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Title of the thesis:

***THERMAL QUALITY CONTROL FOR THE UPGRADE OF THE
CMS TRACKER STRUCTURE FOR THE LHC HIGH LUMINOSITY
PHASE BASED ON ADVANCED CO₂ TWO-PHASE COOLING
SYSTEM***

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“The journey of self-discovery can be filled with countless challenges, but you must undertake it on your own, without avoiding obstacles.

Seek your path alone, change it whenever you wish and follow your dreams.

Do not let education, habits or your own preconceived notions become a prison.

Always have the courage to change yourself, your ideas, your approach and your perspective, because it is the only way to change the things that aren't right and to improve your life and the lives of many others.

And as you search for your path, keep in mind who you want to become. Think about the mark you want to leave, the difference you want to make.

Stay ambitious in your goals, because resigning yourself to a mediocre life is never worth it.”

Sergio Marchionne

Trento, 02-10-2017

Overview – CERN technical student program

This report represents the thesis work completed as part of my Master's degree in Mechanical Engineering with a specialization in Energy, which I pursued during the academic years 2022/2023 and 2023/2024 at the University of Perugia, Department of Engineering. More broadly, this work encompasses a portion of the knowledge I have gained over my five years of study within the Faculty of Mechanical Engineering, where I earned also my Bachelor's degree in Mechanical Engineering during the academic years 2019/2020, 2020/2021 and 2021/2022.

The thesis presented falls within the topics explored in the course on Thermofluid Dynamics and Thermotechnical Systems, with a particular focus on the module of thermofluid dynamics taught by Prof. Giorgio Baldinelli (University of Perugia). In this course, we had the opportunity to delve deeper into heat transfer and applied thermofluid dynamics, particularly in relation to mechanical engineering problems, with a strong emphasis on two-phase flows, a subject of great personal interest. I was fortunate to explore this area further through a 14-month experience at CERN in Geneva, having been selected for the Technical Student Programme. This programme, organized by the world's largest particle physics laboratory, offers university students from various scientific disciplines the opportunity to contribute to the extremely challenging projects currently underway at CERN.

The activities I carried out during this period will be briefly introduced in the introduction of the thesis and further developed in the various chapters. In addition to the 14-month experience, I also participated in three university missions between May and August 2023. These missions, conducted under the valuable guidance of my co-supervisor, Dr. Eng. Francesco Bianchi (University of Perugia), aimed to further immerse me in this field and facilitate the transition to the primary responsibilities I assumed during my work period. These missions were conducted through INFN (National Institute for Nuclear Physics) Perugia section, where I have been an associate student since July 2024.

During my time at CERN, I had the privilege of being initially supervised by Eng. Thomas French (Oxford University) and later directly by Dr. Duccio Abbaneo (Scuola Normale Superiore di Pisa), the coordinator of the entire CMS Tracker upgrade project. The synergy between the Department of Engineering at the University of Perugia, INFN and CERN is a long-standing collaboration, particularly in the area of thermal management, a topic I had the fortune to study during my university courses and later apply in my work. At CERN, I was able to deepen my understanding of advanced engineering concepts related to quality control and thermal management. I had access to cutting-edge machinery and the expertise of world-class professionals, all of which were indispensable for the "success" of the research. This experience not only enhanced my technical skills but also profoundly shaped my personal and professional development. It provided me with a unique opportunity to work in a challenging, interdisciplinary environment, pushing me to think critically and creatively. Furthermore, it aligns perfectly with the overarching mission behind every project developed at CERN: to continually push the boundaries of knowledge and innovation, striving to break new ground in science and technology.

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1. Introduction

The focus of this work is the thermal quality control of the structures for the future CMS tracker, which is currently under production in preparation for the Phase-2 Upgrade of the Large Hadron Collider (LHC). This upgrade is designed to enhance the performance of the CMS detector, making the validation and optimization of cooling systems critical to ensure the proper functioning of the electronic modules that house the silicon sensors of the tracker.

Efficient cooling systems are essential, not only in high-energy physics but also in modern electronics in general [1]. As power density increases and components become more miniaturized, effective cooling becomes crucial to prevent thermal runaway and to maintain stable performance over time. In this context, two-phase cooling systems, especially those using CO₂, offer several advantages. These include high heat transfer efficiency and the ability to miniaturize cooling circuits, making them well-suited for complex applications. This is why, even at CERN, the largest high-energy physics laboratory in the world, two-phase CO₂ systems are already widely used, particularly in the CMS detector, to provide the cooling power density required to maintain optimal temperatures in the tracker modules and other critical components.

To better understand the effectiveness of these systems, it's useful to compare the heat transfer coefficients (HTC) of different cooling approaches. Natural convection systems typically have an HTC ranging from 5 to 25 W/m²K, while forced convection systems have HTC values between 50 and 250 W/m²K. For liquid-based systems using non-metallic coolants such as water or glycol, the HTC can range between 500 and 2000 W/m²K, depending on operational conditions. Metallic liquids, like lead or sodium, used in next-generation nuclear reactors for instance, can surpass 10000 W/m²K due to their superior thermal properties. However, these systems have significant limitations in applications where maintaining constant temperatures is critical, minimizing the mass of the coolant is necessary or achieving high compactness is essential. Additionally, they require high flow rates, which makes them less practical for high-density electronics cooling, where miniaturization and precise temperature control are vital.

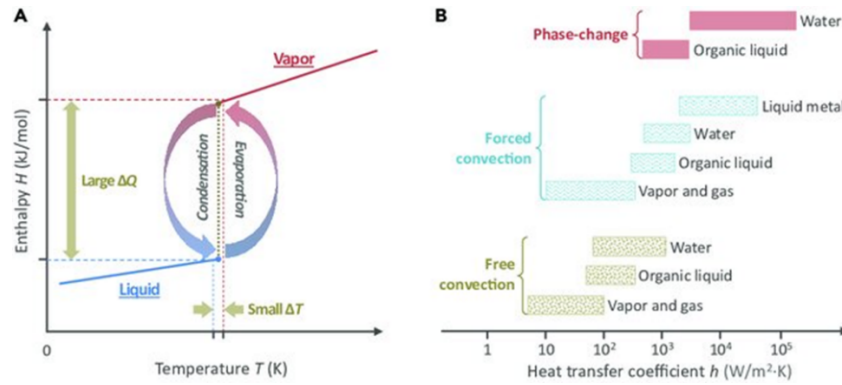


Figure 1 - Liquid-vapor phase-change heat transfer and heat transfer coefficients (HTCs) of phase-change and single-phase convection heat transfer. (A) Liquid-vapor phase-change processes: a large amount of latent heat is absorbed or released under a small temperature difference during the phase transition of the fluids. (B) Comparison of the HTCs for single-phase convection and phase-change heat transfer processes. Due to a large amount of absorbed or released latent heat, the HTCs of liquid-vapor phase-change processes far exceed that of single-phase convection heat transfer. [2]

In contrast, two-phase cooling systems can reach HTCs exceeding 2000 W/m²K, depending on vapor quality and operating conditions. This significant difference highlights the potential interest in studying two-phase cooling solutions, such as CO₂-based systems, which provide high cooling power densities in compact spaces, making them a promising technology for the future of electronics cooling.

Table 1 – HTC values for typical cooling systems [3].

Typical values of the convective heat transfer	
Process	h ($\text{W}/\text{m}^2 \cdot \text{K}$)
Free convection	
Gases	2 - 20
Liquids	50 - 1000
Forced convection	
Gases	25 - 300
Liquids	100 - 40,000
Convection with phase change	
Boiling or condensation	2500 - 100,000

Throughout this thesis, several case studies will be presented, focusing on experimental setups used to test the performance of these two-phase CO₂ cooling systems. These studies represent innovative contributions to the quality control of high-energy physics detectors and provide an in-depth analysis of the benefits of using CO₂ as a refrigerant in high-energy-density applications.

One of the key contributions of this work will be the detailed analysis of the thermal quality control procedures and test setups used for the tracker structures, specifically the TBPS rings (chapter 4) and the TB2S ladders (chapter 5). The TBPS ring test setup was developed before my arrival at CERN, but it became operational during my training period in the summer of 2023. On the other hand, the TB2S ladder test setup is more recent, and it was designed and implemented by me, with the valuable help of my colleagues. This setup was used to test the first TB2S ladders produced, not only under operating conditions but also fully integrated with real modules.

An important analysis of CO₂ behavior as a two-phase fluid will be presented in the chapter on HTC studies (chapter 6), an inherently challenging subject due to the high level of precision required when evaluating this parameter. The complexity arises particularly in the initial phases of boiling, where the transition from subcooled liquid, to superheating and finally to nucleate boiling is difficult to predict accurately and even more challenging to measure in terms of HTC. This topic is crucial because understanding the thermal dynamics in these phases is essential for optimizing cooling performance in compact, high-power-density systems.

In the final chapter, the thesis will cover the methodologies used to validate the design of a crucial cooling loop component: the preheater (Chapter 7). This component is a key element of the innovative cooling system inside the detector, which prevents subcooling and superheating, ensuring optimal thermal performance for modules at the beginning of the cooling loop. This requires a specific performance analysis, as the preheater is one of the components where the highest heat flux is dissipated within the cooling system, reaching values as high as 255000 W/m².

In conclusion, this report, written at the end of a 14-month Technical Student contract at CERN, aims to serve as a useful reference for the continuation of the testing activities that will take place throughout the tracker's production phase. It will provide procedures and guidelines that can be shared with future Technical Students, introducing them to the techniques of thermal quality control and two-phase CO₂ cooling system testing. In addition to focusing on the technical aspects of thermal quality control, this thesis will also provide practical guidance for future users of the various test setups and machinery located in the Lyon Cold Room at CERN's Building 186, where I had the pleasure of working and learning a great deal during my time there. The hands-on experience I gained in this environment played a critical role in my understanding of cooling systems and experimental procedures, which will be detailed throughout the thesis. Among the most innovative contributions of this thesis are the quality control procedures applied to high-energy physics detectors, the use of two-phase systems and particularly the employment of CO₂ as a refrigerant, which can ensure high performance and cooling density in advanced applications.

2. CERN

Particle physics or high-energy physics is the study of the fundamental particles and forces that make up matter and radiation. The field also explores combinations of elementary particles up to the scale of protons and neutrons, while the study of combinations of protons and neutrons is called nuclear physics. In this context, particle accelerators and particle detectors are the tools that allow scientists to carry out experimental research, enabling humanity to expand its knowledge and seek answers to the fundamental questions about the Universe.

The CERN (European Organization for Nuclear Research) is one of the world's leading laboratories dedicated to the study of high-energy physics and it houses the largest particle accelerator ever built: the LHC, or Large Hadron Collider.

CERN was founded in 1954, in the aftermath of World War II, with the goal of restoring scientific excellence to Europe and fostering peaceful collaboration in fundamental research. This collective effort has pushed the frontiers of human knowledge and technology. As more powerful accelerators and experiments were developed, significant discoveries and innovations followed: the multiwire proportional chamber was invented in 1968, neutral currents were discovered in the 1970s, the W and Z bosons were discovered in 1983, the precision measurement of the Z boson and other electroweak theory parameters were achieved in the 1990s through the Large Electron Positron (LEP) collider, the Large Hadron Collider (LHC) began operations in 2009 and the Higgs boson was discovered in 2012. CERN is also the birthplace of the World Wide Web, and it has produced technologies that are applied in other fields, such as medical diagnostics and treatment, and environmental protection [4].

Today, CERN has 23 Member States, 10 Associate Member States and a community of 17000 people from over 110 nationalities. The Laboratory continues to be home to the Large Hadron Collider, the most powerful particle accelerator in the world. Building on its rich legacy of research and technological development, CERN is already looking towards the future, particularly through its exploration of the Future Circular Collider.

CERN was established not only as a research centre but with broader and more visionary objectives. Four key missions define this great organization [5]:

1. Conduct world-class research in fundamental physics.
2. Provide a unique range of particle accelerator facilities that enable research at the cutting edge of human knowledge in an environmentally responsible and sustainable way.
3. Bring together people from all over the world to advance science and technology for the benefit of all.
4. Train new generations of physicists, engineers and technicians, and engage the public in research and scientific values.

Among these, it is point 4 that includes programs like the Technical Student Program, which offers students the opportunity to immerse themselves in this world. The goal is to learn and expand their knowledge, which they can then contribute to CERN or share with the industrial and commercial sectors.



Figure 2- "Family picture" taken on the occasion of CERN's 70th anniversary [6].

2.1 LHC and CMS experiment at CERN

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-kilometre ring of superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way (figure 3).

Inside the accelerator, two high-energy particle beams travel at close to the speed of light before they are made to collide. The beams travel in opposite directions in separate beam pipes, two tubes kept at ultrahigh vacuum. They are guided around the accelerator ring by a strong magnetic field maintained by superconducting electromagnets. The electromagnets are built from coils of special electric cable that operates in a superconducting state, efficiently conducting electricity minimizing resistance or loss of energy. This requires chilling the magnets to -271.3°C , a temperature colder than outer space. For this reason, much of the accelerator is connected to a distribution system of liquid helium, which cools the magnets, as well as to other supply services [7].

The accelerator complex at CERN is a succession of machines that accelerate particles to increasingly higher energies. Each machine boosts the energy of a beam of particles before injecting it into the next machine in the sequence. In the Large Hadron Collider (LHC), the last element in this chain, particle beams are accelerated up to the record energy of 6.5 TeV per beam.

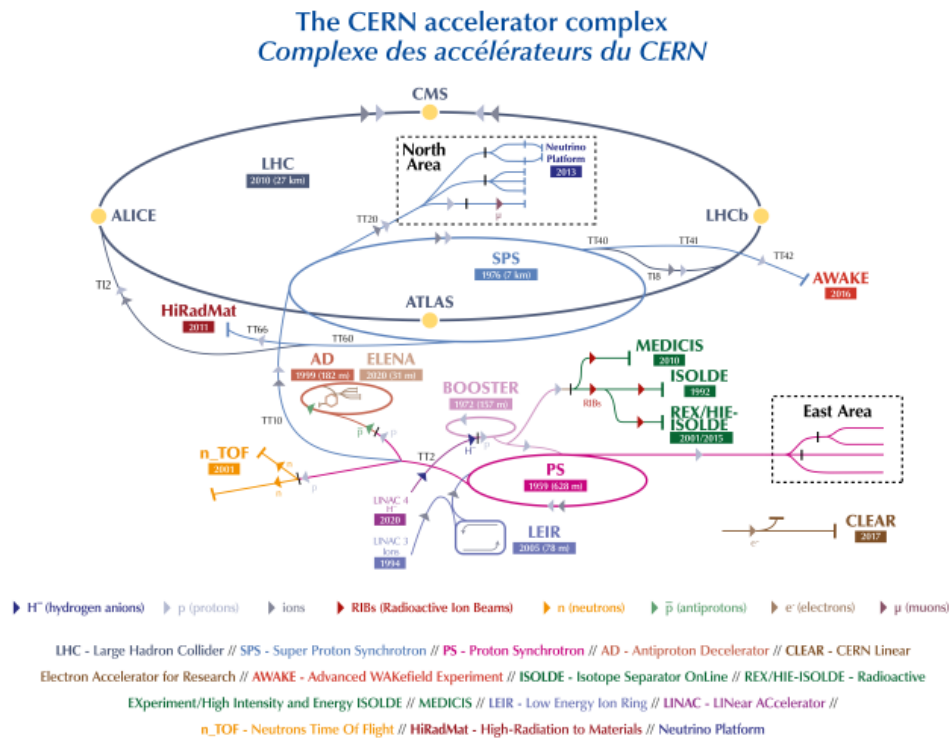


Figure 3- Schematic of CERN's accelerators [8].

The accelerator complex, which includes the Large Hadron Collider (LHC), supports a broad range of experimental programs beyond just the LHC itself. Many of the other accelerators in the chain are utilized for various experiments at lower energy levels, each having its own dedicated experimental halls.

The entire LHC is located at the border between Switzerland and France. With a circumference of 27 km, it is positioned 100 meters underground. The LHC accelerator is designed to collide heavy ions at a center-of-mass energy of up to 14 TeV (tera-electronvolts). The construction of this enormous and intricate system took 10 years and involved the collaboration of thousands of scientists and engineers.

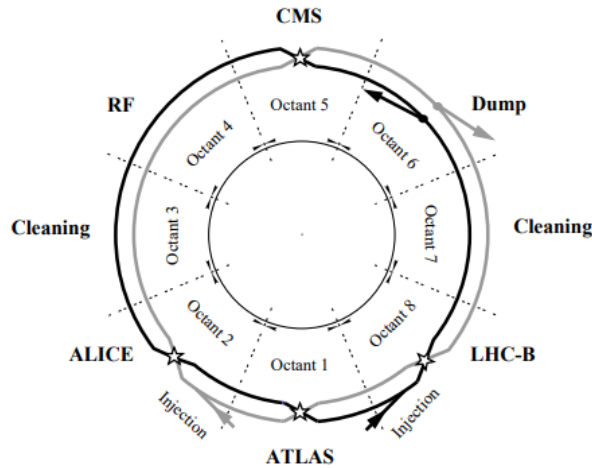


Figure 4- Global Layout of the LHC [9].

At each point in the accelerator where proton beams collide, an experiment is created. Among the four main experiments along the LHC are the particle detectors ALICE, ATLAS, CMS and LHCb, located at key points around the accelerator ring at CERN. The goal of each detector is to analyze every "event," meaning each good collision that occurs at the point where the detector is built.

The CMS experiment, along with the ATLAS experiment, observed the Higgs boson in 2012, almost 50 years after its initial theoretical prediction [10]. This discovery led to Peter Higgs and François Englert being awarded the Nobel Prize in Physics the following year.

The Compact Muon Solenoid (CMS) is designed to study a wide range of particles produced in high-energy proton-proton collisions, with a particular focus on detecting muons. Despite weighing 14000 tonnes, CMS is considered compact, measuring 15 meters high and 21 meters long. For comparison, the ATLAS detector is significantly larger, measuring 25 meters high and 46 meters long, though it operates with a similar purpose [11].

A key feature is its solenoid magnet, the most powerful ever built, which produces a magnetic field of 4 tesla, about 100,000 times stronger than Earth's magnetic field. This magnet, which consists of a cylindrical coil of superconducting wires, allows the detector to bend the trajectories of charged particles as they fly outward from collision points. It operates at extremely low temperatures to maintain superconductivity, enabling it to handle the 18,500 amps of current needed to generate such a powerful magnetic field. The solenoid's design, which allows the Tracker and Calorimeters to be placed inside the coil, makes CMS "compact" despite its immense weight and complexity. The magnetic field is confined within the detector by the surrounding return yoke, which also serves as part of the muon detection system.

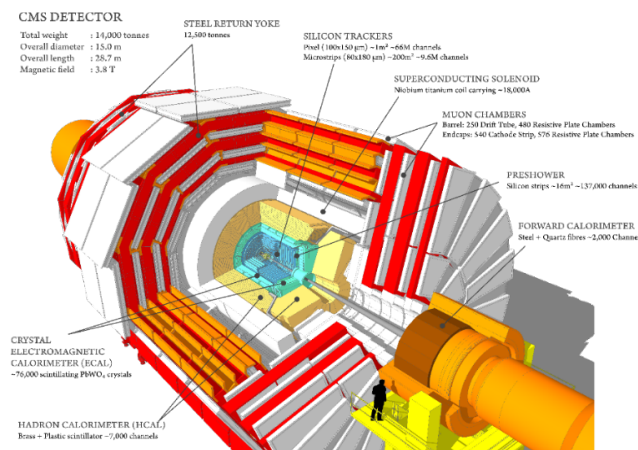


Figure 5 – Overview of CMS detector [11].

The CMS detector consists of several sub-detectors, arranged in concentric layers like an onion. Going from the inner part to the outer part of the detector, these layers are divided into different “sub-detectors”: the silicon tracker, the electromagnetic calorimeter (ECAL), the hadron calorimeter (HCAL) and, outside from the solenoid magnet coil, the muon chambers.

The innermost layer of CMS is the silicon tracker records the paths of charged particles with extreme precision and measures the transverse momentum of charged particles. This is achieved by reconstructing the particles' trajectories in three-dimensional space. These trajectories are curved due to the presence of the strong magnetic field and by measuring the radius of curvature, the transverse momentum of the particles can be calculated: particles with lower momentum follow more curved paths.

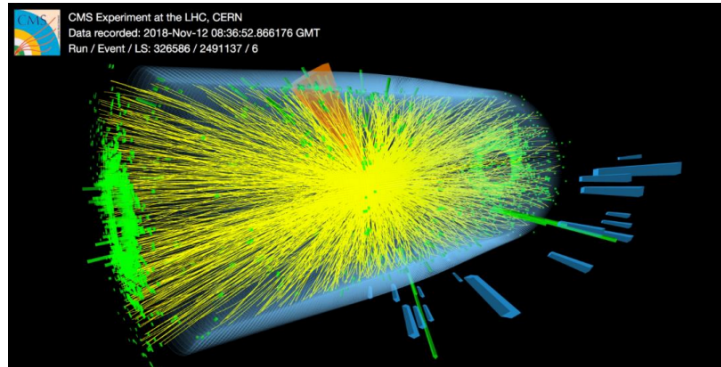


Figure 6- Example of tracked event.

The tracker utilizes silicon-based solid-state semiconductor sensors as its sensitive elements. When a charged particle passes through the silicon layers, it ionizes the material, generating a local charge that can be collected and processed by analog electronics. The exact position of the particle's passage is determined by segmenting the sensor to localize the collected charge. The sensors are arranged in hermetic layers to provide complete coverage around the interaction point, ensuring that all particle trajectories are recorded. The tracker itself measures 5.8 meters in length and 2.5 meters in diameter, making it the largest silicon tracker ever constructed. It consists of two distinct regions with varying levels of granularity depending on their distance from the collision point. The innermost region, known as the pixel detector, is made up of highly segmented pixel sensors.

These are essential for the accurate reconstruction of primary and secondary vertices. The outer region features sensors divided into strips, which provide position information in one direction. Data from the tracker is combined with measurements from other sub-detectors to reconstruct the full picture of each collision event [12].

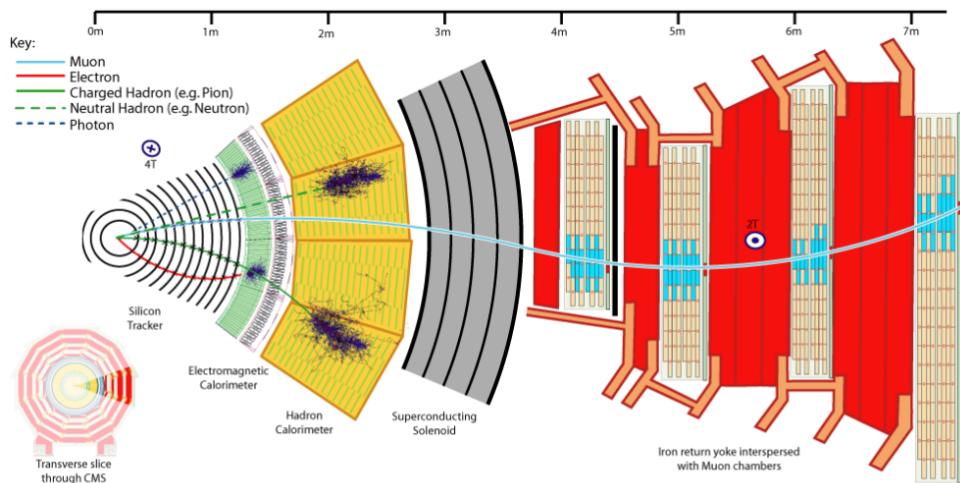


Figure 7- Schematic showing the identification principle of the whole CMS detector [11].

Surrounding the tracker, the ECAL measures the energy of electrons and photons using lead tungstate crystals, which scintillate when these particles pass through. The light produced is proportional to the particle's energy and is detected by specialized photodetectors that work in high magnetic fields and that are glued onto the back of each of the crystals to detect the scintillation light and convert it to an electrical signal. The ECAL is divided into a barrel and endcap sections, with 61200 crystals in the barrel alone [13].

Positioned just outside the ECAL, the HCAL measures the energy of hadrons (particles made of quarks, such as protons and neutrons). It is a sampling calorimeter meaning it finds a particle's position, energy and arrival time using alternating layers of "absorber" and fluorescent "scintillator" materials that produce a rapid light pulse when the particle passes through. The HCAL is designed to be "hermetic," ensuring that no particles escape undetected. It helps identify "invisible" particles like neutrinos by detecting missing energy and momentum in collision events. The HCAL is divided into barrel, endcap, and forward sections, capturing particles from different regions of the collision [14].

As CMS is designed to detect muons, its outermost layer consists of muon chambers that are interleaved with the return yoke to confine the magnetic field. Muons can pass through the calorimeters without being stopped, therefore, chambers to detect muons are placed in the outer part of the experiment where they are the only particles likely to produce a clear signal. The particle path is measured by tracking its position through the multiple active layers of each station; for improved precision, this information is combined with the CMS silicon tracker measurements. Measuring the trajectory provides a measurement of particle momentum. Indeed, the strong magnetic field generated by the CMS solenoid bends the particle's trajectory, with a bending radius that depends on its momentum: the more straight the track, the higher the momentum [15].

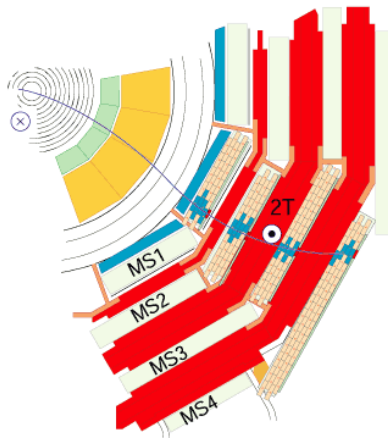


Figure 8 - A muon leaves a curved trajectory in four layers of muon detectors ("stations") [15].

The entire CMS detector unique design allowed it to be constructed in 15 sections above ground, which were then lowered and reassembled underground for easier access and maintenance. This modular design also allows for more straightforward upgrades and maintenance, ensuring that CMS can continue to operate efficiently as part of the LHC experiments.

2.2 LHC Hi-Lumi phase and CMS upgrade

Experiments around the Large Hadron Collider (LHC) began recording collisions in 2009. Following a series of remarkable successes, the scientific community decided to embark on a major upgrade of the entire accelerator, naming this ambitious project the High-Luminosity LHC (HL-LHC). This upgrade aims to achieve significantly higher luminosity levels, enhancing the LHC's performance and "new physics" discoveries potential.

Luminosity is a crucial metric in particle accelerators, representing the number of collisions occurring per unit area per unit time. Essentially, it reflects the effectiveness of an accelerator in producing data through particle

interactions. The higher the luminosity, the more collisions take place, leading to richer datasets for researchers to analyse.

There are two primary units used to measure the luminosity of an accelerator and the collected data size [16]:

1. Luminosity [$\text{cm}^{-2}\text{s}^{-1}$]: this unit describes the number of collisions per square centimeter that occur every second. It highlights the density of the particle bunches and the rate at which collisions happen.
2. Integrated luminosity [fb^{-1}] (femtobarn inverse): this unit measures integrated luminosity over time, representing the total number of potential collisions that have occurred over a specified period. One femtobarn is 10^{-39} m^2 , a very small area, and when expressed in fb^{-1} , it reflects the cumulative collision events. For example, an integrated luminosity of 300 fb^{-1} means that the collider has produced enough data to represent 300 trillion collision events.

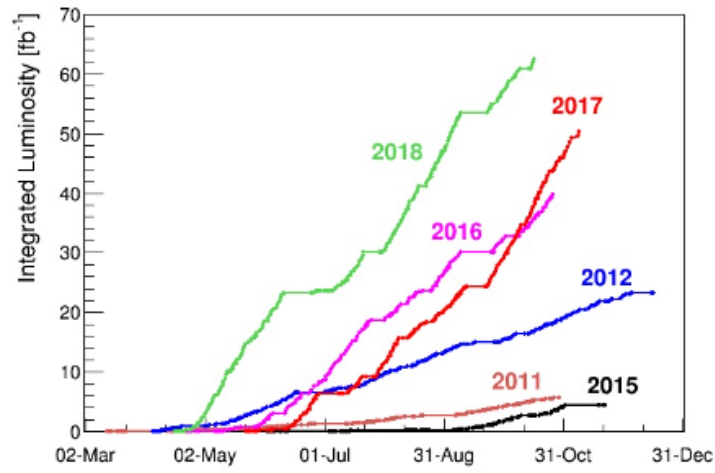


Figure 9 - Integrated luminosity delivered to the ATLAS and CMS experiments during different LHC runs. For instance, the 2018 run produced 65 inverse femtobarns of data, which is 16 points more than in 2017.

The High-Luminosity Large Hadron Collider (HL-LHC) project is set to significantly enhance the capabilities of the LHC, aiming for operations to commence in early 2029 (timeline shown in figure 10). By increasing the integrated luminosity by a factor of ten beyond its original design, the HL-LHC will dramatically boost the number of collisions occurring in a given time frame, enabling researchers to collect vast amounts of data essential for exploring both known and rare phenomena in particle physics.

One of the most exciting prospects of the HL-LHC is its ability to produce at least 15 million Higgs bosons annually, a remarkable increase from the 3 million produced by the LHC in 2017. This surge in Higgs boson production will allow physicists to delve deeper into the mechanisms governing this fundamental particle, potentially uncovering new insights into the fabric of the universe [17].

The HL-LHC will operate at a center-of-mass energy of 14 TeV and aims for instantaneous peak luminosities of up to $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ under optimal conditions. This increased luminosity is expected to enable the ATLAS and CMS experiments to gather around 300 fb^{-1} of integrated luminosity per year, accumulating up to 3000 fb^{-1} over the project's decade-long lifespan. If the ultimate performance is achieved, this could rise to 4000 fb^{-1} [18]. The HL-LHC is expected to run at a centre-of-mass energy of 14 TeV and a time between bunches of 25 ns. It is estimated that there will be about 5 events up to 400 events for each bunch crossing.

Approved by the CERN Council in June 2016, the HL-LHC has been identified as a top priority by both the European Strategy for Particle Physics [19] and the US Particle Physics Project Prioritization Panel [20]. Its significance is underscored by its inclusion in the European Strategy Forum on Research Infrastructures (ESFRI) "Roadmap 2016," which highlights the importance of large research infrastructures.



Figure 10 - LHC/ HL-LHC timeline

All experiments along the Large Hadron Collider will require upgrades to accommodate the new levels of luminosity introduced by the High-Luminosity LHC. Among these, the CMS detector is set for a substantial overhaul during the Long Shutdown 3 (LS3) to fully leverage the increased luminosity. This upgrade is known as the CMS Phase-2 Upgrade.

One of the primary challenges posed by the HL-LHC's enhanced performance is the rise in radiation levels. To address this, the CMS detector must be engineered with improved radiation hardness to ensure its components can withstand the harsher environment. Additionally, the anticipated larger pileup and increased particle density necessitate higher detector granularity. This improvement will help minimize occupancy, ensuring more accurate data collection amidst a greater number of overlapping events.

Furthermore, the upgrade will require an increased bandwidth to accommodate higher data rates generated by the enhanced collision frequency. To manage this influx of information effectively, improved trigger capabilities will be implemented. These advancements will help maintain an acceptable trigger rate, ensuring that the physics potential of the experiments is not compromised.

Overall, the CMS Phase-2 Upgrade is a critical step in preparing for the exciting discoveries that lie ahead with the HL-LHC, allowing researchers to explore fundamental questions in particle physics with unprecedented precision and detail.

All sub-detectors of the CMS experiment will undergo upgrades, but this thesis will specifically focus on the Phase-2 upgrade of the CMS tracker, as this was the project where I worked on during my time as a Technical Student at CERN.

2.3 Phase-2 Tracker Upgrade

The CMS tracker is essential for measuring particle momentum during collisions by tracking the paths of charged particles in a magnetic field. It accurately reconstructs paths of high-energy muons, electrons and hadrons, as well as decays from short-lived particles like beauty quarks. The tracker, designed to be lightweight and resistant to radiation, uses silicon detection elements, including pixels (in the inner part of the sub-detector,

called inner tracker, green in figure 11) and microstrip detectors (in the outer part of the sub-detector, called outer tracker), to produce precise position measurements (μm order).

The upgrade for Phase 2 of the CMS experiment (figure 12), in preparation for the HL-LHC, will involve a complete replacement of the existing silicon tracking system. The present strip tracker was designed to operate with high efficiency at an instantaneous luminosity of $1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with an average pileup of 20-30 collisions per bunch crossing and up to an integrated luminosity of 500 fb^{-1} . Otherwise, the original pixel detector has already been replaced with a new device, the “Phase-1” pixel detector [21], in 2017.

While the tracker has been performing well even at luminosity levels significantly above its design specifications, both the strip tracker and the phase-1 pixel inner tracker will need to be replaced for the HL-LHC phase. This is necessary due to the substantial damage and performance degradation that would occur beyond an integrated luminosity of 1000 fb^{-1} [22].

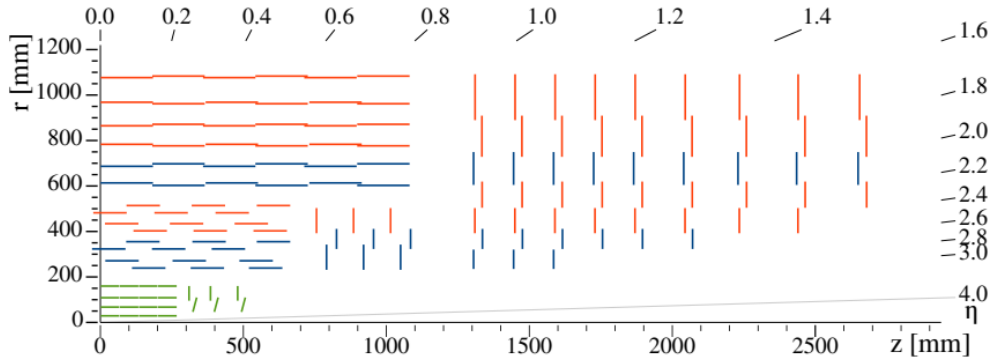


Figure 11 – Schematic of the current tracker at the heart of CMS experiment. [22]

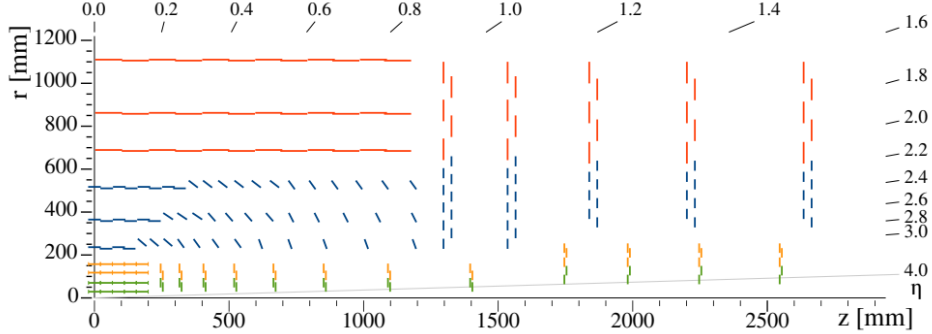


Figure 12- Sketch of one quarter of the future tracker. The yellow and green lines show the Inner Tracker, the blue and red lines show the Outer Tracker. [22]

The Phase 2 tracker will feature an Inner Tracker (IT) composed of pixel modules and an Outer Tracker (OT) made from silicon modules that utilize strip and macro-pixel sensors. Key mechanical engineering requirements for the tracker upgrade include:

- **Higher radiation tolerance:** the tracker must be efficient up to a target integrated luminosity of 3000 fb^{-1} , with a safety margin of 50%. The Outer Tracker should operate without maintenance throughout its entire lifespan. For the pixel Inner Tracker, maintaining the current accessibility design is crucial, allowing for a potential Phase 3 upgrade to replace it as it accumulates significant radiation damage. Given the expected radiation levels, which are estimated to be around two orders of magnitude higher than those for space components, high radiation tolerance is essential.

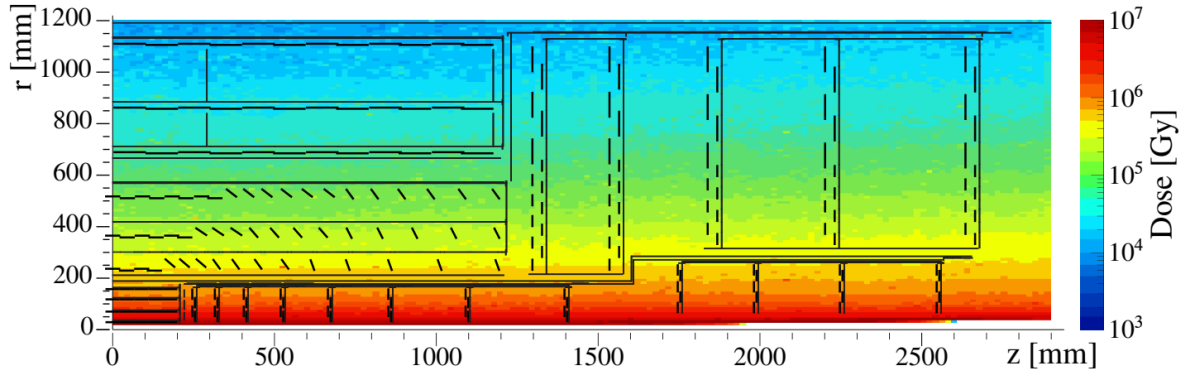


Figure 13- Total ionizing dose in Gy, for the Phase-2 tracker [22].

- Reduced material in the tracking volume: a minimal material budget is critical for effective tracking, as the entire structure should interact as little as possible with the particles being detected, preserving their paths. This upgrade will allow for a reduction in the overall weight of the sub-detector.

Additional planned improvements include increased granularity to ensure efficient tracking performance in high pileup conditions, enhanced track separation capabilities, robust pattern recognition, contributions to the Level-1 trigger and extended tracking acceptance.

Of particular interest for the studies presented in the following chapters are the TBPS and TB2S tracker sub-detectors, shown in the layout of the outer tracker in figure 12 and 14.

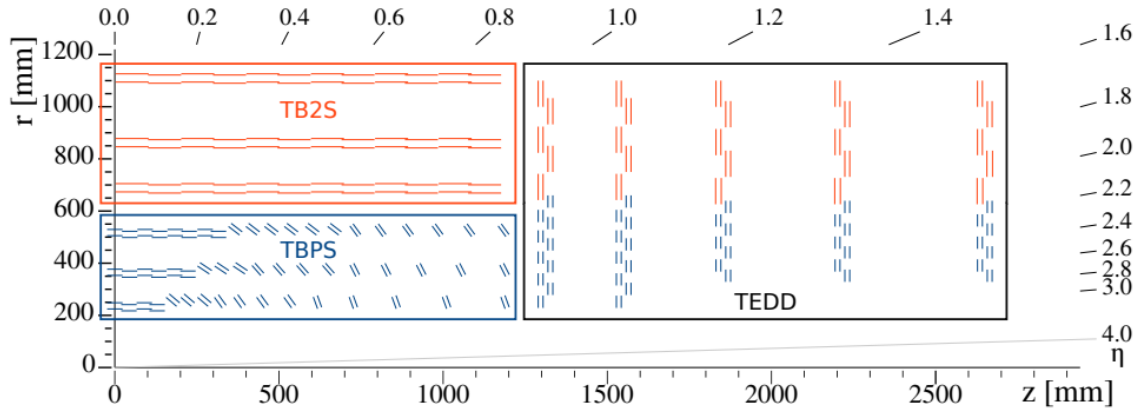


Figure 14 - Sketch of one quarter of the Outer Tracker [22].

To dissipate all the power generated by the electronics in the sensors across all layers of the tracker, an advanced cooling system is required. Additionally, the operating temperature of the silicon sensors must not exceed -20°C , in order to avoid malfunctions and thermal runaway, as investigated in the following chapter. To achieve this, both the outer tracker and inner tracker will use the same cooling system implemented in the Phase 1 inner tracker upgrade, two-phase CO_2 system. This system operates with a set-point temperature of -35°C , corresponding to approximately 12 bar.

Overall, the estimated cost of the entire tracker upgrade in 2017, the year the Technical Design Report was published, is 111,900 kCHF.

3. Advanced two-phase CO₂ cooling systems

The total power dissipated within the tracking volume, along with heat leaks from the surrounding environment, is projected to be around 100 kW for the Outer Tracker and approximately 50 kW for the Inner Tracker. This estimate includes power losses in the cables inside the tracking volume and accounts for some additional margin. The cooling system must effectively remove this heat load while keeping the silicon sensors at a temperature of -20°C or lower. Two-phase CO₂ has been selected as the coolant for this purpose. The system will be designed to operate at a nominal coolant temperature of -35°C , ensuring a temperature of around -33°C at the first silicon module, which represents the warmest point along the cooling loop.

3.1 Thermal runaway in silicon sensors and required operating temperatures

The modules are the fundamental blocks of the CMS tracker, enabling the detection of particle passage through the silicon sensors installed on each module. Each module is composed of various components, including electronics, I/O channels and a mechanical frame. A single module not only detects the presence of particles but also provides highly precise information about their spatial position.

For the Phase-2 upgrade of the CMS tracker, the sensors are based on planar silicon-semiconductor technology. To mitigate radiation damage and ensure optimal sensor performance while minimizing noise from the signal, the sensors must operate at temperatures below -20°C . This requires an advanced cooling system that can efficiently remove the heat dissipated by both the electronics and the sensor itself, while maintaining a lightweight mechanical frame to meet the tracker's material budget requirements.

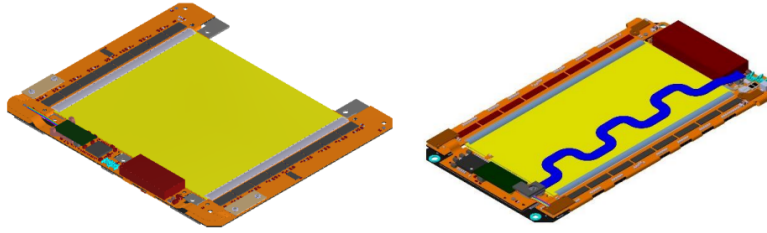


Figure 15: 3D model of a 2S Module (left) and a PS Module (right) for the Outer Tracker of CMS Phase-2 . 2S modules are used in TB2S and PS modules in TBPS tracker sub-detectors.

The modules inside the tracker are powered by a low-voltage connection, enabling the electronics to function and it generates a constant power dissipation throughout the module's operational life. Additionally, the sensors use a high-voltage connection to let it works to detect particles passing through the sensor. Since radiation damage leads to an increase in leakage current in the sensor (current that goes through it due to the presence of the high voltage), this source of heat is negligible at the beginning of the sensor's life but increases as the radiation exposure grows, particularly by the time the integrated luminosity reaches 4000 fb^{-1} . This rise in leakage current results in both increased power dissipation and the risk of thermal runaway.

The thermal runaway phenomenon occurs when the cooling power it's not enough to maintain the temperature of the module under operating temperature condition (about -20°C). The heat generated by the sensor, combined with the heat from the on-detector electronics, must be effectively dissipated. For this reason, it's important to underline that the heat produced by the sensors primarily results from reverse leakage current generated within the sensor bulk volume and this leakage current has a strong temperature dependence, following the relation [23]:

$$I_{leakage} \propto T^2 e^{-\frac{E_g}{2kT}}$$

Equation 1

Where:

- $E_g = 1.21 \text{ eV}$ is the band gap of silicon at -20°C ;
- $k = 8.617 \times 10^{-5} \text{ eVK}^{-1}$ is the Boltzmann constant;
- T is the temperature $[\text{K}]$;

This means the leakage power, and consequently the heat dissipation, rises exponentially as the temperature increases.

Considering the two contributions from low voltage and high voltage (also called bias voltage, U_{bias}) the total amount of power that must be dissipated by a single module ($P_{module} [\text{W}]$) is given by the following equation:

$$P_{module} = P_{l_v} + P_{si}$$

Equation 2

Where:

- P_{l_v} is the power dissipated by the low voltage electronics $[\text{W}]$
- P_{si} , is the power dissipated by the sensor $[\text{W}]$, further defined as:

$$P_{si} = U_{bias} \cdot I_{leakage}$$

Equation 3

Here, U_{bias} is the high voltage supplied to the sensor, and $I_{leakage}$ is the leakage current described in the equation 1. Considering again that the leakage current increases exponentially with temperature, the temperature of the sensors becomes a crucial parameter in estimating total power dissipation. On the other hand, the sensor temperature depends on the ability of the cooling system (two-phase CO_2) to absorb the heat generated. For this reason, it is essential to qualitatively acknowledge that the sensor temperature, T_{si} , will depend on the capacity of the mechanical structure to transfer heat from the sensor to the cooling pipe, as well as the ability of the two-phase CO_2 within the pipe to absorb this heat while increasing its enthalpy. This necessitates creating pathways that facilitate heat transfer, meaning mechanical structures with high thermal conductivity must be employed, while also considering the constraints related to mechanical structures used in a tracker for high-energy physics experiments, as previously mentioned (weight and radiation hardness). Thus, the sensor temperature can be estimated using the following relationship:

$$\text{Cooling power density} = HTC_{eq} \cdot (T_{si} - T_{CO_2})$$

Equation 4

Where the term HTC_{eq} (equivalent heat transfer coefficient, measured in $\text{W}/(\text{m}^2\text{K})$) represents a correction made based on the heat transfer coefficient (HTC) of the CO_2 , which corresponds to the heat transfer between the inner surface of an evaporator pipe and the CO_2 , taking into account the thermal resistance of the path between the sensor and the inner wall of the pipe. This approach allows for simulations and thermal studies that consider not only the heat exchanged between the inner wall of the cooling pipe and the CO_2 flow (HTC) but also the thermal conductivities and geometries of the elements interposed between the module and the cooling pipe, as detailed in the following study [24]. Considering the system under adiabatic conditions, meaning there is no heat transfer by convection with the external air, equation 5 describes that, in general, the

value of HTC_{eq} can be obtained by knowing the HTC (between the CO₂ and the inner wall of the pipe, accounting for the thermal resistance created by the two-phase heat transfer system) and by adding the sum of the i-th resistances of the various material layers and different geometries interposed between the inner wall of the pipe and the heat source elements to be cooled (sensor and electronics), shown as $\sum_i R_i$.

$$HTC_{eq} = \left(\frac{1}{HTC} + \sum_i R_i \right)^{-1}$$

Equation 5

Starting values used in many analyses, as well as in the design and thermal simulations of the tracker's mechanical structures, reference precautionary HTC values of approximately 5000 W/m²·K, given the significant uncertainty in its determination. This value corresponds to the minimum HTC observed at the inlet of an evaporator calculated using a multiline code (COBra). Chapter 6 of this work will present an experimental analysis of some HTC values calculated using a thermal test setup constructed at CERN, which has enabled precise analyses regarding this topic.

The evaluation of this delicate value HTC_{eq} allows for the calculation of the cooling power density [W/(m²K)] of the module - mechanical structure - two-phase CO₂ flow, entire system. Plotting the Silicon Power, equation 3 (to dissipate) P_{si} , and the cooling power density, equation 4 (dissipable), on the following plot (figure 16), we can detect the point A that represents the stable operating temperature of the silicon sensor. Indeed, this operating point represents the power that must be dissipated (indicated by the red line) and is exponentially proportional to the sensor temperature. A small increase in the sensor temperature (point C) causes an increase in cooling power density (yellow line). However, since this increase exceeds the corresponding dissipated power of the module, it leads to a decrease in the module's temperature, which can return to the operating point at A. Conversely, a decrease in the module's temperature results in a dissipated power that is greater than the cooling capacity at point D, again causing the sensor temperature to rise, returning to point A.

The situation differs beyond point B, which is a critical operating point, because the module temperature will no longer be stable. A slight increase in temperature will cause the power to be dissipated by the sensor to always exceed the power that can be dissipated by the cooling system. This results in a temperature rise that, in turn, causes an exponential increase in the sensor's leakage current, leading to an increase in power dissipation that can no longer be managed. These are the conditions under which thermal runaway occurs: indicating that our cooling system is no longer sufficient to maintain a constant temperature for the module, ultimately leading to its failure in a short amount of time.

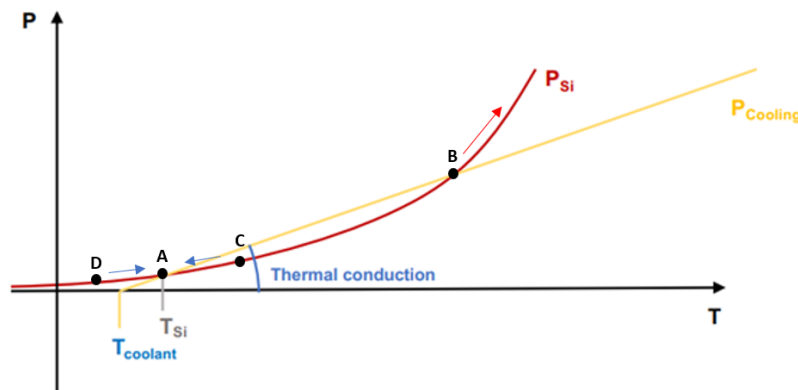


Figure 16 – Plot showing a qualitative good scenario where the cooling power is sufficient to maintain the sensor at a stable operating temperature, represented by point A. Point B represents an unstable operating temperature.

When the silicon sensor is exposed to higher radiation damage the silicon power to dissipate increases due to increasing in leakage current and the P_{Si} line is shifted upper. In this configuration shown on figure 17, the cooling doesn't work (there are no any intersections between the two lines) and the temperature of the sensor is not limited reaching high temperature until the module result definitely broken.

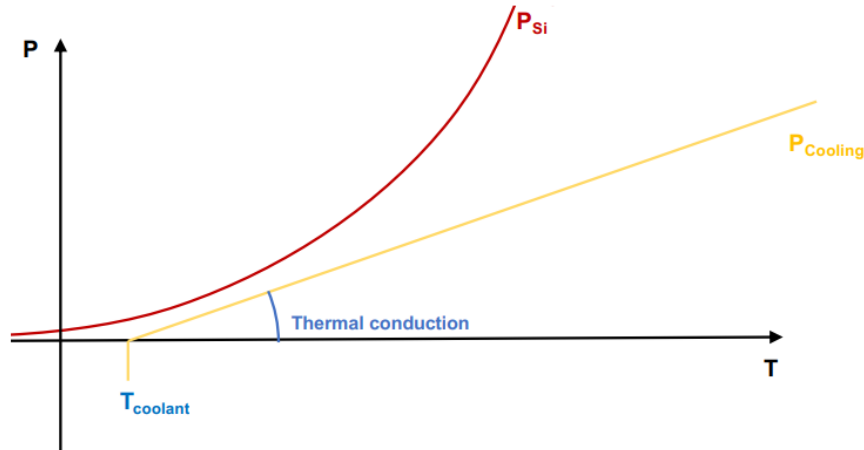


Figure 17 – Plot showing a configuration where there is no intersection between the cooling power line (yellow) and the silicon power line (red). This means that the cooling system will not work, as there is no stable operating temperature for the module. This situation could occur if the sensor is irradiated and/or if the cooling system is not properly designed.

What we can do at this point, it's find a way to let the two lines intercept again. This could be done increasing the HTC_{eq} , equivalent heat transfer coefficient or thermal conduction as named in or lowering the temperature of the coolant. Since an increase in HTC_{eq} is strongly related to add mass to the mechanical structure and since it's supposed to be already well optimized, the best option, if possible, it's to lower the CO_2 temperature, as in the picture shown below.

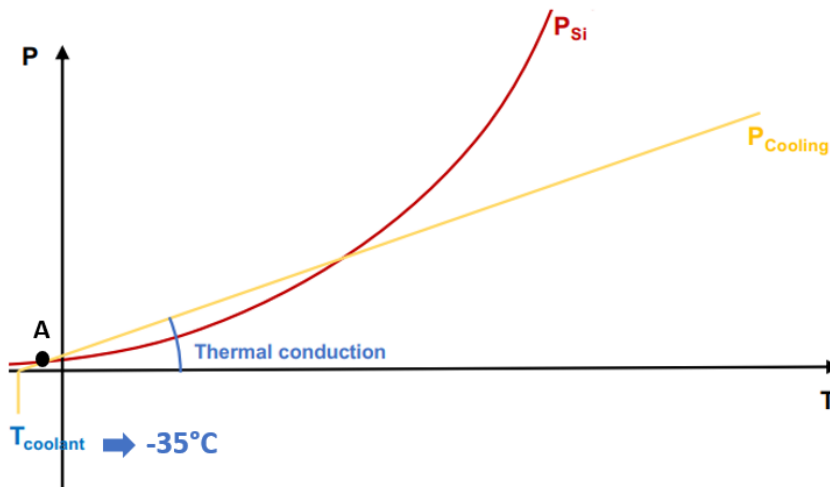


Figure 18 – By decreasing the CO_2 temperature (for example, reaching $-35^\circ C$ as planned for the future CMS tracker), it is possible to find the intersection between the two lines again, resulting in a stable operating temperature for the module.

That's why the CO₂ temperature for the CMS tracker was set at -35°. This temperature ensures sufficient cooling power to dissipate the sensor's heat while keeping the sensor temperature below -20 °C. This helps reduce leakage current and prevent the thermal runaway phenomenon.

3.2 Two phase cooling systems

As said on the incipit of this chapter in order to reach the main requirement of tracker detector, material budget and radiation resistance, two-phase CO₂ based cooling system is used to cool the detector modules. Two-phase cooling systems are used for two main reasons: to maintain a constant coolant temperature within the evaporator and for their superior cooling efficiency compared to single-phase systems.

The first reason can be understood by looking at the pressure-enthalpy diagram of a typical fluid like CO₂. In two-phase evaporative cooling, heat, such as that generated by irradiated modules inside a detector, causes the liquid to evaporate, rather than simply raising the fluid's temperature, as is the case with single-phase systems. This characteristic allows for better control of temperature throughout the detector's evaporators.

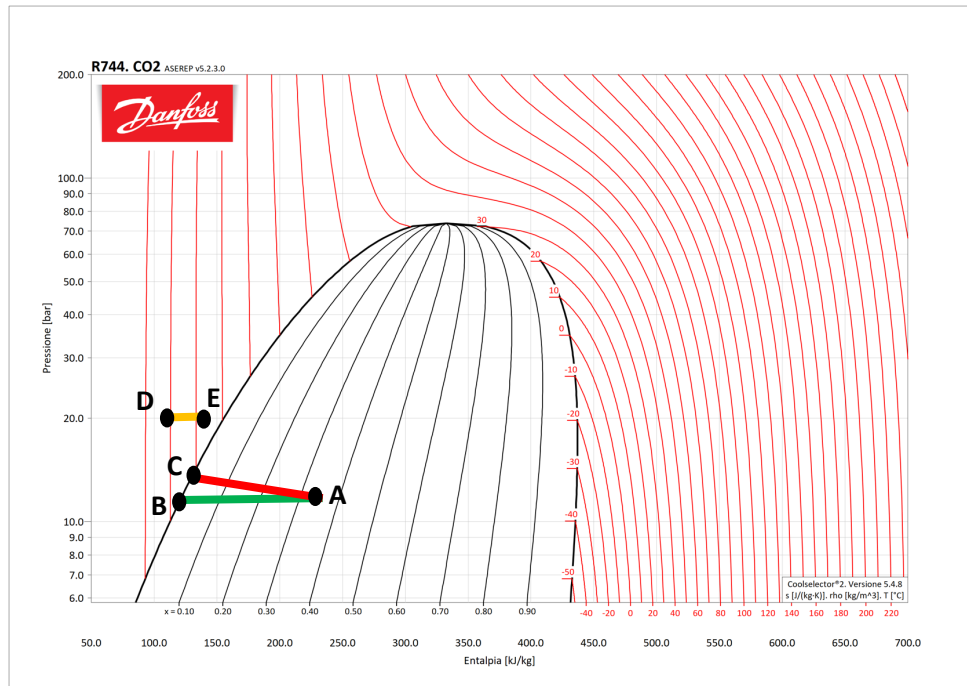


Figure 19 – Pressure-enthalpy diagram of Carbon Dioxide (CO₂), R744. Fixing point A at the outlet of the evaporator, the green line (from B to A) represents the increase in vapor quality due to the evaporation of CO₂ at 12 bar, without accounting for any pressure drop (so with point B at the same temperature as point A). The red line (from C to A) represents the real scenario, where the pressure drop inside the evaporator also causes a temperature drop. Fixing point A means that point C will be at a higher temperature at the beginning of the loop. The yellow line (from D to E) shows an increase in enthalpy in the liquid region, leading to a temperature rise from point D to point E.

For single-phase cooling, the heat dissipated ($\dot{Q}_{single-fluid}$ [W]) can be calculated as:

$$\dot{Q}_{single-fluid} = \dot{m} \cdot c_p \cdot (T_{out} - T_{in})$$

Equation 6

where:

- $\dot{m}$ is the mass flow rate of CO₂ [g/s],
- c_p is the specific heat capacity of CO₂ at -35°C and 20 bar, which is 2.032 J/(g·K),
- (T_{out}-T_{in}) is the temperature difference between the outlet and inlet [K].

Assuming a temperature difference of 1°C, the system can remove 2.032 J/g of CO₂. In contrast, for a two-phase cooling system ($\dot{Q}_{two-phase}$ [W]), the heat dissipated is given by:

$$\dot{Q}_{two-phase} = \dot{m} \cdot (H_{gas} - H_{liquid})$$

Equation 7

where:

- $H_{gas} - H_{liquid}$ represents the enthalpy change from saturated liquid to saturated gas [J/g].

For CO₂, this enthalpy difference is approximately 313.28 J/g, assuming 100% CO₂ vapor at the outlet. This means that, to remove the same amount of heat with a single-phase CO₂ system, you would need a temperature difference of nearly 155°C between the inlet and outlet, assuming the same mass flow rate. While increasing the mass flow rate could be an option, this approach isn't feasible due to material budget constraints, more mass requires heavier cooling system, not feasible in systems where minimizing material is critical.

Another advantage of two-phase cooling is the relatively constant temperature between the inlet and outlet, as can be seen from the green line on the pressure enthalpy diagram (figure 19) that represent a theoretical evaporator without any pressure drop. In this case, once the heat transfer resistance is set, this allows all modules cooled by the same evaporator loop to operate at roughly the same temperature, ideally below -20°C without any increasing in temperature due to the increasing in the temperature value of the CO₂, as it happens for single fluid cooling systems.

However, it's important to note that the temperature of CO₂ within the detector isn't perfectly constant. In a two-phase region, temperature and pressure are linked, and any pressure drop inside the evaporator will cause a temperature drop as well. For example, looking at the red line in the CO₂ diagram, if CO₂ exits the system at -35°C and 12 bar, a 1-bar pressure drop inside the evaporator would result in an inlet temperature of approximately -32.7°C. This means the first modules in the cooling loop will experience a slightly higher temperature than those at the end, with a typical temperature drop of around 2.3°C per bar. This behaviour is the opposite of what is seen in single-phase systems, yellow line in the diagram, where the last modules in the loop typically experience a higher coolant temperature.

3.2.1 CO₂ Heat Transfer Coefficient (HTC) and Vapour Quality (VQ)

The primary characteristic of any two-phase flow is the flow pattern that develops along the cooling pipe. A key experiment referenced for studying two-phase cooling systems, and which will be explored in chapter 6, involves observing the establishment of boiling regimes and variations in the parameters that characterize them using a heated pipe. The flow is introduced in saturated conditions and the temperature along the pipe wall is monitored. The main parameters to consider when analysing two-phase flows are:

1. Heat Transfer Coefficient (HTC): This represents the amount of heat exchanged between the cooled element (in this case, the inner pipe wall) and the refrigerant fluid per unit surface area. It can be calculated using the following equation:

$$HTC = \frac{HF}{T_{inner\ wall\ pipe} - T_{CO2}} \left[\frac{W}{m^2K} \right]$$

Equation 8

Where HF is the Heat flux [W/m²], $T_{inner\ wall\ pipe}$ [°C] is the temperature of the inner pipe wall of the evaporator pipe (or the experimental heated pipe), T_{CO2} [°C] is the temperature of the bulk flow of CO₂ inside the pipe.

2. Vapor Quality (VQ): this is a dimensionless parameter representing the ratio of the vapor mass flow to the total mass flow:

$$VQ = \frac{\dot{m}_v}{\dot{m}_v + \dot{m}_l} = \frac{HF \cdot S}{F \cdot (H_g - H_l)}$$

Equation 9

Where:

- $\dot{m}_v, \dot{m}_l$ represent the vapor and liquid mass flows.
- F is the total mass flow rate, $(\dot{m}_v + \dot{m}_l)$.
- $H_g - H_l$ are the enthalpy values of the saturated gas and liquid phases.

The flow boiling heat transfer is governed by two main mechanisms: nucleate boiling (HTC_{nb}) connected to the formation of vapor bubbles on the tube wall surface and convective boiling (HTC_{cv}), associated with conduction and convection through a thin liquid film, with evaporation occurring at the liquid-vapor interface. The total heat transfer coefficient in a closed channel can be expressed as:

$$HTC = HTC_{nb} + HTC_{cv}$$

Equation 10

The figure 20 provides a schematic representation of a typical flow boiling process in a horizontal round tube. The fluid enters as a single-phase saturated liquid and as the process continues along the tube, the proportion of vaporized fluid increases. Due to mass conservation, as the mean density of the flow decreases (because of vapor formation), the mean flow velocity must increase. This acceleration results in varying liquid and vapor velocities, which lead to a series of changes in the flow regime. In other words, the two-phase flow regime depends strongly on the relative velocities of the two phases.

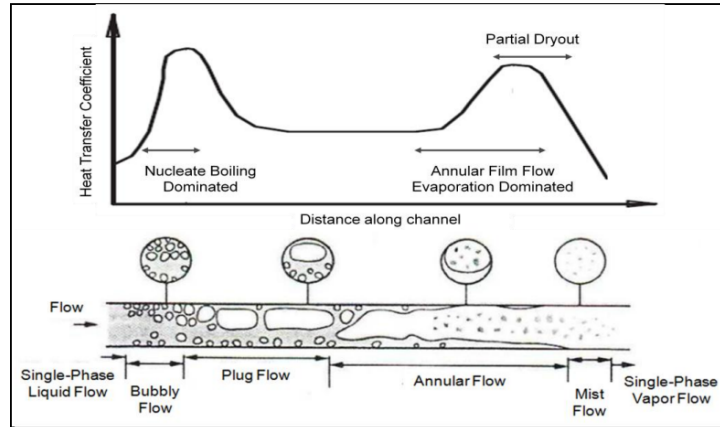


Figure 20 – Heat transfer coefficient qualitative trend and main two-phase flow regimes [25]

In the early stages of boiling [23],[25],[26], local temperatures within the flow exceed the boiling point, leading to nucleate boiling, characterized by small bubbles and high HTC values. As the flow progresses, the entire flow reaches saturation, and boiling becomes widespread, rather than confined to local areas. Bubbles start to coalesce, creating flow regimes known as slug flow or plug flow. Like bubbly flow, plugs of vapor tend to flow in the top of the channel due to buoyancy forces. In this regime, the tube wall is intermittently cooled by liquid slugs and vapor plugs, resulting in a decrease in the heat transfer coefficient. At very low flow rates, stratified flow may occur where the upper portion of the tube is completely occupied by vapor and the bottom by liquid.

As vapor quality increases, meaning more vapor is present in the flow, the system transitions into annular flow, where convective heat transfer dominates due to the lower density and higher mass flux. In this phase, a thin

liquid layer clings to the pipe walls while vapor fills the core. Here, the HTC increases with vapor quality, reaching a maximum just before the onset of dryout, a condition where the liquid phase no longer contacts the pipe walls. During dryout, the vapor touches the pipe surface and liquid droplets are dispersed within the gas, causing a significant reduction in the efficiency of the two-phase heat transfer as nucleate boiling ceases.

The following plots [28] show a qualitative representation of the HTC variation with vapor quality in two-phase flows. Notably, there are two distinct peaks in HTC, one at the beginning of the loop, driven by nucleate boiling and another in the annular flow region, where convective heat transfer increases. The figure 21 and 22 illustrate the summation of these two HTC contributions.

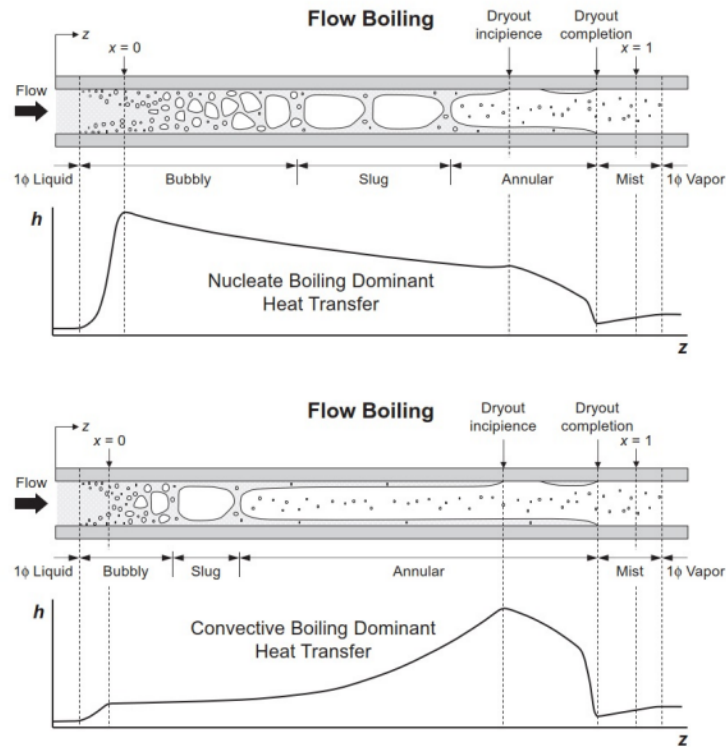


Figure 21 – Schematic of flow regimes and variation of heat transfer coefficient (h is the heat transfer coefficient).[28]

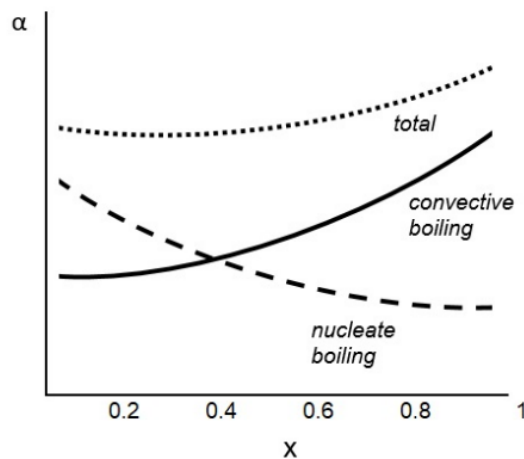


Figure 5.4: General trends of α vs. x .

Figure 22 – General trend of heat transfer coefficient (α) over vapour quality (x). [28]

Looking at the results from some experimental tests regarding the calculation of the Heat Transfer Coefficient (HTC) using two-phase CO_2 as the refrigerant fluid [28], the plot below shows how, with the parameters used

for this test (mass flux, $G = 300 \text{ kg/(m}^2\text{s)}$, heat flux, $q = 7.5 \text{ kW/m}^2$ and different saturation temperatures), a slight local peak in HTC can be observed between 0.05 and 0.2 of vapor quality, especially when the saturation temperature decreases to -30°C and -40°C . This peak could be related to the onset of nucleate boiling. In the second phase, an increase in HTC is linked to the convection effect inside the pipe. Results like these will be the focus of the study conducted at CERN to analyse the heat transfer coefficient values for the pipes used in the TB2S tracker sub-detector, as discussed in chapter 6.

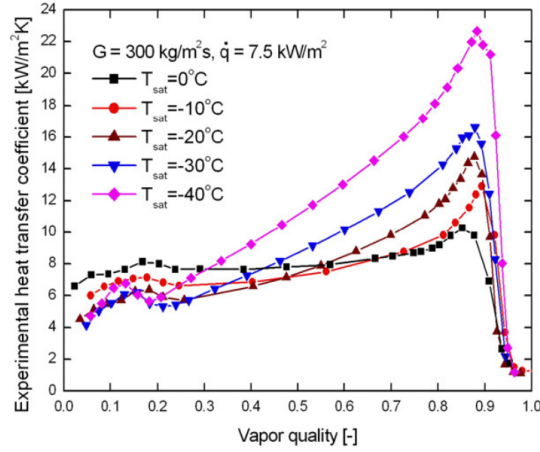


Figure 23 – Experimental heat transfer coefficient results showing mean heat transfer coefficient versus vapor quality at different saturation temperatures [29]

3.3 Benefits of two-phase CO₂ as a refrigerant

The fluid properties of CO₂ make it an ideal medium for cooling of tracking detectors, in particular because of the ability of using smaller diameter, lower-mass tubing than is required with conventional refrigerants or liquid cooling applications. For these main reasons, CO₂ as a refrigerant entered the world of high-energy physics with the LHCb-VELO experiment in 2008 and the AMS-Tracker cooling systems as early as 1998 [22]. Since then, significant research has been conducted, leading to the use of CO₂ in the CMS Phase-1 Pixel Detector for inner tracker cooling starting in 2017.

The choice of CO₂ as a cooling fluid is based on several key advantages, which can be summarized as follows [27,31]:

- Low viscosity, high specific enthalpy and high evaporation pressure: CO₂ evaporates at higher pressures compared to regular refrigerants (51 bar for CO₂ two-phase cooling at $+15^\circ\text{C}$ and 13 bar at -35°C). This higher pressure helps keep the vapor compressed, reducing the circuit volume and the bubbles dimension, creating a more efficient heat removal for nucleation. Consequently, lower flow rates are required, allowing for smaller pipe dimensions, crucial for designing a lightweight detector that minimizes interaction with particles. Although higher pressure requires thicker pipe walls, this is offset by the reduced pipe diameter.

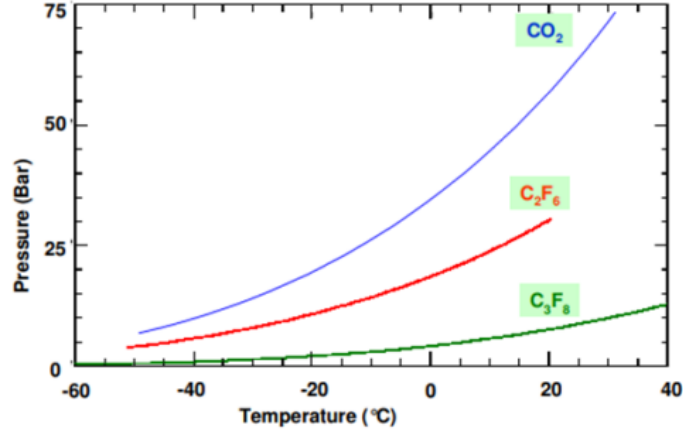


Figure 24 – Saturation curves of radiation hard cooling fluids, CO_2 evaporates at higher pressures compared to the other common fluids [27]

- Right temperature range: CO_2 has the right temperature range for detector operation. The operative temperature range for detector cooling is from 15°C down to -45°C , fitting well in the 2-phase area between the critical point at 31°C and triple point of -56°C .
- Radiation hardness: CO_2 , like fluorocarbons, is radiation-resistant, making it suitable for use in high-radiation environments like particle detectors.
- Environmentally friendly: CO_2 has a much lower global warming potential (GWP) compared to traditional CFC refrigerants (C_2F_6 has a GWP of 6630, while CO_2 has a GWP of 1). This is essential for reducing the carbon footprint in LHC Phase-2 operations. Choosing CO_2 -based cooling systems can save the equivalent of 40,000 tonnes of CO_2 emissions per year, contributing to more sustainable infrastructures [32].
- Safety: CO_2 is non-toxic and non-flammable, making it safe for use in underground environments, such as in detector caverns located 100 meters below ground.
- Well-known technology: the CO_2 cooling system is widely recognized in the field of high-energy physics and is based on the well-established two-phase accumulator controlled loop (2PACL) concept, which will be further described in the next paragraphs.
- Lower flow rates and higher pressures: these characteristics lead to smaller pressure drops inside the cooling loop, maintaining more consistent temperatures inside the evaporator. Pressure drops in two-phase systems can result in temperature variations due to changes in saturation pressure, but CO_2 's properties help mitigate this issue.

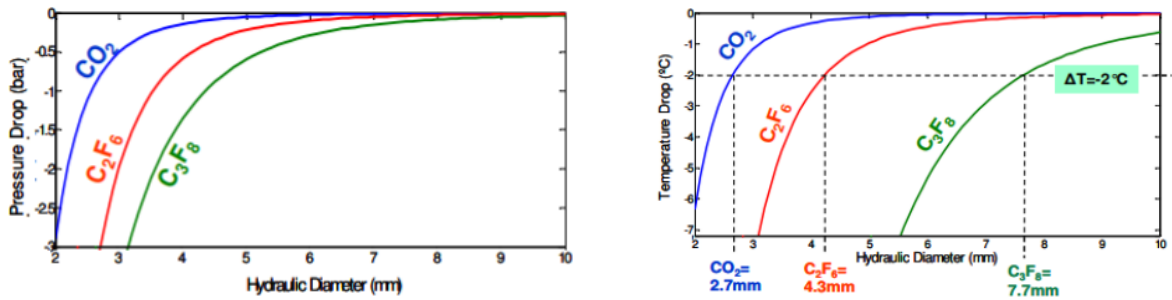


Figure 25 – CO_2 comparison with other fluids. Left- Pressure drop of CO_2 , C_3F_8 and C_2F_6 as a function of tube diameter. Right- Temperature drop of CO_2 , C_3F_8 and C_2F_6 as a function of tube diameter. [27]

In summary, CO_2 stands out as an ideal evaporative cooling fluid for detector systems due to its ability to allow smaller tube diameters, superior heat transfer coefficients (HTC) and an overall smaller environmental

footprint. A comparison under the same operating conditions (-35°C , 75% vapor quality, 680 W load) shows that CO_2 outperforms other radiation-hard coolants by delivering higher HTC and requiring smaller diameter tubes, making it an efficient and sustainable choice for future detector designs.

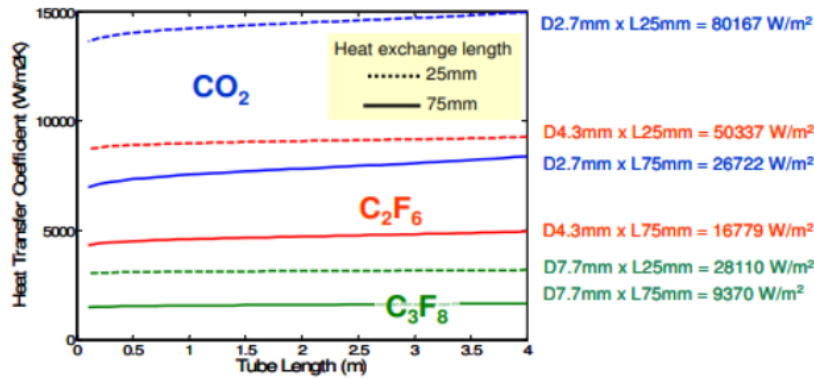


Figure 26 - Heat transfer coefficients' comparison [27]

3.4 2PACL system

All current CO_2 cooling systems at CERN are based on the 2-Phase Accumulator Controlled Loop concept (2PACL). In this system, in contrast to usual two-phase compressor systems, only part of the circulating fluid is evaporated and the return flow from the detector is a mixture of liquid and vapour. The most common cooling systems used in industrial and commercial applications are highly advanced but cooling a detector presents unique challenges. Proper cooling for a detector occurs on the liquid side, whereas compressors (main element presents on Rankine's cycle for commercial two-phase refrigerator systems) typically require gas as input.

To address this, a novel cycle was developed that remains entirely on the liquid side: the externally cooled pump cycle. In fact, the 2PACL (Two-Phase Accumulator Controlled Loop) system offers the distinct advantage that the entire cycle stays on the liquid side, eliminating the need for additional heat after cooling the detector. The pressure (and consequently the temperature) of the cooling loop is controlled by a two-phase vessel located away from the experiment, removing the need for sophisticated local control systems.

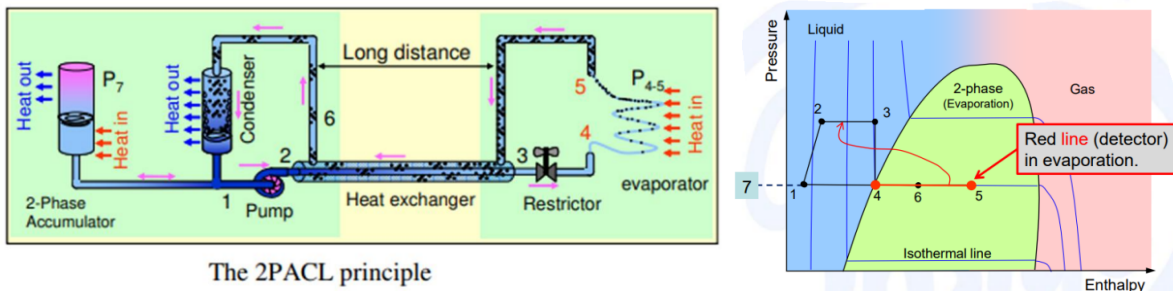


Figure 27 – The 2PACL principle. Left – instrumental chart. Right- p-h diagram highlighting in red the evaporator [30, 42].

Referring to the figures 27 that describe the 2PACL cooling system, the process begins at point 1, where liquid CO_2 is pumped into the circuit. The sole purpose of the pump in this type of system is to overcome the pressure drop in the loop and provide the desired mass flow to cool the detector. From point 1, the liquid enters a coaxial transfer line where it receives heat from the two-phase fluid exiting the experiment, moving toward point 3 and approaching the saturated liquid region.

At point 3, a concentrated pressure drop occurs in the capillaries (small-diameter tubes), which allows the flow to enter the saturated liquid zone. The capillaries serve a dual purpose: they ensure the fluid enters the evaporator (detector) as a saturated liquid and help balance the flow into individual evaporators. By creating a

concentrated pressure drop of about 10 bar, the system becomes insensitive to varying pressure drops across individual evaporators, preventing any imbalance in the flow distribution.

After passing through a preheater at point 4, the saturated liquid enters the evaporator. The preheater's function is to trigger boiling by eliminating any remaining subcooling, reducing the risk of superheating (a phenomenon discussed in chapter 3.5). As the liquid enters the evaporator at point 4, it begins to boil, absorbing heat from the detector modules. Although the process is represented as an isobaric phase change from point 4 to point 5, a pressure drop occurs due to the evaporator's small pipe diameter (about 2 mm) and the initiation of boiling, which increases the pressure drop within the cooling loop.

From point 5, which is at the same pressure set by the accumulator (P7), 12 bar (-35°C), the flow returns through the concentric transfer line, now in the outer tube. During this return, it provides some of its latent heat of condensation to the incoming saturated liquid, reaching point 6. The transfer line's purpose is to connect the cavern, where the detector is located (which is inaccessible during experiments due to high radiation levels and where only passive piping are present), to the service room, where auxiliary services are housed and where maintenance can be performed.

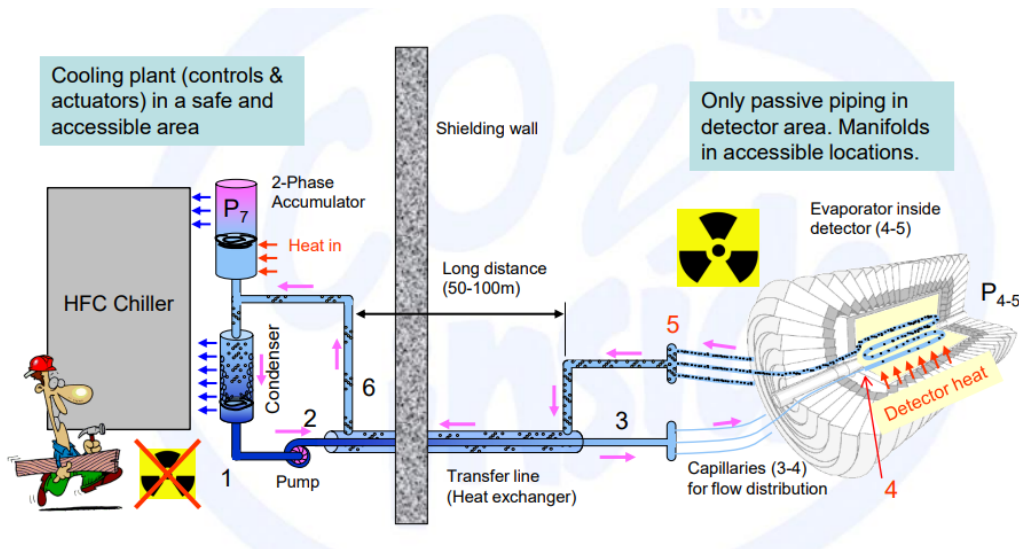


Figure 28 – General schematic of a detector cooled by the described 2PACL cooling system. On the left side of the diagram is the 'service room,' which is accessible during experiment operations. On the right side is the detector cavern, which is not accessible when the experiment is running and is cooled by a passive system provided by the 2PACL [42].

In the service room, the flow passes from point 6 to point 1 through an external heat exchanger, which sub-cools the fluid, preparing it to re-enter the pump and start the cycle again. As shown in the schematic, the circuit is connected to an accumulator at the evaporator's outlet. The accumulator is a single thermobaric component that maintains a constant pressure at the evaporator outlet. It consists of a volume where liquid and gaseous CO₂ coexist. By increasing the gas phase (in a constant-volume system), the pressure rises, shifting the entire loop to higher pressure and saturation temperatures (e.g., 51 bar and 15°C). Conversely, by reducing the gas portion and increasing the liquid component (which is denser), the accumulator pressure drops, allowing the cycle to operate at lower pressures (e.g., 12 bar, -35°C). Both the accumulator and condenser are located in the service room and are connected to an external chiller.

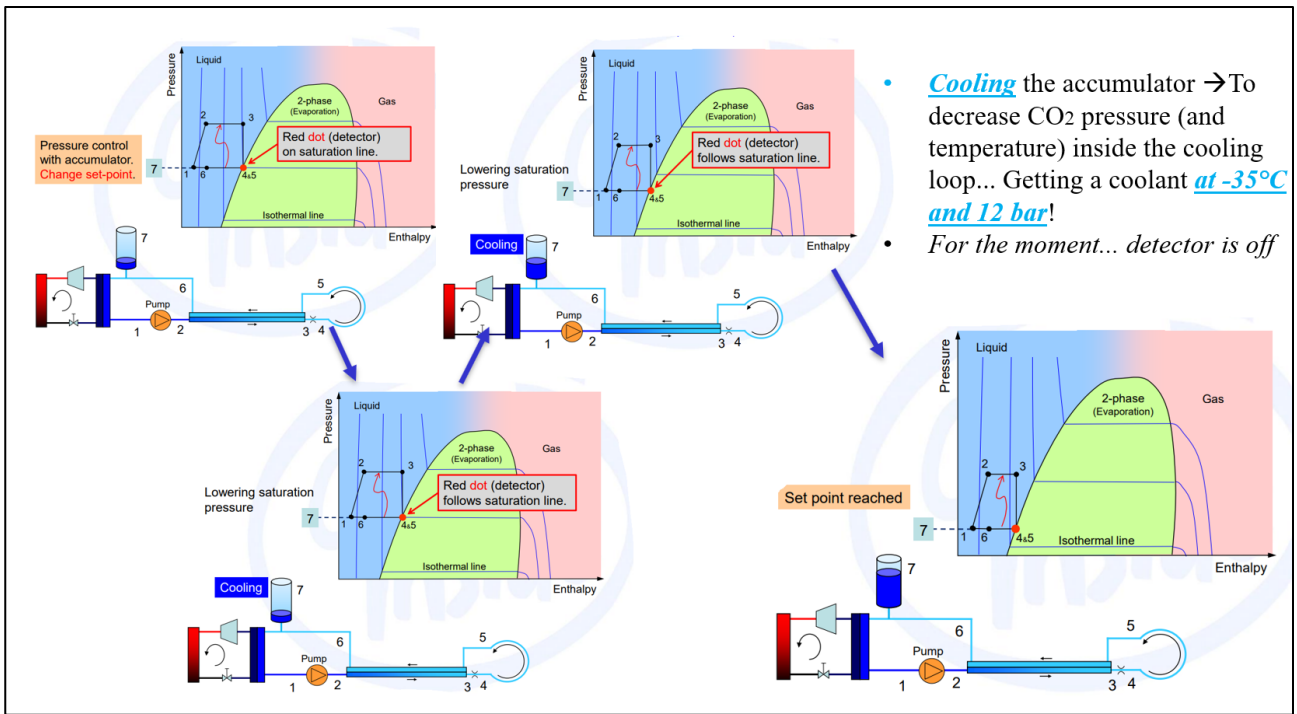


Figure 29 – 2PACL system reaching the operating point of 12 bar, cooling the accumulator [30].

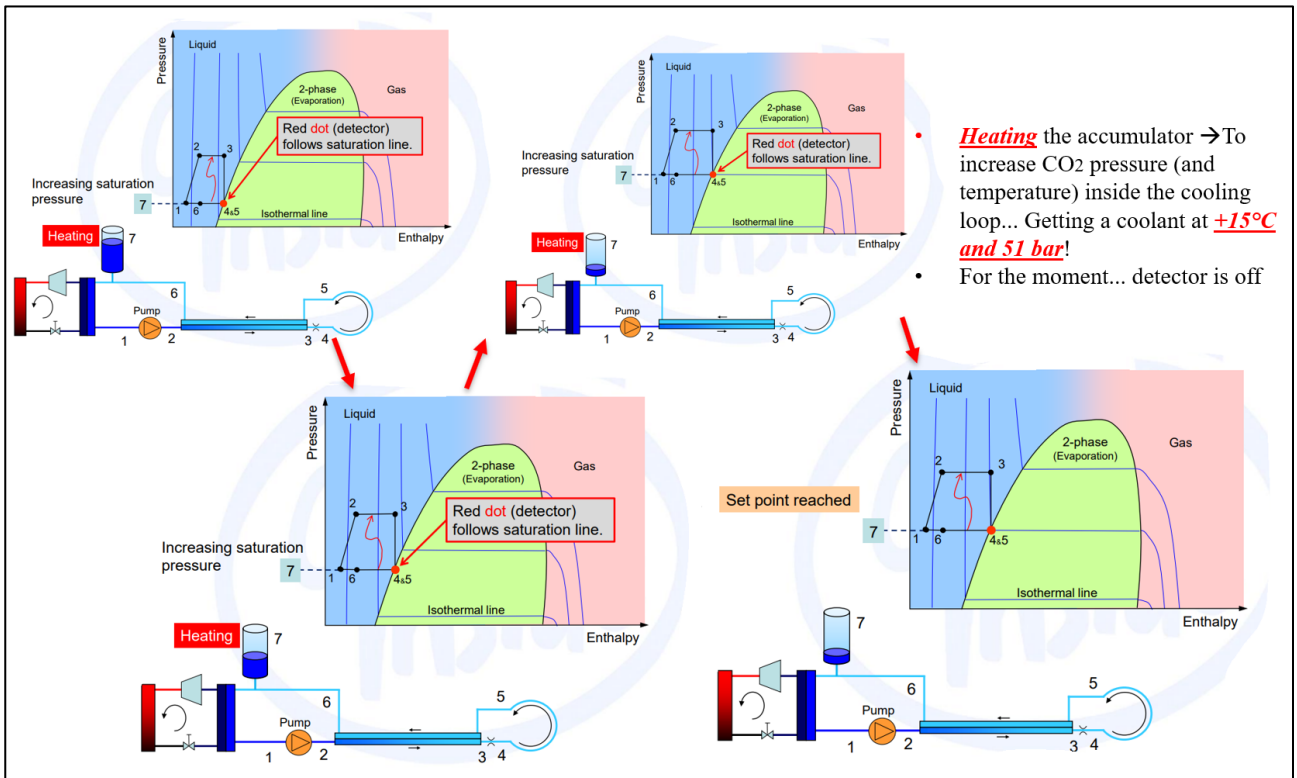


Figure 30 -2PACL system reaching the operating point of 51 bar, heating the accumulator [30].

3.4.1 Lyon Cold room and TRACI CO₂ plant

A large part of the tests and thermal studies I conducted as a technical student at CERN were carried out in the Lyon Cold Room located in building 186-R/S20 on the Meyrin site of CERN. The Lyon Cold Room is a refrigerated cell that can be accessed and inside it various setups were placed, which will be shown in the following chapters. These setups allowed for testing some of the structures that make up the outer Tracker ring for the TBPS sub-detector, ladders for the TB2S sub-detector and other components characteristic of the cooling system, such as the preheaters. Most of these thermal tests were conducted using a CO₂ plant based on the 2PACL operation described above, called TRACI version 2.3 or TRACI+. TRACI is a small cooling plant, optimized for reduced costs and easy operation while maintaining maximum flexibility. In fact, the plant can operate within a temperature range of -35°C to +22°C with a cooling capacity of up to 450 W, depending on the cooling temperature. The following table shows the operating limits of the plant using two operating temperatures that will be used in many tests in the next paragraphs.

Table 2 – TRACI operating values at 51 and 12 bar.

Pressure [bar]	12	51
Temperature [°C]	-35	+15
Flow range [g/s]	0.5-3.1	0.5-3.5
Max pressure drop [bar]	10	10
Cooling capacity [W]	400	450

To underline it's that the settings at 12 bar, are used to run tests at operating temperature, so with CO₂ two phase flowing at -35°C at the outlet of the system, while the data at 51 bar are used to run tests with CO₂ at +15°C, temperature just a little higher than the room temperature dew point simplifying some kind of tests since can be done without the use of dry gas, that must be used to run tests at -35°C in order to avoid condensation, dangerous for the fragile mechanical structure of the Tracker to test.

As can be seen from the following PI diagram built on LabVIEW to control the operating values of TRACI plant, it can be easily observed all the components of the 2PACL cooling system. This diagram was implemented to control the operating values of the plant (pressure, temperatures and flow to the experiment) during the tests.

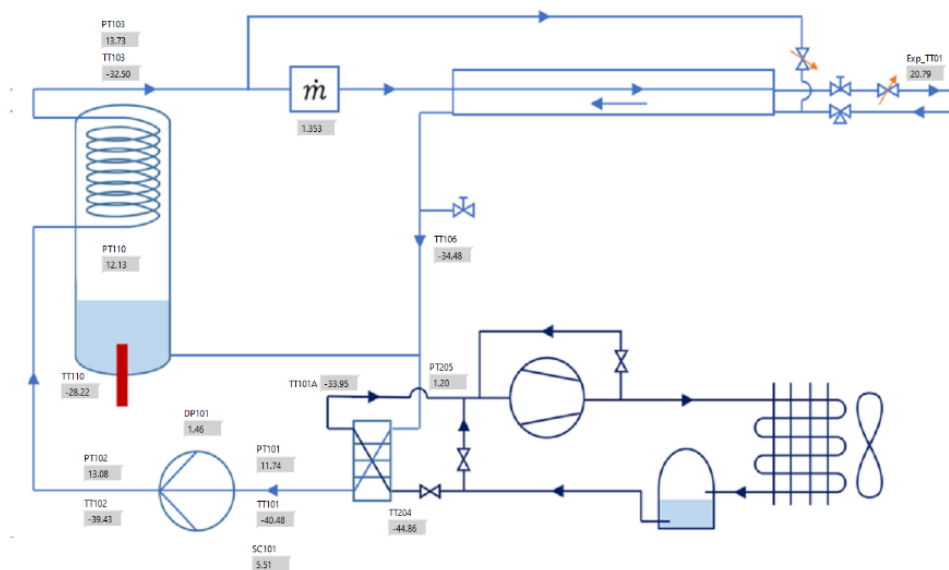


Figure 31 – TRACI piping and instrumentation diagram on LabVIEW.

The TRACI plant is placed outside the Lyon Cold Room, to avoid the heat dissipate by the chiller to interfere with the temperature of the room and the saturated liquid CO₂ produced arrived inside the Cold Room through a coaxial transfer line (as it is in the real 2PACL cooling plant design). Inside the cold room the coaxial transfer line is connected to the local box (figure 32) that is used to connect and disconnect each experiment and to make the vacuum inside the experiment.

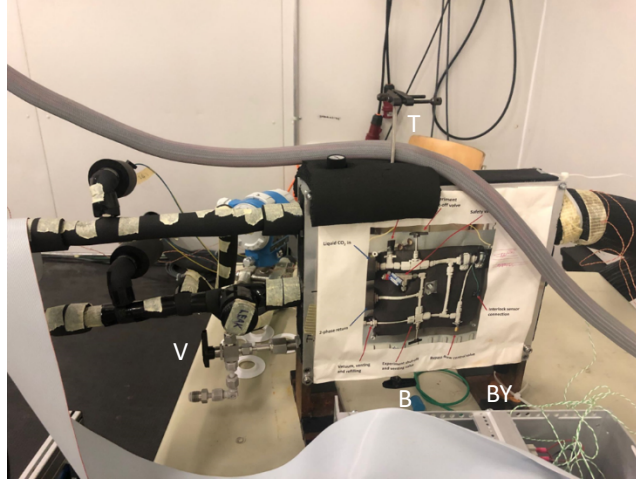


Figure 32 – TRACI local box inside the Lyon cold room

This local box is made of 4 main valves:

- By-pass valve (BY): when this valve is open, the CO₂ coming from TRACI does not flow to the experiment but instead circulates in a closed loop. This is the setup used when the experiment is disconnected. By closing the needle valve, however, it becomes possible to regulate the flow of CO₂ directed towards the experiment.
- Three-way valve (B): positioned at the bottom of the box, this valve allows to either connect the experiment to the by-pass loop or redirect it to the second three-way valve (V).
- Second three-way valve (V), also known as the vacuum valve: this valve is used to link the experiment to the VCR ¼ inch connector, which allows the connection of a vacuum pump to create a vacuum inside the experimental setup. The vacuum is necessary to prevent air (non-condensable gases) from entering the system and to avoid moisture from the atmosphere solidifying into ice at operating temperatures below 0°C, which could interfere with key components of the system, such as the pump.
- Ball valve (T): located at the top, at the CO₂ inlet, this valve controls whether or not CO₂ flows into the experiment, working in conjunction with valve B.

On the inlet and outlet pipes, the following sensors are installed to monitor the CO₂ parameters entering and exiting the experiment:

- 2 absolute pressure sensors, used to measure the absolute pressure of the CO₂ at both the inlet and outlet.
- 1 differential pressure sensor (Endress+Hauser PMD75-24J6/0), used to assess the pressure drop across the experiment.
- 2 temperature sensors (SW-Druck-Mantel-Widerstandsthermometer, PT100 Calss A, 4-wires), embedded within the flow, to monitor the temperature of the CO₂ inside the pipes (these were added in July 2024 to upgrade the measurement system).

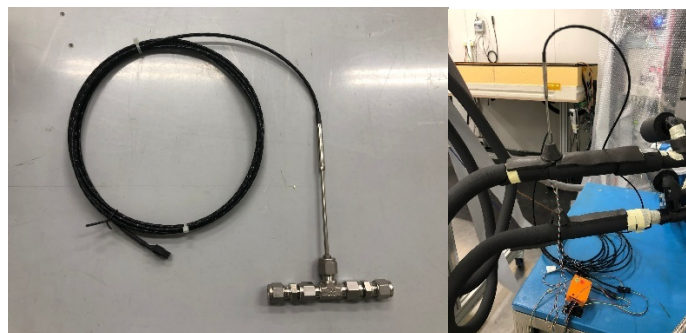


Figure 33 – Pt100 and Tee Swagelok fitting used to place the sensor inside the flow at the inlet and outlet of the experiment. On the right picture is shown also the MiniTRS, flexible device connected WiFi to the CERN network used to read the measurements.

The following sub-chapter outlines several useful procedures that I successfully tested and implemented to safely connect an experiment to the local box.

3.4.1.1 Procedure to connect a general experiment to TRACI

The following procedure can be used to connect a generic setup to the TRACI system located in the Lyon Cold Room at CERN (building 186-R/S20). Once the experiment is connected, the next step is to create a vacuum within the system. This is done as follows:

- 1.a. Begin by connecting the vacuum pump to the system. Attach the VCR connector (with a ¼-inch gasket) from the vacuum pump to valve V of the local box.
- 1.b. Turn on the vacuum pump to initiate the process.
- 1.c. Adjust the valves as follows: open valve V, ensuring the arrow on the valve is pointing downward. Keep valve T closed. For valve B, position it so that the bypass loop is closed off from the experiment (with the arrow pointing to the left) and fully open the bypass valve (BY) by rotating it counterclockwise.
- 1.d. At this point, check for any leaks in the circuit. The pressure should stabilize around $P = 0.04$ bar, with a maximum acceptable pressure of 0.07 bar at both the inlet and outlet. If the pressure remains within these limits, it indicates that there are no significant leaks in the system.
- 1.e. Once the vacuum has been successfully created, close valve V. If the vacuum has been properly established, the pressure should stay constant at the values mentioned above. This confirms that there are no leaks inside the system, and the experiment is ready to be connected to the CO₂, which will be supplied at high pressures.



Figure 34 – Interface of TRACI CO₂ plant

To safely start TRACI, follow the steps below:

- 2.a. First, ensure the system is in the following configuration: valve T should remain closed, valve B should be positioned to the left, valve V should be closed and the bypass valve (BY) should be open.
- 2.b. Now, start TRACI by pressing the "start" button located on the front panel of the cooling plant (figure 34). Upon starting, the subcooling (SC101) will initially display a negative value, which is normal and dependent on the ambient temperature. This indicates that the system does not yet have fully liquid CO₂ present before the pump.
- 2.c. Once TRACI has started, the "pump pre-operation" button will begin to flash. At this stage, it's crucial to monitor the subcooling value, which needs to increase to +1°C. Without sufficient liquid CO₂ before the pump, it cannot safely start due to the potential issues that arise from cavitation.
- 2.d. When the subcooling temperature reaches +1°C, the pump will automatically start and the temperature of SC101 will gradually rise to the operating conditions required for proper functioning.
- 2.e. However, if the subcooling temperature does not reach +1°C within 5 to 10 minutes, this indicates that there is not enough CO₂ in the system. In this case, the plant will need to be refilled (refer to section 3.a of this chapter for the refilling procedure).

The refilling process is necessary when there isn't enough CO₂ in the system. For this procedure, you must have a CO₂ liquid bottle ready for use, usually stored behind the machine. The pressure inside the CO₂ bottle corresponds to the ambient room temperature (since it's a two-phase system inside the bottle). For example, at 15°C, the pressure will be around 51 bar. For safety, the CO₂ bottle should always be secured with a chain, and when not in use, it should be connected to the safety cap (illustrated in figure 35).

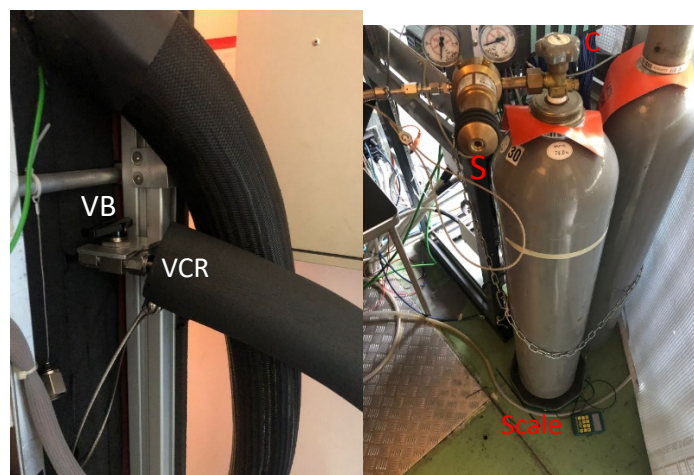


Figure 35- On the left, the valve and ¼" VCR connector used for refilling TRACI from the CO₂ bottle on the right.

- 3.a. Ensure TRACI is off before beginning the refilling process.
- 3.b. Reduce the CO₂ pressure in TRACI. Since the goal is to add liquid CO₂, we need the internal pressure of the system to be around 3 bar (this can be checked by monitoring the PT101 pressure value on the LabView program). To do this, open the valve VB located behind TRACI. (Note: lowering the pressure to 3 bar facilitates the immediate availability of liquid CO₂, as removing more vapor CO₂ speeds up the process.)
- 3.c. Place a scale under the CO₂ bottle to measure the amount of CO₂ being added to the system.
- 3.d. Open valve S fully.
- 3.e. Close valve C.
- 3.f. Tight a bit the VCR connector located behind TRACI (ensure that a ¼-inch gasket is placed on the connector, but do not fully tighten it).
- 3.g. Open valve C. CO₂ gas will begin escaping from the VCR connection behind TRACI. Pay close attention to the escaping gas: when you see the "white gas" (indicating that liquid CO₂ is coming out), immediately close the VCR valve. This signals that liquid CO₂ is now available in the system.
- 3.h. Turn on the scale to measure the amount of CO₂ being added during the refill process.
- 3.i. Open valve VB to start refilling the system with CO₂. The process will stop automatically when the pressure inside the plant's accumulator equals the pressure inside the CO₂ bottle.
- 3.j. Monitor the amount of CO₂ added. A maximum of 1.5 kg of CO₂ should be added to TRACI. However, this amount is not always reached in a single refill operation. If this happens, TRACI should now be in a

state ready for operation and you can attempt to start the system. If, after pressing the start button, the SC101 subcooling temperature doesn't rise above +1°C, repeat the procedure. Ensure that there is still liquid CO₂ in the bottle. If the CO₂ bottle is empty, replace it with a new one before proceeding.

3.k. Close valve VB to stop the refill process.

3.l. Close valve C.

3.m. Open the VCR connection to allow any remaining CO₂ to escape from the pipe. It's important not to leave liquid CO₂ in the pipe, as it will expand and cause the pressure to increase, potentially damaging the connectors.

In the event that insufficient CO₂ (good values are between 1.2 and 1.5 kg) has been added, but TRACI has successfully started the pump and is operational, it is essential to complete the refilling process to avoid issues related to a lack of CO₂ in the system. Follow these steps to refill TRACI in this case:

4.a. Maintain the following setup in the local box:

- i. Close the top valve (T).
- ii. Open the bypass valve (BY).
- iii. Set the bottom three-way valve (B) to the left position.

4.b. Set the target pressure for TRACI: the target pressure for TRACI should be set to 25 bar. This pressure must be lower than that of the gas bottle to facilitate the flow of CO₂ from the bottle into the plant's accumulator.

4.c. Monitor the pressure: wait until the pressure in TRACI reaches the designated setpoint of 25 bar.

4.d. Repeat the refilling process: once the pressure is at the setpoint, repeat the refilling process as outlined in the previous steps (3.a) to ensure that sufficient CO₂ is available in the system.

To ensure a successful testing phase with TRACI, follow the steps outlined below for connecting the experiment and managing the necessary operational conditions:

5.a. Begin by connecting your experimental setup to TRACI. It is crucial to maintain a vacuum within the experiment throughout this process. Once the setup is connected, open valve B in the right direction to pressurize the experiment. Next, open valve T at the inlet to allow CO₂ to start flowing into the setup. After ensuring that CO₂ is flowing, close the bypass valve to direct all CO₂ flow into the experiment, maximizing the effectiveness of the cooling system.

5.b. Set the desired flow rate for your experiment by adjusting the valve located behind the TRACI unit. This valve regulates the pressure differential created by the pump and consequently controls the flow of CO₂ into the experiment. Ensure that the flow rate aligns with the specifications required for your testing parameters.

5.c. Adjust the system pressure to the target level necessary for your test. For example, if you are conducting a test with CO₂ at -35°C, set the pressure to 12 bar. Once you have set the pressure, allow some time for the system to stabilize and reach the desired operational conditions.

5.d. After the test is complete or if you need to disconnect the setup for any reason, follow these steps carefully:

- i. First, open the bypass valve to allow for a safe release of pressure.
- ii. Next, close the top valve (T) to prevent any further flow from the CO₂ source.
- iii. Then, close valve B (set to the left position) to isolate the experiment from TRACI.

5.e. Remove CO₂ from the experiment: open valve V to allow any remaining CO₂ to escape from the system. This step is important to ensure that there is no residual pressure in the ring once you disconnect the setup.

5.f. Stop TRACI: finally, turn off TRACI by following the appropriate shutdown procedure to safely power down the cooling system.

The last important procedure to mention for managing the TRACI system is the one used to create a vacuum within the entire system. This step is essential whenever there is air or humidity present in the system, as it ensures optimal performance by removing any contaminants. Here are the detailed steps to create a vacuum inside the plant:

6.a. To create a vacuum, there are two potential methods for connecting the vacuum pump to TRACI. However, the recommended approach is to connect directly to valve VB behind TRACI, as this method is more

efficient. Connecting the pump to valve V in the local box is not advised, as it requires creating a vacuum throughout the entire system, which can be time-consuming.

- 6.b. Begin by opening valve VB, which is located behind the TRACI unit. This allows the system to start the vacuum creation process.
- 6.c. Allow the pressure to drop to approximately 1 bar. This step is essential for preparing the system for the vacuum process.
- 6.d. Once the pressure reaches 1 bar, wait about an hour. This waiting period is important to allow any CO₂ liquid present in the system to evaporate fully, which will help ensure that the vacuum process is effective.
- 6.e. After the waiting period, connect the vacuum pump to valve VB. This connection is critical for creating a strong vacuum in the system.
- 6.f. Activate the vacuum pump and monitor the pressure as it drops to 0 bar. Note that the pressure may not reach a perfect 0 bar due to the sensor's tolerance; however, the vacuum should be sufficiently strong.
- 6.g. At this point, a vacuum has been successfully created within TRACI.
- 6.h. After creating the vacuum, you can proceed to repeat the refilling process starting from step 3.a to ensure that the system is adequately filled with CO₂.

3.5 Superheating and preheater component

Before concluding this section on the CO₂ cooling systems used at CERN, it is important to consider an interesting yet potentially dangerous phenomenon related to the cooling of sensor detectors using a two-phase system: superheating. The phenomenon of superheating occurs when a fluid's temperature continues to rise even after reaching its saturation temperature at a given pressure. In this state, the fluid behaves as if it were still sub-cooled in the initial phases of the evaporator and the heat received from the evaporator raises its temperature further. A semi-empirical model for describing this phenomenon has been developed by Baldinelli et al. [33] and it has been observed in numerous tests conducted at CERN using two-phase CO₂ as the cooling fluid.

The figure 35 below illustrates how CO₂ in the test setup described here experiences a temperature increase during the early stages of the evaporator before reaching the maximum superheating limit and then dropping to expected temperatures. In an evaporator, the subcooled liquid exiting the capillary is gradually heated by the detector modules and this gentle heating increases the likelihood of the superheating phenomenon.

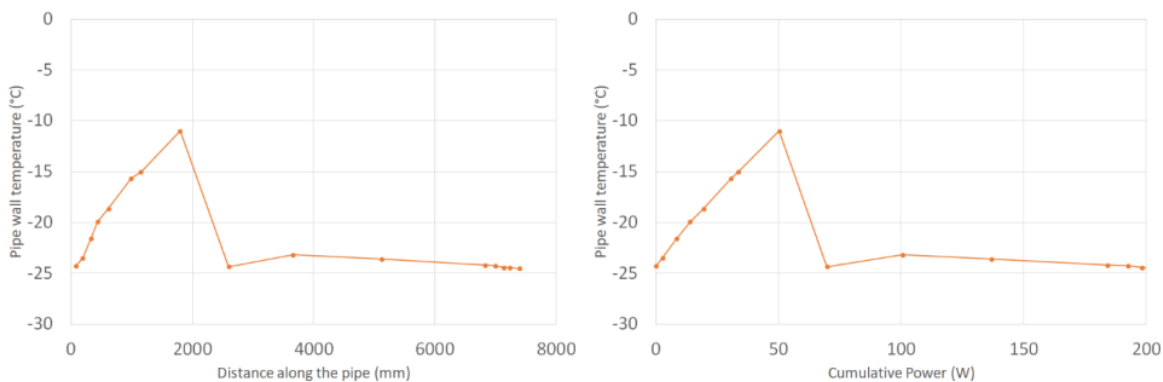


Figure 36 - Plot showing the phenomenon of superheating observed in numerous experiments at CERN. Here, the temperature of the CO₂ is plotted versus the distance from the beginning of the evaporator. The initial positions of the loop (specifically between 0 and 2000) experience a temperature increase, reaching -10°C, well above the saturation temperature of the CO₂ used in these tests, which was $T_{sat} = -23^{\circ}\text{C}$. [33]

The risk of superheating in the evaporators used to cool the CMS tracker detectors could lead to a sharp temperature rise in the first modules, operating well above the -20°C design temperature. This would occur for two main reasons: an increase in refrigerant temperature and a significant decrease in the heat transfer coefficient, which would resemble that of single-phase flow.

To address the superheating issue, two methods have been investigated[33]:

1. Superheat Limit Temperature: a liquid cannot be superheated indefinitely. There is a maximum attainable temperature known as the Superheat Limit Temperature, beyond which homogeneous volume boiling occurs.
2. Nucleate Boiling Initiation: this method triggers boiling before the fluid enters the cooling zone. It can be achieved through localized heat injection using low-power, high-heat flux element called “preheaters” (figure 37), or by creating a sudden change in geometry within the cooling tubes.

As it is perceived to carry the lowest risk, the use of high heat flux preheaters is considered the optimum solution for the CMS tracker upgrade cooling.

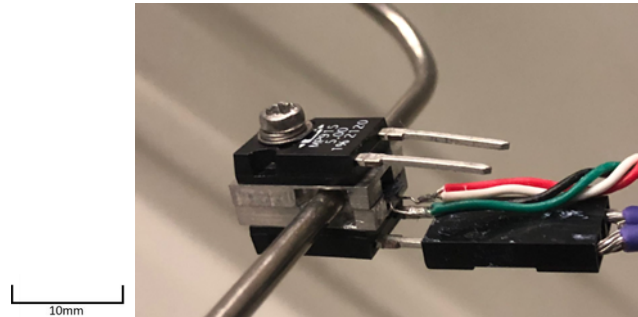


Figure 37 – A partially wired electric preheater’s prototype mounted on a cooling tube [34]

In the plot shown in figure 38, the temperature drop from the superheated scenario in an evaporator can be observed, using the preheater (shown in the figure) with varying power levels supplied to the CO₂ flow before it enters the pipe. The key outcome is the ability to trigger boiling immediately by using a compact component capable of delivering a high heat flux to the pipe. As shown in the plot below, supplying 8 W of power through a resistor placed upstream of the evaporator appears to be an optimal value to ensure effective cooling in the initial stages of the loop, thereby preventing the dangerous phenomenon of superheating. It is also interesting to show how, in the absence of a preheater, the achievement of the superheating limit conditions, known as the superheated limit temperature, can be provided by the evaporator itself. This means that the first modules in the cooling loop act as "preheaters" for the other modules, but they are exposed to higher cooling temperatures, which dangerously increases their own temperature.

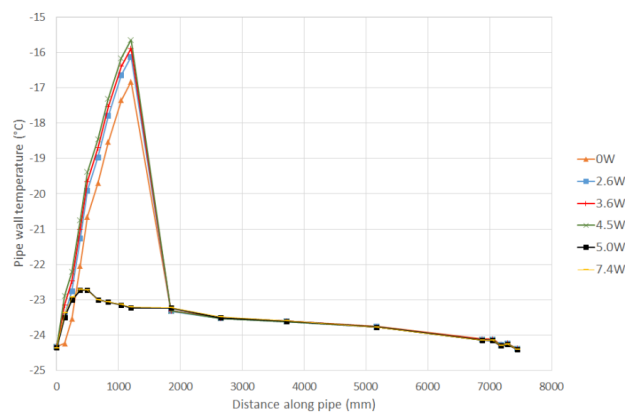


Figure 38 - Graph showing the effect of superheating in the first part of the cooling loop before and after activating the preheater using different power levels. This triggers the boiling of CO₂, preventing high refrigerant temperatures in the initial positions of the cooling loop ($T_{sat} = -23^{\circ}\text{C}$; $M = 1.4 \text{ g/s}$; Inner Diameter = 0.002m , $Q = 134\text{W}$). [33]

The choice of using a preheater in the cooling loop and placing it immediately after the capillaries and just before the evaporator allows the system to avoid the occurrence of superheating. Additionally, a second purpose of having a preheater in this section of the loop is to reduce the subcooling with which the flow would enter the evaporator. In fact, at the exit of the flow from the capillaries, the system is generally still slightly

away from the CO₂ saturated liquid curve to prevent boiling inside the capillary caused by the high pressure drop along this element that could increase the flow resistance and affect the flow balancing on a cooling segment with multiple evaporator loops. The amount of heat supplied by the preheater triggers boiling, allowing the flow to reach the CO₂ saturation curve entering the evaporator in two-phase condition.

Delivering this power output (8W) in a small component requires precise control of the thermal contact between the preheater and the cooling pipe. In fact, given the small size of the preheater (designed to ensure a high heat flux), it is crucial to ensure proper thermal contact between the preheater clamps (machined aluminium blocks that secure the resistors to the pipe) and the pipe itself. This is necessary to avoid the preheater surface reaching intolerably high temperatures. During my time as a technical student, I conducted various thermal studies to determine the optimal geometries for designing a preheater that would ensure efficient heat transfer from the heater (where power is dissipated) to the pipe. The results of these tests will be presented in chapter 7.

3.6 Tracker mechanical structures thermal quality control overview

The tracker designed for the Phase 2 upgrade of the CMS experiment is now entering the production phase. The construction of such a complex detector involves the collaborative efforts of numerous research institutes and universities from around the world, as well as the personnel at CERN. While not all components of the tracker are produced at CERN, all of the Tracker's components equipped with the actual modules will be integrated together in the clean room of Building 186, known as the TIF (Tracker Integration Facility).

All tracker structures in production require stringent quality control to ensure successful performance throughout the detector's lifespan. Among the various quality checks, thermal quality control of the mechanical structures supporting the modules is particularly crucial.

The purpose of these tests, conducted as the final step in the production process before integrating the actual modules into the structures, is to identify any production anomalies that could lead to thermal issues and provide an indication of the operational temperatures achievable by the modules using the produced structure. In this thesis, I will illustrate how the setups for thermal quality control (TQC) were designed for two specific mechanical structures: the rings of the TBPS sub-detector and the ladders of the TB2S sub-detector.

Generally, a test bench designed to identify thermal anomalies consists, primarily, of a support structure that houses the detector, as well as heaters that simulate the thermal power that the actual modules will dissipate and a CO₂ cooling plant that can provide the two-phase coolant. This enables the verification that the detector's cooling system is functioning as expected. By combining equations 4 and 6, and expressing the total power supplied to the evaporator from the individual module as defined by equation 2, we can formulate the following heat balance:

$$\dot{P}_{module} = HTC_{eq} \cdot (T_{module} - T_{CO_2}) \propto \dot{m} \cdot \Delta h$$

Equation 11

From this simple balance, it can be observed that the cooling capacity, defined by the right-hand side (the heat the cooling system can remove due to the thermodynamics of the phase change process), once the CO₂ operating temperature is fixed, depends on the CO₂ mass flow rate. The energy provided to the flow raises the fluid's enthalpy, increasing the vapor fraction. The heat dissipation capacity, or cooling power density, is described by the central term of the equation. Here, it becomes clear that, given the CO₂ operating temperature (flow and pressure setpoint), the only way to maintain the module at the target temperature is to ensure an adequate equivalent heat transfer coefficient (HTC_{eq}) between the module and the CO₂ flow. In simple terms, only by ensuring free and unobstructed heat transfer can the power generated by the module be effectively transferred to the cooling system. In summary, the heat produced by the modules, which in quality control tests is simulated by "dummy modules" (elements that provide the same thermal output as real modules with a very similar geometry), must be dissipated through the thermal contacts present in the mechanical structures. During testing, it is essential to ensure that the heat is dissipated without causing an excessive temperature rise in the

heating element itself (a sign of poor thermal conduction between the element and the CO₂) and that the cooling system design is adequate to remove all the heat produced (to ensure that the VQ at the end of the evaporator is the right one to avoid the dryout phenomenon).

Since the main objective of these tests is to validate the individual mechanical structure of the tracker, a vapor quality of 42% at the outlet has been used as a reference value to avoid detecting potential anomalies unrelated to the mechanical structure itself. This value has been determined to be optimal for ensuring sufficient cooling capacity throughout the entire evaporator, while also minimizing the risk of dryout in the final sections of the cooling loop. By maintaining this vapor quality, the system can effectively handle the heat load, ensuring that any detected issues are due to the mechanical structure and not cooling inefficiencies.

A final aspect to consider in quality control systems for highly specialized machinery like the CMS experiment detectors is the significant cost implications of discarding faulty elements. These structures are highly specialized, expensive and their production, far from mass manufacturing, requires highly specialized processes that are almost unique globally. Therefore, quality control, compared to generic industrial manufacturing processes, must be performed on every produced element with minimal impact on the structure's integrity (since handling during tests can degrade the quality) and without producing "false results" that could lead to the unnecessary rejection of functioning mechanical structures. For these reasons, one of the key elements in CERN's quality control systems is the development and validation of highly precise and meticulous procedures. These processes must minimize the risk of damage to the delicate structures being tested and avoid any potential errors that could compromise the accuracy of the results.

Careful analysis of the results obtained from each thermal test is of critical importance. As will be discussed later, during the development of the quality control procedure, several parameters were defined to accurately characterize a mechanical structure and assess its quality. The use of control parameters allows for the standardization of tests and quality control procedures. However, it is equally important that these parameters enable precise investigations, when necessary, in order to understand the root cause of any detected anomalies.

This means that while each component can be tested in a standardized manner to assess its thermal behaviour, it's essential to recognize that, due to the highly complex nature of these structures, specific components may require additional analysis when necessary. For this reason, it is crucial that quality control tests are conducted by specialized personnel, particularly those with a deep understanding of two-phase cooling systems. This expertise is key to diagnosing and investigating abnormal behaviours, should they arise during individual tests and ensuring that these anomalies are accurately addressed.

4. TBPS tilted rings TQC – Thermal Quality Control

One of the tracker's sub-detector currently in production at CERN is the tilted TBPS. TBPS stands for Tracker Barrel Pixel-Strip module and it is located in the outer tracker at the central part of the detector (hence "Tracker Barrel"). It houses PS-type modules, which are responsible for detecting the passage of particles originating from the collision point, or the reference axis origin in the diagram in figure 39. The term "tilted" indicates that in the new tracker designed for the Phase 2 upgrade of CMS, the modules are positioned at varying angles to point toward the LHC beam interaction point.

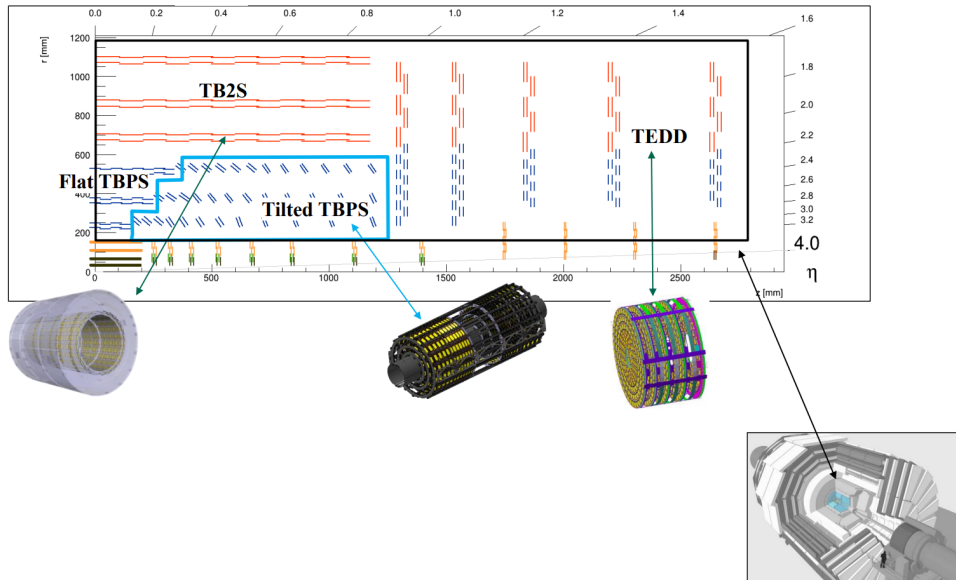


Figure 39 - Sketch of 1/4 tracker layout highlighting the position of the tilted TBPS [35].

This arrangement reduces the number of required modules but complicates the mechanical construction of the detector. The only way to accommodate tilted modules is to create circular-shaped rings, known as the tilted TBPS rings.

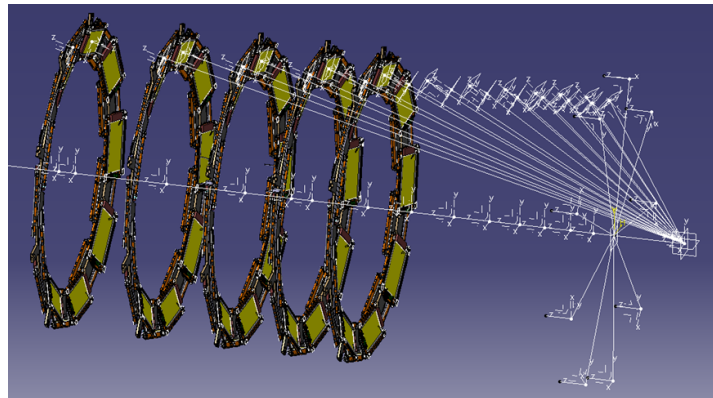


Figure 40 - CAD view showing the hermeticity of the TBPS tilted structure relative to the beam collision point in the CMS experiment.

The detector consists of three layers, corresponding to three different diameters of the rings: Layer 1 (L1, diameter 600 mm), Layer 2 (L2, diameter 850 mm), and Layer 3 (L3, diameter 1150 mm). For each layer, 24 rings will be produced. Since the tracker is symmetrical with respect to the collision point, there will be 12 rings on each side for each layer type. In total, the detector will comprise 72 different rings. Different degree of «tilted modules» are used to guarantee particle track hermeticity inside the detector. Considering the quantities for spares and prototypes, a total of 83 rings will be produced, as shown in the table below.

Table 3 – Production plan of the TBPS tilted rings [36]

Ring ID			Planned			
			Qty per layer	Spare ⁽¹⁾	Proto	Sum
L1	47	L1 47 A	4	1	1	6
		L1 47 B	2			2
	60	L1 60 A	2	1		3
		L1 60 B	4			4
		L1 60 C	2			2
	72	L1 72 A	2	1		3
		L1 72 B	4			4
		L1 72 C	4			4
L2	40	L2 40 A	4	1		5
		L2 40 B	2			2
	55	L2 55 A	2	1		3
		L2 55 B	4			4
		L2 55 C	2			2
	68	L2 68 A	2	1		3
		L2 68 B	4		1	5
		L2 68 C	4			4
L3	44	L3 44 A	4	1		5
		L3 44 B	4			4
		L3 44 C	4			4
	60	L3 60 A	4	1	1	6
		L3 60 B	4			4
		L3 60 C	4			4
Grand Total			72	8	3	83

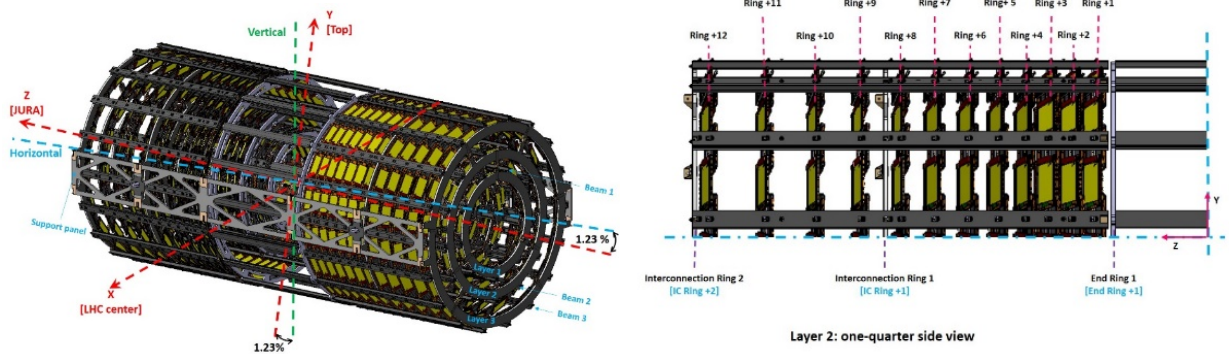


Figure 41 - Assembly of the TBPS tilted ring showing the 3 different layers of rings (left) and the one-quarter side view of the layer 2 ring assembly (right), displaying the 12 rings with different tilt angles to ensure hermeticity with respect to the collision point [36].

The TBPS rings are entirely produced at CERN in the EP-DT facilities, building 187. Each ring is assembled according to a precise manufacturing process, which requires the use of jigs for the bonding process of the various components that make up the ring. For this reason, the entire production process takes place here at CERN in a temperature-controlled room that was set up in 2021. This facility is key for high-precision assembly and gluing operations. Additionally, the facility includes a high-precision machining workshop, as well as laboratory and office spaces within the same building cluster (26).

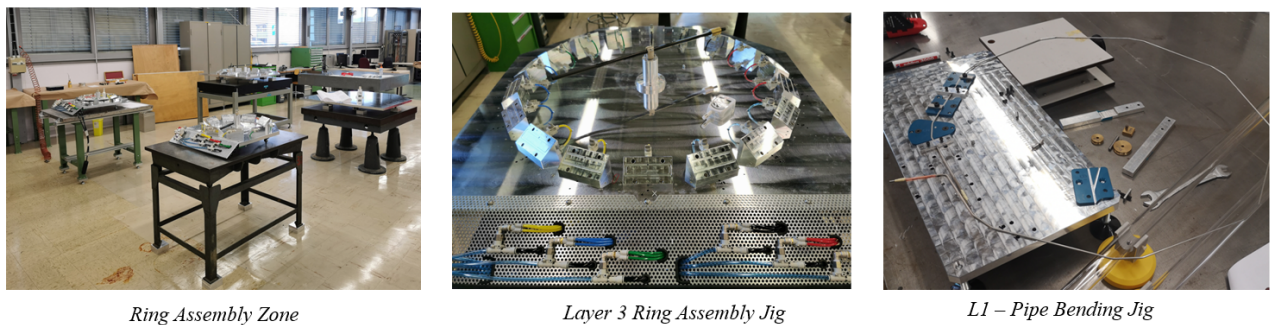


Figure 42 – Different tools in building 187 at CERN used for some stages of the ring assembly process [36].

4.1 TBPS tilted ring structure

Like all structures of the CMS tracker, the TBPS tilted rings are designed for maximum lightweight construction (mass for rings: L1=305 g, L2=530 g, L3=733 g). They are made from radiation-resistant materials to ensure optimal performance (including the cooling of the PS modules) even at the end of the detector's lifetime, with high integrated luminosity rates (3000 fb^{-1}) and a safety margin of 50%. A TBPS ring consists of a main structure made of a carbon fiber and Airex sandwich, providing the circular structure of the ring with both rigidity and lightweight properties. Positioned above the sandwich is the cooling pipe, which is composed of two loops: an inner cooling loop and an outer cooling loop, connected by a copper U-tube that is brazed to form the connection. The two faces of the ring (inner and outer) are where the cooling plates are assembled. These cooling plates are installed to completely cover the circumference of the ring with PS modules, ensuring that there are no gaps where the detector cannot identify the presence of particles.

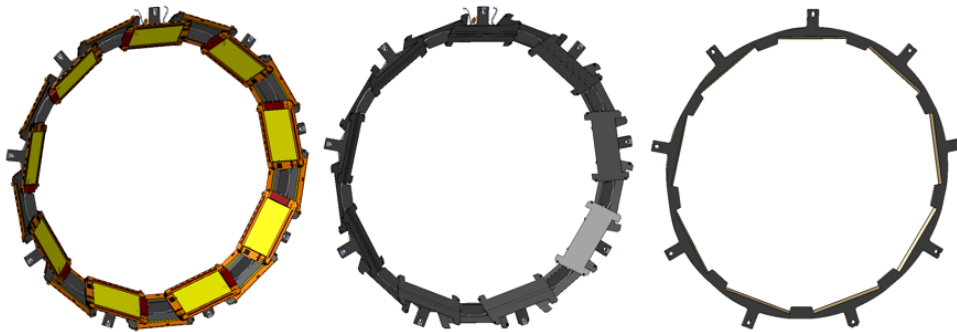


Figure 43- From left to right: the TBPS tilted ring integrated with the CAD model of the PS modules, a CAD view of the assembled ring where the carbon fiber "cooling plates", on which the modules are placed, are visible and the sandwich structure of the ring that ensures rigidity while maintaining the lightness of the structure [35].

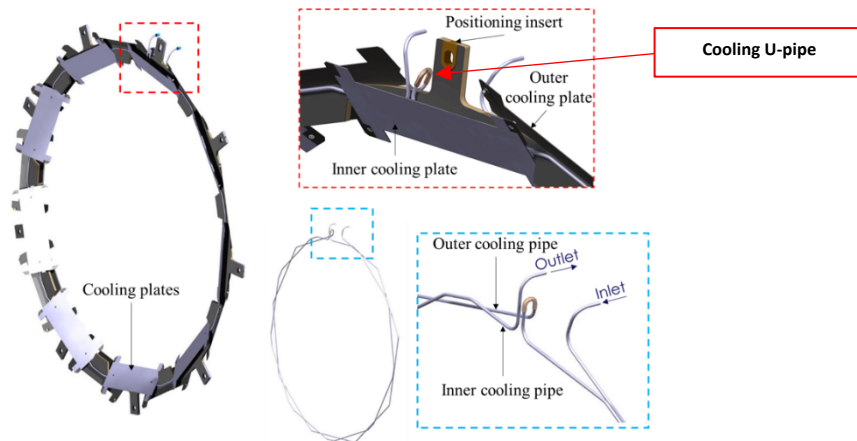


Figure 44 – The cooling loop inside the TBPS ring is used to cool the modules positioned on the outer side and the inner side. The U-pipe, highlighted in red, is located behind the module in position $N/2 + 1$ (N = total number of cooling plates) and is necessary to connect the two sides of the cooling loop [35].

Table 4 – Main materials used for the TBPS ring production

Component	Material
Sandwich Plate Ring	M55J/DT120 carbon-fibre/epoxy + Airex R82.80
Cooling Plate	K13D2U/EX-1515 carbon-fibre/cyanate ester
Cooling Adapter	AlCF 4ppm aluminium/carbon-fibre
Cooling Pipe	Stainless steel 316L
Cooling Pipe conn.	CuNi 70/30
Cooling U-tube	Cu
Positioning inserts	PEI

To ensure good thermal contact between the module, positioned above the carbon fiber cooling plate and to guarantee effective thermal conduction between the plate and the pipe (where CO₂ flows at approximately -35°C) it is necessary to use adaptors made of Aluminum Carbon Fiber (AlCF) for this specific application. This specialized material combines the lightweight structure of carbon fiber with the good heat conduction properties of aluminum. AlCF is particularly useful in applications where weight, thermal conductivity and thermal expansion are primary considerations, such as in the CMS tracker detector (as discussed in Chapter 5, the same material is used in other parts of the TB2S sub-detector). Compared to aluminum, AlCF has a thermal conductivity of 230/120 W/m·K in-plane/through-plane, versus 237 W/m·K isotropic for aluminum and a density of 2.4 g/cm³ compared to 2.7 g/cm³ for aluminum. Given these values, AlCF's thermal conductivity is lower and the small gain in density does not alone justify using a material that is expensive, challenging to machine and prone to potential manufacturing defects. In fact, one challenge with AlCF is achieving precise machining, as processing it generates significant dust that, if not well-controlled, can prevent reaching small tolerances. The main advantage that makes AlCF appealing for high-energy physics detector applications is its Coefficient of Thermal Expansion (CTE) of 4/24 ppm/°C in-plane/through-plane, compared to 23 ppm/°C isotropic for aluminum. For components around 10 cm in length, such as the cooling adaptors for the TBPS rings, aluminum would cause significant stress on the modules when the ring is cooled, given that the CF structure has an almost zero CTE. In contrast, carbon fiber alone is unsuitable for manufacturing complex three-dimensional elements where heat must travel in all directions. In summary, AlCF offers an ideal combination of density, thermal conductivity and low CTE for fabricating critical mechanical elements in specific locations of cold detectors, such as the TBPS tilted rings. In these structures, the AlCF adapter is bonded into specially designed cavities in the cooling plate and the cooling plate, along with the adaptor, is bonded to the pipe using specialized adhesives that are resistant to radiation and have good thermal conductivity.

The integration of the actual module (which will occur later at the INFN labs in Pisa) follows the procedure defined in figure 45. A conductive thermal paste is applied above the cooling plate to maximize all contact surfaces and minimize air gaps between the module and the cooling plate. The PS module is then placed on this layer and secured using three screws (M1.6) and a clamp. The grounding of the module is ensured through contact between the ears of the cooling plate and the module structure.

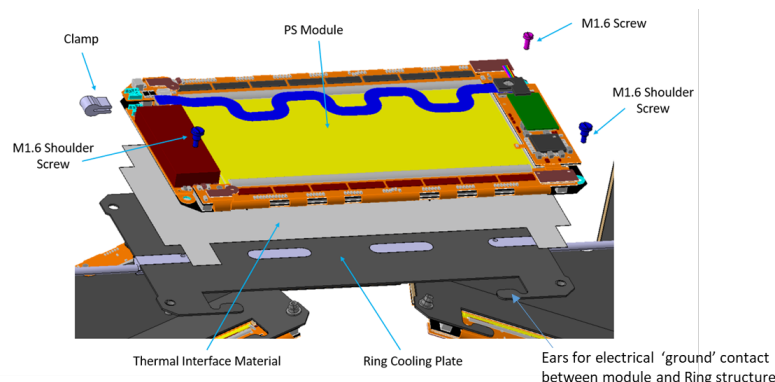


Figure 45 - Connection between the module and the cooling plate, where it is possible to see the thermal interface material placed between the two, aimed at improving thermal contact. For thermal quality control, the contact will be "bare," without any additional material between the cooling plate and the "dummy module" [35].

Every ring produced in building 187 undergoes various quality control checks, including geometry assessment to ensure that the ring dimensions meet the design specifications, stiffness under load and mass. All these tests are conducted within the same building used for production. Only after passing these checks the ring is ready for the final step to validate its quality: thermal quality control. As shown in the flowchart below, this takes place in the Lyon Cold Room in building 186, where the ring can be connected to a test setup specifically designed to interface each type of ring with TRACI, a two-phase CO₂ system based on the 2 PACL principle (described in chapter 3.4.1).

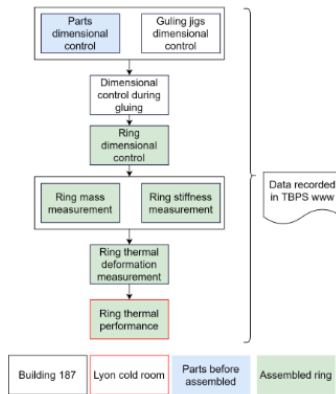


Figure 46 - Quality control tests performed on the TBPS rings. The thermal quality control, done in the Lyon Cold room, is highlighted in red [36].

Here, each ring undergoes two tests: one with two-phase CO₂ at +15 °C and 51 bar, which can be conducted without removing humidity from the environment where the test is performed, as the dew point temperature of the room is around 12 °C, thus preventing the possibility of creating harmful condensation. This test at +15 °C is used to perform thermal quality control through monitoring parameters developed after the testing phase of the initial prototypes and pre-production rings. With this test, it is possible to easily inspect the ring for any defects, attempt to correct them if feasible, and repeat the test multiple times. Once the ring's quality is assessed and/or any non-modifiable “small” anomalies are identified, the process moves on to the test with two-phase CO₂ at -35 °C and 12 bar, which simulates the actual operating conditions of the ring. This provides insight into how any anomalies detected in the +15 °C test may manifest at the -35 °C test, giving an indication of the operating temperatures of the modules and allowing for an initial thermal cycle to be performed on the ring structure for validation.



Figure 47- Rings L1, L2, and L3 ready for shipment to the Lyon Cold Room from the production building for thermal quality control.

4.2 Thermal test setup and assembly procedure

The production phase and initial quality control tests are carried out in building 187, while the test setup for thermal quality control takes place in building 186. The two buildings are approximately 1 km apart, so once the ring is ready, it is transported using specially designed equipment to the Cold Room in building 186.

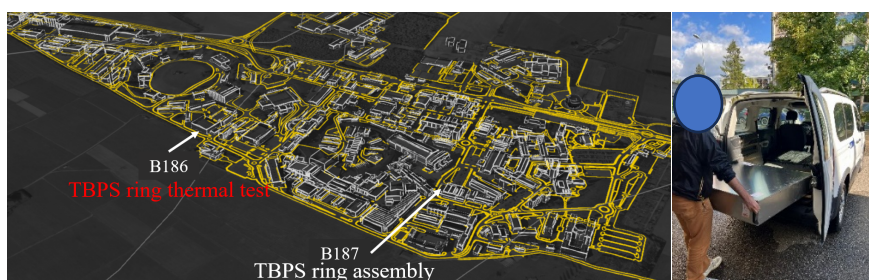


Figure 48 - (Left) Stylized map of the CERN Meyrin site, (Right) Photo taken during the transportation of an L2 ring.

Once each ring has undergone thermal testing in the Lyon Cold Room, it's shipped to Pisa, where the delicate operation of integrating the actual PS modules will take place at the INFN facility. Afterward, the ring will be sent back to CERN, specifically to building 186, to the TIF (Tracker Integration Facility) where the assembly of the entire tracker will take place.

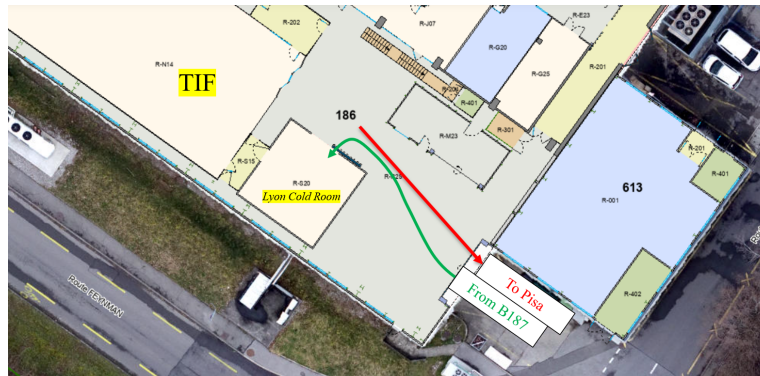


Figure 49 - Map of CERN building 186, highlighting the Lyon Cold Room, the area dedicated to the thermal quality control of the rings, and the TIF (Tracker Integration Facility).

Inside the Lyon Cold Room, there is a setup designed by Dr. Eng. Francesco Bianchi, consisting of a rotatable test bench that can be used to test every type of ring, specifically for each type of layer and tilt angle.

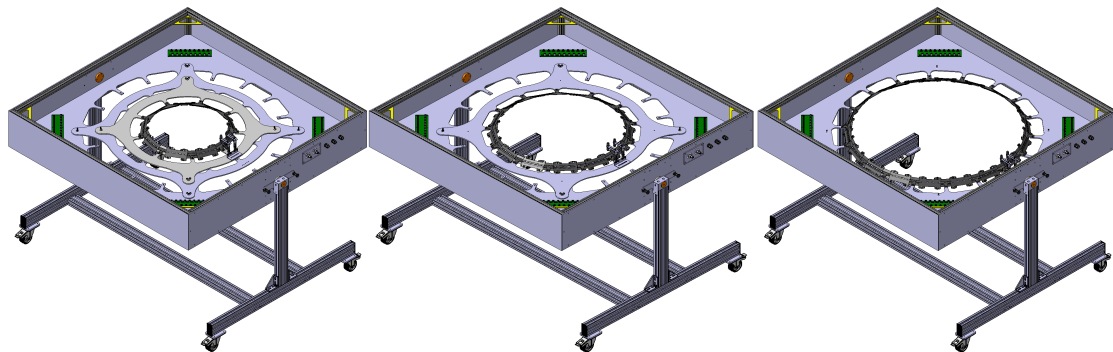


Figure 50 - CAD view of the thermal quality control test bench [37].

To power the rings, dummy modules are used. These heaters have the same geometry as the actual PS modules (see figure 51) and are designed to dissipate the 10W that a real module would generate, using two resistors placed on either side of the module. The dummy modules are always connected to the same positions, each with an identification number assigned according to the CO₂ flow orientation (for instance, P1 refers to the first position encountered by the CO₂ flow at the inlet of the evaporator). In this way, it's possible to ensure that any potential thermal behavior differences in the powering system do not affect the quality control process.

Each dummy module is equipped with an integrated Pt1000 sensor (RTD class A, with a four-wire connection) to monitor the temperature during testing, thereby verifying the cooling performance of the ring. During data processing, the temperature value measured in each module via the sensor integrated into the module's structure, shown in Figure 51, is determined by averaging a set of data collected once the module's temperature has stabilized. For each temperature value, approximately 1000 measurements are averaged. This process yields the actual temperature value of the module, reducing the accuracy error of the Class A temperature sensors. To enhance sensor accuracy and correct any measurement biases, the dummy modules are calibrated during each test after being assembled in the ring. This calibration is performed by sampling measurements in a controlled environment (before connecting the ring to the cooling and/or power system) and assessing the

offsets of each module relative to the average value measured by all the sensors in the modules. This offset is then used as a correction factor for the average temperature of each sensor measured during the testing phase.

The modules are connected to a single power supply (DELTA ELEKTRONIKA B.V. , SM 52-30), which allows the power dissipated throughout the evaporator to be adjusted. This is achieved through four PCBs located at the corners of the test box. Temperature readings are obtained via two MTRS (Multiple Temperature Readout System) boards, hardware developed at CERN, and the data is displayed and optionally stored using a LabVIEW program, which also monitors all other test parameters (CO₂ pressures and flow).

Additionally, to facilitate thermographic analysis, all dummy modules are coated with black paint (emissivity value used for the thermal picture is set at 0.97, which is standard for black dye), allowing for the study of thermal fields and providing further insights for quality control.

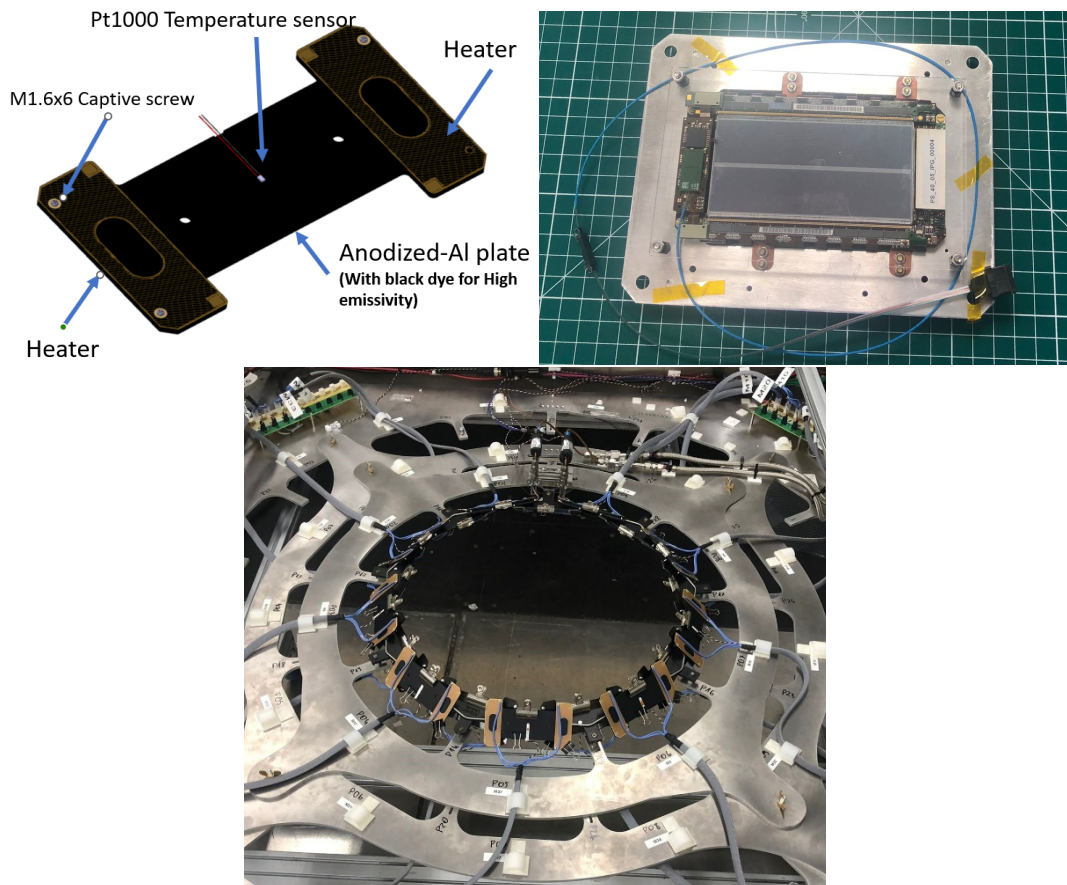


Figure 51 - Top left: dummy module with embedded resistors and temperature sensor used to replicate the power supplied by the real PS module (top right). Below is an L1 ring integrated with all 18 dummy modules for thermal quality control (TQC).

In addition to the data from the TRACI control system and the temperatures of the dummy modules, each test measures the CO₂ inlet and outlet temperatures, CO₂ inlet and outlet pressures, CO₂ flow rate, air temperatures and humidity levels within the test box. The connection of the ring to the setup is a delicate operation due to the manoeuvres required on the “fragile” structure. The following procedure has been developed to install each ring inside the box and assemble the test setup, in order to avoid variations in test conditions (to ensure the same quality control for all the rings produced) and, most importantly, to prevent any damage to the ring.

1. Checking the Mounting Screws

Prior to installation, it should be confirmed that the M4 captive screws, used to secure the ring to the test setup box, are installed with washers in the ring as received. Each ring typically requires between 3 to 5 screws, depending on the layer, though it is not necessary to have all screws installed for testing purposes. The mounting spots with screws should be evenly distributed around the ring, typically with screws installed in alternating spots.

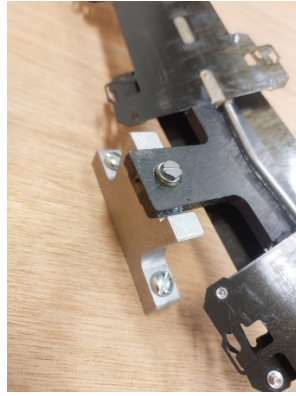


Figure 52 – Mounting screw presents in the ring “as received”. Between 3 and 5 screws are needed to secure the ring to the thermal test box. It is not necessary to install screws in every position, as this would cause greater mechanical stress on the structure.

2. Installing the Support Bushings

Threaded support bushings are installed inside the test box to match the screw pattern on the ring. Initially, these bushings should not be tightened, even by hand, but should instead remain loosely mounted within the elongated holes to facilitate easy position adjustment.

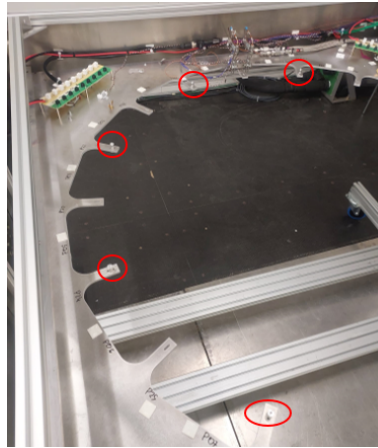


Figure 53 - Support bushings placed on the thermal test bench occupy every other position, matching the pattern of the mounting screws selected and positioned in the ring.

3. Adjusting the Pipe Support

The thermal test pipe support (appendix 1) should be retracted to ensure that no collision occurs with the ring during installation. If a different layer has been tested previously, the height of the support should be adjusted accordingly, as the height varies between layers. It is important to ensure that the copper pipes attached to the support are in contact with the aluminium base plate within the test box using cable ties. These pipes may need to be bent up or down by hand if any misalignment issues arise.

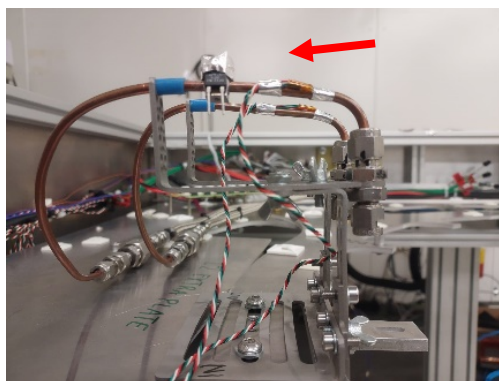


Figure 54 – Thermal test pipe support retracted to ensure the safe positioning of the ring on the test bench.

4. Moving the Ring into the Test Box

The ring should be carefully placed inside the test box. The ring should only be handled using the mounting handles and not by the module inserts. While this task can be completed by one person for Layer 1 (L1) and Layer 2 (L2) rings, it typically requires two people for Layer 3 (L3). Once the ring is positioned on the bushings, it should be confirmed that the bushings are inserted correctly into the counterbored holes of the mounting handles. The captive screws should then be tightened securely by hand, while the screws securing the bushings to the box should remain loose at this stage.

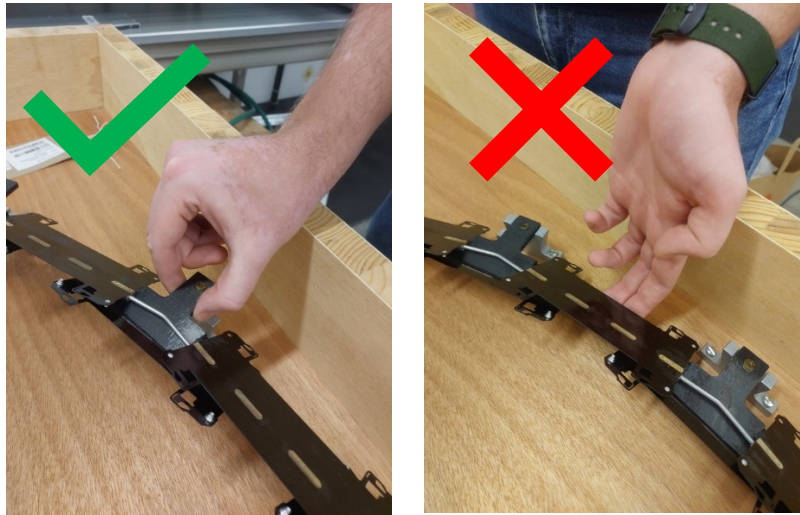


Figure 55 - Correct maneuver for handling the ring (left) and incorrect maneuver (right).

5. Connecting the Cooling Loop

At this point, the cooling loop of the ring must be connected to the pipes of the test setup. A specially designed support (referenced in the drawing in Annex 1 and in the procedure for how to use it in Annex 2) holds the quick-fittings and custom Swagelok connectors designed at CERN. These connectors utilize a rubber O-ring (Inner diameter 4.5 mm and outer diameter 6.5 mm), enabling the sleeves at the inlet and outlet of the ring's cooling pipe to connect without leakage, despite the high pressure of the CO₂ used during testing. Due to the low temperatures encountered during the -35°C test and the abrasive nature of CO₂, the O-rings deform and must be replaced after each test to prevent leakage in the loop. The following procedure was developed to connect the ring using this support, ensuring the cooling pipe (which is extremely prone to deformation) is not stressed and to preserve the integrity of the ring (Annex 2).

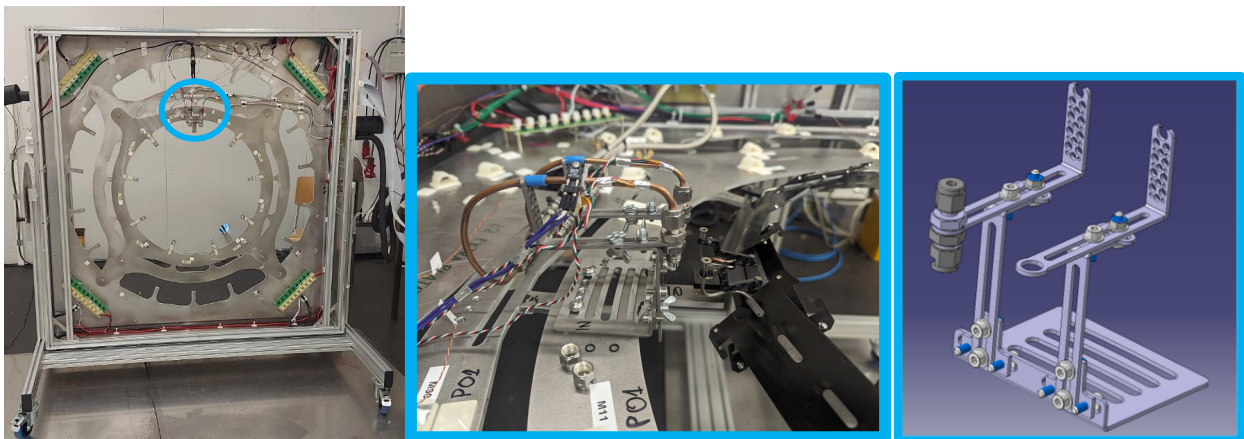


Figure 56 - TBPS thermal test support detailed in Annex 1 and 2.

6. Tightening the bushings

At this stage, once the connections are made, the bushings should be tightened securely using an Allen key.

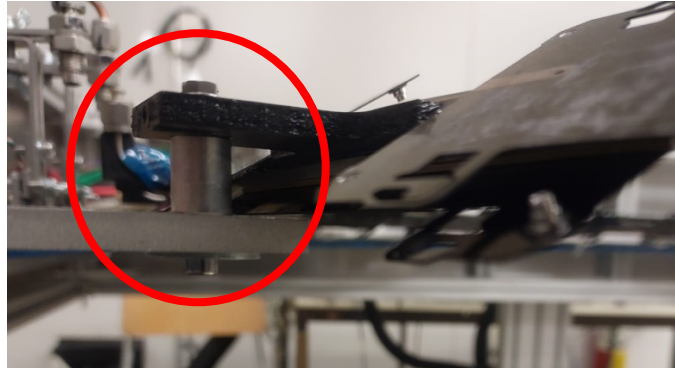


Figure 57 – Bushings to tight after the cooling loop connection.

7. Leak testing

An optional initial leak test may be performed using a vacuum pump or by introducing CO₂ into the system. Vacuum testing tends to be more reliable and faster for an initial check. If any leaks are detected, they can be more easily addressed before the installation of the modules.

8. Installing Dummy Modules

Dummy modules are installed in their designated positions as outlined in the tables provided in the Appendix 1. The M1.6 screws should be tightened using a torque screwdriver set to a maximum of 5.5 cNm. Once the modules are secured, the cables should be fixed using the designed cable clips, and the connectors plugged into the appropriate slots on the appropriate PCB placed on the corners of the box. It should then be verified via LabView that proper sensor output readings are received.

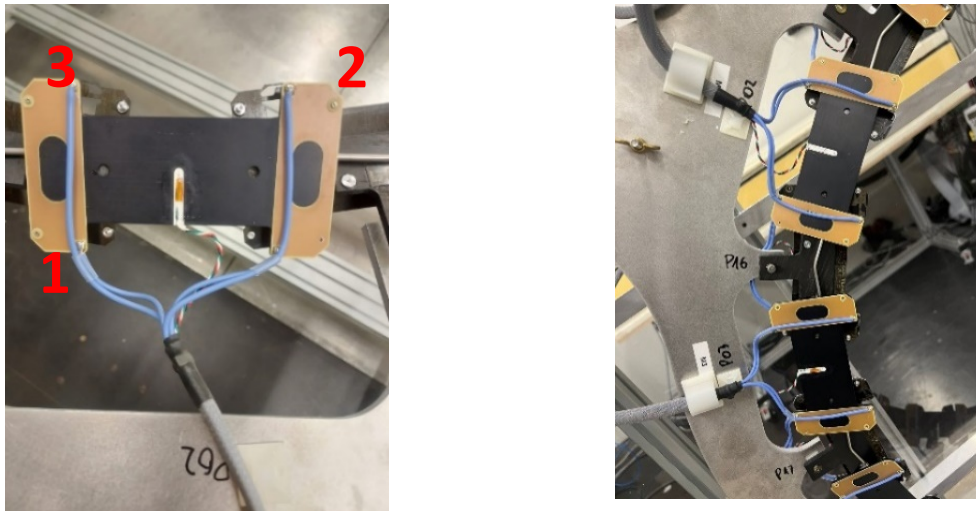


Figure 58 - Picture representing the 3 screws (labelled with red numbers) to tighten in order to place the dummy module on the ring (left) and cables secured to the setup using clips (right) to prevent loose wires.

9. Installing Clips on Dummy Modules

Once the dummy modules are installed, clips must be attached to ensure they are properly secured. Three clips are required to ensure good thermal contact between the module and the ring. The clip in the upper-left corner replicates the one used in the actual detector, while the other two clips are necessary to compensate for the slight lack of flatness in the dummy module. This unevenness, which could lead to imperfect contact between the dummy module and the cooling plate, is not due to any defect in the ring but rather to the powering system used during testing.

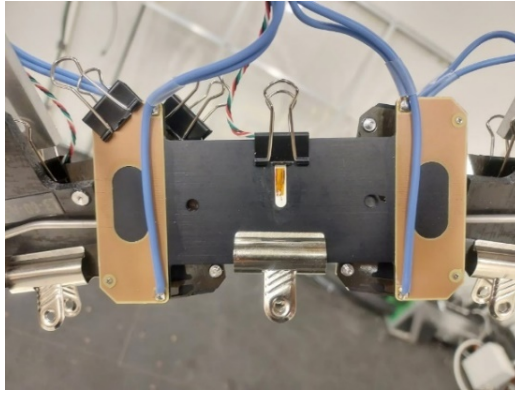


Figure 59 - The three clips installed in the dummy module to complete the fastening on the ring.

10. Connecting the Preheater's cables

The purple power cable is connected to the preheater, along with the temperature sensor.

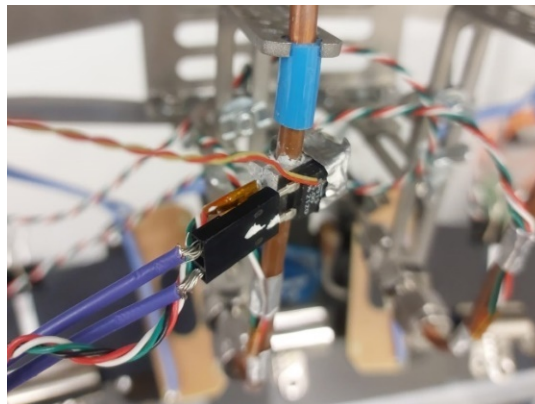


Figure 60 - Preheater, used to trigger the boiling of CO₂ if necessary, positioned at the beginning of the loop and connected with temperature and power sensors.

11. Attaching Thermocouple Sensors

Two thermocouple sensors, used for the interlock system, are attached to the PH block and the last position using aluminium tape. The interlock system is configured to automatically shut down both power supplies if necessary.

Table 5 - Settings of the interlock for the TBPS thermal test setup.

Default interlock settings	
Shut down temperature [°C]	>= 50
Hysteresis [°C]	25
Temp. required to turn on PSs after interlock trigger	<= 25

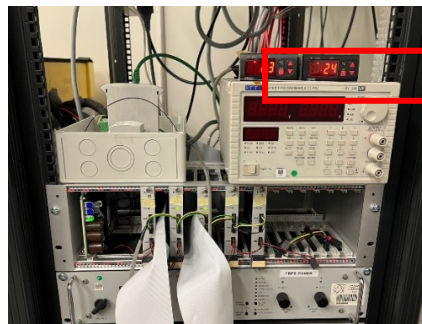
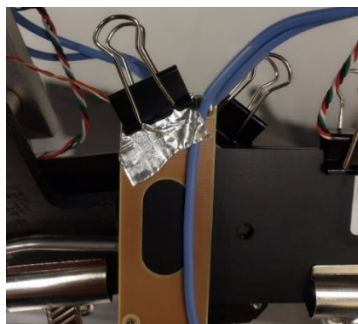


Figure 61 – Interlock sensor placed on the corner of the last dummy module and interlock temperature displayed on the two interface screens. The second interlock sensor is placed on the preheater (figure 60)

12. Starting the TRACI Cooling Plant

The TRACI cooling plant is then started following the instructions provided on chapter 3.4.1.1.

13. Ensuring Leakproof Operation

It must be verified that the test setup is properly sealed and vacuumed. The pressure sensors at the inlet and outlet should indicate values in the range of 0.02 to 0.06 bar. If the pressure is higher than this range, the system should be checked for leaks.

14. Running the +15°C Test

After setting TRACI to 51 bar (which corresponds to a CO₂ temperature of +15°C) and allowing the temperatures to stabilize, the test can begin. The lids should be closed to prevent external heat from the room's air conditioning system from affecting the results. It is crucial to ensure that the correct lids are used, as they are not identical and should be checked for proper labelling. The test can then proceed according to the parameters detailed in Appendix 2.

15. Thermography survey

Thermographic measurements should be taken without the lids in place, as the lids are made of PVC, which is opaque to infrared radiation. A FLIR E75 bolometric thermal camera, with the specifications shown in the Appendix 3, is used to perform the thermographic analysis. Each module is photographed individually, and a complete image of the ring, both from the front and back, is taken to provide an overview of the temperature distribution across the entire ring.

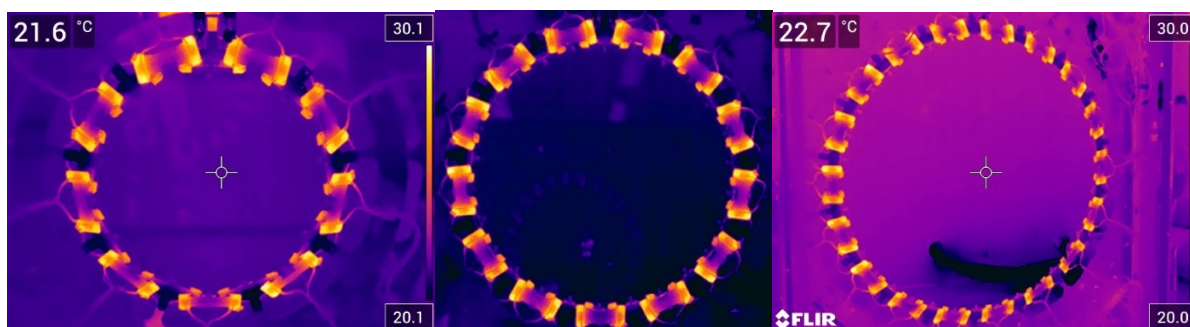


Figure 62 - Example of thermal images taken for a ring of L1 (left), L2 (center) and L3 (right).

16. Running the -35°C Test

To prepare for the -35°C test, the box should be flushed with dry, precooled gas at maximum flow until the humidity sensor inside the box registers a value close to 0.0% RH. Ideally, the dry gas should be allowed to flush through the box overnight to ensure adequate time for establishing proper testing conditions. Once a humidity level of 0% is achieved, the CO₂ temperature within the flow inside the experiment can be lowered by setting TRACI to 12 bar, corresponding to -35°C, as TRACI supply a two-phase flow. To reduce the effect of forced convection inside the box during data acquisition in the -35°C test, the dry gas must be turned off. The box's airtightness is sufficient to maintain dew point temperatures within the test box for a data acquisition window long enough to conduct the test.

17. Disconnecting the System

The power supplies should be turned off before closing any valves. The bypass valve should be opened before closing off the other valves to disconnect the setup from TRACI. The vacuum/drain valve should be opened as soon as possible to release any remaining CO₂ (as explained in detail in chapter 3.4.1). It is critical to avoid trapping cold liquid CO₂, as it will expand to over 100 bar when it transitions into gas. The test box should not be opened if the module temperature is below 10°C to avoid water condensations.

To prepare the setup for hosting the L2 and L3 rings, it is necessary to use the additional components found in Appendix 4: the L2 extra plate, which is used to secure the transfer line pipes inside the local box during the test of layer 2 rings; and the copper pipe extensions for L3, which are an extension of the transfer line pipes useful for connecting the larger diameter L3 rings.

All operations can be performed by one person, except for the transportation of the ring using the transport box, which requires two people. The estimated mounting time for the testing setup is approximately 3-4 hours, while the estimated dismounting time is around 2 hours. The time required to carry out the two quality control tests including all related activities such as transporting the ring, preparing the CO₂ TRACI system, conducting thermographic investigations and any additional investigations in the event of detected anomalies along with the data processing and saving phase, totals approximately 4 days (considering the time required for data processing, too).

4.3 TBPS TQC: outcomes

The thermal performance of each ring is evaluated through tests conducted with CO₂ at two different temperatures: +15°C and -35°C. These tests are designed to calculate key parameters that help monitor and control the ring's thermal performance.

The -35°C test is primarily a quality control check under conditions simulating the operating temperature of the CO₂, though not of the external environment. In reality, the external temperature inside the tracker is expected to range between -10°C and -20°C, while during the test, the air inside the box is kept around 10°C. This higher ambient temperature introduces extra heat into the cooling loop and the modules, leading to an overestimation of the module temperatures compared to real conditions in the detector. This represents a conservative approach for the test.

The main objective of both tests is to establish a consistent quality control method for all rings. The focus is therefore on ensuring the same key environmental parameters for all tests, making it possible to evaluate the tests comparatively and identify rings with worse thermal performance. The +15°C test is easier to conduct because it doesn't require dehumidifying the air inside the box. This allows quicker tests and enables direct intervention on the ring during the test (for example, through thermographic investigations), which is impossible in the -35°C test due to the sealed environment of the box. Furthermore, with the room temperature fixed at 20°C, the tests can be considered nearly adiabatic. The temperature differential between CO₂ and air is 5°C, which minimizes the impact of any natural convection currents that may arise within the box due to elevated temperature differentials during the quality control phase. This controlled environment ensures more accurate measurements and assessments of the cooling system's performance compared to the test conducted at -35°C, where the difference between air temperature and CO₂ temperature is around 40°C within the box. This larger differential introduces an uncertainty due to the heat received by the ring from the surrounding environment.

In both tests, the primary outcome is the measurement of the temperature at the center of each dummy module, which indicates the thermal performance at that specific cooling plate. The module temperatures reflect the quality of the thermal contact and thus the thermal resistance between the module and the CO₂ flowing through the cooling pipe (HTC_{eq} , equation 5). The modules are numbered sequentially according to the direction of the CO₂ flow and each number defines a "position" in the cooling loop.

All module positions are expected to behave similarly, except for the module located at position $N/2+1$ (where N is the total number of cooling plates or modules in the ring). For example, in L1-type rings with 18 modules, position 10 ($N/2+1$, where $N=18$) consistently has worse cooling "by design". This is due to two main reasons:

- The cooling plate at this position is where the external and internal cooling loops meet, via a U-shaped copper pipe. This position has less thermal contact with the cooling loop compared to other positions (figure 63).
- This module is cooled partly by the CO₂ flow from the external loop (which has already absorbed heat from the first $N/2$ modules) and partly by the CO₂ flow exiting the ring. For these tests, the CO₂ flow rate is set to maintain a vapor quality of 42% at -35°C and the same flow rate is used for the +15°C test, but the additional heat from the ambient air (which is not factored into the vapor quality calculation) may trigger early dryout effects, reducing the heat transfer coefficient (HTC) in the later positions, including $N/2+1$, as will be shown in the case study in section 4.3.2.2.

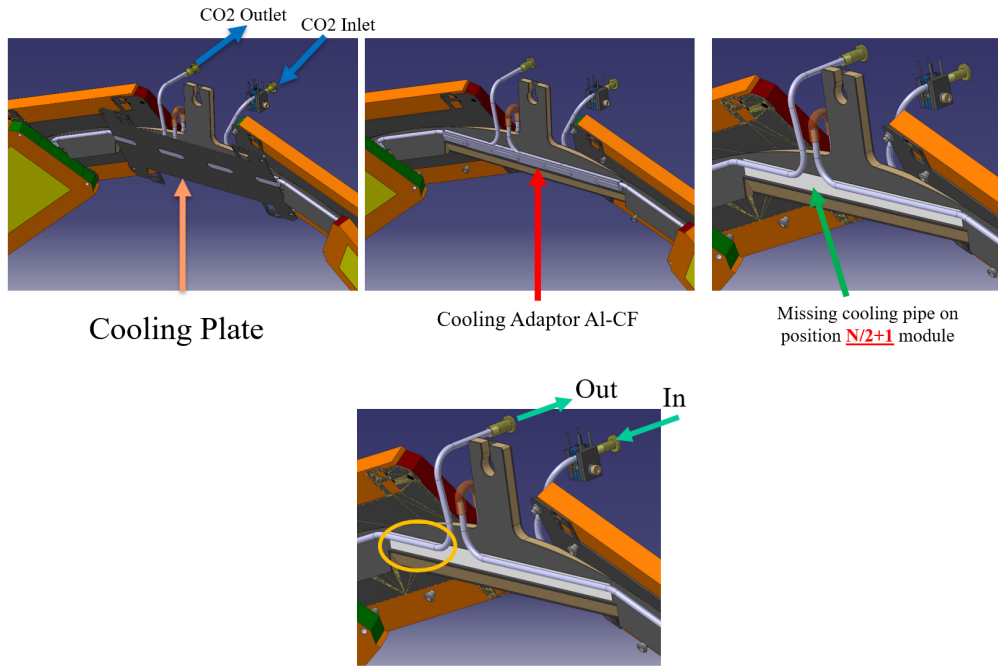


Figure 63 - Thermal resistances present between the cooling plate and the pipe at position $N/2+1$ of the TBPS rings. The shortest contact with the cooling pipe is highlighted in the photo at the top right, while the photo at the bottom shows the last section of the pipe, highlighted in yellow, that cools the module $N/2+1$ before exiting the loop.

The expected result for each test is a temperature profile where the module temperatures decrease from the first position to the last. This temperature drop is driven by the pressure drop in the CO_2 pipe, which leads to a corresponding drop in temperature. Furthermore, near the outlet, the CO_2 vapor quality increases, improving the cooling performance through annular boiling, where the HTC is higher. As a result, the modules closer to the end of the loop tend to be colder, while the ones near the beginning are hotter.

As will be shown in the test results, this temperature gradient is more pronounced in tests conducted at -35°C , where CO_2 exhibits a temperature drop of approximately 2.3°C per bar of pressure drop. In contrast, at $+15^\circ\text{C}$, with saturated CO_2 at 51 bar, the temperature drop is only 0.82°C per bar. Therefore, the decreasing temperature trend in the $+15^\circ\text{C}$ tests is less evident and can be masked by the thermal behavior of individual modules.

To effectively evaluate and compare the cooling performance of individual cooling plates, it is necessary to decouple the module temperatures from the CO_2 temperature. The goal is to focus on the thermal resistance encountered by the heat as it transfers through the mechanical cooling structure, independent of the CO_2 temperature at each position. To achieve this, the measured temperature of each module is compared to an ideal reference temperature, which accounts for the CO_2 temperature drop along the cooling loop. So, a control parameter DT , is calculated between the measured module temperature and the temperature of the interpolating line of the least squares that interpolates all the data points, taking into account the CO_2 temperature drop. In addition to this DT , the following parameters are used to characterize the thermal performance of each ring for both the $+15^\circ\text{C}$ and -35°C tests:

- $T_{\text{avg}} [^\circ\text{C}]$: average temperature of all module positions, excluding $N/2+1$ (the position with the worst cooling by design).
- $S_{\text{meas}} [^\circ\text{C}/N]$: the slope of the fitted line for the measured temperatures at different positions, excluding $N/2+1$.
- $S_{\text{th}} [^\circ\text{C}/N]$: the theoretical slope, calculated based on the measured pressure drop across the ring, and correlated with the theoretical temperature drop divided by the number of cooling plates (N).
- $DT_{N/2+1} [\text{K}]$: temperature difference between position $N/2+1$ and the fitted temperature line.
- $DT_{\text{RMS}} [\text{K}]$: root mean square of the difference between measured temperatures and the fitted line (excluding $N/2+1$).

- DTpos_max [K]: maximum positive difference between the measured temperature and the fitted line (excluding N/2+1).
 - Position DTpos_max: The position corresponding to DTpos_max.
- DTabs_max [K]: maximum absolute difference between the measured temperature and the fitted line, including particularly cold modules.
 - Position DTabs_max: The position corresponding to DTabs_max.
- F [g/s]: CO₂ mass flow rate measured during the test.
- DP [bar]: pressure drop measured across the ring.
- DT_AB [K]: temperature step between side A (outer loop) and side B (inner loop), helping to identify localized pressure drops at the U-pipe.
- DT_ABavg [K]: average temperature difference between side A and side B (excluding N/2+1), used to investigate potential anomalies similar to ΔT_{AB} but calculated differently.
- DP_nopower [bar]: pressure drop measured with CO₂ flow but without power to the dummy modules. This helps identify variations in pressure drop unrelated to CO₂ boiling.
- DT_CO2th(ΔP) [K]: theoretical temperature drop of boiling CO₂, based on the measured pressure drop, used for comparison with measured data.
- DT/DP [K/bar]: temperature drop of CO₂ for each bar, at the saturation pressure conditions under which the test is conducted
- DT_CO2 [K], T_CO2in [°C], T_CO2out [°C], T_PH [°C], Tair_top [°C], Tair_bottom [°C], P_CO2in [bar], P_CO2out [bar]: these are the parameters used to monitor the test conditions, including in order: the temperature difference of the CO₂ between inlet and outlet, the CO₂ inlet and outlet temperatures, the temperature of the preheater (to monitor when it has been turned on), the air temperature inside the box at the top and bottom, and finally the CO₂ pressures at the inlet and outlet.

The +15°C test, by simplifying conditions and decoupling the results from the CO₂ temperature effects, provides a clearer assessment of the thermal resistance of each ring cooling position. This allows for a more efficient quality control process, enabling comparisons between different rings and identifying those with suboptimal thermal performance. For this reason, the threshold parameters established so far have been based on the results of the first nine rings tested at +15°C, which include three prototypes and six pre-production units. These threshold values may be updated in the future as more data is collected from the ongoing production of rings.

Up to now, all produced rings have undergone both the +15°C and -35°C CO₂ tests. The purpose of the -35°C test is to gather information about the ring's performance under conditions closer to the actual CO₂ operating temperature. Additionally, this test allows the ring to experience at least one cooling cycle after the production phase. Since the -35°C test takes an additional working day to complete, there is potential in the future to omit this test. This decision could be made after gaining enough confidence that any thermal anomalies can be reliably detected during the +15°C test. If the -35°C test is removed, the testing process would be roughly twice as fast, allowing two rings to be tested per week instead of one.

The following threshold values have been determined for each type of ring, based on the results from the +15°C two-phase CO₂ test:

Table 6 - Limit values used for the validation of the rings for the main monitored control parameters, categorized by layer type of the ring.

TEST +15°C				
L1 LIMIT VALUES				
Tavg (°C)	DT_n/2+1 (K)	DT_RMS (K)	DT(other positions) (K)	DT_AB (K)
23	2	0.75	1	0.5
L2 LIMIT VALUES				
Tavg (°C)	DT_n/2+1 (K)	DT_RMS (K)	DT(other positions) (K)	DT_AB (K)
23.5	2	0.75	1	0.5
L3 LIMIT VALUES				
Tavg (°C)	DT_n/2+1 (K)	DT_RMS (K)	DT(other positions) (K)	DT_AB (K)
22.5	2	0.75	1	0.5

An essential aspect of the process is the proper storage and sharing of test results obtained from each test. Given the large scale of CERN projects, which involve institutions from various parts of the world, it has been necessary to develop an efficient method for publishing those results. Additionally, due to the high turnover of personnel who have the privilege of working on these projects, a clear and secure data storage system is crucial. This ensures that future teams can easily access the data. For this reason, the data from every test, along with all related analysis and documents, are managed as follows:

- Stored in the CERN EDMS: the Engineering / Equipment Data Management System (EDMS) serves as a secure and easily accessible database for saving all types of reports and documents [38].
- Saved in the production department management system: this system presents results from all quality control tests performed on each ring, ensuring continuous communication with the production team and keeping them informed about the thermal performance of the rings in production [36].
- Uploaded to the DBeaver database: the data is then made available in real time through a Grafana program, developed during the testing of prototype and pre-production rings. This tool is accessible to the entire CERN scientific community, allowing them to track the progress of the tests conducted in the Lyon cold room and review the key results of each test [39].

This structured approach ensures that results are properly documented, securely stored and easily accessible to both current and future project teams.

4.3.1 **TBPS tilted rings TOC: prototype and pre-production phase**

Between April 25, 2024, and January 17, 2024, three prototype rings and six pre-production rings were produced and thermally tested (a total of three rings for each type of layer: 1, 2, and 3). All the rings underwent two test campaigns carried out to ensure the reliability of the thermal test setup and validate the procedures used. Testing each ring under the same CO₂ and ambient temperature conditions using the same procedure, as listed in the previous section of this report, allowed for observing the consistency of the results obtained when testing the same ring, even when handled by different personnel (the turnover of young scientific staff at CERN must not affect any kind of quality control).

Moreover, these tests provided sufficient information to establish the boundary conditions for the validation process. As an example for this study, the ring L2 68 B1 will be considered. The following section presents the plots of the absolute temperatures measured during the test at +15°C and -35°C, as well as the deviations from the fitting line for each individual temperature during the same test.

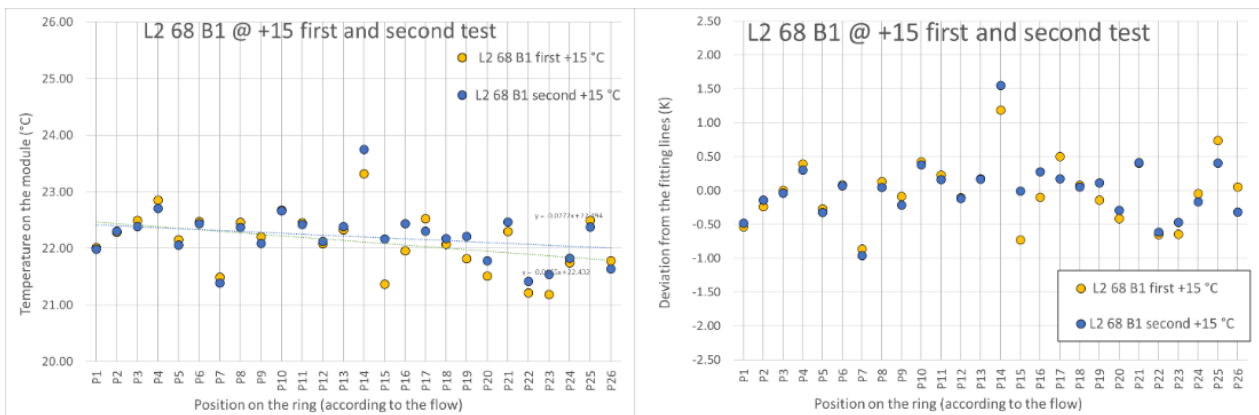


Figure 64- Plots demonstrating the repeatability of the tests conducted with CO₂ at +15°C for the ring L2 68 B1. The absolute temperatures and deviations from the regression line show consistent behaviour in the two tests performed approximately 6 months apart by different personnel. Specifically, it can be observed that the temperature of the module in position N/2+15 (14 for the L2 rings) is higher than that of the other modules, as expected.

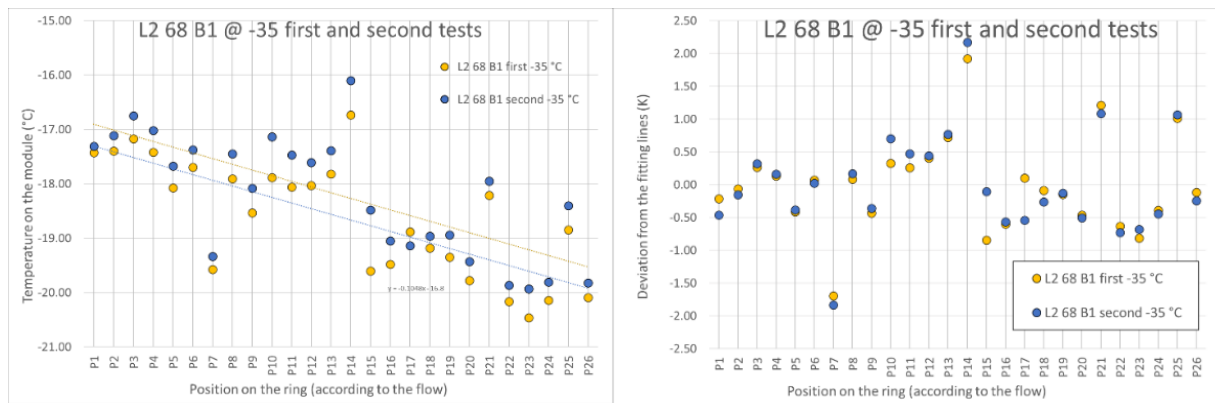


Figure 65 - Plots demonstrating the repeatability of the tests conducted with CO₂ at -35°C for the ring L2 68 B1.

It is clear that the temperatures measured in the same modules, applied in the same positions of the cooling loop, produce highly reliable results, with an average temperature difference of 0.09°C and 0.4°C during the +15°C and -35°C tests, respectively (DT_{average} in the table 7). The differences measured at individual positions ranged between 0.8°C (P15) and -0.15°C (P4) for the +15°C test, and between 1.12°C (P15) and -0.25°C for the -35°C test (results obtained by comparing the temperatures measured in the second test with those measured in the first test).

Table 7 - Tables showing the temperature differences measured in the L2 ring modules 68 B1 between the second test and the first test at 15°C (up) and at -35°C (bottom).

L2 68 B1 Tsecond-Tfirst @+15°C																											
P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	DT average	
-0.03	0.02	-0.10	-0.15	-0.09	-0.04	-0.11	-0.09	-0.12	-0.02	-0.03	0.04	0.06	0.43	0.80	0.48	-0.22	0.10	0.39	0.27	0.17	0.21	0.36	0.08	-0.12	-0.14	0.09	

L2 68 B1 Tsecond-Tfirst @-35°C																											
P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	DT average	
0.12	0.28	0.43	0.40	0.40	0.32	0.24	0.46	0.45	0.75	0.59	0.42	0.43	0.63	1.12	0.42	-0.25	0.21	0.40	0.35	0.26	0.30	0.53	0.34	0.45	0.27	0.40	

The comparison of the parameters processed for each ring during the individual tests, using the ring L2 68 B1 as a reference in the tables below, shows minimal variability in the indicators selected to assess the overall quality of the ring. Notable among these are the differences in the average recorded temperatures (0.07°C in the +15°C test and 0.39°C in the -35°C test), which support the validation of the good repeatability of the setup and the procedure used for conducting the tests and preparing the setup.

Table 8 - Validation parameters of the ring measured during the first and second tests for the L2 ring 68 B1 at both +15°C and -35°C

CO2 at +15°C				CO2 at -35°C			
Parameter	L2 68 B1 first	L2 68 B1 second	Delta (Second-first)	Parameter	L2 68 B1 first	L2 68 B1 second	Delta (Second-first)
Tavg (°C)	22.08	22.15	0.07	Tavg (°C)	-18.69	-18.30	0.39
S_meas	-0.03	-0.02	0.01	S_meas	-0.11	-0.11	0.00
DT _{n/2+1} (K)	1.25	1.61	0.36	DT _{n/2+1} (K)	2.01	2.25	0.24
DT _{RMS} (K)	0.46	0.45	-0.01	DT _{RMS} (K)	0.71	0.75	0.05
DT _{pos_max} (K)	0.74	0.46	-0.28	DT _{pos_max} (K)	1.27	1.14	-0.12
DT _{abs_max} (K)	0.76	0.87	0.11	DT _{abs_max} (K)	1.57	1.72	0.15
Flow (g/s)	1.96	1.95	-0.01	Flow (g/s)	1.97	1.92	-0.05
DP (bar)	0.41	0.41	0.00	DP (bar)	1.78	1.72	-0.05
DT _{AB} (K)	0.11	-0.03	-0.14	DT _{AB} (K)	0.17	0.20	0.02
S _{th}	-0.01	-0.01	-				
Position_DTpos	25	21		Position_DTpos	21	10	
Position_DTabs	7	7		Position_DTabs	7	7	

The positions identified as "anomalous," categorizing the ring as "to be checked," consistently turn out to be the warmest positions repeating the test, especially when observing the results from the test with CO₂ at +15°C. Here, the threshold value identified for all temperatures outside of position N/2+1 is 1°C (the maximum acceptable deviation from the fitting line), and slight fluctuations in the measured temperature can cause the detection or cancellation of some anomalies for positions with deviations between 0.8°C and 1.3°C. This was the case in the ring L2 68 A2, where in the first test, the identified anomalous positions were P7 (maximum measured temperature) with a DT=1.6°C and P12 with a DT=1.3°C. In the second test, the same positions showed DT=1.6°C for P7 and DT=0.9°C for P12, identifying only position P7 as anomalous.

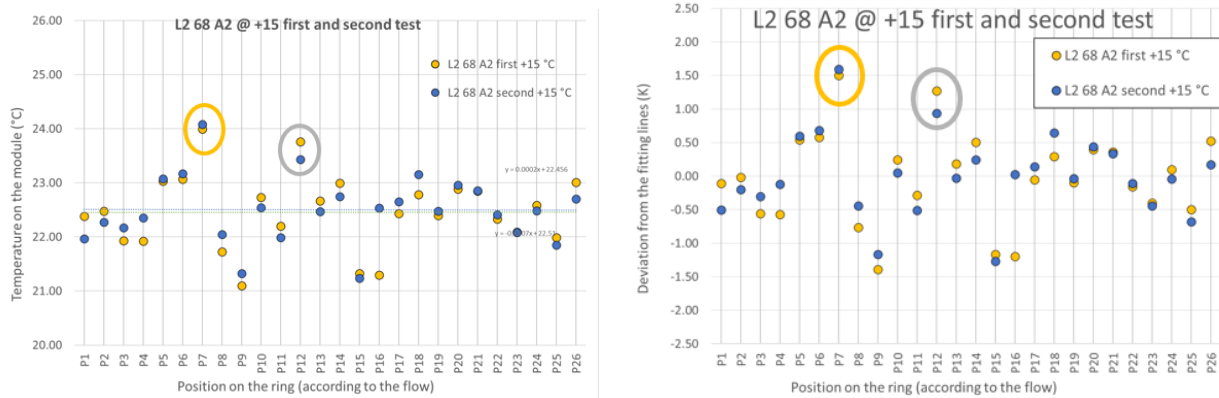


Figure 66 - Comparison of the results obtained during the first test for ring L2 68 A2 at +15°C, where position 7 remained anomalous (DT greater, indicating a significant thermal performance issue of the structure). Position 12, which was "slightly" anomalous during the first test, was measured as "valid" in the second test, with a DT=0.9, which is lower than the threshold limit.

In the Annex (3), the results of the tests performed on all the rings, which were subjected to the same double experimental campaign, are presented. The results obtained during the second experimental campaign, compared with the first, demonstrated the high quality of the reproducibility of the tests. Specifically, for the tests conducted with CO₂ at +15°C:

- The maximum difference in average temperature between the first and second test is DT_{second-first_avg} = 0.5°C for ring L1 47 A1.
- The maximum temperature difference at a specific position between the first and second test is DT = 1.4°C for P11 on ring L1 47 A1.
- Generally, the same anomalies were detected in both tests. Small temperature differences (a maximum of 0.5°C) between positions with the highest measured temperature and the fitting line could cause an anomalous position to be considered normal, or vice versa. This occurred with four rings.
- Both TRACI and the new conditioning system inside the Lyon Cold Room were effective in maintaining consistent test conditions (CO₂ temperature and pressure, air room temperature).

For the tests conducted with CO₂ at -35°C:

- The maximum difference in average temperature between the first and second test is DT_{second-first_avg} = 1.3°C for rings L1 47 A3 and L3 60 A1.
- The maximum temperature difference at a specific position between the first and second test is DT = 2.6°C for P28 on ring L3 60 A2.
- Some difficulties were encountered with TRACI in maintaining stable CO₂ test conditions (P = 12 bar and T = -35°C). However, even when the CO₂ temperature fluctuated, the temperature differences between positions and the fitting lines (deviations) remained consistent between the first and second tests, which is good for detecting anomalies.
- Anomalies detected in the last positions (e.g., L3 60 A2 – P36) are less concerning, given the absolute temperatures at -35°C. This is due to the pressure drop causing a CO₂ temperature drop. Therefore, anomalies identified in the second half of the loop (inner side of the ring), where the CO₂ temperature is lower, may still result in lower module temperatures compared to the first positions of the cooling loop, where the temperature is higher.
- It is promising that the warmest positions detected during the -35°C test are consistently detected during the +15°C test, with similar deviations from the fitting line observed between the two tests. This suggests that, in the future, only the +15°C test could be performed, which would save a full day of testing and double the speed at which tests could be completed.

4.3.2 TBPS tilted rings TQC: production phase

The progress of the tests conducted for the quality control of the rings in the Lyon Cold Room at CERN, located in Building 186, is monitored in real-time using a software called Grafana. This tool is used to generate summary plots by pulling data from a DBeaver database dedicated to the thermal quality control of the TBPS rings. As of the writing of this report, 19 rings have been tested (see figure 67), with a total of 59 tests performed (see figure 68).

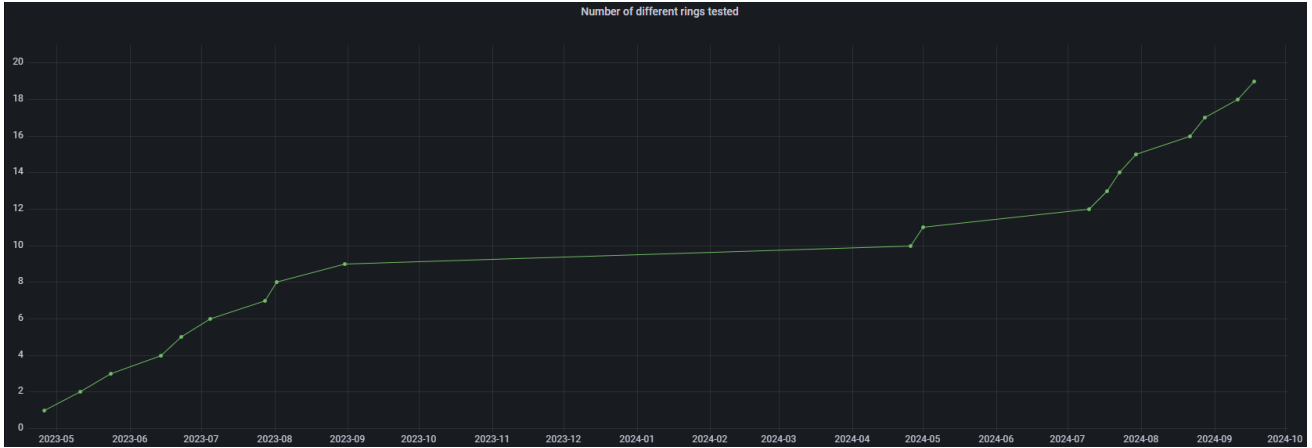


Figure 67 - Plot showing the total number of different rings tested since the beginning. It is possible to notice the pause between September 2023 and May 2024, due to the transition from pre-production to production of the rings [39].

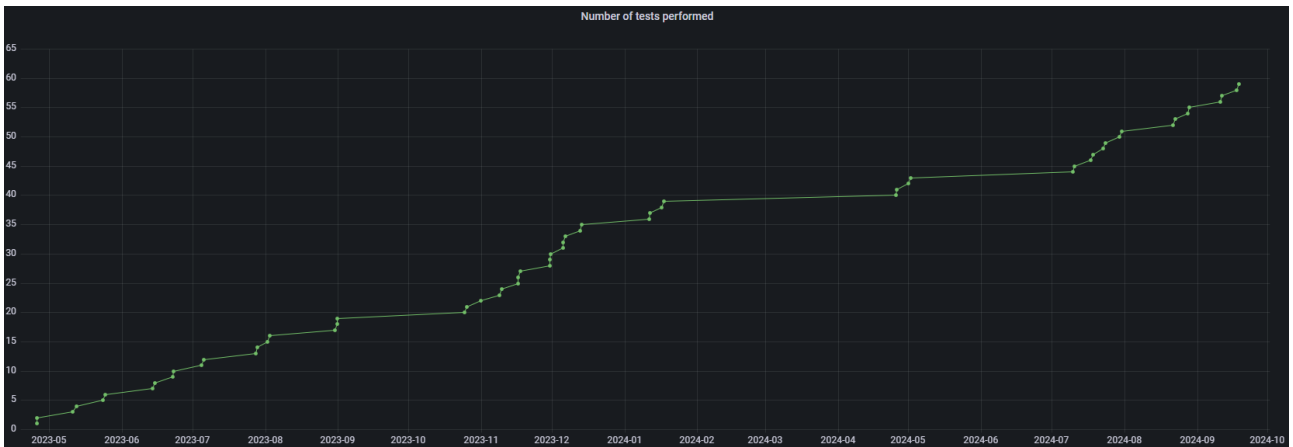


Figure 68 - Plot showing the number of tests conducted since the beginning [39]. The period between pre-production and production was used to carry out the second testing campaign on the available rings, as described in section 4.3.2.

During the test progression, a halt in ring production can be observed from September 2023 to April 2024, when the second testing campaign, as mentioned earlier, was conducted. This pause was due to the transition from the pre-production phase to the production phase. Furthermore, another stop occurred in May and June, caused by the preparation and testing of structures for another sub-detector of the Tracker, TB2S, which is discussed in the section 5.

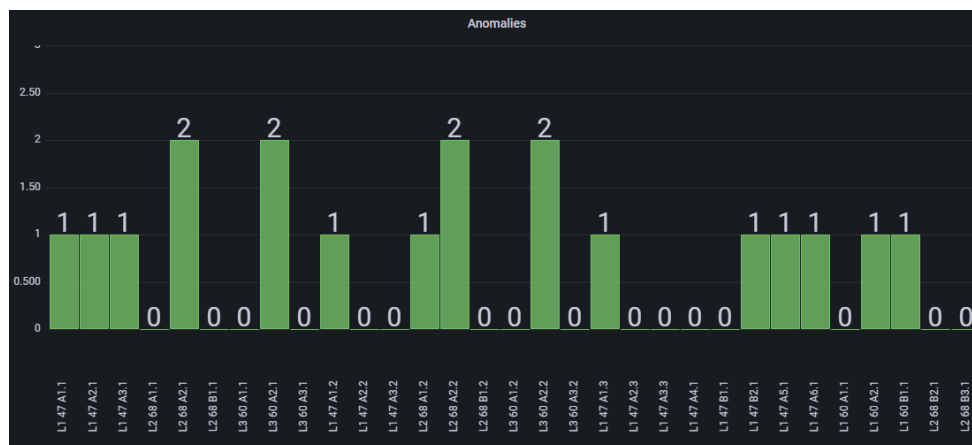


Figure 69 - Anomalies detected to date in the TBPS rings [39]. On the x-axis, the name of the ring is indicated, followed by a serial number that indicates the progressive count of tests conducted at +15°C on that ring.

As of today, the production phase has nearly reached full speed, with the thermal quality control team aiming to test one ring per week. This process will be accelerated to two rings per week if the reliable CO₂ test at +15°C is adopted as the sole reference test. In the Annex (4), data on the parameters processed for each test performed so far, for every ring, are provided. The following two tables present the temperatures during the tests, both at +15°C and -35°C, for the module positions of each L1 and L2 rings (the production phase of these two rings is expected to run concurrently in the initial phase, while the L3 rings will be produced in a later phase).

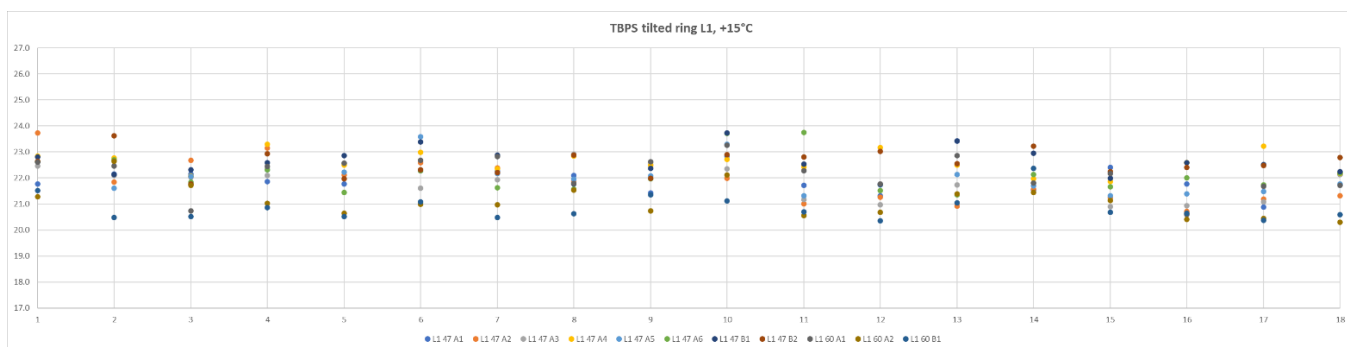


Figure 70 - Absolute temperatures measured in the TQC at +15°C in the "dummy modules" of the L1 rings produced so far, categorized by colour according to the type of ring.

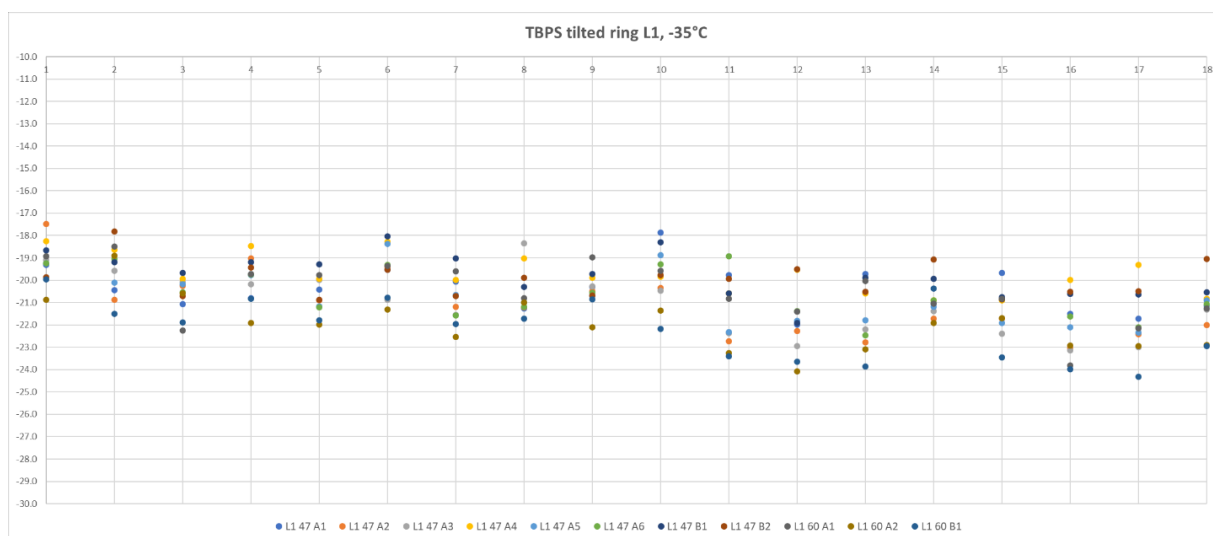


Figure 71 - Absolute temperatures measured in the TQC at -35°C in the "dummy modules" of the L1 rings produced so far, categorized by colour according to the type of ring.

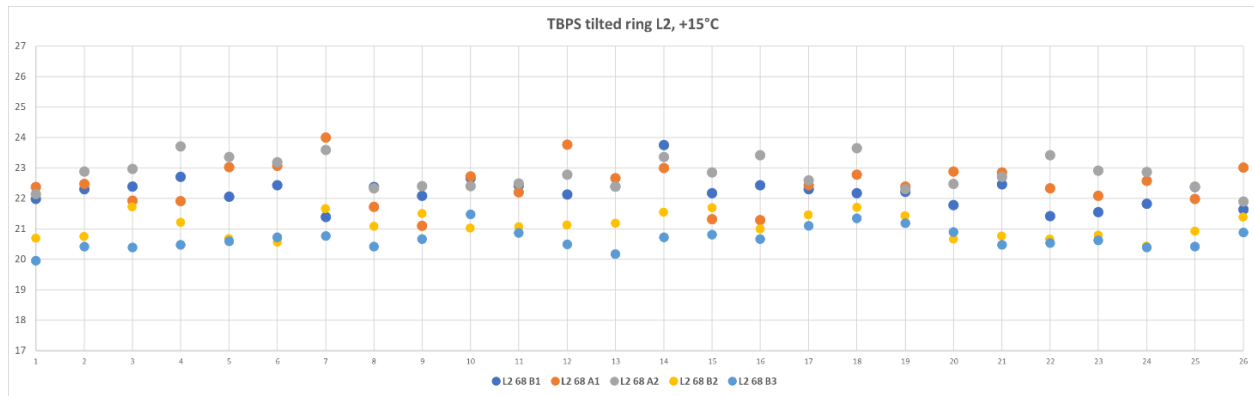


Figure 72- Absolute temperatures measured in the TQC at +15°C in the "dummy modules" of the L2 rings produced so far, categorized by colour according to the type of ring.

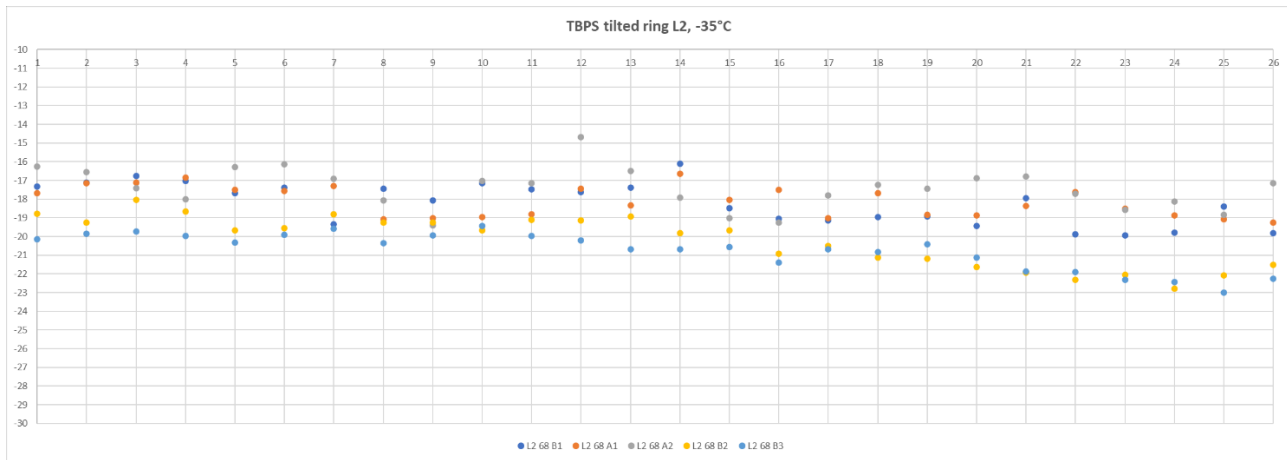


Figure 73- Absolute temperatures measured in the TQC at -35°C in the "dummy modules" of the L1 rings produced so far, categorized by colour according to the type of ring.

By analyzing data from the first rings in production (figure 69, 70, 71 and 72), it is possible to observe the temperature behavior of the modules in each position on the cooling plate during the tests. A decreasing temperature trend along the cooling loop is noticeable due to the CO₂ pressure drop. This phenomenon is particularly evident during tests with CO₂ at -35°C, where the pressure drop across the rings measures 0.9 bar for L1 rings and 1.9 bar for L2 rings. These pressure drops correspond to a theoretical temperature difference (DT_CO₂th in the annex 4) of 2.0°C and 3.9°C, respectively. In many tests, the measured temperature difference of CO₂ between the inlet and outlet matches the theoretical values, as shown by the comparison between DT_CO₂th and the measured DT_CO₂, confirming that the tests were indeed conducted in two-phase fluid conditions.

As expected, this trend results in the first modules of the cooling loop being the most disadvantaged in terms of cooling (except for the module in position N/2+1, which has a different type of contact with the cooling pipe). These modules consistently show higher temperatures compared to the last modules in the cooling loop and this means that an anomaly detected in the latter part of the loop is less critical than one detected at the beginning.

For the tests conducted at +15°C, detecting the decreasing trend is more challenging because the CO₂ pressure drop is smaller in these tests, and the physical properties of CO₂ cause a lower temperature decrease per unit of pressure loss when CO₂ is saturated at 51 bar compared to 12 bar. With a lower CO₂ temperature difference between the inlet and outlet, the temperature variations measured in different modules (due to the variability in thermal contact between the module and the cooling plate) can obscure the overall downward trend.

The plots showing the absolute temperatures measured in the rings allow for the overall cooling quality of each ring to be evaluated. For example, under identical testing conditions, the first two L2 rings tested in production

(L2 68 B2 and L2 68 B3, figure 72 and 73) show lower average temperatures compared to the pre-production rings tested approximately a year and a half earlier, both at +15°C and -35°C. This improvement could be due to refinements made in the gluing process of the cooling plates and rings.

The CO₂ temperatures, CO₂ pressure and air temperatures during each test are available in the annex 3. The highest measured temperatures for L1 and L2 rings during the -35°C tests were -17.5°C for the module in position 1 of ring L1 47 A2 and -14.7°C for the module in position 12 of ring L2 68 A2, respectively.

For L1 rings, the conditions generated by the TRACI system are stable enough to maintain a constant accumulator pressure throughout the test. However, for L2 and L3 rings, where there are more modules (each module dissipates 10 W), maintaining stable CO₂ inlet conditions during the test is more difficult. This makes it challenging to keep the accumulator pressure constant and thus the saturation temperature can fluctuate. This is why the average temperatures measured for L2 and L3 rings are higher than those for L1 rings, simply because the coolant (two-phase CO₂) has a higher average temperature in these tests. Additionally, the tests are performed with an ambient air temperature of approximately 12°C since the testing box is not insulated, adding extra heat to the modules and the cooling system. This, along with the fact that the tests are not conducted with the actual final modules (which will have thermal paste to improve contact with the cooling plate), explains why the tests at -35°C give an overestimated value of the expected operating temperature of the real modules (which are predicted to operate below -20°C).

The graphs below (figure 74, 75, 76 and 77) show the temperature deviations for each position of each ring. This parameter indicates the difference between the measured temperature of the module and the line fitting all temperature data, accounting for the CO₂ temperature drop. This allows for an unbiased quality control introduced otherwise by the two-phase CO₂ thermal behaviour.

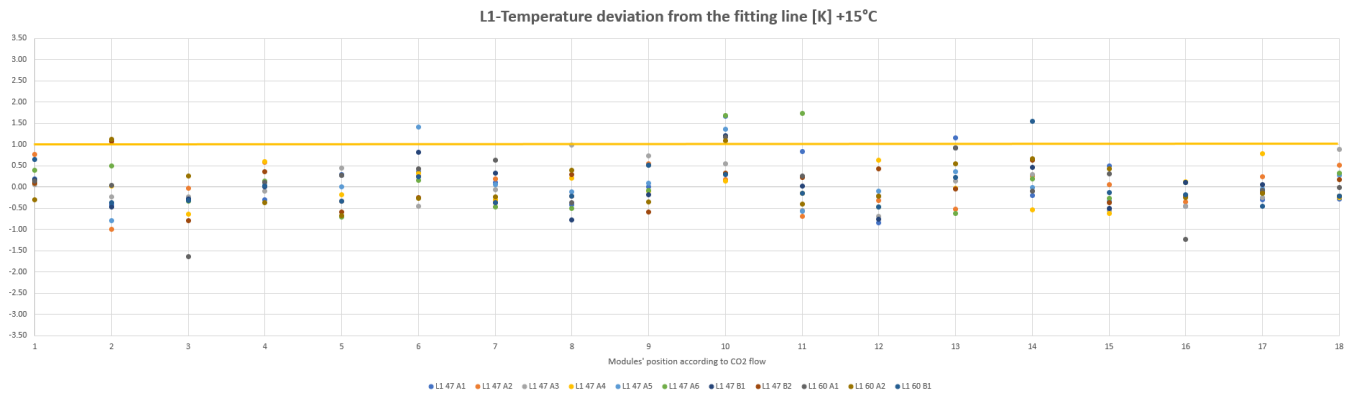


Figure 74 - Temperature deviation from the fitting line measured during the tests with CO₂ at +15°C for L1 rings. The yellow line indicates the threshold limit set at +1°C, above which the temperatures of the modules are considered anomalous during this test.

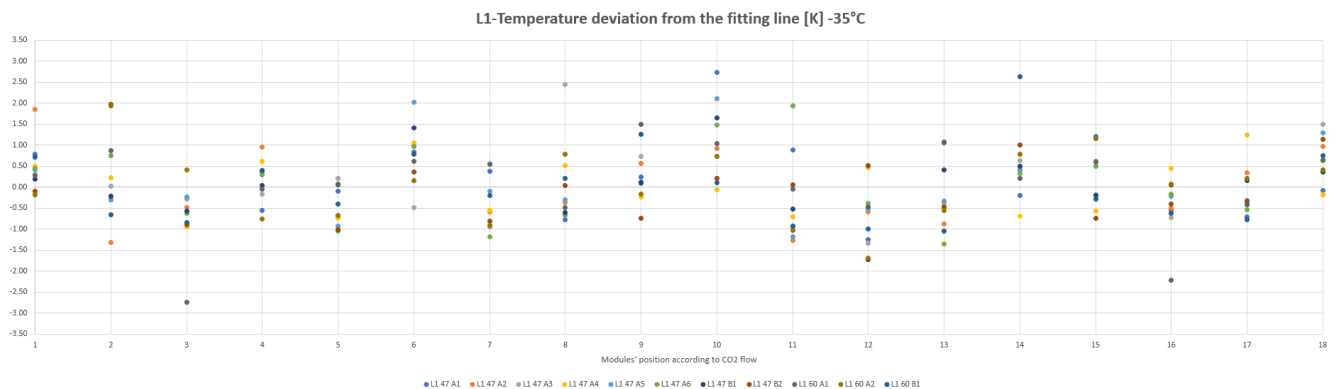


Figure 75- Temperature deviation from the fitting line measured during the tests with CO₂ at -35°C for L1 rings.

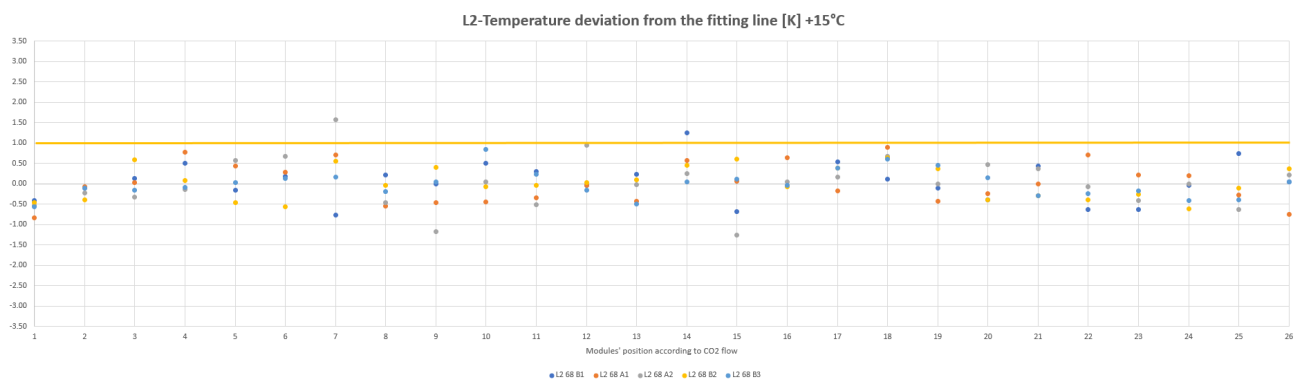


Figure 76 - Temperature deviation from the fitting line measured during the tests with CO₂ at +15°C for L2 rings. The yellow line indicates the threshold limit set at +1°C, above which the temperatures of the modules are considered anomalous during this test.

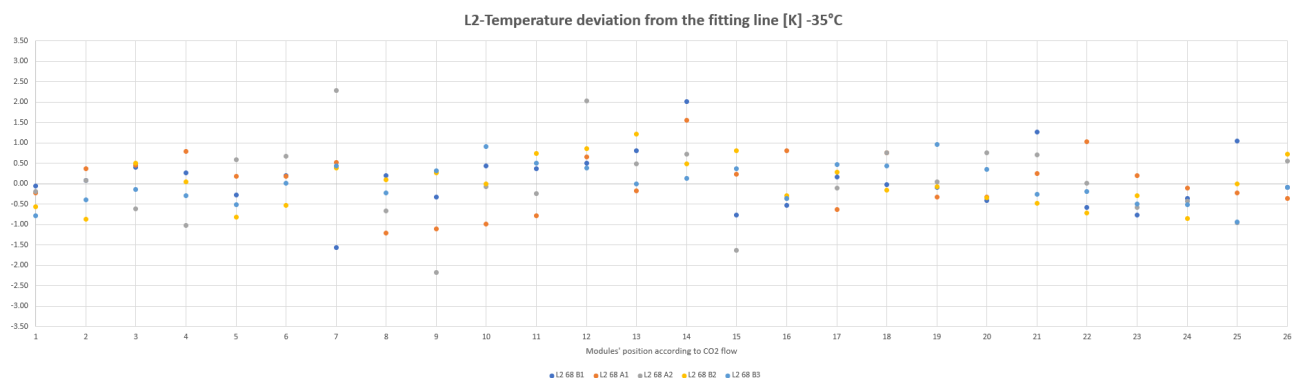


Figure 77- Temperature deviation from the fitting line measured during the tests with CO₂ at -35°C for L2 rings.

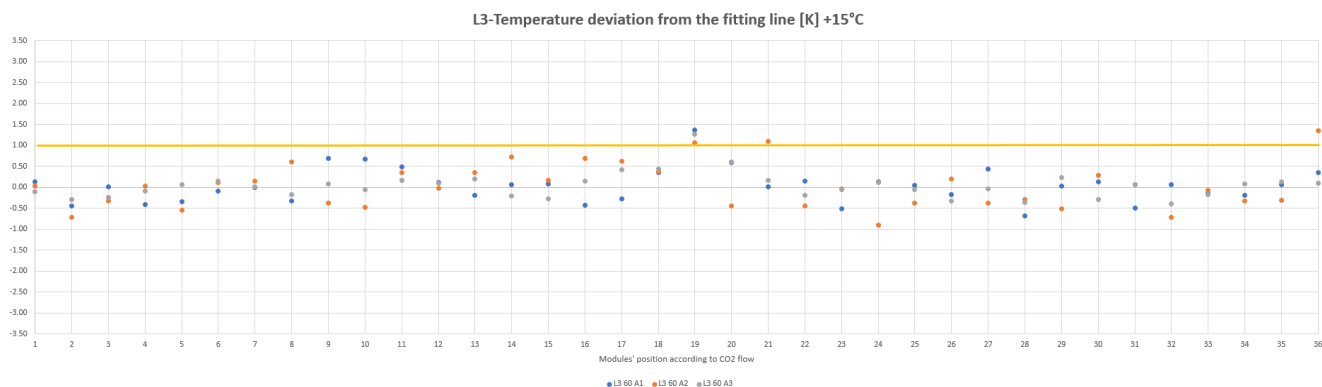


Figure 78- Temperature deviation from the fitting line measured during the tests with CO₂ at +15°C for L3 rings. The yellow line indicates the threshold limit set at +1°C, above which the temperatures of the modules are considered anomalous during this test.

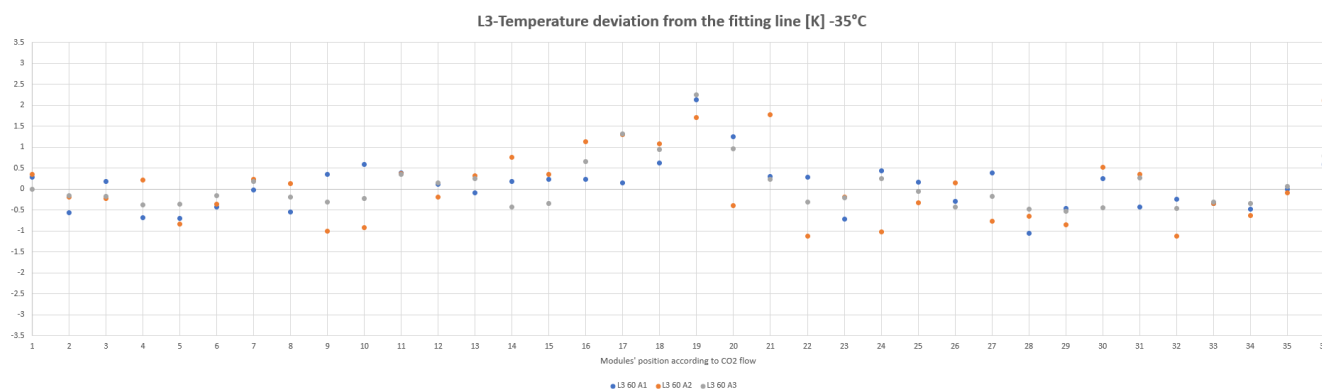


Figure 79 - Temperature deviation from the fitting line measured during the tests with CO₂ at -35°C for L3 rings.

The tests conducted at +15°C included a threshold temperature above which positions are flagged as anomalous. It was observed that the module in position N/2+1 for each type of ring consistently measures a higher temperature compared to others. For L1 rings, 6 anomalies were identified (as shown for each ring in the Grafana chart [40]), representing 3.03% of cooling plates tested. For L2 rings, 1 anomaly was found, accounting for 0.77% of anomalous positions, while 2 anomalies (both observed in the same ring) were identified for L3 rings, totaling 1.85% of anomalous positions.

It's important to note that the current threshold difference (set at +1°C relative to the fitting line) is applied uniformly across all ring types for safety reasons. In the future, this limit might be relaxed for L2 and L3 rings, as these are located in more external regions of the outer tracker, where the impact of radiation damage is less severe and operating temperatures could be slightly higher. This would allow for somewhat lower cooling performance for L2 and L3 rings compared to L1 rings.

Although it is not always possible to pinpoint the exact cause of these anomalies, defects in the ring structure have been identified that can lead to increased temperatures in the dummy module. The most common reasons observed so far are bad alignment between the cooling plate and cooling adaptor (an alignment error greater than 60 µm can cause the DT to rise above 1) and defects in the gluing process (excess glue creates poor thermal contact between the module and the cooling plate). These defects are very difficult to detect through visual inspection, making thermal quality control crucial for identifying them, as demonstrated in the case studies presented below.

Interestingly, every ring flagged as anomalous during the +15°C test also showed anomalous temperatures during the -35°C test, validating the thermal quality control process. The difference between the two tests is that at -35°C, defects, if present, are more apparent, as the DT measured against the fitting line is significantly higher than at +15°C, resulting in greater variability in measured temperatures. Specifically, not only anomalies but also particularly good thermal contacts are highlighted during the test at -35°C compared to the test at +15°C. This can be seen by simultaneously comparing the deviations (DT values) obtained during the tests at -35°C and +15°C. This could be due to the additional heat absorbed by the environment during the "cold" test, which is not in an almost adiabatic state like the test at +15°C, and, in part, to the different characteristics of CO₂ boiling inside the pipe during the test at -35°C, where a saturation pressure of 12 bar is measured, compared to the test at +15°C, where a saturation pressure of 51 bar is measured. The higher pressure leaves less space for bubbles to grow, thereby enhancing the efficiency of nucleate boiling heat transfer.

The following tables present the results of the pressure drop measurements recorded during the tests, with the results for the L1 rings provided as an example. It is important to evaluate the pressure drop measurement in conjunction with the flow rate used during the test, as small variations in flow rate can lead to fluctuations in the pressure drop. Maintaining a consistent pressure drop across each evaporator is essential. As explained in the introductory chapters, the pressure drop across the evaporator (between 1 and 2 bar) is significantly lower than the drop across the capillaries before the evaporator (approximately 10 bar). The capillaries create a high-concentrated pressure drop to ensure better flow balancing across the parallel cooling loops (individual rings) in the cooling system. The consistency of the measured pressure drop across the individual rings of the same type also confirms the absence of defects that could cause significant deviations in this value for any particular ring compared to the average. In the case examined (figure 80), L1 rings show a pressure drop of 0.14 bar (DP_Nopower) when the modules are not powered, increasing to 0.22 bar (DP) when the boiling process is triggered within the cooling loop during the actual test, with power applied to the modules, with CO₂ at +15°C and a flow rate of 1.4 g/s.

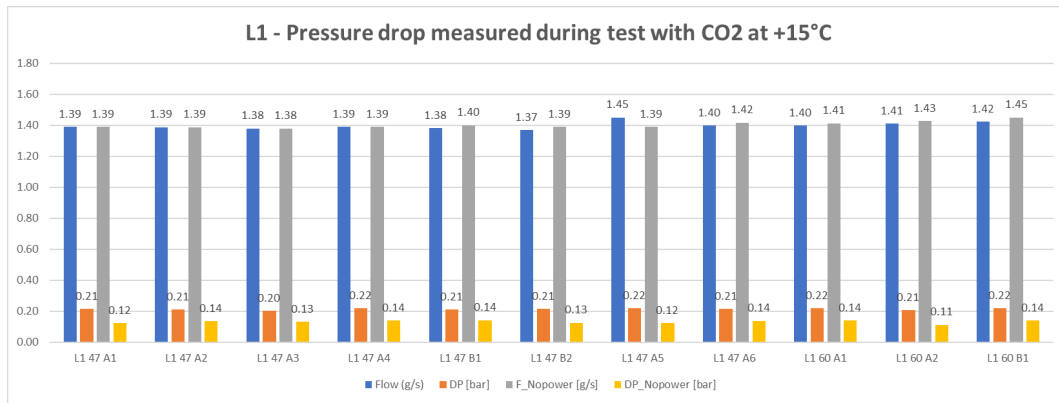


Figure 80 – Pressure drop measured on the L1 rings tested so far at +15°C. Flow and DP are the parameters used while the dummy modules are powered (and thus the CO₂ is boiling inside the pipe); F_Nopower and DP_Nopower are the values measured while the power is off.

In the case of the -35°C test (figure 81), it is observed that boiling at -35°C causes a greater pressure drop for the same flow rate ($F = 1.4 \text{ g/s}$) compared to the tests conducted at +15°C. During these tests, an average pressure drop (DP) of 0.9 bar was measured while power was being supplied to the modules. This higher pressure drop is typical in low-temperature CO₂ tests due to the natural behaviour of this coolant in two-phase flow at lower temperatures and especially at lower pressures, where the vapor bubbles are less compressed within the flow and have the opportunity to grow more easily, creating a greater obstacle to the flow of CO₂. Beyond the increased pressure drop detectable during this test, the results once again confirm the good overall quality of the different rings, with only minimal variations between them. This consistency across rings highlights the reliability of the thermal performance and cooling system under more challenging conditions.

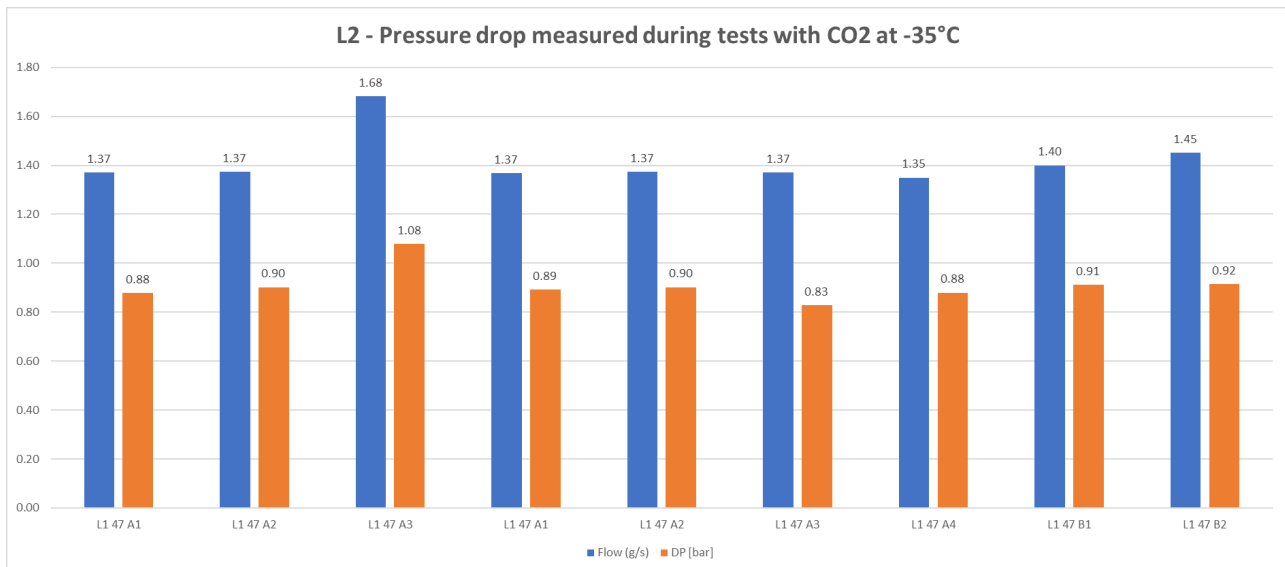


Figure 81 - Pressure drop measured on the L1 rings tested so far at +15°C. Flow and DP are the parameters measured while the dummy modules are powered (and thus the CO₂ is boiling inside the pipe).

The summary tables 9, 10 and 11 provide an overview of the quality control parameters evaluated for each L1, L2 and L3 ring tested at both +15°C and -35°C. These tables allow for a detailed comparison of performance metrics, including temperature deviations, pressure drops, and the identification of any anomalies across the different types of rings under both test conditions. The data offers valuable insights into the cooling efficiency and consistency of the TBPS rings, helping to validate the effectiveness of the thermal quality control process for each ring type.

Table 9 – Overview of the parameters for the L1 rings tested so far, both with CO₂ at +15°C and at -35°C.

Date	L1 47 AH1 25/04/2023	L1 47 AH2 10/5/2023	L1 47 AH3 23/05/2023	L1 47 AH4 25/04/2024	L1 47 BH1 1/5/2024	L1 47 BH2 9/7/2024	L1 47 AH5 19/07/2024	L1 47 AH6 25/07/2024	L1 60 AH1 30/07/2024	L1 60 AH2 22/08/2024	L1 60 BH1 29/08/2024
15											
Tavg (°C)	22.16	21.89	21.83	22.59	22.54	22.58	21.97	22.04	22.10	21.05	20.84
S_meas	-0.01	-0.13	-0.07	-0.02	-0.01	-0.06	-0.06	-0.02	-0.04	-0.06	0.00
DT_n/2+1 (K)	1.66	0.17	0.56	0.14	1.21	0.32	1.36	1.69	1.18	1.10	0.29
DT_RMS (K)	0.61	0.46	0.50	0.40	0.54	0.46	0.54	0.67	0.65	0.52	0.49
DTpos_max (K)	1.16	0.77	0.99	0.78	0.92	1.08	1.42	1.74	0.92	1.13	1.55
DTabs_max (K)	1.16	0.99	0.99	0.78	0.92	1.08	1.42	1.74	1.63	1.13	1.55
F (g/s)	1.39	1.39	1.38	1.39	1.38	1.37	1.45	1.40	1.40	1.41	1.42
DP (bar)	0.21	0.21	0.20	0.22	0.21	0.21	0.22	0.21	0.22	0.21	0.22
DT_AB (K)	-0.10	0.18	0.28	0.01	-0.02	-0.18	0.14	-0.21	0.03	-0.09	-0.04
DT_AB_avg (K)	-0.03	1.29	0.92	0.20	0.07	-0.21	0.69	-0.01	0.44	0.49	-0.02
S_th											
Position DTpos_max	13	1	8	17	13	2	6	11	13	2	14
Position DTabs_max	13	2	8	17	13	2	6	11	3	2	14
T_air_top	20.20	20.21	19.23	21.26	21.9	20.6	21.0	19.4	21.8	21.2	21.3
T_air_bottom	19.87	18.97	18.50	20.99	21.8	20.2	20.9	19.2	21.6	20.8	21.0
-35											
Tavg (°C)	-20.58	-21.15	-21.15	-19.71	-19.88	-19.97	-20.92	-20.69	-20.55	-22.00	-22.19
S_meas	-0.06	-0.21	-0.21	-0.11	-0.12	-0.02	-0.15	-0.12	-0.16	-0.15	-0.18
DT_n/2+1 (K)	2.74	0.92	0.92	-0.06	1.65	0.21	2.11	1.48	1.05	0.73	0.10
DT_RMS (K)	0.95	0.88	0.88	0.64	0.73	0.78	0.86	0.88	1.05	0.86	0.94
DTpos_max (K)	1.21	1.85	1.85	1.25	1.41	1.97	2.02	1.94	1.50	1.94	2.63
DTabs_max (K)	1.26	1.85	1.85	1.25	1.72	1.97	2.02	1.94	2.74	1.94	2.63
F (g/s)	1.37	1.37	1.37	1.35	1.40	1.45	1.39	1.38	1.40	1.38	1.41
DP (bar)	0.89	0.87	0.87	0.88	0.91	0.92	0.87	0.87	0.87	0.87	0.88
DT_AB (K)	-0.08	0.21	0.21	0.11	0.22	-0.18	0.25	-0.23	0.15	0.14	0.30
DT_AB_avg (K)				1.17	1.38	0.05	1.66	0.89	1.65	1.61	1.99
S_th											
Position DTpos_max	15	1	8	17	6	2	6	11	9	2	14
Position DTabs_max	12	1	8	17	12	2	6	11	3	2	14
Tair_top	10.86	12.59	8.77	13.56	14.4	13.5	12.3	11.1	12.8	12.9	12.5
Tair_bottom	9.78	7.13	7.43	10.49	12.7	10.6	10.6	9.3	10.5	10.1	10.4
Status											
Anomalies	1	0	0	0	0	1	1	1	0	1	1
Status	To be checked	Validated	Validated	Validated	Validated	To be checked	To be checked	To be checked	Validated	To be checked	To be checked
Second test	x	x	x								
Notes/Anomalies	P13 bad alignment between CP and cooling adaptor ~60µm	Validated after second test	Validated after second test			P2 (DT=1.1°C)	P6 bad alignment between CP and cooling adaptor ~60µm	P11 bad alignment between CP and cooling adaptor ~60µm		P2 (DT=1.1°C)	P14 (DT=1.55°C)

Table 10 - Overview of the parameters for the L2 rings tested so far, both with CO₂ at +15°C and at -35°C.

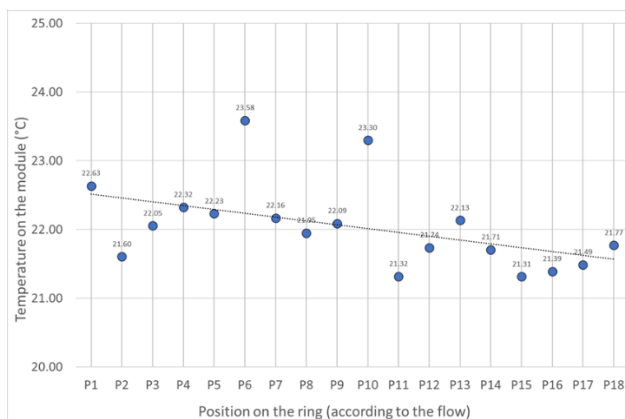
Date	L2 68 BH1 14/06/2023	L2 68 AH1 2/8/2023	L2 68 AH2 30/08/2023	L2 68 BH2 12/9/2024	L2 68 BH3 9/20/2024
15					
Tavg (°C)	22.08	22.81	22.44	21.08	20.7
S_meas	-0.03	-0.01	0.00	0.00	0.012
DT_n/2+1 (K)	1.25	0.57	0.55	0.46	0.1
DT_RMS (K)	0.46	0.49	0.68	0.39	0.3
DTpos_max (K)	0.74	0.90	1.56	0.64	0.854
DTabs_max (K)	0.76	0.90	1.56	1	0.854
F (g/s)		1.92	1.97	1.99	1.97
DP (bar)		0.41	0.43	0.43	0.42
DT_AB (K)	0.11	-0.22	0.27	-0.01	-0.04
DT_AB_avg (K)	0.47	0.03	0.21	0.02	-0.21
S_th	-0.01	-0.01	-0.01		
Position DTpos_max	25	18	7	18	10
Position DTabs_max	7	18	7	18	10
Tair_top	21.64	21.75	22.04	19.52	19.53
Tair_bottom	21.56	21.55	22.08	19.37	19.31
T_CO2_in	15.74	16.09	16.08	15.63	15.55
T_CO2_out	15.53	15.72	15.65	15.44	15.4
-35					
Tavg (°C)	-18.69	-18.18	-17.41	-20.23	-20.80
S_meas	-0.11	-0.06	-0.05	-0.16	-0.11
DT_n/2+1 (K)	2.01	1.56	-0.49	0.49	0.10
DT_RMS (K)	0.71	0.67	1.01	0.58	0.50
DTpos_max (K)	1.27	1.03	2.67	1.22	0.97
DTabs_max (K)	1.57	1.21	2.67	1.22	0.97
F (g/s)	1.97	1.97	2.02	1.97	1.90
DP (bar)	1.78	1.78	1.84	1.99	1.87
DT_AB (K)	0.17	-0.25	0.40	0.30	0.03
DT_AB_avg (K)	1.59	0.57	0.94	2.39	1.55
S_th					
Position DTpos_max	21	22	12	13	19
Position DTabs_max	7	8	12	13	19
Tair_top	11.42	14.94	14.14	12.13	8.58
Tair_bottom	10.08	10.00	12.52	9.17	7.78
T_CO2_in	-26.33	-25.89	-24.51	-28.24	-27.82
T_CO2_out	-29.82	-29.66	-29.02	-31.97	-31.54
STATUS					
Anomalies	0	0	1	0	0
Status	Validated	Validated	To be checked	Validated	Validated
Second test	x	x	x		
Notes/Anomalies			P7 (second test: only P7, bad alignment between CP and Cooling adaptor in one edge ~80µm)		

Table 11 - Overview of the parameters for the L3 rings tested so far, both with CO₂ at +15°C and at -35°C.

	L3 60 A#1	L3 60 A#2	L3 60 A#3
Date	12/13/2023	1/11/2024	1/16/2024
15			
Tavg (°C)	21.04	21.82	21.73
S_meas	-0.02	0.01	0.00
DT_n/2+1 (K)	1.68	0.64	0.97
DT_RMS (K)	0.51	0.50	0.30
DTpos_max (K)	0.95	1.28	0.66
DTabs_max (K)	0.95	1.28	0.66
F (g/s)	2.63	2.70	2.70
DP (bar)	0.43	0.44	0.45
DT_AB (K)	-0.11	0.14	-0.05
DT_AB_avg (K)	0.30	0.10	0.00
S_th	-0.01	-0.01	-0.01
Position DTpos_max	20	36	20
Position DTabs_max	20	36	20
T_air_top	21.35	20.78	21.10
T_air_bottom	20.98	19.83	20.38
T_CO2_in	15.48	15.35	15.61
T_CO2_out	15.42	15.38	15.45
-35			
Tavg (°C)	-18.01	-16.56	-17.56
S_meas	-0.09	-0.06	-0.07
DT_n/2+1 (K)	2.31	1.09	1.72
DT_RMS (K)	0.68	0.82	0.51
DTpos_max (K)	1.42	2.10	1.09
DTabs_max (K)	1.42	2.10	1.09
F (g/s)	2.68	2.62	2.59
DP (bar)	1.79	1.73	1.78
DT_AB (K)	-0.07	0.18	-0.07
DT_AB_avg (K)	1.60	1.40	1.20
S_th			
Position DTpos_max	20	28	20
Position DTabs_max	20	28	20
Tair_top	8.04	7.50	9.37
Tair_bottom	5.21	6.06	5.36
T_CO2_in	-28.79	-22.35	-25.86
T_CO2_out	-29.82	-28.72	-28.76
Status			
Anomalies	0	2	0
Satus	Validated	To be checked	Validated
Second test	x	x	x
Notes/Anomalies	First test showed 0 anomalies	2 anomalies detected after thermal test: P21 and P36 beyond limit value. First test showed 2 anomalies (P21 and P36)	First test showed 0 anomalies

4.3.2.1 Case study L1 47 A5: bad alignment between the cooling plate and the cooling adaptor

By observing the results of the test conducted on ring L1 47 A5, shown below, it is possible to observe how both in the tests with CO₂ temperature of +15°C and in the tests with CO₂ temperature of -35°C, the temperature of the module in position 6 results to be the highest, with absolute anomalous values compared to the temperatures measured in the other cooling plates, considering the cooling plate in position 10 with the worst cooling by design, as repeatedly emphasized in this chapter.



Test parameters	Values
CO2 In [°C]	15.8
CO2 out [°C]	15.6
DT_CO2 [°C]	0.2
Pin [bar]	51.4
Pout [bar]	51.1
Air top [°C]	21.0
Air bottom[°C]	20.9

Figure 82 - Temperatures of the dummy modules measured during the test with CO₂ at +15°C for ring L1 47 A5 on the left. Refrigerant temperature and pressure conditions and ambient temperatures, on the right.

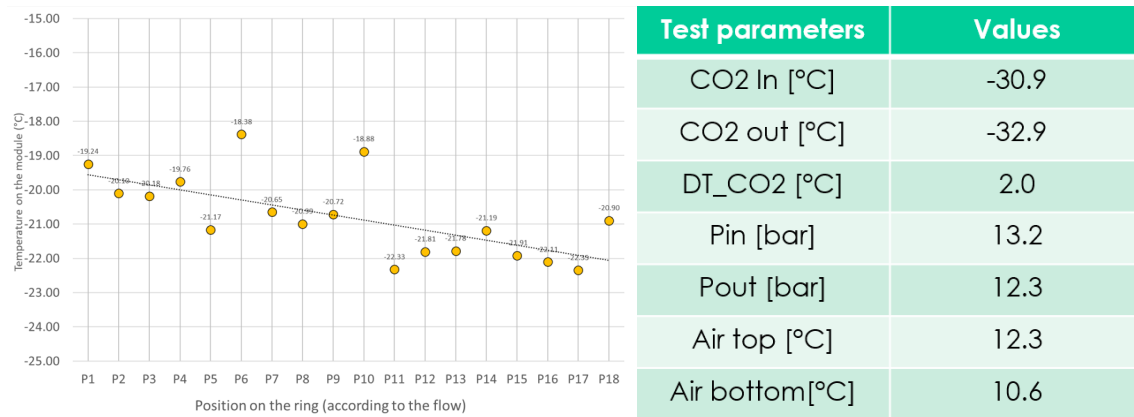


Figure 83- Temperatures of the dummy modules measured during the test with CO₂ at -35°C for ring L1 47 A5 on the left. Refrigerant temperature and pressure conditions and ambient temperatures, on the right.

By analyzing the anomalous behavior observed in both tests, with a measured temperature of 23.58°C in the +15°C test compared to the average temperature of 22.0°C, and by plotting the results of the temperature differences between the measured temperature and the fitting line (plotted as a dashed line in both tests), it is possible to obtain the graph used for the quality control process (figure 84). From this plot, two main points become clear. The first is the close correlation between the temperatures measured in the +15°C and -35°C tests. In fact, the behaviour of the modules appears to be the same despite the variation in the CO₂ test pressure and, consequently, the physical behaviour of the refrigerant inside the pipe. Once again, this validates the good choice of using a test with CO₂ temperatures of +15°C to carry out the TQC in a more efficient way, also adding thermographic analyses as will be shown in the following pages. The second point is that it is easy to identify position number 6 as anomalous, with a deviation from the fitting line of 1.4°C during the +15°C test (blue dot), which exceeds the limit set for this parameter (DT_{limit} = 1.0°C).

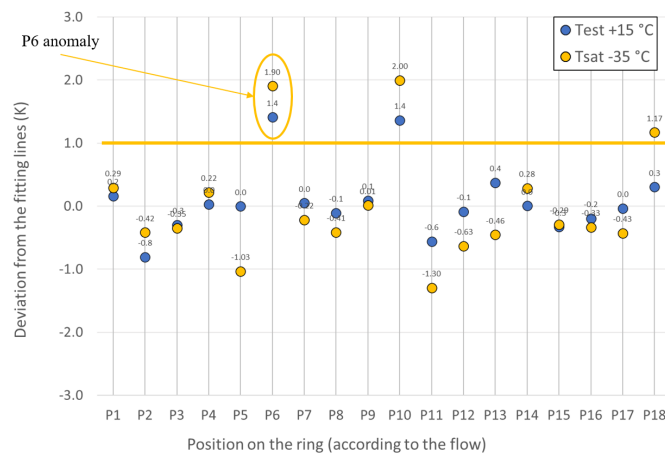


Figure 84 - Deviation of the module temperatures from the fitting line measured in both tests. In yellow are the deviations measured during the -35°C test, and in blue are the deviations during the +15°C test. The two tests show the similarity in the thermal behaviour of the modules at different CO₂ temperatures. The thermal quality control is performed on the +15°C test, with the limit temperature (highlighted by the yellow line) set at DT = +1°C.

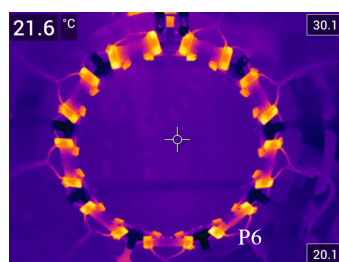


Figure 85 - Thermographic image of ring L1 47 A5, where it is possible to see that the temperature of the module in position 6 is higher than the others.

In cases like this, where an anomaly is highlighted by the TQC, it is interesting to first investigate the reliability of the obtained result, although considerable experience has already been gained regarding the reliability of this test setup. This can be done by conducting a thermographic investigation using a Flir E75 to analyze the thermal field in the dummy modules at positions number 6 and number 5, swapping the dummy modules used to provide power to the ring. Through this investigation (figure 86), it is possible to observe that the temperature of module number 6 remains the same at 23.6°C after switching the two modules, differing by about 1.5°C from a module with a “good” temperature, such as module number 7 (22.1°C). This confirms that the higher temperature recorded is not due to the type of dummy module used: the same analysis has been repeated so far in all the positions identified as anomalous for all rings, consistently confirming the same result. Investigating this temperature difference further shows that the temperature of module 6, when analyzing the thermal field, is consistently higher than the temperature of module 5 along the entire length of the module from left to right (figure 87).

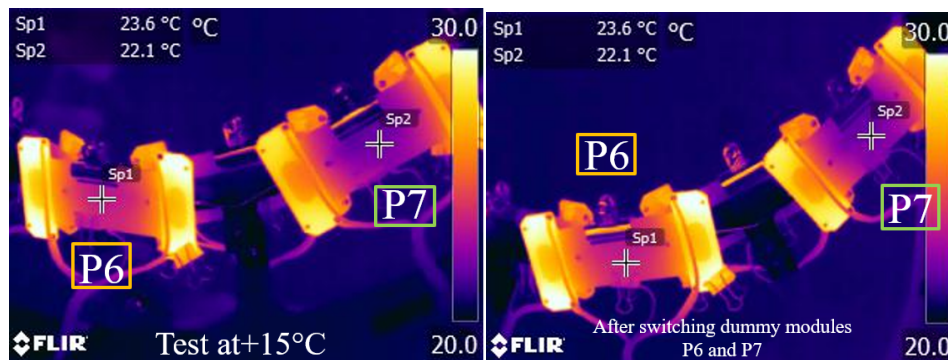


Figure 86 - Validity of the test demonstrated by switching the dummy modules in the “anomalous” position (6) and the nearby “good” position (7) and measuring the temperatures at the center of the module (spot indicated in the upper left corner of each image) before the switch (left) and after the switch (right).

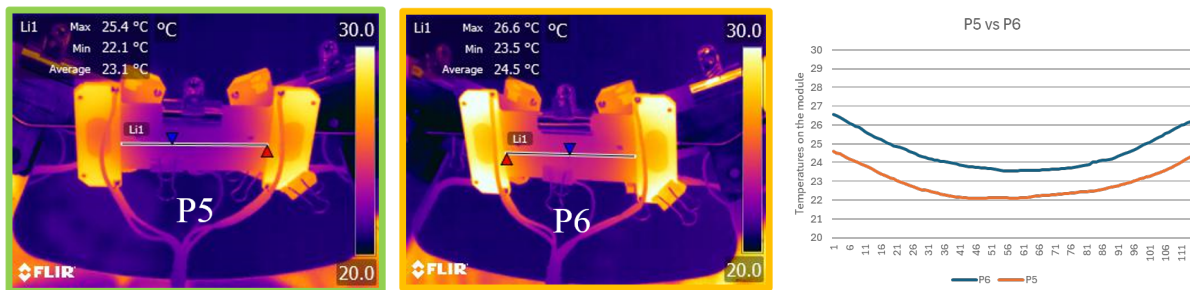


Figure 87- Thermal field distribution along the module in position 5 (left), position 6 (center), and a comparison between the two (right).

The investigation has therefore progressed to the next phase, which involves inspecting the cooling plate to understand the reason for the observed anomaly. By examining the geometric measurements taken on the ring using a 3D Romer Arm scanner (figure 88), it is possible to measure the deviation of each point on the ring compared to the reference CAD model. This investigation ultimately allows us to observe that there is approximately a -60 μm difference between the cooling plate and the cooling adapter at position 6 when comparing deviations from the CAD model. In contrast, position 5, which is in a good position, does not exhibit this difference. The deviations are homogeneous and measure 0.09 mm in all other positions. The observed bad alignment in geometry explains the higher temperatures recorded at position 6 during both tests conducted with CO_2 at +15°C and -35°C. The discrepancies in the positioning of the cooling plate (CP) and adapter (CA) on P6 contribute to increased temperatures, underscoring the importance of precise alignment in thermal performance evaluations. The small gaps between these two elements, created by imperfect alignment, can lead to degraded cooling performance if not filled with a high-conductivity material, in fact, air, a poor conductor of heat with a thermal conductivity of 0.024 W/mK, can significantly hinder thermal performance when present in these gaps. This issue has been observed in 4 out of 144 tested cooling plates for type L1 rings, representing 2.8%, while only 1 out of 130, or 0.8%, was noted for type L2 rings.

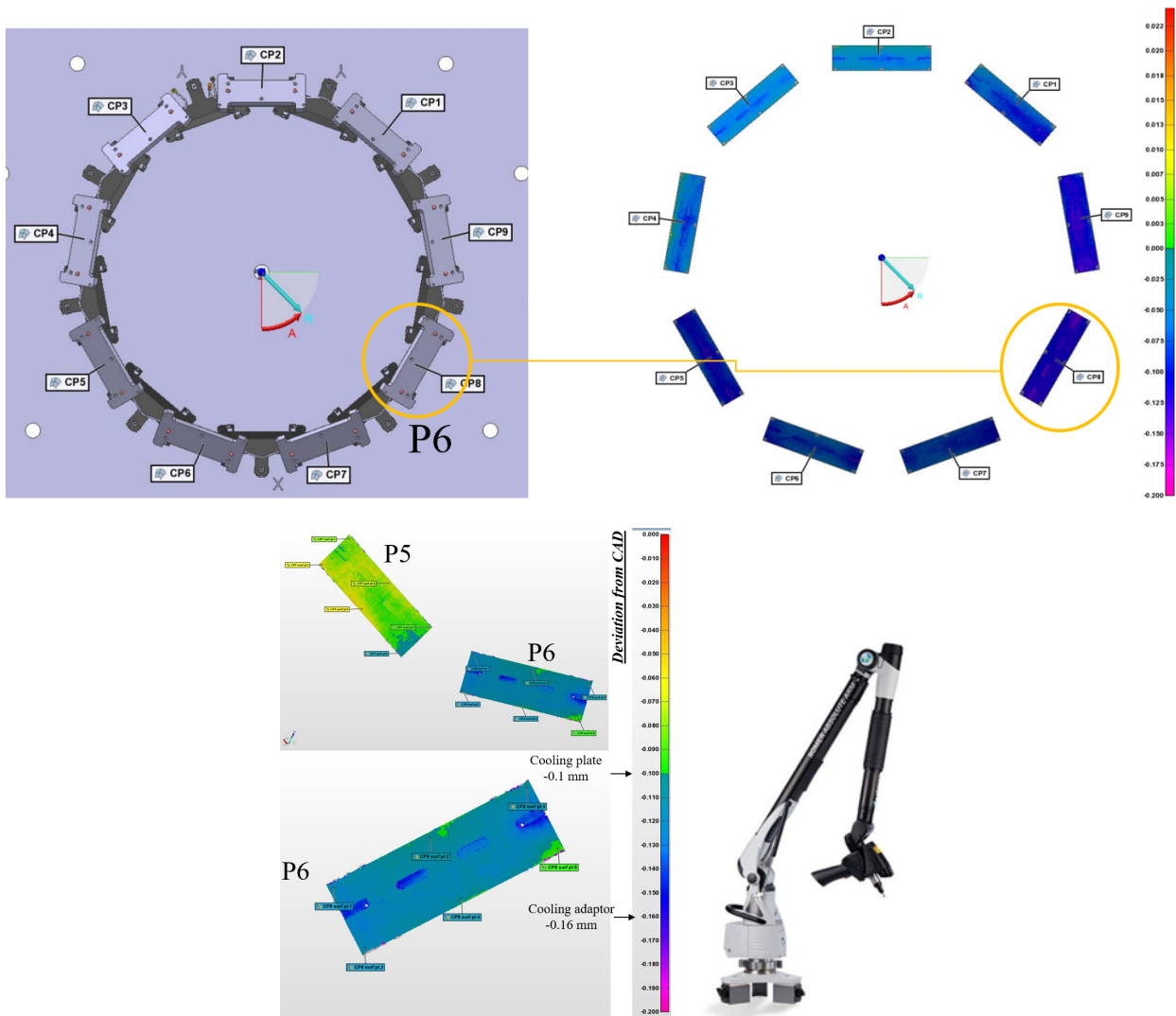


Figure 88 - Geometric deviations measured in ring L1 47 A5 compared to the reference CAD model. By comparing the cooling plates in positions 6 and 5, it is possible to observe an "anomalous" misalignment of approximately 60 μm between the cooling plate and the cooling adapter in position 6, providing a possible explanation for why an anomalous temperature is recorded in this position.

Given this potential defect and with a focus on production continuous improvement, two key considerations arise. First, it is essential to recognize that the contact between the actual module and the cooling plate is not direct, as it is with the dummy modules used for testing. In fact, thermal paste is interposed between the two in the real detector configuration, which helps to mitigate the impact of these gaps. Furthermore, if it is possible to monitor the quality of the assembled cooling plates before they are bonded into the ring, dividing them into "A" and "B" quality levels, this proactive approach can aid in identifying and addressing potential issues early on. "A-quality" cooling plate and cooling adapter assemblies (gap between CP and CA < 60 μm) should be placed in the following positions:

- Position $N/2+1$: this position should be closely monitored to protect it, as it is already the position in the cooling loop with the "worst cooling by design".
- "Outer side modules" between positions P1 and $PN/2$ (starting from P1): this arrangement aims to safeguard the modules placed in positions where higher CO_2 temperatures are expected in the cooling loop (figure 90).

"B-quality" cooling plate and cooling adapter assemblies (gap between CP and CA > 60 μm) should be placed in the following positions:

- “Inner side modules” between positions $N/2+1$ and N (starting from PN): this configuration targets the last part of the cooling loop, where the lowest CO₂ temperatures and highest HTC values are expected. If an anomaly appears in this area, it is less critical since temperatures are generally lower than those recorded in earlier positions, where CO₂ temperatures are higher (figure 90).

By addressing these considerations, we can enhance the thermal management performance of the cooling plates and adapters, ultimately improving the efficiency and reliability of the TBPS detector.

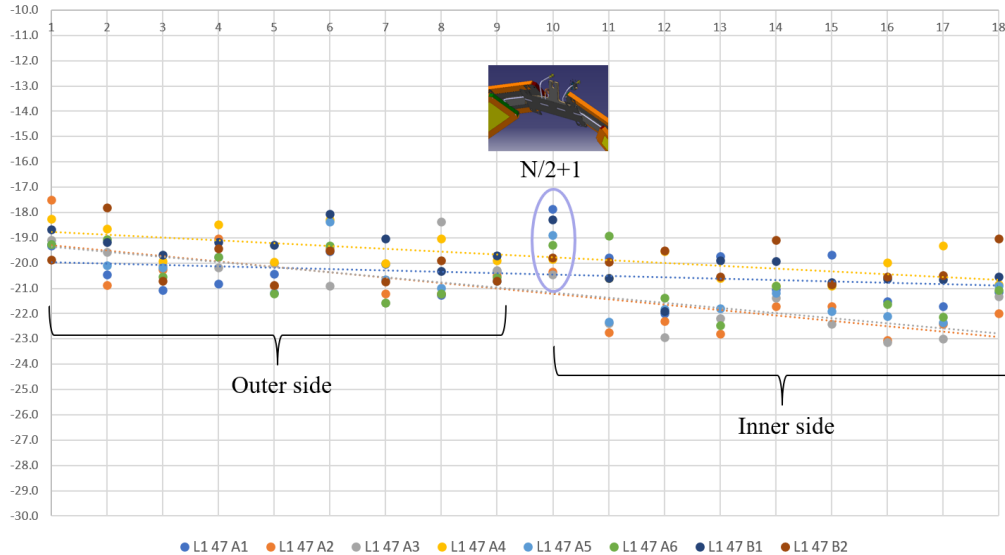


Figure 89- Temperatures measured in all the modules for ring L1. It is possible to highlight that the temperatures at position $N/2+1$ and those on the "outer" side, between positions 1 and $N/2$, are statistically higher than the temperatures measured on the "inner" side of the ring.

4.3.2.2 Case study L1 47 B2: dryout effect

The quality control conducted on ring L1 47 B2 has yielded valuable insights into the performance of two-phase cooling systems utilizing CO₂. During the initial test at the saturation temperature of CO₂ at +15°C, we identified an anomaly at position 2, where the measured temperature deviated by over 1 °C from the fitting line, resulting in a DT of 1.1 °C. Shifting our focus to the subsequent test carried out at -35°C, we observed a noticeable rising trend in temperatures during the second part of the cooling loop, despite them remaining sufficiently low. This upward trend prompted us to investigate the potential onset of a dryout phenomenon, which could be contributing to the increased temperatures in the last modules.

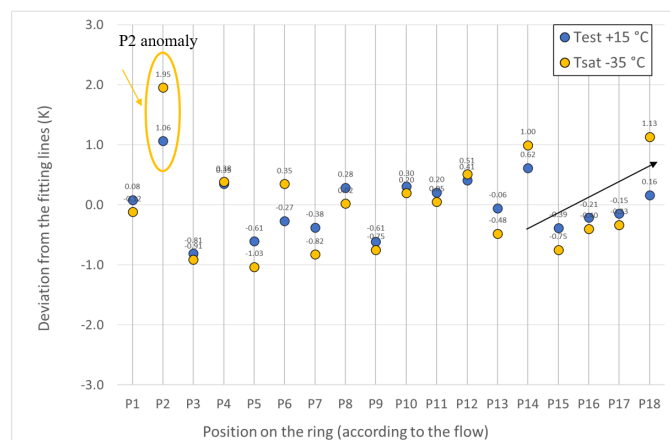


Figure 90- Deviation temperatures measured on the modules of ring L1 47 B2 during the tests at +15°C and -35°C. The black arrow highlights the increasing trend of the temperatures of the last modules, which could be influenced by a dryout phenomenon that causes a loss of the HTC of the CO₂.

To explore this further, we conducted a series of variable flow tests. By varying the flow rates from 1.4 g/s (the standard value for tests) to 1.6 g/s and 1.2 g/s, and so the vapour quality value at the end of the cooling loop, we found clearly that the higher temperatures recorded in the last positions seemed linked to the early signs of dryout and not to any anomalies in the mechanics of the ring. It is important to remember in this case that the temperature of the ring during the tests with CO₂ at -35°C, around 10°C, does not represent an operational condition. Therefore, the dryout onset observed in the last positions of the cooling loop is due to the additional heat provided by the environment to the ring itself during the test. In fact, the flow rate used was set to achieve a vapor quality of 42%, considering adiabatic test conditions. Thus, an increase in vapor quality to values above 50-60% (achievable with the additional heat provided by the environment) could lead the two-phase CO₂ into conditions of dryout, as can be seen in chapter 6. This characteristic phenomenon results in the deterioration of the heat transfer coefficient (HTC) of a two-phase refrigerant liquid, due to the fact that in this state of evaporation there is no longer liquid in contact with the pipe wall, but only vapor phase, thus preventing the phase change from occurring directly in contact with the pipe of the evaporator. Furthermore (figure 91), we found that the dryout phenomenon also affects position N/2+1, which is partially cooled at the end of the cooling pipe. Therefore, in addition to experiencing reduced contact with the cooling pipe due to the mechanics of the loop, which in that area features a jump between the outer and inner sides, this position could also be affected by this phenomenon if the cooling capacity of the CO₂ is insufficient to carry away the heat.

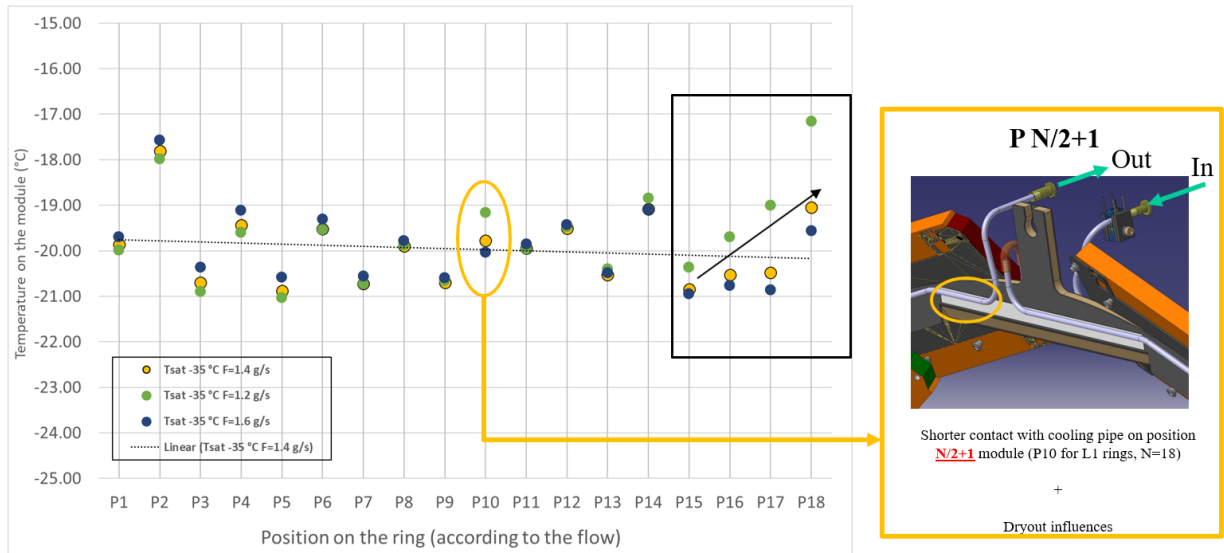


Figure 91 - Tests conducted at -35°C with varying flow rates: from 1.4 g/s (setpoint flow rate for the TQC test, represented by yellow dots) to 1.6 g/s (blue dots) and down to 1.2 g/s (green dots). They show how the onset of the dryout boiling phase influences the cooling of the last positions of the ring, including position N/2+1, which is already affected by a shorter contact time with the cooling pipe.

Through Equation 12, it is possible to evaluate the amount of heat supplied to the modules under the environmental conditions of the test:

$$W = h \cdot S_{modules} \cdot (T_{air} - T_{modules}) \approx 45 \text{ W}$$

Equation 12

where the natural convection coefficient (h) was set at 10 W/(m²·K). In this way, it's possible to estimate that an additional amount of heat supplied from the air accounts for approximately 25% of the heat dissipated by all the modules (considering the 180 W powered to the dummy modules, 10 W per module). Based on these power levels and the various flow rates used, we calculated the following vapor quality values: 46.9% at a flow rate of 1.6 g/s, 53.6% at 1.4 g/s, and 62.5% at 1.2 g/s. As these values approach the dryout zone, they help explain the observed increase in temperatures for the last five modules, from positions 15 to 18, decreasing the flow rate. In fact, increasing the CO₂ flow effectively brings the system closer to an optimal vapor quality value of 42% for CO₂. Additionally, having the same temperature trend as a function of the tested flow rate, it

is clear that position N/2+1 is influenced by this phenomenon, as it is partially cooled by the CO₂ just before it exits the cooling loop.

The final interesting observation that can be made by evaluating the results obtained with the different flow rates from this test in Figure 91 is that the trend of the temperatures measured in the modules varies inversely with the flow rate during the initial phase of the cooling loop. As the flow rate inside the pipe increases, the measured pressure drop within the system also increases. This is proportional to the temperature drop of the CO₂, and in a 2PACL cooling system, where the pressure (and so the temperature) of the CO₂ is set at the evaporator outlet, this results in higher temperatures of the two-phase refrigerant in the first part of the cooling loop. As a result, in the earlier positions of the cooling loop (for example, from positions 1 to 5), it can be observed that the temperatures measured during the test at a flow rate of 1.6 g/s (blue points in the graph) are higher compared to those measured during the test with a flow rate of 1.2 g/s (green points in the graph). Conversely, with lower flow rates, there are higher values of vapor quality at the outlet causing the trend to reverse in the later positions of the cooling loop, as previously described due to the beginning of the “dryout effect”.

4.3.2.3 Case study L2 68 B3: anomaly in the bonding process

This case study details an investigation carried out on the cooling performance of ring L2 68 B3. During an initial test conducted at +15°C, an abnormal temperature reading was observed in position 15 of the cooling loop. Specifically, position 15 showed a temperature of 23.0°C, which was significantly higher than the average temperature of 20.7°C observed in the other modules. This prompted a more thorough investigation to understand the source of the anomaly and the underlying causes affecting the cooling efficiency at that specific point. Upon further examination, position 15 was confirmed to be noticeably warmer than the others, and a more in-depth analysis revealed an asymmetric thermal behavior across the module, which indicated irregularities in the cooling plate’s efficiency.

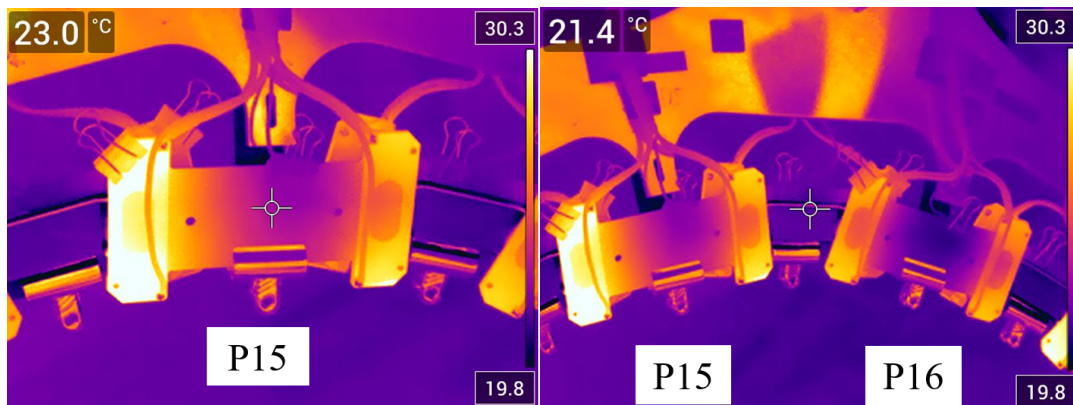


Figure 92 - Comparison between the temperature of the module in position 15 and the module in position 16 shows the asymmetric thermal behavior in module 15, where the left side is significantly warmer than the right side.

When comparing the thermal profiles of position 15, where the anomaly was detected, with position 16, which exhibited normal behavior, (figure 92) it became clear that the module's temperature was significantly higher on the left side than on the right side. This suggested an asymmetry in the cooling performance that was localized in position 15. To better understand this irregularity, the module and cooling plate interface were inspected in detail (figure 93). This closer examination revealed a lack of proper contact between the module's surface and the cooling plate. A visible gap was identified between the two surfaces, which indicated that there was a mechanical issue preventing optimal thermal conduction.

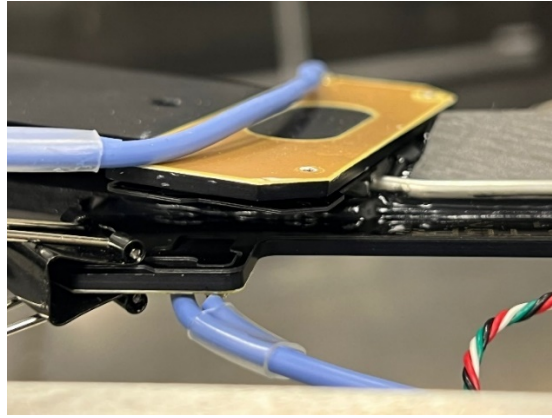


Figure 93 - Visual inspection 1 conducted on the module in position 15 shows a gap between the module and the cooling plate.

Further investigation into the left side of position 15 revealed the presence of an excess amount of glue. This excess glue extended beyond the intended bonding area between the cooling plate and the ring, creating additional thickness that hindered the module from properly seating against the cooling plate. This improper alignment compromised the thermal transfer, causing the observed temperature rise in position 15.

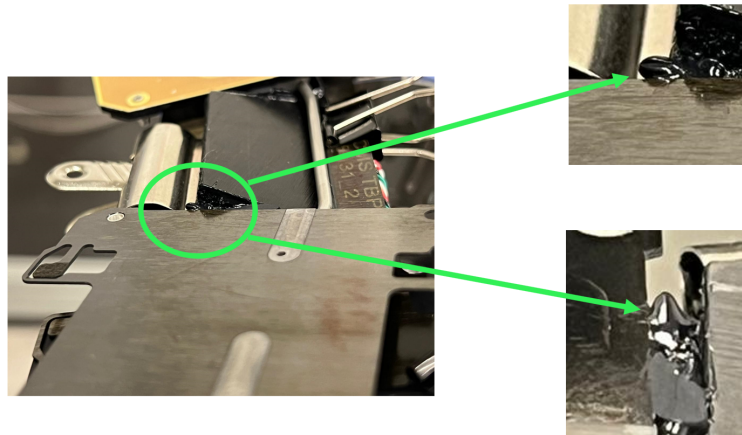


Figure 94 – The small drop of glue found after TQC on ring L2 68 B3

Following the discovery of this mechanical defect, the production team intervened using specialized tools to carefully remove the excess glue. After this correction, a repeat test was conducted under the same conditions of +15°C. The results (figure 95) showed that the temperature in position 15 dropped to 20.9°C, bringing it in line with the optimal levels observed in other modules.

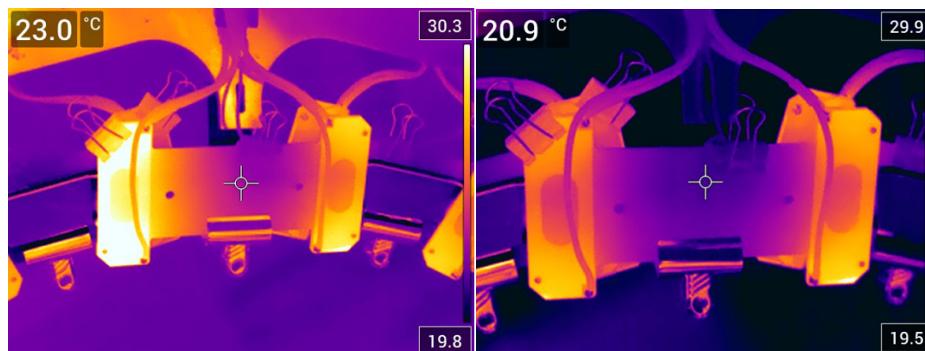


Figure 95 - Temperature of module number 15, before (left) and after (right) the removal of the excess glue following the anomaly identified during the TQC.

Finally, the plot in figure 96 illustrates the difference in temperature deviations between the tests conducted at +15°C and -35°C without the glue defect and the results from the +15°C test with the defect (marked by the

orange dot), where the temperature at position 15 was recorded as highly anomalous. Once again, the thermal test setup proved effective in identifying a critical mechanical issue within the cooling system that could have increased thermal resistance in the ring (decreasing the HTC_{eq} in Equation 11), ultimately reducing the overall efficiency of the detector itself. Detecting and correcting this mechanical defect are essential for ensuring the proper function and longevity of the entire tracker detector.

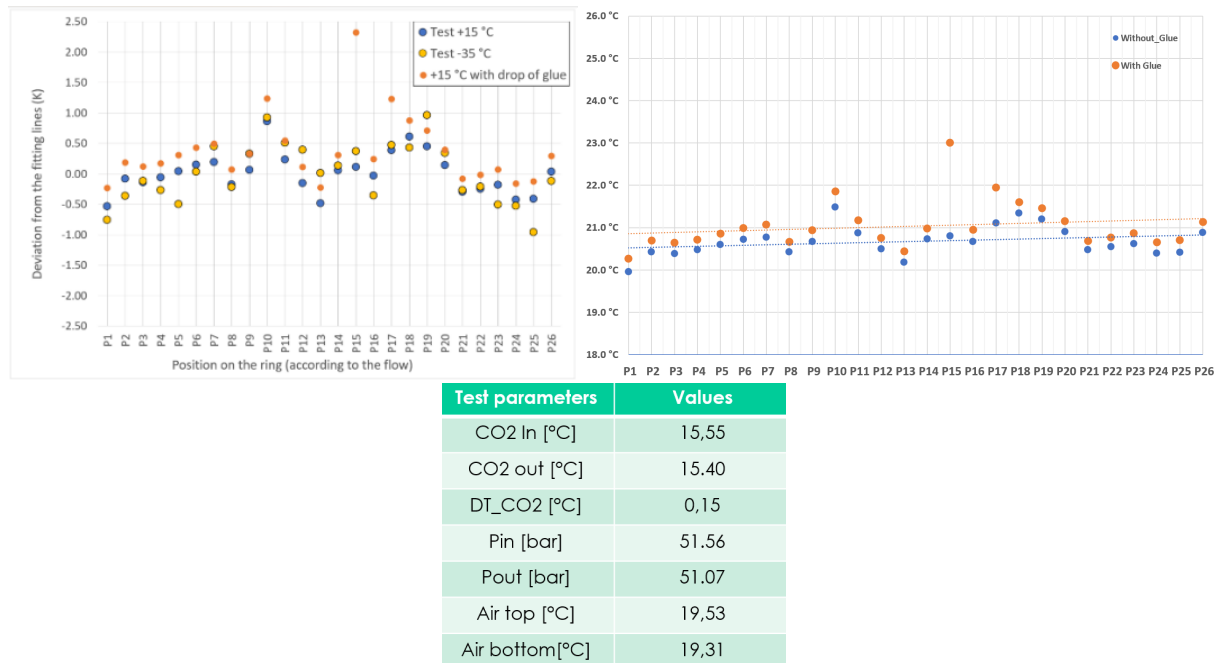


Figure 96- Temperature deviations of the modules relative to the fitting line (left) and absolute temperatures of the modules in the +15°C test (center) before and after the removal of the excess drop of glue (orange and blue dots), as well as during the -35°C test conducted without the anomaly. The operating conditions for the +15°C test are shown in the table on the right.

5. TB2S Ladders TQC – Thermal Quality Control

5.1 TB2S ladder structure

During my year of activity at CERN, I was involved in testing the mechanical structure of the TB2S tracker sub-detector, which stands for Tracker Barrel with 2S Modules. The TB2S is a part of the tracking detector, where the modules are mounted in series on planar structures referred to as "ladders". These ladders are then placed side by side in a circular arrangement to form the cylindrical structure of the barrel (figure 98).

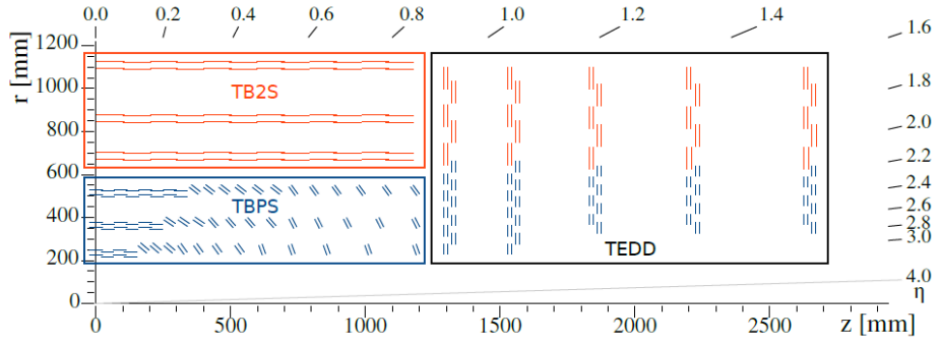


Figure 97- Sketch of 1/4 of the CMS tracker designed for the Phase 2 upgrade, where the position of the TB2S can be observed [22].

The number of modules mounted on each ladder is fixed, with 12 modules organized in two rows. The upper layer is superimposed on the lower layer to ensure hermeticity and a single ladder covers half the length of the barrel. The barrel, cylindrical in shape, has a length of 2360 mm, an outer diameter of 2330 mm and an inner diameter of 1242 mm. It is composed of three concentric layers, each with an increasing diameter to prevent interference between them. Since the ladder design is the same for all layers, the circles progressively accommodate a larger number of ladders.

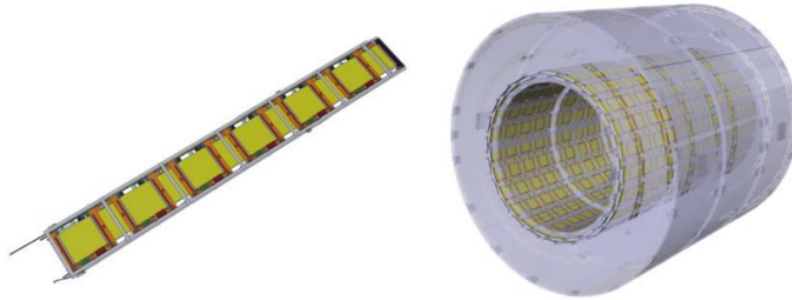


Figure 98 - CAD view of the TB2S "wheel" (right) consisting of the base element called "ladder" on which the modules are positioned [22].

The mechanical frame of each ladder consists of beams made of C-shaped carbon fiber laminates. Along these beams, cantilevered aluminum supports, known as "inserts", are glued to hold the modules on the cooling pipe. Each ladder can host 12 modules and every module, except for Module#1, is connected to the structure through six aluminum inserts that also ensure thermal contact between the modules and the cooling pipe. Modules #1 and #12, located at the two ends of the ladder, have a slightly different configuration. Module #1, in particular, is mounted on two special inserts made of AlCF (aluminum-carbon fiber) and two aluminum inserts, distinguishing its setup from the other modules. In this precise position (module #1), as in the case of the TBPS tilted rings, AlCF material is used in these two special inserts because they are several centimeters longer than the aluminum inserts used for all the other modules. The advantages of using this material in specific positions within "cold detectors" are explained in Section 4.1.

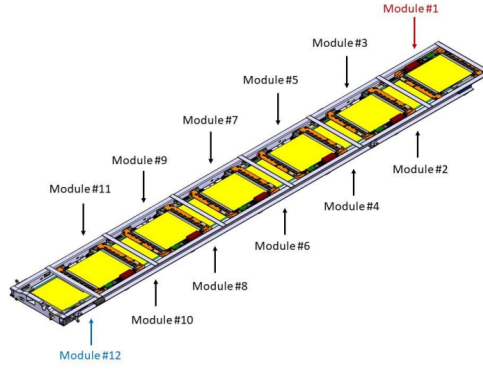


Figure 99 - Reference used to number the modules along the TB2S ladder.

Within the TB2S experiment, each cooling loop consists of two ladders placed in series. The inserts under each module provide crucial mechanical support as well as a thermal link to the cooling system, which ensures the proper functioning of the modules under operational conditions. The production of the ladders takes place in Pakistan through a collaboration with the National Center for Physics (NCP). The two ladders that have been tested as of the date of writing of this paper have a cooling pipe made of stainless steel. However, the current production is shifting towards the use of titanium pipes due to its superior thermal performance. Titanium exhibits less thermal deformation when brought to operating temperatures with CO₂ at -35°C, which reduces the mechanical stress on the pipes and on the modules. Specifically, titanium has a thermal expansion coefficient of $8.14 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$, compared to $12 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ for stainless steel, making it a better material from this perspective. In addition to its reduced thermal expansion, titanium also demonstrates good heat transfer properties, in fact, tests conducted at CERN in June 2024, which are presented in this work on section 6, show that switching from stainless steel to titanium does not result in any reduction in cooling performance, confirming the suitability of titanium pipes for the TB2S ladders.

5.2 TB2S ladder TQC: test setup and procedure

The thermal quality control testing of the ladders is carried out in Pakistan at the end of the production process, using single phase deionized water as cooling system. The purpose of this test is the same of the TQC conducted at CERN for TBPS tilted rings, so to validate all the thermal contacts, ensuring that no inserts (the cooling element of the ladder's structure) exhibit anomalies. In parallel, the first ladders produced will also be tested at CERN, with the aim of validating the quality control tests conducted in Pakistan, where two-phase CO₂ is not used as a refrigerant. During my activity at CERN, I designed a test setup capable of being connected to the two-phase CO₂ TRACI system located in the Lyon Cold Room (Building 186). This setup allows us to perform cross-validation of the thermal tests by replicating them with two-phase CO₂ as the coolant, providing a more accurate simulation of the operational environment of the ladders.

The main objectives of these initial tests conducted at CERN and presented in this report were to analyze the cooling performance of each module contact (each insert) in the TB2S pre-production ladders, using two-phase CO₂ as the coolant in a controlled, cooled environment while also aiming to compare the results with those obtained at NCP in Pakistan, with the goal of establishing a standardized procedure to identify thermal anomalies and enhance the quality of the mechanical structures. Additionally, the setup has been designed with flexibility in mind, allowing us to conduct three other types of tests:

1. Tests to study the heat transfer coefficient, which will be presented in the following chapter 6.
2. Tests conducted on a fully integrated ladder containing all 12 real modules, including one irradiated module. The primary objective of this test is to study the thermal runaway of the irradiated module. The results will be presented in the PhD thesis of Lea Stockmeier (KIT - Karlsruhe Institute of Technology) and will incorporate the simulations conducted on 2S modules by Cristiano Turrioni (INFN- Perugia section).

3. Validation tests for the first prototypes of the preheater, used in the setup.

The test setup was designed to allow testing of two TB2S ladders in series, simulating real operational conditions and consists of an aluminum box mounted on a bosch profile structure. Given that one of the objectives is to test the ladders at approximately -10°C to replicate actual working conditions, the aluminum box is insulated with a second layer of thermal material. This outer layer is made of Swisspor XPS 300 and URSA XPS NWE insulation, forming a thermally insulated, movable box (figure 100). CAF 33 sealant was used to assemble the insulated box. The main dimensions of the insulated box are:

- Wall thickness: 10 cm
- Outer dimensions: 200x101x31 cm
- Inner dimensions: 178.5x81.5x11 cm

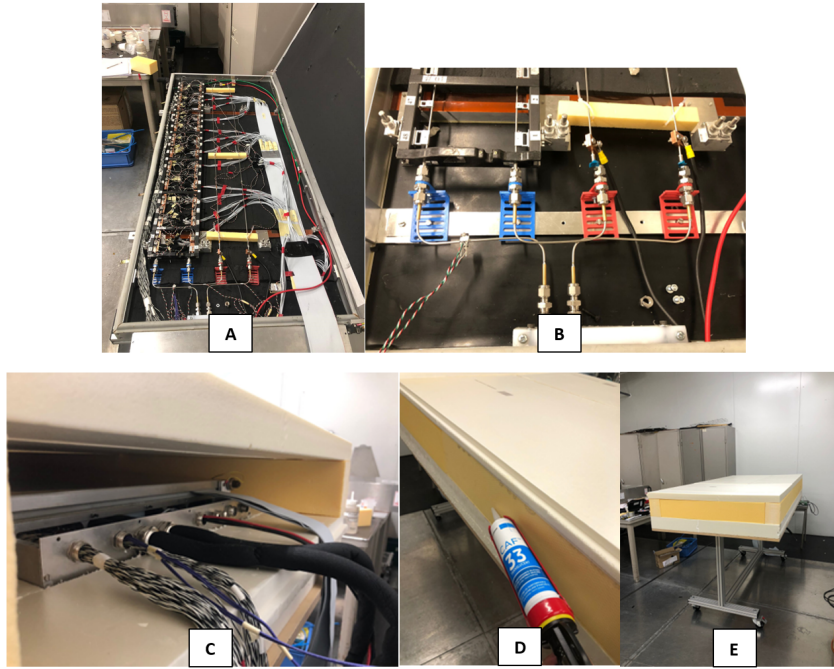


Figure 100 - Different phases of the TB2S test setup assembly process: A - Aluminum box, where two ladders can be positioned in series. B - 3D printed support used to fix the cooling loop. C - Detail of the production of the outer insulation box for the passage of the CO₂ tubes and the power and sensor readout cables. D - Adhesive phase of the insulation box assembly. E - Picture of the TB2S thermal insulated test bench in the Lyon Cold Room.

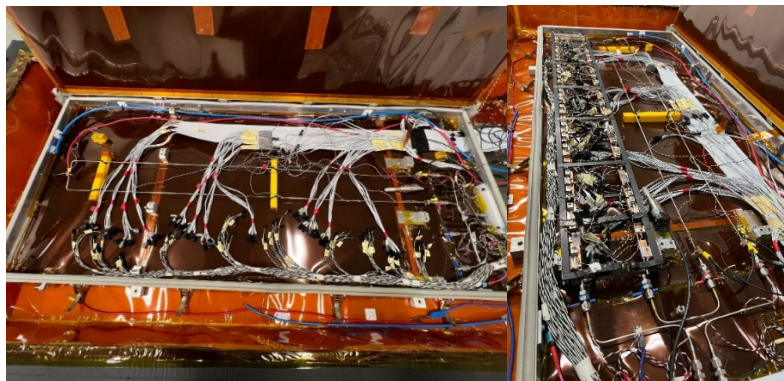


Figure 101 – Internal structure of the completed TB2S setup without the ladder (left) and with one ladder in the first position of the cooling loop (right).

For the thermal quality control of the ladders, heaters of the same type of those used for the tests in Pakistan are employed (figure 101). Each module is attached to 6 inserts, meaning that each heater will dissipate one-sixth of the total power dissipated by a module. The tests will be conducted with a power dissipation of 75 W

for an entire ladder, which corresponds to 6.25 W per module, or roughly 1 W per heater. An additional test, conducted on the first ladder tested, simulates the worst-case scenario, assuming maximum power dissipation from an irradiated module in the least favorable TB2S position, where up to 8 W could be dissipated by a single module due to leakage current at end-of-life conditions. Based on this, this particular test will simulate the scenario where every module in the ladder dissipates 8 W, resulting in a total of 96 W (8 W per module and 1.3 W per heater). The ladder will be qualified in the first position of the cooling loop (figure 101), where the CO₂ temperatures are higher and the heat transfer coefficient (HTC) of the two-phase flow is lower due to incomplete boiling (low vapor quality). To simulate the power load of two ladders in series, a TB2S stainless steel is placed in the second position, connected to a power supply to dissipate the same power as the ladder in the first position.

As shown in the electrical schematic in figure 102, the pipe will be connected via three clamps: the positive terminal connected to the power supply and two negative terminals at the inlet and outlet of the pipe, resulting in an electrical system with two resistances in parallel. The electrical resistance of the pipe was measured during the design phase to dimension the necessary power supply.

The setup requires in total three power supplies:

- One for the preheater (which contains two 10 Ω resistors) of type TX1820P
- One for the 70 heaters connected in parallel attached to the ladder, of type SM 52-30
- One for the heated pipe in the second position, of type SM 52-30

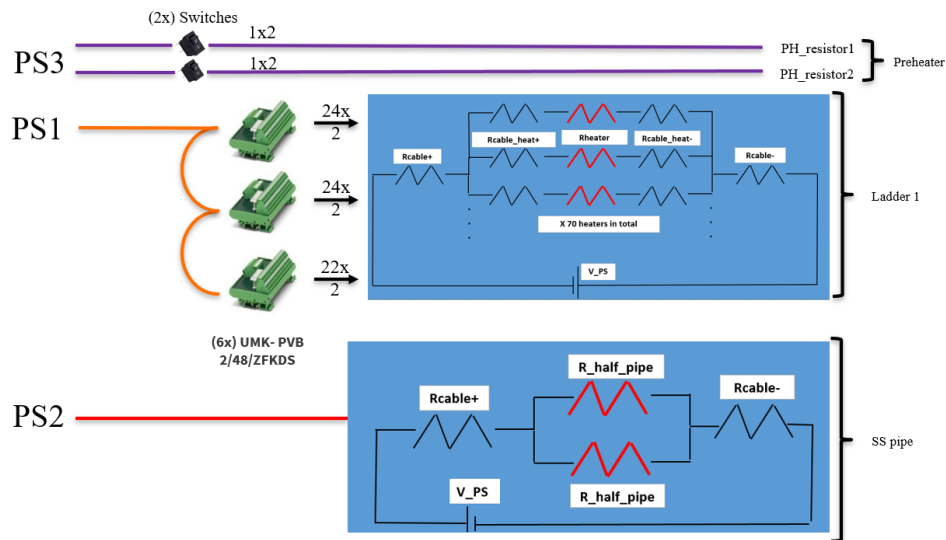


Figure 102 - Electrical diagram used to supply power to the system. In red are the elements where heat is dissipated (the heaters in the ladder and the walls of the pipe), and in black are the additional resistances of the cables used during the design phase of the setup to evaluate the total power dissipated.

The heaters used are Arcol AP851 series resistors, 120 Ω , $\pm 1\%$, dissipating a maximum of 50 W. Each heater is mounted on a copper plate and fastened with a fixing screw. Below each heater (figure 103), a slot is available to position a Pt1000 temperature sensor (RTD Class A, 4 wires). A captive screw with a washer is used to secure the heater to the inserts.

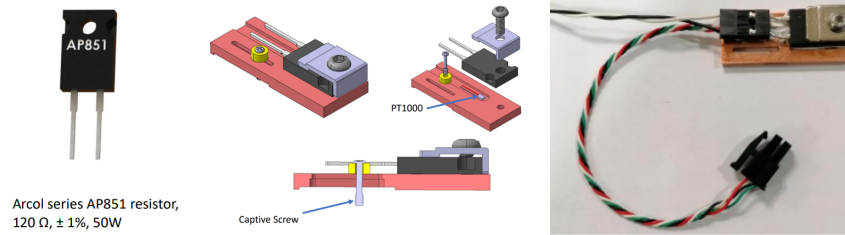


Figure 103 - "Heaters" used to provide power to the ladder inserts and validate their thermal performance.

The entire test setup is equipped with a range of sensors to ensure comprehensive data collection:

- 90 Pt1000 temperature sensors (RTD Class A, 4 wires connection)
- CO₂ inlet and outlet pressure
- Differential pressure sensor (Endress+Hauser PMD75)
- CO₂ flow meter
- Dry gas flow meter
- Humidity sensor

The pressure sensors are connected to a PLC, while the temperature sensors are read by four MTRS (Multiple Temperature Readout System) boards for reading data from Pt1000 4-wire sensors. Each board can handle up to 24 sensors (figure 104). For the thermal test bench, a custom LabVIEW program was developed to monitor and record real-time data during testing.

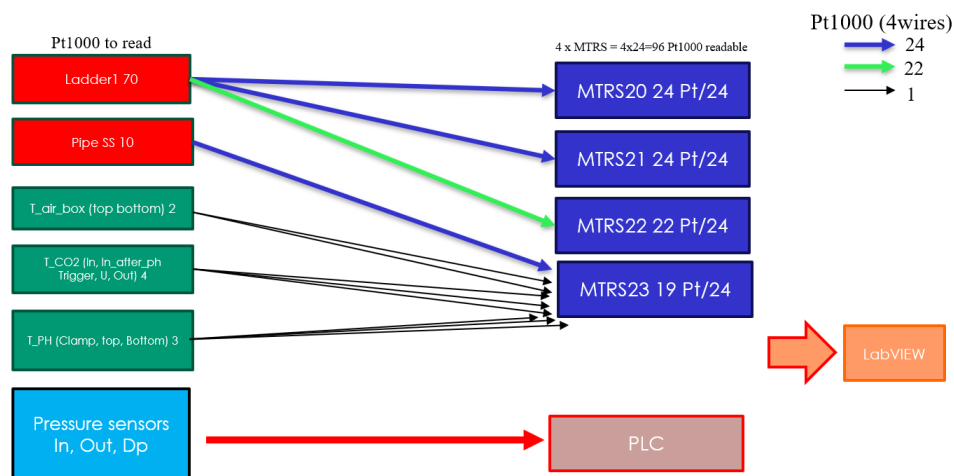


Figure 104 - Schematic of the readout system used for the Pt1000 sensors, which utilizes 4 MTRS boards (each with a maximum capacity of 24 sensors) and the PLC to read the pressure data. All data is monitored through a LabVIEW program.

In total, the 90 Pt1000 sensors are distributed as follows (figure 105):

- 1 Pt1000 sensor per heater (70 sensors in total)
- 10 Pt1000 sensors along the heated pipe in the second position of the cooling loop.
- Preheater temperature sensors (3 sensors)
- CO₂ inlet temperature before and after the preheater (2 sensors)
- CO₂ U-pipe (1 sensor)
- CO₂ outlet (1 sensor)
- Air temperature inside the aluminum box (2 sensors)
- Air temperature inside the insulated box (1 sensor)

The cooling loop consists of the following elements, arranged in the order of CO₂ flow (ID inner diameter, OD outer diameter):

- 2 m insulated transfer line from the TRACI local box to the evaporator (Cu annealed pipe, OD=6 mm, ID=4 mm)
- 22 cm inlet CuNi pipe (OD 2.5 mm, ID 2.0 mm), where the prototype preheater is placed
- Ladder #1 (Stainless steel pipe: OD=2.3 mm, ID=2.0 mm, total length of 2474 mm)
- 15 cm CuNi U-pipe (OD=2.5 mm, ID=2.0 mm)
- Heated TB2S ladder stainless steel pipe (OD=2.3 mm, ID=2.0 mm, total length of 2474 mm)
- 23 cm outlet CuNi pipe (OD=2.5 mm, ID=2.0 mm)
- 2 m insulated transfer line from the experiment back to the TRACI local box (Cu annealed pipe, OD=6 mm, ID=4 mm)

As mentioned earlier, the upgraded TRACI 2.3 cooling plant (informally called "TRACI+") provides CO₂ to the experiment at a controlled temperature as low as -35°C, with a mass flow rate of up to 3 g/s. TRACI+ is located outside the cold room and connected to the local box inside via an insulated coaxial pipe.

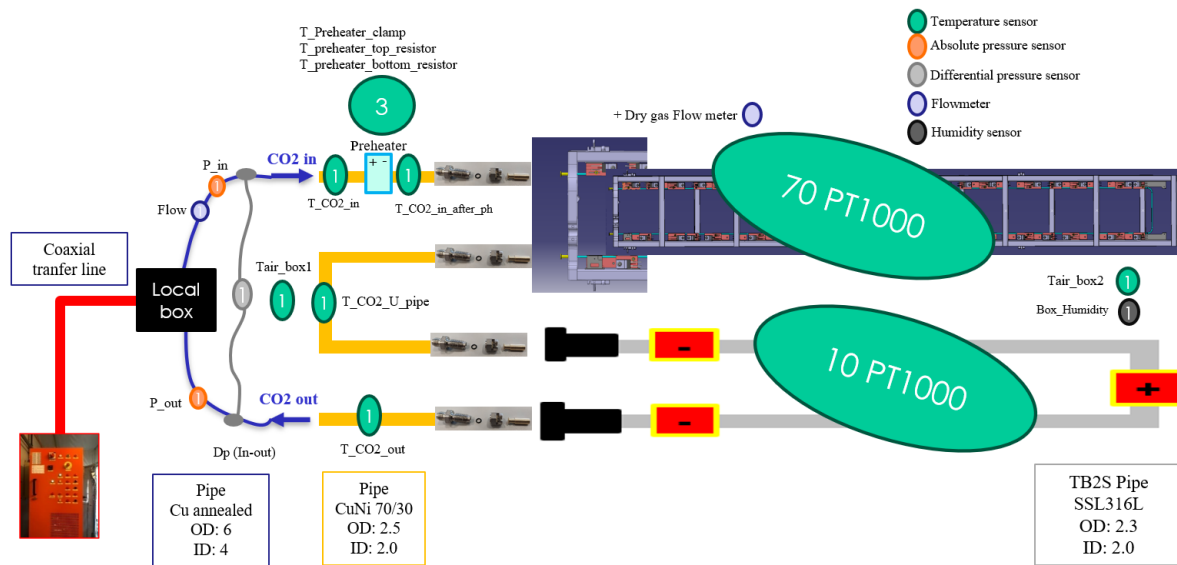


Figure 105 - General overview of the sensors used and the different pipes present in the cooling loop of the TB2S test bench.

To prevent the formation of harmful condensation inside the aluminum box during testing at -35°C, a dry gas supply system is essential. The dry gas is supplied via a dedicated circuit and can be routed either inside or outside the aluminum box, through two appropriate valves. By using two dedicated circuits, it is possible to shut off the dry gas only within the aluminium box during the test, allowing for tests to be conducted without forced convection inside the box caused by gas flushing. The dry gas can remain open in the loop outside the aluminium box, enabling the dew point temperature within the experiment to be maintained at around -40°C (lower than the minimum CO₂ temperature of -35°C). The dry gas, supplied by the facility at approximately 15°C, is cooled to around -15°C before entering the test box, using a chiller equipped with two heat exchangers.

The heaters are mounted on the designated inserts using an M1.6 screw, initially torqued to 10 cNm, as per the design specifications. This is intended to maximize thermal contact between the module and insert in the real setup, or between the heater and insert during quality control tests. However, determining the optimal torque value will be one of the tests conducted in the future on the first produced ladders. This is because high torque values have been observed to cause issues, as they can damage the fragile AICF inserts, either breaking them or damaging the threading. Additionally, high torque can place unwanted mechanical stress on the modules, which should be avoided. In this initial phase of ladders testing, all conducted using these “dummy heaters”, the role of torque will be investigated regarding the effects produced in the TQC of the ladders, aiming to validate or identify anomalies in the future by using lower torque tests to avoid damaging the inserts during

the quality control phase. Moreover, the results of these initial tests may provide insight into the possibility of relaxing the torque during the integration phase of the actual modules.

Despite the focus on torque optimization, the overall test procedure included, apart from the test conducted at -35°C , a $+15^{\circ}\text{C}$ test (which was of secondary importance here, as the main goal was to assess performance under real operating conditions). The primary test involved CO_2 at -35°C , with ambient air around -10°C , simulating real working conditions, viable after removing any moisture from inside the test box using the dry gas system .

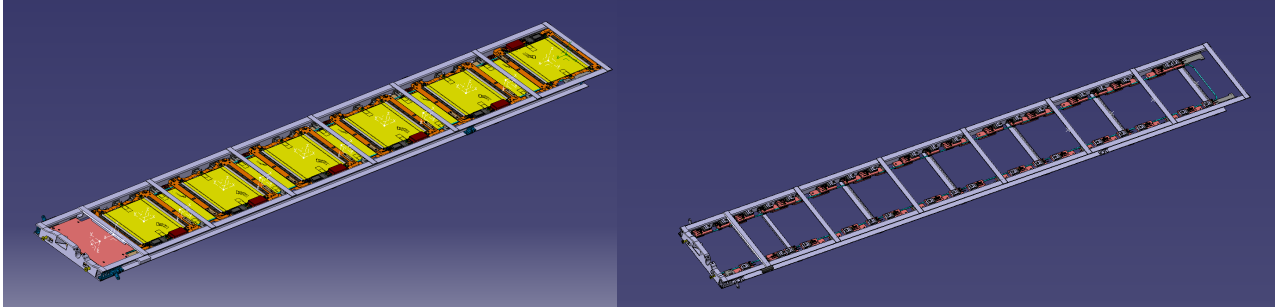


Figure 106 – CAD view of the TB2S ladder embedded with the real 2S modules (left) and the heaters used for thermal quality control (right)

5.3 TB2S ladders TQC: outcomes

Before reviewing the results from the first two tested ladders, it's important to clarify that, to ensure consistency in identification and data tracking, the heaters used in this test are numbered according to the same numbering system used for the inserts in Pakistan. In these tests, the heaters are positioned in each insert where the 2S modules are connected, with each module generally attached to four large inserts and two short inserts. To perform thermal quality control, we distinguish between four different types of inserts:

1. Single Big Insert (AI): large inserts heated only on one side. This includes Insert 48 and Insert 1, with two large heaters heating these two inserts. These heaters are labelled as “single_big” (figure 107).

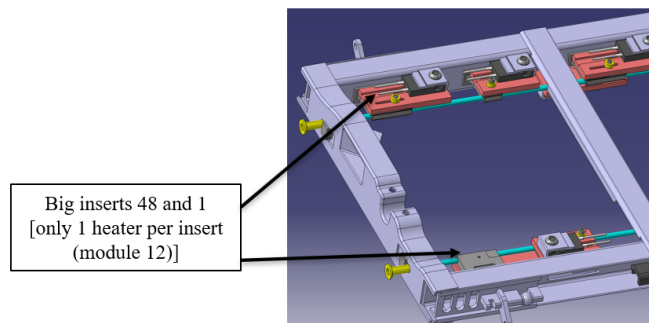


Figure 107 – Figure showing “single_big” heaters.

2. Big Insert (AI): large insert heated on both sides with two heaters. This category comprises 22 inserts heated by 44 heaters. These heaters are simply labelled as “b” (figure 108).
3. Short Insert (AI): short inserts heated only on one side, consisting of 22 inserts heated by 22 heaters. These heaters are referred to as “s” (figure 108).

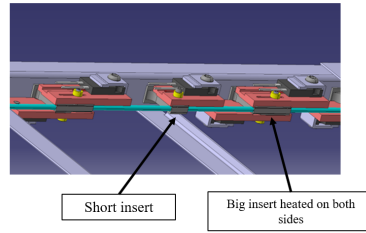


Figure 108 – Figure showing short heaters “s” and big heaters “b”.

4. Special Inserts (AlCF): these insets are heated only on one side and this category includes two aluminium-carbon fiber inserts heated by two heaters, designated as “special”. For these thermal tests, each of these special Al-CF inserts, which differ in geometry and material from the others, had only one heater per insert, leaving the position circled in red in Figure 109 at the end of the ladder empty.

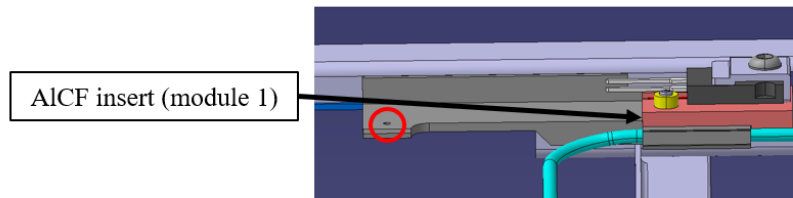


Figure 109 - Figure showing the “special heater” placed on the AlCF insert and the missing heater on the second thread hole of the insert highlighted in red.

In the thermal tests conducted in Pakistan, each of the large inserts is equipped with only one heater per side. However, this configuration, while effective for testing whether each individual insert is properly connected to the cooling pipe, does not accurately represent the true connection configuration of the modules within the ladders, since in all the large inserts (except for numbers 1 and 48), the modules are connected on both sides. For this reason, two heaters were placed in each of these inserts during the tests conducted at CERN, one on each side and to distinguish between the two, the notation “U” (upper) and “D” (down) was used for the upper and lower heaters of the same insert (e.g., T46b_U for the upper heater and T46b_D for the lower heater on big insert 46).

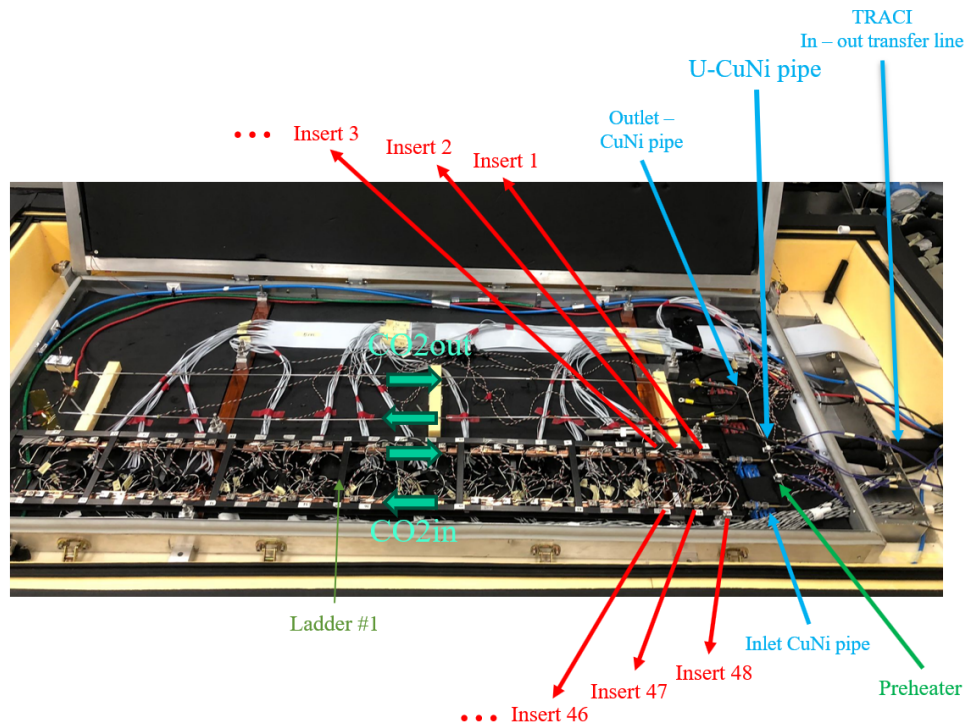


Figure 110 - Overview of the TB2S test setup with the references used to label the inserts.

5.3.1 TB2S ladders TQC: Ladder #1

The tests were conducted with specific power settings to ensure realistic operating conditions. In particular, the nominal power of 75W was selected to simulate standard operating conditions, corresponding to 6.25W per 2S module, which equals approximately 1.1W per heater. Additionally, a worst-case scenario was tested, where each module dissipates 8W, bringing the total power dissipation to 96W per ladder, or about 1.4W per heater.

For the thermal quality control tests carried out at -35°C, the TRACI system was set to provide CO₂ at 12 bar and -35°C, with a mass flow rate of 1.4 g/s. Inside the aluminum box, the temperature was kept around -10°C, and no dry gas was introduced during the test. The room temperature was maintained at 20°C using the HVAC system. The heaters were screwed with a torque of 10 cNm, and the preheater was powered at 8W. The results focused on configurations where both the ladder and the pipe were powered at 75W and 96W as shown in figure 111.

TQC @-35, torque 10 cNm			LADDER	PIPE
1	-75 W ladder, pipe off		ON	OFF
2	-75 W ladder, 75W pipe (operating condition)		ON	ON
3	-96 W ladder, pipe		ON	OFF
4	-96 W ladder, 96 W pipe (full power)		ON	ON

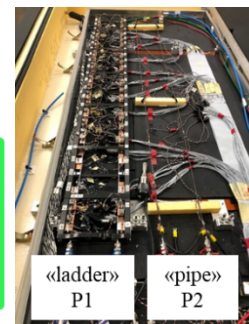


Table 12 - Averages, standard deviations and temperature ranges measured in the different groups of heaters . Test with CO₂ at -35°C, 75W of power per ladder (150W total), 1.4 g/s flow rate and 10 cNm of torque applied.

Type of heater [total number]	T_average	Standard deviation	Range [Tmax-Tmin]
All heaters [70]	-23.0 °C	1.4	7.7 °C
Big [44]	-23.4 °C	0.9	3.7 °C
Short [22]	-22.2 °C	1.4	4.5°C
Single_big [2]	-26.0 °C	-	1.7 °C
Special [2]	-24.9 °C	-	0.6 °C

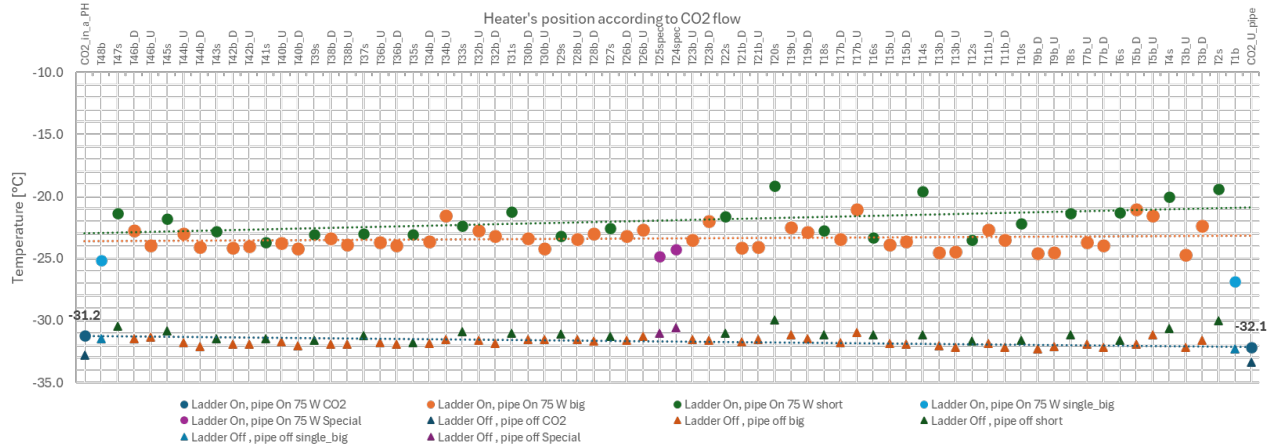


Figure 112 – Absolute temperatures measured in the heaters and in the CO₂ flow, before and after the power is turned on. Test with CO₂ at -35°C, 75W of power per ladder (150W total), 1.4 g/s flow rate and 10 cNm of torque applied.

Looking at the general trend of the absolute temperatures of the heaters in figure 112, the temperature drop of the CO₂ by 0.9°C in the first ladder of the cooling loop does not seem sufficient to produce a corresponding decrease in the heater temperatures (the variability in the thermal contact between the heaters and inserts could mask this trend). Further investigation of this phenomenon has been done during tests conducted on the Ladder#3, chapter 5.3.2.

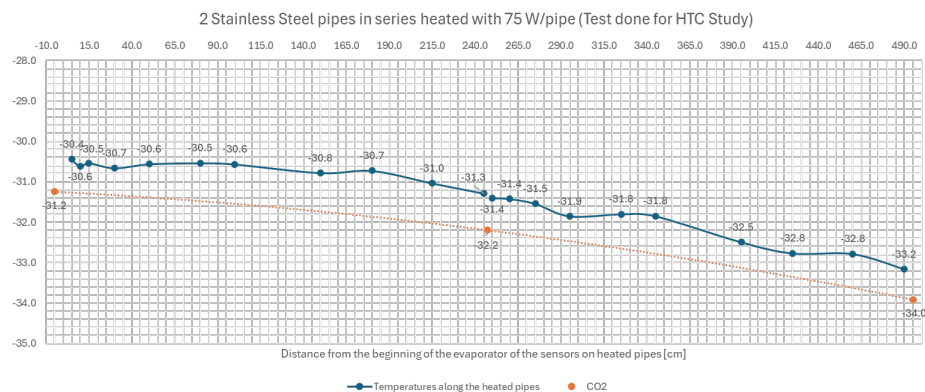


Figure 113 - Temperature of the heated wall of the pipe (blue) compared to the temperature of the CO₂ inside the pipe (orange). It is evident that the temperature drop of the heated wall of the pipe is almost constant in the first position of the cooling loop compared to the second position, reflecting the results obtained during the tests on the first ladder placed in the first position of the loop.

When testing in the worst-case scenario (table 13 and figure 114), where all modules are considered to have the maximum level of radiation (8W/module, 96W/ladder), and comparing these results with the baseline test at 75W per ladder, it was found that increasing the power to 96W/ladder resulted in an average temperature increase of 2.0°C across all heaters. The maximum temperature increase was observed on short insert 14 (DT=2.7°C). Additionally, the variability (the standard deviations) in the measured temperatures increased by approximately about 0.3°C under these conditions of greater power to dissipate (table 13).

Table 13 - Averages, standard deviations and temperature ranges measured in the different groups of heaters. Test with CO₂ at -35°C, 96 W of power per ladder (192W total), 1.4 g/s flow rate and 10 cNm of torque applied.

Type of heater [total number]	T _{average}	Standard deviation	Range [T _{max} -T _{min}]
All heaters [70]	-21.0 °C	1.7	9.0 °C
Big [44]	-21.5 °C	1.1	4.5 °C
Short [22]	-19.8 °C	1.7	5.3°C
Single_big [2]	-24.7 °C	-	1.9 °C
Special [2]	-23.2 °C	-	0.6 °C

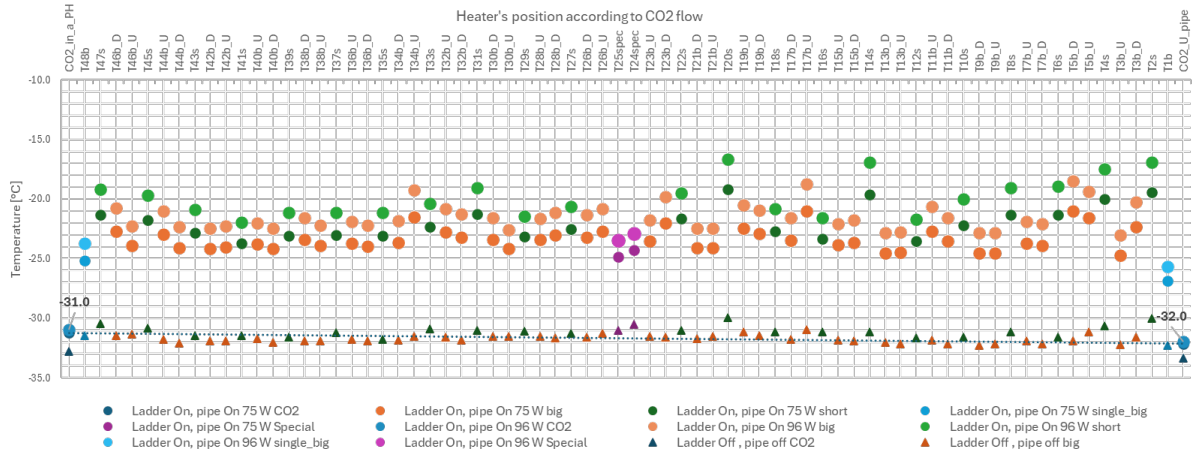


Figure 114 - Absolute temperatures measured in the heaters and in the CO₂ flow during the tests with 0W, 75W, and 96W per ladder. All the tests have CO₂ at -35°C, a flow rate of 1.4 g/s, and 10 cNm of torque applied.

Given the limited statistical data obtained so far, with only two ladders tested, it was not yet possible to perform a precise quality control based on parameters that would allow for the identification of significant anomalies. However, analyzing the data from the first ladder test, using the average value and standard deviation of the temperatures measured on each heater, it is possible to observe that among the heaters placed on the large inserts, heaters 5b_D and 17b_U were detected as outliers (figure 115). These heaters recorded temperatures more than 2°C higher than the average temperature of the large heaters. In this case, the average temperature can be considered a reference value for each element of the cooling loop, given that the CO₂ temperature drop across the first position of the loop is very low and, more importantly, not reflected in the thermal behavior of the individual heaters.

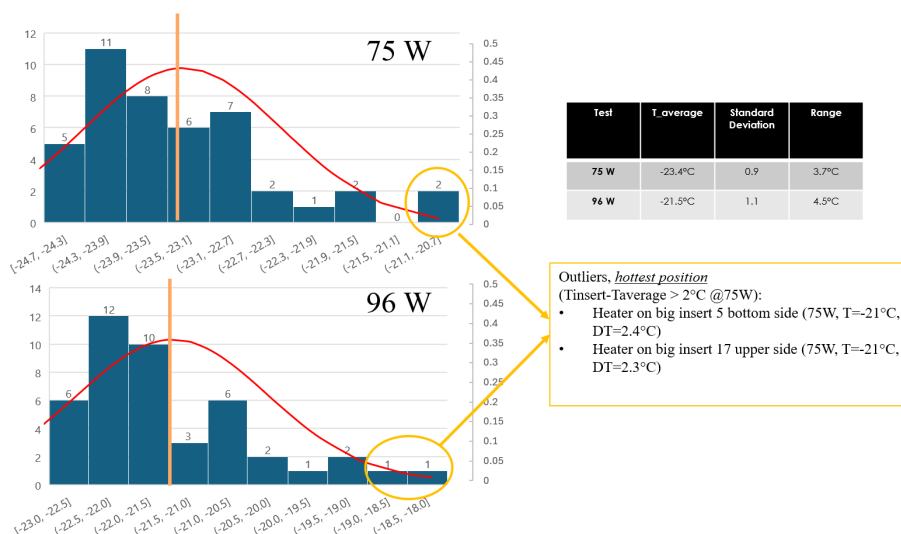


Figure 115 - Attempt to identify outliers by analyzing the temperatures of the big heaters in ladder #1 during the tests with 75W and 96W. Outliers: 5b_B and 17b_U.

Conducting the same investigation of outliers, but focusing on the short inserts (figure 116), reveals higher deviations in these cooling elements, indicating greater variability in their thermal performance. This could suggest a lower production quality, as will be further explored, like a potential issues with the assembly and gluing of the inserts into the cooling pipe. Indeed, as shown in the statistical analysis below, the hottest outliers, those with a temperature difference of more than 2°C compared to the average temperature of the short inserts during the test with 75W of power per ladder, are three, specifically, inserts 20s, 2s and 14s.

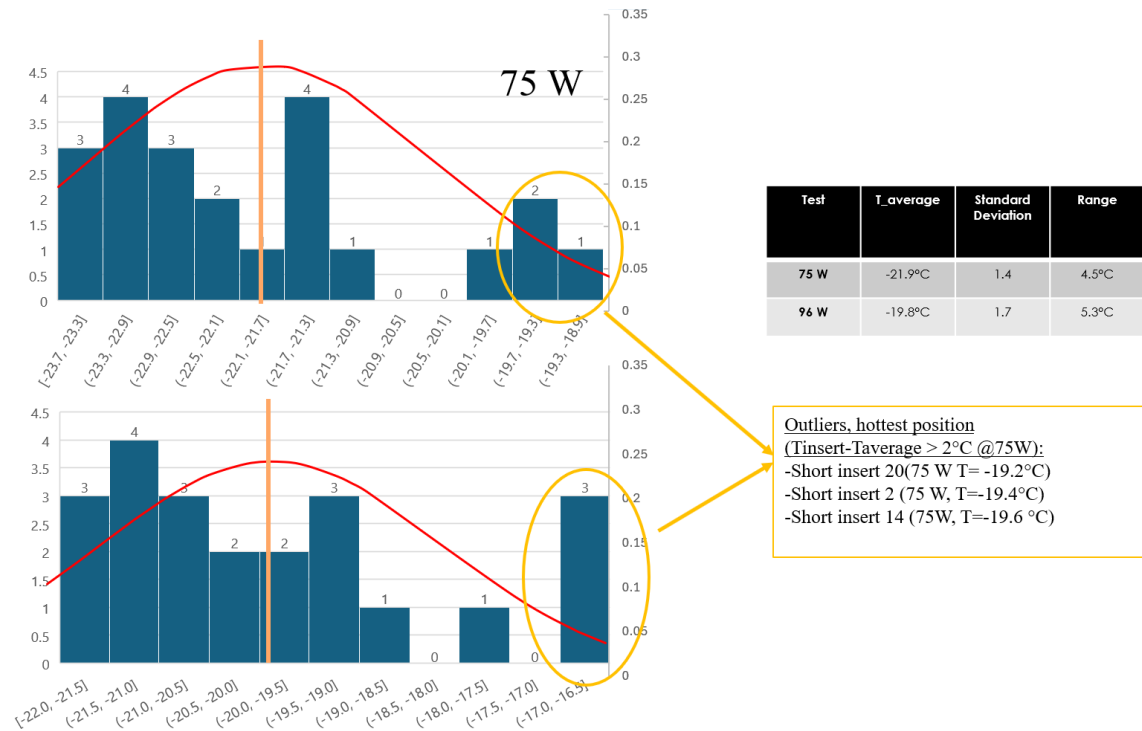


Figure 116 - Attempt to identify outliers by analyzing the temperatures of the big heaters in ladder #1 during the tests with 75W and 96W. Outliers: 20s, 2s and 14s.

Noting the unusually high temperatures, particularly in the short inserts where temperatures exceeding -20°C were recorded (this being the theoretical maximum operational temperature set for a module from the beginning), a visual inspection was carried out on these specific inserts to identify the cause of the anomalies. As seen in the photographic report in figure 117, it is possible to identify issues on the inserts mainly related to the gluing process of the insert into the pipe. In particular, excess glue, observed in all three anomalous inserts, seems spilled along the sides of the insert, creating an obstruction for proper heater placement. This, in turn, hindered the optimal thermal contact between the insert and the heater. Another critical factor affecting the thermal contact between the insert and the heater seems to be the cleanliness of the insert surface in fact, residual glue and dust, even in small amounts, was found to cause imperfections in the thermal contact, degrading the HTC_{eq} (equation 4). Additionally, scratches on the surface, as seen on insert 14, further impacted this contact. By comparing the three "defective" inserts with insert 10, which exhibited a "good" temperature well below -20°C (with the temperature of 14s measured at -22.2°C), it is evident that these two main types of anomalies (excess glue and an imperfectly smooth surface) are responsible for the observed temperature discrepancies.

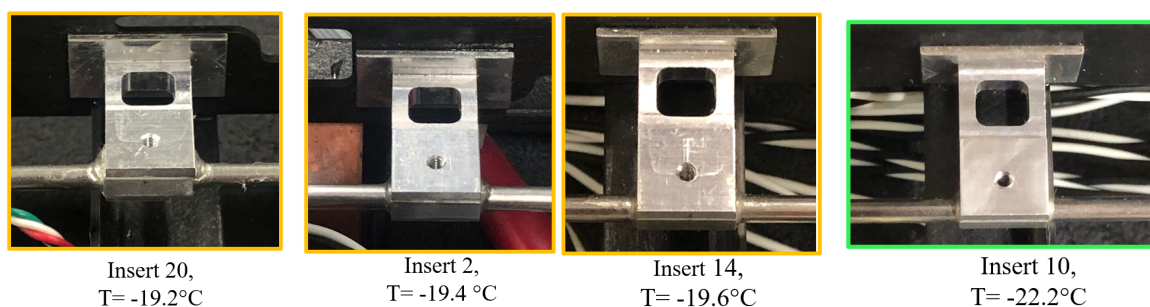


Figure 117- Images highlighted in yellow show the inserts with anomalous temperatures due to excess glue on the sides (insert 20 and 2) and scratches on the contact surface (insert 14). The image circled in green represents the condition of a good insert used as a reference. Below each image, the temperatures recorded by the heaters placed in these inserts are provided.

Finally, for this first ladder, an additional investigation was possible thanks to tests conducted using the same thermal test setup on a fully integrated ladder with 11 non-irradiated modules, among the first 2S modules produced at production centers worldwide and one irradiated module placed in the most thermally unfavorable position of the cooling loop, position 1, where the AICF inserts are located. These tests aimed to determine the CO₂ temperature threshold that could lead to thermal runaway, starting from a setpoint of -35°C at the loop outlet. By performing incremental tests and increasing the CO₂ temperature in steps, the goal was to assess the operating margin, like how many degrees the CO₂ temperature could be raised before inducing thermal runaway, in order to validate the cooling performance of the TB2S ladder structure. The results of this study will not be presented here, as they will form part of the PhD thesis of Lea Stockmeier (KIT - Karlsruhe Institute of Technology), which is yet to be published, along with the simulation work carried out by Cristiano Turrioni (INFN - Perugia). However, a preliminary analysis of these results is interesting for making a comparison between the temperatures measured during the thermal tests (with fictitious power loads provided by the heaters) and the temperatures recorded in the real modules, positioned in the same heaters. To perform the test with the 2S modules, it was necessary to adapt the setup by covering the entire inner surface with Kapton material to contain the dust generated by the insulating material used to create the thermal box, in order to avoid damaging the sensors (Figure 118, right). The approach was to measure the temperature of each module and compare it to the average temperature of the six heaters placed during the thermal quality control in the same inserts of each module. Since the module in position 1 was irradiated, it will not be included in this comparison.

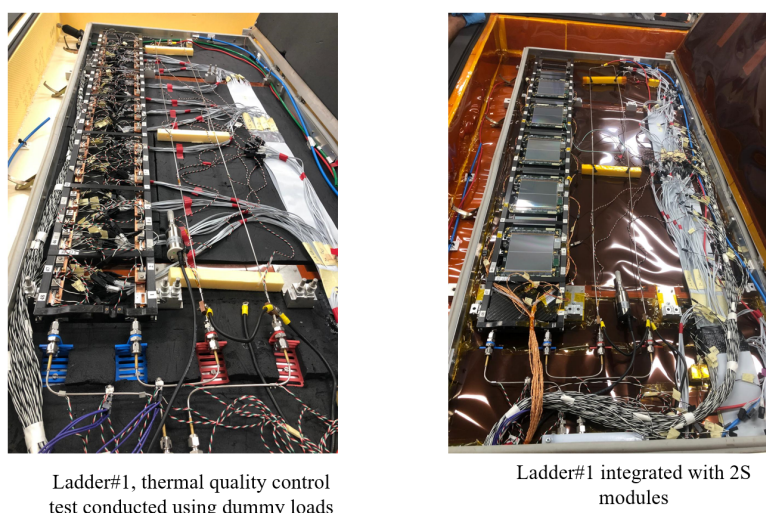


Figure 118- Ladder#1 during the thermal quality control test conducted with the heaters (left) and Ladder#1 assembled with the 12 2S modules (right).

The results (figure 119 top) show that the average temperatures measured on the surface of the real modules appears to match very well with the temperatures obtained from the average of the temperatures measured in the 6 heaters positioned in the same inserts of the module, within approximately 1°C. This alignment confirms the validity of the thermal quality control (TQC) procedure performed using heaters, as it effectively replicates

the thermal behavior of actual modules. Interestingly, the presence of outlier inserts did not appear to significantly impact the module temperatures, as observed in the modules M2, M6 and M12 (modules in which the anomalous short inserts were detected). However, for real modules M4 and M8, the screw torque could not be uniformly set to 10 cNm on all inserts during the integration of the module due to insert threads' anomalies, which likely accounts for the greater temperature differences observed. These differences, though present, were not very large, with a maximum discrepancy of 2.1°C (figure 119 bottom-right). A final observation can be made by looking at the absolute temperature data of the real modules. It can be seen that the highest temperature was recorded in module number 8, measuring -21.4°C, which is in line with the expected operating temperatures of a maximum of -20°C.

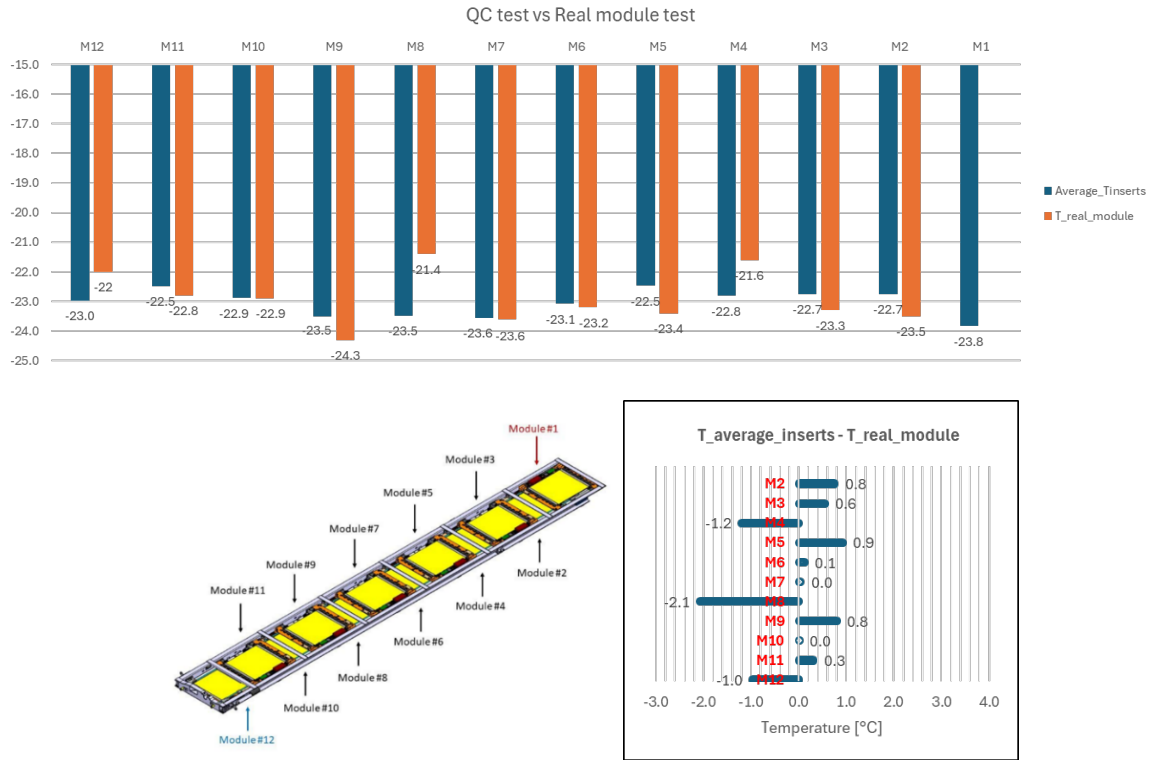


Figure 119 - At the top, comparison between the average temperatures of the six heaters during the TQC (Average_Tinserts) and the temperature of the modules (T_real_module) positioned in the same inserts. The difference between these two measurements is shown in the graph at the bottom right, while the reference used for the module numbering is shown in the ladder picture at the bottom left.

5.3.2 TB2S ladders TQC: Ladder#3

The same setup was used to test the third ladder produced and thermally tested also in Pakistan. Again, the goal of this test was to validate the mechanical structure and identify any anomalies or improvements that could be proposed to the production team to achieve optimal thermal contacts. To conduct thermal quality control the following tests were performed:

- Test with 10 cNm torque using CO₂ at both +15°C and -35°C (operating conditions), with different flow rates and vapour quality levels: 1.2 g/s, 1.4 g/s and 2.0 g/s.
- Test with 8 cNm and 5.5 cNm torque using CO₂ at both +15°C and -35°C, to evaluate the effect of the torques on the thermal quality control and if using 5.5 cNm can reliably detect anomalies, it may be preferable, as using a lower torque during TQC reduces the risk of damaging the inserts' threads.

In each test shown on the following pages, the terms +15°C and -35°C refer to the test conditions detailed in figure 120.

POWER SETTING: 75W/ladder is the <i>nominal power</i>: 6.25 W/module (2S), 1.1W/heater - Total evaporator power = 75W (ladder) + 75W (TB2S pipe)=150W Test CO₂@-35, conditions: - Traci set point: CO₂ 12 bar, -35 °C - Flow rate, F= 1.4 g/s - T aluminium box ≈ -10°C <u>No dry gas flow</u> inside the Al box during the test - Room temperature, HVAC set point: 20°C Test CO₂@+15, conditions: - Traci set point: CO₂ 51 bar, +15 °C - Flow rate, F= 1.4 g/s - T aluminium box ≈ 20°C <u>No dry gas flow</u> inside the Al box during the test - Room temperature, HVAC set point: 20°C

Figure 120 – Test settings for ladder#3 at -35°C and at +15°C

Before starting the test, two improvements were made to the test setup based on data obtained from the first ladder test, to enhance the quality of the heaters used for the dummy load, trying to improve the repeatability of the thermal test.

- It was found that the torque used to secure the resistance onto the copper plate was inconsistent across the heaters. As a result, this torque was standardized to 40 cNm for all heaters. Inconsistent torque values could lead to fluctuations in the heat exchange coefficient between the resistance and the copper plate of the dummy heater, prompting the decision to unify this torque setting.
- The second modification involved the screws used to secure the heaters in the inserts. A new set of captive screws was required because the previous ones could not handle high torque values, often breaking well before reaching 10 cNm. This inconsistency could introduce variability into the tests regarding the torque applied, preventing uniform tightening of the heaters in the inserts due to the inadequate quality of the screws.

Both upgrades significantly improved the quality of the tests, reducing errors introduced by the setup itself and ensuring that any outliers recorded were not due to "setup anomalies" but rather to "anomalies" in the mechanical structure of the detector.

Based on the results obtained (figures 121 and table 14) from the quality control test under operational conditions (CO₂ at -35°C and 10 cNm), and comparing them with the results from the first ladder tested, the following observations can be made:

- Big inserts with 2 heaters are on average 2.3°C hotter compared to big inserts with only one heater [this difference was 2.6°C for ladder#1].
- Short heaters are generally hotter, with an average temperature increase of +1.2°C and show greater variability compared to larger heaters, which indicates they require distinct quality control [this difference was +1.2°C for ladder#1]. This effect was also observed in quality control tests conducted in Pakistan and is due to the fact that both short inserts and big inserts dissipate the same power, but short inserts have a smaller contact surface, leading to higher temperatures.
- Comparing the individual results of average temperatures and deviations between the first ladder and the second ladder (results shown in square brackets in table 14), the analysis of heater temperatures reveals a similarity between the values obtained during the tests on the first two ladders, confirming the good repeatability of the results produced by the test.
- The CO₂ temperature drop of 0.7°C in the first ladder of the cooling loop does not appear sufficient to cause a corresponding reduction in the heater temperatures [this difference was 0.9°C for ladder#1]. This effect was further investigated by testing the ladder in the second position of the loop, in an attempt to trace the CO₂ temperature decline trend on the heater side as well.
- It is clear from the plot shown in figure 121 that some heaters (41s 37s and 8s) exhibit abnormal temperatures, which will be further investigated in the second phase of this analysis report.

Table 14- Averages, standard deviations and temperature ranges measured in the different groups of heaters for Ladder#3. Test with CO₂ at -35°C, 75 W of power per ladder (150W total), 1.4 g/s flow rate and 10 cNm of torque applied. In square brackets, the same values measured during the test on ladder#1.

Type of heater [total number]	T_ average [Ladder#1]	Standard deviation [Ladder#1]	Range [Tmax-Tmin]
All heaters [70]	-22.9 °C [-23.0°C]	1.4 [1.4]	8.1 °C [7.7]
Big [44]	-23.2 °C [-23.4°C]	0.8 [0.9]	3.6 °C [3.7]
Short [22]	-22.0 °C [-22.2°C]	1.6 [1.4]	6.2°C [4.5]
Single_big [2]	-25.5 °C [-26.0°C]	-	0.1 °C [1.7]
Special [2]	-25.5 °C [-24.9°C]	-	0.4 °C [0.6]

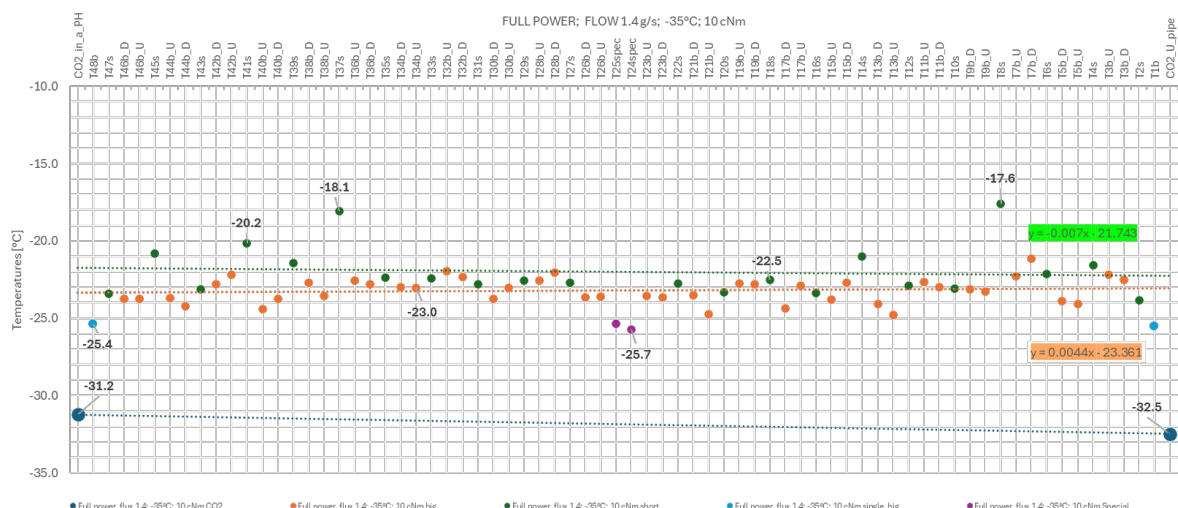


Figure 121 - Absolute temperatures measured in the heaters and in the CO₂ flow during the tests with 75W per ladder. All the tests have CO₂ at -35°C, a flow rate of 1.4 g/s, and 10 cNm of torque applied.

Additionally, by comparing the data from the thermal quality control tests conducted in Pakistan with the results from ladder#3, with cooling and power on (figure 122), we can observe some important correlations. It should be noted that deionized water, a single-phase cooling fluid, was used in the Pakistan tests, which explains the increasing heater temperatures observed during testing. In particular, the hottest temperatures recorded in Pakistan (positions 8s, 37s and 41s, circled in red and yellow in the figure 122) are also the hottest in the tests conducted at CERN. This demonstrates that, despite using different heater batches and two distinct thermal test setups, it is still possible to identify anomalies using this testing methodology.

In Pakistan, the big inserts only have one heater per side, making direct comparisons of the big heater measurements more challenging. However, the special AICF inserts show similar thermal behavior, with generally lower temperatures compared to other inserts.



Figure 122- Comparative analysis of the TQC test results conducted in Pakistan at NCP [40] (above) and those conducted at CERN (below). The same inserts identified as anomalous in both tests are highlighted in red and yellow.

By observing the absolute temperature values measured during the test at -35°C with a torque of 10 cNm applied to the heaters of ladder#1 and ladder#3 (figure 122), it is clear that, although we do not have a large statistical sample of ladders, the temperatures of the heaters, despite the "anomalous" positions recorded in those tests, which will be analyzed in detail for ladder#3 later in this document, exhibit good repeatability. The same positions show minimal differences in thermal behavior, indicating a strong performance of the test setup and stable quality conditions for the ladders produced thus far.

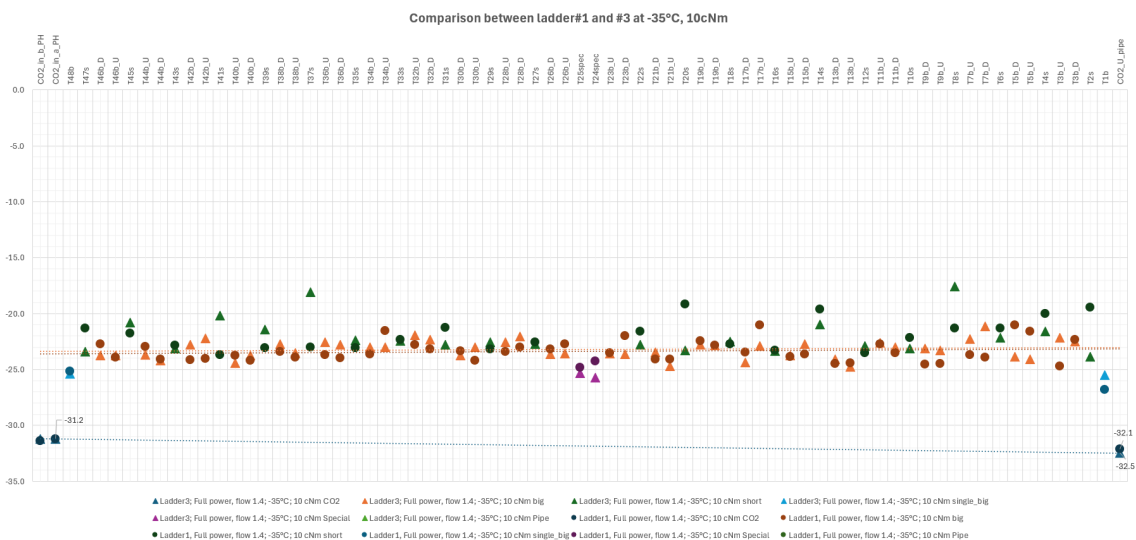


Figure 123 - Comparative analysis of the temperatures measured in the test on ladder#1 and ladder#3 using the same setup and same operating conditions.

Having analyzed the repeatability of the test and made an initial comparison with the results obtained in Pakistan, we proceeded with ladder#3 by developing an initial method to detect potential anomalies. This method is still in development but follows a similar approach to what was done for the TBPS rings produced at CERN. The idea, which is also suggested for a more detailed analysis of the tests conducted in Pakistan, is to use the interpolated line from the measurements of each type of heater (big heater and short heater separately) as a reference. This line accounts for the increasing trend in the Pakistan tests (due to the single-phase fluid) or the decreasing trend in tests using two-phase CO₂, in the event that the pressure drop is sufficient to cause a noticeable temperature drop in the heaters.

By doing this, we move away from relying solely on the absolute temperature measured on each heater, which would naturally vary depending on its position in the cooling loop. Instead, we calculate the difference between the measured temperature and the value determined by the fitting line at that position. The result, similar to the method used for the rings, is a DT, which shows how much hotter a heater is compared to its reference temperature. This DT, combined with statistical analysis and further testing during the initial production phase, will allow us to establish a threshold beyond which a temperature can be classified as anomalous. This would indicate an insert with higher thermal resistance, which degrades HTC_{eq} , requiring further investigation and potential modification.

For this ladder, based on the results obtained so far, an initial threshold value of +1.5°C has been set. The following plots (figure 124 and 125) show the validation process, where the DT of all heaters was evaluated, distinguishing between big heaters (excluding special AICF and inserts with a single heater). The heaters with abnormal temperatures, indicated by yellow arrows, are those with a deviation from the fitting line (DT) greater than 1.5°C. Specifically, these include 41s (DT = 1.7°C), 37s (DT = 3.8°C) and 8s (DT = 4.6°C) for the short inserts, as well as 7b_D (a big heater placed on the big insert 7 in the down position) with a DT = 1.9°C for the big inserts. To further ensure that the detected anomalies were not caused by any issues with the heater components used in those positions (or the power supply system), the performance of the test setup was evaluated by switching the heaters from the anomaly positions with those from good positions, maintaining the same high temperature on the same inserts meaning that the anomalous temperature recorded was not due to the type of heater used but to actual thermal anomalies in the insert.

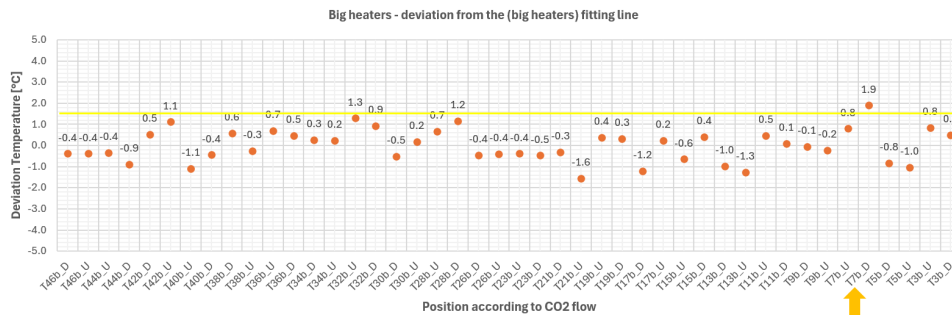


Figure 124 – Looking for outliers: deviation values from the fitting line of the temperatures of the big heaters (DT). The yellow line represents the initial threshold value set ($DT_{limit}=1.5^{\circ}C$).

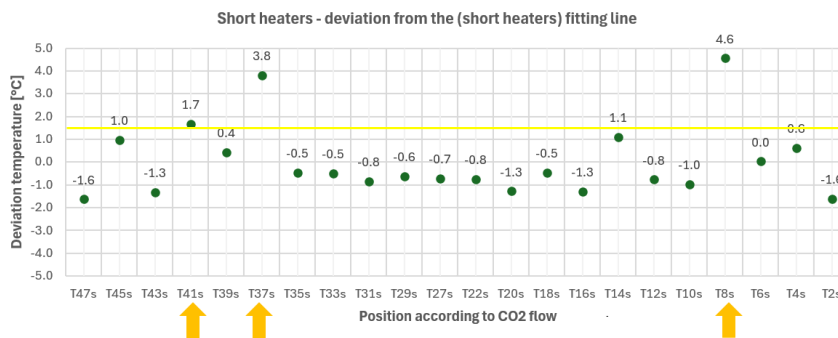


Figure 125 - Looking for outliers: deviation values from the fitting line of the temperatures of the short heaters (DT). The yellow line represents the initial threshold value set ($DT_{limit}=1.5^{\circ}C$).

In analyzing these hotter positions for the short inserts, a comparison with a good insert (for example, 4s in figure 126) reveals again that the thermal anomalies appear to be due to excessive adhesive present on the sides or the upper surface of the insert. In both cases, this prevents the heater from making full contact with the aluminum surface of the insert, thereby reducing the equivalent heat transfer coefficient between the heater and the CO₂. A notable case is that of insert number 41s, where after cleaning the surface with a cloth and alcohol, the adhesive residue was successfully removed from the surface of the insert. Upon repeating the test, the measured DT decreased by 1.7°C, confirming the hypothesis that poor contact was primarily due to this type of anomaly. This information is valuable for improving the assembly process of short inserts, particularly by paying attention to the amount of glue used and carefully cleaning any excess to avoid poor thermal contact quality.

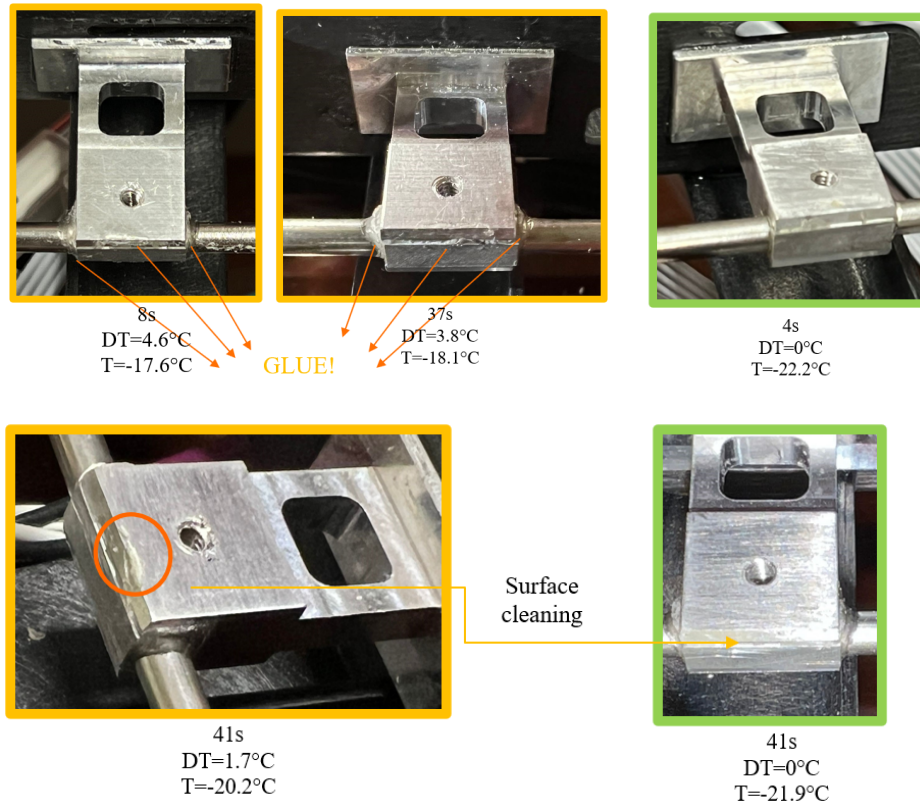


Figure 126 - Highlighted in yellow are the anomalous short inserts identified by the TQC both at CERN and in Pakistan, where the excessive amount of glue present on the sides and partially on the surface of the insert is evident. Highlighted in green are the 4s inserts (used as a "good" reference) and insert 41s after the careful cleaning process performed on its surface.

The same analysis was conducted on the only anomalous big heater detected, but no issues were found regarding the quality of the gluing process. Therefore, in an effort to investigate this anomaly more closely, it was observed that even though the large inserts have the same geometric dimensions, they feature different internal machining to accommodate various modules in the correct position, ensuring hermeticity for particle flow through the detector. Indeed, as shown in figure 127, in module number 10 (where the anomalous heater 7b_D is located), the contact surface between the big inserts and the heaters on the left side is slightly larger than that with the big heaters on the right. This explains the slightly higher temperatures detected on the left side compared to the right, as well as the "anomalous" temperature at position 7b_D, which appears to be solely due to the varying contact in this position rather than any real production anomalies.

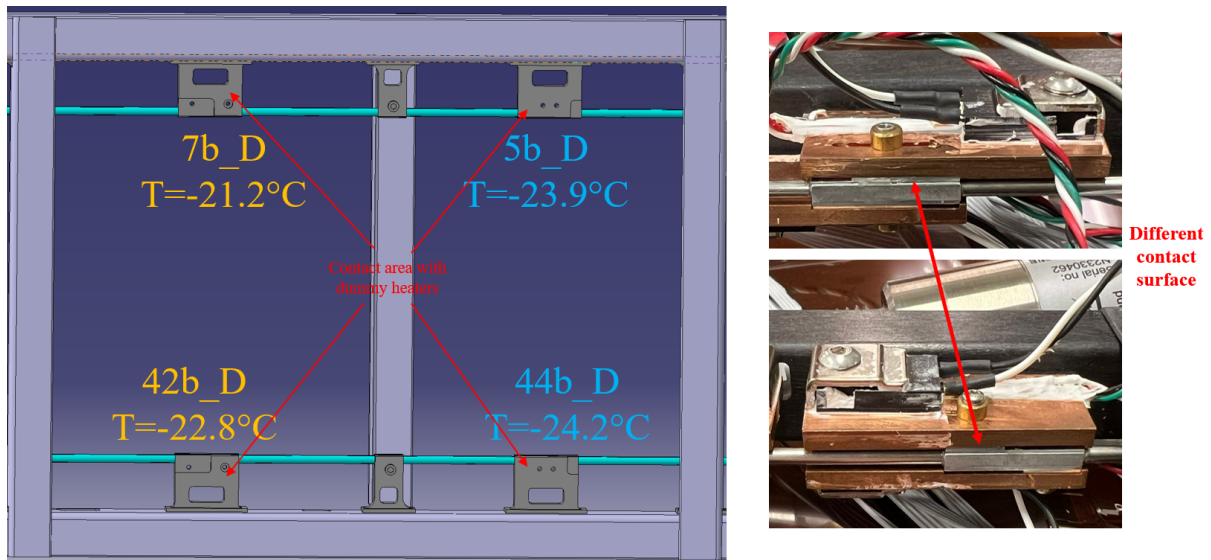


Figure 127 - On the left, the CAD model of the inserts present in module position number 10, showing the different contact surface between the large inserts positioned on the left and right sides, which correlates with the higher temperatures recorded on the left side. On the right, an image depicting the different contact of the heater in case 7b_D (at the bottom) and 5b_D (at the top).

To address this in future thermal quality control analyses, two approaches could be pursued to identify a DT value that effectively reveals true anomalies for all type of big inserts:

- Option 1: separate the large inserts based on their shape, resulting in a total of at least five different types of inserts to check separately.
- Option 2: use a higher DT limit that accounts for these differences and perform quality control with just one type of large insert.

From this type of thermal quality control testing, it is also possible to estimate the temperatures of the real 2S modules that will be positioned in this ladder. The estimation was made by averaging the temperatures of the six contact inserts in the module, a hypothesis that was verified during tests conducted in ladder#1 with actual modules. The results indicated that all modules maintained a good temperature, remaining below -20°C . As expected, module 9 shows a higher temperature due to the presence of a significantly anomalous insert ($\text{DT}_{8s} = 4.6^{\circ}\text{C}$), which contributes to an estimated increase in the module's average temperature of 1.3°C .

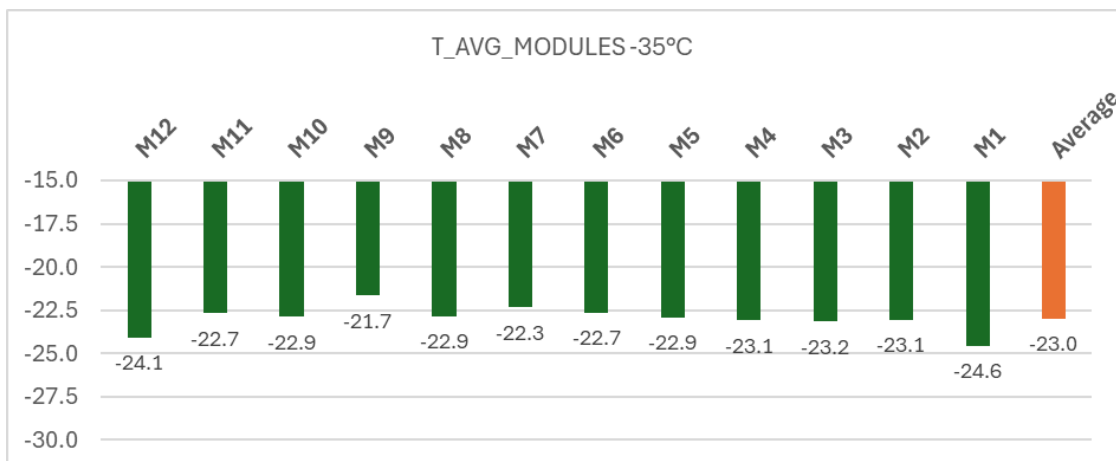


Figure 128 - Estimated temperatures of the modules on ladder#3, obtained by averaging the temperatures measured in the heaters in the six inserts of each module.

Another test that can be conducted, while maintaining the screw torque at 10 cNm, is to place the ladder in the second position of the cooling loop (figure 129), which is closer to the outlet of the loop. By placing ladder 3 in this position, it becomes possible to observe, as hypothesized during the tests for ladder#1, the characteristic

decrease in temperatures typical of a two-phase cooling system throughout the entire cooling loop. In the plot in figure 130, the temperatures of the same ladder in both the first and second positions of the loop are displayed. It is evident that there is a temperature drop for both the big heaters and short heaters when they are positioned in the second part of the loop compared to the first. This is illustrated by the negative slopes of the fitting lines, due to the fact that in a two-phase system, the CO₂ exiting is colder than the CO₂ entering, due to the pressure drop measured along the evaporator.

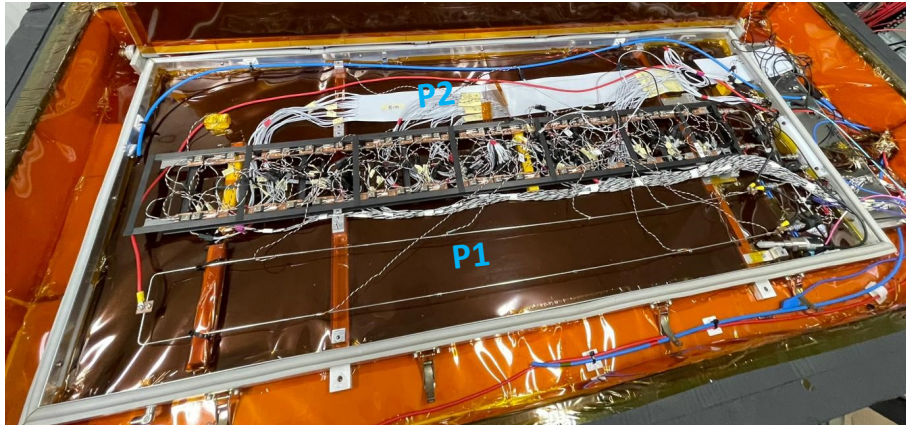


Figure 129 – Test conducted placing ladder#3 in the second position of the cooling loop.

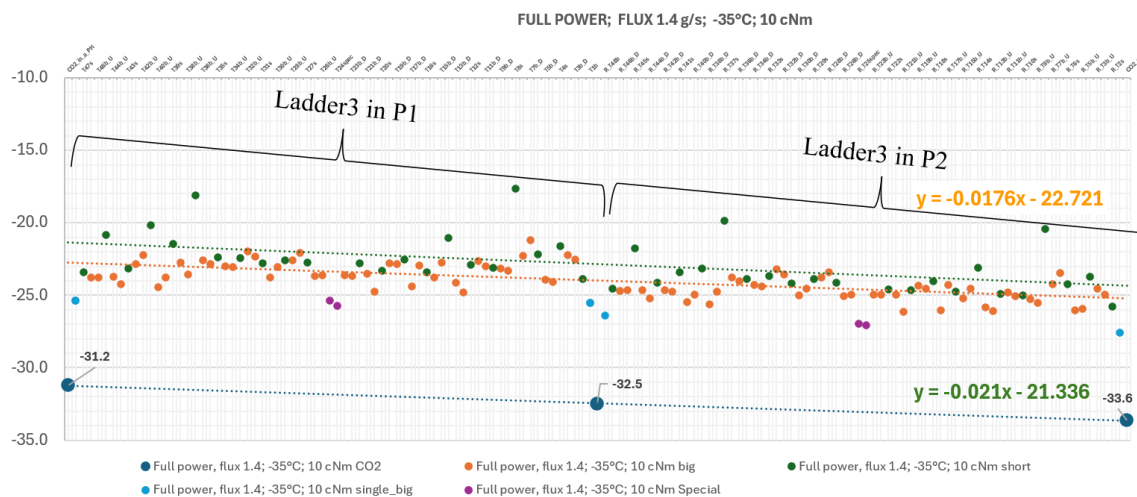


Figure 130 -Temperature measured on the heaters placed on ladder#3, with the ladder placed in the first ad second position of the cooling loop.

Repeating the tests shown so far, with different torques (10 cNm, 8 cNm, and 5.5 cNm, figure 131) has shown that the thermal behavior of the anomalous positions is clearly visible even at lower torques. Since there are no significant differences in the thermal behavior of the heaters as the torque varies (figure 131), future quality control tests could be conducted at lower torques (even at 5.5 cNm) to safeguard against damaging the threads of the aluminum inserts. However, the same cannot be said about the torque level to use for the integration of the actual modules on the ladder at the time of writing this document, as it is a more complex structure that will likely require a dedicated tests in the future (a ladder with a fully integrated module) to understand the effect of varying torque on the module's temperature. This would allow for evaluating the possibility of reducing the design torque from 10 cNm to 8 or even 5.5 cNm, in order to avoid overstressing the module itself, which could create issues not in terms of thermal performance, but in the electronics of the module. The highly miniaturized electronic systems are very delicate and could be more prone to damage if tightly secured at high torque values.

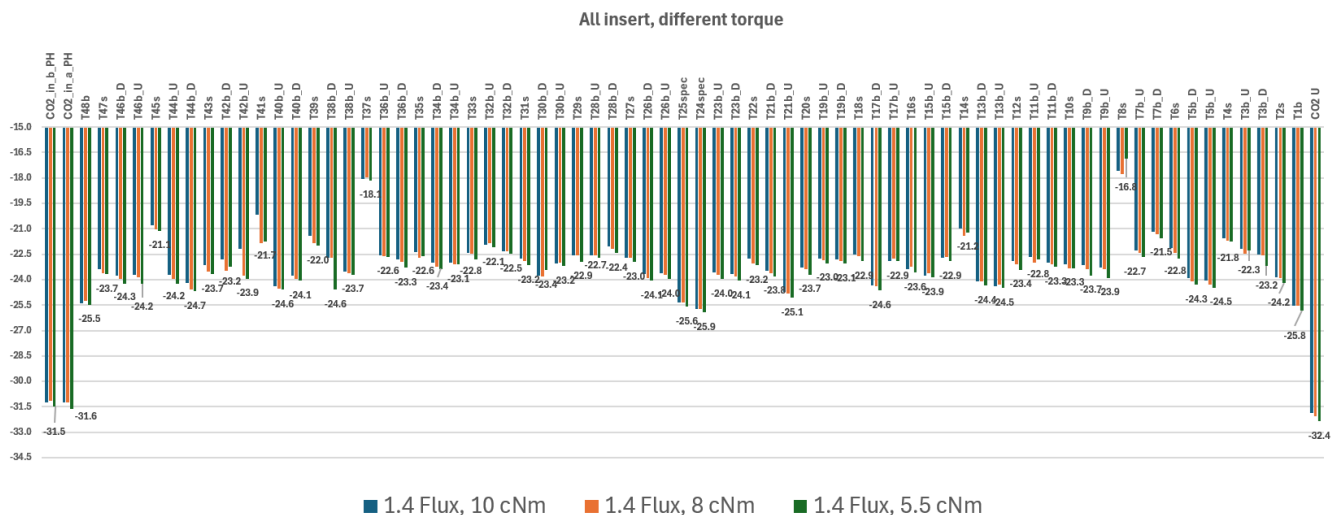


Figure 131 - The temperatures of the inserts measured while varying the torque show nearly constant temperatures, allowing for thermal quality control tests to be performed even with lower torque settings to safeguard the integrity of the inserts.

Finally, for this ladder, all tests conducted with CO₂ at +15°C and 51 bar (with only the test at 10 cNm shown in figure 132) clearly identified defects in the most anomalous positions. This suggests that testing at +15°C can serve as a valid option for detecting mechanical anomalies that induce a degradation in thermal performance. If it will be necessary to conduct these tests systematically also at CERN in the future, to conduct the test using CO₂ at +15°C accelerates the testing phase by eliminating the need to wait for the operational conditions of -35°C for CO₂ and the lowering of the dew point in the box (flushing with dry gas). Additionally, it allows for continuous access during the test itself, as it does not need to be performed in a controlled environment and this could facilitate the resolution of detected anomalies (acting on the structure during the test, such as cleaning the inserts or repositioning the heaters) and also opens up the possibility for thermal investigations using thermal cameras.

Table 15 - Average temperature, standard deviation and temperature range measured in the different groups of heaters during the test conducted at +15°C with a torque of 10 cNm. It shows similar standard deviation values compared to the tests conducted at -35°C, demonstrating the similar thermal behavior in the tests conducted with CO₂ at different temperatures.

Type of heater [total number]	T_average	Standard deviation	Range [Tmax-Tmin]
All heaters [70]	22.0	1.1	6.3
Big [44]	21.8	0.7	3.1
Short [22]	22.8	1.3	4.8
Single_big [2]	20.2	-	0.3
Special [2]	20.75	-	1.7

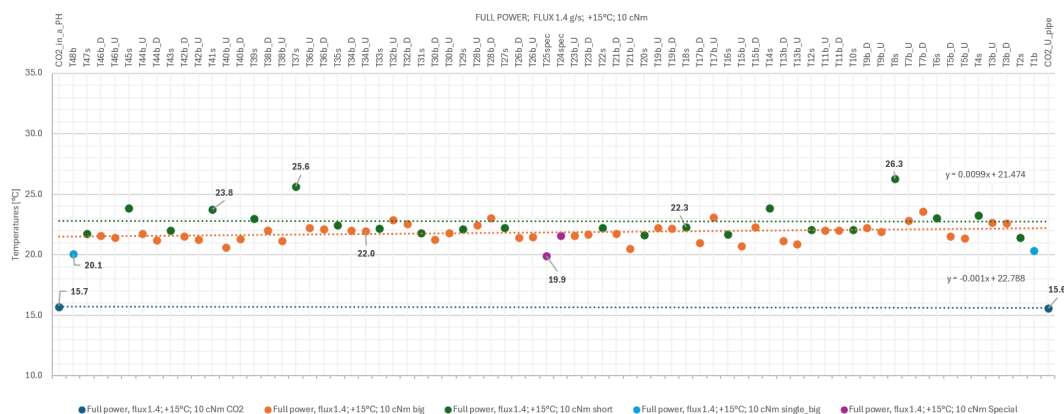


Figure 132 - Absolute temperatures measured during the test conducted with CO₂ at +15°C showed the same abnormal temperatures measured in the test at -35°C (inserts: 8s, 37s and 41s).

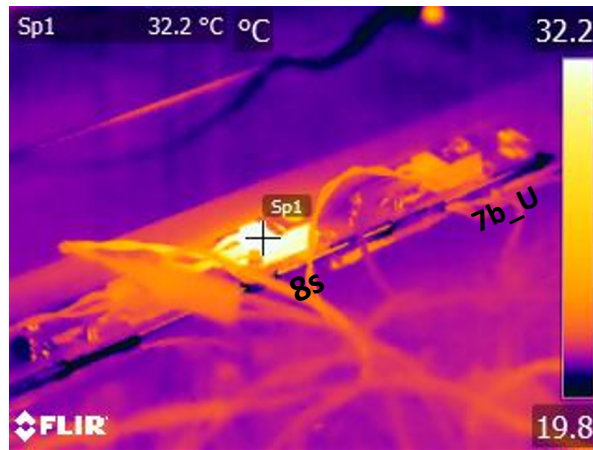


Figure 133 - An example of thermal investigation that can be performed during the test with CO₂ at +15°C shows the temperature of the surface of the heater 8s, which is clearly abnormal compared to the temperatures of the nearby heaters.

6. Heat Transfer Coefficient (HTC) of two-phase CO₂ cooling studies

As extensively described in the third chapter of this work, one of the key aspects in considering the equivalent heat transfer coefficient (HTC_{eq}), between the module and the CO₂ two-phase flow, lies in evaluating the heat transfer coefficient (HTC) between the CO₂ flow and the pipe wall. This HTC value for thermal simulation was set at 5000 W/m²K for safety reasons, as previously explained. In the case of the equivalent heat transfer coefficient, the HTC value is "degraded" by the addition of all the thermal resistances that the heat flow encounters through the various layers and materials specific to each mechanical structure on which the modules are mounted, following equation 5.

A fundamental aspect of calculating this value is assessing the ability of two-phase CO₂ to remove heat from the inner wall of the evaporator pipe. It can be extrapolated through simulations using a multiline tool called COBra ("CO₂ Branches Calculator"), developed at CERN to calculate the CO₂ flow balance across different detector branches, enabling the design of capillaries. This prevents scenarios where, due to the higher pressure drop experienced by CO₂ flow in a single branch, the resulting decrease in mass flow rate would lead to high vapour quality values in the final sections of the evaporator. Such a situation could cause the dangerous dryout phenomenon, resulting in a loss of cooling performance for the detector. For this reason, it is crucial to predict the pressure drop, heat transfer coefficient and flow pattern along the detector evaporators, where fluid properties and flow regimes continuously change. The COBra software enables the evaluation of these parameters by dividing the detector tube into small and equal-length sections [41]. However, the results obtained are estimates that must be validated through testing. For this reason, during the final phase of my work period at CERN, I focused on building a test setup capable of evaluating the heat transfer coefficient for two-phase CO₂, designing a system to test the heat transfer coefficient on pipes from the TB2S experiment ladders and, in the future, pipes with different geometries and materials for other types of sub-detectors if necessary.

Two experimental campaigns were conducted in total. The first, conducted in June 2024, tested pipes with the same geometry but made from two different materials: stainless steel and titanium. The aim of this testing was to evaluate the heat transfer coefficient under the same testing conditions while varying the material type. This provided valuable insights into the thermal behavior of titanium pipes, where available literature is scarce. The goal was to validate the idea of transitioning from stainless steel to titanium pipes, offering the opportunity to use lighter pipes with a lower coefficient of thermal expansion and contraction, thus improving the quality of the TB2S experiment ladders. Additionally, the data obtained, after processing as described in the next paragraph, will be subjected to comparative analysis against the results obtained from simulations using the multiline COBra tool at a later stage through other studies not presented in this report.

The second testing campaign, conducted in October 2024, followed small but significant upgrades to the measurement system, which will be discussed later. The purpose of this second campaign was to evaluate the repeatability of the tests performed during the first experimental campaign.

6.1 Methods of calculation of the heat transfer coefficient

This paragraph presents the methods used for calculating the experimental HTC. From the well-known equation 8, the necessary data to sample during an experimental analysis to evaluate this coefficient can be identified.

HF [W/m²], the heat flux, can be measured by dividing the power supplied to the evaporator directly through the pipe walls (P) (using the electrical system explained in section 6.2) by the surface area of the pipe's internal cylindrical wall (S_{inner}) with inner radius r_{inner} and total length L. So, the heat flux can be calculated using the following equation:

$$HF = \frac{P}{S_{inner}} = \frac{P}{2 \cdot r_{inner} \cdot \pi \cdot L}$$

Equation 13

The temperature of the pipe's inner wall is calculated based on the temperature of the outer wall of the pipe the only one where is possible to place the temperature sensor during the tests. The temperature difference between the two walls of the pipe ($DT=T_{\text{outer_wall}}-T_{\text{inner_wall}}$), can be estimated as follow:

$$DT = \frac{P \cdot \ln\left(\frac{r_{\text{outer}}}{r_{\text{inner}}}\right)}{2 \cdot \pi \cdot L \cdot k} = \frac{HF \cdot r_{\text{inner}} \cdot \ln\left(\frac{r_{\text{outer}}}{r_{\text{inner}}}\right)}{k}$$

Equation 14

Once the geometry of the pipe (inner and outer radius, r_{inner} and r_{outer}) and the material (thermal conductivity $k=16\text{W/mK}$ for both stainless steel and titanium) are defined and fixed, this DT value becomes proportional to the heat flux (HF), which, at this point, depends solely on the variation of the total power (P) supplied to the evaporator as shown in equation 13. However, it consistently remains in the range of hundredths of a degree in the tests conducted so far, with heat flux values varying between 4827 W/m^2 for the test with a total of 150 W supplied to the evaporator and 9654 W/m^2 for the test with 300 W supplied to the evaporator. This results in an estimated temperature difference between the outer and inner wall of 0.048°C in the first case and 0.097°C in the second case. In each test conducted, these amounts will be subtracted from the value measured on the external wall of the pipe, providing a more accurate indication of the temperature of the inner wall of the pipe and so of the measured HTC values.

The temperature of the CO_2 must be evaluated locally at each point of the cooling loop where the coefficient is to be calculated. Since it is not easy to measure the CO_2 temperature along the heated pipe wall, three measurements are taken during each test: one immediately before the CO_2 enters the evaporator ($T_{\text{CO}_2_after_preheater}$), one at a junction point between the two ladders of the evaporator ($T_{\text{CO}_2_U_pipe}$) and one at the evaporator outlet ($T_{\text{CO}_2_out}$). With these three CO_2 temperature measurements, models can be developed to determine the CO_2 temperature at any point along the evaporator.

In detail, four types of methodologies, corresponding to four different methods for calculating experimental HTC , have been analyzed to estimate the CO_2 temperature in local points of the evaporator. These are illustrated as follows:

1. HTC_{lin} (Linear Heat Transfer Coefficient). This method estimates the CO_2 temperature at each point along the evaporator by fitting a straight line between the measured temperature of the CO_2 after the preheater ($T_{\text{CO}_2_after_preheater}$) and the temperature at the U-pipe ($T_{\text{CO}_2_U_pipe}$). A similar linear fit is applied between the U-pipe temperature and the outlet temperature ($T_{\text{CO}_2_out}$). This approach assumes a linear temperature profile in the sections of the evaporator.
2. HTC_{dp} (Pressure Drop Heat Transfer Coefficient). In this approach, the CO_2 temperature is evaluated based on the pressure drop per unit length ($\Delta P/L$) along the evaporator. The outlet pressure ($P_{\text{sat,out}}$) is calculated from the outlet temperature ($T_{\text{CO}_2_out}$) under two-phase flow conditions. Then, the saturation pressure ($P_{\text{sat,i}}$) at each point is determined using the pressure drop along the evaporator's length. With the saturation pressure known at each position, the corresponding saturation temperature ($T_{\text{sat,i}}$) is calculated, providing the local temperature of the CO_2 . One aspect to consider in this analysis is the fact that the pressure difference between the inlet and outlet of the CO_2 is not measured exactly across the evaporator but also takes into account the pressure losses that occur in the connecting pipes between the setup and the local box, as described in the following paragraph. This could lead to an overestimation of the pressure drop measured solely along the evaporator.
3. HTC_{3pt} (Three-Point Heat Transfer Coefficient). This method uses a second-order Lagrange interpolation to approximate the temperature profile along the evaporator. A curve is fitted to the three measured CO_2 temperature points: after the preheater ($T_{\text{CO}_2_after_preheater}$), at the U-pipe ($T_{\text{CO}_2_U_pipe}$) and at the outlet ($T_{\text{CO}_2_out}$). This method captures a more complex, potentially non-linear temperature distribution compared to linear fitting.

4. HTC_vq (Vapor Quality Heat Transfer Coefficient). This approach involves estimating the CO₂ temperature at each point by first calculating the vapor quality (vq,i) at various points in the cooling loop. After this, the specific enthalpy in each point (h,i) is derived, starting from the outlet temperature (T_CO2_out) and accounting for two-phase flow conditions and so knowing also the saturation pressure at the outlet (P_{sat,out}). Knowing the vapour quality and the specific enthalpy is possible to estimate the CO₂ temperature (T_CO2,i) in each point of the cooling loop. Although this method is strictly correct for evaluating the CO₂ temperatures along the evaporator, it introduces uncertainties due to the high sensitivity of the model to the estimation of the vapour quality and the enthalpy of the flow along the evaporator and these values cannot be directly measured experimentally but can only be obtained through theoretical considerations during post-data processing, introducing unsuitable uncertainty errors. For this reason, in this study, this model was not implemented in the cases analysed.

Where:

- The subscript “i” refers to the position along the evaporator, measured as the distance from the starting point of the evaporator.
- L represents the total length of the evaporator.

Using these methods, it is possible to gather all the necessary data (T_{CO2}, T_{inner wall pipe} and HF) in every point of the evaporator, to calculate the HTC (equation 8) along the walls of the evaporator as a function of the vapor quality of the CO₂ flow at each measurement point of the setup.

6.2 HTC thermal test setup and procedure

The setup used for testing the heat transfer coefficient (HTC) of CO₂ in the pipes of the TB2S ladders is the same as that employed for the thermal quality control of the produced ladders: an aluminum box containing the cooling loop, placed inside an insulated box where tests can be conducted at low temperatures (around -10°C) thanks to the supply of cold dry gas available in the Lyon Cold Room at CERN. The primary difference is the cooling loop structure within the setup lies in the placement of a bare pipe not only in the second position of the loop but also in the first position (replacing the TB2S ladder placed there). As illustrated in the sketch shown in figure 134, the cooling loop consists of the following elements, arranged in the order of CO₂ flow (ID inner diameter, OD outer diameter):

- 2 m insulated transfer line from the TRACI local box to the evaporator (Cu annealed pipe, OD=6 mm, ID=4 mm)
- 22 cm inlet CuNi pipe (OD 2.5 mm, ID 2.0 mm), where the prototype preheater is placed
- Heated TB2S ladder first stainless steel and then titanium pipe (OD=2.3 mm, ID=2.0 mm, total length of 2474 mm)
- 15 cm CuNi U-pipe (OD=2.5 mm, ID=2.0 mm)
- Heated TB2S ladder first stainless steel and then titanium pipe (OD=2.3 mm, ID=2.0 mm, total length of 2474 mm)
- 23 cm outlet CuNi pipe (OD=2.5 mm, ID=2.0mm)
- 2 m insulated transfer line from the experiment back to the TRACI local box (Cu annealed pipe, OD=6 mm, ID=4 mm)

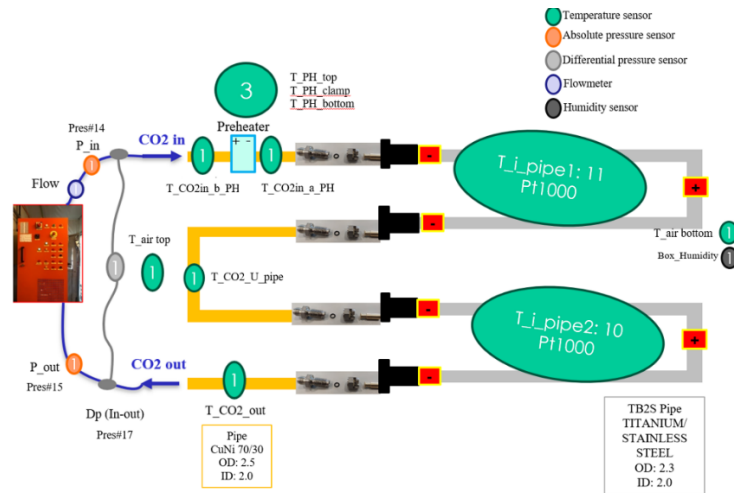


Figure 134- Sketch illustrating the cooling loop located inside the aluminum box of the setup used to conduct the HTC tests of CO₂.

The following table shows the characteristics of the tested pipes, specifically the pipes used in the TB2S ladders, both the stainless steel and titanium versions.

Table 16- Characteristics of TBPS pipes tested

Name	Material [-]	Inner_diameter [mm]	Outer_Diameter [mm]	Pipe length [mm]	Cooling loop length (2 pipes in series) [mm]
SS_Pipes	Stainless: 316L Soft Annealed	2	2.3	2474	4948
Ti_Pipes	Titanium: Grade 2 Soft Annealed	2	2.3	2474	4948

To measure the temperatures required for calculating the HTC, in addition to the sensors already present in the setup within the local connection box to the CO₂ TRACI system (to monitor absolute pressure, differential pressure and flow, section 3.4.1), the following sensors were placed along the walls of the various pipes in the cooling loop and the evaporator:

- Sensors along the pipe in position 1 of the evaporator (11 Pt1000, 4 wires)
- Pt1000 sensors along the pipe in position 2 of the evaporator (10 Pt1000, 4 wires)
- Preheater temperature sensors (3 Pt1000, 4 wires)
- CO₂ inlet temperature before and after the preheater (2 Pt1000, 4 wires)
- CO₂ U-pipe (1 Pt1000, 4 wires)
- CO₂ outlet (1 Pt1000, 4 wires)
- Air temperature inside the aluminum box (2 Pt1000, 4 wires)
- Air temperature inside the insulated box (1 Pt1000, 4 wires)

Specifically, the sensors used for calculating the local HTC, at various points where the temperature sensor was placed in the evaporator, were arranged according to the order shown in table 17. The reference system's origin was set at the beginning of the evaporator, that is, the start of the first heated pipe.

Table 17- References regarding the positioning of the sensors along the evaporator.

	Sensor	Distance from the beginning of the evaporator (cm) [±1 cm]
CO2 temperature	CO2_in_b_PH	-15.0
	CO2_in_a_PH	-5.0
Heated pipe 1 of the evaporator	T1pipe1	5.0
	T2pipe1	10.0
	T3pipe1	15.0
	T4pipe1	30.0
	T5pipe1	50.0
	T6pipe1	80.0
	T7pipe1	100.0
	T8pipe1	150.0
	T9pipe1	180.0
	T10pipe1	215.0
	T11pipe1	245.0
CO2 temperature	CO2_U_pipe	247.0
Heated pipe 2 of the evaporator	T1_pipe	250.0
	T2_pipe	260.0
	T3_pipe	275.0
	T4_pipe	295.0
	T5_pipe	325.0
	T6_pipe	345.0
	T7_pipe	395.0
	T8_pipe	425.0
	T9_pipe	460.0
	T10_pipe	490.0
CO2 temperature	CO2_out	495.0

All the Pt1000 sensors shown are Class A RTD temperature sensors, with a tolerance of $\pm 0.15^{\circ}\text{C}$. To reduce the sensor's intrinsic precision error, each measured value is obtained by averaging at least 100 samples, taken under stable conditions for each test analyzed. As shown in figure 135, each sensor is positioned on the pipe using commercial heat sink compound DOWSIL 340 to enhance thermal contact between the probe and the outer wall of the pipe. The sensor is then held tightly against the pipe using a clamp. Finally, kapton tape is used to insulate the sensor leads, preventing any short circuit between the sensor wires and the pipe.

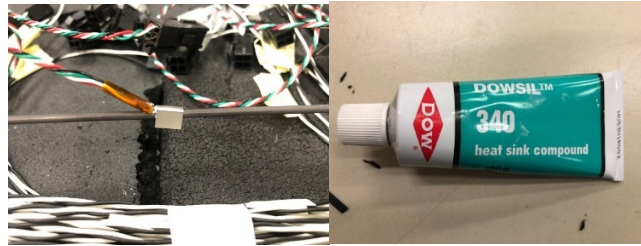


Figure 135 – Pictures showing the method of positioning the sensor in the pipe (left) and the heat sink compound used to enhance thermal contact between the pipe and the sensor (right).

The temperature sensor acquisition system was implemented using two MTRS units (with the capability to read 24 Pt1000 sensors per board), while the pressure sensors (inlet pressure P_{in} , outlet pressure P_{out} , and pressure drop D_p) are read via a PLC. All the data are monitored and recorded during the tests through a LabVIEW interface specifically developed for this purpose. The power to the individual pipes and the preheater is supplied through three separate power supplies (DETA ELEKTRONIKA BV, SM 52-30). This power supply has 3.5 digit and has an accuracy of $2\%+2d$ on the voltage output. For the heated pipes, as in the case of the thermal quality control test of the TB2S ladders using the same setup, the power is provided by using the electrical resistance of the pipe wall to dissipate the heat. The rack containing the power supplies and the MTRS boards used for the acquisition system is shown in figure 136.

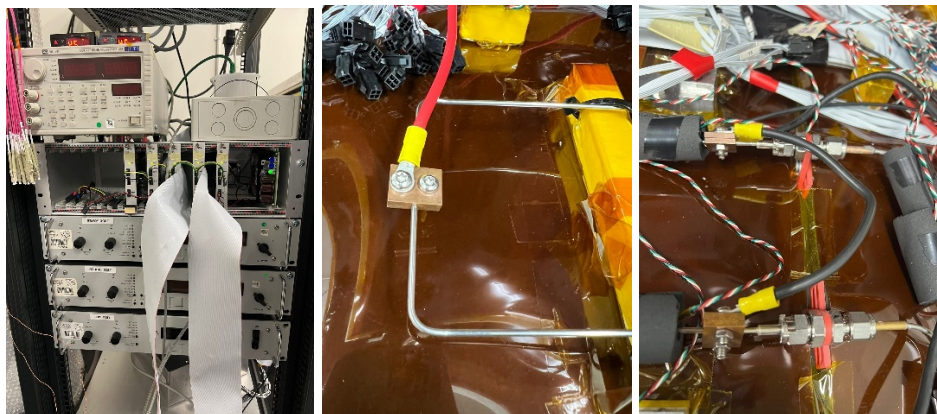


Figure 136 – The three power supplies used to power the two evaporator pipes and the preheater inside the rack (on the left). The powering system for the TB2S pipes used in the HTC tests with the power connector (center) and ground connectors (right).

The setup described so far was used for the first test campaign to evaluate the HTC of pipes made of stainless steel and titanium. The second test campaign involved an upgrade in temperature measurement by attempting to insulate each individual sensor with a 2 cm thick layer of Armaflex. In addition, more sensors were added during this test to validate the measurements taken. Specifically, redundant sensors were placed at the inlet before the preheater, after the preheater, in the U-pipe and at the outlet of the cooling loop, all of them being Pt1000 4-wire sensors. These were installed to verify the quality of the measurements from the sensors in this area.

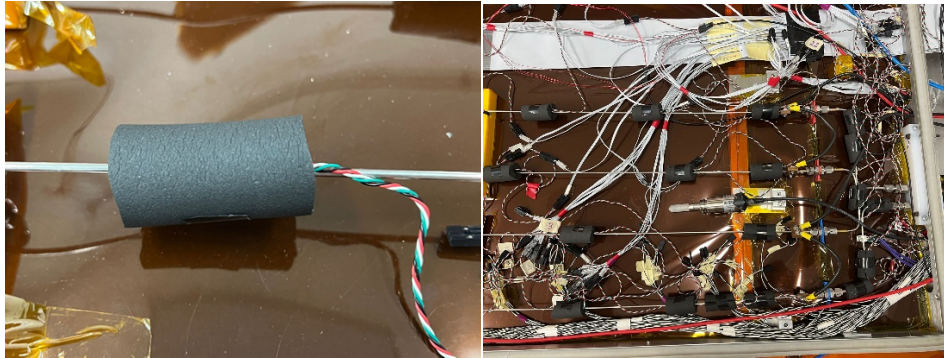


Figure 137 – Upgrades to the measurement systems implemented for the second campaign included insulating all the sensors with Armaflex material and adding redundant sensors to ensure the reliability of the CO₂ temperature measurements.

Furthermore, between the first and second test campaigns, 2 temperature sensors were added, integrated into the flow within the local box to monitor the CO₂ at both the inlet and the outlet of the loop (2 meters before and after the experiment's box). Of particular interest is the temperature of the sensor embedded within the flow at the outlet (T_CO₂_out_embedded), which allows measurement of the CO₂ flow's setpoint temperature at the outlet. This value is required by the COBra software for analyzing the cooling circuit if one wishes to consider the entire loop, including the transfer lines from the test setup box to the local box and not just the evaporator loop inside the aluminum test setup box. However, the HTC evaluation is always carried out using the sensors placed in the same conditions as during the first test campaign.

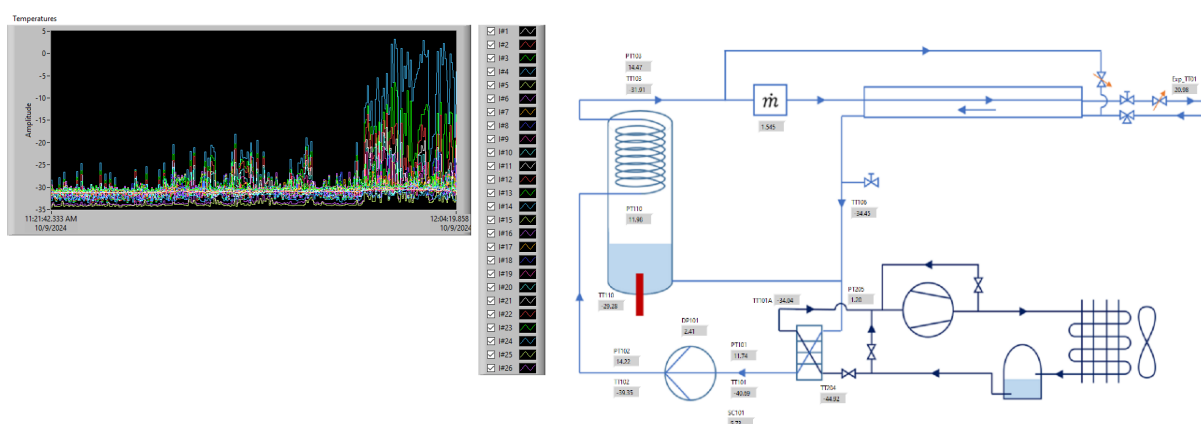


Figure 138- LabVIEW interface screenshots displaying the plots of the sensors positioned on the heated pipe show spikes during the test with 'full' power, highlighting the dryout phenomenon in the last positions of the evaporator (left). The right side shows the interface used to monitor temperatures and pressures of the 2PACL cooling system (TRACI conditions).

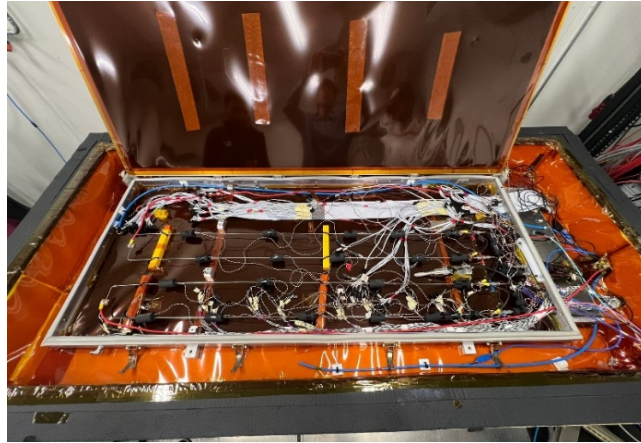


Figure 139 – Overview of the cooling loop inside the “HTC test bench”

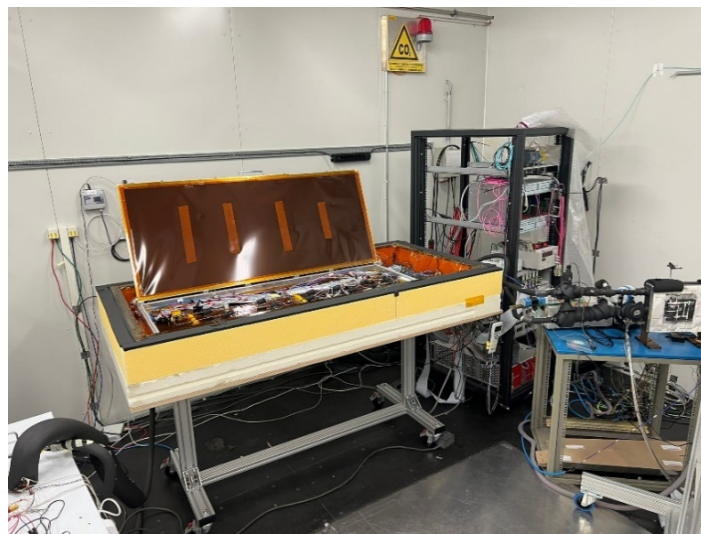


Figure 140 – “HTC test bench” located inside the Lyon cold room. From left to right: the chiller for supplying cold dry gas, the insulation box containing the test setup, the rack that houses the power supplies and TRACI local box used to connect and disconnect the cooling loop.

6.3 Outcomes of the first HTC tests campaign (June 2024): comparison between TB2S stainless steel and titanium pipes

During this first experimental campaign, the pipes of the TB2S ladders were tested, both those produced in stainless steel (SS) and those produced in titanium (Ti). For each type of evaporator (made of 2 pipes in series), the following tests were conducted:

- 75 W per pipe (150 W total), preheater off;
- 75 W per pipe (150 W total), preheater on;
- 100 W per pipe (200 W total), preheater on;
- 125 W per pipe (250 W total), preheater on;
- 150 W per pipe (300 W total), preheater on;
- 180 W per pipe (360 W total), preheater on;
- 210 W per pipe (420 W total), preheater on;
- +30% Flow: $F = 1.8 \text{ g/s}$, 75 W per pipe (150 W total), preheater off;
- -30% Flow: $F = 1.0 \text{ g/s}$, 75 W per pipe (150 W total), preheater off.

The initial tests were conducted with a CO_2 flow rate of 1.4 g/s , increasing the power supplied to the evaporator in order to analyse the variation of the Heat Transfer Coefficient (HTC) as the vapour quality increased at the evaporator outlet. The last two tests simulate a change in vapour quality not due to a variation in heat flux (the

supplied power) but due to a change in mass flux (the flow rate). Among all the tests, the one with a power of 75 W per pipe, totaling 150 W to the evaporator, is the closest to the operating conditions of the TB2S pipes when integrated into the ladders to dissipate the power of the modules at the beginning of their lifespan. Meanwhile, the test with 100 W per pipe, totaling 200 W to the evaporator, represents the highest level of power that can be received by these pipes at the end of the Hi Luminosity phase. During all tests, the set point of the TRACI system is fixed at 12 bar, which corresponds to -35°C. The temperature inside the aluminum box where the test is conducted is around -10°C, there is no flow of dry gas inside the box during the test and the power of the preheater when on ("preheater on") refers to a setpoint value of 8 W given to the CO₂ mass flow before entering in the evaporator through this component.

The results of the experimental tests from this campaign (detailed in the next 2 paragraphs), including all measured temperature and pressure values during each individual test, along with the analysis of the Heat Transfer Coefficient (HTC) evaluated using the methods HTC_lin, HTC_dP and HTC_3pt, both locally at different points along the evaporator and as average values measured during each test, can be found in Annex 5 attached to this report.

6.3.1 Analysis of pressure drop and estimation of HTC values along TB2S stainless steel pipe evaporators

The first aspect to analyze (Figure 141) concerns the trend of pressure drop within the evaporators as the test conditions vary. It can be observed that as the power (or the heat flux) to the evaporator increases from zero power ("off") up to 210 W per pipe (420 W in total supplied to the two pipes in series), the pressure drop increases while maintaining a constant flow rate of around 1.4 g/s. This is due to the increase in vapour quality within the evaporator, which goes from 35% in the test with 75 W per pipe to value of 100% in the case of 210 W per pipe supplied. The increase in vapour quality causes the turbulence associated with the boiling process inside the pipes to create an additional obstacle to the flow of CO₂, thereby increasing the pressure drop.

As the CO₂ flow rate within the pipes increases ($F = 1.8$ g/s) or decreases ($F = 1.0$ g/s) from 1.4 g/s mass flow, comparing the results of the tests where the same power (75 W per pipe) is supplied, it can be observed that the pressure drop within the system increases from 1.1 bar to 1.4 bar in the case of a flow rate of 1.8 g/s, while it decreases to 0.9 bar in the case of a flow rate of 1.0 g/s. This trend is due to the increased turbulence inside the pipe caused by the higher flow velocity. So, it is interesting to note that the mass flow rate has a more significant impact on the pressure drop compared to the variation in vapour quality. Indeed, while maintaining constant power at 75 W per pipe, as the flow increases to 1.8 g/s, the vapour quality at the evaporator outlet reaches 27% compared to 35% with a flow of 1.4 g/s and 46% with a flow of 1.0 g/s. The increasing trend of vapour quality, which, as seen in the tests with varying power at a constant flow rate, would typically cause an increase in pressure drop, is overshadowed in these tests by the corresponding increase in pressure drop due to an increase in flow velocity as the flow rate rises.

In summary, it can be said that there are two factors causing the increase in pressure drop within a two-phase system: the increase in vapour quality and the increase in refrigerant flow, with the latter having a more significant impact compared to the former in the overall picture.

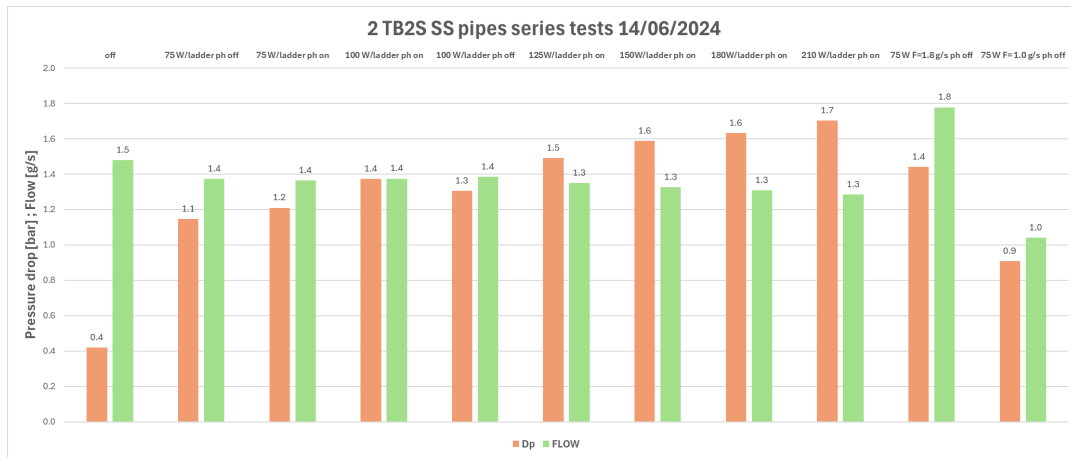


Figure 141 - Pressure drop [bar] and flow rate [g/s] measured during the tests conducted on the TB2S pipes in stainless steel (SS).

Figures 142 and 143 show the trends of the CO₂ temperatures measured at the inlet, in the connecting U-pipe of the two heated pipes and at the outlet. It can be observed that as the power supplied to the evaporator increases, while maintaining a constant flow rate, or as the flow rate increases while keeping the supplied power constant, there is an increase in the temperature difference (DT) of CO₂ between the inlet and outlet of the evaporator. This is closely linked to the pressure drop variations measured in Figure 141, as in a two-phase evaporation system, an increase in pressure drop is associated with an increase in temperature drop.

From the data on the measured absolute temperatures, it can be seen that the temperature of the CO₂ measured immediately after leaving the evaporator is approximately -34°C, obtained while maintaining the TRACI system setpoint at 12 bar (accumulator pressure of the 2PACL). In tests with power levels above 150 W per pipe, reaching vapour quality values greater than 70%, the temperature measurement of the CO₂ at the outlet is affected by local overheating of the vapour phase, which begins to behave locally along the flow like saturated vapour. This effect is evident in the test with 210 W per pipe, where the vapour quality gets to 100%, resulting in an output with completely vapour flow in a single phase, where the cooling is related to an increase in the refrigerant fluid temperature, which indeed reaches values of 3.6 °C at the outlet in this test, significantly losing refrigerating performance, as will be shown in the following pages.

Finally, it can be observed that even without supplying power to the evaporator ("SS off" in figure 142 and 143), a temperature difference (DT) of 0.9°C can be noted for the CO₂. This is due to the fact that the CO₂ supplied by the system is always in a saturated liquid state, in fact this temperature drop of 0.9°C is linked to the pressure drop of 0.4 bar observed during this test. The initiation of boiling with the power supply to the evaporator, in the case of 75 W per pipe, increases this temperature drop to 2.6°C, caused by the rise in pressure drop, which, as noted earlier, reaches values of 1.1 bar.

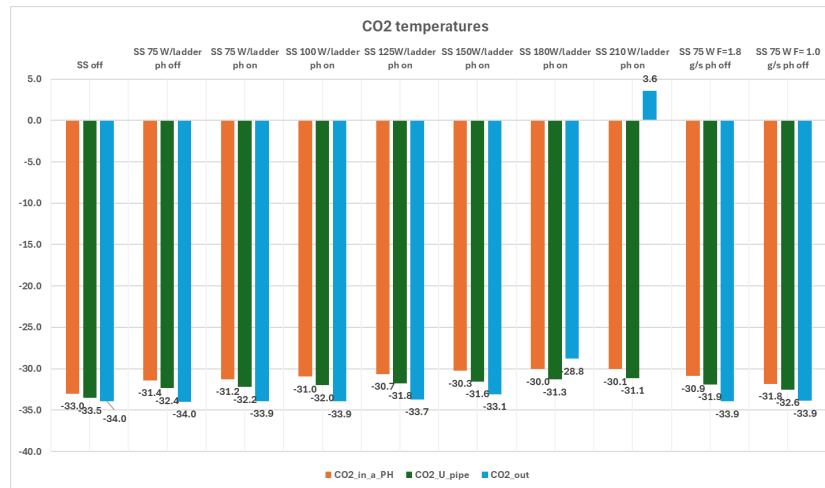


Figure 142- Value of the absolute temperatures measured at the inlet (CO2_in_a_PH), at the central point of the connecting evaporator of the two heated pipes (CO2_U_pipe), and at the outlet (CO2_out).

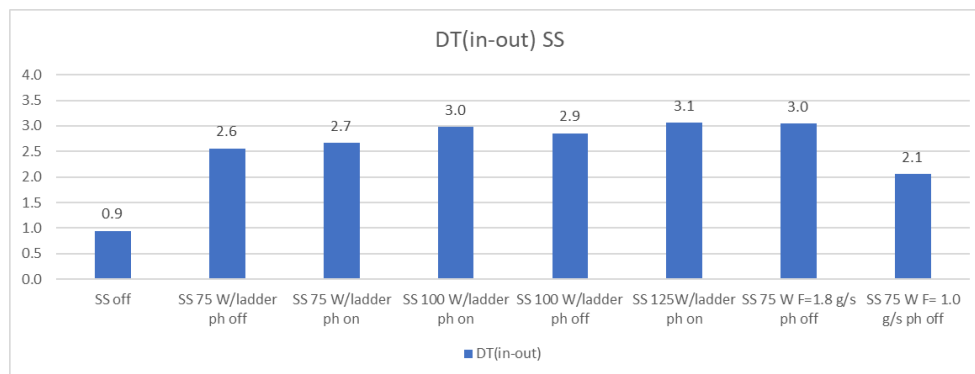


Figure 143- Difference between the inlet and outlet temperatures of the CO₂, with a negative value indicating that the CO₂ is boiling within the system.

By examining the trends of the temperatures recorded during the tests, it is possible to analyze the necessary temperatures for estimating the behavior of the Heat Transfer Coefficient (HTC) along the evaporator. In Figure 144, the temperature profile along the inner wall of the heated pipe can be observed during the test with 75 W per pipe and a flow rate of 1.4 g/s, which, considering the dimensions of the pipe section provided in Table 16, corresponds to a heat flux (HF) of 4827.3 W/m² and a mass flux (G) of 437.5 kg/(m²s). Specifically, each point of the blue polyline represents the estimated temperature of the inner wall of the pipe, obtained by measuring the temperature of the outer wall and subtracting from this value the delta obtained from equation 14.

The CO₂ temperature is measured only at three points (marked with a thicker dot in the CO₂ line in figure 144), while the other points are estimated using the three models discussed previously (HTC_lin, HTC_dp, and HTC_3pt). The two linear regression models (CO2_lin) and the second-order model (CO2_3pt) use all three measured CO₂ values and thus pass through these three points, while the CO2_dp method relies only on the knowledge of the outlet temperature (red dot in figure 144) and, knowing the pressure at that point and the pressure drop of the evaporator, allows for the calculation of all other temperatures of the CO₂ flow along the pipe. Since all three methods yield very similar output results, only the calculations using the second-order curve passing through the three measured points (CO2_3pt) will be presented subsequently.

From these measurements in figure 144, it is possible to obtain an immediate overview of the temperature trends of the heated pipes (the evaporator in these tests) compared to the temperature trends of the CO₂ flow inside the pipe. The difference between these two values allows for the evaluation of the HTC in the system under examination. As an initial observation, it can be noted that, with this combination of power and flow

resulting in a vapour quality of 35% at the outlet, good cooling is achieved along the entire wall of the heated pipe, whose temperatures follow the descending trend of the CO₂ temperatures inside the pipe due to the pressure drop.

In the test shown in Figure 145, the trend of the same temperatures during the same test is observed, but with the preheater on, dissipating 8 W in the CO₂ before it enters the evaporator. As previously highlighted and confirmed by the comparison between these two tests, the activation of the preheater in this setup does not significantly alter the flow conditions of the CO₂ at the inlet, as it is already supplied in fully saturated conditions from TRACI (this setup doesn't use capillaries, which is one of the reasons why we need the preheater on the cooling loop, as will be discussed in Section 7).

Furthermore, throughout all the tests conducted, there were no instances of superheating at the inlet, which in case should be mitigated by the triggering of boiling through the preheater. So, in this setup, when the preheater is on, the only effect is an increase in the total power applied, and this causes an increase in the pressure drop within the system of +0.1 bar that can be observed in figure 141. This results in a slight increase in the inlet temperatures of the CO₂ by 0.2°C, which is reflected in a corresponding increase in the temperatures of the initial positions of the heated pipe wall.

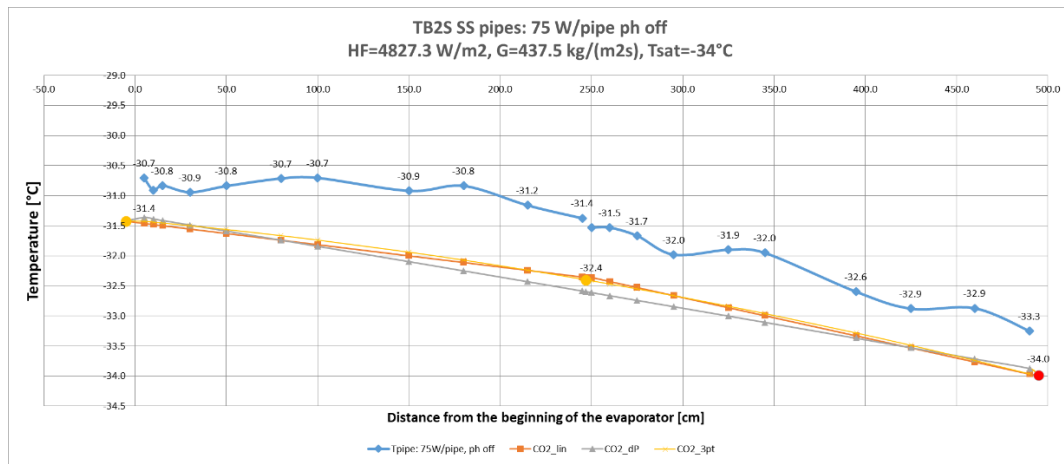


Figure 144- Temperature trends along the inner heated pipe wall (blue) and of the CO₂ inside the pipe with the three models: CO₂_lin (orange), CO₂_dp (grey) and CO₂_3pt (yellow). Test on TB2S SS pipes with 75W per pipe ad preheater off.

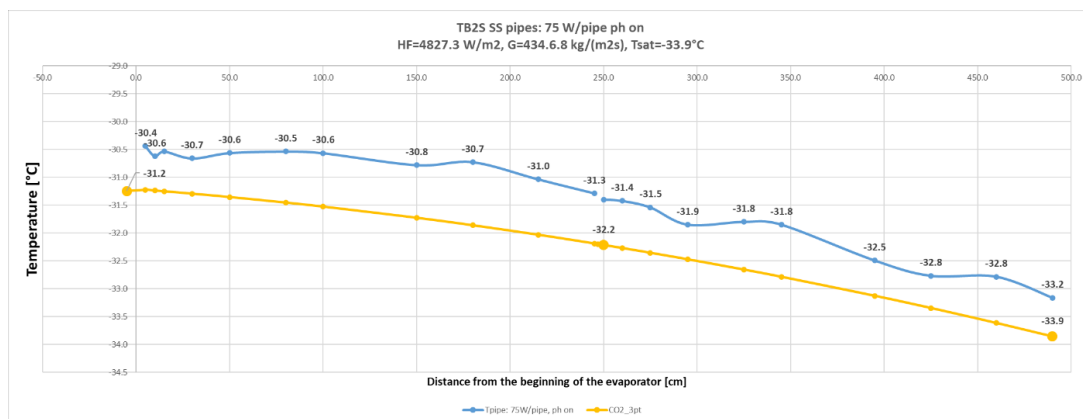


Figure 145- Temperature trends along the inner heated pipe wall (blue) and of the CO₂ inside the pipe with the three models: CO₂_lin (orange), CO₂_dp (grey) and CO₂_3pt (yellow). Test on TB2S SS pipes with 75W per pipe ad preheater on (8W).

Using Equation 8, it is now possible to evaluate the behavior of the Heat Transfer Coefficient (HTC) values along each point of the evaporator. In Figure 146, the measured HTC values during the analyzed test, both with and without the preheater on, can be observed. The similarity of these values along the evaporator confirms what was previously stated in the analysis of the two cases. Focusing on the analysis of one of the two cases, specifically the one with the preheater on, it can be noted that the trend of the HTC for CO₂ in these

tests is almost constant, showing little variation in the HTC value along the evaporator. However, upon closer examination, it can be observed that the trend created by the HTC seems to represent the model provided by Equation 10 [25], where two local peaks in the HTC value as a function of the distance from the beginning of the evaporator can be observed (which is proportional to the level of vapour quality along the flow, as shown in Figure 147).

Indeed, after an initial maximum corresponding to the initial phase dominated by nucleation, noticeable in the first 50 cm of the evaporator (between 0% and 5% vapour quality), the HTC value appears to drop sharply to minimum values before beginning an upward trend as the energy supplied to the flow increases (and thus its vapour quality). In this second phase, an increase in HTC values is observed, attributed to the onset of the annular flow phase, where the convective heat transfer within the two-phase flow is maximized. Simulations conducted using the COBra program show only the increasing trend along the entire evaporator, as the vapour quality increases, until the dryout phenomenon is reached (causing a drop in cooling performance). Overall, along the entire evaporator in this test, an average HTC value of 6505 W/(m²K) is recorded, with a maximum and minimum measured value of 8995 W/(m²K) and 4418 W/(m²K), respectively (see figures 150). It is interesting to note that the trend of the average HTC, which takes into account the "modeled" temperatures of the CO₂ within the pipe, is very similar to the average HTC value calculated only at the four points where the CO₂ temperatures are directly measured and not estimated (immediately after the inlet, immediately before and after the U-pipe and just before the outlet), which measures 6434 W/(m²K) (HTC_average_selected_positions, in figure 151).

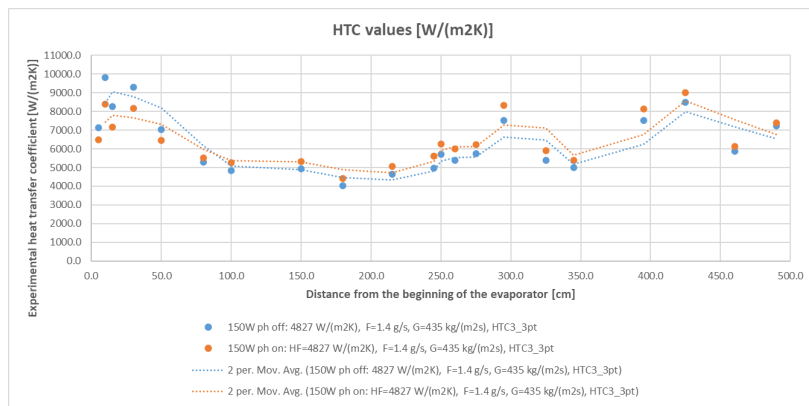


Figure 146- HTC values measured as a function of the distance from the beginning of the evaporator, with the preheater on or off.

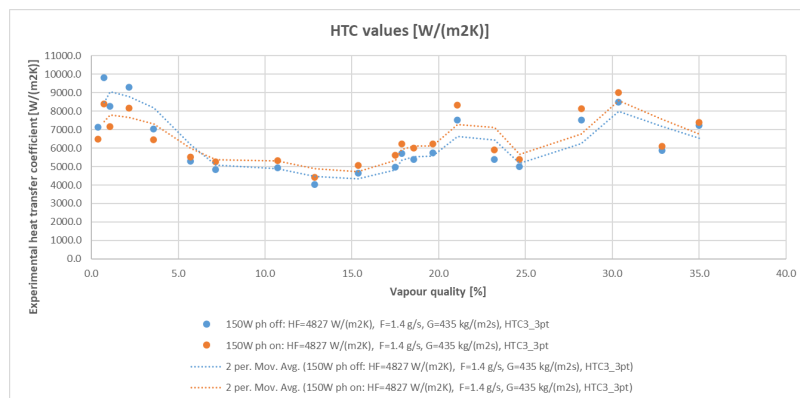
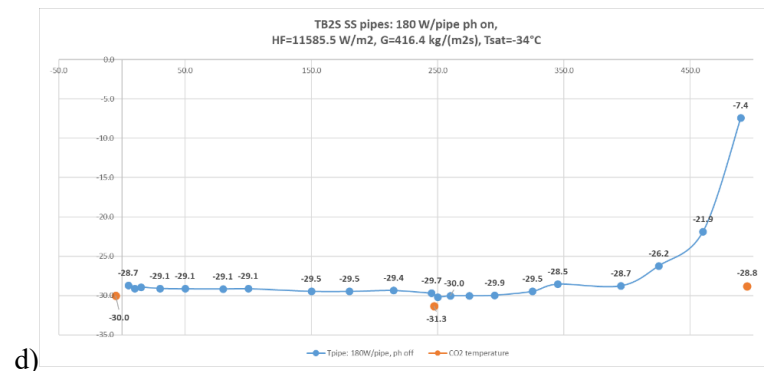
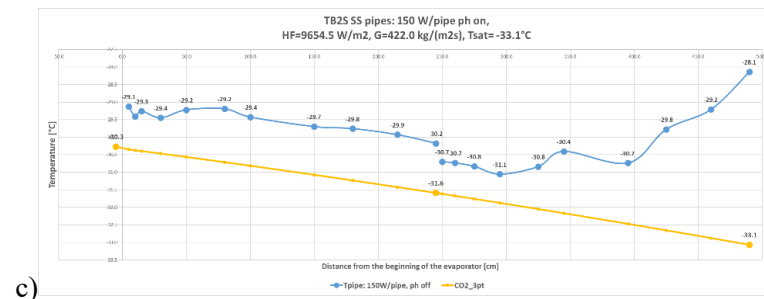
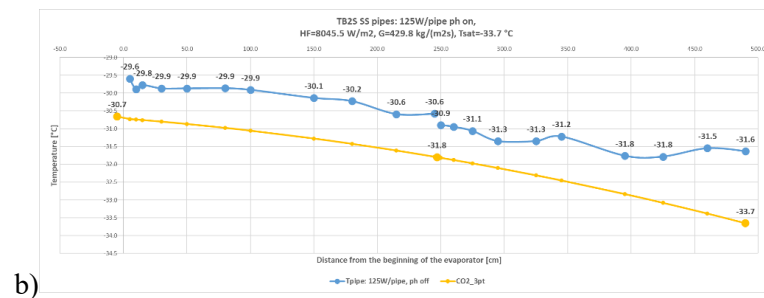
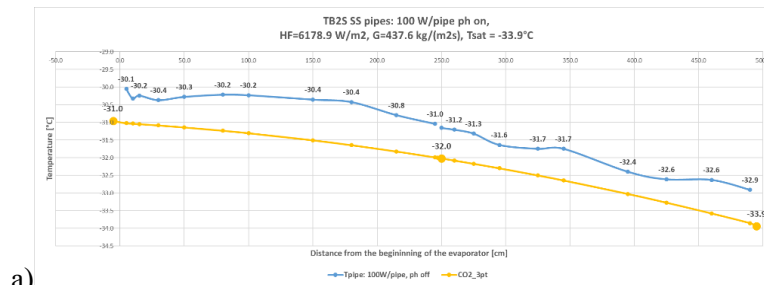


Figure 147- HTC values measured as a function of the vapour quality, with the preheater on or off.

Observing the trends of the measurements along the pipe wall in Figure 145 and the plots shown in Figure 148, the thermal behavior of the internal surface temperatures of the heated pipe with different power levels can be seen. In these tests, the heat flux (HF) was varied according to the following values (in W/m²): 4827.3, 6178.9, 8045.5, 9654.5, 11585.5 and 13516.4. As a consequence of these increases in power to be dissipated, with the

flow rate maintained at approximately 1.4 g/s, the vapour quality at the evaporator outlet increases. The estimated vapour quality values in each case, in percentage, are: 35%, 47%, 60%, 73%, 89% and 100%.

The increase in vapour quality at the outlet of the cooling loop causes the phenomenon of dryout. In fact, already with vapour quality values around 50%, as seen in the test with 125W per pipe (148 b), there is a halt in the downward temperature trend along the pipe wall in the final sections. The wall temperatures no longer follow the CO₂ temperature drop inside the pipe but begin to rise, reversing the trend observed along the pipe wall. This initial stage of dryout becomes evident when vapour quality exceeds 70% at the system's outlet (148 c), with pipe wall temperatures reaching -28.1°C, which is 5°C higher than the CO₂ temperature inside the pipe. This effect is caused by the end of the annular flow phase of CO₂ boiling inside the pipe and the onset of the mist flow phase, where phase change no longer occurs at the pipe walls because, at this point in the boiling process, only CO₂ vapor is present in contact to the inner wall. The pipe wall temperatures increase sharply, especially when dissipating 180W per pipe (148 d), where about 89% vapour quality is reached at the outlet. With 210W per pipe (148 e), the final section of the loop exits the two-phase liquid region and the fluid, now in a purely vapor state, behaves as a single-phase gas, resulting in poor heat transfer coefficients, which cause the pipe temperature to rise up to 27°C.



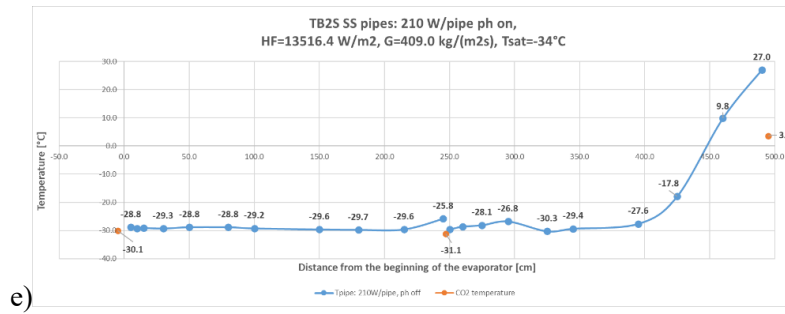


Figure 148 - Temperature trend of the internal wall of the pipe and the CO₂ inside the pipe in the TB2S stainless steel evaporator as the heat flux varies.

Continuing the analysis, we can observe the behavior of the heat transfer coefficient (HTC) along the evaporator as a function of the power supplied and thus the heat flux (HF). By comparing the tests with HF values of 4827 W/m² and 9654 W/m², as shown in Figure 149, several observations can be made. The equation 8 for calculating HTC indicates that this coefficient is directly proportional to the HF and inversely proportional to the increase in the temperature difference between the CO₂ and the heated pipe wall.

In these tests, even though this temperature difference increases, the increase in HF has a stronger influence on the HTC calculation. Essentially, a doubling of the HF does not result in a doubling of the temperature difference between the pipe and the CO₂, which increases, but at a smaller scale. This allows us to observe that the HTC values measured with higher HF are higher. For example, with an HF of 9654 W/m², the average and maximum HTC values are 7857 W/m²K and 13127 W/m²K, respectively, compared to 6505 W/m²K and 8995 W/m²K in the test with an HF of 4827 W/m².

Increasing the HF while keeping the flow rate constant causes the flow to enter a dryout phase beyond a certain length of the evaporator, reaching vapour quality values significantly above the 50-60% limitcase, with 150 W per pipe, resulting in a total of 300 W to the evaporator, the dryout occurs after 350 cm from the evaporator's start (figure 149), leading to a marked reduction in HTC, which reaches minimum values of 1993 W/(m²K) compared to the minimum values of 4418 W/(m²K) measured in the test with an HF of 4827 W/m².

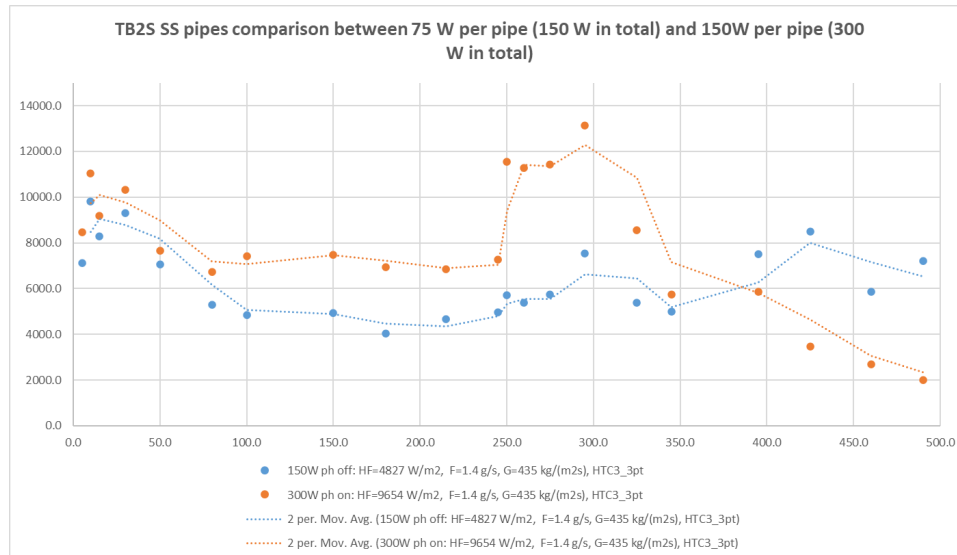


Figure 149- Comparison of the measured HTC values for the case of 75 W per pipe (150 W total and HF of 4827 W/m²) and 150 W per pipe (300 W total and HF of 9654 W/m²). The effect of dryout is noticeable in the second test beyond 350-400 cm from the start of the evaporator.

Observing the HTCs from all tests as a function of vapor quality, plotted in Figure 150, we can see that after the initial peak in the 0% to 5% vapor quality range, the HTC values show a rising trend, reaching a maximum between 35% and 42% vapor quality. Beyond this point, the trend reverses and decreases, indicating a decline in the cooling capabilities of the two-phase fluid due to the dryout effect. Finally, in Figure 151, a summary of

the average, minimum and maximum HTC values measured during the individual tests is shown. In this plot, the trend of the HTC_average_selected_positions is also shown, which represents the average HTC values calculated in the only 4 positions where the CO₂ temperature is measured and not modelled. This value should not include any potential errors introduced by modelling the trend of the CO₂ temperature within the pipe. Nonetheless, it can be observed that it actually differs little from the average HTC value measured along all positions of the evaporator, indicating an acceptable estimation of the trend of the CO₂ temperature based on the proposed models. This summary confirms the previous analyses regarding the impact of increasing HF on HTC values.

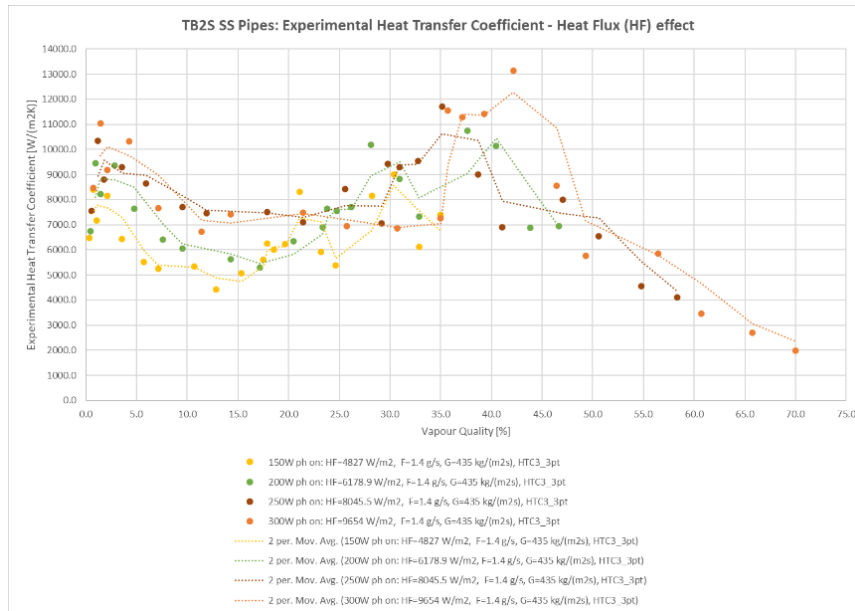


Figure 150 - Values of HTC measured as a function of heat flux and vapour quality.

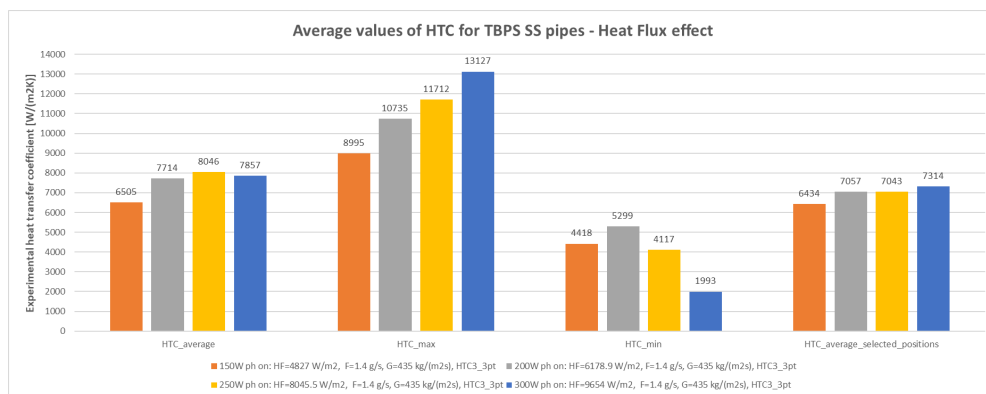


Figure 151 - Calculation of HTC in the different tests conducted as the Heat Flux (HF) varies. The measured values include average, maximum, minimum, and "average selected positions", special parameter described above.

The final study regarding the stainless steel pipes used in the TB2S ladders focuses on the analysis of HTC trends as the mass flux varies (figure 152 and 153). In this context, three tests were conducted with a constant power supplied to the pipe, corresponding to a heat flux of 4827.3 W/m², at different flow rates of 1.8 g/s, 1.4 g/s and 1.0 g/s. These flow rates correspond to mass flux values of 566, 435 and 330 kg/(m²s) based on the geometry of the pipe. A significant increase, from 6386 to 7330 W/(m²K), in the average HTC is observed with the increase in mass flux from 435 to 566 kg/(m²s), attributed to the greater contribution of convective heat transfer associated with the higher flow velocity within the pipe. However, as the mass flux decreases from 435 to 330 kg/(m²s), the HTC value remains relatively constant. This stability may be due to the fact that although the flow velocity of CO₂ inside the pipe decreases, optimal vapor quality values at the end of the

cooling loop for lower mass fluxes (around 45% at the outlet) may offset the expected decrease in HTC caused by the lower mass flux in this test.

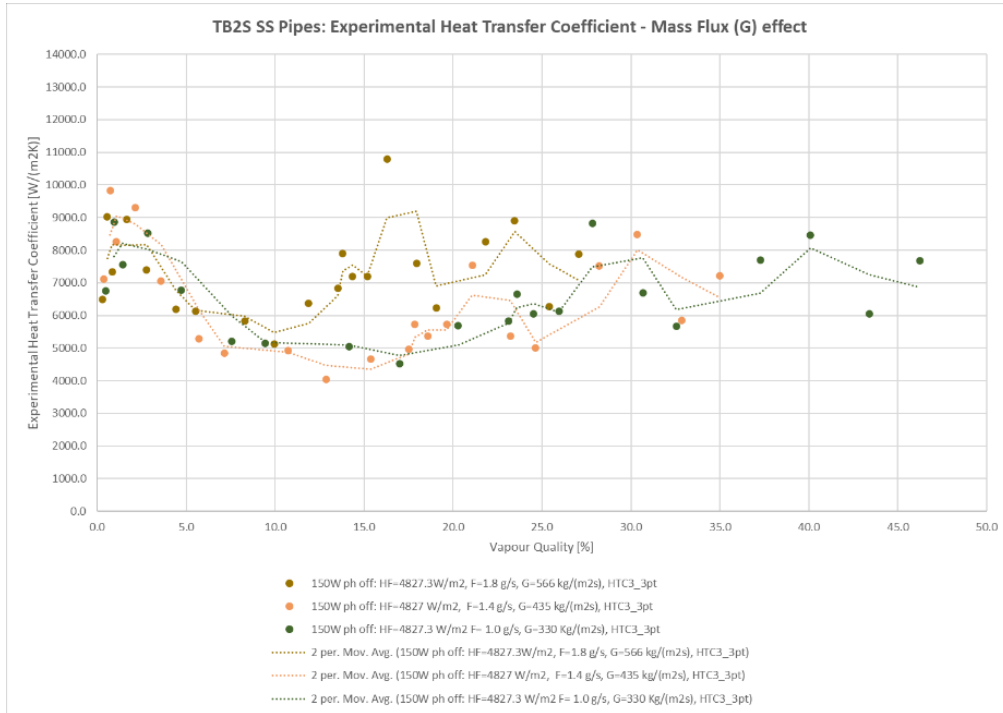


Figure 152 - Trends of HTC as a function of vapour quality in tests conducted with varying mass flux.

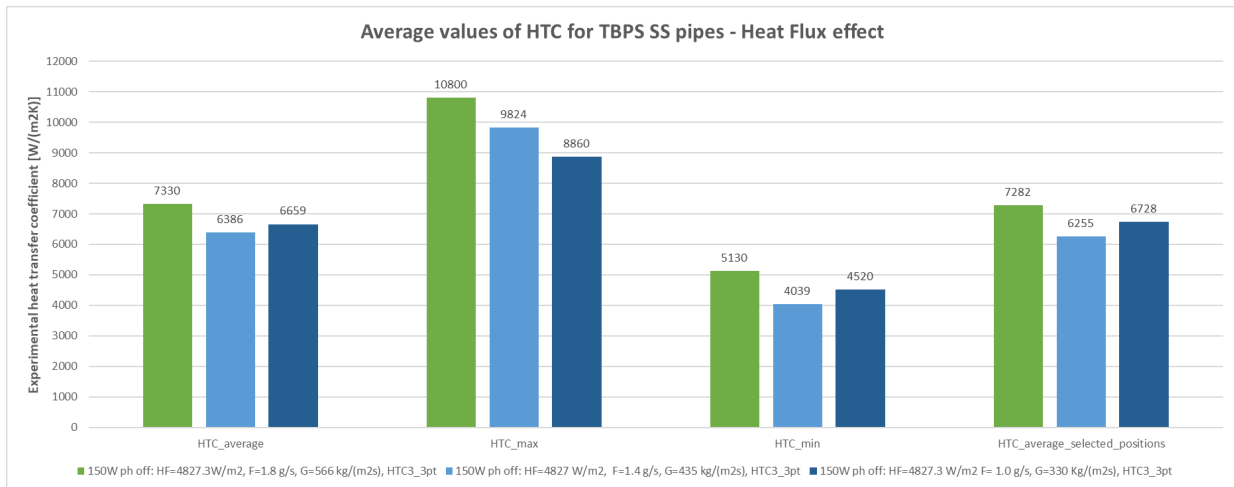


Figure 153 - Averages, maximum and minimum values of HTC along the evaporator with varying mass flux.

6.3.2 Analysis of pressure drop and estimation of HTC values along TB2S stainless steel and titanium pipe evaporators: a comparison

The second phase of the tests conducted in June 2024 for estimating the HTC in the TB2S pipes was conducted by testing the first titanium pipes produced for upgrading the ladder's mechanical structure, focusing on improving thermal performance and material budget. To validate the replacement of the stainless steel pipes used in the initial "pre-production" ladders tested in Section 5 of this report with titanium pipes, it was important to assess their heat transfer coefficient. Therefore, the same tests were conducted on the new titanium pipes under the same setup conditions as those performed with the stainless steel pipes, allowing for a comparison of results. Although the detailed results from each test conducted on the titanium pipes, including the HTC calculations based on the three models described earlier, are provided in Annex 5, this section will

present a comparative analysis between the titanium pipes and the stainless steel pipes used in the TB2S ladders.

The first analysis was conducted by examining the measured pressure drop values during the tests. In Figure 154, the pressure drop profiles within the titanium (Ti) evaporator are compared with those within the stainless steel (SS) evaporator. For a more detailed comparison, it's essential to include the CO₂ mass flow trends recorded during the tests, as even small variations between the two tests could lead to misunderstandings when evaluating the results. Interestingly, it was observed that, when using titanium pipes compared to stainless steel pipes, the overall behavior in terms of pressure drop was quite similar across the different tests. However, there was a consistent increase of 0.1 bar in pressure drop in the titanium pipes compared to the stainless steel ones. This was observed across various test conditions, including different levels of heat flux applied to the evaporator and varying CO₂ mass flow rates (thus varying mass flux) at a constant power level, set to the project specification of 75 W per ladder, totalling 150 W, as two ladders are in series in each evaporator.

This difference of around 0.1 bar was also reflected in the CO₂ temperature difference measured between the evaporator inlet and outlet (Figure 155). The additional 0.1 bar pressure drop in the tests using titanium pipes led to a higher temperature drop of the CO₂ flow between the inlet and the outlet, ranging from 0.2°C to 0.4°C, compared to the stainless steel pipe tests. This temperature delta aligns with expected values for two-phase CO₂ flow at a saturation temperature of approximately 12 bar at the outlet, where a theoretical 2.3°C temperature drop occurs for each bar of pressure drop, so measuring 0.1 bar of higher pressure drop should lead to about 0.23°C of theoretical temperature drop. This confirms the precision of the CO₂ temperature measurements during the tests.

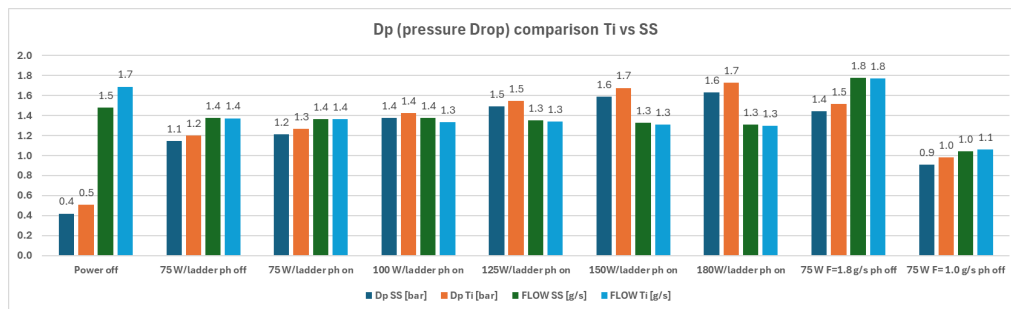


Figure 154- Comparison of the measured pressure drops along the evaporator with pipes of the same geometry made of stainless steel and titanium. For completeness, the measured CO₂ mass flow used during these tests is also reported.

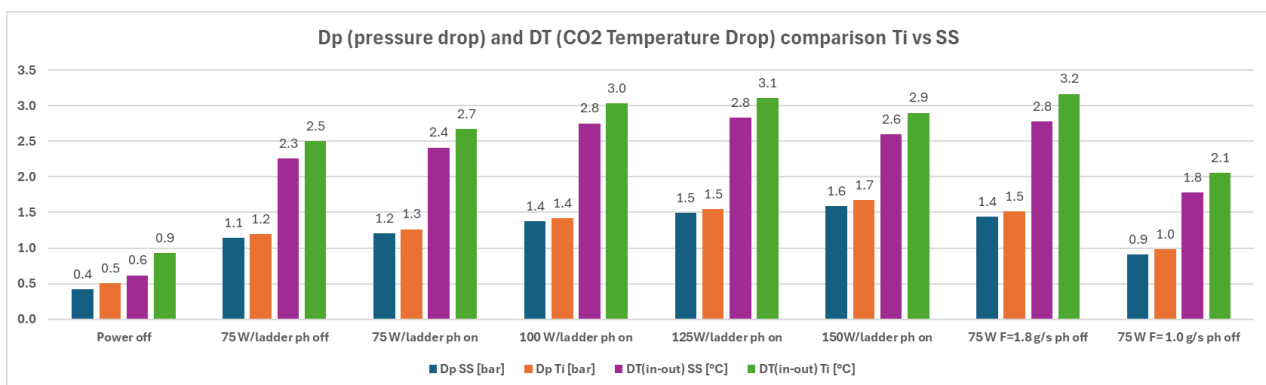
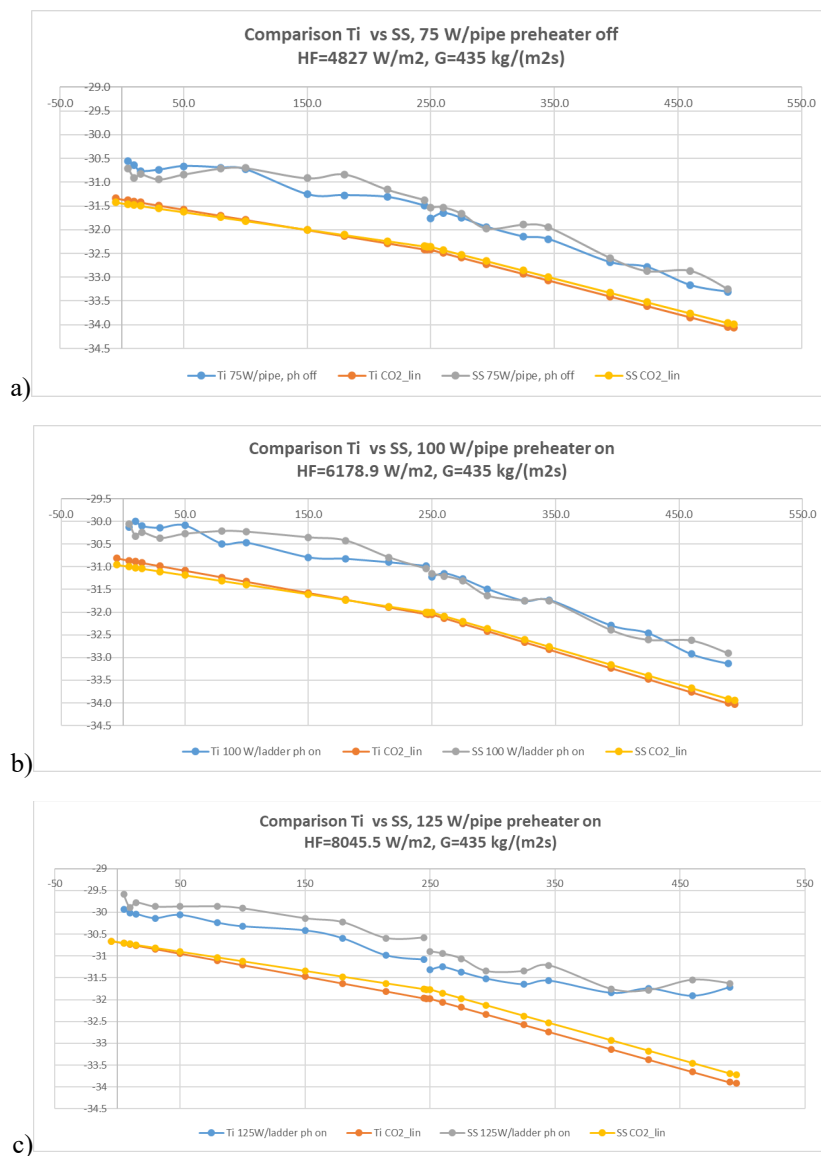


Figure 155 - Pressure drop and temperature drop of CO₂ inside the evaporator during the tests of the two different pipes' material.

When analyzing the results obtained in Figure 156, it is possible to observe the temperature trends along the wall of the heated titanium evaporator pipes compared to the temperatures measured in the case of stainless steel pipes. Observing the results with a heat flux of 4827 W/m², we can note that, with similar CO₂ temperatures inside the pipe (shown here with the linear model CO₂_lin for both SS and Ti) provided by the TRACI plant, the temperatures measured on the pipe walls for both types of pipes are very similar. Specifically, in the initial phase of the loop, up to the first 100 cm of the evaporator, the temperatures measured in the SS

pipe seem to be slightly lower (with absolute differences between 0.1 and 0.3 °C) compared to those measured in the titanium pipe. In this phase, higher HTC values are recorded at the beginning of the cooling loop in the SS pipe, so at lower vapour quality levels. However, this trend reverses in the second part of the evaporator, where the temperatures measured in the titanium pipe are lower, with differences also between 0.1 and 0.3°C, corresponding to slightly higher HTC values in the second part of the loop for the titanium pipes, so at higher vapour quality levels.

As the heat flux increases from 4827 W/m² to 6178.9, 8045.5 and 9654 W/m², thus varying the vapour quality at the evaporator outlet from 35% to 47%, 60% and 73%, the phenomenon of dryout occurs similarly in both types of pipes. Beyond the 50% vapour quality threshold in these tests (figure 156 c and d), the temperatures of both kind of heated pipes in the final part of the loop begin to rise due to the degradation of the HTC of the two-phase CO₂. Figure 156 shows the HTC trends in the different tests performed with increasing heat flux in the titanium pipes, which demonstrate a degradation in cooling performance once vapour quality exceeds 50%, similar to what was observed in Figure 148 for the stainless steel pipes. This analysis confirms the thermal behavior similarity between the two types of pipes when dryout occurs inside the pipe.



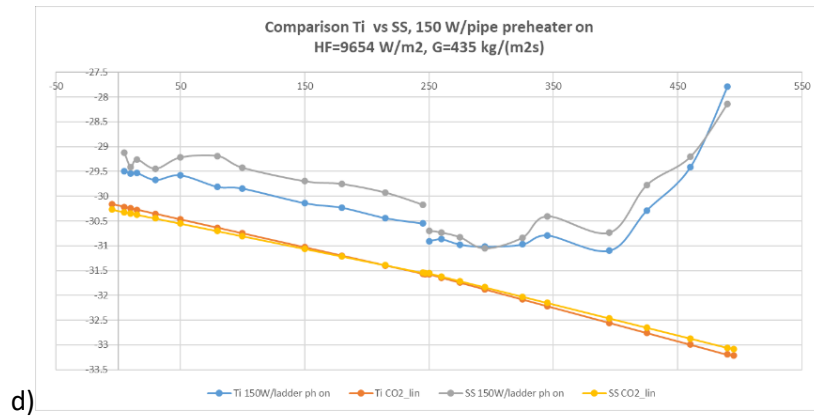


Figure 156- Comparison of thermal performance between stainless steel (SS) pipes and titanium (Ti) pipes, focusing on the internal pipe wall temperatures and CO2 temperatures inside the pipes (calculated using the CO2_lin linear model), as the power supplied to the evaporator (heat flux) increases while keeping the CO2 flow rate (mass flux) constant.

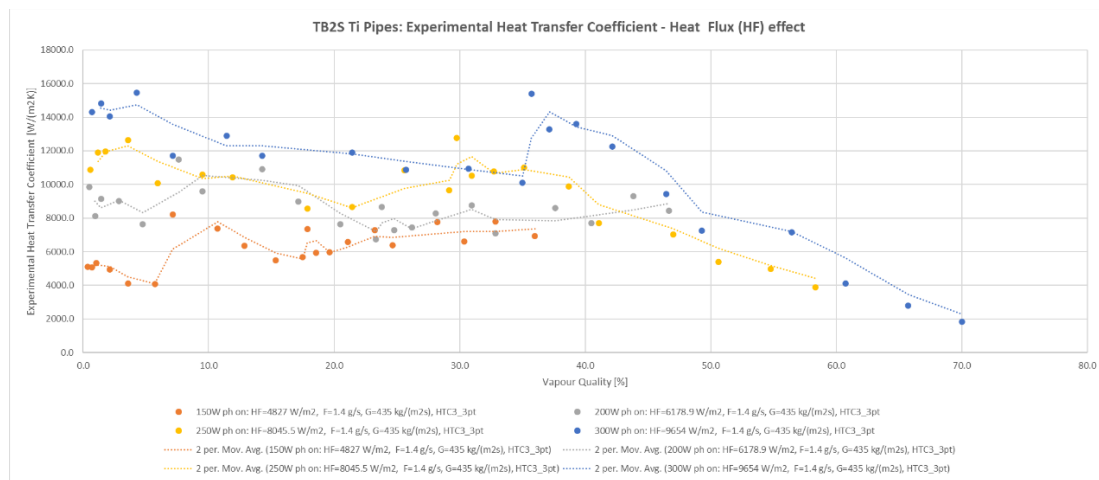


Figure 157- HTC trends in the tests conducted with an evaporator consisting of two TB2S titanium pipes in series, as a function of vapour quality and varying heat flux supplied.

We can analyze the average, maximum and minimum values obtained in the calculation of the HTC for the tests conducted on titanium pipes, compared with the tests on stainless steel pipes. From Figure 158, we can observe that during the test with the design heat flux for these pipes at the beginning of the detector's lifespan (4827 W/m^2), similar average HTC values were reached for both stainless steel (SS) and titanium (Ti) pipes, with $6505 \text{ W/(m}^2\text{K)}$ measured for SS compared to $6210 \text{ W/(m}^2\text{K)}$ for Ti pipes. As the heat flux increases, all HTC values show an upward trend for both tests, as highlighted previously in the HTC calculations for SS pipes. Specifically, increasing the heat flux, the titanium pipes appear to perform better in terms of cooling efficiency, reaching an average HTC of $9533 \text{ W/(m}^2\text{K)}$ compared to $8046 \text{ W/(m}^2\text{K)}$ for SS pipes during the test with a total power of 250 W supplied to the evaporator (125 W per pipe, corresponding to a heat flux of 8045.5 W/m^2).

From this type of analysis, examining the minimum HTC values in each test, it is evident that these values remain consistently above $4000 \text{ W/(m}^2\text{K)}$ under the design heat flux of 4827 W/m^2 , while they rise above $5000 \text{ W/(m}^2\text{K)}$, specifically $6756 \text{ W/(m}^2\text{K)}$ for Ti pipes and $5299 \text{ W/(m}^2\text{K)}$ for SS pipes, when 100 W per pipe is supplied to the evaporator, or 200 W in total, corresponding to a heat flux of 6178.9 W/m^2 . This second case (with 100 W per pipe) allows us to evaluate the thermal performance of the pipes in the TB2S ladders, integrated with modules exposed to end-of-life conditions (dissipating around 8 W per module, 96W with 12 modules in the same "end of life" conditions), in the most disadvantaged position of the detector. For this scenario, simulations conducted during the design of the detector's mechanical structures adopted conservative HTC values along the evaporator of $5000 \text{ W/(m}^2\text{K)}$, a choice that appears to be fully supported by these experimental data obtained for both pipe types but, for a less conservative but more precise estimate, it could

probably be adjusted to 6000 W/m²K for the next simulations, due to the transition to the new type of titanium pipes for the TB2S ladders.

Moreover, as the heat flux increases to values of 8045.5 and 9654 W/m², which represent operating conditions beyond the evaporator's design, and as vapour quality at the outlet exceeds optimal levels (exceeding the range between 35% and 45%), the minimum HTC values begin to decline. They drop to 3878 and 823 W/(m²K) for titanium and 1823 and 1993 W/(m²K) for SS pipes, due to the reduced cooling performance of the two-phase CO₂, which begins to enter the dryout phase at the evaporator outlet. This dryout causes an increase in pipe wall temperatures at the outlet, as noted in Figures 156 and 148.

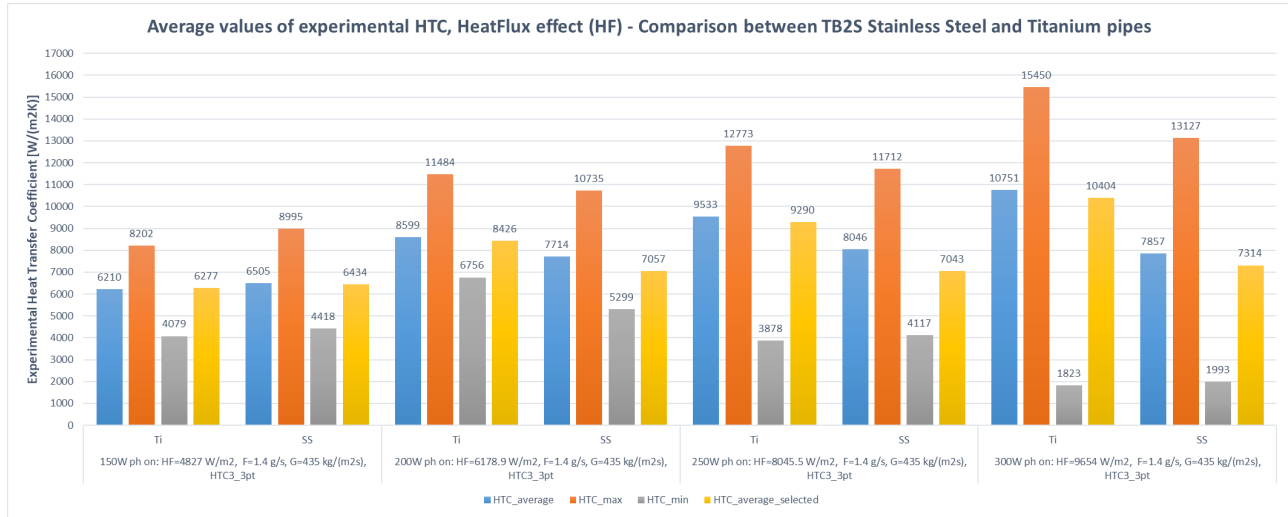


Figure 158 - Comparison of the experimental HTC values measured in tests with evaporators using stainless steel and titanium pipes as a function of heat flux.

The same comparative analysis can be carried out by varying the mass flux (figure 159) from 435 kg/(m²s) with a CO₂ flow of 1.4 g/s, increasing it to 566 kg/(m²s) (flow of 1.8 g/s) and decreasing it to 330 kg/(m²s) (flow of 1.0 g/s). This allows for an evaluation of how, by maintaining a constant heat flux of 4827.3 W/m², similar results are obtained in terms of HTC for both types of pipes, with titanium pipes consistently showing slightly higher values in all three tests, both in terms of average, maximum and minimum values, compared to those obtained with stainless steel pipes. Specifically, it can be observed that by increasing the flow to 566 kg/(m²s) and reducing the vapour quality at the outlet to 27.3% (from 35% at a mass flux of 435 kg/(m²s)), the measured HTC for the titanium pipes increases from an average of 6814 W/(m²K) to 9032 W/(m²K). A similar phenomenon is observed in the stainless steel pipes, where the HTC at higher mass flux reached values of 7330 W/(m²K).

As previously noted in the stainless steel pipe analysis, this effect can be attributed to the increased CO₂ flow velocity, which enhances the convective heat transfer coefficient (HTC_{cv} in Equation 10) within the two-phase flow. Conversely, when the mass flux is decreased to 330 kg/(m²s), corresponding to a flow rate of 1.0 g/s, no drop in the average HTC values is observed; instead, there is an increase, as also seen in the stainless steel pipe tests. The rise in all measured values (average, maximum and minimum) could be explained by the fact that while the reduced flow velocity inside the pipe would typically diminish convection, in this test, the vapour quality at the loop outlet increases to 47% (from the 35% estimated in the tests with a mass flux of 435 kg/(m²s)). This brings the system into a region where CO₂ boiling achieves optimal heat transfer coefficient values, possibly compensating for the degradation in performance due to the lower flow velocity.

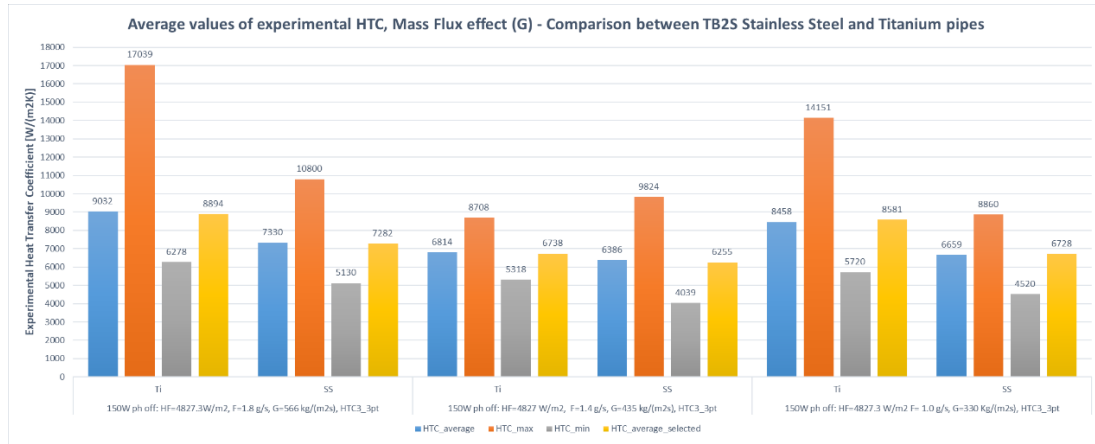


Figure 159- Comparison of the experimental HTC values measured in tests with evaporators using stainless steel and titanium pipes as a function of mass flux.

Overall, these tests have confirmed the feasibility of transitioning from stainless steel pipes to titanium in the assembly of TB2S ladders. This change aims to achieve improvements related to lower thermal expansion and greater lightness of titanium. Importantly, the tests have shown that this transition does not interfere with the cooling performance of the detector, specifically the HTC values of CO₂ within the pipe. In fact, there is a consistent or even slight improvement in the average HTC values along the walls of the titanium evaporators compared to those of stainless steel, as demonstrated by the results presented in this analysis.

6.4 Second tests campaign (October 2024) on TB2S stainless steel pipes

In the last few weeks as a technical student, I had the opportunity to conduct additional experimental tests to estimate the HTC in stainless steel pipes, implementing the improvements outlined in section 6.1. The analysis of the data obtained will contribute to further refinements aimed at improving the estimation of pressure drop and HTC within the TB2S stainless steel pipe evaporators, allowing for comparisons with data obtained from simulations using the COBra program, which were conducted with the input geometries described in this section. The experimental data for the HTC and pressure drop were calculated under the same flow and power conditions used in the initial experimental campaign in June 2024, along with additional tests conducted with varying flows and, notably, examining the variation of HTCs as a function of the setpoint pressure of the TRACI accumulator. Overall, all tests are summarized in table 18.

Table 18- Tests conducted during the second experimental campaign on calculating the HTC of TB2S pipes made of stainless steel. Data from the tests are available in Annex 6 attached to this document.

TB2S - HTC_SS_2pipes_second_test		
Pressure [bar] TRACI setpoint (Tsetpoint [°C])	Flow set point [g/s]	Title (power per pipe[W], flusso [g/s], Tsetpoint [°C])
12 bar (-35°C)	1.4	0W-off, 1.4 g/s, -35°C
		75 W/ladder ph on, 1.4 g/s, -35°C
		75 W/ladder ph off, 1.4 g/s, -35°C
		100 W/ladder ph off, 1.4 g/s, -35°C
		125 W/ladder ph off, 1.4 g/s, -35°C
		150 W/ladder ph off, 1.4 g/s, -35°C
		180 W/ladder ph off, 1.4 g/s, -35°C
		200 W/ladder ph off, 1.4 g/s, -35°C
	1.2	75 W/ladder ph off, 1.2 g/s, -35°C
		100 W/ladder ph off, 1.2 g/s, -35°C
		125 W/ladder ph off, 1.2 g/s, -35°C
		75 W/ladder ph off, 1.0 g/s, -35°C
	1.6	75 W/ladder ph off, 1.6 g/s, -35°C
	1.8	75 W/ladder ph off, 1.8 g/s, -35°C
11 bar (-37.5°C)	1.4	75 W/ladder ph off, 1.4 g/s, -37.5°C
17 bar (-24.7°C)	1.4	75 W/ladder ph off, 1.4 g/s, -24.7°C
23 bar (-14.9°C)	1.4	75 W/ladder ph off, 1.4 g/s, -14.9°C
40 bar (+5.3°C)	1.4	75 W/ladder ph on, 1.4 g/s, +5.3°C
51 bar (+15°C)	1.4	75 W/ladder ph on, 1.4 g/s, +15°C

The results from the tests conducted during this campaign are available in Annex 6 attached to this thesis. Of particular interest for this report are the comparisons that can be made between the average HTCs measured at positions where the CO₂ calculation models do not interfere (designated as HTC_average_selected_positions). This comparison aims to evaluate the repeatability of the tests conducted and the results presented in the

previous two sections. In particular, Figures 160 and 161 illustrate the average HTC measured in the same type of evaporator, consisting of two TB2S stainless steel pipes in series, as a function of both heat flux and mass flux. The HTCs measured in the second test reflect the trends and absolute values evaluated in the first test, with variations in the average HTCs measured during the same test falling within $\pm 800 \text{ W}/(\text{m}^2\text{K})$. This represents the worst-case scenario for repeatability in the tests, as shown in Figure 161, where a mass flux of $566 \text{ kg}/(\text{m}^2\text{s})$ resulted in an average HTC $768 \text{ W}/(\text{m}^2\text{K})$ higher in the first test compared to the second test.

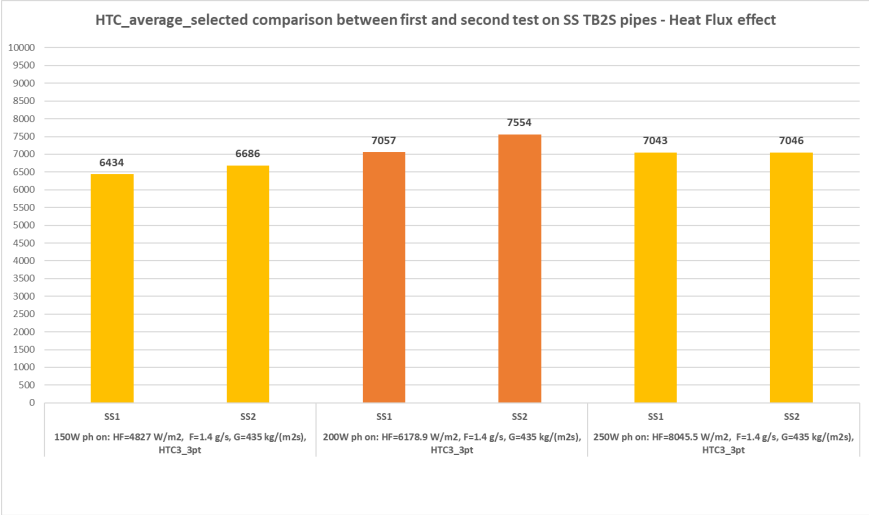


Figure 160- Comparison of the average HTC measured during the first testing campaign in June (SS1) and the second in October (SS2), in the same tests conducted at varying heat flux.

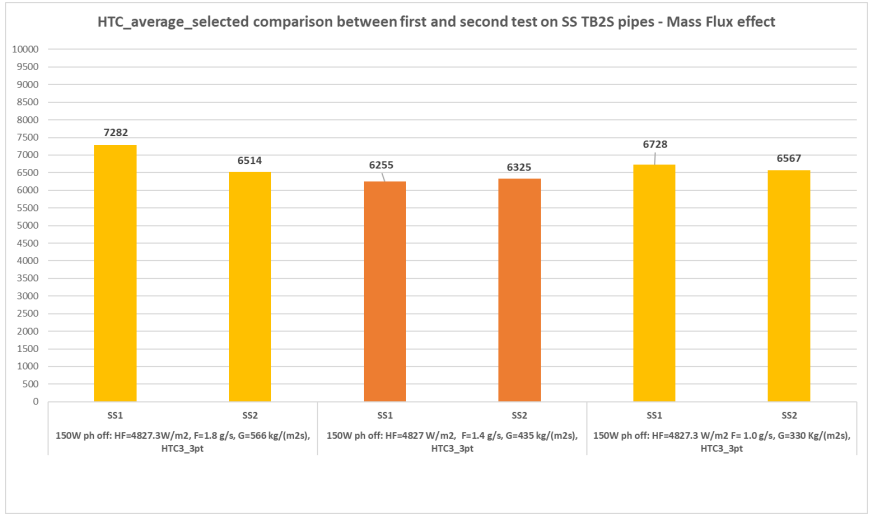


Figure 161- Comparison of the average HTC measured during the first testing campaign in June (SS1) and the second in October (SS2), in the same tests conducted at varying mass flux.

7. Preheaters: prototype validation and thermal quality control

One of the key components in the cooling loop of the future CMS tracker is the preheater. This component, as described in chapter 3.6, serves to reduce the risk of poor cooling in the first detector modules at the beginning of an evaporator after the capillaries.

As shown in the qualitative diagram illustrating the cooling loop used within the CMS tracker (figure 162), the incoming CO₂ flow, after passing through the transfer line and receiving heat from the return flow of CO₂ from the evaporator through a concentric transfer line that also acts as a heat exchanger, is then split by the distribution manifold to reach each individual evaporator uniformly. Each loop is responsible for cooling dedicated zones of the detector. For example, in this work, thermal tests were presented on each TBPS ring (Section 4) and on two ladders in series TB2S (Section 5), both representing a single evaporator that requires a sufficient mass flow of CO₂ to ensure optimal cooling. At the loop outlet, CO₂ vapor quality must remain below a maximum of 42%, to avoid entering the dryout zone of two-phase cooling systems, where the heat transfer coefficient (HTC) drops significantly below 5000 W/m²K (Section 6), making it impossible to maintain the temperature of the modules within safety margins and avoid thermal runaway, particularly in modules more exposed to radiation within the detector.

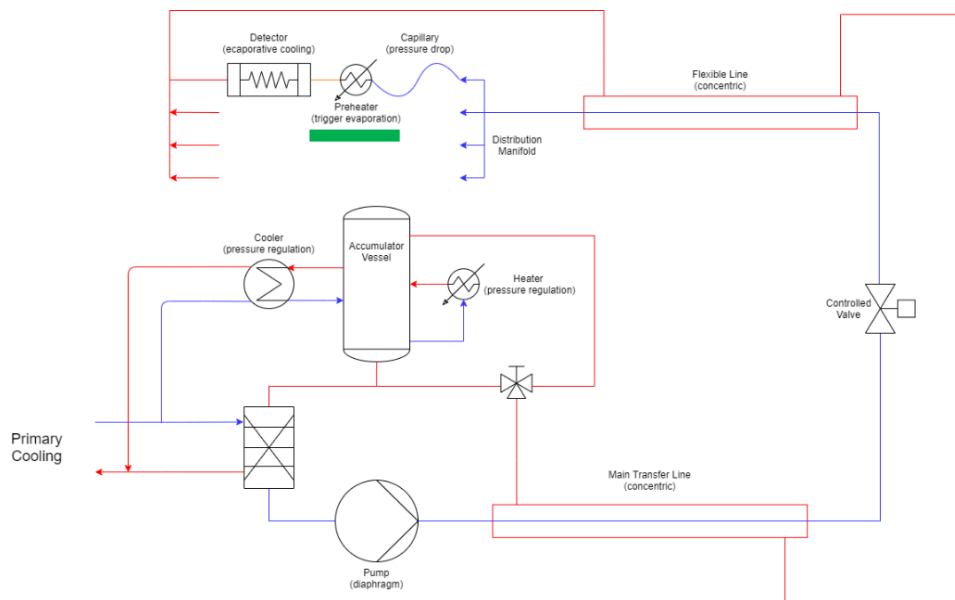


Figure 162 - General overview of the cooling loop used to cool the Tracker detector. Highlighted in green is the preheater position, located just after the capillary and immediately before the evaporator.

The flow balance from the distribution manifold (where the flow is divided into individual loops) is a key element, passively controlled through the use of capillaries. Using electrical analogy, once the system's pressure drop (equivalent to potential difference in an electrical system) between inlet and outlet in two parallel lines (connected to the same manifold at both ends) is defined, each line offers its resistance (analogous to electrical resistors in parallel) to the CO₂ flow (analogous to electric current). More mass flow of CO₂ will naturally occur in the loop with less resistance. Only by ensuring that the two parallel lines present the same resistance to flow, we can guarantee an even distribution of the initial flow. Capillaries are introduced into the loop mainly for this purpose. They act as a bottleneck in the cooling loop, causing a localized pressure drop of around 8-10 bar, which makes the CO₂ flow "partially insensitive" to potential pressure drop variations across individual cooling loops. These variations are mainly caused by potential mechanical asymmetries in the sub-detector structures (hence why the homogeneity of the pressure drop across each cooling loop is continuously monitored during quality control thermal tests, as shown for the tilted TBPS rings in Section 4) or by variations in the thermal load of each loop. The latter, being subjected to different radiation damage rates depending on the specific loop's position within the tracker, can result in higher vapor quality rates at the outlet, thus opposing greater resistance to CO₂ flow. This phenomenon is analyzed in detail in Chapter 6, where pressure drops across a TB2S sub-detector evaporator were studied as a function of heat flux.

However, for capillaries to function properly, they require liquid CO₂, since boiling inside the capillaries would not only result in a loss of cooling capacity but also increase the resistance to flow due to the effect of boiling in small-diameter pipes (around 1/16 inch). As shown in the figure 27, capillaries must operate just before the evaporator, in a subcooled fluid region, and at their outlet, they should ensure a flow in saturated fluid conditions. Due to potential slight variations in individual loop behavior, the flow exiting the capillaries may still be subcooled. This is where the preheater plays a crucial role in getting closer to the saturation temperature: transitioning from subcooled to two-phase flow to enhance the heat transfer coefficient right at the beginning of each evaporator.

Beyond this, the main reason for using the preheater is to avoid the onset of the superheating phenomenon, described in chapter 3.6 where we must avoid the subcooled liquid exiting the capillary being gently heated by the detector modules (gentle heating increases the possibility of superheating). As shown in the figure below, the preheater is positioned at the capillary outlet, just before each evaporator. It is designed to ensure a high heat flux (values of about 250000 W/m²) maximizing performance against superheating, but making the preheater one of the most critical components to cool within the entire detector. To achieve this, the component is constructed with two electric resistances, placed on two aluminum clamps used to fasten the preheater to the cooling pipe, maximizing contact. Ensuring good thermal contact between the preheater and the pipe is crucial because, given the high heat flux of the preheater, if the heat conduction between the resistor and the CO₂ flow is not sufficiently high, the component no longer transfers heat to the circuit, effectively rendering it non-functional. Furthermore, since it is now only cooled by the surrounding air through natural convection (characterized by a convection coefficient of about 15 W/(m²K)), it heats the air and interferes with the temperatures of nearby modules, thereby worsening their cooling performance. In this case, given the low natural convection coefficient, the preheater's temperature could rise above the limits required for proper operation, potentially causing it to break. During my time working at CERN, I was involved in developing a setup to test the effectiveness of this contact between the preheater clamp and the pipe's outer surface, by varying the geometry and size of the clamp.

7.1 Prototype's design

The primary components that constitute each preheater are as follows (Figure 163):

- A main resistor of 10 Ohms, used to dissipate the required heat through Joule effect to trigger boiling.
- A backup resistor, included as a substitute for the main resistor, as there will be no further access to the preheaters after the Tracker assembly phase. To ensure a replacement option if the primary resistor fails, a secondary resistor is included to dissipate heat if needed.
- A pair of machined aluminum blocks or clamps, which secure the resistors to the pipe, maximizing heat transfer from the resistor to the cooling pipe.
- Additional components needed for mounting the preheater on the pipe, such as socket head screws, threaded inserts, washers, split spring washers and epoxy adhesive.
- A Pt1000 RTD sensor, placed in a dedicated slot designed in the clamp geometry and bonded to it, used to monitor the temperature of the preheater. This provides useful information about the operational state of the preheater and, indirectly, of the cooling loop. As it is a component with high heat flux to dissipate, it will reach the highest temperatures in the event of cooling failure, providing an additional indication of the cooling state of each evaporator before the modules are powered on.

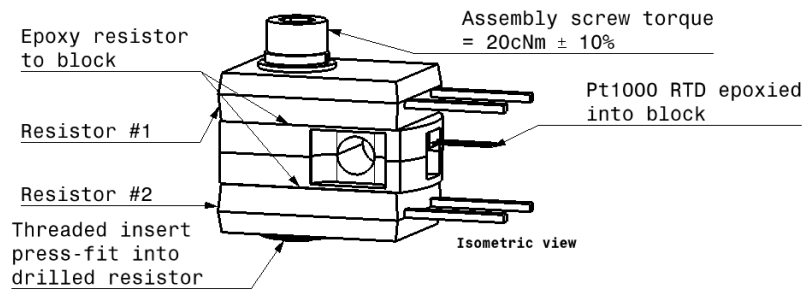


Figure 163 – Isometric view of a preheater prototype designed for the CMS Tracker

The first prototype was made for CuNi pipes with an outer diameter of 2.5 mm and an inner diameter of 2.0 mm, both with a tolerance of ± 0.03 mm. Based on studies by Baldinelli et al. [33], it features an optimized contact length of 5 mm. This component's particularity lies in its requirement to dissipate a high heat flux (approximately 255000 W/m² for the first prototype tested with the specifications above, with 8 W of power dissipated from the resistor to the CO₂ flow). It is essential to ensure good thermal conduction between the resistor (the power source) and the CO₂ flow (the heat sink). Additionally, this high conductivity must be maintained even as the pipe dimensions, especially the outer diameter, vary due to production tolerances. To achieve this, a clamp geometry with an ovalized hole was developed at CERN by engineer Thomas French (appendix 5). This ovalization is achieved by leaving a 0.1 mm gap between the two clamps before drilling (Figure 164). When joined, the clamps form a slightly oval shape for positioning the preheater on the pipe, ensuring effective contact between the clamp and pipe, even when diameter variations occur due to tolerances.

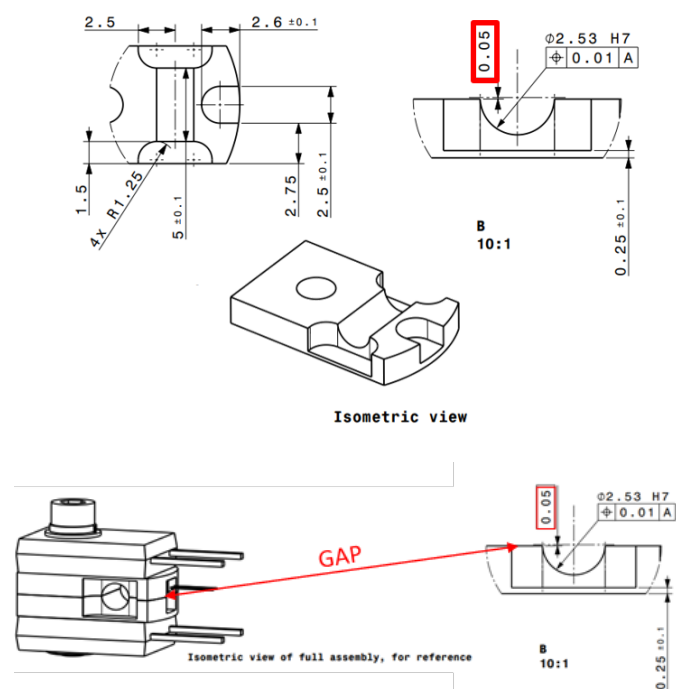


Figure 164 - Detail of the preheater clamp design, which includes an ovalized hole to accommodate slight variations in the pipe diameter due to its tolerance.

At this point, the dimensions used for the preheater hole are determined not by the nominal value of the pipe's outer diameter but by its maximum size, accounting for the additional value given by the tolerance. In the initial design, the entire component is held tightly together by a 20 cNm pair, securing the different layers. The first prototype, manufactured and thermally tested for the type of pipes described above, was thus made with a 2.53 mm hole (2.50 mm + 0.03 mm tolerance), as shown in the CAD drawing in Appendix 5.

7.2 Preheater's prototypes TQC: test setup and procedure

The test setup used for the thermal quality control phase of this preheater prototype is located in the Lyon Cold Room, Building 186 at CERN (figure 165). The refrigerant fluid used is M20 silicone oil, produced at +12°C, allowing it to operate in an uncontrolled humidity environment, thus eliminating the need for dry gas since the dew point inside the room is around 10°C. This chiller can operate between +20°C and -20°C, with a flow rate of 5 g/s. The produced refrigerant fluid, in single-phase liquid form, enters a U-tube located inside an insulated box (figure 165), similar to those in which the actual preheater will be placed within the tracker (CuNi OD = 2.5 mm and ID = 2.0 mm in this case). The U-tube is connected via two Swagelok tube fittings (SS-6M0-6-4M) to the inlet and outlet manifolds of the refrigerant. The choice to use a fluid other than two-phase CO₂ for verifying thermal contact lies in the fact that the contact between the preheater clamps and the pipe is independent of the type of fluid cooling it. The primary objective of this setup is to validate the actual quality of the thermal contact between the two elements. Additional investigations to determine the operational temperatures of the preheater using CO₂ in a two-phase state at -35°C have been conducted and will be analyzed in Chapter 7.3. In this type of test, the silicone fluid produced by an industrial chiller (which is more readily available) allows for better stable temperature conditions, making the test repeatable regardless of fluid conditions. This is more complex to manage if using a two-phase CO₂ fluid. Therefore, this setup is ideal not only for the current thermal validation phase but also, with minor upgrades, for the quality control of all preheaters during the production phase.

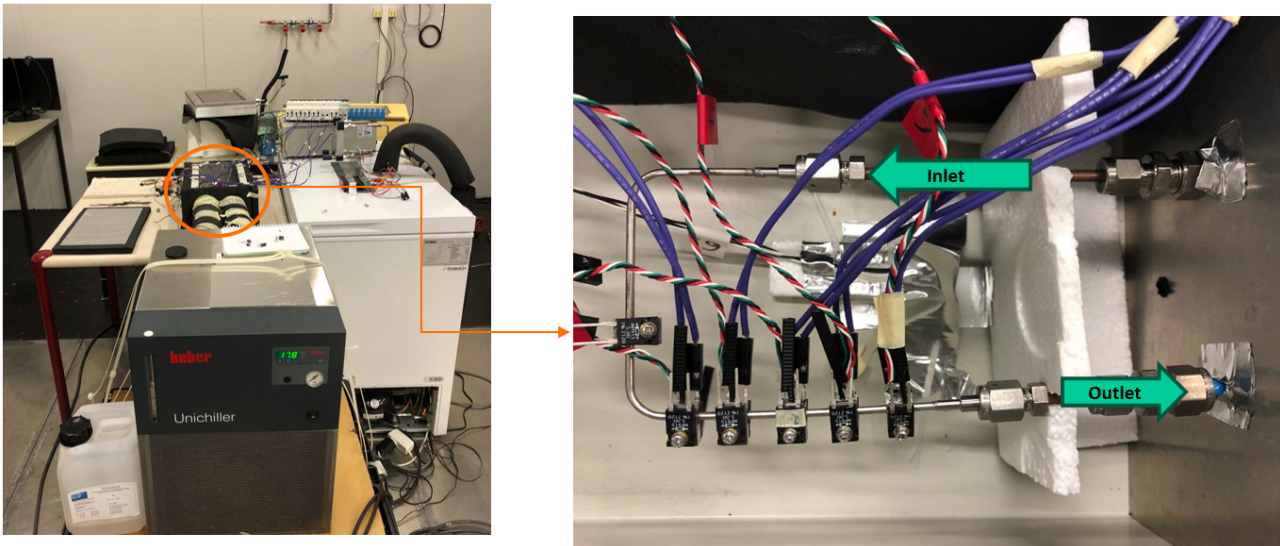


Figure 165- Preheaters TQC setup placed in the Lyon Cold Room, Building 186 (left), with a detailed picture of preheaters placed on the CuNi U-pipe used to test the actual clamping of the preheater on this type of pipe (right).

To study the ability of the preheater clamp to exchange heat with the pipe, considering possible variations in the pipe's outer diameter due to tolerance, and to ensure that the operating temperature of the preheater does not exceed unacceptable and unstable values due to poor thermal contact, three groups of different types of clamps were tested using the same resistors and the same pipe to reduce variability in the results caused by changes in these factors. A total of 18 preheaters were tested, each identified by the hole diameter:

1. Three old brass preheaters [Brass 1, Brass 2 (2.52), Brass 3 (2.52)]: these were the first “raw” productions, featuring standard cylindrical holes manufactured on the aluminum clamps, where issues of poor contact were highlighted during some thermal tests conducted to evaluate the performance of the cooling segment for the TB2S subdetector.
2. Preheaters with aluminum clamps without a gap [2.48 (1), 2.48 (2), 2.47]: this geometry was used to assess potential differences in the thermal behavior of the preheater when made with a standard hole that is always smaller than the pipe's outer diameter (considering variations due to pipe tolerances).

3. Preheaters with a gap of 0.1 mm between the two aluminum clamps, left during the machining of the hole, creating an ovalized hole, as suggested by the design of the first prototype preheater [2.55, 2.55 (1), 2.55 (2), 2.55 (3); 2.53, 2.53 (1), 2.53 (2), 2.53 (3); 2.52, 2.52 (1), 2.52 (2), 2.52 (3)].

As can be seen, each preheater is identified using the hole dimensions and a serial number in the case of multiple versions of the same geometry. The primary objective of the test is to determine whether the designed geometry is suitable for achieving a stable preheater temperature at acceptable values. Additionally, the choice to test slightly different diameters for each geometry stems from the fact that, by keeping the type of pipe used constant with a measured outer diameter of 2.50 mm, it is possible to evaluate the effect of variations in the pipe due to tolerance by altering the diameter of the preheater clamp, which can be more easily monitored through precise manufacturing. For example, if we fix the diameter of the preheater at 2.53 mm, and the pipe diameter is larger than nominal, the thermal contact should behave like that of preheater 2.52 in our test. If the pipe diameter is smaller, it resembles the case of using preheater 2.55.

During this testing phase, each preheater was also tested with and without thermal grease. The heat sink compound used was DOWSIL 340, which has a thermal conductivity of $k = 0.6 \text{ W/(mK)}$. Specifically, these types of thermal pastes are used to enhance thermal contact between two surfaces, especially when that contact is not perfect, filling voids where air would otherwise reside, which has poorer thermal conductivity (approximately 0.024 W/(mK)). The effect of the thermal paste was assessed through the following tests for each preheater (figure 166):

- Without thermal grease
- With thermal grease between resistors and clamps
- With thermal grease between resistors and clamps, and between clamps and pipe

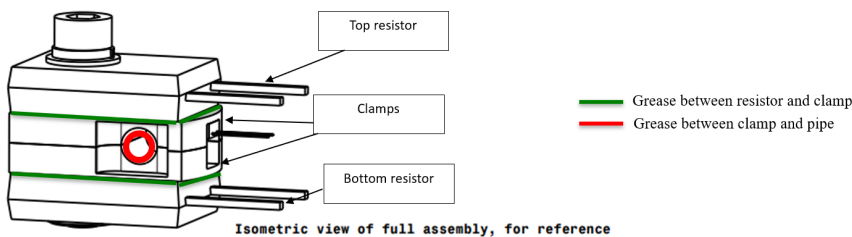


Figure 166 - Nomenclature used to name the resistors of the preheater during this testing phase (top and bottom) and the positions where thermal paste (DOWSIL 340) was applied to evaluate its effect.

During the testing phase, each preheater is positioned along the pipe and secured using $20 \text{ cNm} \pm 1$, as per the design. A power of $6 \text{ W} (\pm 5\%)$ was supplied to each preheater, provided solely by the bottom resistance (figure 166), using a power supply from AIM-TTI INSTRUMENTS type TSX1820P. The temperatures are read using 5 mini temperature readout systems (hardware developed internally at CERN), each of which can read up to 6 Pt1000 or Pt100 sensors. The temperatures are displayed and saved during the test using a LabVIEW program developed for this purpose.

For each preheater, we measured the following three temperatures using three Pt1000 sensors:

- T_t : temperature measured by the Pt1000 RTD Class A (4-wire type) placed on the top resistor (an extra Pt1000 used solely for thermal tests).
- T_c : temperature measured by the Pt1000 RTD Class A (4-wire type) placed between the two clamps at the designated location for detecting the preheater's temperature inside the actual detector.
- T_b : temperature measured by the Pt1000 RTD Class A (4-wire type) placed on the bottom resistor (an extra Pt1000 used solely for thermal tests).

Following the temperature notation for each component of each preheater (T_c , T_b and T_t , figure 167), the term “g” indicates the temperatures measured with thermal grease applied between the resistor and each clamp

(green column in the outcome plots). The term “gg” indicates tests conducted with thermal grease applied both between the resistor and clamp and between the clamp and pipe (red column in the outcome plots). Finally, tests without any thermal paste do not have any additional designation (blue column in the outcome plots).

In one preheater, for each diameter analyzed, the Pt1000 sensor in the clamp was glued using a hard radiation-tolerant adhesive, Scotch-Weld DP 490, to assess any potential effects of the adhesive, that will be used for the future preheaters’ production, on the measured temperatures. This preheater is designated with its diameter value followed by the serial number (e.g., 2.55 1), followed by the term “glued” to indicate this type of sensor positioning in the slot (resulting in “2.55 1 glued” for the preheater number 1, with a hole diameter of 2.55 mm where the Pt1000 positioned in the clamp has been glued, as per the official preheater specification). The other sensors placed in the clamp were inserted also into the dedicated slots designed to accommodate the Pt1000, but were subsequently held in contact using a clip instead of glue.

To conduct the test, one preheater at a time is powered on, and we wait for it to reach stable temperatures. Afterward, the temperature of each sensor is recorded by averaging the last approximately 50-100 samples, yielding the average temperatures recorded during the test under stable conditions for the top resistor, the clamps and the bottom resistor (from which power is supplied).

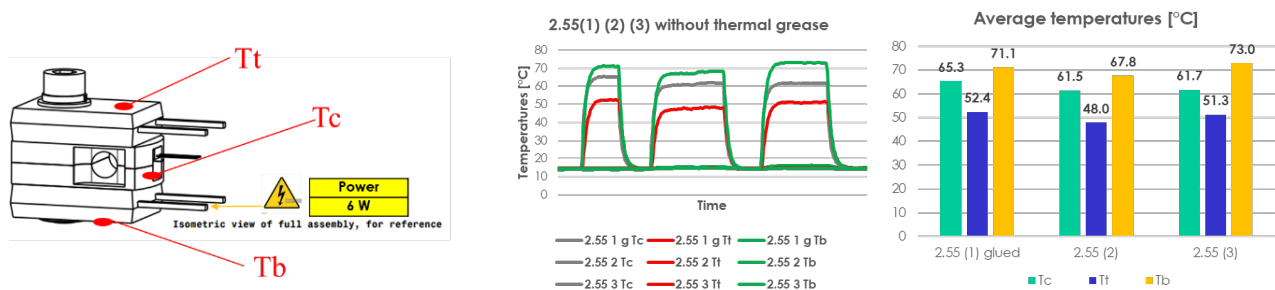


Figure 167 - Reference nomenclature used for the temperatures measured on the preheater, providing power from the "bottom" resistor during these tests (left). Example of the testing phase with one preheater powered at a time (center) and the respective average temperatures measured (right).

7.2.1 Prototypes thermal validation: outcomes

The following are the temperatures measured during the testing phase for each of the preheaters analyzed, using silicone oil M20 as the refrigerant at a temperature of $12^{\circ}\text{C} \pm 1^{\circ}\text{C}$ while maintaining an ambient temperature of $20^{\circ}\text{C} \pm 1.5^{\circ}\text{C}$. In all tests conducted, we expect to observe that the temperature of the sensor positioned above the "bottom" resistor is the highest, as this is where the power is supplied, followed by the temperature of the clamp (where the heat must pass to reach the cooling pipe), and finally the temperature of the "top" resistor, which is not directly involved in the heat transfer from the resistor to the CO_2 flow during these tests. We expect to see a continuous decrease in temperatures by adding thermal grease, first between the resistor and the clamp and subsequently between the clamp and the pipe. In this latter case, the reduction in temperatures is greater the worse the "bare" thermal contact is between the clamp and the pipe, highlighting, in case, the need to improve the geometry design or to add thermal paste also in the real design.

The first preheaters tested were some old models made with brass clamps with a diameter of 2.52 mm, featuring a hole made without the gap technique between the two clamps, resulting in an ovalized hole (figure 168). These clamps were the first produced (drafts), as mentioned earlier for a thermal test developed to validate something entirely different, but they raised the alarm about the difficulty of achieving good contact between the preheater and the pipe unless thermal grease was added to enhance it. During these thermal quality control tests, the same results were obtained, with the temperature of the bottom resistor, where the current is dissipated, exceeding 95°C (maximum temperature measured was not in stable conditions but before shutting off the power to avoid damaging the setup) in the case where no thermal paste was added, reaching adequate operating temperatures with thermal grease applied both between the resistor and clamp and between the clamp and pipe at around 60°C . The same test was repeated for all three preheaters classified as “old brass,” yielding the same results, with a temperature difference of 30°C between the case with and without thermal paste, indicating the necessity of using thermal paste for contact with this geometry. It is interesting to note that the

addition of thermal paste between the resistor and clamp creates a homogenization of temperatures, with the maximum temperatures measured in the bottom resistor equalizing those of the clamps and the top resistor.

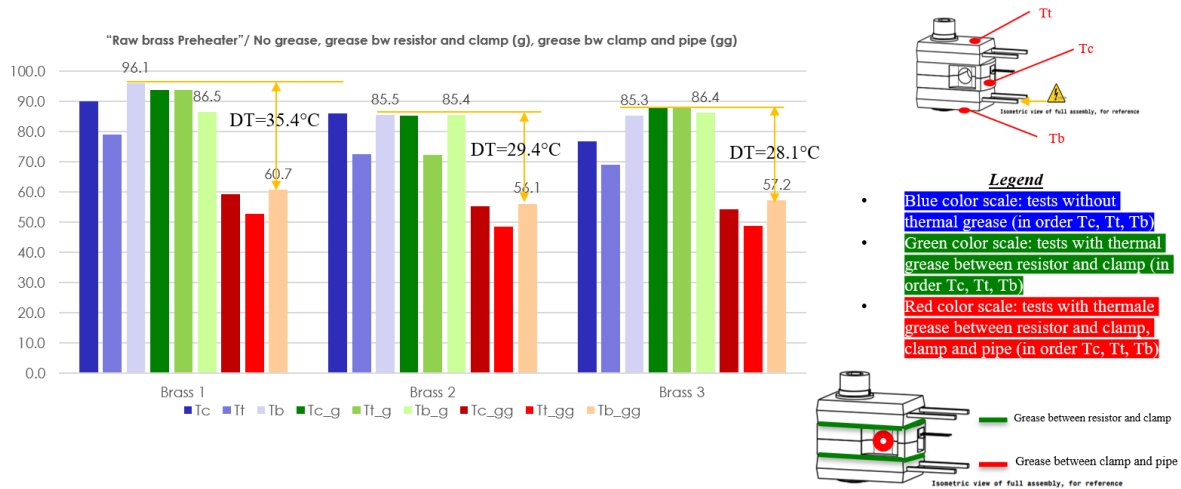


Figure 168- Temperatures measured in the 3 "raw brass preheaters" showed that, without thermal grease, a stable temperature was not achievable, underscoring the need to design a geometry that ensures better thermal contact.

The second block of tests (figure 169) was conducted using preheaters that did not have the designed geometry described in paragraph 7.1. Instead, the holes on the clamps were made without leaving a gap between the two during the assembly phase, resulting in a perfectly cylindrical hole. However, the hole dimensions were set to the minimum limits of the pipe diameter to ensure contact between the preheater and the pipe. This type of geometry proved to be effective in achieving stable and uniform temperatures across all components of the preheater (resistors and clamps). Without thermal paste, the temperatures measured were 66.5 °C for preheater 2.47 and 65.3 °C for 2.48 (2). With thermal paste applied between the resistor and clamp, and between the clamp and pipe, the temperatures dropped to 56.9 °C for 2.47 and 53.7 °C for 2.48 (2). The measured temperature difference between the case without thermal paste and the case with thermal paste ranged from 11.6 °C for 2.48 (2) to 9.6 °C for 2.47. The temperatures measured in the bottom resistor decreased by improving the contact between the resistor and clamp when thermal paste was applied only there, with temperature drops of 5.7 °C for 2.47 and 8.2 °C for 2.48 (2). Overall, clamps with holes (2.48, 2.47) smaller than the minimum pipe diameter ($OD = 2.50 \pm 0.03$ mm) showed good heat exchange even without thermal grease.

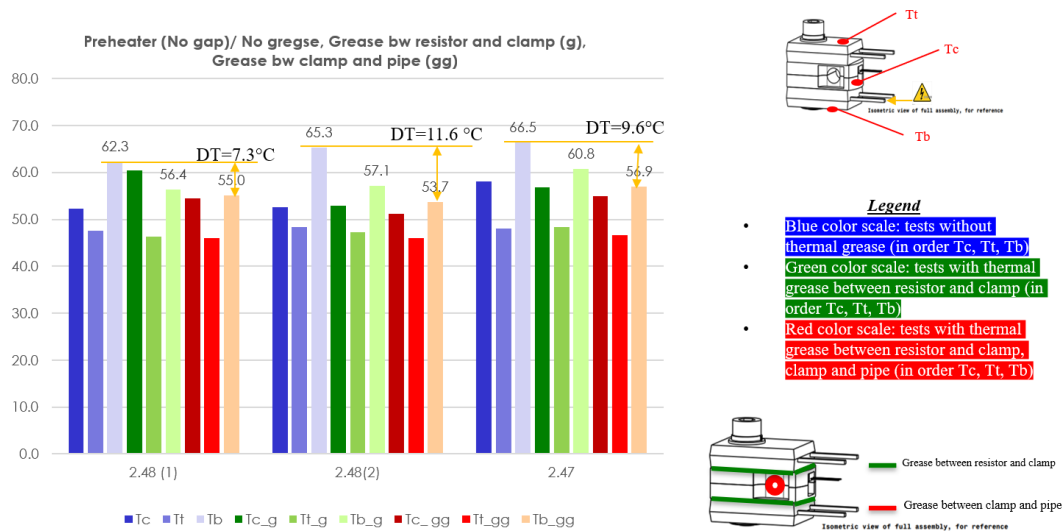


Figure 169- Preheater clamps designed with smaller diameter holes (2.48 and 2.47) compared to the pipe diameter enable good and stable temperatures even without thermal paste.

With the geometry designed for the prototype preheater by Thomas French (figure 170), clamps with holes (2.55, 2.53, 2.52) larger than the maximum allowable diameter for the pipe demonstrate good heat exchange even without thermal grease. Among all the measured temperatures, the maximum temperature difference (DT) between the temperatures in the bottom resistor measured without thermal paste and with thermal paste between the resistor and clamp and between the clamp and pipe, was 17.1 °C for 2.52(3), while the minimum DT measured was 10.0 °C for 2.52. It is notable that there is a slight variability in the preheater temperatures when varying the diameter from 2.52 to 2.55 mm, simulating potential differences in the pipe geometry due to manufacturing tolerances. This essentially shows how the design of the ovalized hole geometry adapts well to possible variations in the pipe. During these tests, it was also observed that in the preheaters 2.55 (1), 2.53 (1) and 2.52 (1), with the Pt1000 sensor measuring Tc (which is the only temperature measured within the detector on the preheater) glued in the designated slot on the clamp itself, the temperatures were very similar to those measured in the preheaters of the same dimensions without the glued Pt1000 but held in contact using a clip, confirming the choice to glue the sensor in the preheater within the actual detector. Additionally, in this test, as with all those conducted using this setup, the "expected" temperature trend is observed: the temperature measured in the resistor where power is applied is highest, followed by the temperature measured in the clamp, and finally, the temperature measured in the top resistor (not powered in these tests).

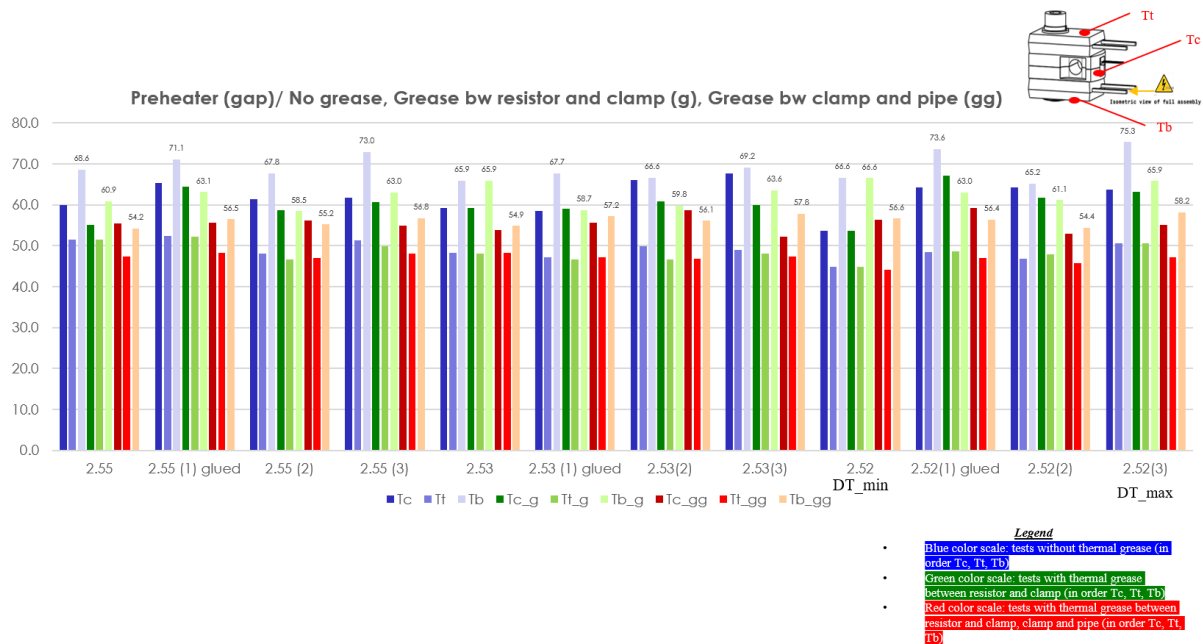


Figure 170 - Temperatures measured in preheaters with the new ovalized hole design show stable and satisfactory results even without thermal paste, with the addition of thermal paste reducing the bottom resistor temperature by 10°C to 17°C. The thermal performance of each clamp appears consistent across different hole sizes, effectively simulating potential pipe variations due to production tolerances.

As shown in figure 171, which displays all the temperatures measured in the bottom resistor of each tested preheater, both without thermal grease (blue column), with thermal grease between the resistor and clamp (green column), and with thermal grease between the resistor and clamp, and between the clamp and pipe (red column), it can be observed that among the preheater prototypes designed with the ovalized hole, the 2.53 prototype appears to have the most homogeneous and lowest temperature. This confirms the hypothesis of using the highest possible outer diameter of the pipes ($2.50 + 0.03$ mm), accounting for manufacturing tolerances, to dimension the hole between the two clamps of the preheater, leaving a 0.1 mm offset between them.

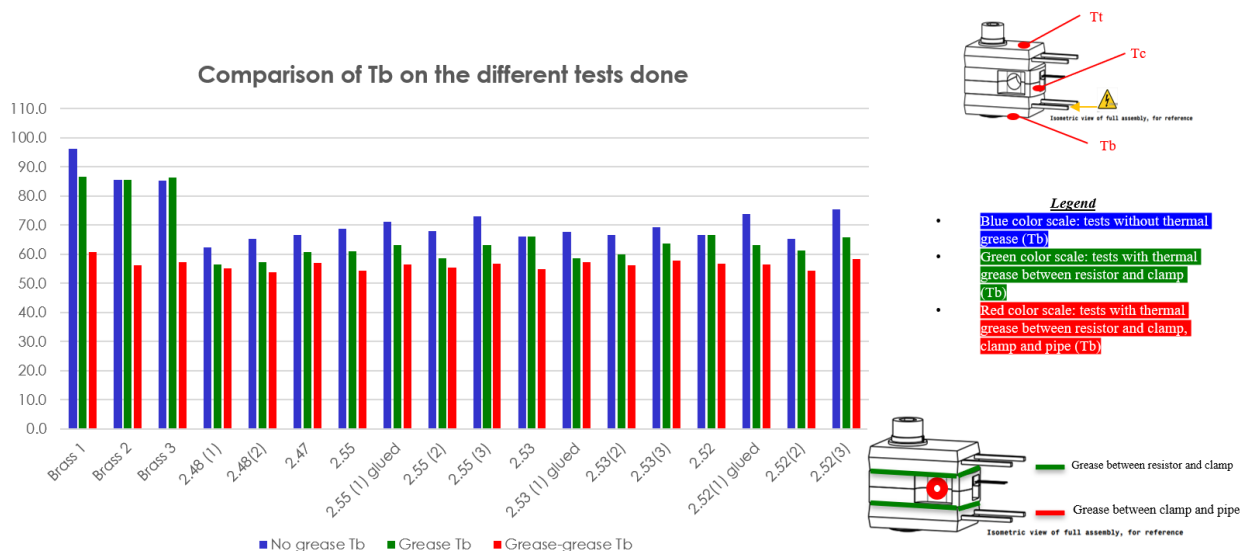


Figure 171 - Temperatures recorded in the bottom resistor during all tests confirm the effective design of the ovalized hole and support the decision to use the maximum pipe diameter as a reference, accounting for tolerance values.

The last test conducted on these initial prototypes using the described test setup involved gluing the resistor and the clamp together to simplify the assembly on the pipe, reducing the number of moving components from

four to two. This is illustrated in figure 172, where the layer of glue used to affix the Pt1000 sensors to each resistor for measuring Tt and Tb is also visible. By gluing the resistors and clamps (without thermal grease between the clamp and the pipe) on the preheaters 2.55 (1), 2.53 (2), and 2.52 (3) (violet columns), we obtained results similar to those achieved with thermal grease between the resistors and clamps (green columns). This is a positive outcome, as it allows for a simpler component to assemble within the detector, with only two elements free to move rather than four, thus making assembly easier. Specifically, for the preheater 2.53 designated as optimal for this type of pipe (CuNi OD=2.5 mm +/- 0.03 mm), we achieved a temperature difference of 8.8°C between the case with the resistor glued to the clamp and without thermal grease between the clamp and the pipe, compared to the case with the addition of thermal grease between the clamp and pipe. This effectively minimizes the necessity of using thermal grease, while still leaving the latter as an optimal solution to ensure the lowest operational temperatures and, consequently, the maximum heat transfer from the preheater to the pipe.

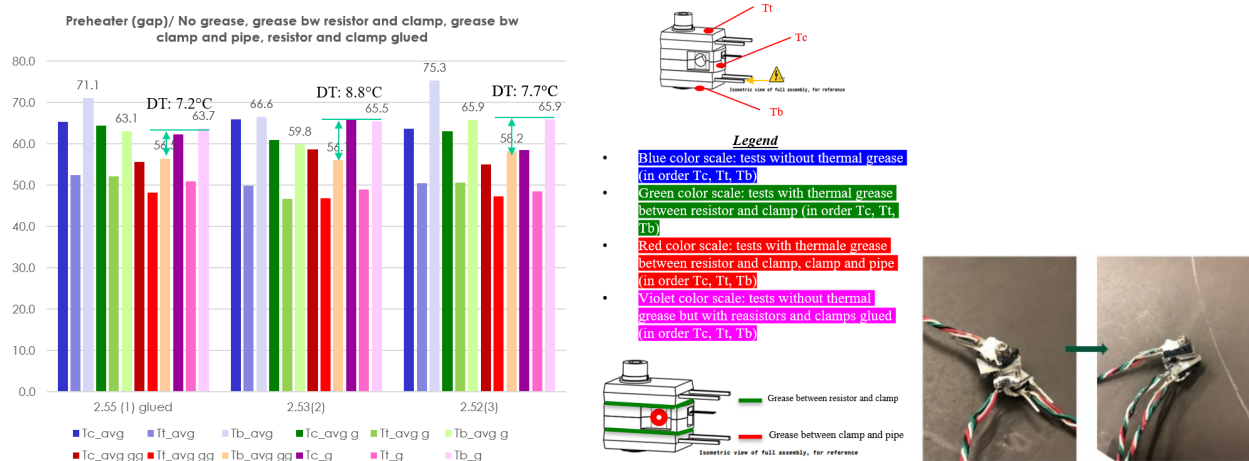


Figure 172 Temperatures measured in the preheater having an ovalized hole with the resistor glued to the clamp (purple columns) exhibit the same thermal behavior as with the addition of thermal grease between the two components (green columns), presenting an optimal choice for a more compact component (2 moving elements instead of 4) and improved thermal performance. This approach effectively reduces the incremental benefit gained by adding thermal grease between the clamp and pipe (red columns).

All the tests shown here were also conducted using the top resistor as the power source, revealing thermal behaviors and temperatures that were very similar to those obtained in the tests presented thus far, where the power was supplied by the bottom resistor. In conclusion, this subsection summarizes the results, which can be divided into two areas: the first related to the geometry of the preheater and the second related to the assembly process. Specifically, regarding the geometry:

- Any of the “new” preheater geometries (both with smaller cylindrical and larger oval holes) seem to work well and represent an improvement over the 'old' brass pieces, which were roughly made. This improvement is due to their smaller hole diameter (new clamp with a smaller hole than the pipe diameter) and a better metal-to-metal clamping mechanism on the pipe (prototype clamp with an ovalized hole).
- The new clamp with “offset” drilled hole (ovalized hole) should assure the same thermal behaviour also with larger tolerances on the pipe.
- The diameter for the new clamp with the offset that seems to work better is 2.53 mm (temperature lower and more homogeneous). Choosing this diameter, if the pipe diameter is bigger than the nominal it's like preheater 2.52 in our test, if the pipe diameter is smaller, it's like preheater 2.55: both of them work fine.

Regarding the assembly process of each individual preheater, it can be concluded that:

- A precise manufacturing process is required to ensure that any pair of clamps remains coupled from the manufacturing stage to the preheater assembly. Mixing clamps from an inconsistent manufacturing process can result in a nearly complete loss of good thermal contact between the preheater and the pipe.
- The glued temperature sensor should be positioned on the clamp in contact with the resistor where power is applied (there can be a 5-10 °C difference if we measure the temperature of the clamp attached to the other resistor).
- Gluing resistors to clamps can simplify assembly and reduce the maximum temperature reached.

Adding grease to the pipe contact can lower the resistor temperature by 5 to 10 °C (based on tests conducted with silicone oil as the coolant). However, applying grease between the clamp and the pipe may not be worthwhile due to the additional complication and potential contamination of surrounding electronics.

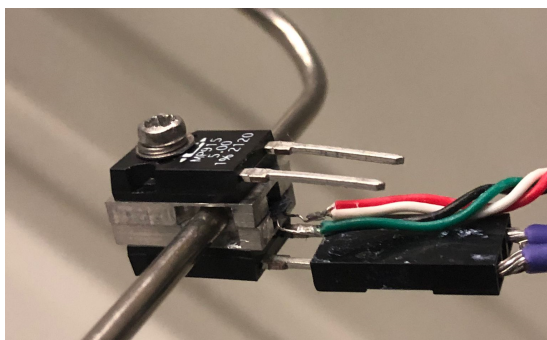


Figure 173 - Example of a preheater placed on the pipe during testing (preheater assembly follows the prototype design), with power cables and Pt1000 sensors not yet in their final design configuration.

7.3 Prototypes thermal validation in operating condition inside TB2S thermal test setup

During the testing phase of the TB2S ladders using the setup shown in Figure 139, it was possible to test these first prototypes of preheaters also under operational conditions, with CO₂ at the evaporator exit set to -35°C, and TRACI set to 12 bar. In all tested preheaters of type 2.53, geometry validated by previous tests as the reference for CuNi pipes with an OD of 2.50 mm, all sensors were glued inside the designated slot, while only the preheater 2.53 (2) had the resistor and clamp glued together. The tests were performed on three types of 2.53 preheaters, with the geometry validated by previous tests as the reference for CuNi pipes with an OD of 2.50 mm, the same ones used for previous tests, with the addition that each sensor placed in the clamp was glued as per the design. Each preheater was powered to provide the nominal 8 W of power first to one resistor (main resistor), then to the second resistor (backup resistor) individually. Finally, each preheater was also tested in full power mode, providing a total of 16 W, 8 W per resistor simultaneously.

The goal of the test was to understand if the component could dissipate 250000 W/m² of heat flux, due to the 8 W dissipated over 5 mm of contact length, considering the internal surface of the pipe of 2.0 mm and all the heat dissipated from the preheater to the flow of CO₂, in conditions of adiabaticity not fully verified either in the test conditions or presumably in the actual detector conditions, where the average general temperature should range between -10°C and -20°C. All tests were conducted without using thermal paste between the clamp and the pipe, a solution that could be investigated in the future as a backup to improve contact. In each test, the preheater was placed on the pipe with torque values on the fastening screw never less than 20 cNm.

Observing the results from the first preheater tested (2.53, Figure 174), it is noticeable that the average temperature on the resistor where power is provided, with a CO₂ temperature at the evaporator inlet of -32.8 °C, measured along the CuNi pipe exactly 8 cm before the preheater, is -3.7°C when the main resistor is functioning and -4.8°C when the backup resistor is functioning. The two resistors are exactly the same, and any differences in the measured temperature may be due to uncertainties of the resistance (from the Caddock MP915 datasheet, 1% uncertainty on the resistance) and the power supplied (+/-5%) as well as possible differences in thermal contact between the upper and lower clamp with the pipe. It is interesting to note that the temperature of the clamp in the preheater, the only temperature measured inside the actual detector, is

consistently closer to the temperature of the main resistor. In fact in every test, this sensor is glued to the clamp attached to the main resistor, indeed recording -15.8°C on this clamp when power is supplied to the resistor attached to the clamp, while -22.5°C when the same power is given to the backup resistor, not directly joined to the clamp where the sensor is positioned. The good clamping of the preheater is also observable from the data obtained in the case of both resistors being powered, with approximately 16 W total dissipated in the pipe, where the resistors reach a temperature around 2°C , while the temperature measured on the clamp rises to -11.2°C .

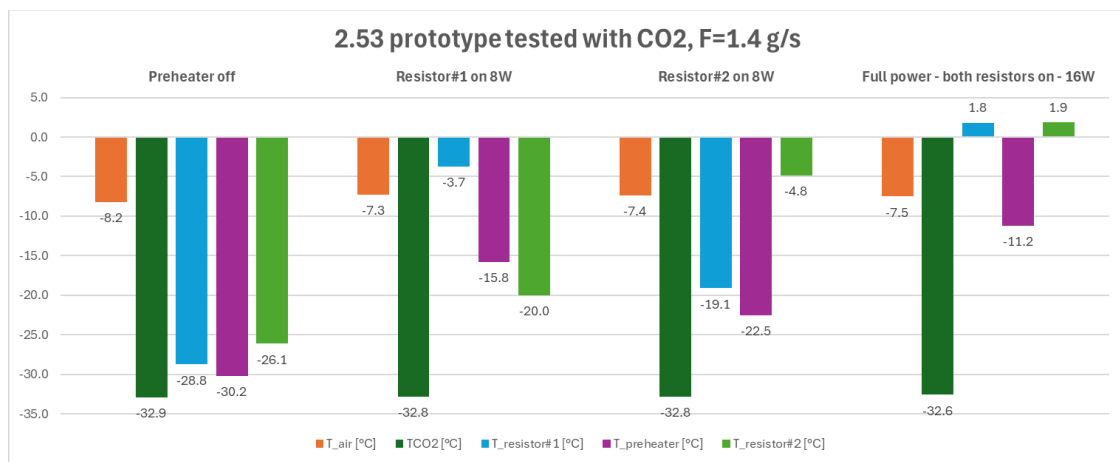
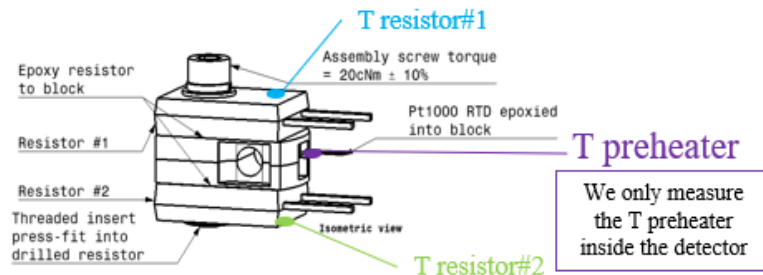


Figure 174 Plot showing the temperatures measured in operational working conditions on the preheater 2.53, in the order of power off, 8 W on the main resistor (resistor #1), 8 W on the backup resistor (resistor #2), and in full power mode, with a total of 16 W dissipated. Above is the summary diagram of the preheater with the nomenclature used for the sensors during these tests.

Similar temperatures were obtained by testing the prototype of preheater 2.53 (1) (Figure 175), with temperatures of the main resistor reaching -9.5°C when power is supplied directly to it, while the backup resistor reached 0.8°C . In this case, the preheater, when powered at full capacity, also reaches stable temperatures. The temperatures measured on the clamp are very similar to those measured in the preheater 2.53, specifically they are slightly higher by about 1°C , likely due to the CO₂ temperature during the test being 1.1°C higher.

It is interesting to note in both of these first examples how the temperature measured on the clamp (T_{preheater}) is a good indicator of the CO₂ temperatures at the inlet, with a delta T of 2.7°C and 2.6°C

between the temperatures measured on the clamps of the two preheaters 2.53 and 2.53 (1) and the CO₂ at the inlet when no power is supplied to the preheater.

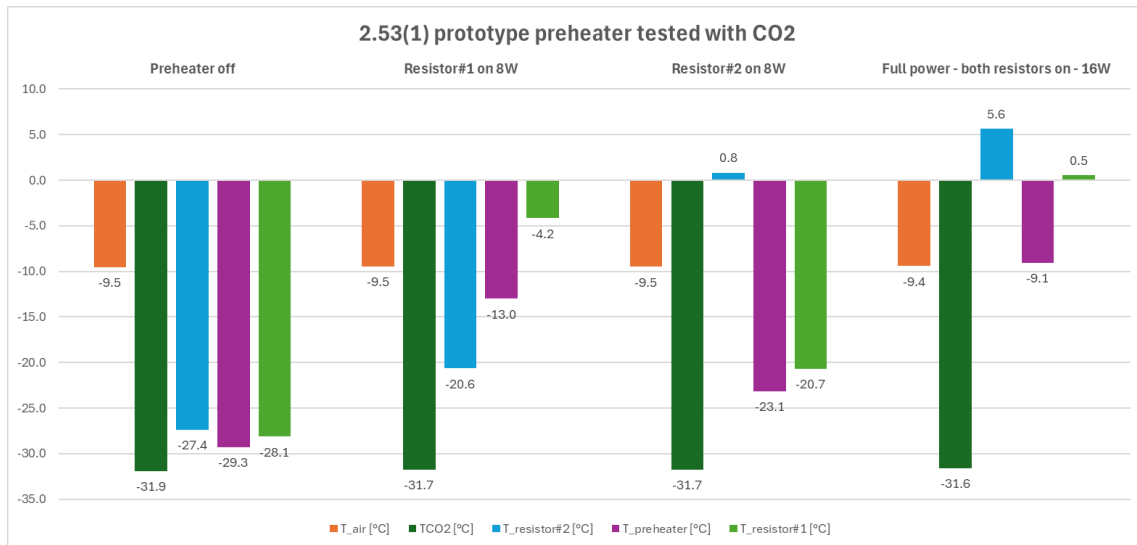


Figure 175 - Plot showing the temperatures measured in operational working conditions on the preheater 2.53 (1), in the order of power off, 8 W on the main resistor (resistor #1), 8 W on the backup resistor (resistor #2), and in full power mode, with a total of 16 W dissipated

The last preheater tested thermally using CO₂ (2.53 (2), figure 176) allows for an analysis of the importance of the sensor bonding process to the designated slot in the clamp. In this preheater, the bonding process, which has not yet been standardized for the production of preheaters in general, was not performed optimally. Traces of glue between the two clamps resulted in a significant increase in the thermal resistance of the entire component, preventing it from operating at optimal temperatures. In this case, the temperature reached 48.3°C in the clamp of the preheater, which, unlike the previous cases, is the element that reaches the highest temperatures in the assembly. This is likely due to the high thermal conductivity between the resistor and the clamp, but not between the clamp and the pipe, where heat transfer is hindered by glue residues. These residues act as insulators (since glue has low conductivity values) and impede the clamping of the preheater on the pipe, effectively negating the benefits of the ovalized hole geometry that is supposed to ensure adequate clamping on the pipe, provided that nothing is interposed between the two.

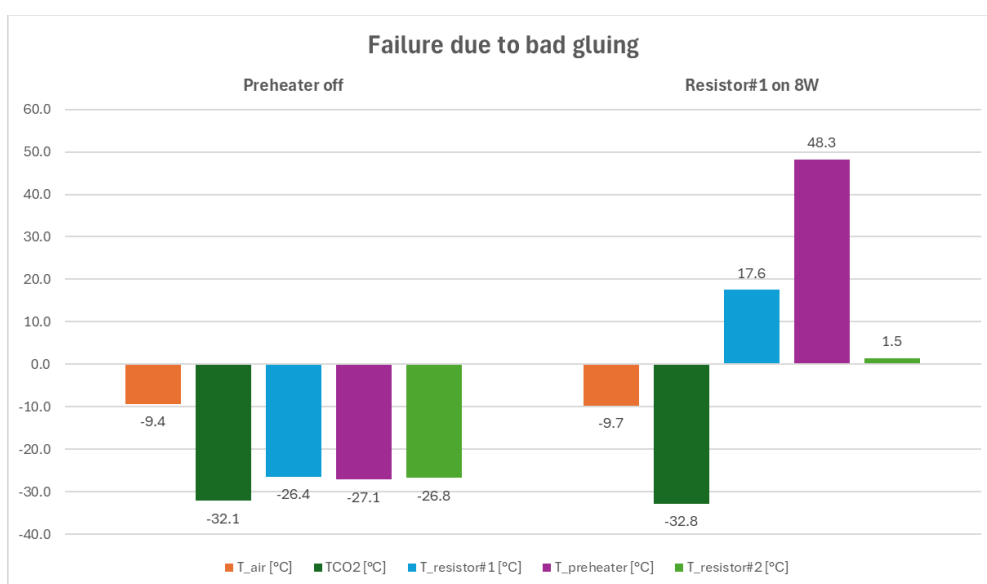


Figure 176 - Plot showing the temperatures measured in operational working conditions on the preheater 2.53 (1), in the order of power off, 8 W on the main resistor (resistor #1). Anomalous thermal contact detected due to poor gluing process.

A final test was conducted on the preheater 2.53 (1) to evaluate its operating temperatures as a function of the CO₂ temperature, which was varied by adjusting the TRACI pressure in incremental steps of 1 bar for each test. In Figure 177, the measured pressures at the inlet and outlet of the cooling loop can be observed over time, as the system's setpoint pressure and thus the pressure of the 2PACL accumulator changes. Figure 178 illustrates the temperatures measured in the preheater: in the clamp (T_{PH_clamp}), in the resistor located below (T_{PH_bottom}) and in the resistor positioned above in the assembly (T_{PH_top}). The same power of 8W was supplied to the preheater during each test. Under CO₂ temperature conditions of -31.7 °C and air temperature of -15.9°C, the preheater achieved stable operating temperatures of -6.7°C in the bottom resistor, -15.2 °C in the clamp (the only temperature effectively measured inside the detector) and -21.7 °C in the top resistor used in these tests as a backup resistor. In the case of the preheater being off, the temperature measured in the clamp, with an ambient temperature of -16.8 °C, was 1.8 °C higher than the temperature measured at the inlet. As the pressure of the TRACI accumulator increased, thus raising the CO₂ temperature at the outlet of the loop, the temperature of the preheater increased as expected, maintaining a temperature difference between the preheater and CO₂ of 16.4 °C with TRACI at 12 bar, down to 13.6 °C with TRACI at 26 bar (Figure 179), showing a nearly constant delta between the CO₂ and the maximum temperature measured on the preheater. The decreasing trend in the temperature delta between the preheater and CO₂, visible in Figure 178, is due to the variation in air temperature inside the box, which does not increase proportionally with the CO₂ temperature but increases to a lesser extent, making the system less adiabatic and enhancing the cooling effect of the air on the preheater. In fact, by comparing the two extreme cases tested with a setpoint of 12 bar and a test with a setpoint of 26 bar, it can be observed that the air temperature in stable conditions is 9.2 °C lower than the temperature of the preheater resistor in the first case, while in the second case, the air is 15.9 °C colder than the preheater in stable conditions, thereby allowing for better natural convection cooling of the preheater in the latter case.

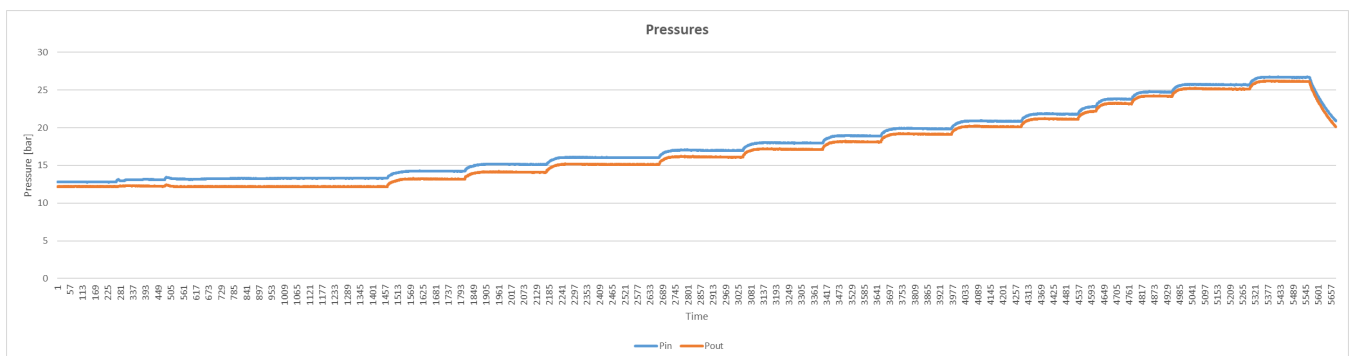


Figure 177 - Inlet and outlet pressures measured during the test in the CO₂ flow varying the setpoint pressure of the TRACI accumulator.

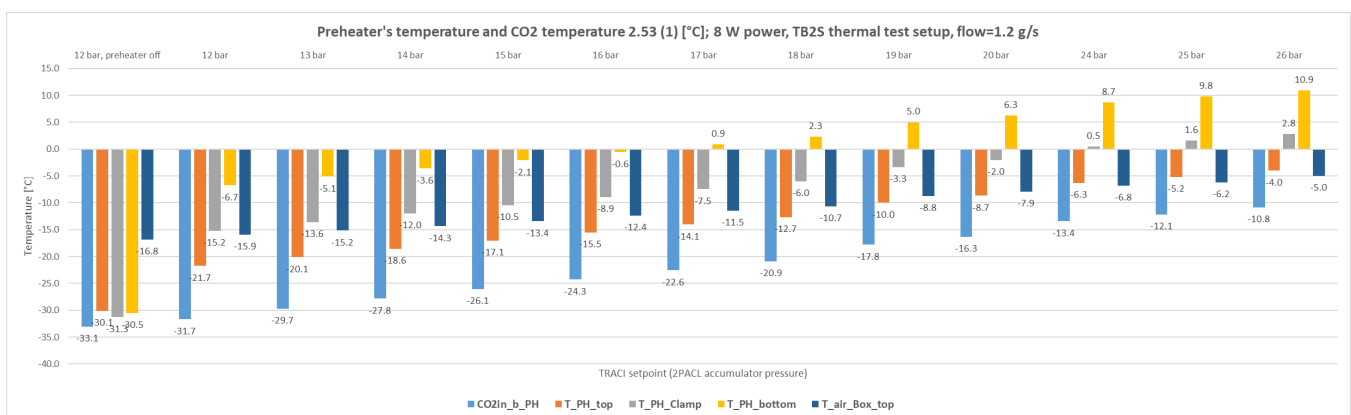


Figure 178 - Temperatures measured in the preheater 2.53 (1) during the test while varying the setpoint pressure of the TRACI accumulator, with the preheater off and during the powering of the preheater with 8 W on the bottom resistor.

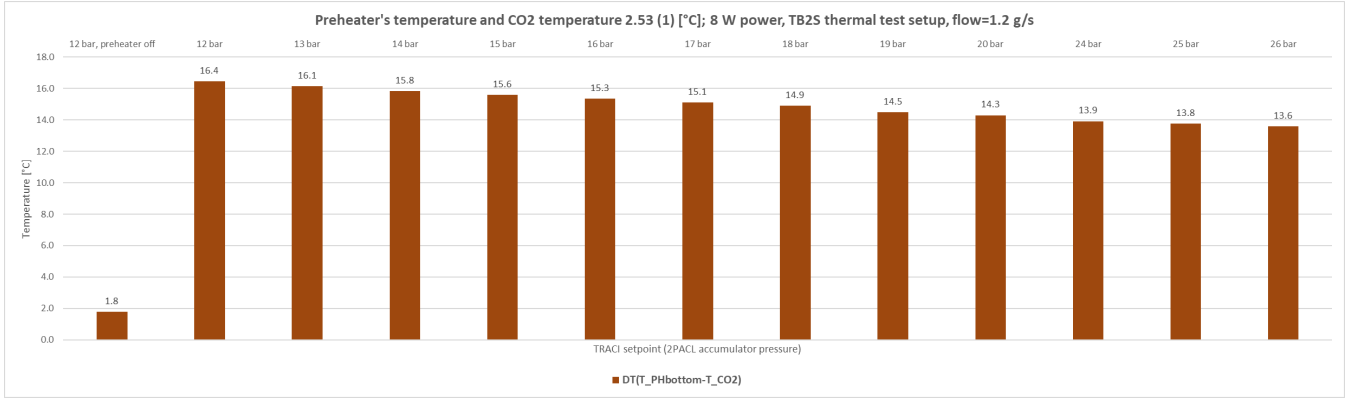


Figure 179 - Difference between the temperature measured at the bottom resistor where power is supplied (maximum temperature recorded in the component) and the temperature of the CO₂, varying the setpoint pressure of TRACI accumulator.

Finally, from Figure 180, a comparison can be made between an estimate of the preheater temperature under adiabatic conditions and the temperatures measured during this test. Considering the contact length of the preheater for this type of pipe, which is 5 mm, and the inner diameter of the pipe at 2.0 mm, it is possible to calculate the theoretical value of heat flux provided by the preheater (in which 8 W are dissipated due to the Joule effect) to the CO₂ flow, assuming adiabatic conditions for the system, meaning without any cooling of the preheater from the air. To evaluate the theoretical temperature of the preheater, we can estimate the temperature assuming perfect surface contacts (which is not always true, especially in the clamping between the preheater and pipe, as previously seen, which can be very susceptible to assembly anomalies) using the following equation:

$$T_{preheater} = T_{CO_2-inlet} + (HF \cdot R_{tot})$$

Equation 15

Where the total thermal resistance between the source of power and the heat sink, assuming perfect contact between all surfaces, can be estimated as:

$$R_{tot} = R_{clamp} + R_{pipe} + R_{CO_2} = \frac{t_{clamp}}{k_{al}} + \frac{OD/2 \cdot \ln\left(\frac{OD}{ID}\right)}{k_{CuNi}} + \frac{1}{HTC} \quad \left[\frac{m^2 \cdot K}{W} \right]$$

Equation 16

With:

- R_{clamp} , thermal resistance of the aluminium clamp (thickness, $t_{clamp}=2$ mm e thermal conductivity, $k_{al} = 237$ W/(mk)).
- R_{pipe} , thermal resistance of the 70/30 CuNi pipe (outer diameter, OD=2.5 mm; inner diameter, ID=2.0 mm; $k_{CuNi}=29$ W/(mK))
- R_{CO_2} , thermal resistance of the two-phase CO₂ flow, which is the inverse of the heat transfer coefficient (HTC). To estimate this value, which is difficult to consult in scientific literature, the HTC value measured during the testing phase of the titanium pipes of the TB2S ladders was used. At the first point at the entrance of the evaporator, where the preheater is located, under the maximum tested heat flux condition of 9700 W/m², an HTC value of approximately 14000 W/(m²·K) was measured.

As shown in Figure 180, with the assumptions described above, it is possible to predict a preheater temperature of -9.4 °C, which is not far from the experimental value of -6.7 °C measured during the test conducted on the preheater at an ambient temperature of -15.9 °C. The difference between the two values can mainly be attributed to the failure to account for the cooling of the preheater due to CO₂, the variability of the actual contact between the surfaces of the preheater and the pipe (that it's not perfect), the estimated value for the

high heat flux of the CO₂'s heat transfer coefficient (HTC) and the fact that the temperature in the preheater is measured above the resistor and not between the resistor and the clamp, as estimated by the model illustrated in equations 14 and 15. Nevertheless, the fact that the experimental temperature of the preheater is no more than 3 °C away from the theoretical temperature indicates both the good quality of the test conducted and the actual good contact of the preheater 2.53 with this ovalized hole geometry on pipes with a 2.5 mm outer diameter, created according to the technique shown in Appendix 5. If this were not the case, poor contact would have led the temperature to be significantly more than 3 °C higher than the theoretical temperature (as observed in the case of preheater 2.53(2), where an anomaly in the sensor gluing process was highlighted), calculated by assuming perfect contacts between surfaces.

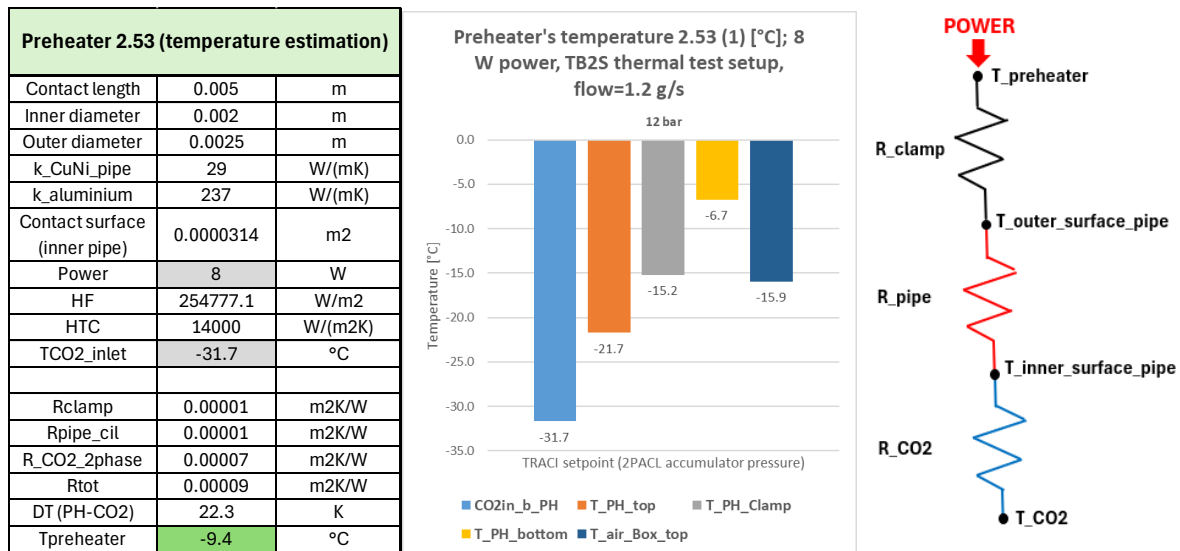


Figure 180 - Simulation of the temperature of the preheater providing 254777 W/m² of heat flux and all the others data used for the calculation (left). Temperatures measured during the testing phase in the preheater, with T_{PH_bottom}, the temperature value to be used for comparison with the simulated T_{preheater} (center). Diagram of the thermal resistances placed between T_{preheater} and T_{CO₂}, used for simulating the temperature of the component (right).

8. Conclusions

This thesis originates from the work carried out at CERN during the 14-month contract as a Technical Student. The guiding thread connecting all the topics developed in this work concerns thermal quality control activities, specifically the construction of setups and test procedures for verifying the quality of the HTC_{eq} coefficient (equation 4 and 5) for certain structures and components of the CMS tracker currently in production for the Phase 2 upgrade of the experiment, in preparation for the High Luminosity phase of the LHC accelerator. This work presents the setups developed and currently operational in the Lyon Cold Room at CERN, capable of performing thermal quality control on the TBPS tilted rings, the TB2S ladders and the preheaters. Additionally, the setup used for quality control tests on TB2S ladders has also allowed for an experimental estimation of HTC coefficients of two-phase CO_2 , supporting validation of values used in the design of structures in simulations to calculate the thermal runaway margins of the modules cooled in this part of the tracker.

Overall, quality control activities are still ongoing, utilizing the same procedures reported in this work, and will continue throughout the production phase, allowing each structure to be tested at the end of its production process. By the end of the 2023-2024 biennium, it is expected that thermal testing and qualification will have been completed for 29 TBPS rings, 2 TB2S ladders (including 1 also tested in real operating conditions, fully integrated with the 12 2S modules) and 2 validated preheater prototypes (in addition to the preheater 2.53, finalizing the design and production of the first prototype preheaters for pipes with different geometric characteristics for other sub-detectors in the Tracker is currently in progress). Furthermore, there were 3 HTC tests conducted, 2 on stainless steel pipes and 1 on titanium pipes for the TB2S sub-detector and additional tests are soon to be conducted on the Inner Tracker TFPX pipes, supported by a sufficiently flexible setup.

This thesis shows the quality control performed on the first 19 TBPS rings (section 4), where 9 anomalous cooling positions were identified out of a total of 436 analyzed (without distinguishing between rings from different layers), indicating a 2.06% anomaly rate. All tests conducted on the first 9 pre-production rings were repeated approximately 6 months later to ensure the stability of the initial rings, confirming their quality over time and the absence of significant degradation, as well as the ability of the setup to repeat the same measurements, validating the procedure used. In detail, the identified anomalies are distributed across one pre-production L3 ring, containing 2 anomalies, one L2 ring and six L1 rings, each with a single anomaly. For the identified anomalies, the temperature differences never exceeded $2^\circ C$ relative to the reference temperature used for each cooling position; these deviations, slightly above the allowed limits, make it difficult to pinpoint the exact cause of the defect. However, the setup allowed investigation of certain positions where the anomaly was “characterized”. Of these anomalies, for instance, 4 (3 in L1 rings and 1 in the L3 ring) showed DT (reference parameter used for TQC) values around $1.1^\circ C$ (with the DT limit set at $1^\circ C$). These anomalies, which do not significantly affect the overall thermal performance of the ring, were attributed to slight misalignments between the cooling adapter and the cooling plate (the latter being slightly raised), with gaps between the two below $60\ \mu m$. For gaps exceeding $60\ \mu m$ (with a maximum value identified so far in around $80\ \mu m$), the anomalies tended towards higher DT values, ranging from $1.1^\circ C$ to $1.6^\circ C$. This type of anomaly, difficult to improve upon after ring assembly, has led to improvements in the production process for future rings. Though it does not fully prevent the recurrence of this minor defect, it allows for the assembly of cooling plates of lower quality in less critical cooling loop sections, such as near the evaporator outlet, where, once the dryout is avoided, CO_2 has lower absolute temperatures, thus reducing the temperatures measured in the final modules of the loop even if they have these small anomalies. Additionally, this type of anomaly can be mitigated in the actual detector by adding a thermal filler between the actual module and the cooling plate, if necessary, to maximize the structure’s thermal performance. The other main type of anomaly was identified in an imperfect gluing process, where residual glue could cause invalidating alterations in the ring, with DT values easily exceeding $2^\circ C$, as seen with the L2 68 B3 ring, rendering the cooling position highly anomalous with significantly worsened HTC_{eq} values. However, these types of anomalies can be corrected during testing by modifying the ring structure, bringing the abnormal values to the desired levels and making the final production process TQC an essential tool for not only measuring and identifying but also actively improving each ring's thermal performance before it progresses further in its lifecycle.

Thermal quality control performed on the first two pre-production ladders (section 5) validated their cooling performance, enabling a cross-check of results obtained at CERN using two-phase CO_2 and recording the same

types of anomalies found in Pakistan, where quality control will be systematically conducted on each ladder produced (similarly to CERN's testing for TBPS rings) using deionized water as the cooling fluid. In addition, quality control identified issues in the glueing phase of the ladders' short inserts, where 5 out of 44 tested short inserts were anomalous, giving an 11.4% thermal defect rate. In all analyzed inserts, these anomalies were due to glueing process issues, with excess glue obstructing perfect contact between the heated and cooled surfaces, resulting in temperature deviations from the reference values exceeding 2°C, indicating a significant deterioration of HTC_{eq} . Careful analysis of the production process of the short insert glueing phase onto the cooling pipes will allow to control this anomaly for the next ladders produced.

The double thermal quality control on preheaters (section 7), using both a setup with single-phase silicone fluid and a two phase CO₂-based setup, validated a geometry designed to ensure proper clamping on the pipe and good heat conductivity between the heat source and heat sink, allowing for the dissipation of approximately 250 kW/m² heat flux through this component. These thermal tests conducted also in real operating conditions ensure stable and suitable operating temperatures for the preheater within the detector. Similar thermal analysis will be conducted in the coming months on new preheaters designed for pipes of different sizes and tolerances using the same ovalized hole technique developed for the preheater 2.53 analyzed in this work.

Finally, the setups developed during this period at CERN have facilitated interesting analyses on the experimental estimation of HTC coefficients for CO₂ in stainless steel and titanium pipes made for TB2S ladders (section 6). The analysis was conducted mainly to verify that the measured HTC values aligned with the HTC values of 5000 W/(m²K) used conceptually in equation 5 for CFD simulations to simulate the thermal performance of mechanical structures and to compare the thermal performance of these two materials by assessing HTC values of boiling CO₂ within the pipe. The minimum HTC values measured during tests under heat flux conditions of 9654 W/m², representative of the experiment's end-of-life conditions (where, as per equation 2, each module will dissipate not only the fixed portion of heat from electronics but also radiation damage heat in the sensor, reaching peak values at this stage), were 5299 W/(m²K) for stainless steel pipes and 6756 W/(m²K) for titanium pipes, reasonably close to the conservative simulation values of 5000 W/(m²K) used to simulate all the evaporators. Furthermore, an optimal range of vapor quality at the evaporator outlet was identified, between 35% and 45%, with 42% appearing to be a good design setpoint for the VQ at the outlet of the single cooling loop, considering two-phase CO₂ at a 12 bar saturation pressure and pipes with an internal diameter of 2.0 mm, with similar thermal behavior across materials (titanium and stainless steel) used, identifying the same HTC degradation levels with increasing vapor quality at the evaporator outlet due to the onset of dryout. Furthermore, the comparative analysis of results between stainless steel and titanium pipes shows that titanium performs equally well, if not better, than stainless steel pipes, with HTC values remaining similar under low heat flux evaporator start-of-life conditions (with average measured values of 6505 W/(m²K) for stainless steel pipes and 6210 W/(m²K) for titanium pipes). However, titanium pipes perform better at higher vapor quality values and higher heat flux, reaching 9533 W/(m²K) compared to 8046 W/(m²K) for stainless steel pipes. This finding makes titanium pipes an interesting option for the TB2S ladder upgrade, where recent preliminary thermal tests on the first prototypes in Pakistan with new titanium pipes have shown promising improvements, partially anticipated in these tests. Pressure drop values measured across the evaporator, changing pipe materials, are consistent, with titanium pipes showing a slight 0.1 bar increase in each test. In general, confirmation of these comparative studies, by repeating tests on the newly assembled ladders with the new titanium pipes also in the CERN setup, could open the possibility of using titanium for building two-phase CO₂ cooled circuits with high saturation pressures, exploiting the improved thermal and mechanical characteristics of a new generation of pipes for future upgrades in the realm of high-energy physics detectors.

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10. Appendix

- References used to position the cooling plates of the ring (numbered in the 'Positions' column according to the CO₂ flow), the dummy modules (uniquely identified with labels and numbers in the 'Module' column) and to connect them to the correct connector for both the temperature sensor readout and power supply to the module (the 'PCB' column refers to one of the four boards in the setup, and the 'Channel' column indicates the connector number on the board).

Layer 1

Position	Module	PCB	Channel
1	11	4	3
2	15	4	1
3	6	3	4
4	12	3	2
5	37	3	0
6	3	2	2
7	18	2	0
8	4	1	3
9	10	1	1
10	16	1	0
11	33	4	2
12	26	4	0
13	32	3	3
14	24	3	1
15	30	2	3
16	34	2	1
17	31	1	4
18	20	1	2

Layer 2

Position	Module	PCB	Channel
1	30	4	5
2	26	4	3
3	3	4	1
4	11	3	5
5	16	3	3
6	31	3	1
7	37	2	6
8	34	2	4
9	32	2	2
10	15	2	0
11	18	1	5
12	24	1	3
13	33	1	1
14	7	1	0
15	9	4	4
16	13	4	2

17	8	4	0
18	25	3	4
19	20	3	2
20	12	3	0
21	10	2	5
22	4	2	3
23	6	2	1
24	38	1	6
25	2	1	4
26	1	1	2

Layer 3

Position	Module	PCB	Channel
1	18	4	7
2	3	4	5
3	11	4	3
4	16	4	1
5	26	3	8
6	33	3	6
7	30	3	4
8	13	3	2
9	1	3	0
10	7	2	7
11	24	2	5
12	9	2	3
13	2	2	1
14	37	1	8
15	31	1	6
16	34	1	4
17	15	1	2
18	32	1	0
19	36	4	8
20	12	4	6
21	17	4	4
22	23	4	2
23	22	4	0
24	21	3	7
25	5	3	5
26	19	3	3
27	20	3	1
28	38	2	8
29	8	2	6
30	25	2	4
31	6	2	2
32	10	2	0
33	4	1	7
34	14	1	5
35	29	1	3
36	35	1	1

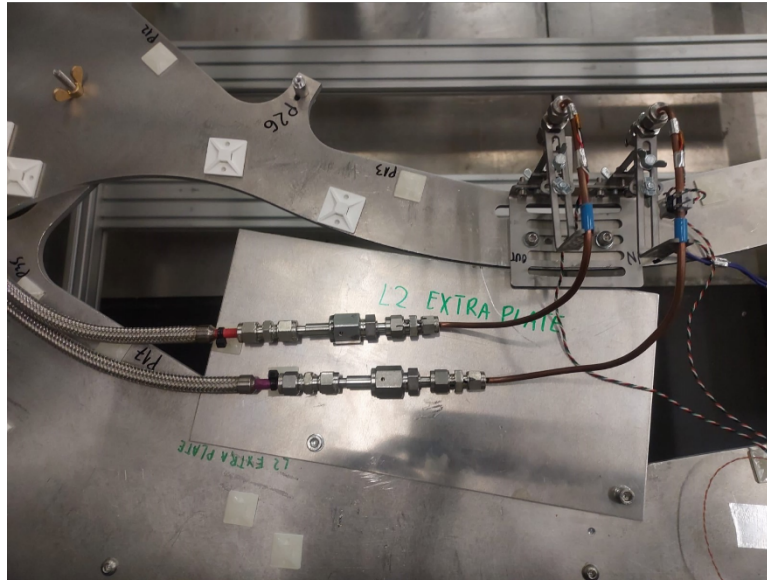
2. TBPS thermal quality control settings for CO₂ parameters and the power supply used for tests with CO₂ at +15°C and -35°C.

TBPS cooling test settings						
	L1		L2		L3	
Test temp. [°C]	+15	-35	+15	-35	+15	-35
TRACI pressure [bar a]	51	12	51	12	51	12
Flow rate [g/s]	1.4	1.4	2.0	2.0	2.7	2.7
Power per module [W]	10	10	10	10	10	10
Power in total [W]	180	180	260	260	360	360
Voltage on PS [V]	15.7	14.5	15.7	14.5	15.7	14.5
Current on PS [A]	11.5	12.6	16.7	18.1	23.0	25.2

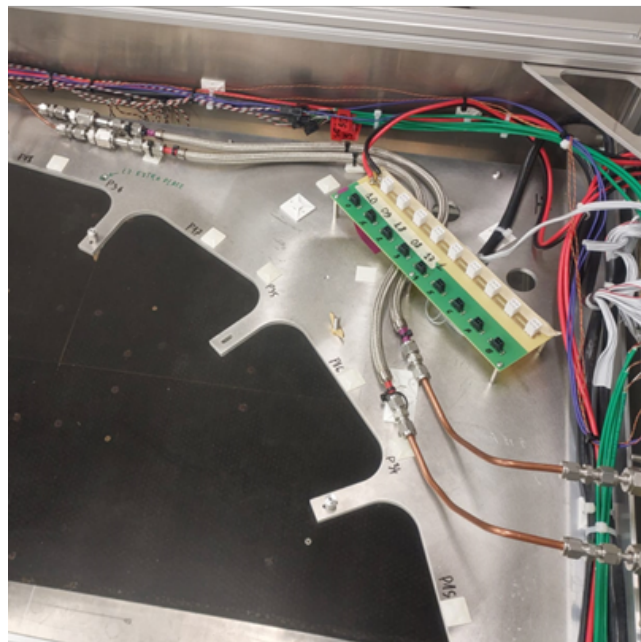
3. FLIR E75 bolometric thermal camera specifications.

SPECIFICHE				
Caratteristiche per termocamera	E53	E75	E85	E95
Risoluzione IR	240 × 180 (43.200 pixel)	320 × 240 (76.800 pixel)	384 × 288 (110.592 pixel)	464 × 348 (161.472 pixel)
UltraMax®	—	307.200 pixel	442.368 pixel	645.888 pixel
Intervallo di temperatura	da -20 °C a 120 °C (da -4 °F a 248 °F) da 0 °C a 650 °C (da 32 °F a 1200 °F)	da -20 °C a 120 °C (da -4 °F a 248 °F) da 0 °C a 650 °C (da 32 °F a 1200 °F) Opzionale da 300 °C a 1000 °C (da 572 °F a 1830 °F)	da -20 °C a 120 °C (da -4 °F a 248 °F) da 0 °C a 650 °C (da 32 °F a 1200 °F) da 300 °C a 1200 °C (da 572 °F a 2192 °F)	da -20 °C a 120 °C (da -4 °F a 248 °F) da 0 °C a 650 °C (da 32 °F a 1200 °F) da 300 °C a 1500 °C (da 572 °F a 2732 °F)
Messa a fuoco	Manuale	Continua, misuratore di distanza laser (LDM) a singolo impulso, contrasto, manuale	Continua, misuratore di distanza laser (LDM) a singolo impulso, contrasto, manuale	Continua, misuratore di distanza laser (LDM) a singolo impulso, contrasto, manuale
Campo visivo (FOV)	24° × 18°	42° × 32° (ottica 10 mm), 24° × 18° (ottica 18 mm), 14° × 10° (ottica 29 mm)	42° × 32° (ottica 10 mm), 24° × 18° (ottica 18 mm), 14° × 10° (ottica 29 mm)	42° × 32° (ottica 10 mm), 24° × 18° (ottica 18 mm), 14° × 10° (ottica 29 mm)
Identificazione ottica	—	Automatica	Automatica	Automatica
TimeLapse (infrarosso)	—	—	—	da 10 secondi a 24 ore
Misurazione area con laser	—	—	SI	SI
Misurazione distanza con laser	—	SI, su schermo	SI, su schermo	SI, su schermo
Preset di misurazione	Nessuna misurazione, punto centrale, punto caldo, punto freddo, 3 punti, punto-punto caldo*	Nessuna misurazione, punto centrale, punto caldo, punto freddo, preset utente 1; preset utente 2	Nessuna misurazione, punto centrale, punto caldo, punto freddo, preset utente 1; preset utente 2	Nessuna misurazione, punto centrale, punto caldo, punto freddo, preset utente 1; preset utente 2
Puntatore a Spot	3 in modalità dal vivo	1 in modalità dal vivo	3 in modalità dal vivo	3 in modalità dal vivo
Area	1 in modalità dal vivo	1 in modalità dal vivo	3 in modalità dal vivo	3 in modalità dal vivo
Picture-in-Picture	Area infrarosso centrata sull'immagine visiva	Ridimensionabile e mobile	Ridimensionabile e mobile	Ridimensionabile e mobile
Caratteristiche comuni		Memorizzazione immagini		
Tipo e pitch sensore	Microbolometro non raffreddato, 17 µm	Supporto di memorizzazione SD Card rimovibile (8 GB)		
Sensibilità termica/NETD	<0,04 °C a 30 °C (86 °F), ottica 24°	Formato file immagine Standard JPEG con dati di misura inclusi		
Banda spettrale	7,5 - 14,0 µm	Registrazione video e streaming		
Frequenza immagine	30 Hz	Registrazione video IR radiometrico	Registrazione radiometrica in tempo reale (.csq)	
Numero F	f/1,3l, ottica 24°	Video IR non radiometrico o nel visibile	H.264 su scheda di memoria	
Zoom digitale	1-4x continuo	Streaming video IR radiometrico	SI, su USB o Wi-Fi	
Streaming video IR non radiometrico		Streaming video IR non radiometrico	H.264 o MPEG-4 su Wi-Fi; MJPEG su UVC o Wi-Fi	
Modalità e presentazione immagini		Interfacce di comunicazione	USB 2.0, Bluetooth, Wi-Fi, DisplayPort	
Display	LCD touch screen da 4", 640 × 480 con rotazione automatica	Uscita video	DisplayPort su USB Tipo-C	
Fotocamera digitale	5 MP, FOV 53° × 41°	Ulteriori specifiche		
Tavolozze colori	Ferro, Grigio, Arcobaleno, Artico, Lava, Arcobaleno Alto contrasto	Tipo batteria	Batteria agli ioni di litio, ricaricabile nella termocamera o con un caricatore separato	
Modalità immagine	Infrarosso, nel visibile, MSX®, Picture-in-Picture	Autonomia della batteria	Circa 2,5 ore con temperatura ambiente di 25 °C (77 °F) e in condizioni di utilizzo tipiche	
MSX®	Sovrappone i dettagli del visibile sull'immagine termica	Gamma di temperatura d'esercizio	da -15 °C a 50 °C (da 5 °F a 122 °F)	
Misure e analisi		Gamma di temperatura di stoccaggio	da -40 °C a 70 °C (da -40 °F a 158 °F)	
Accuratezza	±2 °C (±3,6 °F) o ±2% della lettura, per temperatura ambiente da 15 °C a 35 °C (da 59 °F a 95 °F) e temperatura oggetto sopra +0 °C (32 °F)	Impatti/Vibrazioni/Protezione; Sicurezza	25 g / IEC 60068-2-27, 2 g / IEC 60068-2-6, IP 54 / IEC 60529; EN/UL/CSA/PSE 60950-1	
Allarmi	Allarme umidità, allarme isolamento, allarmi misura	Peso/dimensioni	1 kg, 27,8 × 11,6 × 11,3 cm	
Allarme colore (isoterma)	Sopra/Sotto/intervallo/condensa/isolamento	Contenuto della confezione		
Bussola, GPS	SI, aggiunta automatica di tag di geolocalizzazione GPS nell'immagine	Termocamera con ottica, batteria (2 pz), caricatori, protezione anteriore, fasce (mano e polso), Custodia rigida, laccetti, copriobiettivo, panno per pulire le lenti, alimentatori, SD card 8 GB, giravite Torx, cavi da USB 2.0 A a USB tipo-C, da USB Tipo-C a USB Tipo-C, da USB Tipo-C a HDMI)		
METERLINK®	SI; molteplici letture			
Puntatore laser	SI; tasto dedicato			
*Misurazione Delta tra punto caldo e punto centrale				
Le specifiche sono soggette a modifiche senza preavviso. Per le specifiche più aggiornate, visitate www.flir.com				

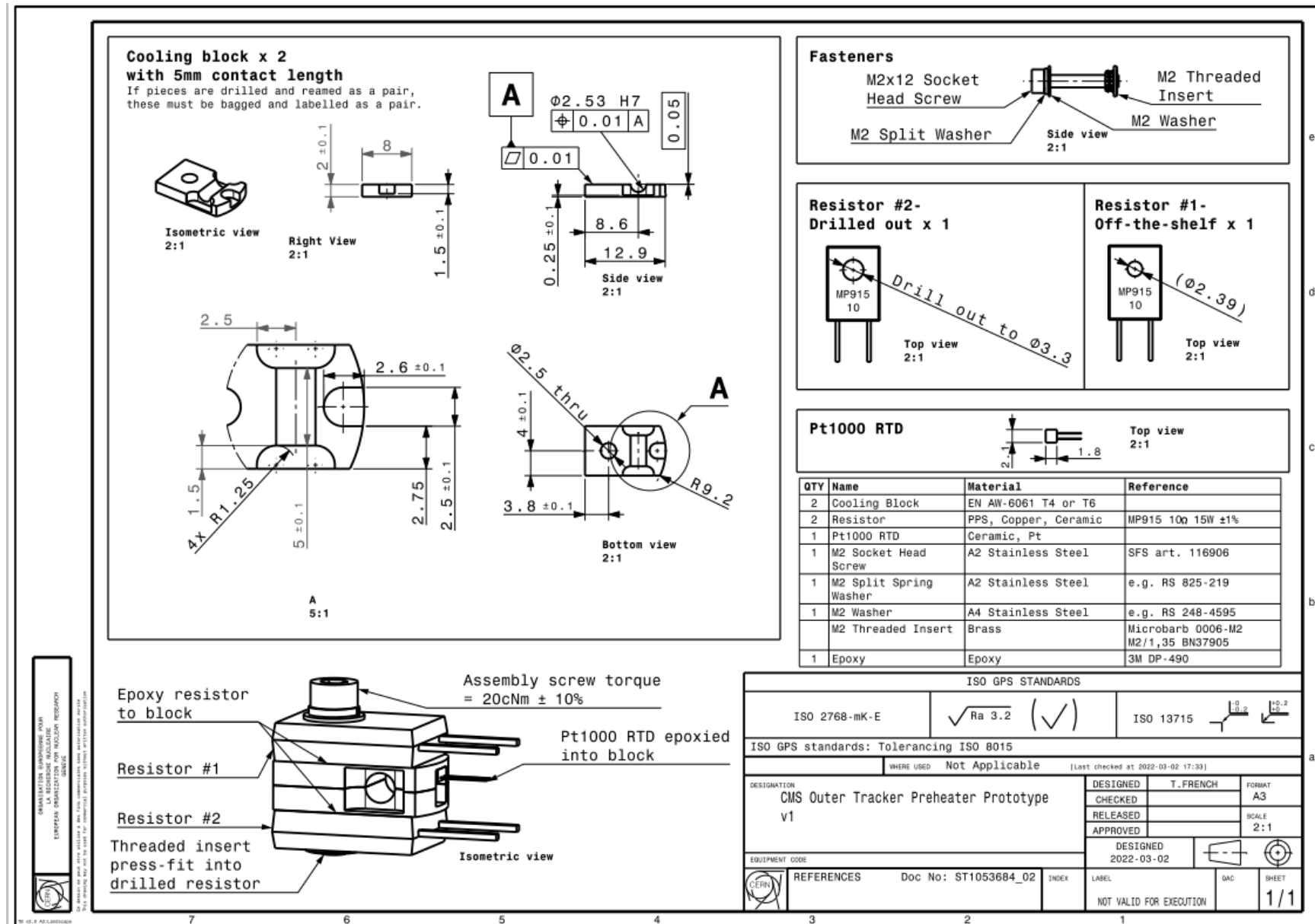
4. Additional parts for Layer 2 and Layer 3 TBPS test setup
 - a. L2 extra plate:



- b) Copper pipe extension for L3:



5. CMS Outer Tracker Preheater Prototype v1 (drawing)



11. Annex

1. TBPS thermal test support drawings: <https://edms.cern.ch/document/3019505>
2. TBPS cooling test ring assembly procedure using TBPS thermal test support: <https://edms.cern.ch/document/2999713>
3. CMS Phase 2 – “Annex_3 Thermal QC results of the Tilted TBPS pre-production rings (second tests round)”: 4, <https://indico.cern.ch/e/1358376>
4. Excel document attached to this report: “Annex_4 TBPS tilted rings TQC outcomes 16-10-2024”
Overview of the data obtained from the quality control tests conducted on the rings as of 10/16/2024, the date of drafting this document. In the attached Excel file, you can evaluate:
 - A. In Sheet 1: the control parameters processed for each test conducted on each ring.
 - B. In Sheets 2 and 3: the absolute temperatures measured during the tests at +15°C and -35°C.
 - C. In Sheets 4 and 5: the difference assessed between the measured temperature of the "dummy modules" and the temperature of the interpolating line (parameter DT).
5. Excel document attached to this report: “ANNEX_5 HTC results stainless steel vs titanium pipes for TB2S June24 tests”.
6. Excel document attached to this report: “ANNEX_6 HTC results stainless steel pipes for TB2S, second test October24”.

12. Acknowledgments

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