

Design and Commissioning of a Temperature-Controlled Readout Station for CMS 2S Modules

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Nick Thamm

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First examiner: PD. Dr. Oliver Pooth

Second examiner: Prof. Lutz Feld

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1. Introduction

In particle physics the focus of research is aimed at understanding the fundamental properties of the constituents, which make up matter and radiation. Using particle accelerators, large collaborations of physicists try to prove the Standard Model and test predictions made by new theories. The largest particle accelerator is the Large Hadron Collider (LHC) located at the European Council for Nuclear Research (CERN) in Geneva, Switzerland. It is located in a 27 km long tunnel about 100 m below earth's surface and is able to produce a center of mass energy for protons of 14 TeV. It enabled to collect experimental evidence of the Higgs Boson by colliding protons and confirmed the corresponding theory established in 1964. Even though the Standard Model is widely accepted and successful in explaining the major discoveries of the current state of research, some aspects remain unanswered. These aspects include the existence of dark matter and the fact that there are neutrinos that are not massless.

Data is collected by experiments like the Compact Muon Solenoid (CMS), which is located in a cavern underground. Its subdetectors form cylindrical layers around the beam pipe, in which the protons travel at about the speed of light, and each layer contributes in their own way to the physics results of the measurement, by measuring the particles momentum or kinetic energy.

However, currently the experiments at LHC are reaching their limits in terms of radiation damage and have to be replaced in the so called Phase-2 Upgrade. Starting in 2024, the LHC will be upgraded to the High Luminosity LHC, which is planned to produce an integrated luminosity of 3000 fb^{-1} until 2038, ten times higher, than the goal of the last run. This will enable high precision measurements through a lot more statistics.

The increase in luminosity however imposes multiple problems on the experiments, as up to 200 simultaneous interactions would be too many to be differentiated by the current design and read-out. Also the increase in flux of particles through the detector requires detectors with a much higher radiation tolerance.

In the context of the Phase-2 Upgrade, the CMS Tracker, the innermost subdetector, will be completely replaced. The Outer Tracker (OT) will be replaced with a concept consisting of two different modules, the PS and 2S modules. Both types consist of a two silicon sensor design and will later contribute to the trigger scheme of the whole detector

using information generated on each module. This will vastly decrease the amount of data, which has to be read out and stored by the data acquisition electronics.

As a part of the global CMS community, the RWTH Aachen University will be one of the German assembly centers and contribute about 1000 2S modules. During the module prototyping phase, individual modules have to be tested regarding their performance under operational conditions at temperatures as low as -35°C . Therefore, a dedicated station is needed, which provides an easy way of conducting several tests, like temperature cycling, read-out and irradiation with particles.

This thesis will start with a short introduction into the LHC accelerator and the CMS experiment in chapter 2 and its Phase-2 upgrade in chapter 3. In chapter 4 a concept for a temperature-controlled read-out station is presented and its performance is shown in chapter 5. The following chapter 6 contains first measurements on the first functional prototype assembled in Aachen including measurements of the silicon sensor properties and the noise behavior of the read-out chips under varying temperature.

2. The Compact muon solenoid at CERN

Interactions between particles are induced by colliding them with velocities close to the speed of light. The fundamental interactions taking place between those particles are observed by measuring and analyzing their decay products using particle detectors. Many particle physics experiments require high center-of-mass energies and large amounts of interactions to reach the energy-regions, where specific particles can be observed and to make high precision measurements possible.

The following chapter introduces the LHC [1], located at the CERN site in Geneva, Switzerland, which is by now the largest circular particle accelerator build by human hand. The chapter further explains the operating principle of CMS experiment, which contributed alongside ATLAS to the discovery of the Higgs boson in July 2012, one of the major discoveries of modern particles physics [2, 3].

2.1. The Large Hadron Collider

The LHC collider is a 27 km long ring located in a tunnel about 50 m to 175 m underground. Its main construction is made of two separate high vacuum beam pipes, each of which contains one beam of particles that go in opposite directions. Radiofrequency cavities generate an alternating field of 400 MHz allowing for a further acceleration of the particles to a center of mass energy of $\sqrt{s} = 14$ TeV. 1232 superconducting dipole magnets with a field strength of 8.3 T are used to bend the movement direction of the beams making use of the Lorentz force. To keep the beam profile small, 392 quadrupole magnets focus and defocus the beam along its way. Higher orders of magnet configurations yield minute corrections to further improve beam shape and alignment [4].

One particle beam is comprised of $N_b = 2808$ so called bunches, which contain about $n = 10^{11}$ particles each. These beams, with a diameter in X and Y direction of about $\sigma = 16 \mu\text{m}$, are collided at a bunch crossing rate of $f = 40$ MHz yielding a theoretical

2. The Compact muon solenoid at CERN

luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, following Equation 2.1.

$$L = \frac{n_1 n_2 f N_b}{4\pi \sigma_x \sigma_y} \quad (2.1)$$

In the operation of the LHC, a luminosity of $2.06 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ could be achieved with a total integrated luminosity of 50 fb^{-1} of recorded data [5]. A schematic view of the LHC and its pre-accelerators is shown in Figure 2.1.

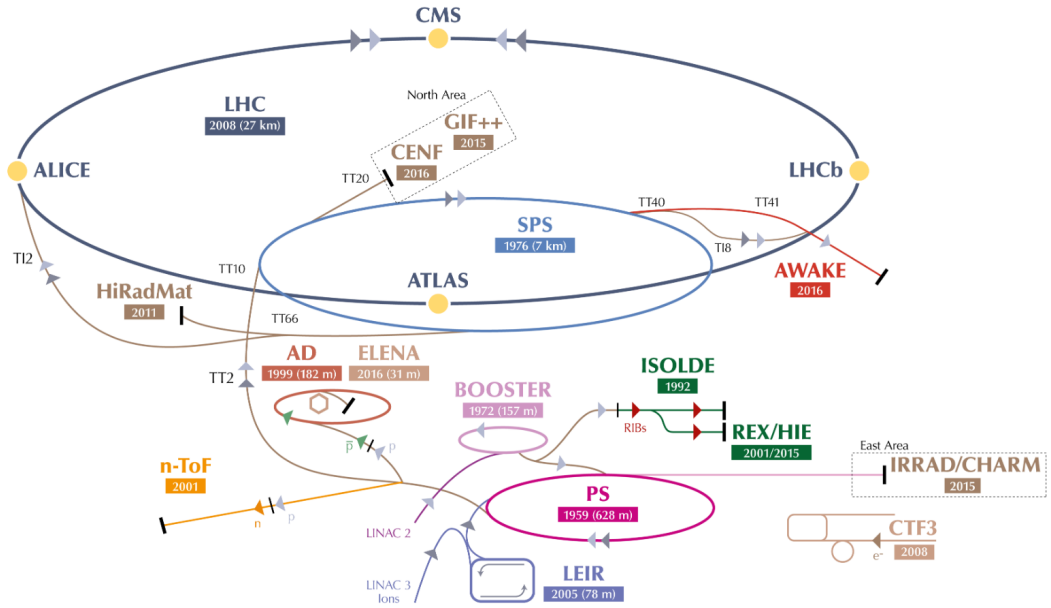


Figure 2.1.: Schematic view of the LHC accelerator complex and its pre-accelerators. The four largest experiments ATLAS, ALICE, LHCb and CMS are shown in their position along the beam-pipe [6].

2.2. The Compact Muon Solenoid experiment

The Compact Muon Solenoid (CMS) is a multi-purpose particle detector and, besides ATLAS, LHCb and ALICE, one of the four large experiments located at CERN. The CMS detector's size is relatively compact with a diameter of 15 m and length of 21 m in comparison to the ATLAS experiment, although being considerably heavier with a weight of approximately 14 000 t [7]. Whereas the first part of the name of the CMS experiment is derived from its size, the second part results from its strong focus on

precisely measuring muons, which pass through the whole detector. The bending magnet inside the detector is a solenoid, being the last part of the name giving convention. CMS consists of multiple layers of subdetectors built around the LHC-beam pipe, which all contribute to a specific part in the detection of high energy particles. Overall the experiment consists of six distinct layers, four of which are active parts of the detection of particles while the other two are passive ones that give structure, enhanced efficiency and increased physics capabilities. Each active layer is composed of a barrel around the beam pipe and an endcap located at either side, giving the CMS a cylindrical shape. Figure 2.2 illustrates the structure of the six CMS layers:

- Tracker
- Electromagnetic calorimeter
- Hadronic calorimeter
- Magnet (passive)
- Muon detectors
- Return yoke (passive)

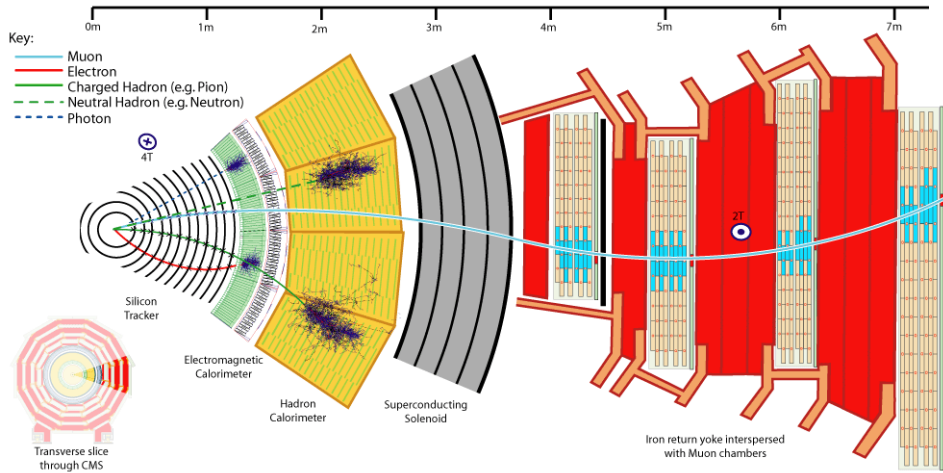


Figure 2.2.: Schematic view of a slice of the CMS detector [8]. All particles pass through the tracking detector and get stopped in the respective calorimeter. The muons pass through the whole detector and leave a track with varying curvature, as they get past the solenoid magnet, where the direction of the magnetic field changes.

2.2.1. Tracker

The innermost layer, the tracking detector, detects the bend traces of charged particles going through with high spacial resolution to allow the reconstruction of secondary vertices close to the initial interaction point. The innermost layer itself consists of two sublayers, namely the silicon pixel detector and the silicon strip detector. Overall the tracking detector of the CMS experiment features about 75 million individual read-out channels, that take care of a position measurement accurate up to $10\,\mu\text{m}$ [9].

2.2.2. Electromagnetic and hadronic calorimeter

The CMS calorimeter is divided into two separate detectors. Constructed of lead-tungstate crystals (PbWO_4), the electromagnetic calorimeter (ECAL) is aimed to measure the energy of electrons, positrons and photons. The kinetic energy of the particles is converted into scintillation photons, which are detected by Avalanche photodiodes (APDs) [10] and vacuum phototriodes in the barrel and endcap region respectively. Hadrons are stopped in the hadronic calorimeter (HCAL), which is made of layers of brass and plastic scintillators. The hadrons interact strongly in the dense brass material and the subsequent showers produce scintillation photons in the plastic scintillators. Via wavelength shifting fibers embedded in the scintillator, the photons are guided towards Silicon Photomultipliers (SiPMs) [11].

2.2.3. Magnet and return yoke

The superconducting solenoid magnet takes passively part in the measurements, as it provides a magnetic field of about 3.8 T to bend the traces of charged particles. It is made from Niobium-Titanium superconductor operated at 4.5 K using liquid helium cooling. With a maximum current of about 19 kA, approximately 2.6 GJ of energy are stored [4]. The magnetic field lines go along the beam pipe and in the opposite direction on the outside of the magnet. With the magnetic field strength and direction known, the momentum and charge of any throughgoing charged particle can be determined. An iron return yoke forms the magnetic field lines inside the detector and acts as a carrying structure for the various subsystems. Its weight of about 12 500 t makes up most of the overall weight of the detector.

2.2.4. Muon detectors

The outer layers target the detection of muons, which pass through all the previous layers. Multiple different mechanical designs for the muon chambers are used, such as Cathode Strip Chambers (CSC), Drift Tubes (DT) and Resistive Plate Chambers (RPC) to detect the muons and yield valuable trigger information for the data acquisition.

2.2.5. Trigger and Data Acquisition

All the subsystems of the CMS experiment measure about 1 MB of data per event at a total rate of 600 million events per second [12]. As it is not possible to read out and store data for each event, a trigger system has to be deployed, to filter out the physically interesting events. The so called Level-1 trigger (L1), implemented in hardware, bases its decision on data from the calorimeters and muon chambers to reduce the total amount of events down to a rate of 100 kHz [13]. The High-Level-Trigger (HLT), implemented in software, further reduces the data down to a rate of about 300 Hz by also using data from other subdetectors like the tracker [14].

3. High Luminosity LHC

Starting in 2024, various components of the LHC will be upgraded to form the High Luminosity LHC (HL-LHC). This update will enable deriving further insight into the Standard Model of physics via precision measurements, which require more statistics and thus a higher amount of particle interactions. The upgrade is aimed to increase the instantaneous luminosity to about $L = 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. To achieve this, new 11 T to 12 T superconducting dipole magnets, cavities and various other parts will be installed. A detailed schedule is shown in the Appendix A.

3.1. CMS Phase-2 Tracker Upgrade

In the course of the conversion the LHC to the HL-LHC, the CMS experiment will also be updated. The upgraded CMS allows coping with the much higher amount of particle flux. With a larger amount of flux, the number of simultaneous particle interactions observed in one bunch crossing, called pile-up, is also increased. Part of this upgrade is the Tracker upgrade, which is going to completely replace the existing Tracker detector, both Inner (IT) and Outer Tracker (OT). For the innermost layers an exposure of about $2.3 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ 1 MeV neutron equivalent fluence is expected, being about one order of magnitude higher than the values for the current tracking detector [15]. Thus, the new tracking modules have to have an increased radiation tolerance to operate under these conditions. Higher granularity ensures that the detector can deal with the increased pile-up rate of 140-200 by increasing the tracking efficiency and reducing occupancy. The coverage of the tracking volume will be increased to pseudo rapidity regions up to $|\eta| = 4$ [15]. Figure 3.1 shows the structure of a quarter of the full tracker in cylindrical coordinates as well as the pseudo rapidity coverage.

3.1.1. OT modules and trigger information

The new OT modules will consist of a stack of two single sided silicon sensor-plates at a known distance. This stack will enable including tracking data into the L1 trigger system. On-board electronics evaluate the passage of a particle through the sensor plates. The

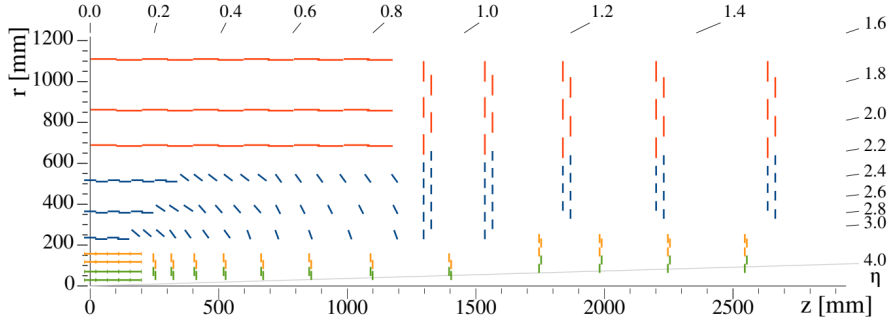


Figure 3.1.: Drawing of a quarter slice through the CMS experiment. The inner tracker modules are colored green and yellow, the outer tracker ones blue and red. New to the geometry are slanted modules [15].

initial hit in the first sensor-plate seeds the algorithm to decide, if a 'stub' is valid or not. A valid stub will be formed if the particle of the initial hit passes through a window of acceptance on the second plate. This acceptance window is correlated to the transverse momentum p_T of the particles, as their tracks are bend by the solenoid magnetic field. Particles that do not pass through the acceptance window form an invalid stub[15]. The concept of stub triggering is visualized in Figure 3.2.

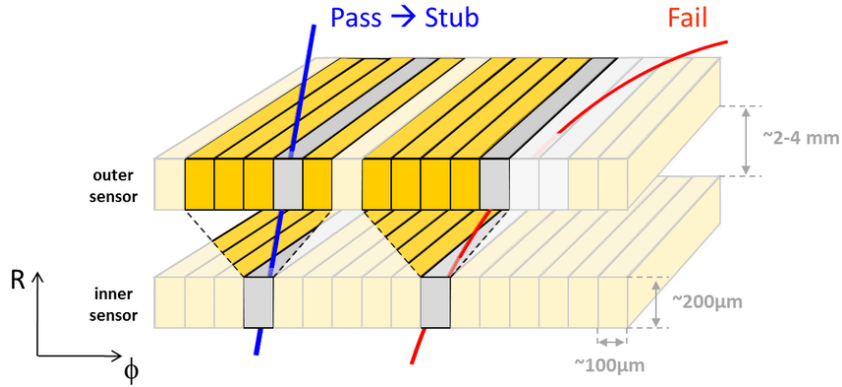


Figure 3.2.: Sketch of the stub trigger mechanism. Particles of high transverse momentum, form a stub by passing an acceptance window (non-transparent strips) due to their small track curvature. Slow particles create tracks with larger curvature and thus can not hit the acceptance window (transparent strips), forming an invalid stub. The stub information gets forwarded to the track finding trigger deciding on a read-out [16].

The OT will be composed of two different kinds of modules. Closer to the beam pipe will be the PS modules, which consist of a stack of a macro-pixel sensor and a strip sensor, at three different spacing distances 1.6 mm, 2.6 mm and 4 mm. The 2S modules are made up of a stack of two strip sensors and will come in two different spacing distances, 1.8 mm and 4 mm. In total 5616 PS and 7680 2S modules will be installed in the OT [15].

3.1.2. RWTH Aachen's contribution to the Phase-2 upgrade.

The RWTH Aachen University will be one of the German module assembly centers and will provide about 1000 2S modules, which will be installed in the tracker endcaps. Other manufacturing contributors are located in Belgium, India, Pakistan and the USA. Construction will start mid 2021, once all the final components are available. In the currently ongoing prototyping phase, which will last until the end of 2020, the assembly procedures are developed, tools for the series production designed and the functionality of individual modules are tested concerning functionality and mechanical specifications.

3.2. The 2S module

The 2S module is one of the two designs used in the upcoming Outer Tracker. Its construction is shown in Figure 3.3. The individual components making up a functional module are described in the following.

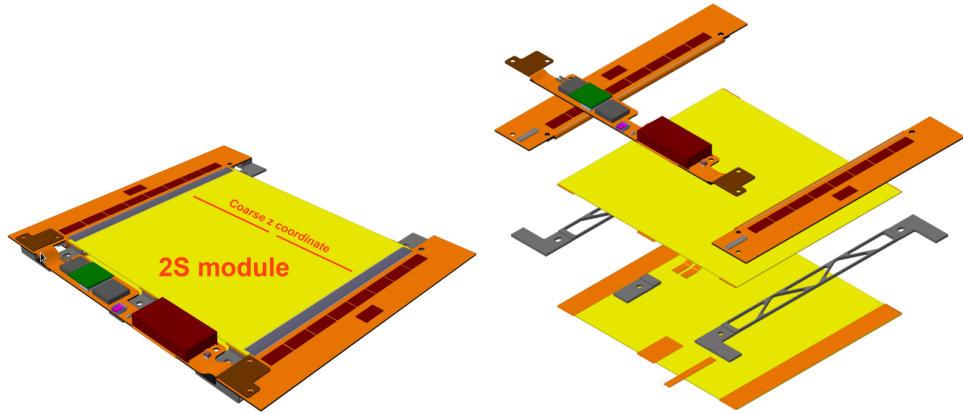


Figure 3.3.: CAD drawing of a 2S module in an assembled (left) and exploded (right) view. Each module consists of mainly four components: Sensor plates, Al-CF bridges, Frontend and Service Hybrid [15].

3.2.1. Silicon strip sensors

Each sensor features an active area of about $10\text{ cm} \times 10\text{ cm}$, which is divided into two halves. On each half are 1016 strips with a length of 5 cm. The strips are $25\text{ }\mu\text{m}$ wide with a pitch of $90\text{ }\mu\text{m}$. Capacitive coupling prevents the flow of leakage current through the read-out electronics. The sensor material is chosen to be n-in-p-doped silicon as it features less dependency of the irradiation on the charge collection efficiency, as it is seen in p-in-n-doped silicon materials [15, 17]. No final decision on the sensor thickness was done until now, but the sensor thickness will range between $200\text{ }\mu\text{m}$ and $320\text{ }\mu\text{m}$. The sensor thickness will in turn decide the value of the depletion voltage used in the experiment. For unirradiated sensors of the above thickness, the operational voltage is aimed to be between 150 V and 300 V. High voltage is supplied via high voltage (HV) pigtails, which are a small flexible circuits glued to the backside of the sensor and wire bonded directly to the aluminum backside. One of the two pigtails features a thermistor, which can be used to monitor the sensor temperature.

3.2.2. Al-CF-Bridges

To ensure the correct spacing between the sensor plates, the two sensor-plates are glued to Aluminum Carbon fiber composite (Al-CF) bridges. Insulation between the aluminum backside and the Al-CF material is achieved through small strips of Kapton with a thickness of $25\text{ }\mu\text{m}$. The Al-CF material is chosen as it has a very similar Coefficient of Thermal Expansion (CTE) as silicon. A large mismatch in CTE could lead to breaking module components due to mechanical stress arising from temperatures different to the temperature at the assembly stage. Depending on the spacing of the module, different sets of bridges are used that are optimized to mechanical strength with respect to weight [15]. Besides providing mechanical stability to the overall module, they also act as mounting points for the read-out electronics to the module and mounting points of the module itself to the larger cooling structures of the tracker assembly. Each module features three bridges, two larger ones on either side and a so called stub bridge in the center on one side. As shown in Figure 3.4 this yields five contact points to the cooling structure.

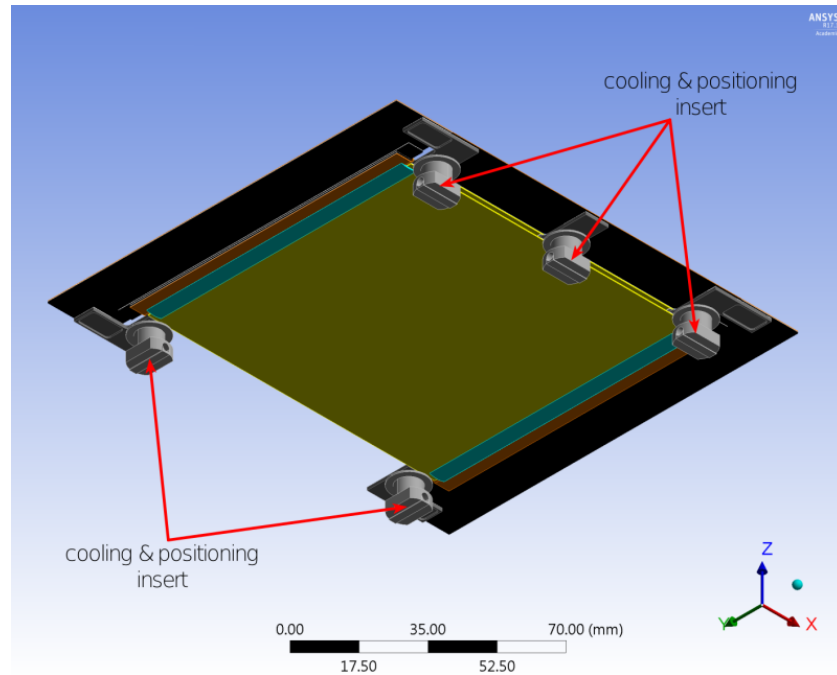


Figure 3.4.: Underside of 2S module with the posts, called inserts, on which they are mounted for thermal contact [15].

3.2.3. Frontend Hybrid

Frontend Hybrids (FEHs), flexible printed circuit boards, are glued onto those bridges. The electrical connection between the individual sensor strips and the frontend chips on the hybrids is made by wedge wirebonding. The FEH consists of a high density, four-layer polyimide circuit board, which is laminated to a carbon fiber stiffener with 500 μm thickness. Each FEH connects to 2032 silicon strips, 1016 strips from the upper and lower sensor each. Therefore the bond-pads are aligned in two rows, of which one is folded over to the back side of the FEH. The FEH features eight CMS Binary Chips (CBCs), performing the analog-to-digital read-out and the stub hit correlation of 254 strips each (127 from each sensor-plate) [18]. The CBC forwards the stub data to the Concentrator integrated circuit (CIC), which is also located on the FEH. The CIC compresses the information thus preparing the data to be send out to the data acquisition. Currently, this chip is still under development, so the prototype FEHs are read out directly via a flex-PCB flap and an additional read-out card.

3.2.4. Service Hybrid

Communication with the data acquisition (DAQ) is managed over the Service Hybrid (SEH), which is located between both FEHs. The SEH is composed of a polyimide circuit board and carbon fiber stiffener, similar to the structure of the FEH. It acts as a service station, providing an interface via fibers to the DAQ and low and high voltage to the digital read-out electronics and sensors. The fiber interface is the Versatile Transceiver plus (VTRx+), which is supplied with data from the Low power Gigabit Transceiver (LpGBT) that serializes the input from both CICs on the module. It is capable of controlling the front-end electronics via I^2C interfaces and distributing clock and trigger signals. Each module will be powered with a 11 V line. DC-DC converters generate the individual voltages for the electronics. The connection between FEH and SEH is achieved over high precision miniature connectors.

In the current prototyping phase, the LpGBT is not yet available, so the SEH features a Gigabit Transceiver (GBTx) and Short Strip Asic (SSA) chip located on a 'balcony'. The SEH also features a stub connector for the external high voltage connection, which will also be provided by the CERN facilities.

3.2.5. Cooling and thermal performance

Overall the Outer Tracker electronics will dissipate about 100 kW of heat. At the high amounts of power, thermal runaway could occur. The thermal runaway temperature characterizes the temperature at which the temperature increase induced by the sensor leakage current creates a positive feedback loop with the increasing flow of leakage current due to its exponential temperature dependency. To avoid a thermal runaway, which is expected to be between -21.6°C and -23.4°C , a two-phase CO_2 cooling system will be installed, which features a coolant temperature of -35°C .

Due to the two-phase nature of the cooling concept, the warmest module will be located at the beginning of the cooling loop, as the cooling efficiency increases with more heat introduced to the cooling loop. Prior to the prototyping phase of the 2S module assembly, the thermal performance was modeled using Finite Element Analysis (FEA) in ANSYS using a simplified CAD model [15].

Table 3.1 shows the power consumption of the main electronics components located on the 2S module.

Component	Power consumption [mW]
2 x 8 CBCs	2188
2 CICs	625
LpGBT	500
VTRx+	306
DC-DC converters	1770
Total	5389

Table 3.1.: Thermal load of the frontend components modeled in the thermal Finite Element Analysis (FEA) of the 2S module [15].

The heat produced by the silicon sensors at room temperature due to leakage current after irradiation is given by

$$P^{RT} = \alpha \cdot \Phi \cdot V \cdot U,$$

with α being the damage constant, Φ the expected fluence in 1 MeV neutron equivalents per square centimeter obtained from FLUKA simulations for a given module type at the worst case location in the volume of the Outer Tracker for a certain integrated luminosity, V the active sensor volume and U the bias voltage [15].

For the expected fluences shown in Table 3.2 of integrated luminosity, three different scenarios are studied:

1. Integrated luminosity of 3000 fb^{-1} , nominal heat loads, bias voltage of 600 V, $\alpha = 5.35 \text{ A cm}^{-1}$ with an uncertainty of $\pm 10\%$,
2. As 1., but with $V = 800 \text{ V}$ and $\alpha = 6.16 \text{ A cm}^{-1}$,
3. As 2., but with an integrated luminosity 4000 fb^{-1} .

Module type	Sub-detector	Fluence [$1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$]
1.8 mm	TB2S	2.3
1.8 mm	TEDD	2.2
4.0 mm	TEDD	3.0

Table 3.2.: Fluence for 2S modules used for the thermal FEA. TB2S specifies the Tracker Barrel region, while TEDD describes the Tracker Endcaps [15].

In Figure 3.5, the performance for the three scenarios simulated for a 1.8 mm module located in the Tracker Endcap is illustrated.

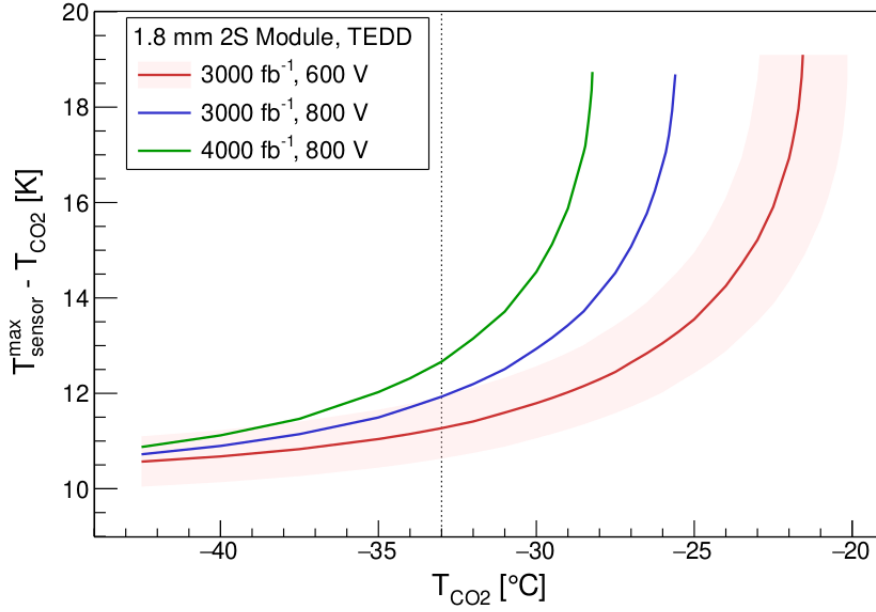


Figure 3.5.: Simulated runaway of a 1.8 mm tracker endcap module [15].

The heat generated by the leakage current of the silicon sensor has to be calculated using [19]

$$I(T) \propto T^2 \cdot e^{-\frac{E_{ef}}{2k_B T}}. \quad (3.1)$$

The leakage current I depends on the silicon temperature T , with the Boltzmann constant k_B and an effective energy bandgap E_{ef} . In the worst-case-scenario, one silicon sensor is expected to produce about 0.3 W of heat. In total the sum of all heat loads of an end of life 2S module is predicted to be about 6 W. This value was used as an estimate for the design of the read-out station, which will be introduced in the following chapter.

4. Read-out box

4.1. Design

In the prototyping phase of the CMS 2S tracker modules, individual modules have to be tested in a temperature-controlled environment in order to detect design flaws and test module functionality at operational temperature. Due to the design of the CO₂ cooling loops in the Phase-2 CMS Outer Tracker, the warmest modules, which are the first ones in each cooling loop, will be operated at a temperature of -33°C . Along the cooling pipe, the modules get colder, as more CO₂ gets close to the phase change and thus the cooling power is increased [15]. A nominal coolant temperature of -35°C is desired over the length of the whole cooling pipe in the final detector and set as a constraint for the single module test case. In order to avoid the formation of dew on sensitive components due to the low temperature, and thus the risk of damage, the modules have to be operated in a dry air atmosphere.

Besides these two requirements concerning temperature and relative humidity in a read-out box, other important aspects in designing a case for the read-out of the 2S modules were:

- Safe mounting procedure: Since the sensors and stiffeners are very fragile, a safe mounting option is required, which reduces the risk of breaking the module.
- Small footprint: As all the read-out electronics for the 2S module are located in a standard 19" rack, it was decided to also locate the case inside the rack to reduce the amount of required laboratory space and simplify cable management.
- Ease of use: As the setup consists of many smaller components, a unified way of operating is desirable.
- Future-proof design: The layout of the FEHs and the read-out electronics are rapidly developing and continuously changing, so the case is designed in such a way that it allows adapting to all versions with only minor changes.

- Measurements with particles: To check the performance of the prototype modules not only with noise measurements, but also with incident particles, trigger detectors should be included in the case.
- Dark environment: Since the detector modules are sensitive to light, the whole case has to be light tight in order to avoid unwanted illumination of the detector.
- Full module read-out: To be able to test the whole read-out chain of an early prototype 2S module, the read-out of both FEHs is desirable.

In the following, the main design choices to achieve the set requirements are explained.

4.1.1. Mechanics

Clamping

In the final CMS detector, each module is mounted to so-called inserts, which have direct contact to the cooling pipe, as illustrated in Figure 3.4. To simplify the handling of the 2S module during encapsulation, each module is mounted to an aluminum carrier plate, which is also used for storage and transportation after the completed assembly. A picture of the first functional 8CBC2 1.8 mm module from the RWTH Aachen University mounted on its aluminum carrier frame [20] is shown in Figure 4.1.

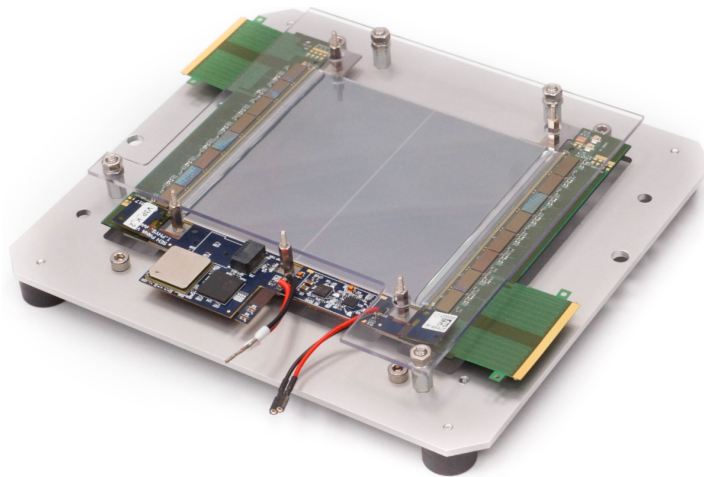


Figure 4.1.: Image of the first functional 8CBC2 1.8 mm module assembled in Aachen [20]. It is mounted to the aluminum carrier frame, which is used for handling and transportation.

The cooler geometry is designed to contact the whole carrier plate for mounting in order to avoid handling the module directly. Thermal contact between the aluminum plate and the cooler is achieved via toggle clamps, which apply even pressure to the plate down onto the cooler. The inner assembly is shown in Figure 4.2.

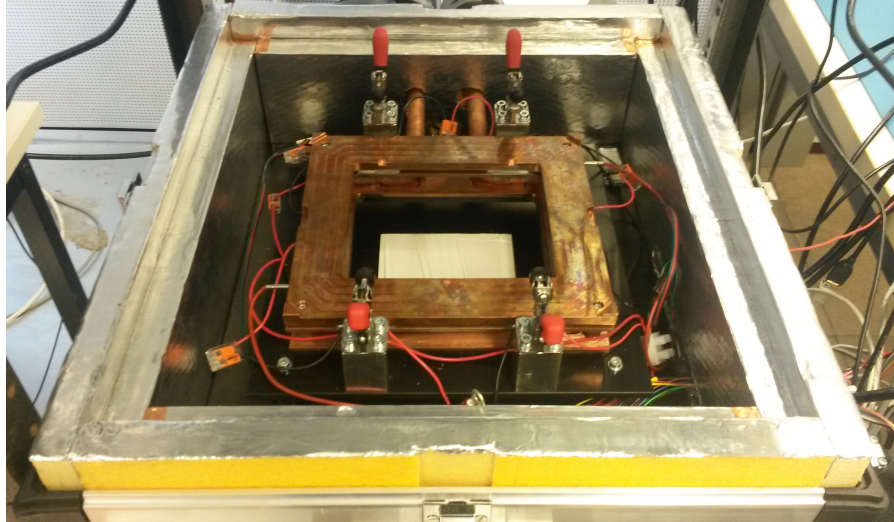


Figure 4.2.: Picture of the internals of the case. Four toggle clamps clamp the aluminum carrier frame down onto the heatspreader. In the center the scintillator is visible, which is wrapped in white teflon tape.

Size

The current version of FEHs, 8CBC2, are not directly connected to the SEH, so they have to be read out individually over an external read-out PCB. Each FEH connects to the read-out PCB via a short flexible flap of the FEH. The cables used to connect a FEH read-out PCB to the read-out electronics come in the Very-High-Density Cable Interconnect (VHDCI) standard and are stiff and short. The length is limited to 1 m to retain signal quality, as operation with longer cables would be impossible due to external noise. Therefore the FEH read-out PCB is installed vertically to the aluminum carrier frame, on which the 2S modules are mounted. Two different brackets were designed to hold the PCB in place and provide a strain relief for the flex cable of the 8CBC2-FEH. For rapid prototyping a 3D printed version was used. Later in the measurements, they were replaced by aluminum brackets to provide a better ground connection for the electronics. Pictures of both version are shown in Figure 4.3, a picture of the read-out PCB installed to the carrier frame is shown in Figure 4.4.



Figure 4.3.: On the left the 3D printed 8CBC2 right angle bracket is shown. The right picture shows the aluminum version, which was later used to improve grounding connections and reduce noise.

The strain relief is necessary, as the small amount of torque produced by the bending of the flex PCB could potentially break the Al-CF-bridges. With respect to future design changes of the FEHs and SEHs, the case has been designed large enough to also house all known upcoming versions, but small enough to still fit inside the 19" rack. This includes various SEH layouts, the 8CBC3-FEH with a Universal Interface Board version 2 (UIB v2) read-out and the CIC mezzanine, which will be the first use case of the CIC chip. A CAD drawing of the 8CBC2 and 8CBC3 read-out chains are shown in Figure 4.5.

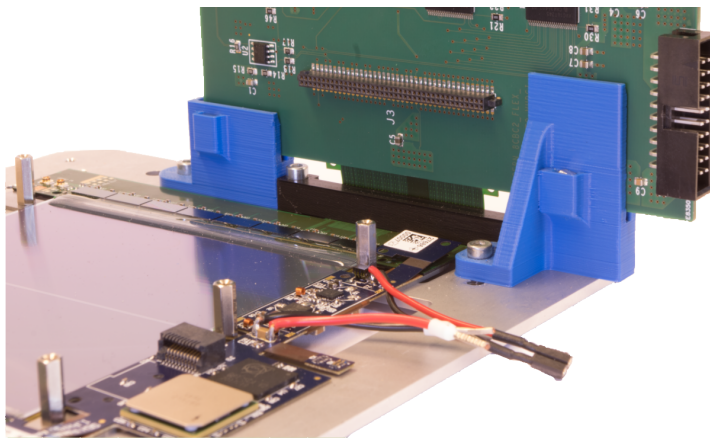


Figure 4.4.: Picture of the 3D printed read-out PCB mount (blue) installed to the aluminum carrier. The strain relief, the black bar, clamps the flexible 8CBC2-FEH connector to avoid breaking the Al-CF bridge.

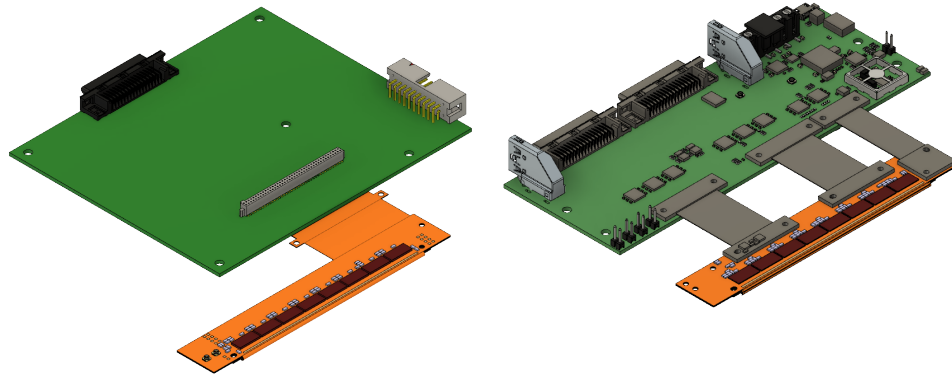


Figure 4.5.: On the left one can see a CAD drawing of a 8CBC2-hybrid, connected to its interface PCB. A VHDCI cable connects to the black connector opposite to the connection side of the hybrid. The right drawing shows 8CBC3-hybrid connected to the Universal Interface Board Version 2 via three small flex connectors. The same approach of a rectangular attachment to the aluminum carrier frame can be used as it was done by the 8CBC2 version. The CIC mezzanine will use two of the three connectors on the 8CBC3 hybrid and replace the UIB, giving it a smaller footprint.

Case profiles and insulation

The outer shell is made of aluminum profiles specifically designed for the construction of aluminum cases [21]. It features slits on the edges for mounting walls, which in this case are made of a stack of two sheets of 1 mm aluminum with a 6 mm polystyrene insulation layer in between. To provide additional insulation against the room temperature inside the lab, 40 mm extruded polystyrene with a low thermal conductivity of $\lambda = 0.033 \text{ W m}^{-1} \text{ K}^{-1}$ is used as an internal casing. This casing is also lined with aluminum foil to prevent polystyrene dust from falling onto the module sensor. Two cut-outs are placed in the lid to let the read-out PCBs stick out for an easy connection. A picture of the outer shell is shown in Figure 4.6.

Dry air

Before any module can be cooled in the read-out box, it is crucial to check the dew point inside the box. With falling temperatures, dew can form on surfaces with temperatures lower than the dew point temperature of the air. Due to the high voltage applied to the 2S modules, liquid forming on the electronics can result in shorts that may destroy

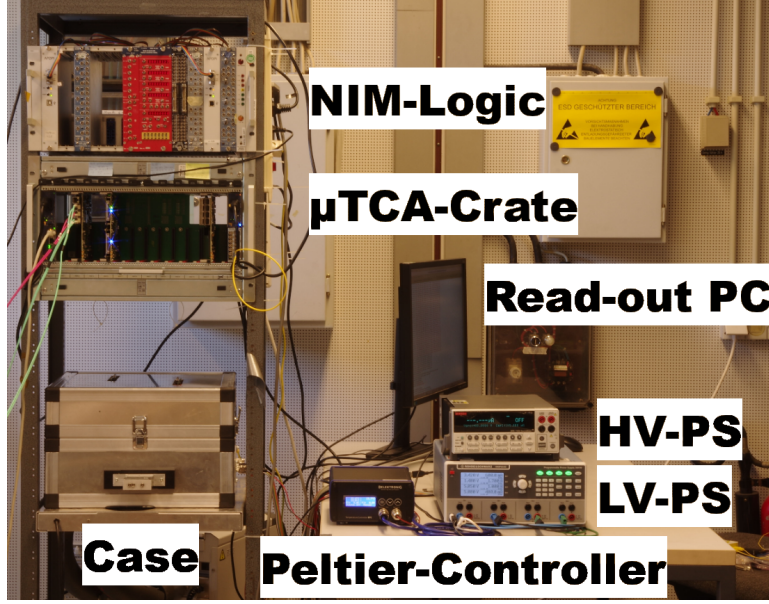


Figure 4.6.: Picture of the complete setup with the external electronics. The liquid chiller is located behind the rack.

the detector module. Dry air is introduced into the case via an entrance hole on the back side and regulated through a needle valve. It is supplied by a SPX Hankison DKC 9 Desiccant Dryer [22], which is installed in the laboratory space. According to the datasheet, a pressure dew point of -40°C at a nominal input air pressure of 7 bar and temperature of 35°C is provided, which equals a dew point at atmospheric pressure of about -56.7°C according to the Equation 4.1

$$T_{dp} = \frac{c\gamma_m(T, RH)}{b - \gamma_m(T, RH)} \quad (4.1)$$

$$\text{where } \gamma_m = \ln \left(P \frac{RH}{100} \exp \left(\frac{bT}{c + T} \right) \right). \quad (4.2)$$

T defines the air temperature, RH the relative humidity in the air and P the air pressure relative to atmospheric pressure [23]. The constants b and c depend on the underlying model acquired from measurements. For this calculation, the constants from the National Oceanic and Atmospheric Administration (NOAA) are used with $b = 17.67$ and $c = 243.5^{\circ}\text{C}$ [24]. Conversion charts from temperature, humidity and air pressure to the corresponding dew point is shown in Figure 4.7.

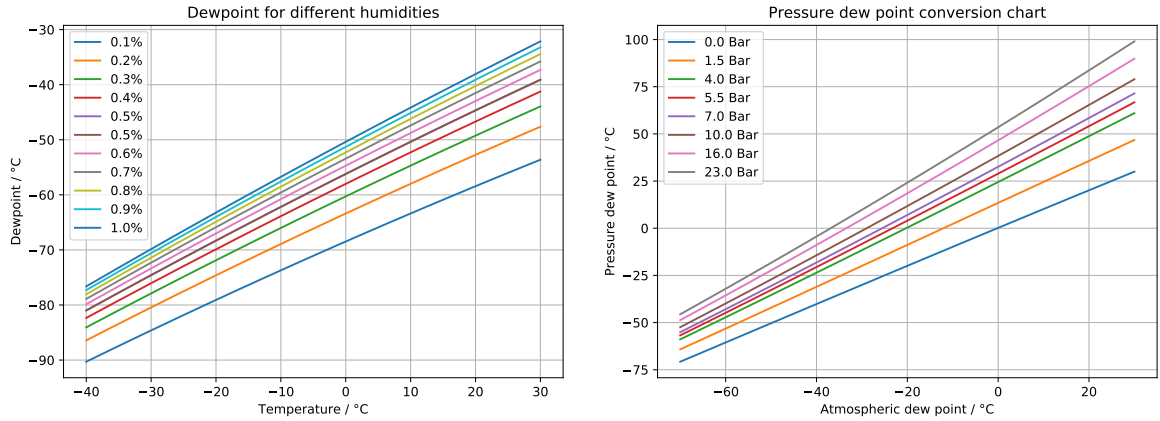


Figure 4.7.: On the left one can see the calculated dew point using the temperature and humidity, which can be measured by digital sensors. On the right one can see a conversion chart to convert pressure dew point values to dew point values at atmospheric pressure. The pressure dew point of -40°C provided by the desiccant dryer equals a dew point of -56.7°C .

4.1.2. Patch panel

The final 2S modules can be operated using three external attachments, a glass fiber pair, a low voltage and a high voltage cable. Besides these connections, the patch panel for a read-out case will have to feature the possibility to connect auxiliary voltages for additional read-out hardware during prototyping, connections for sensors and the possibility to power the cooling electronics inside the case. To protect the module from wrongly applied settings, the plugs are chosen to be different in their pin-count or shape. A detailed picture of the patch panel can be found in Figure 4.8.

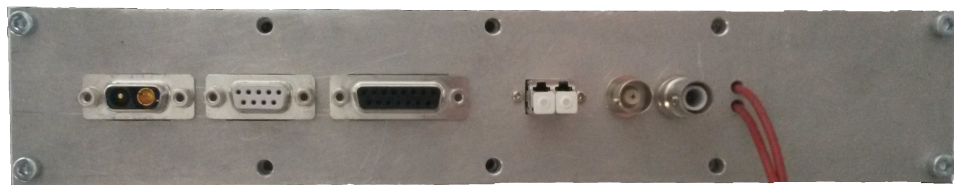


Figure 4.8.: Picture of the patch panel. The connectors from left to right are: High Current D-Sub2 (Peltier supply), D-Sub9 (auxiliary voltage), D-Sub15 (sensors), fiber inlet (optical communication), BNC (low voltage), SHV (high voltage), inlet for temperature sensors (Peltier controller).

4.1.3. Cooling

Liquid

The 2S module will produce a heat load of approximately 6 W in an irradiated state, which is removed by a two stage cooling concept. The first stage of the cooling concept consists of a circulating chiller, which uses a water-glycol-mixture as coolant. For this setup the chiller FL601 from Julabo [25] is used, as it was already existing in the local lab. It features a minimum coolant temperature of -20°C with a maximum cooling power of 200 W at that temperature, read from the data-sheet in Appendix C. As a coolant 'WS K hlsolkonzentrat N'-coolant concentrate is used, which contains additives against bacteria buildup and corrosion to keep the system clean. A dilution of 60/40 % concentrate/deionized water ensures a viscosity, low enough for the internal pump of the chiller to handle while avoiding freezing of the coolant inside the tempering bath.

The chiller is attached to a custom liquid cooler made of 16 mm inner diameter copper tubing and 3 mm copper plates. For a better thermal connection the copper tubing is soldered directly to the upper copper plate. A picture of the assembly can be found in Figure 4.9. A custom solution is chosen to precisely match the dimensions of the 2S module carrier frame, while also featuring a hole in the center to allow for measurements with radioactive sources, which would be blocked by a copper layer.

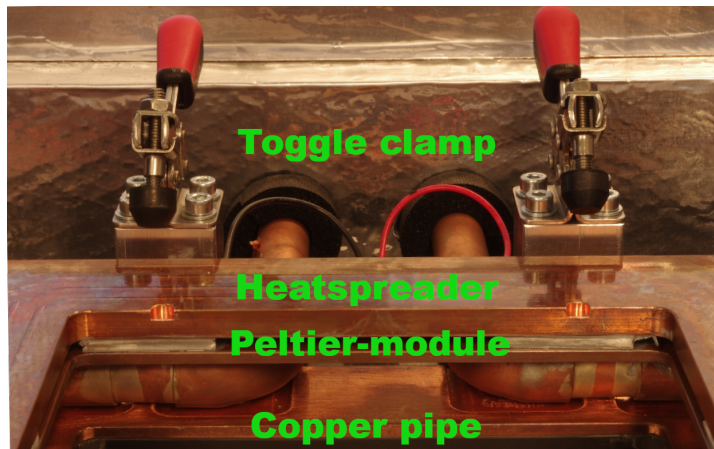


Figure 4.9.: In the picture, one can see the structure of the copper cooler used in the read-out station. The copper pipe is soldered to a copper plate, which interfaces the Peltier-modules (white rectangles).

The chiller is attached to the copper cooler via PVC piping, which is insulated using 20 mm ARMAFLEX foam tube insulation.

Electric cooling

In order to reach the desired temperature of -35°C , a remaining temperature difference of -15°C from the chiller minimum temperature has to be overcome. Six Thermoelectric coolers (TECs) TEC1-12706 made by CUI Inc. are used, which are mounted with thermal grease to the copper cooler plate. The TECs are 6 A rated modules, operating at 15.4 V. However, these are the maximum ratings provided by the manufacturer and they should only be operated at 70% maximum current [26]. 90 % maximum current is acceptable for short term operation. This yields 5.4 A modules operating at about 14 V. On top of the TECs a second copper plate is placed that acts as a heatspreader. This plate is screwed down with four nylon screws to ensure adequate mounting pressure to the TECs.

TECs are made from two ceramic plates, between which junctions of semiconductors are soldered. They transfer heat from one ceramic plate to another. The side, from which heat is moved away is called 'cold side', the other side is called 'hot side'. The direction of electric polarity determines the direction of heatflow, reversing polarity also reverses the heat-flux direction. This means, TECs only generate a temperature-difference, depending on the applied current. TECs are based on the so-called Peltier-effect, thus they are sometimes called Peltier-modules. The TEC efficiency ceases for higher temperature differences between both sides [27]. The inner resistance of TECs depends on their temperature, so their efficiency also drops as the hot side temperature decreases.

These devices are sensitive to rapid changes in temperature as the inner structures break under the thermal stress. Also driving them without a linear current source could damage them, as varying currents (ripple) cause varying temperature differences. Therefore, a special Peltier-module driver is used. The Belektronig BTC-LAB-A20 [28] is a PID-based temperature controller with an output-power of 270 W. The 270 W output-power are achieved by 27 V at 10 A, and can be used to heat or cool by reversing polarity of the output voltage. It features a temperature resolution and control accuracy of 0.1°C and uses two PT1000 temperatures sensors to monitor the temperature. The PT1000 temperature sensors are mounted with thermal grease in holes on the heatspreader to give an accurate reading of the heatspreader temperature, which is not affected by the incoming dry air flow.

Two parallel chains, with three modules in series each, are formed to be able to use the whole 270 W of electrical power provided by the Peltier-controller. So each module can be operated with 13.5 V at 5 A.

Estimation of cooling power

The bottleneck of the cooling chain is the Julabo chiller. Its 200 W of cooling power are already dominated by the 270 W electrical power provided by the Peltier-controller and limit the overall cooling capabilities of the assembly. In this section, the approximations made to estimate the cooling power of the whole setup are explained.

The incoming heat from the surroundings of the case are approximated using a room temperature of 25 °C and an internal case temperature of −35 °C which yields a temperature difference of $\Delta T = 60$ °C. The size of the case is measured in the CAD drawing and amounts to 400 mm × 430 mm × 250 mm which equals a surface area of $A = 0.76$ m². Wall thickness is estimated to be in total $l = 46$ mm. This includes the interior polystyrene case and the polystyrene lining inside the case walls. Any aluminum cladding is neglected, as it has a much higher thermal conductivity coefficient. Using the thermal conductivity coefficient of extruded polystyrene $\lambda = 0.033$ W m^{−1} K^{−1} [29] the heatflow into the case from outside can be calculated using

$$Q = \frac{A \cdot \lambda \cdot \Delta T}{l}.$$

This adds up to a heatload of about 32 W from the environment. Other heatloads have to be considered for the prototyping phase, as the different FEH-versions are not read out over the SEH. So for the FEH read-out PCB or the Universal Interface Board about 20 W are considered, 10 W per side. Later in the final state these electronics are not necessary anymore, reducing the heatload even further. The sum of all heats shown in Table 4.1 is equally divided between the six Peltier-modules, with one module having to cool about 10 W.

Device	load
Irradiated module	6 W
Environment	32 W
Additional electronics	20 W
Sum	58 W

Table 4.1.: Assumption of all heatloads inside the case. Additional read-out electronics for the different prototypes are considered for the overall design with a heatload of about 20 W. These include the 8CBC2 read-out PCB or later the Universal Interface Board for the 8CBC3-hybrid.

Peltier-modules however produce heat themselves while holding a temperature difference. As the cooling efficiency drops at lower temperatures at the hot side of the

module, their efficiency has to be approximated. Using the two characteristic lines of cooling power at a certain temperature difference provided in the data-sheet in Appendix C, a linear interpolation of their cooling capabilities, shown in Figure 4.10, was done. Two values are read of assuming a reading-error of about 1 W. From the two datapoints, the slopes for a linear function are calculated for the worst and best case scenarios. The hot side temperature of -20°C , which is the minimum temperature of the chiller, is used as a reference point for the operation of the TECs. The sum of heat introduced to the upper cooling plate and the heat produced by the Peltier-modules has to be smaller than the cooling capabilities of the chiller.

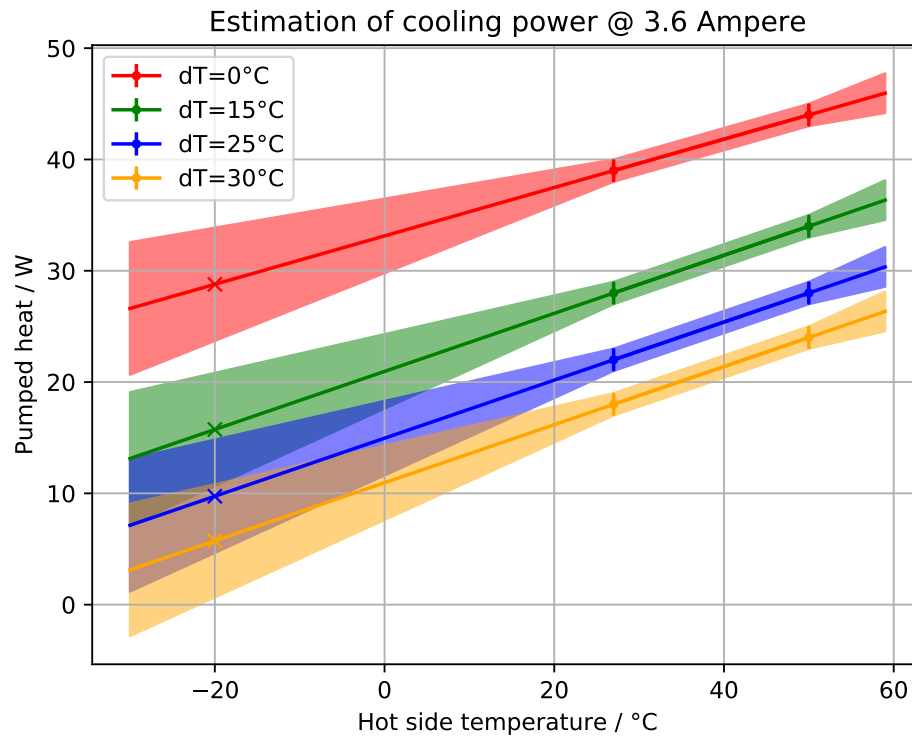


Figure 4.10.: Linear interpolation of the two data points provided by the manufacturer. The cooling power at -20°C on the hot Peltier side is estimated to about 10 W at an input current of 3.6 A. This includes a reading error from the data-sheet of 1 W and a worst case interpolation. The point marked with the cross is the hot side temperature of -20°C provided by the chiller.

The Peltier-modules generate about 19 W of heat while holding the temperature difference of 15 °C and constantly removing 10 W. Thus the total amount of cooling power needed to chill all six modules is 174 W, which is below the 200 W cooling capacity of the chiller.

4.1.4. Scintillator trigger

Inside the case, one scintillator is placed underneath the cooling unit to provide a trigger detector for incoming particles. This detector is based on the Muon Track fast Tag (MTT) [30] technology developed at the RWTH Aachen University and features a BC 404 plastic scintillator read out with two Silicon Photomultipliers (SiPMs) on a small PCB. A second scintillator housed in a plastic case can be mounted on top of the case, a schematic view can be found in Figure 4.11.

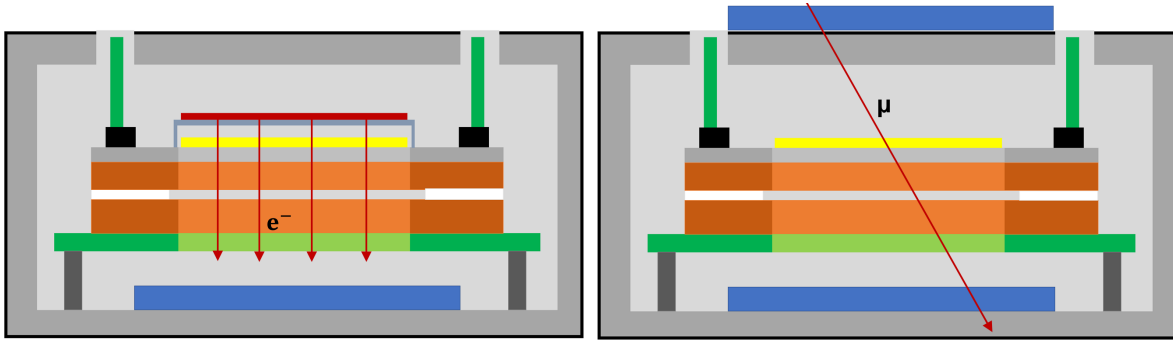


Figure 4.11.: Schematic view of the read-out case with an installed 2S module (yellow) and the trigger scintillator (blue). The red arrows indicate the incident particle. The copper cooler is depicted as the brown rectangles.

This enables a self-triggered module read-out based on particle tracks, which have passed through the 2S module. Either beta-sources can be brought close to the 2S module or muons can be used as trigger particles.

4.2. Read-out electronics

For a module read-out of a 2S module, various external electronics have to be used. The following sections explain the whole chain of read-out electronics required and their use will be explained.

4.2.1. FC7

The FC7 is a multi-purpose Field Programmable Gate Array (FPGA) Advanced Mezzanine Card (AMC) card build specifically for Micro TCA (μ TCA) crates [31] and the main data acquisition board for the prototyping phase. Its main FPGA is a XILINX KINTEX 7 FPGA, which serves as a platform for two FPGA Mezzanine Card (FMC) slots, which can be used to connect a variety of different input-output devices. The firmware, named μ DTC [32], former d19c, is stored on microSD cards and can be loaded via a PC connected to the μ TCA crate. Depending on the version of the module that is read out, the firmware has to be reconfigured, as the various FEHs require different FMC adaptors. This is done through the program Vivado provided by XILINX and additional user-scripts.

The 8CBC2-FEH requires one VHDCI FMC, which interfaces with the FEH read-out PCB. The read-out PCB is required, as the CIC chip is currently under development and not available for the 8CBC2-FEH and so the event-data has to be read from the FEH directly. A full module read-out can be achieved using two FMCs and one FC7. For later versions with the CBC3 chip, other FMCs are required, to interface with the UIB as the pin assignment changes. This UIB requires two VHDCI connections, so two FC7 boards are required for the complete read-out of a 8CBC3 module.

4.2.2. AMC13

The AMC13 [33] is a clock, timing and DAQ service module for the 13th AMC slot in a μ TCA-crate [34]. It is constructed of a stack of three PCBs, with the labels T1, T2 and T3. Its latest version, the AMC13XG, supports a ten gigabit optical fiber and backplane interface. Besides the optical fiber inputs, it can also be accessed via LEMO connections, which are mounted on the optional T3 card. In this application, the AMC13 is used as a trigger board, which converts incoming triggers in the form of TTL pulses into a backplane trigger, which can be registered by the FC7. Configuration of the two FPGAs built into the AMC13 is achieved by the software-package AMC13Tool2.exe provided by the developers. Firmware versions for the T1-card above 0x6064 and the T2-card above 0x32 have to be installed, in order to get the correct backplane trigger from the LEMO connections. Then the software can be used to address the individual backplane channels and to enable an internal L1A trigger. A complete set of commands used to configure the AMC13 is given in the Appendix B. The AMC13 is used as a trigger board, because a full module read-out occupies a whole FC7 and thus no external trigger signal can be transmitted to the middleware via a free FMC socket. If only a one sided read-out is desired, a DIO5 [35] can be installed to one of the FMC slots. The 8CBC3-FEH will

be read out via different FMC connectors, which feature a LEMO connection for an external trigger signal.

4.2.3. Trigger electronics

Trigger processing electronics are provided in nuclear instrumentation module (NIM) standard form-factor equipment. Analogue pulses from the SiPM read-out are digitized by a discriminator-module and converted from NIM to TTL pulses, which can directly be fed into the AMC13. The muon trigger requires an additional coincidence module, as both scintillators have to trigger independently in a short time window.

The used modules are:

- Discriminator (LeCroy 620BL) [36]
- Coincidence (LeCroy 622) [37]
- NIM to TTL converter (Phillips Scientific Model 726) [38].

The whole triggering scheme is shown in figure 4.12. Each hybrid is able to generate its own internal trigger signal to test FEHs without an external trigger. This can be used to calibrate a module with respect to its noise behavior.

4.3. Read-out software

4.3.1. Phase-2 Acquisition and Control Framework

The Phase-2 Acquisition and Control Framework (Ph2_ACF) [39] is the middleware, used to interface a PC with the FC7 firmware. It contains an Application Programming Interface (API) which includes the description of the hardware components (8CBC2, FEH, SEH...), utilities to read out the data of a module and several tools to perform calibration and data test tasks. In order to perform tests on a module, a settings-file has to be compiled, which has to be given to the Ph2_ACF as a command-line argument. It contains the settings for the link to the FC7 and the configuration and settings of the hybrids, chips and testing procedures.

4.3.2. Sensors

Data on temperature, humidity and leakage detection is taken using several kinds of sensors read out by an Arduino micro-controller board [40]. For dedicated temperature measurements, the Maxim Integrated DS18B20 [41] is used, which is capable of

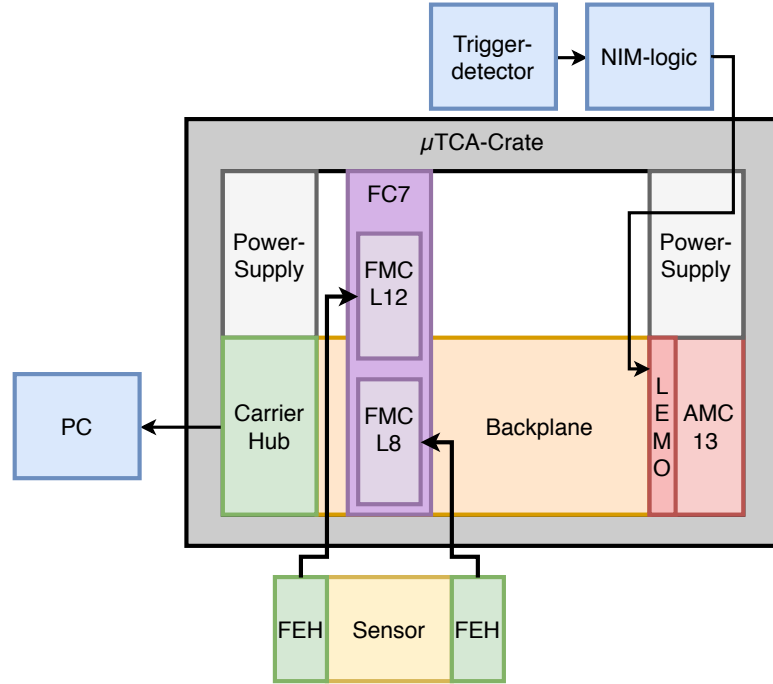


Figure 4.12.: Schematic of the AMC13 read-out. The AMC13 is used as a bridge between the NIM trigger pulses and the electronics in the μ TCA crate. Pulses from the NIM modules are sent via the backplane to the corresponding FC7 and trigger the read-out of the module. Results are sent via ethernet to the read-out PC.

measuring the temperature with an accuracy of 2°C to as low as -55°C . A combined measurement of relative humidity and temperature can be achieved using the Adafruit DHT22 [42]. This sensor provides a temperature resolution of 0.1°C and accuracy of 0.5°C . Its humidity measurement has a temperature resolution of 0.1% and a worst case accuracy of 5% , defined in the data-sheet in Appendix C. Leakage detection is accomplished by a Grove Water Sensor [43], which registers a current flow once a liquid touches its exposed metal strips. This is installed to ensure that the high and low voltages as well as the cooling chain are turned off in case of a leak of the water-glycol-chiller inside of the case. Temperature sensors are attached to any point for measurements using copper tape as it sticks to metal surfaces very well, even at lower temperatures.

5. Commissioning

5.1. Dry air

Before any module is placed inside the case, the dew point has been monitored over the full cooling process down to -35°C . It is indirectly measured with the DHT22 sensors, which are able to measure temperature and relative humidity. The conversion to the dew point was performed by using equation 4.1. The DHT22 data-sheet states a maximum deviation of the relative humidity measurement of 5 %. Measurements have been conducted in the corner close to and opposite of the inlet of the dry air, in order to also check the influence on places, where the air is potentially trapped. One sensor was placed on top of the cooling ring to mimic the position of the 2S module. A fourth sensor is mounted outside of the case to ensure correct operation of the read-out.

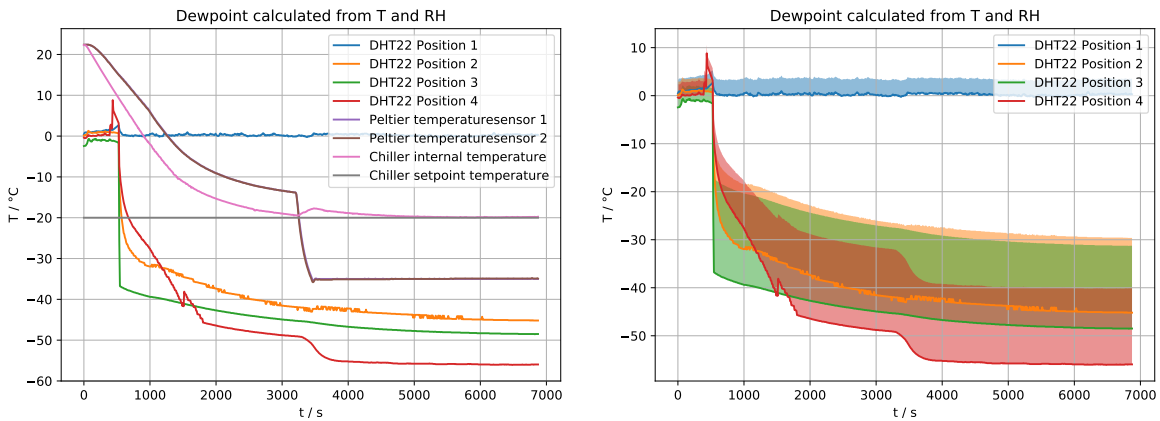


Figure 5.1.: Measurement of the dew point at various locations inside the box. One sensor was placed outside the box as a cross check. The left plot shows the correlation of the dew point measurement with the actual temperature inside the case. The right shows that even with the maximum accuracy error of 5 % on the humidity measurement as specified in the DHT22 data-sheet, the dew point is still below -35°C .

As shown in Figure 5.1, the dew point measured on top of the heatspreader is the coldest surface in the case and it does not exceed -35°C , even on the assumption of the maximum deviation on the humidity measurement. The accuracy of the temperature measurement can be neglected due to its much smaller influence on the calculation. Thus, it is safe to operate electronic devices inside the case, while sustaining a constant flow of dry air to ensure a stable dew point.

5.1.1. Artificial load

In order to simulate a 2S module inside the case, an aluminum carrier plate was prepared with five 5 W ceramic resistors, with a resistance of $22\,\Omega$, each attached to the positions, where the 2S module will be mounted. Thermal grease is applied to one side of the resistor and it is fixed to the carrier plate with copper tape. A picture of the prepared aluminum carrier frame is shown in Figure 5.2. All five resistors are wired in parallel and attached to the same output of a power supply. The carrier plate is then placed into the case and after cooling down to -35°C , the electrical power through the resistors is ramped up in 0.5 W steps. As Figure 5.3 shows, the temperature of the Peltier modules stays stable and no thermal runaway is observed.

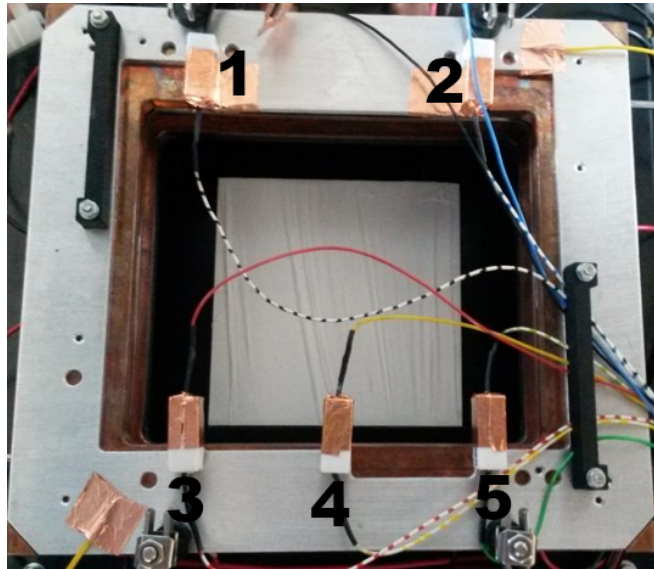


Figure 5.2.: Picture of the prepared 2S carrier frame for the studies as an artificial load. The numbers mark the positions, where thermocouples are mounted for temperature crosschecks.

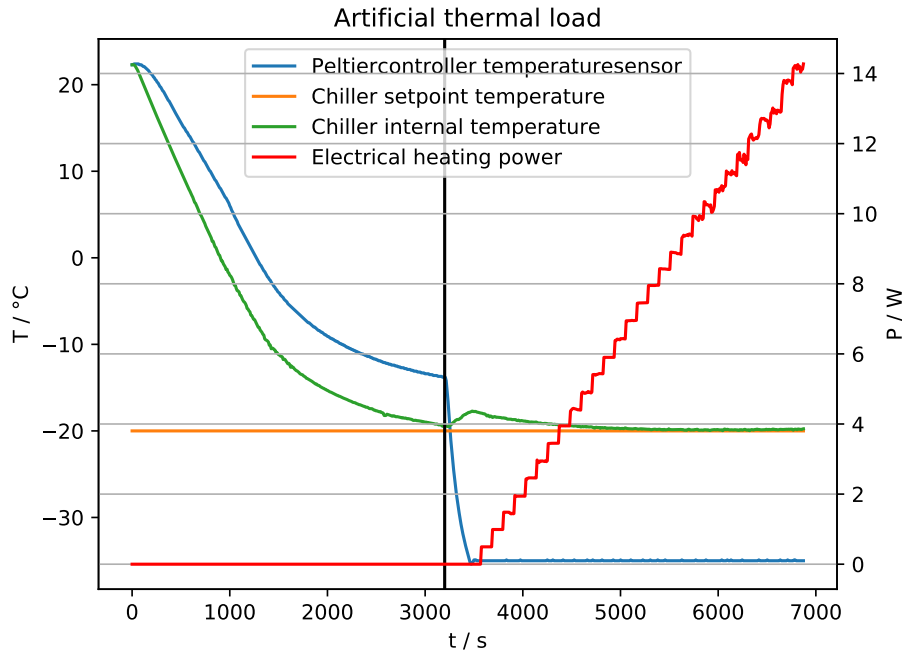


Figure 5.3.: Cooling process of the artificial load. The Peltier-driver is activated at around 3200s (black line), close to the point where the chiller reaches its minimum temperature. The internal sensor of the chiller shows an expected reaction to the increased thermal load of the now activated Peltier-modules (bump in the chiller internal temperature).

5.1.2. Temperature crosscheck

The temperature on top of the aluminum carrier frame was additionally measured close to the 2S module mouting points using thermocouples. This was done with a constant load of 6 W. A setpoint temperature of -35°C was set at the Peltier-controller and its temperature readings compared to the thermistor-temperatures at an equilibrium state.

P-Sensor 1	P-Sensor 2	Pos. 1	Pos. 2	Pos. 3	Pos. 4	Pos. 5
-35.0°C	-34.9°C	-33.9°C	-33.8°C	-33.3°C	-33.2°C	-33.3°C

Table 5.1.: Crosscheck of temperatures on the aluminum carrier. All values have a reading-error of 0.1°C , which is given by the thermistor read-out electronics.

Table 5.1 shows the expected temperature distribution on the aluminum carrier. Position one and two have more thermal mass close to the resistors, combined with more area of thermal contact, making it easier for cooling. On-carrier-temperatures of -35°C can be achieved by adjusting the Peltier-controller setpoint accordingly.

5.2. Cooling capabilities

5.2.1. Minimum temperatures

To study the influences of the different levels of dry air flow and its associated heating power on the minimum achievable temperature, multiple cooling cycles are performed with varying dry air flow. As the dry air supply does not feature a way to read off the amount of air flow, the rate of air flow is divided into four sections: no, low, medium and high airflow. These are qualified with a closed valve, an opened valve until an audible stream of air is detected, a halfway opened and a fully opened valve. In addition to the measurements using different amounts of airflow, one measurement was conducted using the low airflow setting with an electric load from the resistors of about 7.5 W.

The DS18B20 temperature sensors proved to be more dependent on the mounting pressure and seem to be more suitable for ambient temperature measurements, as opposed to direct contact measurements. Thus, the temperature readings are acquired from the Peltier-driver temperatures sensors and verified with two thermistors mounted to the top of the aluminum frame using copper tape.

Settings	Peltier Sensor 1 / $^{\circ}\text{C}$	Peltier Sensor 2 / $^{\circ}\text{C}$
no airflow, no load	-43.7	-44.1
low airflow, no load	-43.3	-43.6
mid airflow, no load	-37.1	-37.6
high airflow, no load	-34.8	-35.2
low airflow, 7.5 W load	-38.5	-38.2

Table 5.2.: Minimum achievable temperature under different conditions of operation measured using the Peltier-controller temperature sensors.

As the values in Table 5.2 show, the lowest achievable temperature shifts towards higher temperatures with a constant load of 7.5 W and increased air-flow. The minimum achievable temperature, however, is still below -35°C . This shows that the cooling system is capable of cooling down an irradiated 2S module to operational temperature.

5.3. 2S surveyor

Unification of the individual components used in the temperature regulation as well as sensing of temperatures and humidity is reached through a Graphical User Interface (GUI). For the implementation, the widely spread PYTHON scripting language [44] is used, as it does not require complicated compilation routines. The QT5 framework [45] provides an easy way of defining user interfaces with multi-threading capabilities. This GUI enables the operator to safely set temperatures inside the case, without the risk of breaking any of the equipment by choosing wrong settings.

Each piece of hardware is equipped with a dedicated software thread, which allows for individual logging of their individual aspects. These threads are encapsulated in smaller widgets, which map the corresponding buttons to the functions that interface with the hardware. A schematic view of the program structure is shown in Figure 5.4. Due to the nature of smaller widgets, the GUI can easily be extended and pieces of equipment can be exchanged should the equipment change over the course of the prototyping phase. Parts of the code can also easily be reused for other GUIs, as they are only specific for individual measurement devices and not bound to the overall code structure of the GUI.

A connection to the Ph2_ACF is provided via system-calls, which avoid the risk for the GUI of becoming incompatible, once updated versions of this framework are available.

Pictures of the GUI in operation are shown in Figure 5.5.

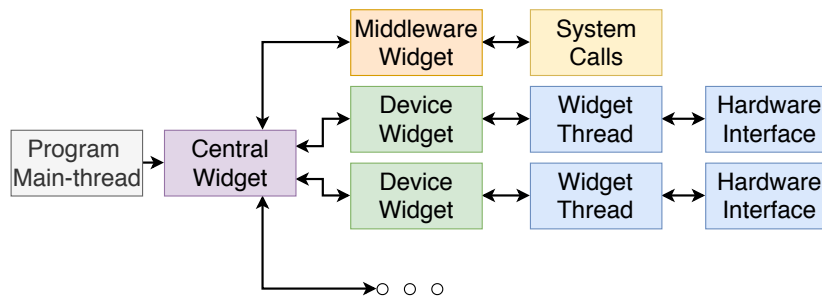


Figure 5.4.: Schematic of the software-layout. The individual widgets are only connected over the central widget, which is controlled by the main program loop, and thus can easily be detached, replaced and reused.

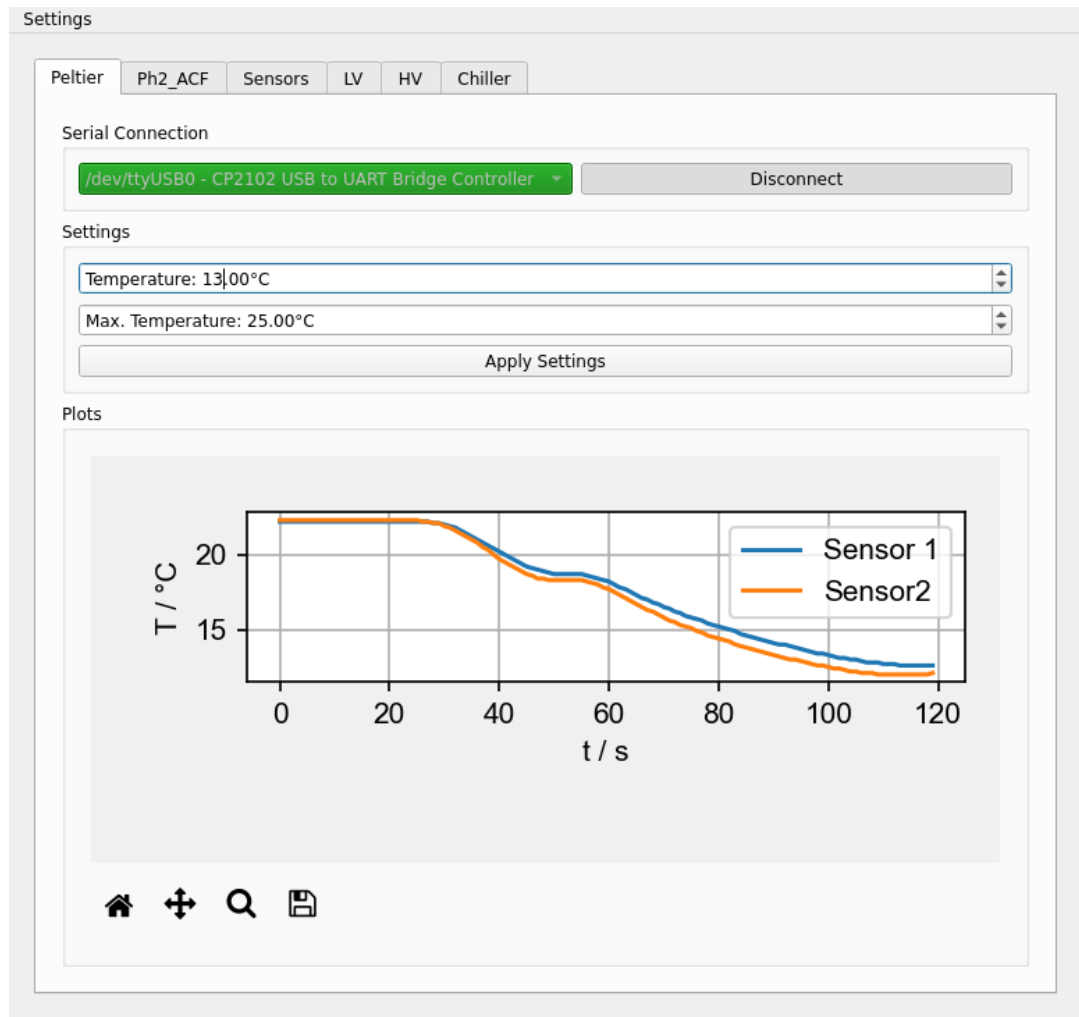


Figure 5.5.: Picture of one of the GUI tabs. For easy monitoring sensor-data is displayed as graphs. Each individual tab corresponds to a separate piece of hardware and can easily be exchanged, if other hardware is deployed. Read-out measurements of the module can also be started from this GUI.

6. Measurements on the first functional 1.8 mm 8CBC2 module

After the successful commissioning of the read-out station, measurements with the first functional 2S module from Aachen are conducted. It is a 1.8 mm module featuring FEHs with CBCs in the version 2. A SEH is temporarily attached and functions as a distribution board for the high voltage supply to the sensor plates. The sensor plates are full size 320 μm -thick Float-Zone silicon with a deep diffusion thickness of 200 μm .

6.1. IV curves

During the assembly procedure the change of leakage-current through the prototype modules sensors are monitored at certain steps to register the effects of the individual steps or any problems concerning the breakdown voltage. Using the read-out station, this monitoring can be extended to measurements in an assembled state of the module with changing operational temperature. For this test, the current through the sensor plates was measured using a Keithley 2410 Sourcemeter [46] which is capable of supplying the required voltages while also measuring the output current. Its 'low' potential is connected to the carrier frame onto which the module is mounted, while the 'high' potential is directly connected to the SEH. The high voltage circuit has to be completed using the 8CBC2 read-out PCB, as the high voltage ground is routed through the FEHs. A cable attached to one of the read-out PCBs grounding points and the carrier plate completes the circuit. Both sensors can be plugged into the SEH individually using their Kapton pigtails, so that the IV curves for both sensors can be measured independently.

For each measurement, the voltage is scanned from 0 V to -1000 V in 10 V increments taking 5 measurements with a 1 s delay between each one. After ramping up to a new voltage setting, 5 s were allowed to elapse before any new measurement to let the leakage current stabilize. As a safety measure, the current is limited to 7 μA . Temperatures are measured in the heatspreader plate of the cooling jig using the Peltier-driver PT1000 sensors. Before the measurement, the case is flushed with dry air and then the flow adjusted to a low setting, holding a constant overpressure of dry air inside the case.

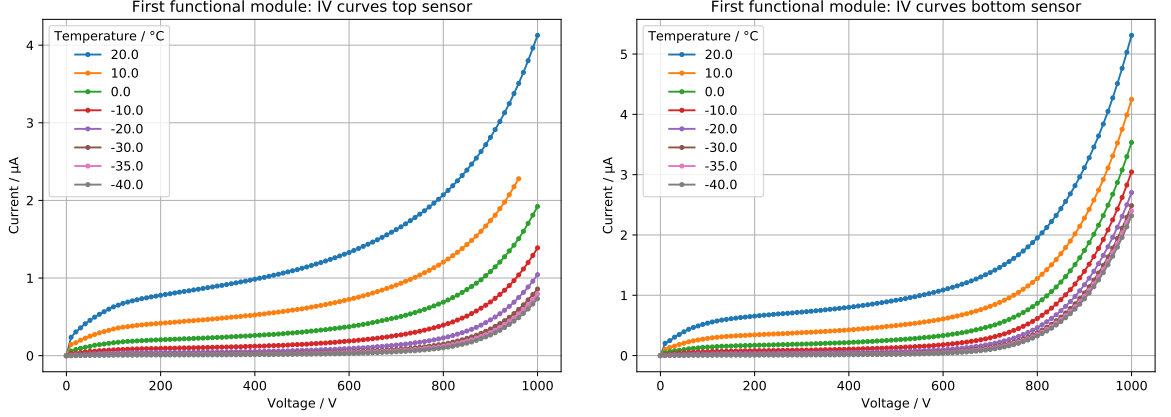


Figure 6.1.: The left and right plot show the leakage current measured for the applied bias voltage for the top and bottom sensor respectively. No unexpected behavior in the shape of the curve can be observed and the leakage current decreases as expected for lower temperatures.

In Figure 6.1, the measured curves show a typical behavior without any unexpected deviations. At first, the leakage current increases resembling a square-root dependency to the point of full depletion at about 200 V. After this point, the increase of leakage current follows a much steeper slope induced by the beginning breakdown of the detector.

At the operational voltage of 250 V the theoretical expectation [19]

$$I(T) = I(T_0) \cdot \frac{T}{T_0} \cdot \exp\left(-\frac{E_{ef}}{2k_B} \cdot \left(\frac{1}{T} - \frac{1}{T_0}\right)\right) + I_{offset}$$

was fitted to the measured values. Here $I(T_0)$ is an initial current at an initial temperature T_0 , T the measured temperature and I_{offset} a constant measurement offset in the current measurement.

As Figure 6.2 shows, this fit can only be understood as an estimate for the general behavior and not as an absolute measurement of the leakage current. The actual sensor temperature differs from the temperature measured on the copper heatspreader [47] and can later be measured more precisely using a thermistor glued to the backside of one sensor plate [15]. This will greatly increase the accuracy of the measurement. However until the read-out of this thermistor is possible, the IV-curve measurement done in this thesis can be used as a functionality test for the prototype module under operational temperatures.

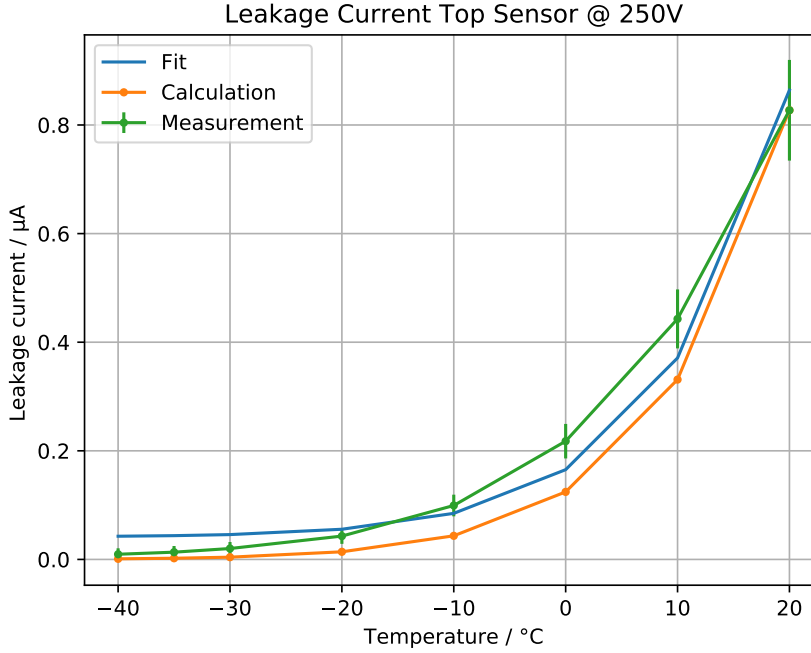


Figure 6.2.: Comparison of the leakage current measurement with the expectation values. The uncertainty on the leakage current is estimated the measurement accuracy of the Keithley power supply and a 10 % uncertainty on the leakage current induced by the deviation of the measured temperature from the actual sensor temperature.

6.2. Noise measurement

6.2.1. Theory

Silicon sensor noise is typically qualified in Equivalent Noise Charge (ENC), being the number of electrons contributing to the noise [48]. All contributions add up quadratically

$$ENC = \sqrt{ENC_C^2 + ENC_{I_L}^2 + ENC_{R_P}^2 + ENC_{R_S}^2},$$

with ENC_C^2 being the load capacitance, $ENC_{I_L}^2$ the shot noise from leakage current, $ENC_{R_P}^2$ the parallel thermal noise and $ENC_{R_S}^2$ the serial thermal noise from the metal

strip resistance [48]. Both temperature dependent noise contributions

$$ENC_{R_P} = \frac{e}{q_e} \sqrt{\frac{k_B T \cdot t_p}{2R_p}},$$

$$ENC_{R_S} = C_d \cdot \frac{e}{q_e} \sqrt{\frac{k_B T \cdot R_s}{6t_p}}$$

contribute with a $\sqrt{T}$ dependency to the overall ENC. Here, R_s and R_p are series and parallel resistance, C_d the load capacity, t_p the peaking time, q_e the electron charge and e the Euler number. However, the most significant contribution to the sensor noise is the load capacitance. ENC values from older CMS tracker detectors confirm this, with a total ENC value of 1518 to 1556 e^- with an ENC_C of about 1480 e^- [48]. The specific values for the used sensor are not measured, as there was no decision on the specific sensor version yet. However, no significant temperature dependency of the sensor noise is expected.

6.2.2. Calculation of noise

The CBC chips provide a digital output via a per channel analogue front-end. This front-end, shown in Figure 6.3, consists of a preamplifier, gain amplifier and finally a comparator. An incoming signal to the preamplifier is integrated and initially amplified. The outgoing pulse is then fed into the gain amplifier.

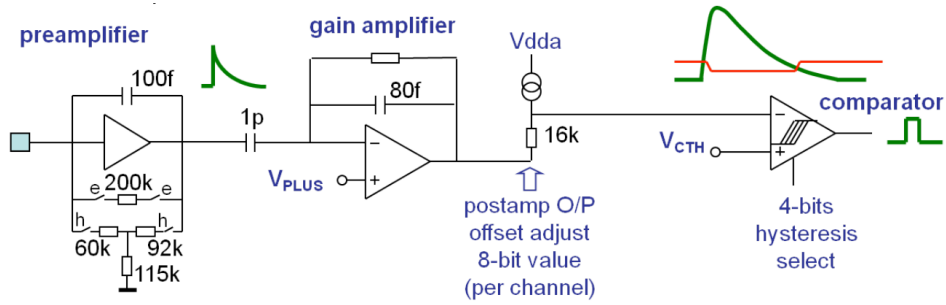


Figure 6.3.: Diagram of the amplification chain of the CBC2 chip. The charge collected by the sensor is amplified in three distinct steps and afterwards a comparator produces the digital signal for the CIC chip [18].

The gain amplifier features the setting V_{plus} , which is used to adjust the baseline voltage of all strips to a global value. From this baseline an offset per channel can be set

via the offset-trim parameter. Digital signals are generated by the comparator, applying a global comparison voltage V_{CTh} . This analogue front-end is susceptible to voltage noise in the strip region, which could mimic a passing particle in its signature. To minimize the amount of noise transferred to the output signal, a so called S-curve scan is executed. This scan measures the occupancy of all channels for a user-defined number of events at an applied comparator voltage and sweeps this voltage over its usable range. At very low comparator threshold, even the smallest noise signals are converted into digital signals, whereas at very high thresholds, no fluctuation is high enough to make it past the comparator. Between these two high and low values, the curve has the shape of an error-function

$$S(x) = \frac{1}{2} \operatorname{erf} \left(\frac{x - \mu}{\sqrt{2}\sigma} \right).$$

The 50 % occupancy line defines the pedestal value of the V_{CTh} and the width of the S-curve is used as a measure for the module noise. Noise is quantified in V_{CTh} -units, with $1 V_{CTh} \approx 320$ electrons [49]. A baseline of 1000 electrons of noise is desired for 2S modules, as simulations have shown [15], which equals a noise in V_{CTh} -units of about $3 V_{CTh}$. In the Ph2_ACF, the noise is either directly determined via an error-function fit or by numerically differentiating the curve and calculating the mean and RMS values for the distribution. All following noise values shown are calculated using the numerical differentiating method.

6.2.3. Grounding

In order to achieve a good signal to noise ratio, the module has to be grounded and shielded from outside influences. Multiple grounding schemes for the 8CBC2 read-out have already been evaluated [20, 50] and have been applied to this particular read-out station. Small adjustments are conducted in order to further minimize the noise. A complete grounding scheme can be found in Figure 6.4. As a general idea, large ground loops were minimized to decrease the risk of outside signals to couple into the module electronics.

The silicon sensor is operated at a voltage of 250 V, which has also been used during measurements of the first prototype modules built at CERN. Noise was measured for the individual FEHs on their own and for both at the same time to evaluate the overall performance and investigate, if there are any adverse side-effects with a double-sided read-out. No significant increase in the noise can be observed between the measurements, as shown in Table 6.1. CBC chips with increased noise above $3 V_{CTh}$ are linked to a

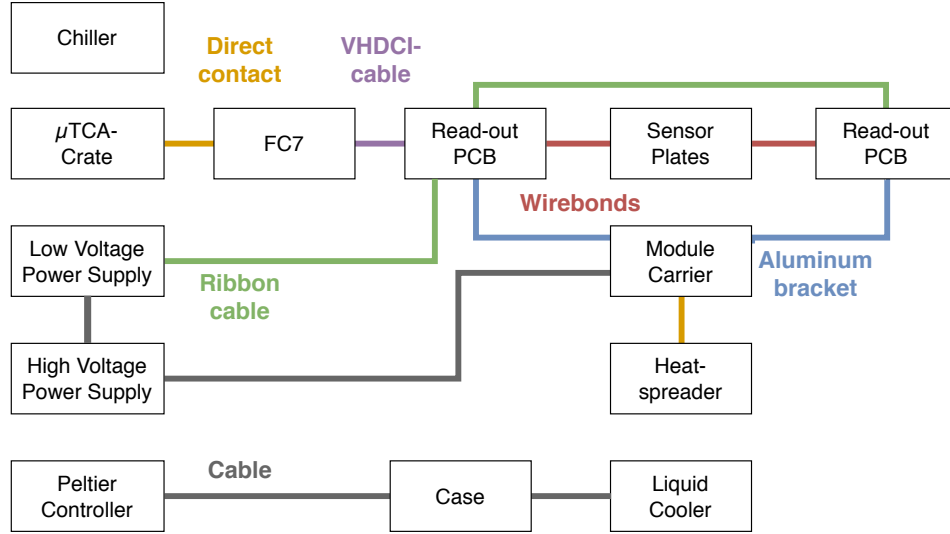


Figure 6.4.: Grounding scheme for this read-out case, which has shown the best noise.

known CBC2 glitch, which shows problems during the read-out at high occupancies. An exemplary S-curve including the glitch is shown in Figure 6.5.

CBC	right / V_{CTh}	left / V_{CTh}	CBC	right / V_{CTh}	left / V_{CTh}
1	2.47 ± 0.20	2.46 ± 0.26	1	2.65 ± 0.18	2.55 ± 0.20
2	2.53 ± 0.21	2.72 ± 0.20	2	2.53 ± 0.19	2.72 ± 0.17
3	2.43 ± 0.20	2.88 ± 0.22	3	2.52 ± 0.18	2.88 ± 0.20
4	2.93 ± 0.23	2.55 ± 0.18	4	3.02 ± 0.26	2.59 ± 0.21
5	2.73 ± 0.22	2.69 ± 0.22	5	2.72 ± 0.18	2.63 ± 0.19
6	2.58 ± 0.18	2.45 ± 0.20	6	2.57 ± 0.21	2.44 ± 0.19
7	2.67 ± 0.19	2.75 ± 0.20	7	2.62 ± 0.19	2.82 ± 0.18
8	2.43 ± 0.21	3.32 ± 0.34	8	2.47 ± 0.23	3.50 ± 0.38

Table 6.1.: Comparison between a single-sided calibration with individual powering (left table) and a double-sided calibration with simultaneous powering (right table). No significant difference can be observed, so no additional noise is introduced by a double-sided read-out. All measurements were conducted at room temperature. 'Right' and 'left' in the table header corresponds to the individual FEH on the 2S module.

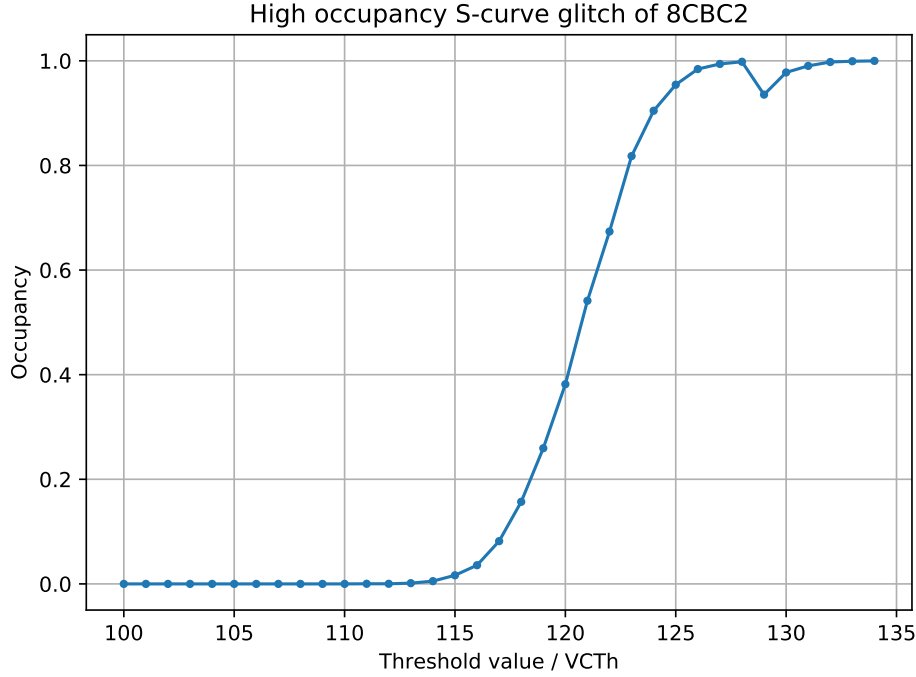


Figure 6.5.: S-curve measurement showing the high occupancy glitch, which affects the calculation of noise.

6.2.4. Temperature dependency of module noise

According to the theory, the temperature dependency of the module noise can be neglected, as it only depends on the sensor capacity, which does only slightly vary with temperature. Thus, a uniform distribution of noise across the whole temperature range should be observed. To prove this prediction, the noise was measured of the right 8CBC2-hybrid of the module for temperatures down to -40°C . A single sided read-out was chosen to eliminate as many sources of external noise as possible.

Figure 6.6 shows an increase in noise for lower temperature, which is not expected. Additional measurements with switched off Peltier-controller and chiller in various configurations are conducted to estimate their influence. It can be observed that switching on the Peltier-controller does affect the noise measurement. For lower temperatures the output voltage and current are increased, which can be linked to the increase of noise. A comparison of the noise measurements at -20°C with the whole cooling chain and about -18°C only provided by the chiller show a difference of about 10 %.

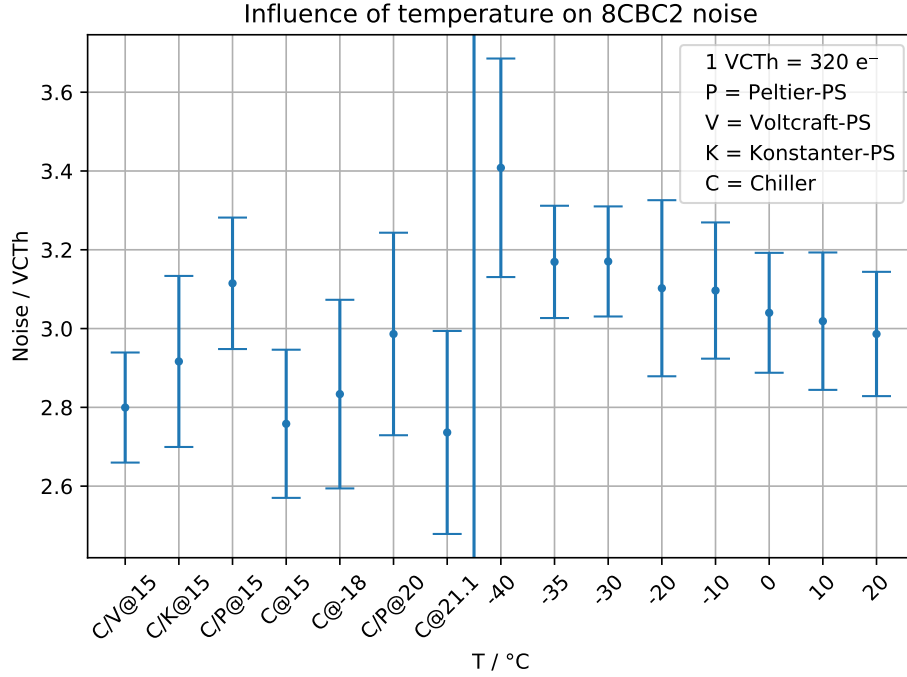


Figure 6.6.: Measurement of the noise of the right 8CBC2 hybrid of the 2S module at various temperatures. An increase of noise can be observed at lower temperatures on the right side of the vertical line. This can be linked to noise introduced by the Peltier-controller. The left side shows individual measurements at fixed temperatures using various power supplies. The Peltier-controller power supply shows the highest amount of noise.

A dedicated test was performed by taking ten noise measurements for five different settings with a power cycle for the CBC chips between each measurement. A baseline was measured with only a running chiller set to 20 °C. Then, the Peltier-controller was operated at a constant voltage of 3 V and at a voltage of 7 V, as these are typical values at which it operates while regulating the temperature inside the case. Thereafter, the Peltier-controller was replaced with a dedicated adjustable power supply and the same voltages were set. The noise for one whole 8CBC2-FEH is calculated by taking the mean of all individual CBC2-chips. Figure 6.7 shows that the Peltier-controller has an impact on the 8CBC2 noise measurement, which could be linked to its 20 kHz switching frequency. The power supply operates at a higher frequency of 120 kHz. To further study this assumption, a secondary low pass filter was installed between the power supply of

the Peltier-controller and the Peltier-modules. As Figure 6.8 shows, this does decrease the noise-level to comparable values with the Voltcraft power supply. However, the increase of noise at lower temperatures can still be observed, which is also present with the Voltcraft power supply. Up to this point, this effect is not understood and it has to be evaluated, if this is related to an effect inside the read-out electronics or CBC chips or if this is an attribute associated with the read-out case. For precise measurements during module production, this issue has either be taken into account in terms of calibration or should be eliminated by further looking into the temperature dependence of the FEH.

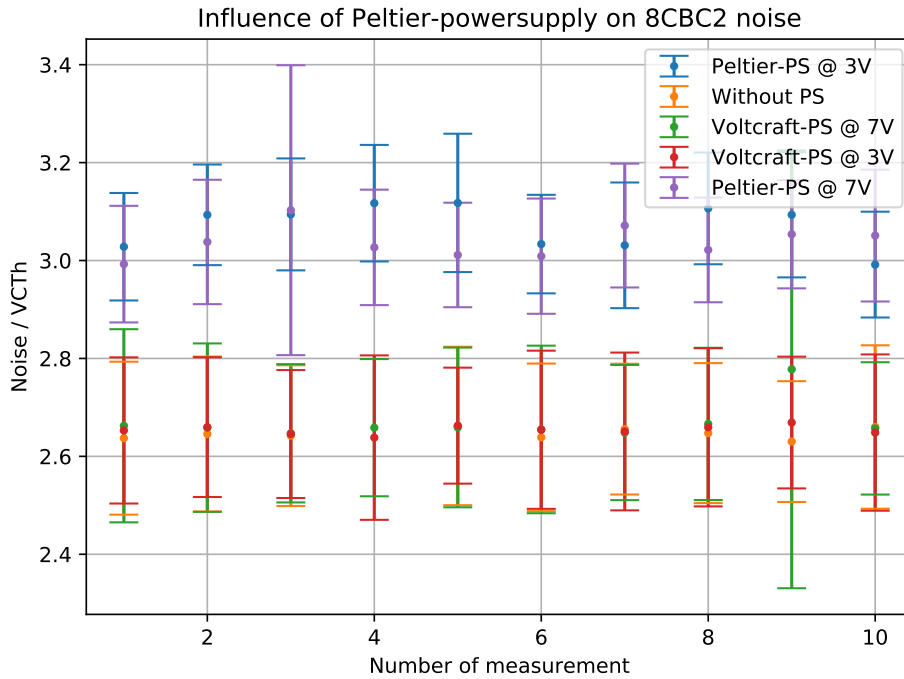


Figure 6.7.: Noise measurements using different powersupply setups. All measurements with the internal power supply of the Peltier-controller show increased noise compared to a Voltcraft lab-power supply. Measurements, in which the error-bars are larger compared to the other measurements, one CBC2 chip did not correctly turn on. This results in a much larger noise distribution, affecting the whole calculation.

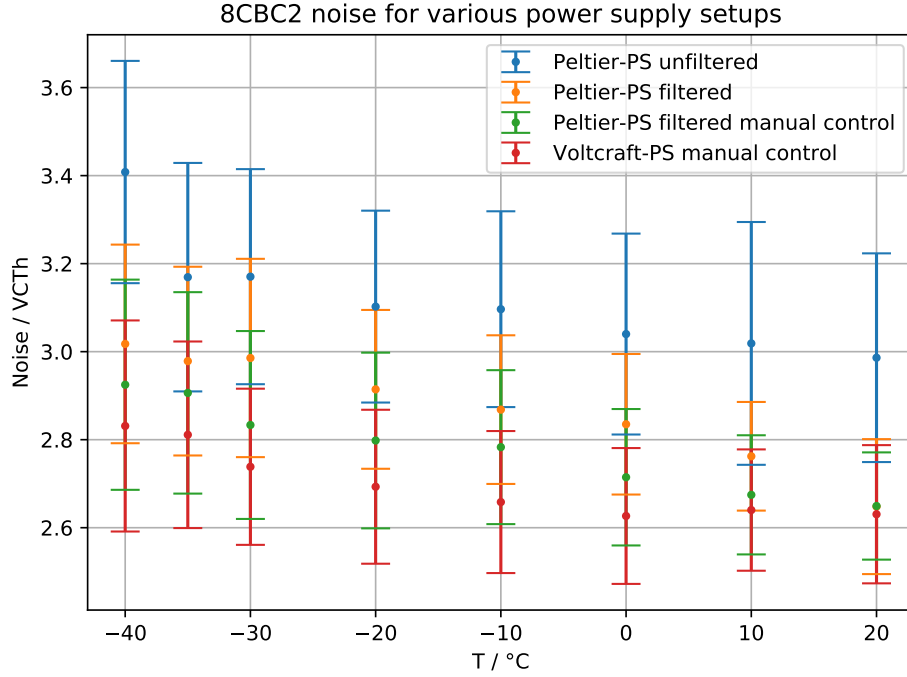


Figure 6.8.: Temperature dependence of the right FEH of the 2S module. The additional low pass filter reduces the general noise-level. The unexpected behavior for lower temperatures can be observed across all power supplies and is not understood.

6.3. Module read-out

6.3.1. Radioactive sources

Once a low noise value is achieved and the module is correctly calibrated, its tracking capability can be tested using real particles. For first tests, two different ^{90}Sr beta sources are used. One square area source with an active area of $100\text{ mm} \times 100\text{ mm}$ and an activity of 12.9 kBq is able to illuminate all strips at once. Using aluminum shields, patterns of strips can be irradiated to investigate specific areas of the sensor. A 3.3 MBq point-like source enables fast tests with a hit-distribution, which can be easily discriminated from background signals.

6.3.2. Internal triggering

If no external trigger is desired, internal triggering of the module is possible multiple ways. Either a predefined frequency, ranging from 1 kHz to 1 MHz can be used to trigger a read-out in equally spaced intervals. An exemplary read-out is shown in Figure 6.9. Signals can only be observed, if a particle passes the detector in a time slot of 25 ns corresponding to the bunch-crossing-time at the LHC. Or a hit-based triggering could be achieved using either the 'or254' or 'orSTUB' settings of the CBC, which correspond to either a single hit in any of the channels or a correct stub, in a momentum window defined by the user.

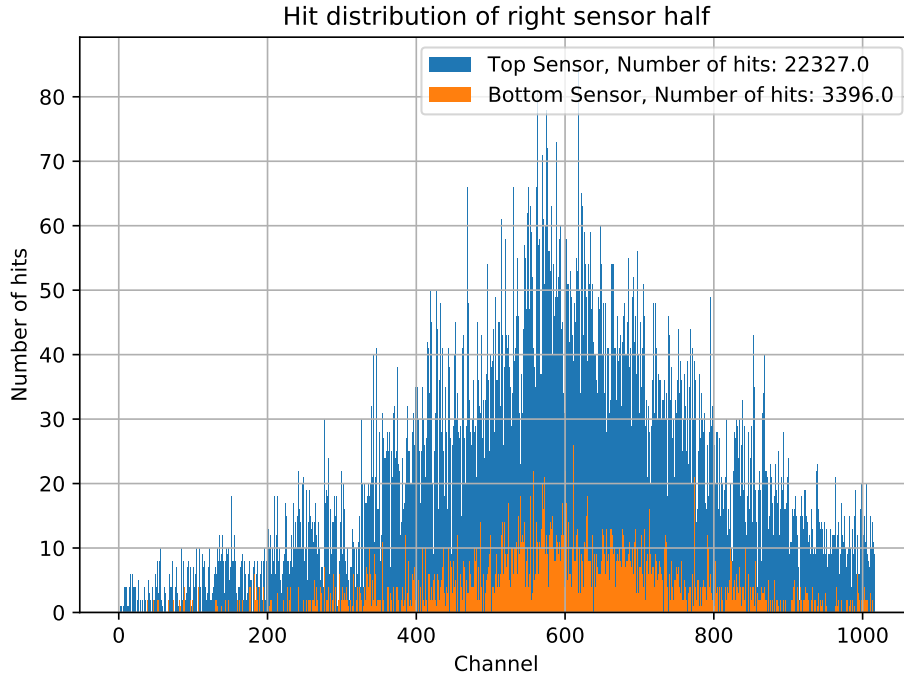


Figure 6.9.: Read-out of 100000 events using a fixed frequency of 1 kHz and a threshold value of 90, which is about 7σ away from the pedestal. A distinct difference in the amount of hits per sensor can be observed, as more low energy electrons hit the upper sensor and get stopped.

6.3.3. External triggering

The trigger latency has to be estimated to correctly utilize an external trigger, as the trigger issues a backward read in the pipeline of the 2S module. This is achieved by setting a latency value and then reading out a fixed amount of events using the external trigger. The latency is scanned over the entire usable range from 0 to 255 in address values of the pipeline and the amount of all hits is calculated in the predefined number of events. The correct latency value is found at the position of the bin, containing the maximum amount of hits. To be sure, the correct latency is found and read-out artifact is seen, additional latency was added via a NIM-delay-box. The latency scan was repeated using the overall same values and the expected shift in latency was observed. An exemplary latency scan as well as the crosscheck measurement can be found in Figure 6.10. Once the correct latency value is found, the module can be read out using the

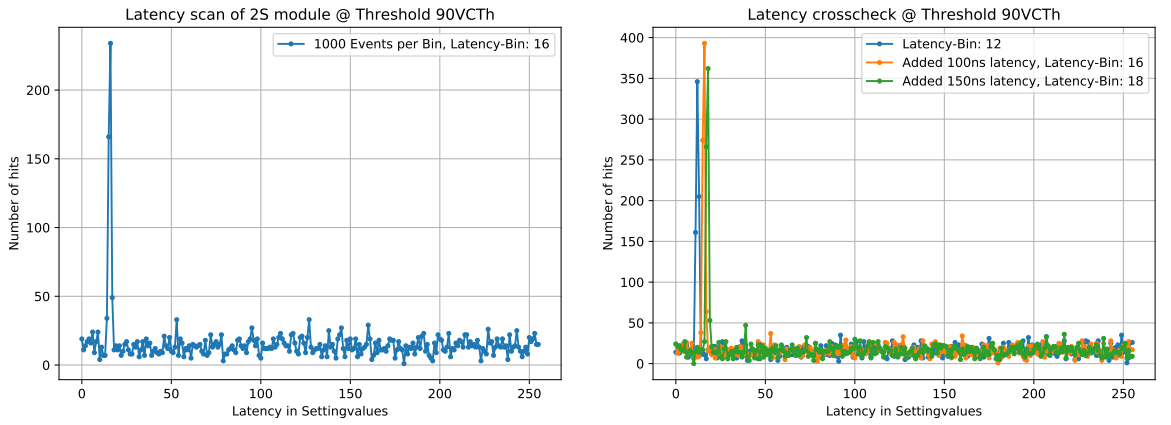


Figure 6.10.: On the left side: Latency scan for the scintillator trigger with the AMC13 as the hardware interface. A latency value of 12 bunch-crossings is found, which is used for later measurements. On the right side: Crosscheck of latency scan by manually adding latency via a NIM-delay-box. The amount of added latency corresponds to the shift in the x-direction, using the same settings for the read-out.

external trigger. A measurement using a point-like radioactive source can be found in Figure 6.11 for 10000 events. The amount of hits in the histogram is much lower than the expected number. With the correct latency-tuning, an efficiency much higher than 90 % is expected. This behavior is linked to a malfunction in the middleware, which was already adapted for the 8CBC3 read-out and has proven not to be completely backwards compatible.

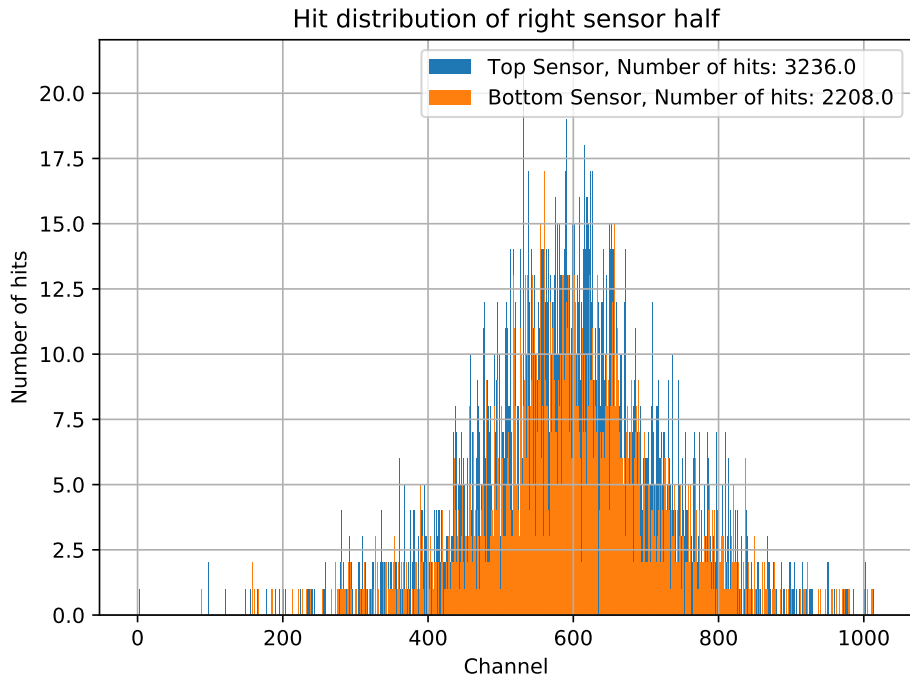


Figure 6.11.: Hit distribution for top and bottom sensor of the point-like radioactive source over the right sensor side triggered using the AMC13. A threshold value of 90 was chosen, taking 10000 events. The height of both histograms is closer to each other, as expected due to the fact that trigger electrons have to pass through both sensor to reach the scintillator.

7. Summary and outlook

During the upgrade of the Large Hadron Collider to the High Luminosity LHC in 2024, the CMS experiment gets partially exchanged in the Phase-2 Upgrade. The Outer Tracker will be completely replaced and two types of new silicon modules are currently in development. All tracker modules will be assembled by institutes from the CMS community and have to be individually checked for assembly quality and performance under operational CMS temperature. Over the course of this thesis a read-out station was designed and commissioned, to enable module measurements at operational CMS temperature during the prototyping phase.

The 2S module read-out station is capable of cooling down prototype-modules including their read-out hardware using a two stage cooling system. A glycol-water based liquid cooling circuit is used to stabilize the temperature of a copper plate to -20°C . Six Peltier-modules are installed as the second stage, generating a temperature difference of -15°C to enable module measurements at operational CMS temperature of -35°C .

The amount of cooling power needed is estimated using approximations from theoretical models and the cooling performance is qualified with heating resistors. A minimal usable temperature of -40°C has been measured, which exceeds the required -35°C , which would be provided by the CO_2 -cooling loop. Safe operation even at the lowest temperatures is ensured by a dry air atmosphere.

All the different hardware components required for the operation of such a read-out station are tied together with a Graphical User Interface which enables safe measurements during the prototyping phase. A logging option can be used to keep track of the atmosphere inside the case to review the measurements of individual modules.

Due to the fragility of the 2S modules, toggle clamps are used as safe and easy way of fixation. Radioactive sources can be placed over the sensor plates to introduce electron particle tracks. A plastic scintillator installed in the bottom of the case acts as a trigger source for the read-out electronics. Also muons can be used as a trigger source with a coincidence trigger by using a secondary scintillator placed above the module. The

AMC13 is used as an interface between the NIM-trigger logic and μ TCA read-out FPGAs.

Basic qualification measurements are performed on the first functional module build at the RWTH Aachen University including IV-curves, noise measurements and signal read-out using radioactive sources. This ensures that no external influences disturb the measurements of upcoming modules. The IV-characteristics of the module could be qualified as well as a low noise achieved at room temperature below the 1000 electron threshold. Measurements at various temperatures show that the Peltier-controller affects the noise measurements, which should be investigated further to enable precise statements during the assembly phase. First experiments with radioactive sources show the correct operation of the read-out chain, but also reveal some issues in the middleware.

With the upcoming 8CBC3 and service hybrids, new measurements will be enabled, getting closer to a final 2S module. A reworked middleware will simplify calibration and read-out tasks and in turn even more insight into the 2S module characteristics. The cooling approximations and insights can be used for multi-module cooling stations, which are required for the assembly phase.

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Glossary

AMC AMCs are electronic circuits following the PCI industrial computers manufacturers group specification. They are designed to work as standalone cards but can also be plugged into ATCA or μ TCA crates. 28

CBC Each CBC collects the data from 254 strips and identifies stubs, which are provided as unparsified data to the CIC. 12

CERN The CERN is the european organization for nuclear research. It is run by 23 countries and provides a particle accelerator infrastructure to various experiments. 1, 3

CIC The CIC receives data from the front-end chips and handles the communication with the LpGBT for the readout. 12

CMS The CMS experiment is a cylindrical particle detector located at the LHC. It focuses on the detection of Higgs bosons, heavy ion collisions and hints for supersymmetric particles. 1, 3

FMC A FMC is a standard intended to define I/O expansion boards for FPGA boards. 28

FPGA A Field Programmable Gate Array is an integrated circuit with the capability to be reconfigured using hardware description languages. 28

Frontend Hybrid The Frontend Hybrid provides an interface between the silicon strip detectors and the readout electronics of each module through the CBC and CIC chip. 12

LHC The Large Hadron Collider (LHC) is a particle accelerator located at the CERN site in Geneva (Switzerland). 1, 3, 8

Low power Gigabit Transceiver The LpGBT is a radiation-hard variant of the GBT, which features a subset of the original functionality while consuming less power. 13

OT The Outer Tracker is the outer detector layer of the CMS tracker. It is part of the tracker detector and will house 2S and PS modules. 1

Ph2_ACF The Ph2_ACF software package provides an interface between a computer and the μ DTC, which handles configuration and readout. 29

PID PID is a control loop feedback mechanism, which evaluates the difference between a setpoint and the actual value of a process variable. It uses proportional, integral and derivative terms to apply a correction to the control loop. 24

Service Hybrid The Service Hybrid provides an interface between the module and the DAC of the CMS experiment. 13

VHDCI The VHDCI specifies a 68-pin connector used to connect two devices using the small-computer-system-interface-3 standard. 18

μ TCA The μ TCA standard is a smaller form- and costfactor standard to the ATCA standard, which follows the same design philosophy. 28

Acronyms

AMC Advanced Mezzanine Card. 28, *Glossary*: AMC

CBC CMS Binary Chip. 12, *Glossary*: CBC

CERN Conseil européen pour la recherche nucléaire. 1, *Glossary*: CERN

CIC Concentrator integrated circuit. 12, *Glossary*: CIC

CMS Compact Muon Solenoid. 1, 5, *Glossary*: CMS

FEH Frontend Hybrid. 12, *Glossary*: Frontend Hybrid

FMC FPGA Mezzanine Card. 28, *Glossary*: FMC

FPGA Field Programmable Gate Array. 28, *Glossary*: FPGA

LHC Large Hadron Collider. 1, 3, *Glossary*: LHC

LpGBT Low power Gigabit Transceiver. 13, *Glossary*: Low power Gigabit Transceiver

OT Outer Tracker. 1, *Glossary*: OT

Ph2_ACF Phase-2 Acquisition and Control Framework. 29, *Glossary*: Ph2_ACF

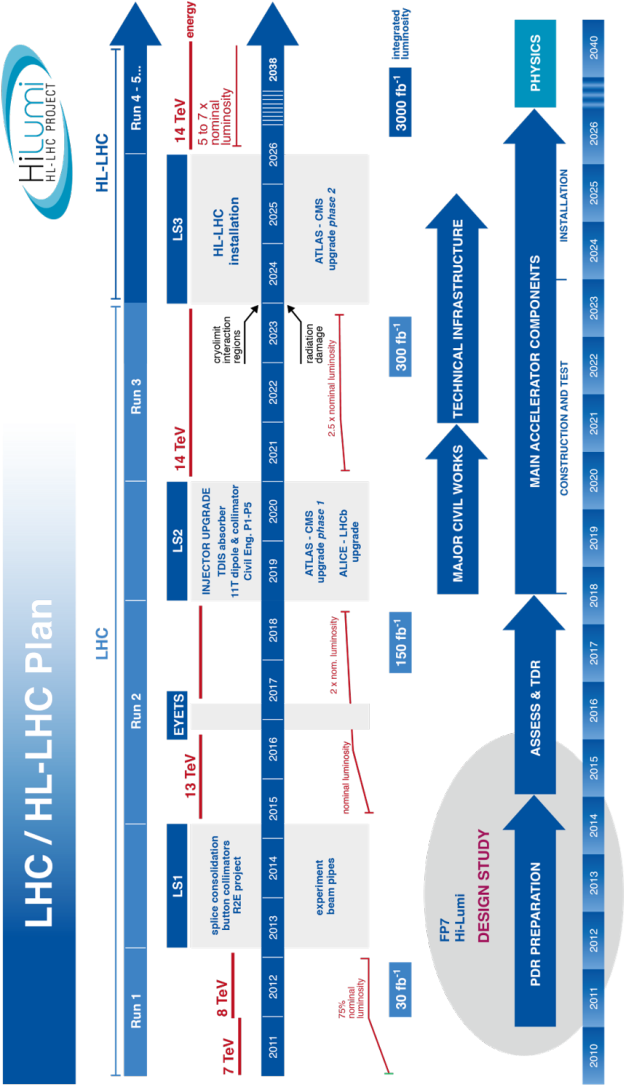
SEH Service Hybrid. 13, *Glossary*: Service Hybrid

TEC Thermoelectric Cooler. 24, *Glossary*: TEC

VHDCI Very-High-Density Cable Interconnect. 18, *Glossary*: VHDCI

μTCA Micro TCA. 28, *Glossary*: μTCA

A. HL-LHC schedule



Schedule for the upgrade strategy for the LHC to HL-LHC [51].

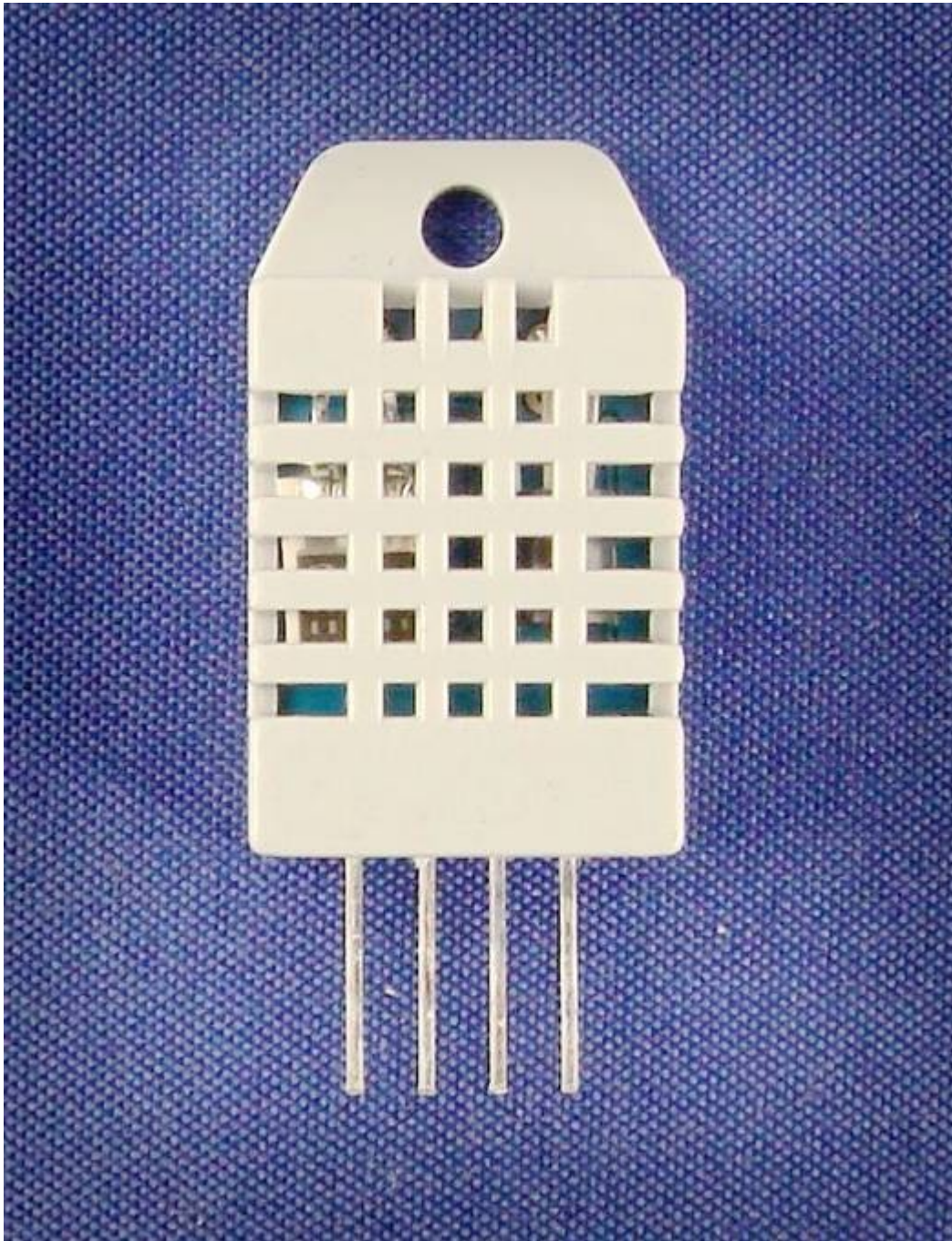
B. AMC13 configuration

Command	Description
AMC13Tool2.exe -c 399	Connect to AMC13 with ID 399
en 3	Enable third slot of μ TCA-crate
wv CONF.TTC.ENABLE_INTERNAL_L1A 1	Enable internal L1A trigger for backplane
wv CONF.TTC.T3_TRIG 1	Allow triggering via LEMO connection
wv CONF.TTC.RESYNC.COMMAND 0x02	Resync AMC13 clock with crate/fc7
wv CONF.TTC.RESYNC.MASK 0x1	Resync AMC13 clock with crate/fc7
wv CONF.DIAG.FAKE_TTC_ENABLE 1	Enable fake TTC signal
wv CONF.LOCAL_TRIG.FAKE_DATA_ENABLE 1	Generate fake trigger signals
Register Name	Value
clock_source	0
fc7_daq_cnfg.ttc.ttc_enable	1
fc7_daq_cnfg.fast_command_block.trigger_source	1

C. Data-sheets

Digital-output relative humidity & temperature sensor/module

DHT22 (DHT22 also named as AM2302)



Capacitive-type humidity and temperature module/sensor

Aosong Electronics Co.,Ltd

Your specialist in innovating humidity & temperature sensors

1. Feature & Application:

- * Full range temperature compensated
- * Relative humidity and temperature measurement
- * Calibrated digital signal
- * Outstanding long-term stability
- * Extra components not needed
- * Long transmission distance
- * Low power consumption
- * 4 pins packaged and fully interchangeable

2. Description:

DHT22 output calibrated digital signal. It utilizes exclusive digital-signal-collecting-technique and humidity sensing technology, assuring its reliability and stability. Its sensing elements are connected with 8-bit single-chip computer.

Every sensor of this model is temperature compensated and calibrated in accurate calibration chamber and the calibration-coefficient is saved in type of programme in OTP memory, when the sensor is detecting, it will cite coefficient from memory.

Small size & low consumption & long transmission distance(20m) enable DHT22 to be suited in all kinds of harsh application occasions.

Single-row packaged with four pins, making the connection very convenient.

3. Technical Specification:

Model	DHT22
Power supply	3.3-6V DC
Output signal	digital signal via single-bus
Sensing element	Polymer capacitor
Operating range	humidity 0-100%RH; temperature -40~80Celsius
Accuracy	humidity $\pm 2\%$ RH (Max $\pm 5\%$ RH); temperature ± 0.5 Celsius
Resolution or sensitivity	humidity 0.1%RH; temperature 0.1 Celsius
Repeatability	humidity $\pm 1\%$ RH; temperature ± 0.2 Celsius
Humidity hysteresis	$\pm 0.3\%$ RH
Long-term Stability	$\pm 0.5\%$ RH/year
Sensing period	Average: 2s
Interchangeability	fully interchangeable
Dimensions	small size 14*18*5.5mm; big size 22*28*5mm

4. Dimensions: (unit----mm)

1) Small size dimensions: (unit----mm)



SERIES: CP60 | DESCRIPTION: PELTIER MODULE

FEATURES

- solid state device
- precise temperature control
- quiet operation



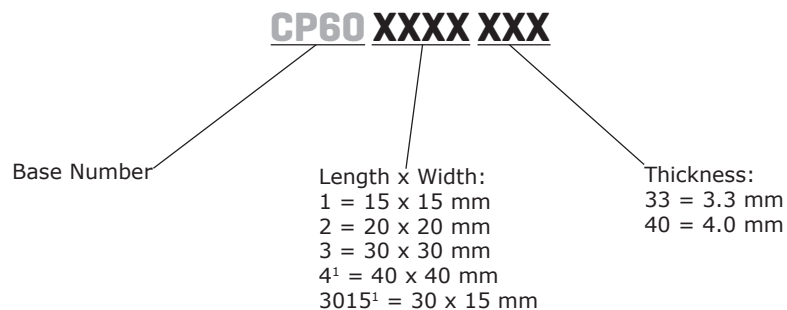
MODEL

MODEL	input voltage ¹ max (Vdc)	input current ² max (A)	output Q _{max} ³		output ΔT _{max} ⁴	
			T _h =27°C (W)	T _h =50°C (W)	T _h =27°C (°C)	T _h =50°C (°C)
CP60133	3.8	6.0	12.2	13.6	66	72
CP60233	8.6	6.0	27.9	31.2	66	72
CP60333	15.4	6.0	50.5	56.5	66	72
CP60140	2.1	6.0	7.1	7.9	68	75
CP60240	3.8	6.0	13.0	14.5	68	75
CP60301540	4.2	6.0	14.5	16.1	68	75
CP60340	8.6	6.0	29.0	32.4	68	75
CP60440	15.4	6.0	53.0	59.3	68	75

Notes:

1. Maximum voltage at ΔT_{max} and T_h=27°C
2. Maximum current to achieve ΔT_{max}
3. Maximum heat absorbed at cold side occurs at I_{max}, V_{max} and ΔT=0°C
4. Maximum temperature difference occurs at I_{max}, V_{max} and Q=0W (ΔT_{max} measured in a vacuum at 1.3 Pa)

PART NUMBER KEY



Notes:

1. Only available in 4.0 mm thickness

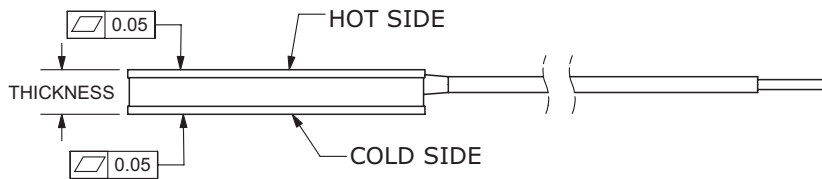
SPECIFICATIONS

parameter	conditions/description	min	typ	max	units
internal resistance ¹	CP60133	0.45	0.50	0.55	Ω
	CP60233	1.08	1.20	1.32	Ω
	CP60333	1.98	2.20	2.42	Ω
	CP60140	0.261	0.29	0.319	Ω
	CP60240	0.477	0.53	0.583	Ω
	CP60301540	0.513	0.57	0.627	Ω
	CP60340	1.089	1.21	1.331	Ω
	CP60440	1.953	2.17	2.387	Ω
solder melting temperature	connection between thermoelectric pairs	138			$^{\circ}\text{C}$
assembly compression	all other models			0.98	MPa
	CP60301540			1	MPa
hot side plate				80	$^{\circ}\text{C}$
RoHS	2011/65/EU				

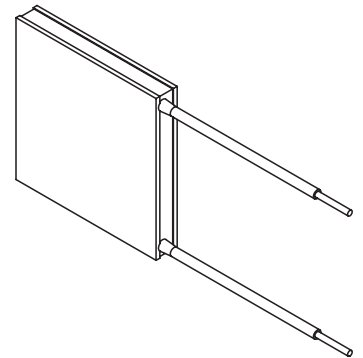
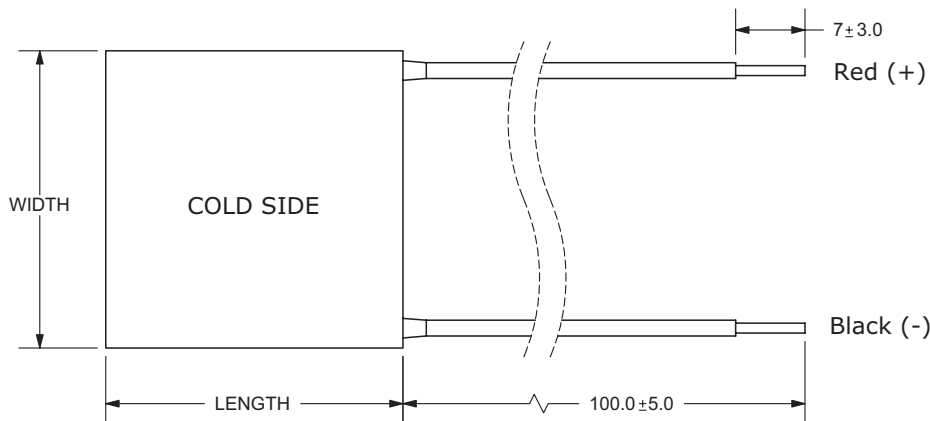
Note: 1. Measured by AC 4-terminal method at 25 $^{\circ}\text{C}$

MECHANICAL DRAWING

units: mm

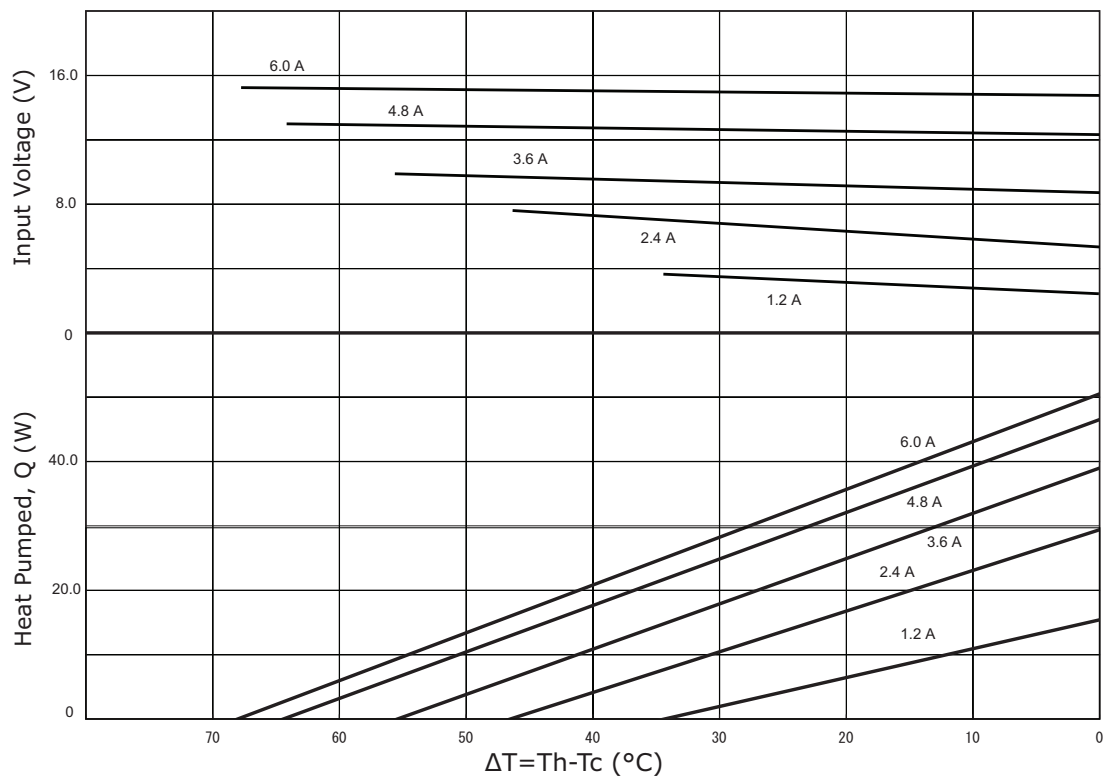


	MATERIAL	PLATING
ceramic plate	96% Al_2O_3	
wire leads	20 AWG	tin
sealer	silicon rubber 703 RTV (between cold and hot side plates)	
joint cover	silicon rubber 703 RTV	
marking	P/N & S/N printed on cold side surface	

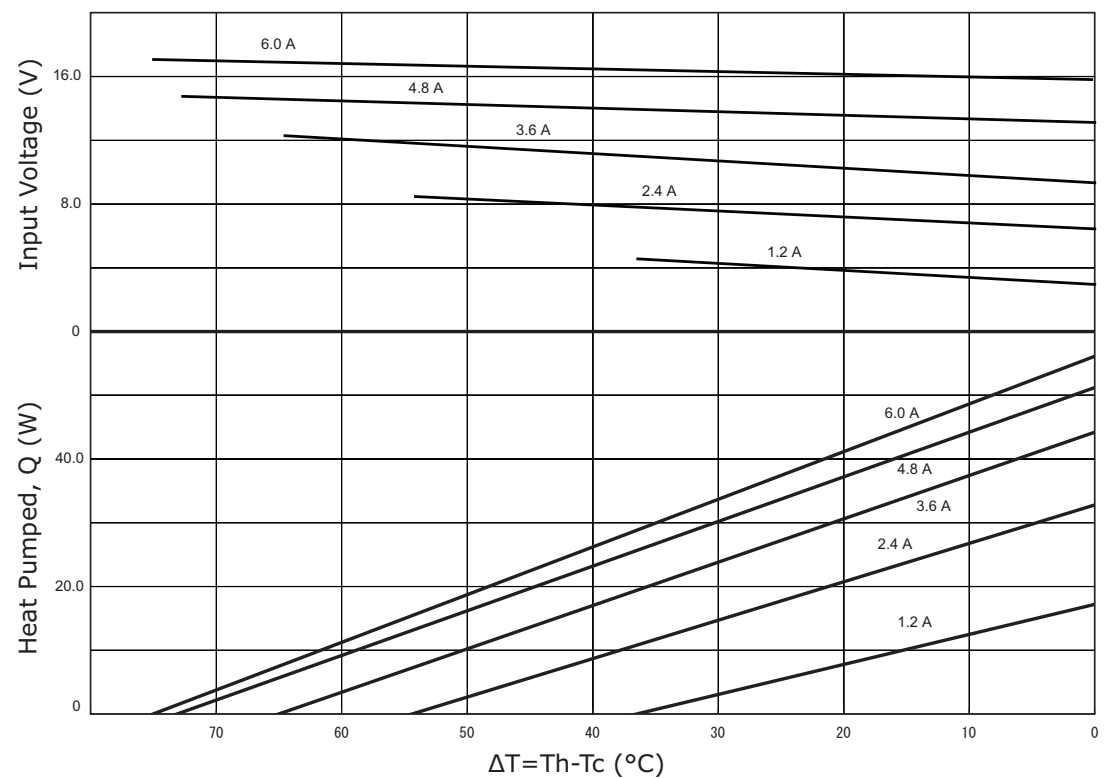


MODEL NO.	LENGTH (mm)	WIDTH (mm)	THICKNESS (mm)
CP60133	15 ± 0.3	15 ± 0.3	3.3 ± 0.1
CP60233	20 ± 0.3	20 ± 0.3	3.3 ± 0.1
CP60333	30 ± 0.3	30 ± 0.3	3.3 ± 0.1
CP60140	15 ± 0.3	15 ± 0.3	4.0 ± 0.1
CP60240	20 ± 0.3	20 ± 0.3	4.0 ± 0.1
CP60301540	30 ± 0.3	15 ± 0.3	4.05 ± 0.1
CP60340	30 ± 0.3	30 ± 0.3	4.0 ± 0.1
CP60440	40 ± 0.3	40 ± 0.3	4.0 ± 0.1

CP60333 PERFORMANCE (Th=27°C)



CP60333 PERFORMANCE (Th=50°C)



FL601 Umlaufkühler / Umwälzkühler

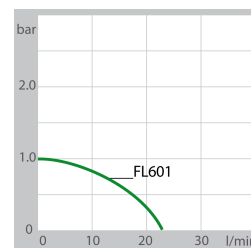
Mehr als 20 Modelle für Anwendungen in Labor und Industrie

Umlaufkühler für wirtschaftliches und umweltfreundliches Kühlen.

Die FL-Reihe bietet eine neue Generation von Umlaufkühlern für vielfältige Kühlaufgaben in Labor und Industrie. Die Temperaturkonstanz der PID-Regelung beträgt $\pm 0.5^\circ\text{C}$. Die Geräte sind mit einer leicht zu reinigenden und spritzwassergeschützten Folientastatur mit LED-Temperaturanzeige ausgestattet, zusätzlich befinden sich an der Gerätefront eine RS232 Schnittstelle sowie ein Alarm-Ausgang. Die Einfüllöffnung ist gut zugänglich an der Oberseite angebracht, geschützt durch eine aufklappbare Abdeckung. Ein weiteres aufklappbares Fach dient zur Ablage der Betriebsanleitung oder weiteren Geräteunterlagen. Das abnehmbare Lüftungsgitter ermöglicht eine einfache Reinigung des Verflüssigers, hinter dem Gitter befindet sich der Ablaufhahn. Zur weiteren Ausstattung bei allen Modellen gehört eine gut sichtbare Füllstandsanzeige. Ein weiterer Vorteil ist der Verzicht auf seitliche Lüftungsschlitze, die Geräte können dadurch direkt neben anderen Geräten aufgestellt werden (Platzgewinn).

Ihre Vorteile

- Ergonomisches Design und einfache Bedienung
- Spritzwassergeschützte Folientastatur mit integriertem Netzschalter
- Große, leuchtstarke LED-Temperaturanzeige
- Zuverlässige Mikroprozessor-PID-Temperaturregelung
- Füllstandsanzeige
- Dauerbetriebssichere, leistungsstarke Eintauchpumpen
- Zulässige Rücklauftemperatur $+80^\circ\text{C}$
- Einfache Befüllung von oben durch aufklappbare Einfüllöffnung
- Unterniveauschutz mit optischem und akustischem Signal
- Integrierte Edelstahl-Badgefäße
- Abnehmbares Lüftungsgitter zur leichten Reinigung des Verflüssigers
- Leicht zugänglicher Ablaufhahn an Frontseite
- Keine seitlichen Lüftungsschlitze
- RS232 Schnittstelle für direkten PC-Anschluß
- IP-Klasse nach IEC 60529: 21
- Alarmausgang, potentialfreier Wechselkontakt (max. 30 VA)



● Pumpenleistung (Wasser)

Technische Daten

Bestellnr.	9661006
Modellreihe	FL Reihe
Kategorie	Umlaufkühler / Umwälzkühler
Arbeitstemperaturbereich ($^\circ\text{C}$)	-20 ... +40
Temperaturkonstanz ($^\circ\text{C}$)	± 0.5
Einstell- /Anzeigeauflösung	0.1 $^\circ\text{C}$

Temperaturanzeige	LED					
Kälteleistung (Medium Ethanol)	°C	20	10	0	-10	-20
	kW	0.6	0.5	0.4	0.33	0.2
Pumpenleistung Förderstrom (l/min)	23					
Pumpenleistung Förderdruck (bar)	1.0					
Pumpenanschlussgewinde	M16x1					
Schlaucholiven Ø mm I.W	8 / 12					
Füllvolumen (Liter)	5.5 ... 8					
Kältemittel Stufe 1	R452A					
Füllvolumen Kältemittel Stufe 1 (g)	325					
Treibhauspotential für R452A	2140					
Kohlendioxidäquivalent Stufe 1 (t)	0.696					
Digitale Schnittstelle	RS232					
	Optional: Profibus					
Zulässige Umgebungstemperatur	5...40 °C					
Abmessungen B x T x H (cm)	32 x 50 x 60					
Gewicht (kg)	48					
Schalldruckpegel (Abstand 1 m) max. (dBA)	55					
Lieferumfang	Je 2 Schlaucholiven für Schlauch 8 und 12 mm I.W. (Pumpenanschlüsse mit M16x1 Außengewinde)					
Kühlung Kältemaschine	Luft					
Lieferbare Spannungsvarianten	230 V / 50 Hz					
	115 V / 60 Hz					
	230 V / 60 Hz					

Einsetzbare Medien: Wasser, Wasser-Glykol-Gemische, JULABO Thermal-Temperierflüssigkeit.

Eigenschaften

Anzeige



Gut erkennbar

Große LED Temperaturanzeige für Istwert und Sollwert (Anzeigeauflösung 0.1 °C)

Temperaturregelung



Präzise

PID Temperaturregelung mit fest eingestellten Regelparametern, Konstanz $\pm 0.02 \dots \pm 0.2$ °C

Technische Ausstattung



Serielle Anbindung

RS232 Schnittstelle zur PC-Anbindung, z. B. für Datenkommunikation bzw. Messwertaufzeichnung

Bedienung



Einfach und schnell

Bequeme 3-Tasten-Bedienung für Sollwerteinstellung (FL Modelle)

Kältetechnik



Kälteleistung stabil halten

Leicht abnehmbares Lüftungsgitter zur bequemen und einfachen Entfernung von Staub