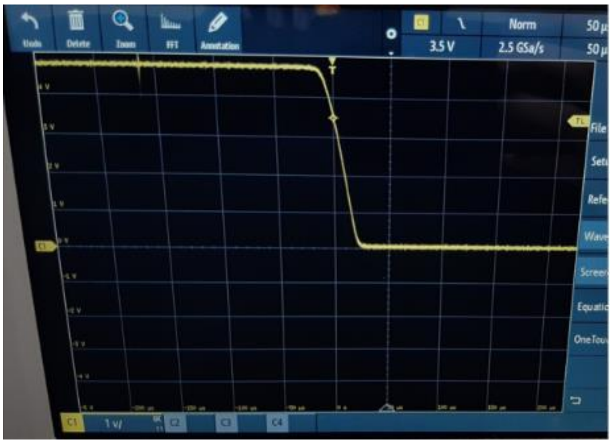


Figure 49: Low voltage of Jig 2 after the interlock has been triggered

Connection to the Influx DB

InfluxDB is an open-source time series database designed specifically to handle large volumes of time-stamped data, such as metrics, events, logs, and other time-based data. It's widely used for monitoring, analytics, and managing time series data in various fields, including IoT (Internet of Things), DevOps, and financial applications.

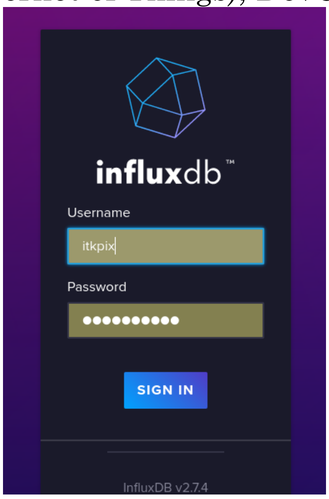


Figure 50: Connection of the PC connected to the interlock board using the itkpix account to log in the InfluxDB

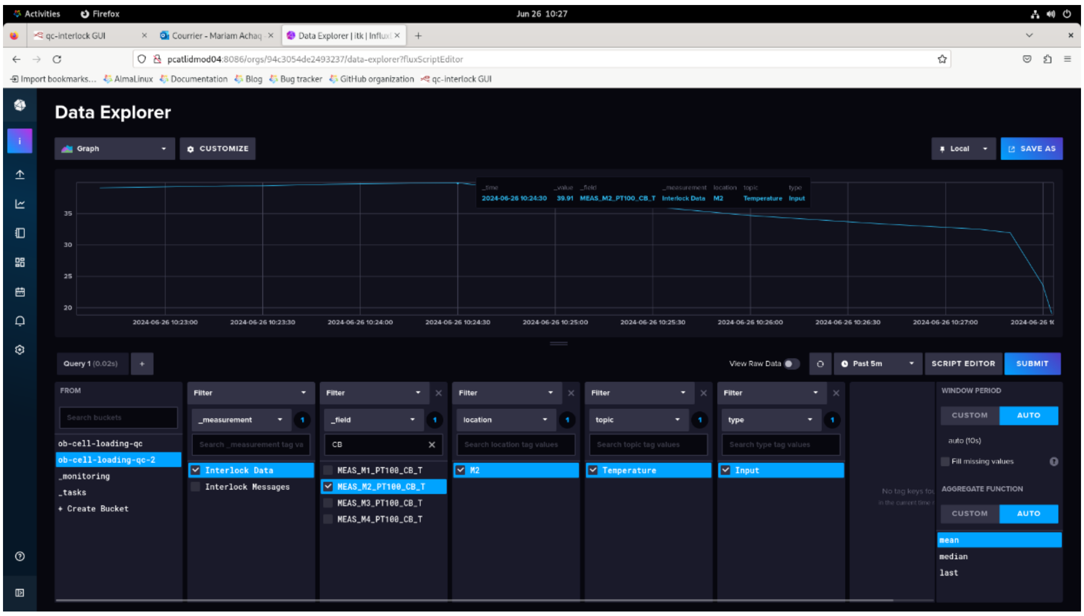


Figure 51: Connection etablished

Commissioning of the setup using a dummy cell


Figure 52: Applying thermal paste

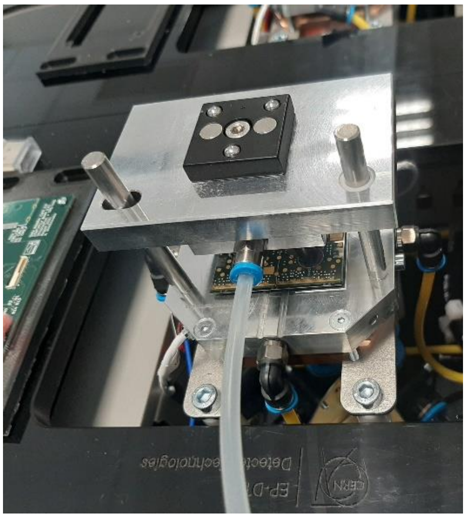


Figure 53: Installing the dummy cell

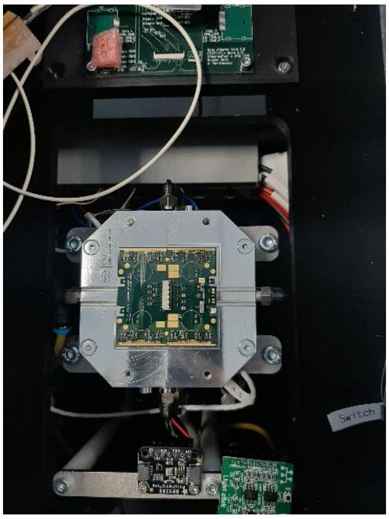


Figure 54: dummy cell fixes on the jig

Conducting tests with different Voltage values applied to the peltiers PSUs responsible for cooling the cell and taking measurements for the different parameters (for 4 positions)

First Conditions for tests				
Dew point (in C)	Chiller (in C)	Test number	Voltage of the **4 Bottom** Peltier module (in V)	Voltage of the **4 Top** Peltier module (in V)
		0	15V | 8.3A	4V | 4.1A
		1		4V | 4.2A
		2		5V | 4.9A
		3		6V | 5.7A
		4		7V | 6.4A
		5	16V | 8.7A	8V | 7.1A
		6		4V | 4.36A
		7		5V | 5.0A
		8		6V | 5.7A
		9		7V | 6.4A
		10	17V | 9.3A	8V | 7.1A
		11		4V | 4.2A
		12		5V | 4.9A
		13		6V | 5.7A
		14		7V | 6.4A
		15	18V | 9.8A	8V | 7.1A
		16		4V | 4.5A
		17		5V | 5.0A
		18		6V | 5.7A
		19		7V | 6.5A
		20	19V | 10.3A	8V | 7.2A
		21		4V | 4.2A
		22		5V | 5.0A
		23		6V | 5.8A
		24		7V | 6.5A
Below -25	22	25	20V | 10.9A	8V | 7.3A

	Position: jig2								
Test number	Dew point	Air pressure	NTC temperature	Humidity	Env temperature	Duration (minute	PT 1 temperatur	PT4 temperature	CB temperature
0	-32.73	1 bar	21.39	1.97	23.70	10 min	-17.93	-18.43	23.60
1	-31.33	1 bar	21.29	1.51	23.95	10 min	-20.67	-21.07	23.16
2	-28.77	1 bar	21.32	1.93	23.93	10 min	-18.10	-18.43	23.13
3	-30.46	1 bar	21.39	1.64	23.91	10 min	-19.60	-20.04	23.33
4	-30.39	1 bar	21.31	1.65	23.90	10 min	-19.70	-20.20	24.08
5	-28.91	1 bar	21.28	1.90	23.90	10 min	-18,33	-18.63	23.54
6	-28.58	1 bar	21.36	1.96	23.92	10 min	-18.03	-18.27	22.49
7	-31.13	1 bar	21.39	1.54	23.90	10 min	-20.14	-20.70	24.01
8	-35.02	1 bar	21.29	01.05	23.88	10 min	-24.30	-24.67	23.70
9	-32.96	1 bar	21.28	1.29	23.89	10 min	-21.90	-22.40	23.67
10	-32.58	1 bar	21.37	1.34	23.92	10 min	-21.70	-22.10	24.31
11	-33.65	1 bar	21.29	1.20	23.96	10 min	-19.27	-19.40	22.39
12	-34.15	1 bar	21.29	1.13	24.11	10 min	-22.74	-23.20	24.25
13	-33.40	1 bar	21.39	1.22	24.07	10 min	-22.64	-23.17	24.31
14	-37.25	1 bar	21.39	0.84	23.96	10 min	-26.10	-26.54	24.31
15	-31.97	1 bar	21.30	1.43	23.83	10 min	-21.34	-21.64	24.11
16	-26.30	1 bar	21.38	2.81	22.21	10 min	-16.23	-15.99	24.28
17	-27.19	1 bar	21.30	2.58	21.36	10 min	-16.80	-16.43	23.23
18	-27.68	1 bar	21.28	2.46	21.56	10 min	-17.63	-17.46	24.52
19	-28.08	1 bar	21.39	2.38	21.49	10 min	-18.07	-17.70	23.77
20	-29.23	1 bar	21.29	2.13	21.52	10 min	-18.77	-18.50	24.69
21	-30.20	1 bar	21.39	1.94	21.56	10 min	-19.84	-19.60	24.52
22	-28.73	1 bar	21.39	2.17	22.02	10 min	-18.57	-18.20	24.28
23	-30.20	1 bar	21.39	1.88	22.03	10 min	-20.14	-19.67	23.81
24	-31.12	1 bar	21.34	1.73	22.02	10 min	-21.07	-20.54	23.98
25	-31.47	1 bar	21.39	1.61	22.56	10 min	-21.04	-20.67	24.86

Figure 55: Test conducted on jig 2

First Conditions for tests				
Dew point (in C)	Chiller (in C)	Test number	Voltage of the **4 Bottom** Peltier module (in V)	Voltage of the **4 Top** Peltier module (in V)
		0	15V | 8.3A	4V | 4.1A
		1		4V | 4.2A
		2		5V | 4.9A
		3		6V | 5.7A
		4		7V | 6.4A
		5	16V | 8.7A	8V | 7.1A
		6		4V | 4.36A
		7		5V | 5.0A
		8		6V | 5.7A
		9		7V | 6.4A
		10	17V | 9.3A	8V | 7.1A
		11		4V | 4.2A
		12		5V | 4.9A
		13		6V | 5.7A
		14		7V | 6.4A
		15	18V | 9.8A	8V | 7.1A
		16		4V | 4.5A
		17		5V | 5.0A
		18		6V | 5.7A
		19		7V | 6.5A
		20	19V | 10.3A	8V | 7.2A
		21		4V | 4.2A
		22		5V | 5.0A
		23		6V | 5.8A
		24		7V | 6.5A
Below -25	22	25	20V | 10.9A	8V | 7.3A

	Position: jig4								
Test number	Dew point	Air pressure	NTC temperature	Humidity	Env temperature	Duration (minute	PT 1 temperatur	PT4 temperature	CB temperature
0	-26.32	1 bar	21.22	2.69	22.14	10 min	-16.30	-16.36	22.52
1	-27.59	1 bar	21.43	2.41	22.04	10 min	-17.66	-17.66	22.69
2	-27.96	1 bar	21.35	2.20	21.93	10 min	-17.83	-17.96	22.49
3	-28.18	1 bar	21.43	2.30	21.90	10 min	-18.20	-18.27	23.30
4	-28.50	1 bar	21.42	2.23	21.88	10 min	-18.30	-18.40	22.69
5	-29.96	1 bar	21.21	1.89	22.32	10 min	-19.84	-19.97	23.40
6	-30.22	1 bar	21.40	1.86	22.21	10 min	-20.10	-20.20	23.27
7	-30.41	1 bar	21.36	1.83	22.19	10 min	-20.20	-20.23	23.27
8	-30.55	1 bar	21.31	1.81	22.18	10 min	-20.50	-20.57	23.33
9	-30.67	1 bar	21.30	1.78	22.19	10 min	-20.47	-20.57	23.43
10	-30.78	1 bar	21.44	1.76	22.22	10 min	-20.57	-20.67	23.54
11	-30.89	1 bar	21.21	1.74	22.25	10 min	-20.70	-20.77	23.40
12	-31.01	1 bar	21.42	1.72	22.26	10 min	-20.87	-20.97	23.50
13	-31.07	1 bar	21.26	1.71	22.27	10 min	-20.97	-21.14	22.79
14	-31.20	1 bar	21.25	1.69	22.28	10 min	-21.14	21.24	23.64
15	-31.26	1 bar	21.42	1.68	22.30	10 min	-21.20	-21.27	23.81
16	-31.44	1 bar	21.22	1.64	22.33	10 min	-21.27	-21.40	22.93
17	-31.51	1 bar	21.42	1.63	22.33	10 min	-21.00	-21.10	23.64
18	-31.98	1 bar	21.43	1.55	22.38	10 min	-21.97	-22.04	23.70
19	-31.92	1 bar	21.43	1.55	22.48	10 min	-21.77	-21.87	23.84
20	-32.07	1 bar	21.39	1.54	22.35	10 min	-21.97	-22.04	23.84
21	-32.12	1 bar	21.19	1.54	22.28	10 min	-22.10	-22.20	23.70
22	-32.23	1 bar	21.21	1.53	22.22	10 min	-22.24	-22.27	23.74
23	-32.31	1 bar	21.40	1.52	22.20	10 min	-22.27	-22.34	23.91
24	-32.29	1 bar	21.43	1.51	22.19	10 min	-22.24	-22.30	24.01
25	-32.47	1 bar	21.44	1.46	22.67	10 min	-22.37	-22.44	24.14

Figure 56: Test conducted on jig 4