

# **Thermal Measurements and Characterizations for the CMS Phase-1 Barrel Pixel Detector and the CMS Phase-2 Upgrade Tracker 2S Module with Evaporative CO<sub>2</sub> Cooling Systems**

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## Zusammenfassung

Bei dem Phase-1-Pixeldetektor und dem Phase-2-Spurdetektor handelt es sich um Upgrade-Detektoren für den Siliziumspurdetektor des CMS-Experiments am LHC am CERN. Die Upgrades sind notwendig für den erfolgreichen Betrieb des CMS-Spurdetektors bei den höheren instantanen und integrierten Luminositäten des LHC bzw. HL-LHC. Der Phase-1-Pixeldetektor wurde im Winter 2016/2017 eingebaut und der Phase-2-Spurdetektor wird zwischen 2025 und 2027 installiert werden.

Beide Detektoren werden Strahlenschäden erleiden, die beinahe eine Größenordnung höher sind als die Werte, für die die ursprünglichen Detektoren ausgelegt wurden. Die höheren Strahlenschäden, größtenteils Defekte im Kristallgitter, führen zu höheren Leckströmen in den Siliziumsensoren. Die Stärke der Leckströme hängt etwa exponentiell von der Temperatur ab und verdoppelt sich bei einer um etwa 7 K höheren Sensortemperatur. Durch den Effekt des „thermal runaway“, dem unkontrollierten Selbstaufheizen des Siliziumsensors, werden die Detektoren nach gegebener Zeit nicht mehr funktionsfähig sein. Zur Verlängerung der Betriebsdauer müssen die Leckströme durch Kühlung bei niedrigen Temperaturen deutlich verringert werden. Der Betrieb der Detektoren hängt aus diesem Grund entscheidend von der Funktionsweise und Auslegung ihrer Kühlung ab. Die Kühlung erfolgt bei Temperaturen, die 20 K oder mehr unter dem Gefrierpunkt liegen. Die Mechanik des Detektors muss für geringe Temperaturunterschiede zwischen Siliziumsensor und Kühlmittel optimiert werden.

In beiden Detektoren wird eine zweiphasige CO<sub>2</sub>-Kühlung benutzt, die eine nominelle Kühlmitteltemperatur von  $-22^{\circ}\text{C}$  bzw.  $-35^{\circ}\text{C}$  hat. Thermische Messungen mit Testprototypen sind während der Planung des Detektors von großer Relevanz und unerlässlich. In dieser Arbeit werden thermische Messungen und Charakterisierungen des Phase-1-Pixeldetektors und des 2S-Moduls für den Phase-2-Spurdetektor mit zweiphasigen CO<sub>2</sub>-Kühlsystemen präsentiert. Die Ergebnisse beider Projekte haben innerhalb der CMS-Tracker-Kollaboration wesentlich zum Verständnis der thermischen Eigenschaften der beiden Detektoren beigetragen.

Das 2S-Modul wird detailliert in seinen thermischen Eigenschaften charakterisiert. Bei dem 2S-Modul handelt es sich um ein Siliziumstreifenmodul mit zwei Siliziumstreifensensoren und drei elektronischen Hybriden. Der Leistungsverbrauch eines 2S-Moduls liegt typischerweise bei 5.4 W für die Hybride und bei 0.3 bis 0.5 W für einen Sensor. Systematische thermische Messungen wurden mit 2S-Testmodulen in einem Aufbau, der speziell für diesen Zweck entwickelt wurde, und mit einem hauseigenen CO<sub>2</sub>-Kühlsystem bei  $-30^{\circ}\text{C}$  durchgeführt. Zunächst wird das 2S-Modul ohne Hybride charakterisiert, wobei die Temperaturwiderstände im Modul und die thermische Anbindung an die Umgebung bestimmt werden. Im Folgenden werden die thermischen Eigenschaften des 2S-Moduls mit Hybriden und Drahtbonds untersucht. Der Effekt des „thermal runaway“ wird nachgestellt. Alle Messergebnisse werden mit Vorhersagen aus Finite-Elemente-Simulationen verglichen und die darin gemachten Annahmen konnten durch die Messergebnisse bestätigt werden.

Mit einem Testaufbau einer Halbschale der zweiten Lage des Barrels des Phase-1-Pixeldetektors wurden thermische Messungen an einem LUKASZ-CO<sub>2</sub>-Kühlsystem durchgeführt. Bei einer Wärmeleistung von rund 200 W treten Temperaturgefälle von 4 bis 5 K entlang einer Kühlschleife aufgrund des Druckabfalls im zweiphasigen CO<sub>2</sub> innerhalb des Rohres auf. Dieser Temperaturgradient führt zu einer systematischen Temperaturverteilung im Detektor und der temperaturabhängige Leckstrom der Siliziumpixelsensoren wird direkt davon beeinflusst. Im realen Detektor wurden Leckstromverteilungen beobachtet, die sich durch relative Faktoren von 1.4 zwischen den einzelnen Power-Sektoren unterscheiden, was mit den Messungen im Testaufbau kompatibel ist. Mit dem Testaufbau wurde vorhergesagt, dass das Temperaturgefälle im Detektor durch Reduzierung des CO<sub>2</sub>-Massenflusses verringert werden kann, und dieser Effekt konnte im Detektor verifiziert werden.



## Abstract

The CMS Phase-1 pixel detector and the CMS Phase-2 tracker are upgrade detectors for the silicon tracker of the CMS experiment at LHC, CERN. The upgrades are inevitable for the efficient performance of the CMS tracker at higher instantaneous and integrated luminosities of the LHC and the HL-LHC, respectively. The Phase-1 pixel detector was installed in winter 2016/2017 and the Phase-2 upgrade tracker will be installed from 2025 to 2027.

The detectors will experience radiation damage at levels which are nearly an order of magnitude higher than the values the original detectors were designed for. The higher radiation damage leads to higher leakage currents in the silicon sensors, because of induced defects in the crystal lattice. Their values depend approximately exponentially on the sensor temperature, with roughly a factor 2 at a temperature increase of 7 K. The effect of thermal runaway, which denotes the non-linear self-heating of the silicon sensors because of their leakage current, will eventually make the detectors inoperative. By cooling the detectors to low temperatures, the leakage currents can be drastically mitigated and their longevity enhanced. Hence, the thermal performance of the cooling structure is crucial for the operation. Coolant temperatures (a few 10 K below 0 °C) are necessary. The mechanics of the detectors have to be optimized for small temperature gradients in the order of 10 K between the silicon sensors and the coolant.

Both detectors use the concept of evaporative CO<sub>2</sub> cooling systems at nominal coolant temperatures of −22 °C and −35 °C, respectively. Thermal measurements with test prototypes, so-called thermal dummies or mock-ups, are an important part of the detector design and construction. This thesis presents measurements and characterizations of the thermal properties for the Phase-1 barrel pixel detector and for the 2S modules of the Phase-2 Upgrade tracker with evaporative CO<sub>2</sub> cooling systems. Within the CMS Tracker collaboration, the results of both measurement projects contributed substantially to the understanding of the thermal properties of these detectors.

For the Phase-2 part, a detailed characterization of the thermal properties of the 2S module is presented. The 2S module is a silicon strip module with two silicon sensors and three electronic hybrids. Typical power values are 5.4 W for the hybrids and 0.3 to 0.5 W for each sensor. Dummy 2S modules were built and systematic thermal measurements were made. A dedicated test setup was developed, constructed, and commissioned. A custom CO<sub>2</sub> system with a cooling temperature of −30 °C was used. The thermal resistance of the sensors to the cooling system was measured with bare modules with no hybrids attached and the thermal coupling of the sensors to the ambient was estimated. The thermal performance of a fully assembled 2S module with hybrids and wirebonds is studied. The effect of thermal runaway is demonstrated. All test results are directly compared to predictions from Finite Element simulations which have been developed. The mechanical assumptions made in the Finite Element model could be confirmed with measurements.

For the Phase-1 part, thermal measurements with a thermal mock-up of one Layer 2 barrel pixel detector half-shell and 112 thermal pixel dummy modules were conducted. The measurements were made with a LUKASZ CO<sub>2</sub> cooling system. At the full heat load of 200 W temperature drops of 4 to 5 K along one cooling line could be observed because of pressure drops in the two-phase CO<sub>2</sub> in the pipes. The temperature gradient in the detector leads to a systematic temperature distribution in the detector. This effect directly affects the temperature dependent leakage currents of the silicon pixel sensors. The observed leakage current distributions with relative factors of 1.4 between power sectors in the real BPIX detector are compatible with the predictions from the measurements with the mock-up. It was predicted from the measurements and shown in the real detector that changing the CO<sub>2</sub> mass flow reduces the temperature gradients in the detector.



# Thesis





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# 1. Overview

The CMS (Compact Muon Solenoid) experiment [1] is one of the leading high-energy physics experiments in the world. It is located at the LHC (Large Hardon Collider, [2]) at CERN (European Council for Nuclear Research, [3]) next to Geneva, Switzerland. The CMS experiment measures the nature of physical states and processes produced in LHC collision events since 2010. The LHC is mainly operated with proton-proton collisions at a center-of-mass energy of  $\sqrt{s} = 7, 8, \text{ and } 13 \text{ TeV}$ . The CMS experiment, together with the other major LHC experiments, holds a unique potential for physical measurements at these energy scales.

The CMS experiment uses a multi-purpose particle detector which is built hermetically around one LHC interaction point. Final state particles arising from LHC collision events are detected and identified, which makes the reconstruction of the physical interaction process in an event possible. CMS is capable of reconstructing events on energy scales ranging over several orders of magnitude, from a few 100 MeV up to approximately 10 TeV. The CMS detector consists of several subdetector systems, with dedicated functions assigned to each subdetector. With a silicon tracker detector in a 3.8 T magnetic field CMS measures the momentum and the charge sign of charged particles and the vertices of the collisions. The energy of electromagnetic particles ( $e^\pm$  and  $\gamma$ ) are measured in an electromagnetic calorimeter. The energy of hadronic particles is measured in an hadronic calorimeter. Muons are identified in a muon detector system which provides also a momentum measurement.

The silicon tracker of the CMS experiment reconstructs and measures the vertices and tracks of charged particles produced in high-energy particle collisions at the LHC. It consists of two subdetectors, the strip detector and the pixel detector. The pixel detector uses hybrid pixel modules for the reconstruction of primary and secondary vertices. The strip detector uses silicon strip modules in order to measure transverse momentum of charged particles in the 3.8 T magnetic field of CMS. The harsh radiation environment close to the LHC interaction point limits the longevity of these detectors. The LHC exceeded its design instantaneous luminosity of  $1.0 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  already in 2016. In 2017 and 2018, instantaneous luminosities of a factor of two higher than the design instantaneous luminosity were reached. For the high-luminosity upgrade of the LHC instantaneous luminosities of  $5.0 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  are planned. The original detectors become inefficient under the conditions of the higher event rates at higher instantaneous luminosities.

For the pixel detector it was estimated from simulations that the hit efficiency of the old pixel detector would decrease by 16 % for an instantaneous luminosity of  $2.0 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  in the innermost layer. The tracking efficiency (fake rate) would have decreased (increased) substantially. The hit resolution would have suffered by a factor of two from less charge collection in the sensors because of radiation damage, with a significant impact on e.g. the vertex resolution and the b-tagging performance. As a consequence, the original pixel detector of CMS (Phase-0 Pixel Detector) was replaced in winter 2016/2017 with a new pixel detector (Phase-1 Pixel Detector) [4]. The Phase-1 Pixel Detector has got a fourth barrel layer and the innermost layer is moved towards the interaction to a radius of 2.9 cm. A new readout chip with larger data buffers and a digital readout is used in the detector in order to lower the inefficiencies. The material budget of the upgrade detectors is optimized by using the principle of DC-DC conversion and a two-phase CO<sub>2</sub> cooling concept in the active detector volume. In the Phase-1 Pixel Detector, it is the first time that these technologies are used in the active detector volume in the CMS experiment.

The current strip detector cannot be operated after an integrated luminosity of about  $1000 \text{ fb}^{-1}$ , mainly because of the high radiation damage of the silicon sensors. The radiation damage would

lead to an unacceptable decrease in the tracking performance. The current tracker would be also limited in terms of readout bandwidth and trigger latency. In 2025/2026, a replacement of the entire silicon tracker with the CMS Phase-2 Tracker is foreseen as part of the CMS Phase-2 Upgrade [5]. The new tracker has to withstand radiation levels up to  $2.3 \cdot 10^{16}$  neq/cm<sup>2</sup> in the innermost layers and it will have an increased granularity compared to the current tracker. By the implementation of a track trigger system the Phase-2 tracker will contribute to the Level-1 trigger system of CMS. The acceptance of the new detector will be extended to  $\eta = 4$ . The implementation of a CO<sub>2</sub> cooling system and a DC-DC conversion scheme will contribute to the reduction of the material budget of the upgrade tracker.

The high radiation damage from the LHC collisions increases the leakage currents in the silicon sensors and hence the power consumption. This power has a characteristic exponential dependence on the sensor temperature, increasing with temperature. A temperature difference of about 7 K raises the leakage current by about a factor of 2. The non-linear thermal characteristics of the leakage current can lead to a situation that the sensors would heat up in an uncontrolled way and no stable working point of the cooling would be possible. This effect is commonly called thermal runaway. For the longevity under high radiation damage conditions it is therefore necessary to operate the detector at low CO<sub>2</sub> cooling temperatures. The nominal cooling temperature is  $-22^\circ\text{C}$  for the Phase-1 Pixel Detector and  $-35^\circ\text{C}$  for the Phase-2 Tracker. The mechanics in the active detector volume has to guarantee a stable and reliable cooling performance at the lowest material budget possible. Low diameter cooling pipes with inner diameters equal or smaller than 2 mm and thin carbon fiber structures are used for the detector construction.

An insufficient layout of the cooling system or of the mechanical cooling structure can affect the operation of the detector severely. Detector failures in any order, because of an insufficient cooling, are highly unacceptable and have to be avoided at any moment. A good and detailed understanding of the thermal properties and performance is therefore crucial during both the design and prototyping phase of the detector and the operation phase of a detector. For that purpose, prototype test setups which only demonstrate the thermal characteristics of the detector, but have no physical functionality, have to be developed and constructed. With these so-called dummies or mock-ups thermal measurements are conducted.

This thesis presents thermal measurements and characterizations for the Phase-2 Outer Tracker 2S modules and the Phase-1 Pixel Detector made with mock-ups and dummies. Their mechanics are as similar as possible to the real detector structures and assembled with the procedures of the real detector assembly. The measurements are performed with evaporative CO<sub>2</sub> cooling systems at temperatures similar to the real detector operation temperatures. The measurement results of both projects are the most detailed thermal characterizations of the respective subdetector part that are available in the CMS Tracker collaboration by the time of writing this thesis.

The 2S module for the Phase-2 Upgrade tracker is a device containing two approximately  $10\text{ cm} \times 10\text{ cm}$  large silicon strip sensors, two front-end hybrids, and a service hybrid for the optical readout and the power distribution. The power consumption of one 2S module is in the order of 6 W. Two thermal dummy modules were built with the assembly processes foreseen for the series production. Their thermal properties were systematically measured. A dedicated thermal test setup was developed, constructed and commissioned. The measurements were performed with a CO<sub>2</sub> cooling system at RWTH Aachen at CO<sub>2</sub> temperatures of  $-30^\circ\text{C}$ . A cooling structure like in the endcaps of the Phase-2 Tracker is used for the tests. The thermal characteristics of the mechanics of the 2S dummy modules are presented. The characterization was done in two steps, firstly with two dummy bare modules without hybrids, and secondly with a fully assembled dummy module with dummy hybrids. Thermal interchange of the 2S module and the test setup with the ambient was identified and incorporated as corrections into the thermal analysis. This enables the elimination of many measurement uncertainties. The results

of the thermal measurements were compared to Finite Element simulations made in COMSOL<sup>®</sup> Multiphysics. The assumptions on the mechanical properties of the 2S module in the FE model were checked with the measurements. The effect of thermal runaway was simulated in the FE simulations and also demonstrated in the test setup under certain assumptions.

The thermal measurements of the Phase-1 barrel pixel (BPIX) detector are made with a thermal mock-up of one Layer 2 half-shell. The mechanics of the half-shell is identical to the mechanics in the real BPIX detector. It is equipped with 112 thermal dummy pixel modules. The mechanics and the modules of the mock-up is constructed with left-over or spare components from the BPIX detector assembly. The temperature distribution in the mock-up generated by the CO<sub>2</sub> cooling is investigated. The cooling pipes in the active detector volume have a length of about 450 cm and an inner diameter of 1.5 mm. The pressure drop along the thin cooling pipes leads to a temperature distribution in the detector with temperature differences in the order of up to 5 K. This effect was measured with the mock-up. The temperature distribution in the detector directly affects the leakage currents in the detector. Differences in the leakage current per module varying by factors larger than 1.4 were measured in the real BPIX detector. The leakage current distribution in the detector is estimated from the mock-up data and compared to the BPIX leakage currents.

Chapter 2 comprises the standard model of particle physics. Chapter 3 describes the LHC at CERN. A description of the CMS experiment with its subdetectors and an overview of its planned upgrades is given in Chapter 4. The Phase-1 Pixel Detector is described in Chapter 5 and the Phase-2 Upgrade tracker is described in Chapter 6. Chapter 7 contains the part on the thermal measurements with the 2S module and Chapter 8 contains the part on the thermal measurements with the BPIX Layer 2 Mock-up. The thesis closes with a summary and a conclusion in Chapter 9.





## 2. Standard Model of Particle Physics

The Standard Model is the well-established theory in particle physics. It comprises three of four fundamental forces in physics, the electromagnetic, the weak, and the strong force. In the Standard Model, these interaction forces are exchanged by force carriers ( $\gamma$ ,  $W^\pm$ ,  $Z$ , gluons), and the physical states participating in the interactions are matter particles (leptons, quarks). In order to keep local gauge invariance and to allow at the same time for massive exchange particles of the weak force, the 'Higgs mechanism' completes the Standard Model with the Higgs field and its excitation, the Higgs boson (H) [6].

The Standard model does not predict the masses of the elementary particles, but they have to be experimentally determined. The measured masses of particles range from sub-eV orders, where only upper limits on the masses can be set (neutrinos), to the order of 100 GeV ( $W^\pm$ ,  $Z$  and H boson, and top quark). Since the discovery of the Higgs boson in 2012, the existence of all Standard Model particles is experimentally confirmed.

Many theoretical predictions from the Standard Model have been experimentally probed, with high accuracy and positive success. Nevertheless, the Standard Model is still considered to be incomplete as there are observations in nature which cannot be explained, such as e.g. the matter-antimatter asymmetry, the amount and nature of dark matter in the universe, the hierarchy problem, or the gravitational force. Many theoretical extensions to the Standard Model (e.g. supersymmetry) partially answer these open questions. Searches for new physics can be based on such models or be model independent.

Generally, particle physics experiments are performed at various mass scales with different scopes, detector designs and precision. They focus on precision measurements of standard model physics or on search for new physics, or on both. In accelerator experiments for particle physics two important key parameters can be defined: the center-of-mass energy and the luminosity. An increase of center-of mass energy in particle collisions makes it possible to explore higher energy and mass scales. The instantaneous luminosity is a measure of the intensity of a particle beam: the event rate of a given physical process is proportional to its cross section and to the instantaneous luminosity of the particle beam(s). With higher integrated luminosity the statistics of the recorded data is increased and measurements can be analyzed with higher precision, increasing sensitivity to rare physical processes.

Currently, the highest center-of-mass energies at very high luminosities are achieved at the Large Hadron Collider, which is described in more detail in the following chapter.



### 3. The Large Hadron Collider (LHC)

The LHC (Large Hadron Collider [2]) is a superconducting synchrotron and collider for protons and heavy ions. It is located at CERN (European Center of Nuclear Research [3]) in the city region of Geneva, Switzerland. In terms of energy, luminosity, magnetic field strength, financial budget and many other parameters, it is the largest particle accelerator ever constructed. It has a circumference of approximately 27 km and was built in a tunnel up to 175 m beneath earth's surface. Its design proton energy is 7 TeV which leads to a design center-of-mass energy of 14 TeV in proton-proton collisions. The design peak luminosity was  $\mathcal{L}_{\text{inst}} = 1 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$ . With these parameters, the LHC holds a unique potential for measurements and discoveries in high-energy physics. The spacing time between two particle bunches in the ring is 25 ns, resulting in a bunch crossing frequency of 40 MHz. The LHC is mostly operated with proton beams only, but it has also been operated as a proton-Pb, a Pb-Pb, or Xe-Xe collider. In the following only the operation mode with proton-proton collisions is considered.

The LHC is filled from a complex pre-accelerator chain, shown in Figure 3.1, where the energy of the beams is ramped up step-wise in consecutive accelerators. Many key parameters of the proton beams are formed in the pre-accelerator chain, like e.g. the beam emittance or the number of particles per bunch. Protons are obtained from dissociated hydrogen atoms and are rapidly accelerated in the LINAC 2 (linear accelerator) and the PS booster (PSB, four parallel synchrotrons) to a relativistic energy of 1.4 GeV. The PS (Proton Synchrotron) and the SPS (Super Proton Synchrotron) accelerate the beams consecutively to an energy of 450 GeV until they are fed into the LHC ring. In the LHC ring, more than 1200 superconducting dipole NbTi magnets with a maximum field strength of 8 T bend the particle beams along the ring. More than 800 superconducting quadrupole and additional higher order multipole magnets form the beam optics.

Four major high-energy physics experiments (ALICE [7], ATLAS [8], CMS [1], and LHCb [9]) are installed at four interaction points of the LHC. They differ in size, detector design, and versatility and focus on different physics phenomena. ATLAS and CMS use hermetic multi-purpose detectors and their measurement programs cover a wide range. Both detectors are designed to sustain the highest LHC luminosities and have similar capabilities. Up to now, their greatest success was the discovery of the Higgs boson in 2012 [10, 11]. LHCb uses a one-sided forward spectrometer and its physical program focusses on b-quark physics, especially on rare b-decays and CP-violation. The measurement program of ALICE is focussed on physics in heavy ion collisions.

Figure 3.2 shows the history and the schedule of the LHC operation. Stable operation began in 2010. It is planned to exploit the full potential until the late 2030s. During Run 1 (2010 - 2012), the center-of-mass energy of the proton-proton collisions was 7 and 8 TeV and during Run 2 (2015 - 2018) it was 13 TeV. In Run 2, instantaneous luminosities higher than  $\mathcal{L}_{\text{inst}} = 2.0 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$  were reached. By the end of 2018, the LHC has delivered an integrated luminosity of nearly  $200 \text{fb}^{-1}$  to ATLAS and CMS.

For maintenance and upgrade works, the operation of the LHC is regularly paused in the so-called long shutdowns. Long Shutdown 1 (LS1) lasted from 2013 until 2014 and Long Shutdown 2 (LS2) has started at the beginning of 2019 and will be ended in early 2021. Long Shutdown 3 (LS3) is expected to last from 2025 until 2027. The LHC is being consecutively upgraded to the HL-LHC (High-Luminosity LHC) until the end of LS3. The HL-LHC is planned to reach luminosities of  $\mathcal{L}_{\text{inst}} = 5.0 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$  and will deliver an additional integrated luminosity of  $3000 \text{fb}^{-1}$  to ATLAS and CMS.

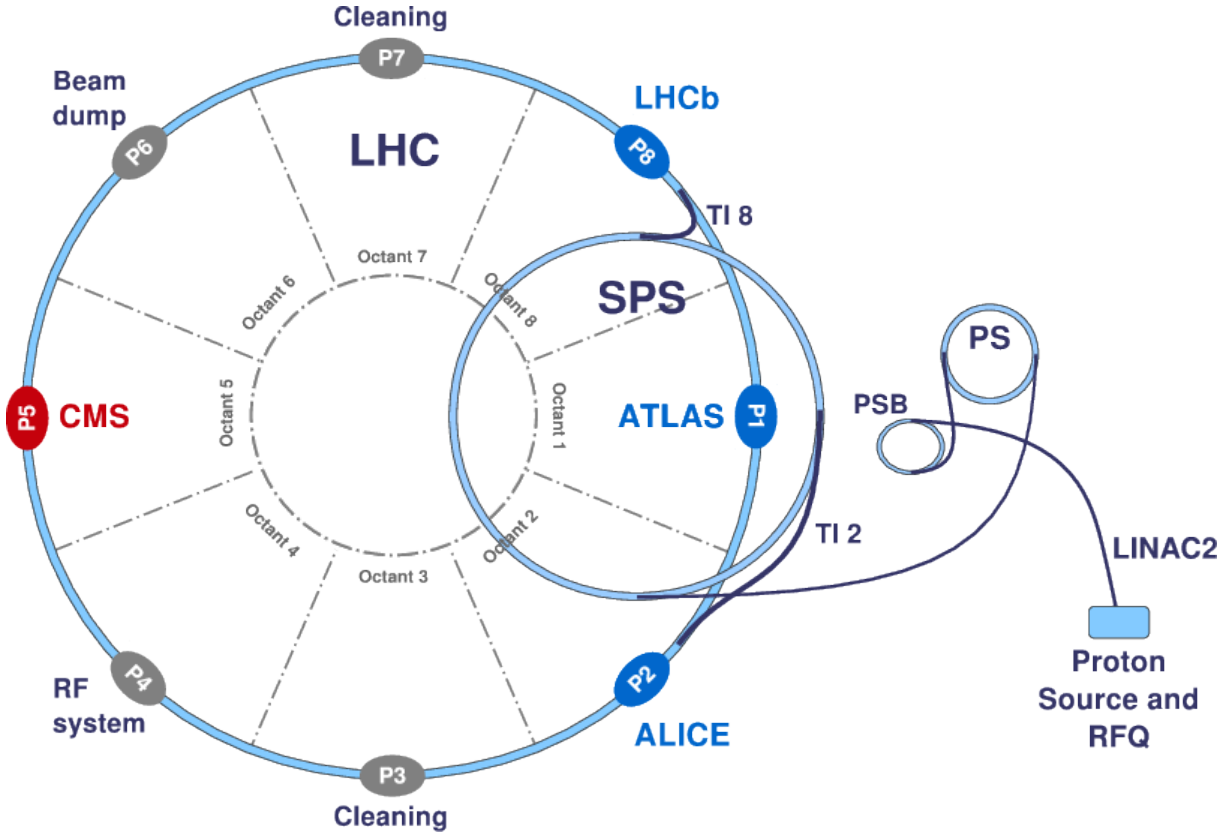


Figure 3.1.: Accelerator chain of the LHC complex. The accelerator chain for LHC protons consists of the LINAC 2, the PS Booster, the PS, the SPS, and finally the LHC. Image taken from Ref. [12].

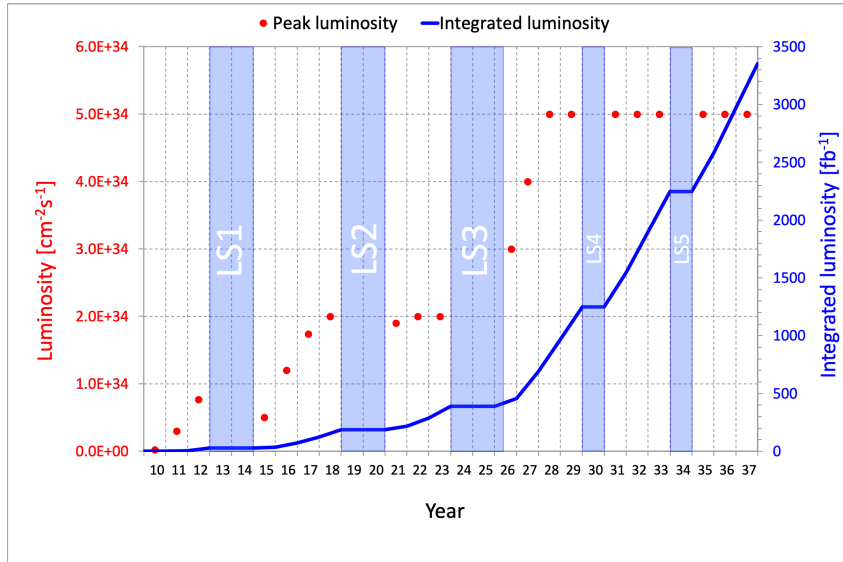


Figure 3.2.: Long-term schedule of the LHC from 2010 to 2037 [13]. Light blue areas denote the Long Shutdown periods. The operation of the HL-LHC will start after LS3. The instantaneous luminosity is increased up to  $\mathcal{L}_{\text{inst}} = 5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . For the end-of-lifetime, the minimum planned integrated luminosity of HL-LHC is  $\mathcal{L}_{\text{int}} = 3000 \text{ fb}^{-1}$ . Recently, it was decided to postpone LS3 by one year. No updated version of this plot is available yet.

## 4. The CMS Experiment

The CMS (Compact Muon Solenoid [1]) experiment is one of the four major high-energy physics experiments at the LHC. The CMS experiment covers and studies a wide range of topics and questions in modern high-energy physics. Both the precise testing of the Standard Model of Particle Physics and the search for new physics phenomena are subject to the measurement program of CMS. The name 'CMS' originates from its relatively compact construction and extent (*Compact*), from its advanced ability to measure muons (*Muon*), and from its 3.8 T superconducting solenoidal magnet (*Solenoid*). CMS started physics data taking in 2010 when the LHC started its regular operation. Since then CMS has recorded data with an integrated luminosity of nearly  $\mathcal{L}_{\text{int}} = 200 \text{ fb}^{-1}$  of proton-proton collisions.

### 4.1. Physics Program Overview

In 2012, CMS announced the discovery of the Higgs boson  $H$  at a mass of 125 GeV in the decays  $H \rightarrow 4\mu$  and  $H \rightarrow \gamma\gamma$  at a center-of-mass energy of  $\sqrt{s} = 7$  and 8 TeV, together with the ATLAS experiment [10, 11]. Since then, more precise analyses have been conducted, also at the higher center-of-mass energy of  $\sqrt{s} = 13$  TeV. Many properties of the Higgs boson predicted by the Standard Model have been confirmed with good success in more detail [14, 15]. The coupling to the heavy bosons and the Yukawa-coupling to third-generation fermions was measured [16]. In 2018, the most probable decay of the Higgs boson to two b-quarks ( $H \rightarrow b\bar{b}$ ) could be observed [17]. CMS expects to measure the decay to two muons,  $H \rightarrow \mu\mu$ , and the Higgs self-coupling, e.g.  $gg \rightarrow X \rightarrow HH$ , at the HL-LHC. In the Standard Model physics program CMS performs high-precision cross-section measurements in a range of ten orders of magnitude. With these measurements, CMS probes the Standard Model and is sensitive to rare processes. Important parts of the measurement program are the measurements of multijet production, vector boson production and decays, vector boson plus jets production, and multi-boson production and couplings. CMS gives constraints on particle probability density functions. The running of the strong coupling constant,  $\alpha_s$ , versus the momentum transfer is also measured with good precision at the energy frontier [18]. CMS conducts an extensive measurement program of the  $t\bar{t}$  and single-top production cross sections and kinematics in various final states, and makes important contributions to the world average values of the top quark measurements. Presumably, CMS will measure the four top-quark production cross section ( $pp \rightarrow X \rightarrow t\bar{t}t\bar{t}$ ) within the next years. CMS is also intensely involved in measurements in the sector of B-quark physics. In 2015, CMS published a paper together with the LHCb experiment on the measurement of the rare decay  $B_s^0 \rightarrow \mu\mu$ , which has a branching fraction of approximately  $3 \cdot 10^{-9}$  [19]. CMS supports an intensive program for the search for supersymmetry (SUSY) which has been predicted to exist for several decades, but no evidence for its existence has been observed so far in direct searches. CMS searches for supersymmetry in e.g. single-lepton, di-lepton, hadronic, photon, and missing transverse momentum final states. Many production modes (e.g. squarks, gluinos, charginos, neutralinos, ...) and SUSY models (e.g. GMSB) are investigated. The mass limits which are e.g. set for gluinos (squarks) in different SUSY models clearly exceed the value of 1 TeV (500 GeV). Searches for new physics are also performed in more exotic sectors, like e.g. the searches for leptoquarks or for new heavy resonances. CMS performs a wide measurement program in the field of heavy-ion physics with data from PbPb and pPb collisions at the LHC [20].

## 4.2. Detector Overview

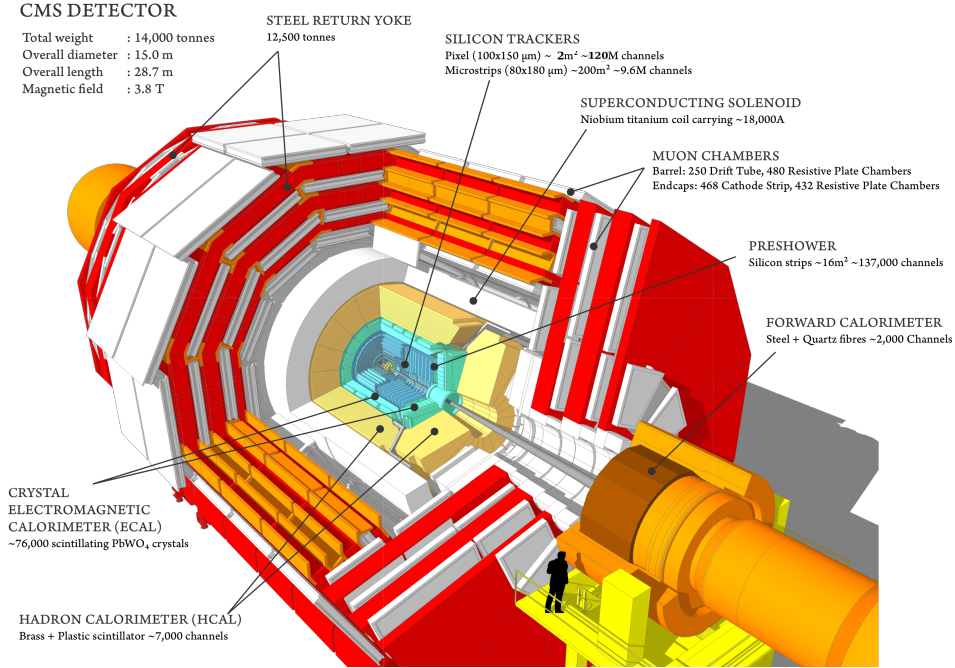


Figure 4.1.: Schematic view of the CMS detector. The interaction point of the LHC is located in the beam pipe (grey) in the center of the detector. It is surrounded by the Tracker (blue) with the pixel and the strip detector, the electromagnetic calorimeter (green), and the hadronic calorimeter (yellow). They are located in the inner volume of the solenoidal magnet (white). Outside the solenoid the muon system (white and orange) is embedded into the iron return yoke (red). The hadron forward calorimeter (orange) is located in the very forward position. A person is shown for scale. Image from Ref. [21] and edited.

## 4.2. Detector Overview

The CMS detector is located at LHC Point 5 in Cessy, France, in a cavern about 100 m under earth's surface. It is a multi-purpose detector which records and reconstructs the data of physical states produced in LHC collision events by detecting and combining the final state particles. A schematic view of the CMS detector is shown in Figure 4.1. The CMS detector is cylindrically shaped and has a length of 21 m and a diameter of 14 m. It is built hermetically around the LHC interaction point. The CMS detector design is optimized for a low-material budget tracking system with good momentum resolution, for identification and energy measurement of photons and electrons, and for clear signatures and momentum measurements of muons. A schematic view of the particle identification principle of CMS and its subdetectors is shown in Figure 4.2. The core of the CMS design is the superconducting solenoidal magnet. In its inner volume it produces a homogeneous field of 3.8 T parallel to the beam axis. All major subdetectors of CMS consist of a barrel part and an endcap part. Inside the magnet, the tracker detector, the electromagnetic calorimeter, and the hadronic calorimeter are located, and outside the magnet the muon system is located. The tracker reconstructs the vertices of collision events and measures the charge sign and the transverse momentum of charged particles. The electromagnetic calorimeter absorbs electrons and photons and measures their energy. The hadronic calorimeter absorbs hadronic particles and measures their energy. The muon system is embedded in the iron return yoke. It identifies muons and contributes to the measurement of their momentum as muon tracks are matched with the tracker information. Neutrinos are identified by reconstructing the missing transverse momentum in an event. A Particle Flow Algorithm is used for object identification and an improved energy resolution for charged components of hadronic jets. The CMS detector takes data at the LHC bunch crossing frequency of 40 MHz. A two-staged trigger system decides if a

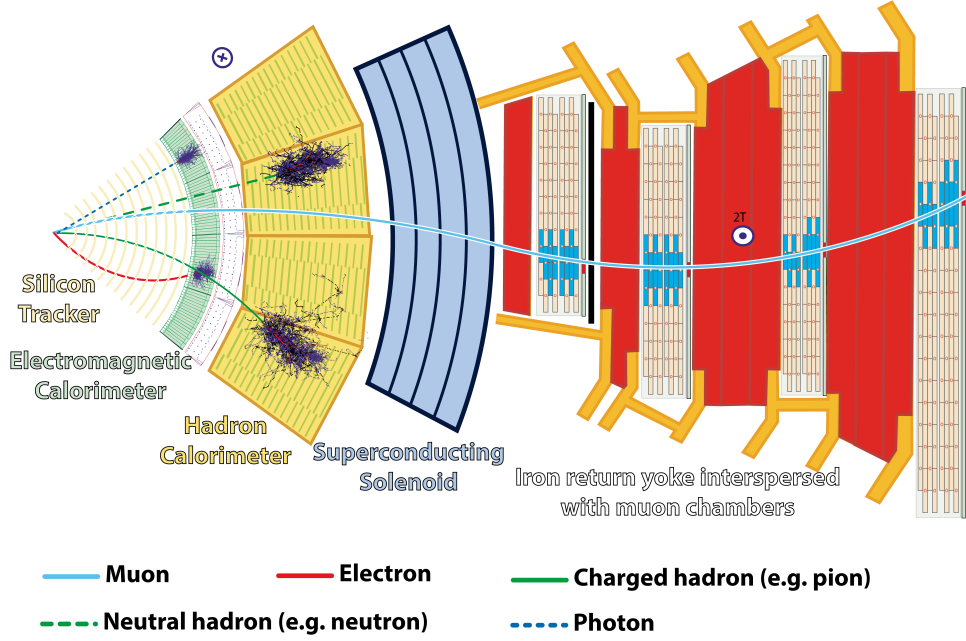


Figure 4.2.: Illustration of the particle identification principle of CMS [22]. Different types of particles generate characteristic signatures in the subdetectors. Neutrinos escape the detector and are reconstructed through the missing transverse momentum.

recorded event is saved to disk, reducing the event rate to approximately 1 kHz. In each triggered bunch crossing event several proton-proton collisions, so-called pileup events, are reconstructed. The number of pileup events per bunch crossing is a statistical process and is in the order of 50. The individual subdetectors are described in more detail in the following Sections 4.3 to 4.8.

CMS uses a right-handed coordinate system with its origin in the interaction point. The  $z$ -axis points along the counter-clockwise LHC beam direction, the  $x$ -axis points to the center of the LHC ring, and the  $y$ -axis points upwards. The radius  $r$  is measured from the origin and the azimuthal angle  $\phi$  is measured from the positive  $x$ -axis. The transverse plane is the  $r\phi$ -plane and it is orthogonal to the  $z$ -axis. The polar angle  $\theta$  is measured from the positive  $z$ -axis. The pseudorapidity  $\eta$  is defined in the  $rz$ -plane as  $\eta = -\ln(\tan \theta/2)$ . The transverse momentum  $\vec{p}_T$  of a particle is the projection of the particle momentum  $\vec{p}$  onto the transverse plane. The missing transverse momentum  $\vec{p}_T^{\text{miss}}$  of an event is defined as the negative sum of the transverse momenta of the particles in the event:  $\vec{p}_T^{\text{miss}} = -\sum_i \vec{p}_{T,i}$ .

### 4.3. The Magnet

The CMS magnet is a superconducting solenoidal magnet with a diameter of 6 m and a length of 13 m. The magnet cables are made of niobium-titanium filaments and conduct a current of about 18 000 A. The magnet produces a homogeneous magnetic field in its inner volume and the design magnetic field strength is 4 T. In order to increase the longevity of the magnet, it is operated with a field strength of 3.8 T. The magnetic flux is returned compactly through an iron yoke in the outer volume of the solenoid where the magnetic field is mostly below 2 T. The full weight of the magnet including the iron yoke is about 12 000 tons. The CMS magnet is the largest superconducting magnet ever built.

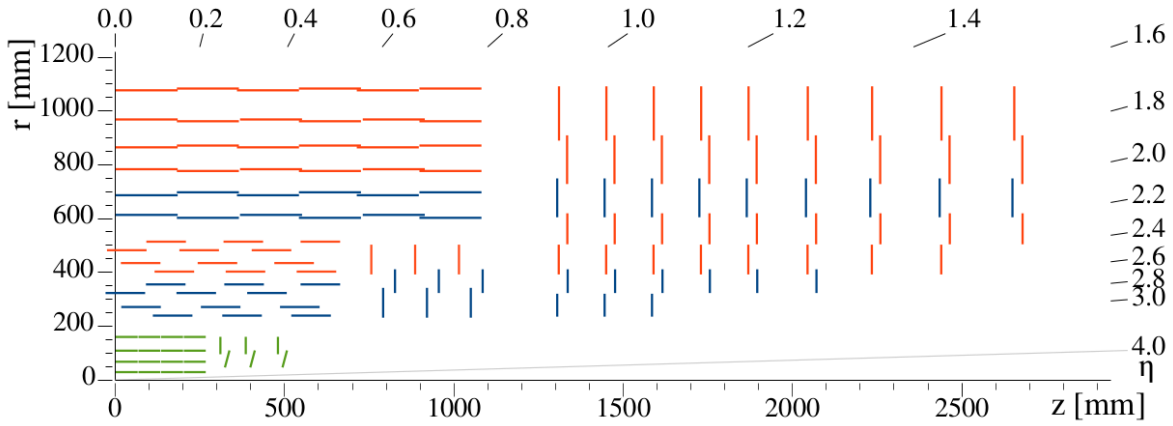


Figure 4.3.: Schematic view of one quadrant of the current CMS tracker in the  $rz$ -plane. The positions of the modules in the Phase-1 pixel detector are drawn in green. The positions of the modules of the strip detector are drawn in blue and red, where blue lines denote double-sided strip modules and red lines denote single-sided strip modules. [5]

## 4.4. The Tracker

The CMS tracker measures the trajectories of charged particles. Tracks of charged particles are bent in the magnetic field. They are reconstructed in the tracker from a fit to measured space points and the transverse momentum  $\vec{p}_T$  is computed. Primary and secondary vertices from collision events are reconstructed. The information on the tracks of charged particles emerging from an event is essential for the event reconstruction in CMS. The detector consists of two subdetectors, the silicon strip detector and the silicon pixel detector. Figure 4.3 shows a schematic view in the  $rz$ -plane of the current tracker. The transverse momentum resolution of the tracker is the best at  $|\eta| = 0$  and decreases for higher  $|\eta|$ -regions. For muons with  $1 \text{ GeV} < p_T < 10 \text{ GeV}$  it ranges from sub-percent levels in the barrel region to  $\approx 2\%$  in the endcap regions. For muons with  $p_T \approx 100 \text{ GeV}$ , transverse momentum resolutions from  $\approx 3\%$  in the barrel to  $\approx 10\%$  in the endcaps are achieved [23].

### 4.4.1. Pixel Detector

The Phase-1 pixel detector is the second pixel detector installed in CMS. It was installed in the year-end technical stop in winter 2016/2017. It is the subdetector closest to the interaction point and its active volume has an extent of about  $36 \text{ cm} \times 100 \text{ cm}$  and covers an  $\eta$ -range from 0 to 3.0. It is part of the tracking system and mainly used for a precise primary and secondary vertex reconstruction. The detector is divided into a barrel part (BPIX) and a forward part (FPix). BPIX consists of four layers which are arranged cylindrically and parallel to the beam pipe at radii between 2.9 cm and 16 cm in the  $z$ -region between  $-27 \text{ cm}$  and  $+27 \text{ cm}$ . FPix consists of three disks at either end. The vertex position resolution in the transverse plane is in the order of a few  $10 \mu\text{m}$ , which makes the reconstruction of secondary vertices from e.g. b-quark or  $\tau$  decays possible. The pixel detector is installed in a harsh environment with high particle hit rates (nearly  $600 \text{ MHz/cm}^2$  in the innermost layer). It is exposed to high radiation levels which exceed a hadron fluence of  $1.2 \cdot 10^{15} \text{ neq/cm}^2$  and an ionizing radiation dose of  $500 \text{ MRad}$ , for an integrated luminosity of  $\mathcal{L}_{\text{int}} = 300 \text{ fb}^{-1}$ . The Phase-1 pixel detector is described in more detail in Chapter 5.



#### 4.4.2. Strip Tracker

The Strip tracker tracks charged particles in the magnetic field of CMS. It surrounds the pixel detector and has an extent of  $2.4\text{ m} \times 5.8\text{ m}$  and covers the region  $|\eta| < 2.5$ . From the bending direction and the bending radius of the tracks the sign of the charge and the transverse momentum of a particle can be deduced. The detector is divided into four subsystems, the Tracker Inner Barrel (TIB), the Tracker Outer Barrel (TOB), the Tracker Inner Disks (TID), and the Tracker End Caps (TECs). Various variants of silicon strip modules are installed. Their strip pitch, which is the distance between two adjacent strips, is between  $80\text{ }\mu\text{m}$  at smaller radii and  $205\text{ }\mu\text{m}$  at larger radii. In TIB and TOB the strip direction is parallel to the beam axis and in TID and TEC it is vertical to the beam axis. TIB and TOB consist of four and six barrel layers of modules, respectively. TID and TEC consist of three and nine disks of modules, respectively. In the modules charged particles produce a current pulse in the sensor and the signal heights on the strips are read out. Clusters are formed from hits in adjacent strips and the cluster position is calculated as the mean of the hit position weighted with the value of the signal height. In the region  $|\eta| < 2.4$  tracking is possible with 8 to 14 hits per track.

#### 4.4.3. Preshower Detector

In the forward region in front of the endcaps of the electromagnetic calorimeter, silicon strip sensors are installed in order to detect  $\gamma\gamma$ -pairs from highly-boosted  $\pi_0$  decays, which otherwise might be misidentified in the electromagnetic calorimeter as a photon.

### 4.5. Electromagnetic Calorimeter

The electromagnetic calorimeter (ECAL) is a lead-tungstate ( $\text{PbWO}_4$ ) crystal calorimeter. It surrounds the tracker and is used for measuring the energy of electrons and photons. It is built out of about 76 000 lead-tungstate crystals. Lead-tungstate crystals provide a fast signal response, a short radiation length ( $X_0 = 0.89\text{ cm}$ ), and a small Molière radius ( $R_M = 2.2\text{ cm}$ ). The barrel (EB) of the ECAL covers a pseudorapidity range of  $|\eta| < 1.48$  and the endcap (EE) covers a pseudorapidity range of  $1.48 < |\eta| < 3.0$ . The front faces of the crystals have a cross section of  $2.2\text{ cm} \times 2.2\text{ cm}$  in EB and  $2.86\text{ cm} \times 2.86\text{ cm}$  in EE. They are oriented towards the interaction point and form a crystal surface with high granularity. The crystals have a length of  $23.0\text{ (}22.0\text{)}\text{ cm}$  which corresponds to radiation length of  $25.8\text{ (}24.7\text{)}X_0$  in the EB (EE).

Photons and electrons lose their energy in the lead-tungstate crystals by pair production and bremsstrahlung, respectively. Blue light is produced in the crystals and the light gain is read out. Electron and photon identification is possible in the region  $|\eta| < 2.5$  where the Tracker can measure tracks in front of the ECAL. For electrons from Z-decays with  $p_T = 45\text{ GeV}$ , energy resolutions below 2 % (2 % to 5 %) in the central (forward) ECAL regions are achieved. For photons from a Higgs decay with a transverse momentum of  $p_T = 60\text{ GeV}$ , energy resolutions of 1.1 % to 2.6 % (2.2 % to 5 %) are achieved in the EB (EE). The energy resolution of the EB can be parametrized with

$$\frac{\sigma(E)}{E} = \frac{3\%}{\sqrt{E}} \oplus \frac{0.1}{E} \oplus 0.3\%,$$

where  $E$  is given in units of GeV and  $\oplus$  denotes the quadratic sum [24]. The first term of the expression refers to the stochastic contribution to the energy resolution, the second term to the contribution from the electronic noise, and the third term is a systematic constant. Together with the HCAL information, the ECAL energy information is forwarded to and used in the CMS Level-1 trigger.

## 4.6. Hadronic Calorimeter

The hadronic calorimeter (HCAL) is a sampling calorimeter with alternating brass plates and plastic scintillators, which are read out with silicon photomultipliers (SiPMs). It is built around the ECAL and is the outermost subdetector in the inner volume of the magnet. Hadrons escaping the tracker and the ECAL lose their energy in the brass plates and generate light in the scintillators. The deposited energy is reconstructed from the scintillator light yield. The hadronic calorimeter (HCAL) consists of a barrel part (HB,  $0 < |\eta| < 1.2$ ), an endcap part (HE,  $1.2 < |\eta| < 3.0$ ), a forward part (HF,  $2.9 < |\eta| < 5.0$ ) and an outer part (HO) in the barrel outside the magnet. The HB is divided into  $\eta\phi$ -segments with a size corresponding to  $5 \times 5$  ECAL crystals. The number of corresponding ECAL clusters is smaller in HE. Together with the corresponding ECAL crystal cluster, the HB or HE segments form a calorimeter tower. The combined energy resolution of ECAL and HCAL (HB and HE) for charged pions can be parametrized as

$$\frac{\sigma(E)}{E} = \frac{84.7\%}{\sqrt{E}} \oplus 7.4\%$$

where  $E$  is given in units of GeV and  $\oplus$  denotes the quadratic sum [25]. The combined calorimeter information is used for the CMS Level-1 trigger.

The HF is a Cherenkov calorimeter with a steel absorber. The light is read out with scintillating quartz fibers and photomultiplier tubes. The HF is located at a position of  $|z| = 11$  m.

The HO is located outside the solenoid magnet and made out of plastic scintillators. As the thickness of HB is limited by the magnet diameter, HO serves as a detector for tails of hadronic showers which escaped HB and the solenoid. It improves the energy resolution of HB and vetoes the hadron tracks in front of the muon system.

## 4.7. Muon System

The muon system identifies muons and measures their momentum. It is located in the outer volume of the magnet and covers the region  $|\eta| < 2.4$ . It is embedded in the iron return yoke which provides the magnetic field necessary for the momentum measurement. Three detector technologies are used: drift tubes (DTs) in  $|\eta| < 1.2$ , cathode strip chambers (CSCs) in  $0.9 < |\eta| < 2.4$  and resistive plate chambers (RPCs) in  $|\eta| < 1.6$ . Drift tubes are cells with a size of  $13 \text{ mm} \times 42 \text{ mm}$  in an aluminum case with an anode wire in its center. The electric field in the drift tube is formed by properly positioned cathodes. Muons traversing the charge volume generate negative electric charge carriers which are collected at the anode wires. The charge arrival time is measured and from the calculated drift time the position of the muon is measured. The drift tubes are installed such that most of the tubes measure the position in the  $r\phi$ -plane, and some of them measure in the  $rz$ -plane. Eight layers of staggered DT cells form one Super Layer where the staggering improves the spatial resolution. One DT chamber is composed of three Super Layers. The spatial resolution of one DT chamber is in the order of  $80 - 120 \mu\text{m}$ . The CSCs are multiwire proportional chambers with anode wires and cathode strip segments. The CSCs are oriented in the detector such that the anode wire measure the radial position and the strip segments measure the  $\phi$ -position. The spatial resolution of the CSCs is in the order of  $40 - 150 \mu\text{m}$  and the time resolution is 3 ns. The RPCs are double-gap chambers operated in the avalanche mode. They have a worse spatial resolution, but provide fast timing signals with a time resolution in the order 1.5 ns. The measured muon tracks are matched with tracks measured in the tracker. In the barrel a resolution of  $1.3 - 2.0\%$  can be achieved for  $20 \text{ GeV} < p_T < 100 \text{ GeV}$  and a resolution better than 10% for tracks with  $p_T = 1 \text{ TeV}$ . The muon system contributes to the CMS Level-1 trigger.

## 4.8. Trigger System

The CMS trigger system preselects online the most interesting and promising collision events. Signatures for those events are typically a high photon, lepton or jet  $p_T$  or high  $E_T^{\text{miss}}$ . The trigger system consists of two stages, the Level-1 trigger (L1 trigger) and the High-Level-Trigger (HLT). The L1 trigger is a custom hardware trigger which receives information from the calorimetry system and the muon system at the LHC bunch crossing frequency of 40 MHz. Its latency is  $3.2\,\mu\text{s}$ . The design L1 trigger rate is 100 kHz. If triggered, the CMS detector is fully read out and the event is propagated to the software-based HLT. The HLT uses the full event information (i.e. also the tracker data) for the trigger decision and usually triggers events at a rate in the order of approximately 1 kHz. The triggered events are stored offline for further analysis.

## 4.9. CMS Upgrades

Two upgrade phases are defined for CMS, Phase-1 and Phase-2. The Phase-1 upgrade started in LS1 and will have been finished in LS2. It contained improvements to the existing design of CMS, but no major changes to the detector and its working principle have been applied. Phase-2 will start in full in LS3. The Phase-2 upgrade is necessary for CMS to be capable of efficient data taking during the HL-LHC period. Major points of physical interest are the Higgs pair production, the Yukawa-coupling in the second generation (e.g.  $H \rightarrow \mu\mu$ ), and the search for long-lived particles. For the measurement of vector-boson fusion processes, the coverage will be extended to the region  $|\eta| < 4$  in most subdetectors. The granularity of e.g. the muon system and the tracker are increased and the endcap calorimeters will be completely replaced. An overview over the activities in the Phase-1 and the Phase-2 upgrades is given below.

### 4.9.1. CMS Phase-1 Upgrades

Several upgrades were done in LS1 and have been finished in LS2. The main upgrade was the Phase-1 Upgrade of the pixel detector which was a complete replacement of the Phase-0 pixel detector in the year-end technical stop in winter 2016/2017. This project is described in more detail in Chapter 5. Further upgrade activities were conducted in the muon system, the hadronic system, and the trigger system. In HB and HE the hybrid photo diodes were replaced with silicon photomultipliers and in the HF the phototubes were replaced. In HB a longitudinal granularity is introduced in the readout of the towers, which will give more detailed information on the hadronic shower shape and thus improve the calorimeter performance at higher luminosities. In order to improve the performance of the L1 trigger the electronics of the calorimeter, muon and global trigger systems were upgraded. The VME standard was replaced with the  $\mu\text{TCA}$  standard which makes the system more flexible and a higher bandwidth possible.

### 4.9.2. CMS Phase-2 Upgrades

The increased radiation damage and the higher pileup at the instantaneous luminosity of  $5 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1}$  at the HL-LHC drive most of the CMS Phase-2 upgrades.

The efficiency of the existing tracker detector would significantly be reduced because of the radiation damage in the sensors. The efficiency would drop because of less charge collection in the irradiated sensors. The higher leakage currents in the sensor would make a significant fraction of the modules inoperative after  $\mathcal{L}_{\text{int}} = 1000 \text{fb}^{-1}$ . The current tracker will be exchanged completely and be replaced with the Phase-2 tracker. The Phase-2 tracker will contain a pixel detector whose forward coverage is extended to  $|\eta| = 4$ , and will introduce new strip module concepts. The Phase-2 tracker will have an on-module  $p_T$ -discrimination and will contribute to the L1-trigger. The Phase-2 tracker Upgrade is described in more detail in Chapter 6.

A Minimum ionizing particle Timing Detector (MTD) will be installed around the tracker [26]. With a time resolution of the MTD of 30 ps, the about 180 ps long collision region per bunch crossing is divided into several subregions. This makes the four-dimensional reconstruction of vertices in time-space coordinates possible and thus reduces the pileup disambiguities in the vertex and track reconstruction. The detector will be implemented as one layer between the tracker and the calorimeters. For the fast timing signals, silicon photomultipliers will be used in the barrel and low-gain-avalanche photodiodes in the endcaps.

The maximum Level-1 trigger rate will be increased from 100 kHz to 750 kHz and the latency time for the detector will be increased from 3  $\mu$ s to 12.5  $\mu$ s [27].

The endcaps of the electromagnetic and the hadronic calorimeter will be replaced with a High-Granularity Calorimeter (HGCAL [28]). The HGCAL will consist of an electromagnetic part with steel-clad lead absorbers and silicon sensors with a cell-size of 1 cm<sup>2</sup> or smaller as detection material. It will contain 6 million readout channels. The hadronic part will be built out of silicon and scintillating tiles which are read out with SiPMs. It will contain 400 000 read out channels. The granulated detector design in three dimensions makes it possible to implement the particle-flow concept and to measure jet substructures and shower shapes, and the pileup rejection is improved.

In order to cope with the increased Level-1 trigger rate, the electronics of the muon system will be replaced completely for the DTs and the CSCs. In the region  $1.6 < |\eta| < 2.2$ , GEM chambers will be installed in order to increase the granularity of the muon system in the forward region [29].

## 4.10. CO<sub>2</sub> Cooling in High-Energy Physics Experiments

In the LHC era, both the challenges for and the abilities of vertex and tracking detectors are increased compared to previous accelerators and experiments. The radiation damage of the silicon sensors and the power consumption because of the readout at high rates increase the power of the detectors significantly compared to previous detectors. More powerful and stronger cooling systems are required. In most cases detector temperatures below 0 °C are needed. The low temperatures are necessary to keep the leakage currents of the silicon sensors low. Another beneficial effect of low silicon temperatures is that reverse annealing is avoided [30]. Reverse annealing is an unwanted evolution of radiation damage effects that predominantly occurs at high temperatures. Both effects require the cooling liquid to be in the order of −20 °C or colder. At the same time it is pursued that the contribution of the cooling system to the detector material budget is reduced. As a solution for this issue, the concept of evaporative (or also: two-phase) CO<sub>2</sub> cooling has been developed and established in the past 20 years. In 2008, the operation of the first two-phase CO<sub>2</sub> cooling system in high-energy physics started at the LHCb VELO detector [31]. Since then CO<sub>2</sub> cooling systems have been installed for the ATLAS IBL [32, 33] and the CMS Phase-1 pixel detector [34]. The Phase-2 tracker will also use two-phase CO<sub>2</sub> cooling systems.

Many properties of CO<sub>2</sub> make it a good choice as coolant for low-material tracking detectors with many advantages compared to common cooling liquids. CO<sub>2</sub> is a non-toxic gas and is environmentally more friendly than other commonly used refrigerants. Between room temperature and its freezing point at −56 °C, CO<sub>2</sub> exists on its vapor pressure curve at relatively moderate conditions. Its vapor pressure ranges from 57 bar at +20 °C to e.g. 12 bar at −35 °C. Using CO<sub>2</sub> in the two-phase state as a coolant makes it possible to remove heat by evaporation of the liquid state. The evaporation process takes place at a constant temperature and pressure until the vapor quality, the mass fraction of the gaseous state, is 1. Two typical thermodynamical cycles are shown in Figure 4.4. The evaporation enthalpy,  $H$ , of CO<sub>2</sub> is in the order of 150 to 400 J/g between +20 °C and −40 °C. Typical mass flows,  $\Phi$ , per cooling line are in the order of 2 g/s.

The heat transfer coefficient of boiling CO<sub>2</sub> is in the order of 5 000 W/m<sup>2</sup>/K or above, which is higher than in common liquid cooling systems [35]. The high pressure of the CO<sub>2</sub> makes it possible to use thin low-mass cooling pipes with typical inner diameters between 1.5 and 2.0 mm. The thin cooling pipes provoke an unavoidable pressure drop in the pipes because of the mass flow. Because of the pressure drop, the temperature of the two-phase CO<sub>2</sub> decreases typically by 2 to 5 K along a cooling line, depending on parameters like e.g. the inner pipe diameter, mass flow, or heat load.

An example calculation for room temperature shows the ability of the two-phase cooling concept with CO<sub>2</sub>: with the parameters described above, a power  $P_{\text{load}}$  of

$$P_{\text{load}} = H \cdot \Phi = 150 \frac{\text{J}}{\text{g}} \cdot 2 \frac{\text{g}}{\text{s}} = 300 \text{ W} \quad (4.1)$$

can be removed with one cooling line in the two-phase state at constant temperature. In a liquid water cooling line with the same mass flow the coolant temperature would be increased by

$$\Delta T = \frac{P_{\text{load}}}{c_{P,\text{H}_2\text{O}} \cdot \Phi} = \frac{300 \text{ W}}{4.2 \frac{\text{J}}{\text{gK}} \cdot 2 \frac{\text{g}}{\text{s}}} = 36 \text{ K}, \quad (4.2)$$

where the specific heat capacity of water  $c_{P,\text{H}_2\text{O}} = 4.2 \frac{\text{J}}{\text{gK}}$  was used.

#### 4.10.1. The 2PACL Method

The 2PACL (2-Phase Accumulator Controlled Loop [36]) method is a working principle for evaporative CO<sub>2</sub> cooling systems. It is well suitable for the application in high-energy physics detectors as no active components of the system have to be installed in the detector volume. The full cooling system can be completely controlled from the remote cooling plant in an accumulator located at the end of the cooling cycle. A schematics of the 2PACL working principle as implemented in the Phase-1 pixel detector is shown in Figure 4.5. In the following the thermodynamical cycle is explained referring to the numbers indicated in Figures 4.4 and 4.5:

9 → 10:

The temperature and the pressure of the CO<sub>2</sub> is controlled in the accumulator defining a point on the CO<sub>2</sub> vapor pressure curve.

10 → 11:

The CO<sub>2</sub> is cooled down in order to provide the fully liquid state for the pump. The heat input to the system is removed.

11 → 1:

The liquid CO<sub>2</sub> is pumped towards the detector.

1 → 2 → 3:

The CO<sub>2</sub> is transferred to the detector. With preheaters heat is put into the CO<sub>2</sub> and the CO<sub>2</sub> approaches the two-phase state at nearly constant pressure in large diameter pipes.

3 → 4:

The CO<sub>2</sub> is adiabatically expanded in capillaries with a significant pressure drop.

4 → 5:

The CO<sub>2</sub> passes a preheating region with smaller diameter pipes and a heat input. The CO<sub>2</sub> enters the 2-phase state.

#### 4.10. CO<sub>2</sub> Cooling in High-Energy Physics Experiments

5 → 6, 7, 8:

The CO<sub>2</sub> cools the active detector region in the two-phase state. Temperature and pressure stay nearly constant with respect to the scale of the overall system.

8 → 9:

The CO<sub>2</sub> is returned to the accumulator.

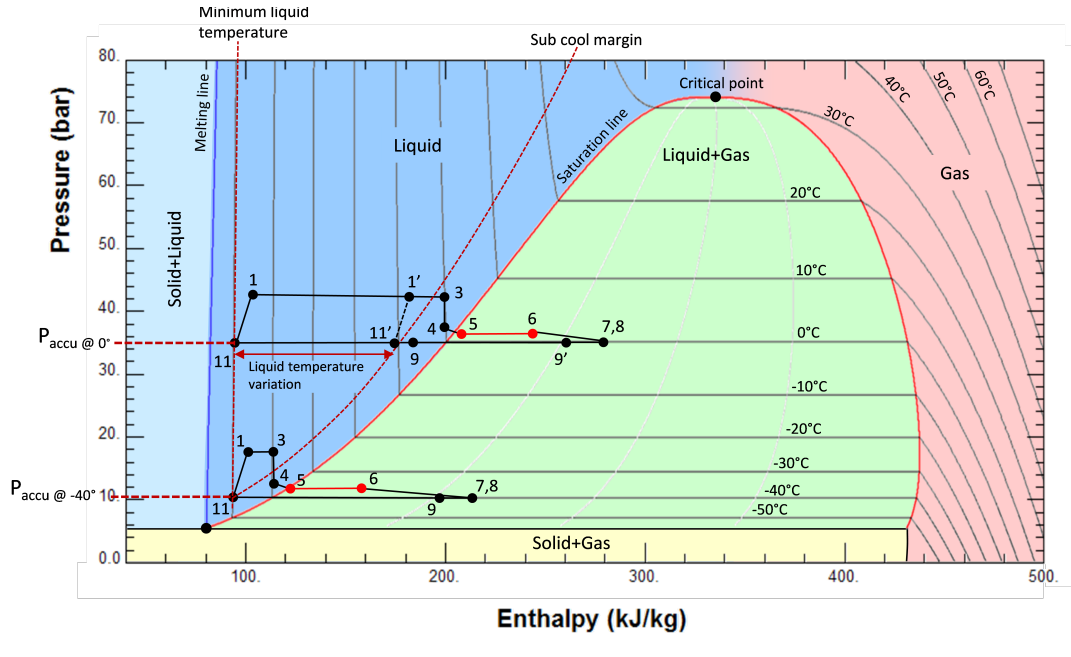


Figure 4.4.: Schematic view of the thermodynamical cycle of the 2PACL method in the pressure-enthalpy diagram as implemented in the CMS Phase-1 Pixel Detector. The cycles are drawn for the operating temperatures of 0 °C and −40 °C. [5]

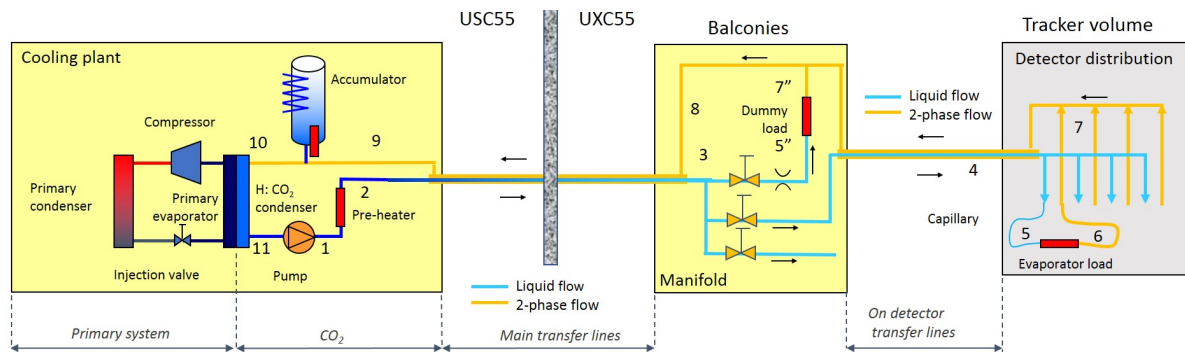


Figure 4.5.: Schematic view of the 2PACL method as implemented in the CMS Phase-1 pixel detector. The cooling plant with the accumulator (left) is located in the service cavern outside the experimental cavern. The cooling lines are transferred to the experimental cavern and the detector volume (right). No active components are located in the active detector volume. [5]

## 5. The CMS Phase-1 Pixel Detector

During LHC Run 1 and the first two years of Run 2, CMS operated the original Phase-0 pixel detector, which was designed for maximum instantaneous luminosities of  $\mathcal{L}_{\text{inst}} = 1 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1}$ . Already during Run 2, the luminosity of the LHC exceeded this value by a factor 2. Under these conditions the Phase-0 pixel detector would have had an unacceptable loss of efficiency because of the high hit rates and limitations in the data buffers in the readout chip. As a consequence, during the extended year-end technical stop in 2016/2017 the original pixel detector was replaced with the Phase-1 Pixel Detector [4]. This chapter firstly gives a coarse overview of the Phase-1 pixel detector. Secondly, the mechanics, the cooling loops, and the power system are described. These descriptions are important for the measurements with the BPIX mock-up in Chapter 8.

### 5.1. Detector Overview

The main upgrades from the Phase-0 to the Phase-1 pixel detector were an additional fourth barrel layer and a third forward disk, a new readout chip with digital charge readout, a two-phase CO<sub>2</sub> cooling system, and a new powering scheme based on DC-DC converters. During LS1, the old beam pipe with a diameter of 58 mm inside the pixel detector volume was replaced with a new beam pipe with a diameter of 45 mm. The new beam pipe made it possible to place the innermost pixel detector layer closer to the interaction point, to a transverse distance of 2.9 cm, which improved the vertex resolution. A schematic view of the active volume of the Phase-1 pixel detector is shown in Figure 5.1. The detector is divided into one barrel part (BPIX) and one forward part (FPIX) on each  $z$ -side. The barrel part (BPIX) contains four layers at radii between 2.9 cm and 16 cm in the  $z$ -region between  $-27$  cm and  $+27$  cm. The pixel detector is served from the BPIX supply tube and from the FPIX service cylinder which are shown in Figure 5.2. The BPIX supply tube contains the DC-DC busboards, where the DC-DC converters are placed, auxiliary electronics, and optical links. The cooling pipes are guided through the BPIX supply tube to the active detector volume.

BPIX and FPIX contain together 1856 hybrid pixel modules. This is roughly the double amount of modules compared to the old detector, because of the new fourth layer in BPIX and the third disk in FPIX. An exploded view of the BPIX module is shown in Figure 5.3. A pixel module

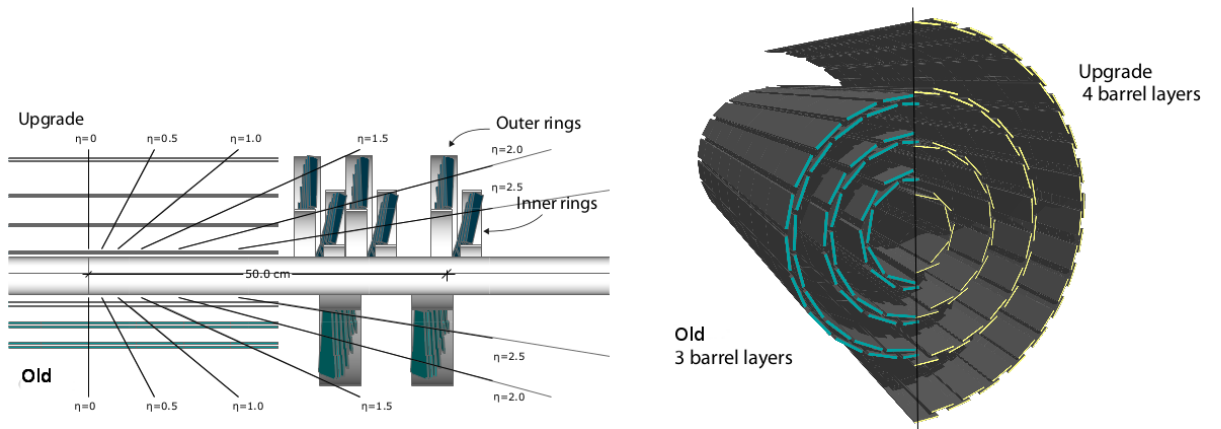


Figure 5.1.: Schematic view of one half of the Phase-1 pixel detector (Upgrade) compared to one half of the old detector. The left image shows a view in the  $rz$ -plane on one  $z$ -side. The right image shows the barrel structure. [4]

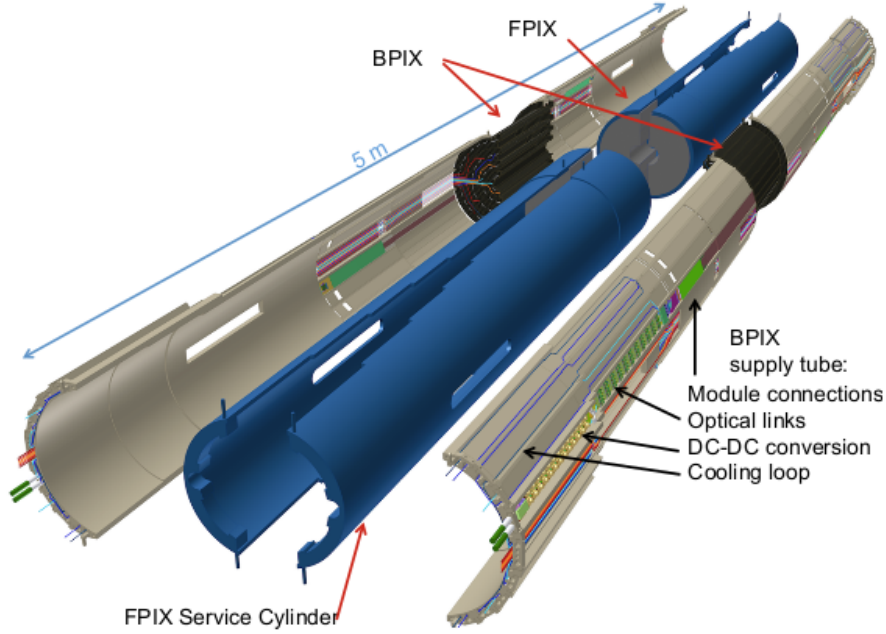


Figure 5.2.: The supply tube of the BPIX detector (grey) and the service cylinder of the FPIX detector (blue) are shown. They surround the beam pipe at higher  $|z|$  positions. The active pixel detector volume is located in the center. [4]

has a an active size of  $1.6\text{ cm} \times 6.5\text{ cm}$  and contains an  $n^+$ -in- $n$  silicon pixel sensor with 66 560 pixels, each with a size of  $150\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ . The silicon sensor is bump-bonded to eight readout chips (ROCs). Layer 2-4 modules use the PSI46digV2 ROC [37]. For the Layer 1 modules the PROC600 chip was developed and used, which is thinner and capable of processing higher hit rates [38]. Charged particles produce a current pulse in the sensor and the signal is fed through the bump bonds into the ROCs. The ROCs read out the position and the signal height of the pixel hits and digitize the charge signal. The High-Density Interconnect (HDI) is glued on top of the sensor and connected to the back-end with micro-twisted pair cables. It distributes the high-voltage and the low-voltage on the module. The Token Bit Manager (TBM) is located on the HDI. It manages the sequential readout of the ROCs. Layer 2-4 modules are glued to silicon nitride base strips for the mounting in the detector. Layer 1 modules do not have base strips, but they are pressed to the support structure directly with clamps.

## 5.2. DC-DC Converters

The double amount of pixel modules in the Phase-1 detector with respect to the Phase-0 detector leads to a factor 2 in the low voltage power consumption of the detector. The existing power cables in the detector had to be reused. The factor 2 higher current would lead to a factor 4 higher power loss on the supply cables because the power loss depends quadratically on the current ( $P_{\text{cable, loss}} \propto R_{\text{cable}} I_{\text{cable}}^2$ ) and the operating voltages for the ROCs have not changed. As a consequence, a novel powering scheme based on DC-DC converters was developed and installed [39, 40].

The implemented DC-DC converters convert an input voltage of approximately 10 V with a conversion ratio  $r$  to an output voltage between 2.4 and 3.5 V. The input current is converted to the output current in the inverse direction with the ratio  $1/r$ . Three different output voltages are used: 2.4, 3.3, and 3.5 V. The converters with an output voltage of 2.4 V power the analog part of the pixel module ROCs. The converters with an output voltage of 3.3 V power the digital part of the



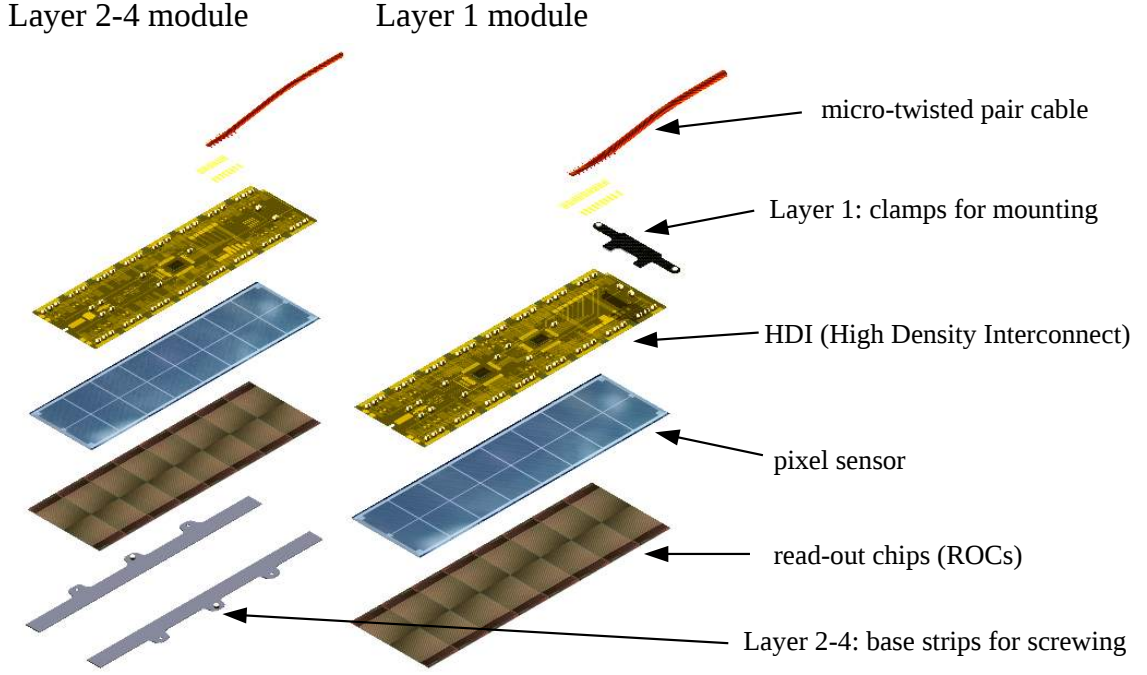


Figure 5.3.: Exploded view of a BPIX Layer 1 module (right) and a BPIX Layer 2-4 module (left). Image taken from Ref. [4] (edited).

ROCs in the BPIX Layer 1, 3, and 4 modules, and the converters with an output voltage of 3.5 V power the digital part of the ROCs in BPIX Layer 2 and FPIX. The TBMs are also powered by the DC-DC converters. The DC-DC converters are grouped in pairs of one analog and one digital voltage converter. One pair powers a common group of modules. The DC-DC converters are built as PCB devices with a footprint of 28 mm  $\times$  16 mm. The DC-DC converters have an output power in the order of 10 W and an intrinsic efficiency of 80 % or higher, depending on their conversion ratio, output current, and temperature. The inefficiency of about 20 % leads to a heat production of about 2 W in the DC-DC converter. The DC-DC converters are installed outside the active tracking volume of the pixel detector in the BPIX supply tube or in the FPIX service cylinder.

### 5.3. BPIX Mechanics

The BPIX detector has four layers and it is divided into two separate and independent half-shells which together form the full BPIX detector, as indicated in Figures 5.4 (a) and (b). Each half-shell covers an azimuthal angle of 180° from top to bottom, resulting in a full 360° coverage in  $\phi$ . The skeleton of the mechanics of each BPIX layer is the cooling pipe structure, which is shown in Figure 5.5 (a). Inlet and outlet of one cooling loop are always on the same  $z$ -side. The cooling pipes run back and forth in  $z$ -direction and they are routed in a meander-like form in  $\phi$ -direction through the detector. With this way one cooling loop covers a certain sector in  $\phi$ . The cooling pipes are made out of stainless steel and have an outer diameter of 1.7 mm and a wall thickness of 50  $\mu$ m. Along the  $\phi$ -direction carbon fiber plates with a length of approximately 54 cm, so-called ladders, are glued to the pipe structure, as shown in Figures 5.4 (b) and (c), and Figure 5.5 (b). The ladders are the support structure for the pixel modules. They face alternately to the inner and to the outer of the barrel detector. Table 5.1 gives an overview

on the numbers of ladders in the BPIX layers. Openings are milled into the ladders for the reduction of material in the detector. The ladders are made out of K13D2U carbon fiber, which was chosen because of its high thermal conductivity in order to improve the thermal contact to the cooling pipes [41, 42]. Each ladder has two contact surfaces to the cooling loops. The cooling pipes are glued into approximately  $200\text{ }\mu\text{m}$  deep grooves in the ladders to provide enough cooling contact surface.

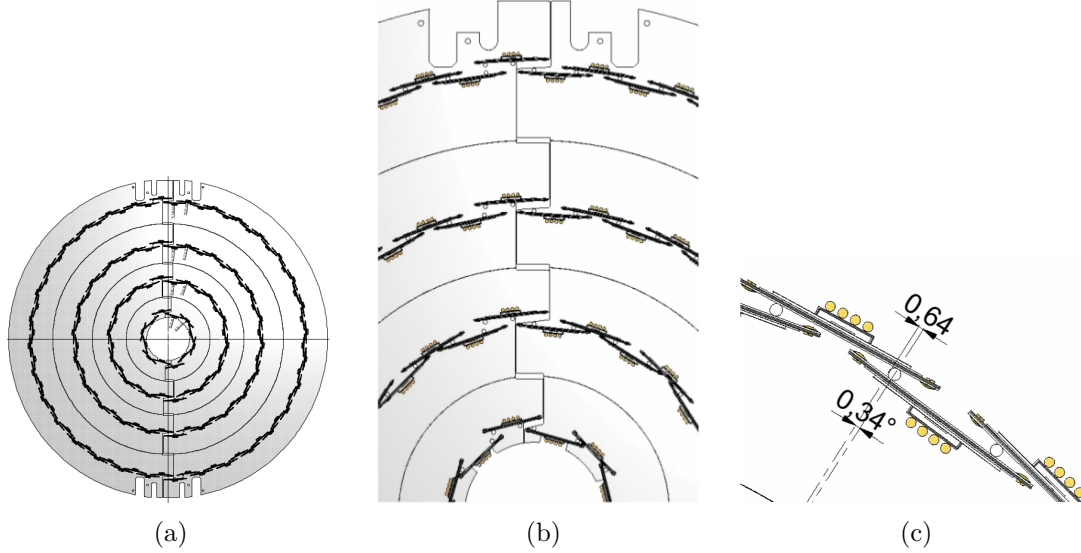


Figure 5.4.: The mechanical support structure of BPIX in an  $r\phi$ -view: two half-shells covering  $2\pi$  in  $\phi$  (a), zoomed view into the connection region between two half-shells (b), and an enlarged view of the ladder and cooling pipe structure (c). The small gray circles indicate the cooling pipes. The yellow bumps indicate the connection cables of the pixel modules.

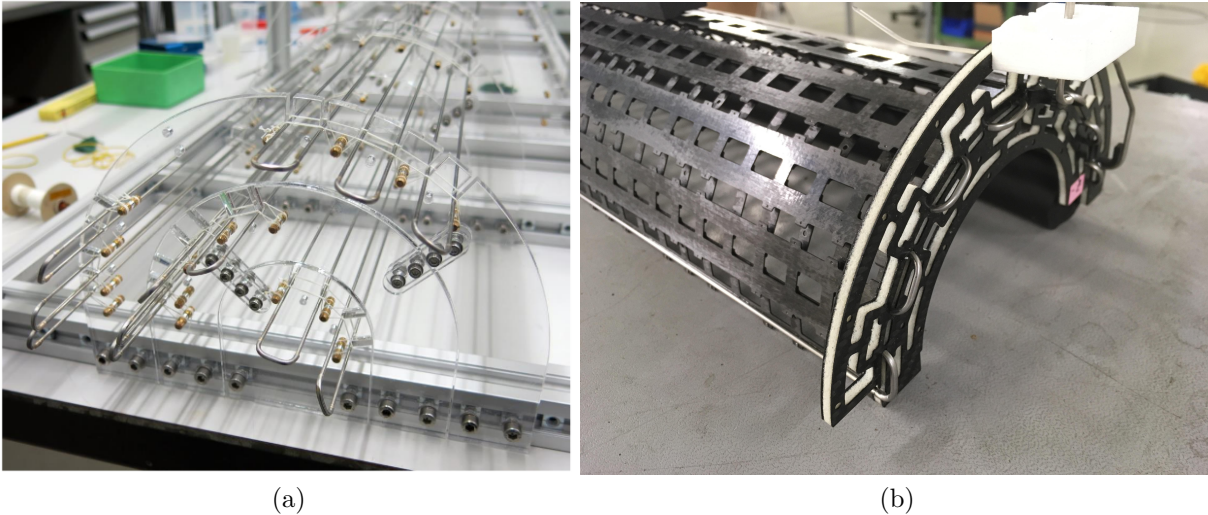


Figure 5.5.: Prototypes of the cooling pipe skeleton at the University of Zurich (a) [43] and the carbon fiber support structure of one half-shell of BPIX Layer 2 (b) [44].

## 5.4. Cooling Loops

The Phase-1 pixel detector is cooled with an evaporative CO<sub>2</sub> cooling system at a nominal CO<sub>2</sub> temperature of  $-22^{\circ}\text{C}$ . The BPIX detector is cooled by 24 cooling loops. The routing of the cooling loops is explained above and shown in Figure 5.5 (a). Each cooling loop leaves the detector at the  $z$  side where it is also connected from, but at a different  $\phi$  coordinate. A schematic view of the distribution of the cooling loops is shown in Figure 5.6. Table 5.1 lists the number of cooling loops per BPIX layer. Twelve cooling loops are connected from the positive  $z$ -side and twelve loops are connected from the negative  $z$ -side. The length of one cooling loop in the active detector is different between the layers and ranges from 2.2 m in Layer 1 to 4.5 m in Layer 2 and 4. The BPIX cooling loops enter the detector through the BPIX supply tube. In front of the BPIX supply tube the CO<sub>2</sub> is expanded through capillaries. In the BPIX supply tube the CO<sub>2</sub> cools the DC-DC converters. The heat production from the inefficiency of the DC-DC converters is used as the preheating power for the CO<sub>2</sub>. The power of further devices installed in the supply tube (i.e. the pixel opto-hybrids and the CMS control unit) contributes also to the preheating power. Depending on the cooling loop and the amount of converters which are cooled with the CO<sub>2</sub>, the preheating power for one cooling loop is in the order of 30 to 60 W. After the preheating section the CO<sub>2</sub> enters the active detector volume in the two-phase state.

Table 5.1.: Overview table on the amount of ladders, modules, and cooling loops per BPIX layer. The length of the cooling loop in the active detector volume is also given.

| Layer | Ladders | Modules per sector | Cooling loops | Loop length |
|-------|---------|--------------------|---------------|-------------|
| 1     | 12      | 3                  | 4             | 2.2 m       |
| 2     | 28      | 4 or 8             | 4             | 4.5 m       |
| 3     | 44      | 8 or 12            | 8             | 3.5 m       |
| 4     | 64      | 16                 | 8             | 4.5 m       |

## 5.5. Power Sectors

Each BPIX layer is divided into four quadrants: BmI, BmO, BpI, and BpO. The first letter 'B' denotes the word "barrel", the second letter 'm' ('p') refers to the negative (positive)  $z$ -side in the CMS coordinate system, and the third letter 'I' ('O') denotes the BPIX half-shell installed at the positive (negative)  $x$ -position and facing to the inner (outer) part of the LHC ring. Each quadrant of the BPIX detector is divided into eight power sectors, where the amount of modules per power sector increases from Layer 1 to Layer 4. The distribution of the power sectors for the four layers is shown in Figure 5.7. The number of modules per power sector is listed in Table 5.1. CAEN A4603 power supplies are used to provide low voltage (LV) to the DC-DC converters and high voltage (HV) to the pixel modules [46]. One power supply LV channel powers one group of DC-DC converters. The DC-DC converter group related to one LV channel serve power sectors with the same index of either Layer 2 and 3 or Layer 1 and 4 pixel modules. Each HV channel provides high-voltage to the pixel modules in one power sector in one layer. In all cases the current of individual modules cannot be measured. In the HV case the current information is distinct for the four layers. In the LV case the current information is only available for power sectors of two layers in common.

In the HV part, the high voltage power per power sector is given by

$$P_{\text{HV}} = U_{\text{bias}} \cdot I_{\text{leak}}.$$

The HV power of a single pixel module can then be estimated by  $P_{\text{HV}}$  of one power sector divided by the number of active modules in this power sector.

## 5.5. Power Sectors

The LV power of one power channel can be estimated as

$$P_{LV} = (U_{LV, \text{dig}} \cdot I_{LV, \text{dig}} + U_{LV, \text{ana}} \cdot I_{LV, \text{ana}}) \cdot \eta_{\text{DC-DC}},$$

where  $\eta_{\text{DC-DC}} \approx 82\%$  is the average value of the efficiency of the DC-DC converters, and  $U_{LV, \text{dig/ana}}$  and  $I_{LV, \text{dig/ana}}$  are the digital and analog voltage and current of the low voltage power channel, respectively. The power of one pixel module can then be estimated as the low voltage power  $P_{LV}$  divided by the active modules connected to the corresponding power channel. This assumption is only coarse because modules located closer to the interaction point receive higher hit rates and thus higher digital currents in the ROCs and TBMs.

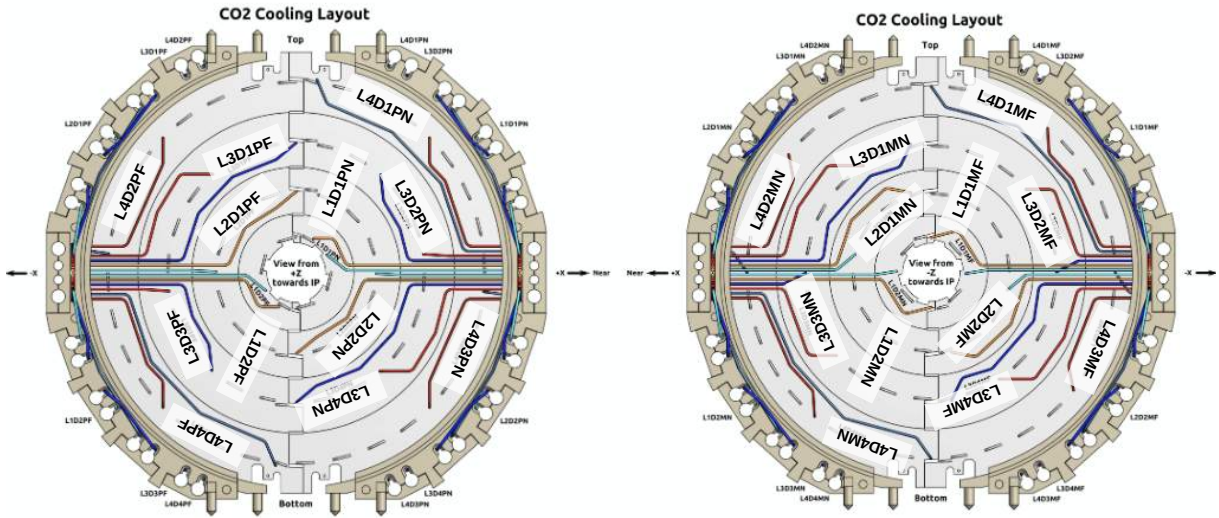


Figure 5.6.: Schematic view from the  $+z$  (left) and  $-z$  (right) direction on the cooling pipe inlet and outlet routing in the BPIX detector. Blue (turquoise) lines denote inlet pipes in Layer 3 and 4 (Layer 1 and 2). Red (orange) lines denote outlet pipes in Layer 3 and 4 (Layer 1 and 2). The cooling pipe name is written between corresponding inlets and outlets. The small grey strips indicate the turn-around of the cooling pipe at the end of a ladder. The nomenclature “ $LxDyXY$ ” of the cooling loops is the following. “ $Lx$ ” denotes the BPIX layer where  $x$  is between 1 and 4. “ $Dy$ ” denotes the cooling loop number  $y$  counted from the positive  $y$  axis with  $y$  between 1 and 2 (1 and 4) for Layer 1 and 2 (Layer 3 and 4). The letter  $X = M, P$  denotes whether the cooling loop is connected from  $+z$ -side (P for “Plus”) or from the  $-z$ -side (M for “Minus”). The letter  $Y = F, N$  denotes whether the cooling loop is in the outer (F for “far”) or in the inner (N for “near”) half-shell, seen from the center of the LHC ring. [45] (edited).

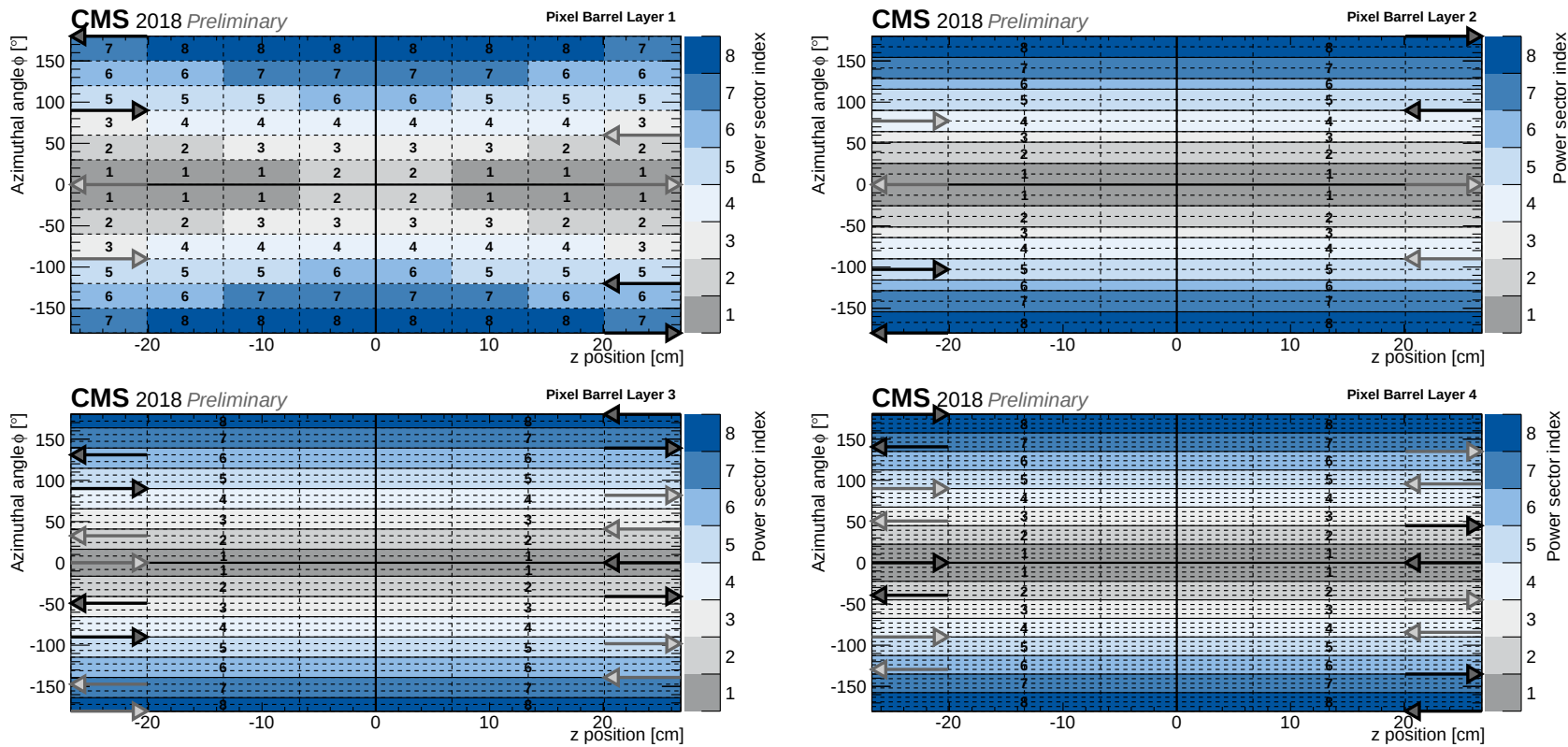


Figure 5.7.: Power sectors in the BPIX Layer 1 (top left), Layer 2 (top right), Layer 3 (bottom left), and Layer 4 (bottom right). The power sectors per quadrant are color coded. For Layer 2 to 4 solid lines indicate the power sectors and dashed lines indicate the extents of individual pixel modules. In Layer 1 the power sectors are not coinciding with the ladder structure and only dashed lines indicate the extents of individual pixel modules. The positions of inlet and outlet of the cooling loops are indicated with arrows. Adjacent arrows with the same color denote the inlet and the outlet of the same cooling loop.





## 6. The CMS Phase-2 Strip Tracker

The current CMS tracker cannot be operated at HL-LHC conditions. Significant deterioration of the performance is expected for values beyond the current tracker design values. The radiation damage in the silicon sensors leads to higher depletion voltages, less charge collection, and larger leakage currents. The sensors would draw too much power, making it impossible to cool them sufficiently. It was studied that a large fraction of the silicon strip modules would not be operational after  $\mathcal{L}_{\text{int}} = 1000 \text{ fb}^{-1}$  [5]. In addition the detector efficiency would decrease to unacceptable values at the higher particle hit rates. As a consequence, the current silicon tracker will be replaced during Long Shutdown 3 with the CMS Phase-2 Upgrade tracker [5].

The Phase-2 strip tracker is designed to fulfill all requirements for the operation over the full period under HL-LHC conditions, i.e.  $\mathcal{L}_{\text{inst}} = 5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , a pileup of 140, and  $\mathcal{L}_{\text{int}} = 3000 \text{ fb}^{-1}$ . The radiation hardness of the sensors is improved and the cooling temperature is reduced to  $-35^\circ \text{C}$ . The acceptance of the overall tracker will be increased up to  $|\eta| \approx 4$ . The granularity will be increased in order to keep the occupancy at an acceptable level for all detector parts. As the first tracking detector in high-energy physics, it will contribute to the Level-1-trigger with an online reconstruction of high  $p_{\text{T}}$ -tracks.

### 6.1. Overview on the Detector Geometry

A schematic view of one quarter of the Phase-2 tracker is shown in Figure 6.1. It will consist of an Inner Tracker and an Outer Tracker.

The Outer Tracker will be based on a novel strip tracker concept. It will be built with two types of silicon modules: PS modules with a macro-pixel sensor and a strip sensor, and 2S modules with two strip sensors. Both modules will feature on-module  $p_{\text{T}}$ -discrimination in the readout chips for the contribution to the Level-1 trigger.

The Outer Tracker will be installed at radii between 200 mm and 1200 mm and at  $z$ -positions with  $|z| < 2700 \text{ mm}$ . The detector is divided into three subdetectors, the Tracker Barrel PS (TBPS), the Tracker Barrel 2S (TB2S), and two Tracker Endcaps (TEDDs). The transition between TBPS and TB2S to the TEDDs is at a position of  $|z| \approx 1250 \text{ mm}$ . The TBPS has three layers with PS modules at radii of  $200 \text{ mm} < r < 550 \text{ mm}$ . In the central  $|\eta|$ -region a barrel structure is implemented with the modules forming a barrel around to the beam axis. In order to reduce detector material and the amount of PS modules needed, a tilted design is implemented at higher  $|\eta|$  in which the sensors face towards the interaction point. The TB2S is built of three barrel layers of 2S modules at radii  $650 \text{ mm} < r < 1150 \text{ mm}$ . Each TEDD consists of five double-disks where PS and 2S modules are mounted in rings. PS modules are located at radii smaller than 600 mm and 2S modules are mounted at radii  $600 \text{ mm} < r < 1150 \text{ mm}$ .

The Inner Tracker will be a pixel detector with a four-layer barrel in the region  $r < 16 \text{ cm}$  and an endcap on each side with 12 disks reaching to  $|z| \approx 250 \text{ cm}$ . The disks will have a radius of 20 cm (30 cm) for  $|z| < 160 \text{ cm}$  ( $|z| > 160 \text{ cm}$ ). The Inner Tracker will be built with two types of pixel modules. Smaller modules in the inner regions will have two read-out chips with a  $1 \times 2$ -arrangement and larger modules in outer regions will have four readout chips with a  $2 \times 2$ -arrangement. Both types of modules will have pixel sizes of either  $25 \mu\text{m} \times 100 \mu\text{m}$  or  $50 \mu\text{m} \times 50 \mu\text{m}$ , where the final decision has not yet been made. The Inner Tracker will have an active silicon surface of  $4.9 \text{ m}^2$  and utilize 2 billion read-out channels. The mechanics will be designed such that repair or partial exchange of components in the Inner Tracker will be possible during Long Shutdowns. At HL-LHC, in the regions of the pixel detector the ionizing

radiation dose will be 1.2 GRad, the hadron fluence will be  $2.3 \cdot 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ , and the hit rate in the innermost layers will be higher than  $2 \text{ GHz}/\text{cm}^2$ .

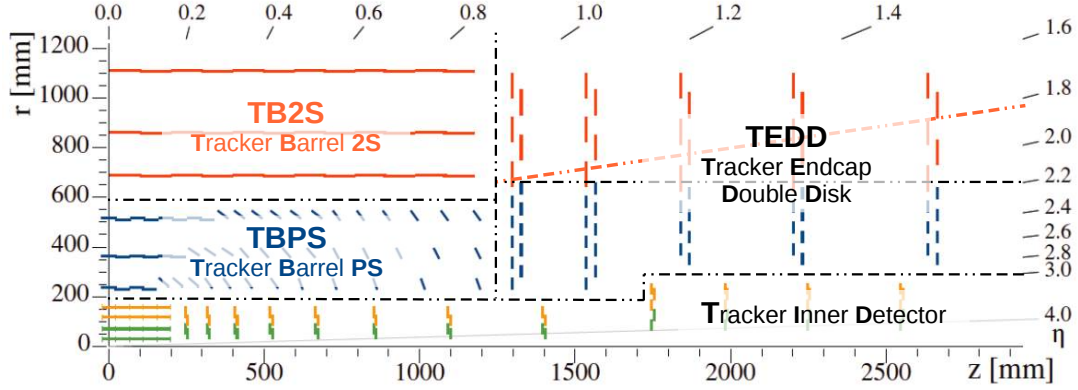


Figure 6.1.: Schematic  $rz$ -view of one quadrant of the CMS Phase-2 tracker. In the inner radial region the Inner Tracker is located. Green (yellow) lines indicate hybrid pixel modules with a  $1 \times 2$  ( $2 \times 2$ ) readout chip arrangement. In the outer radial region the Outer Tracker system is located. It consists of the Tracker Barrel PS, Tracker Barrel 2S, and two Tracker Endcap Double Disks. Blue lines indicate the positions of PS modules and red lines indicate the positions of 2S modules. [5]

## 6.2. Overview on Phase-2 $p_T$ -Modules

The design of the Phase-2  $p_T$ -modules is driven by the desire to contribute to the L1 trigger. As a full readout of the Tracker (and thus a full track reconstruction) is not possible at a rate of 40 MHz, it is necessary for the modules themselves to perform a  $p_T$ -measurement. This is implemented by finding small tracklets, so-called stubs, on the modules which might belong to high  $p_T$ -tracks. Tracks of charged particles are bent in the magnetic field and the bending radius in the transverse plane is proportional to the transverse momentum. Low- $p_T$  tracks have a larger curvature and thus a larger displacement in  $\phi$ -direction. On the 2S modules (PS modules) two silicon strip sensors (one silicon strip sensor and one macro-pixel sensor) with a strip pitch of  $90 \mu\text{m}$  ( $100 \mu\text{m}$ ) are aligned in parallel at a spacing of a few millimeters. The hits of the two sensors are formed to clusters and the mean position of the clusters, here referred to as hit positions, are correlated in the readout electronics. The principle is illustrated in Figure 6.2. The hit position on the first sensor defines an acceptance window in the second sensor where a high- $p_T$  track with low displacement in  $\phi$ -direction would pass through. When a hit position within this window is found, a stub is formed. The stub contains the information on the position

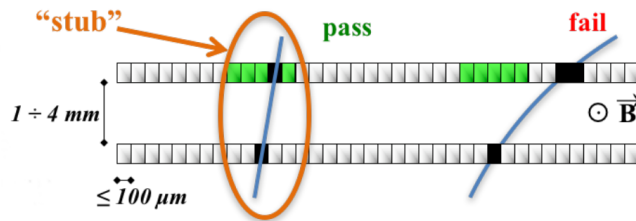


Figure 6.2.: Illustration of the stub finding principle in the barrel region. For a hit on the bottom sensor an acceptance window (green) is opened on the top sensor. A high  $p_T$ -track (left) would pass through this window and a low  $p_T$ -track (right) would miss it. [5]



of the first cluster and the position of the second cluster relative to the first cluster. The size of the acceptance window and the spacing of the sensors depends on the module position. It is optimized for optimal  $p_T$ -discrimination and reasonable stub rates. For PS modules the sensor spacings are 1.6, 2.6, or 4.0 mm, and for the 2S modules 1.8 or 4.0 mm.

The  $p_T$ -module concept invokes requirements for the geometry and the design of the 2S and the PS modules. A module has to contain two sensors with a defined sensor spacing and parallel strip direction. The signal hits in the two sensors have to be fed into the same front-end ASIC at bunch-crossing frequency. The cluster and stub finding logic has to be performed in this ASIC and the stubs have to be sent out to the Level-1 track finder. For the contribution to the Level-1 trigger with its latency of  $12.5\,\mu\text{s}$ , the Level-1 track finder will have to reconstruct high  $p_T$ -tracks from stubs within about  $5\,\mu\text{s}$ . When the L1 trigger is sent, the full event is read out.

### 6.3. The 2S Modules

Figure 6.4 shows a CAD drawing of the 2S module in an isometric and in an exploded view. The 2S module has an extent of  $14.5\,\text{cm} \times 12.5\,\text{cm}$  in the  $xy$ -plane and a mass of about 40 g. The active parts of a 2S module are two silicon strip sensors with outer dimensions of approximately  $10\,\text{cm} \times 10\,\text{cm}$  and a thickness of  $320\,\mu\text{m}$ . The sensors are mounted with parallel strip alignment back-to-back on so-called spacers, which define the sensor spacing. Front-end Hybrids (FEHs) produced with a fold-over technique contain the read-out ASICs and are glued to extensions of the spacers ('ears'). The strips of both sensors are connected to the FEHs from the top side and the bottom side, respectively, with encapsulated wirebonds. A Service Hybrid (SEH) manages the low and high voltage distribution, the data serialization and the optical readout. The 2S module is a stand-alone system which needs only a high voltage and a low voltage connection, and an optical readout fibre. This thesis uses a right-handed local coordinate system for the 2S module with the  $x$ -axis parallel to the strip direction and the  $z$ -axis perpendicular to the sensor plane.

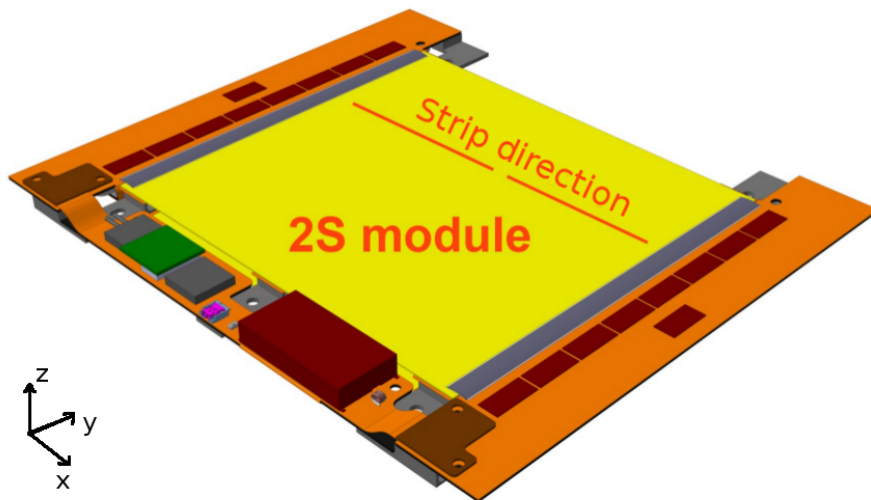


Figure 6.3.: Isometric view of the CMS Phase-2 2S module with the strip direction indicated [5] (edited).

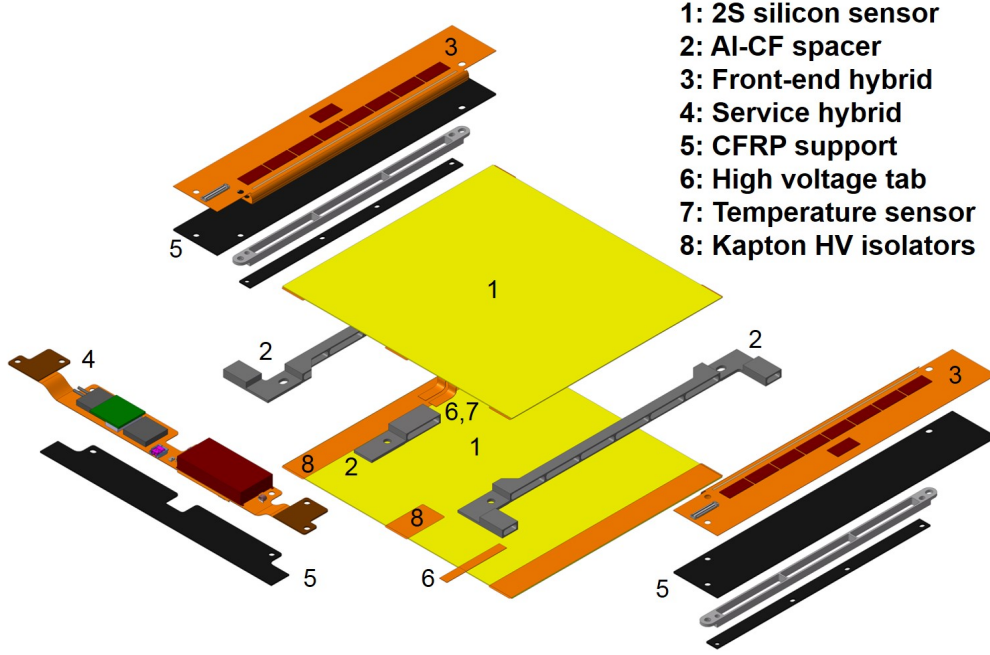


Figure 6.4.: Exploded view of the CMS Phase-2 2S module [5] with a legend for the individual components.

### 6.3.1. 2S Module Sensor

The silicon strip sensors for the 2S modules have outer dimensions of  $102.7 \text{ mm} \times 94.2 \text{ mm}$ . Each sensor contains two rows of 1016 strips with a length of  $\approx 5 \text{ cm}$  and a strip pitch of  $90 \mu\text{m}$ . The strips are implemented as n-in-p implants. Figure 6.5 shows a sketch of the structure of the 2S silicon strip sensor. The strip direction is parallel to the  $x$ -axis of the 2S module coordinate system as indicated in Figure 6.4 (left). The negative high-voltage potential is applied to the backplane of the sensor via pigtail cables and the strip side is at ground potential. Recently the collaboration decided that the sensors will have an active thickness of  $290 \mu\text{m}$  and a physical thickness of  $320 \mu\text{m}$ . The active thickness defines the region where the sensor will be effectively depleted and where the process of charge generation takes place. The depletion voltage of the unirradiated sensor is in the order of  $250 \text{ V}$ . After the irradiation at  $\mathcal{L}_{\text{int}} = 3000 \text{ fb}^{-1}$  depletion voltages of  $600 \text{ V}$  are foreseen. For the potential case of an integrated luminosity of  $\mathcal{L}_{\text{int}} = 4000 \text{ fb}^{-1}$  depletion voltages of even  $800 \text{ V}$  are considered.

### 6.3.2. AlCF Spacers

The two sensors are glued with their backplane to three spacers. The spacers provide  $2.5 \text{ mm}$  diameter screwing holes for the positioning and fixation of the modules and the connection to the cooling system. Two long spacers are used which provide the screwing holes in the corners of the 2S module. An additional short spacer, the so-called stump bridge, is implemented on the service hybrid side of the module. The stump bridge was necessary for the module design in order to provide a fifth cooling contact. The spacers define the sensor spacing and are available in two versions, differing for the  $1.8 \text{ mm}$  and the  $4.0 \text{ mm}$  module. The height of the spacers is chosen such that the centers of the active sensor regions have the specified spacing. Cut-outs in the spacers optimize the material budget of the spacers. The spacer material is AlCF (Carbon Fiber Re-inforced Aluminum [47, 48]) which was chosen in order to minimize the difference between the

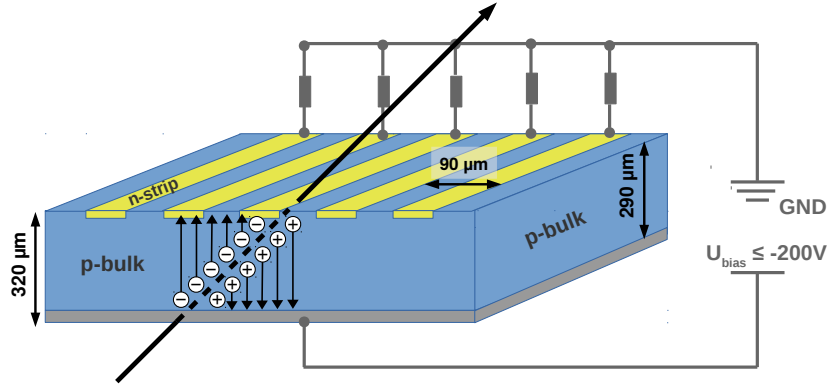


Figure 6.5.: Sketch of the structure of the 2S silicon strip sensor. A charged particle traversing the sensor volume (long black arrow) generates electron-hole pairs. Electrons are accelerated in the electric field towards the strip segmentation and the read-out front-end, which is not shown.

coefficient of thermal expansion (CTE) of the silicon sensors and the spacers. Silicon has a CTE of  $\approx 4$  ppm/K whereas common aluminum alloys have a CTE of  $\approx 24$  ppm/K. AlCF material is made of an aluminum alloy in which carbon fiber pieces with a size smaller than  $500 \mu\text{m}$  are embedded. The CTE of the material can be tuned by varying the concentration of carbon fiber pieces. The CTE of silicon can be matched with a precision better than 1 ppm/K. The carbon fiber pieces are oriented in the  $yz$ -plane in the 2S module coordinate system. The in-plane orientation of the carbon fiber pieces in the material leads to an anisotropic thermal conductivity in the material, which is nominally  $\mathcal{K}_{\text{AlCF}} = \{k_{xx}, k_{yy}, k_{zz}\}_{\text{AlCF}} = \{120, 230, 230\} \text{ W/m/K}$  [48].

### 6.3.3. HV Kapton Isolators

As the backplane of the sensors, where the bias high voltage is applied, is glued to the spacers, a high voltage isolator is glued between the sensors and the spacers in order to prevent electrical contact and sparkover between them. The high voltage isolator is a  $25 \mu\text{m}$  thick Kapton strip with a dimension of approximately  $1 \text{ cm} \times 10 \text{ cm}$ . Kapton MT foil is used, which has an improved thermal conductivity of  $0.46 \text{ W/m/K}$ , compared to common Kapton foils ( $0.12 \text{ W/m/K}$ ) [49, 50]. The Kapton strips protrude from the sensor edge by  $700 \mu\text{m}$  at their short edge. Glue layers of  $20 \mu\text{m}$  or less are defined for the glue junction between sensor and Kapton strip and between Kapton strip and spacer.

### 6.3.4. The Front-end Hybrid

The 2S module carries two Front-end Hybrids (FEHs). Each FEH receives signals from one strip row of both sensors. The FEH is a folded flexible PCB, which makes it possible to route the signals from the bottom sensor to the top side of the hybrid. The concept is shown in Figure 6.6. The top sensor strips are connected with wirebonds to the top side of the hybrid and the bottom sensor to the bottom region of the hybrid, which is folded over by  $180^\circ$ .

The flat regions of the FEH are supported with CFRP (Carbon Fiber Reinforced Polymer) stiffeners, which are laminated to the backplane of the hybrid. The stiffeners have a thickness of approximately  $500 \mu\text{m}$  and are made of the high-tensile carbon fiber K13D2U or K13C2U [51]. The thermal conductivity of the plate is in the order of  $300 \text{ W/m/K}$  in-plane and in the order of  $1 \text{ W/m/K}$  through-plane. The hybrids are available in two versions, one for the 2S  $1.8 \text{ mm}$  module and one for the 2S  $4.0 \text{ mm}$  module. The only difference is the length of the fold-over part,

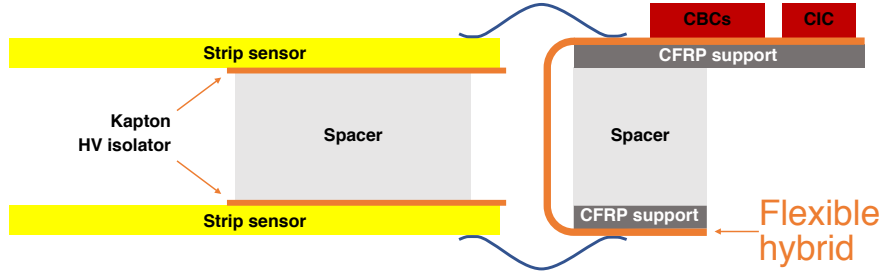


Figure 6.6.: Illustration of the flex-hybrid principle for the FEH and the connection of the top and bottom sensor to the FEH with wirebonds. [5]

which is longer and has a larger radius for the 4.0 mm version. Therefore, an AlCF spacer is implemented between the two carbon fiber stiffeners in the 4.0 mm case. On the top side of the FEH the readout chips are located, namely eight CBC3s (CMS Binary Chip 3, [52, 53]) and one CIC (Concentrator Integrated Circuit, [54]). The CBC3 chip receives the signal of each strip and compares the pulse height to a threshold. It contains the stub finding logic and generates the stub information for every bunch crossing. A binary hit information is generated for all channels and buffered during the trigger latency. The CIC concentrates the data of all CBC3s and sends the data electrically to the Service Hybrid.

### 6.3.5. The Service Hybrid

Each 2S module carries one Service Hybrid (SEH). The SEH is a flexible PCB laminated to a CFRP stiffener with a small part of the hybrid folded around the stiffener. It is glued to the two long spacers and the stump bridge. Two parts can be distinguished for the SEH, the optical readout part which serializes the data from the FEH and transmits and receives signals optically, and the power part, which distributes the low and high voltages on the module. The SEH is connected to the FEHs with electrical connectors.

In the readout part the Low-power Giga Bit Transceiver (LpGBT-ASIC [55]) receives and serializes the data, both the stub and hit data from the FEHs, and the communication data from the back-end like configuration commands or triggers. The Versatile Link Plus Transceiver (VTRx+, [56]) is an optical link module for data transmission for the conversion between electrical and optical signals (and vice versa).

The power part consists of a two-staged DC-DC conversion scheme. The BPOL12V DC-DC converter receives an input voltage of about 11 V and converts it to an output voltage of 2.55 V [57]. This output voltage is used as input voltage for the BPOL2V5 DC-DC converter which generates an output voltage of 1.25 V [58]. The BPOL12V (BPOL2V5) DC-DC converter uses air-core inductors with an inductance of 200 nH (100 nH). As the DC-DC converters switch their input and output with a frequency of several MHz, an aluminum shield box is mounted over the inductors and the converter ASICs, in order to shield electromagnetic emission. The CBC3s and the CICs on the FEHs, the LpGBT and the VTRx+ receive the 1.25 V output voltage. The VTRx+ additionally requires the 2.55 V output voltage from the first conversion stage.

The high voltage is smoothed with a filter and connected to the sensors with pigtailed from the foldover region on the bottom side of the SEH. A temperature sensor is connected from the SEH to the top sensor with a pigtail cable. It is read-out by the LpGBT.

## 6.4. Power and CO<sub>2</sub> Cooling of the 2S Modules

The power consumption of a 2S module will be about 6 W, or even up to 7 W after the full HL-LHC period. The power consumption can be divided into two parts. The low voltage power, which is consumed by the electronic components in the low voltage circuit, is described in Section 6.4.1. The high voltage power, which is generated by the leakage current of the silicon sensors, is described in Section 6.4.2.

### 6.4.1. Low Voltage Power

The low-voltage power is produced on the FEHs by the 16 CBC3s and the 2 CICs, and on the SEH by the LpGBT, the VTRx+, and the power losses in the DC-DC converters caused by their inefficiency. Table 6.1 gives an overview of the estimated power consumption of the components. The power consumption of one FEH is estimated to be 1.4 W, summing up to 2.8 W for both FEHs, and the power of the SEH is estimated to be 2.6 W. The power of all hybrids is estimated to be  $P_{\text{hybrids}} = 5.4 \text{ W}$ .

Table 6.1.: Overview of the nominal power consumption of the low-voltage components of the 2S module. [5]

| Hybrids               | Full hybrid power | Component        | Power |
|-----------------------|-------------------|------------------|-------|
| Service hybrid        | 2.6 W             | LpGBT            | 0.5 W |
|                       |                   | VTRx+            | 0.3 W |
|                       |                   | DC-DC converters | 1.8 W |
| Two front-end hybrids | 2.8 W             | 16 CBC3s         | 2.2 W |
|                       |                   | 2 CICs           | 0.6 W |
| All hybrids           | 5.4 W             |                  |       |

### 6.4.2. High Voltage Power

The high voltage power  $P_{\text{sensor}}$  is the power produced in the silicon sensor. It is given by the product of the reverse leakage current,  $I_{\text{leakage}}$ , and the reverse bias voltage,  $U_{\text{bias}}$ :

$$P_{\text{sensor}} = U_{\text{bias}} \cdot I_{\text{leakage}}. \quad (6.1)$$

For unirradiated sensors, the leakage current is relatively low (in the order of a few  $\mu\text{A}$  in the 2S module case) and negligible in terms of power consumption. Several current production processes contribute to the leakage current. With irradiation, defects in the crystal structure of silicon are produced and the thermal generation of charge carriers in the crystals becomes the predominant source of leakage current [59, 60]. Figure 6.7 illustrates the band structure of silicon, with the conduction and the valence band, and the band gap in between. Electrons in the conduction band can conduct electrical current, contributing to the leakage current. The leakage current per unit area is given by

$$j_{\text{leakage}} = q_e \cdot G_{\text{th}} \cdot d_{\text{sensor, active}} = \frac{q_e \cdot d_{\text{sensor, active}} \cdot n_i}{\tau_g}, \quad (6.2)$$

with the elementary charge  $q_e$ , the thickness of the depleted sensor volume  $d_{\text{sensor, active}}$ , and  $G_{\text{th}}$  is the thermal generation rate of charge carriers. The thermal generation rate  $G_{\text{th}}$  is related the intrinsic charge carrier concentration  $n_i$  and the charge carrier generation lifetime  $\tau_g$  by the

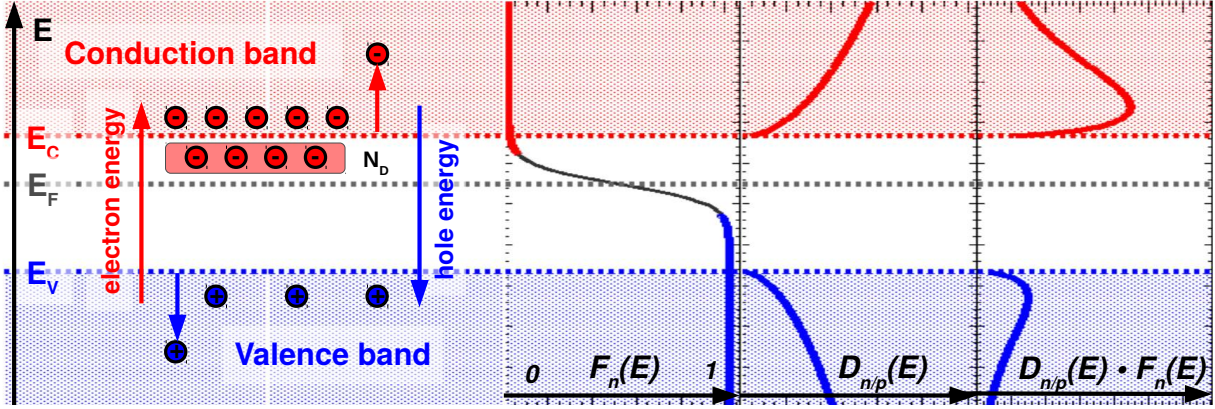


Figure 6.7.: Illustration of the electronic band structure of an n-type semiconductor with the valence band (blue) and the conduction band (red), the n-doping concentration  $N_D$ , the band gap in between, the band gap edges at energy levels  $E_C$  and  $E_V$ , and the Fermi-level  $E_F$ . The figure is divided into four subfigures showing (from left to right): the charge carriers in the band structure, the Fermi-Dirac distribution  $F_n(E)$ , the density of states  $D_{n/p}(E)$ , and their product  $F_n(E) \cdot D_{n/p}(E)$ . Axes have arbitrary units. Figure created after Ref. [59].

equation  $G_{th} = n_i/\tau_g$ . It is also proportional to the defect concentration,  $N_t$ , which is equivalent to a linear dependence on the radiation damage constant,  $\alpha_{\text{damage}}$ . The full leakage current of one sensor,  $I_{\text{leakage}}$ , is then given by multiplication with the sensor area:

$$I_{\text{leakage}} = j_{\text{leakage}} \cdot A_{\text{sensor}} = \frac{q_e \cdot d_{\text{sensor, active}} \cdot n_i}{\tau_g} \cdot A_{\text{sensor}} = \frac{q_e \cdot n_i}{\tau_g} \cdot V_{\text{sensor, active}}, \quad (6.3)$$

where  $V_{\text{sensor, active}}$  is the active sensor volume. The values of the charge carrier concentration  $n_i$  and the charge carrier lifetime  $\tau_g$  are temperature dependent, leading to a temperature dependent leakage current. The coarse derivation of the characteristic temperature dependence of these both quantities is shortly presented in the following.

### Charge carrier concentration

For the charge carrier concentration, the occupation probability of a state in dependence of the energy,  $E$ , follows the Fermi-Dirac distribution

$$F(E) = \frac{1}{1 + e^{\frac{E - E_F}{k_B T}}}$$

where  $E_F$  is the Fermi energy,  $T$  is the temperature, and  $k_B$  is the Boltzmann constant. For energy levels which fulfill the condition  $|E - E_F| > 3k_B T$  the Fermi-Dirac distribution of electrons and holes can be approximated by

$$F_n(E) \simeq e^{-\frac{E - E_F}{k_B T}}, \quad (6.4)$$

shown in Figure 6.7 (second from left), and

$$F_p(E) = 1 - F_n(E) \simeq e^{-\frac{E_F - E}{k_B T}}, \quad (6.5)$$

respectively. The density of states in an infinitesimal kinetic-energy interval,  $D(E_{\text{kin}})$ , which is shown in Figure 6.7 (second from right), is given by

$$D(E_{\text{kin}}) dE_{\text{kin}} = 4\pi \left( \frac{2m}{h^2} \right)^{\frac{3}{2}} E_{\text{kin}}^{\frac{1}{2}} dE_{\text{kin}},$$



where  $m$  is the effective mass of the charge carrier, and  $h$  is the Planck constant. The kinetic energy  $E_{\text{kin}}$  is measured from the band gap edge. The density of negative charge carriers, i.e. electrons, is then calculated with the integral from the band gap edge towards the conduction band:

$$n = \int_{E_C}^{\infty} D(E) F(E) dE_{\text{kin}} \quad (6.6)$$

$$= \int_0^{\infty} 4\pi \left( \frac{2m_n}{h^2} \right)^{\frac{3}{2}} E^{\frac{1}{2}} e^{-\frac{E+E_C-E_F}{k_B T}} dE \quad (6.7)$$

$$= 2 \left( \frac{2m_n \pi k T}{h^2} \right)^{\frac{3}{2}} e^{\frac{E_C-E_F}{k_B T}} \quad (6.8)$$

$$=: N_C(T) e^{\frac{E_C-E_F}{k_B T}}. \quad (6.9)$$

Similarly one obtains the density of positive charge carriers, i.e. holes, by integration over the valence band:

$$p = \int_{-\infty}^{E_V} D(E) F(E) dE_{\text{kin}} \quad (6.10)$$

$$= \int_0^{\infty} 4\pi \left( \frac{2m}{h^2} \right)^{\frac{3}{2}} E^{\frac{1}{2}} e^{-\frac{E+E_F-E_V}{k_B T}} dE \quad (6.11)$$

$$= 2 \left( \frac{2m \pi k T}{h^2} \right)^{\frac{3}{2}} e^{\frac{E_C-E_F}{k_B T}} \quad (6.12)$$

$$=: N_V(T) e^{\frac{E_F-E_V}{k_B T}}. \quad (6.13)$$

As the concentrations of free electrons and holes have to be equal in the semiconductor ( $n = p = n_i$ ), one obtains the charge carrier concentration  $n_i$  as

$$n_i = \sqrt{np} = \sqrt{N_C(T)N_V(T)} \exp\left(-\frac{E_C-E_V}{2k_B T}\right) = \sqrt{N_C(T)N_V(T)} e^{-\frac{\Delta E}{2k_B T}} \quad (6.14)$$

$$\propto T^{\frac{3}{2}} \exp\left(-\frac{\Delta E}{2k_B T}\right), \quad (6.15)$$

with the band gap of silicon  $\Delta E = 1.21 \text{ eV}$  at  $-20^\circ \text{C}$ .

### Charge carrier generation lifetime

The derivation of the charge carrier generation lifetime  $\tau_g$ , which occurs in Equation 6.2, is based on the description of the emission and capture rates of electron and holes in the semiconductor and their respective rates and cross sections. For fully depleted semiconductors it is inversely proportional to the thermal velocity  $v_{\text{th}} = \sqrt{\frac{2k_B T}{m}}$ :

$$\frac{1}{\tau_g} \propto v_{\text{th}} = \sqrt{\frac{2k_B T}{m}} \propto T^{\frac{1}{2}}. \quad (6.16)$$

### Temperature dependence of the leakage current

The full temperature dependence of the sensor leakage current is then given by multiplying the temperature dependent factors from Equations 6.14 and 6.16 in Equation 6.2:

$$I_{\text{leakage}}(T) \propto I_{\text{leak},0} \left( \frac{T}{T_0} \right)^2 \exp\left(-\frac{\Delta E}{2k_B} \left( \frac{1}{T} - \frac{1}{T_0} \right)\right) \quad (6.17)$$

## 6.4. Power and CO<sub>2</sub> Cooling of the 2S Modules

where  $I_{\text{leak},0}$  is the leakage current at a reference temperature  $T_0$ , and  $\Delta E = 1.21$  eV is the band gap of silicon.

The leakage current is directly proportional to the active sensor volume, which is given by

$$V_{\text{sensor, active}} = A_{\text{sensor}} \cdot d_{\text{sensor, active}}, \quad (6.18)$$

where  $A_{\text{sensor}}$  is the area of the active, depleted sensor volume in the  $xy$ -plane and  $d_{\text{sensor, active}}$  is the active sensor thickness in the  $z$ -direction. The active region of the sensor is the volume in which the sensor is effectively depleted by the electrical field under operational high voltage and where the ionization and charge collection process takes place. Depending on the sensor design and production technology the active sensor volume can be identical to the entire sensor volume. In other cases the active sensor volume is produced upon a thin silicon substrate layer leading to a higher total sensor thickness than the active thickness. The radiation damage depends on the particle flux  $\Phi$  the sensor was exposed to. An empiric radiation damage constant,  $\alpha_{\text{damage}} = 5.35 \cdot 10^{-17}$  A/cm, is taken from [5, 61]. The increment  $\Delta I_{\text{leakage}}$  can be written as

$$\Delta I_{\text{leakage}} = \alpha_{\text{damage}} \cdot \Phi \cdot V_{\text{sensor, active}} = \alpha_{\text{damage}} \cdot \Phi \cdot A_{\text{sensor}} \cdot d_{\text{sensor, active}}. \quad (6.19)$$

With the assumption that the leakage current of an unirradiated sensor is negligible, the sensor power produced by the bulk current is given by

$$P_{\text{sensor}}(T_{\text{sensor}}) = U_{\text{bias}} \cdot I_{\text{leak},0} \cdot \left( \frac{T_{\text{sensor}}}{T_0} \right)^2 \exp \left( - \frac{\Delta E}{2k_B} \left( \frac{1}{T_{\text{sensor}}} - \frac{1}{T_0} \right) \right) \quad (6.20)$$

$$= U_{\text{bias}} \cdot \Phi \cdot \alpha_{\text{damage}} \cdot A_{\text{sensor}} \cdot d_{\text{sensor, active}} \cdot \left( \frac{T_{\text{sensor}}}{T_0} \right)^2 \exp \left( - \frac{\Delta E}{2k_B} \left( \frac{1}{T_{\text{sensor}}} - \frac{1}{T_0} \right) \right) \quad (6.21)$$

The sensor power at the reference temperature of  $-20^\circ\text{C}$  for various active sensor thicknesses, integrated luminosities and high voltage values is listed in Table 6.2.

Table 6.2.: Sensor and module power at the reference sensor temperature of  $-20^\circ\text{C}$  for various scenarios of active sensor thickness, HV bias voltage, and integrated luminosity. The value  $P_{\text{sensor}}^{-20^\circ\text{C}}$  refers to the reference power of a single sensor.

| $d_{\text{active}} [\mu\text{m}]$ | $\mathcal{L}_{\text{int}} [\text{fb}^{-1}]$ | HV [V] | $P_{\text{sensor}}^{-20^\circ\text{C}} [\text{W}]$ | $P_{2\text{S module}} [\text{W}]$ |
|-----------------------------------|---------------------------------------------|--------|----------------------------------------------------|-----------------------------------|
| 200                               | 3000                                        | 600    | 0.32                                               | 6.04                              |
|                                   | 4000                                        | 800    | 0.56                                               | 6.52                              |
| 240                               | 3000                                        | 600    | 0.38                                               | 6.16                              |
|                                   | 4000                                        | 800    | 0.67                                               | 6.74                              |
| 290                               | 3000                                        | 600    | 0.46                                               | 6.32                              |
|                                   | 4000                                        | 800    | 0.81                                               | 7.02                              |
| 320                               | 3000                                        | 600    | 0.51                                               | 6.42                              |
|                                   | 4000                                        | 800    | 0.90                                               | 7.20                              |

### 6.4.3. Full Module Power

With the power values of the top and the bottom sensor,  $P_{\text{sensor}}^{\text{top}}$  and  $P_{\text{sensor}}^{\text{bottom}}$ , the full module power can be written as

$$P_{2\text{S module}} = P_{\text{sensor}}^{\text{top}}(T_{\text{sensor}}^{\text{top}}) + P_{\text{sensor}}^{\text{bottom}}(T_{\text{sensor}}^{\text{bottom}}) + P_{\text{hybrids}} \quad (6.22)$$

$$= U_{\text{bias}} \cdot I_{\text{leak},0} \cdot \sum_{i=\text{top, bottom}} \left( \frac{T_{\text{sensor},i}}{T_0} \right)^2 \exp \left( - \frac{\Delta E}{2k_B} \left( \frac{1}{T_{\text{sensor},i}} - \frac{1}{T_0} \right) \right) + P_{\text{hybrids}}, \quad (6.23)$$



where  $T_{\text{sensor, top}}$  ( $T_{\text{sensor, bottom}}$ ) in the sum denote the temperature of the top (bottom) sensor, and the leakage current  $I_{\text{leak}, 0}$  is assumed to be the same for the top and the bottom sensor. The full module power for various integrated luminosities and HV values is also listed in Table 6.2. A generic estimation for the 2S module power after an integrated luminosity of  $3000 \text{ fb}^{-1}$  would be

$$P_{2\text{S module}} = P_{\text{sensor}}^{\text{top}} + P_{\text{sensor}}^{\text{bottom}} + P_{\text{hybrids}} = 0.38 \text{ W} + 0.38 \text{ W} + 5.40 \text{ W} \approx 6.2 \text{ W}. \quad (6.24)$$

This power estimation is the baseline estimation used in this thesis. The power value of  $0.38 \text{ W}$  per sensor refers to an active sensor thickness of  $240 \mu\text{m}$ , a sensor temperature of  $-20^\circ\text{C}$ , a bias voltage of  $600 \text{ V}$ , and an integrated luminosity of  $3000 \text{ fb}^{-1}$ . It is based on an estimation of the irradiation of  $\Phi = 3.0 \cdot 10^{14} \text{ neq/cm}^2$ . The estimation for the sensor power was made at a time when an active sensor thickness of  $240 \mu\text{m}$  seemed to be the probable choice for the 2S sensors. Recently, the tracker collaboration decided to use sensors with an active thickness of  $290 \mu\text{m}$ . The corresponding reference power after  $3000 \text{ fb}^{-1}$  is then  $0.46 \text{ W}$  per sensor.

As the estimation of the sensor reference power depends on many parameters and assumptions, this thesis will later present a discussion of different scenarii regarding the choice of these parameters (Section 7.12.3).

#### 6.4.4. CO<sub>2</sub> Cooling of the 2S Modules

The Phase-2 Outer and Inner Tracker will be cooled with an evaporative CO<sub>2</sub> cooling system with the 2PACL concept, which is described in Section 4.10.1. The nominal CO<sub>2</sub> temperature is  $-35^\circ\text{C}$ . The maximum expected CO<sub>2</sub> temperature from pressure drops along the cooling lines is  $-33^\circ\text{C}$ . This temperature is thus stated as the reference temperature in most considerations. The cooling structure is optimized for best performance at a low material budget in the active tracking volume. The material of the cooling pipes will be stainless steel. The cooling pipes have an outer diameter of  $2.2 \text{ mm}$  and an inner diameter of  $2.0 \text{ mm}$  with a wall thickness of  $100 \mu\text{m}$ . The 2S modules will be mounted on five cooling blocks. Figure 6.8 left (right) shows the cooling blocks in the TEDD (TB2S). The cooling blocks in the TEDD are called inserts. In the TB2S, a cuboid geometry of the cooling blocks is used and in the TEDD a cyclindrical form is used. The cooling blocks and inserts embrace the cooling pipe. They are built as a larger main part where the 2S modules are mounted on, and a smaller cap piece which completes the contact surface on the full pipe circumference. The connection to the cooling pipe is made with an about  $20 \mu\text{m}$  thick glue layer. The material foreseen for the cooling blocks is AlCF in the TB2S ladders, and aluminum in the TEDDs. In TB2S, 2S modules are mounted both from the top and the bottom side to a cooling block, while in the TEDD only one 2S module is connected to one insert. The length of the contact surface to the pipe differs between TB2S and TEDD. In the TB2S ladder the contact length of one cooling blocks is  $26 \text{ mm}$  at the four corners of the 2S module and  $8 \text{ mm}$  at the stump bridge. The inserts in the TEDD have a cyclindrical shaft with a diameter of  $8 \text{ mm}$ . Two designs are under discussion in the collaboration. The insert could be formed purely cylindrically with a contact length of  $8 \text{ mm}$  to the pipe. The contact surface could also be enhanced by keeping the cyclindrical shaft of the insert, but extending the contact length by e.g.  $4 \text{ mm}$  in pipe direction. This version is shown in Figure 6.8 (left).

#### 6.4.5. Thermal Runaway

The cooling power of the cooling system can be described linearly with the thermal resistance of the cooling structure,  $\alpha_{\text{cooling}}$ . The cooling power,  $P_{\text{cooling}}$ , is given by

$$P_{\text{cooling}} = \frac{1}{\alpha_{\text{cooling}}} (T - T_{\text{cooling}}), \quad (6.25)$$

where  $T$  is the temperature of component which has to be cooled, and  $T_{\text{cooling}}$  is the coolant temperature. In case of an irradiated sensor in the 2S module with the power consumption like in Equation 6.23, a stable working point of the cooling system would exist at the temperature  $T_{\text{sensor}}$  when the equations

$$P_{\text{cooling}}(T_{\text{sensor}}) = P_{2\text{S module}}(T_{\text{sensor}}) \quad (6.26)$$

and

$$\frac{1}{\alpha_{\text{cooling}}} = \frac{dP_{\text{cooling}}}{dT_{\text{sensor}}} > \frac{dP_{2\text{S module}}}{dT_{\text{sensor}}} = \frac{dP_{\text{sensor}}}{dT_{\text{sensor}}} \quad (6.27)$$

are fulfilled. Otherwise no stable working point is reached and the effect of thermal runaway occurs. The situation is illustrated in Figure 6.9. The solid blue line shows a possible cooling power of a cooling system with a cooling liquid temperature of  $-35^\circ\text{C}$ . Once the module is powered, the sensors will heat up to the temperature and the power of the working point, where the curves of the module power and the cooling power intersect. This working point is stable as it would be restored under small fluctuations of the sensor temperature and the coolant temperature. The second intersection point, which is not shown in the figure, is not a stable working point. Small fluctuations to higher sensor temperatures would lead to thermal runaway of the sensor power. Small fluctuations to lower sensor temperatures would produce the situation that the cooling power is greater than the sensor power and the stable working point would be restored. At higher coolant temperatures and the same thermal resistance of the cooling system the situation can occur that no stable working point exists. The sensor would immediately enter the thermal runaway and no stable operation of the sensor would be possible.

The illustration shows that two criteria need to be fulfilled for a thermally stable operation of the detector. The most important point is the thermal resistance,  $\alpha_{\text{cooling}}$ , of the structure. Only low values of  $\alpha_{\text{cooling}}$ , which correspond to high slopes of the blue line in Figure 6.9, make low temperature gradients between sensor and coolant possible. A good thermal layout of the detector mechanics is thus crucial. The other point is the temperature of the coolant, which is in this case two-phase CO<sub>2</sub>. The coolant temperature has to be sufficiently low enough in order to produce the working point shown in Figure 6.9, with a given thermal resistance  $\alpha_{\text{cooling}}$  of the mechanics. However, the coolant temperature cannot be set arbitrarily low for technical reasons, with the final limitation that the freezing point of CO<sub>2</sub> is at about  $-56^\circ\text{C}$  on the vapor pressure curve. The illustration implies also that a (too) badly designed thermal layout cannot be compensated by decreasing the coolant temperature by a few degrees only. Figure 6.9 implies that for cooling powers with a high  $\alpha_{\text{cooling}}$ , i. e. low slope of the blue line, situations might arise where even a decrease of the cooling temperature by e. g. 20 K might not produce a working point. Hence, the thermal design and layout of the detector structure, i. e. a low thermal resistance  $\alpha_{\text{cooling}}$ , is crucial for the longevity of the detector.

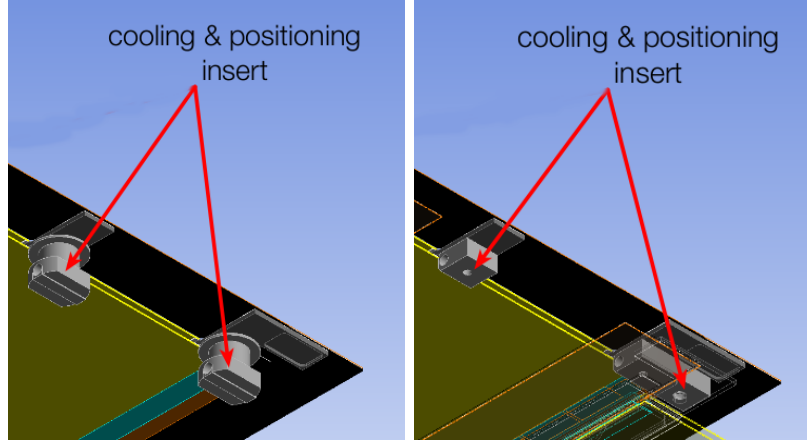


Figure 6.8.: Two TEDD cooling inserts in the enhanced cooling pipe contact length design (left). The cooling blocks in the TB2S (right). Two 2S modules are mounted to the long cooling block at the module corner whereas only one module is connected to the cooling block at the stump bridge. [5]

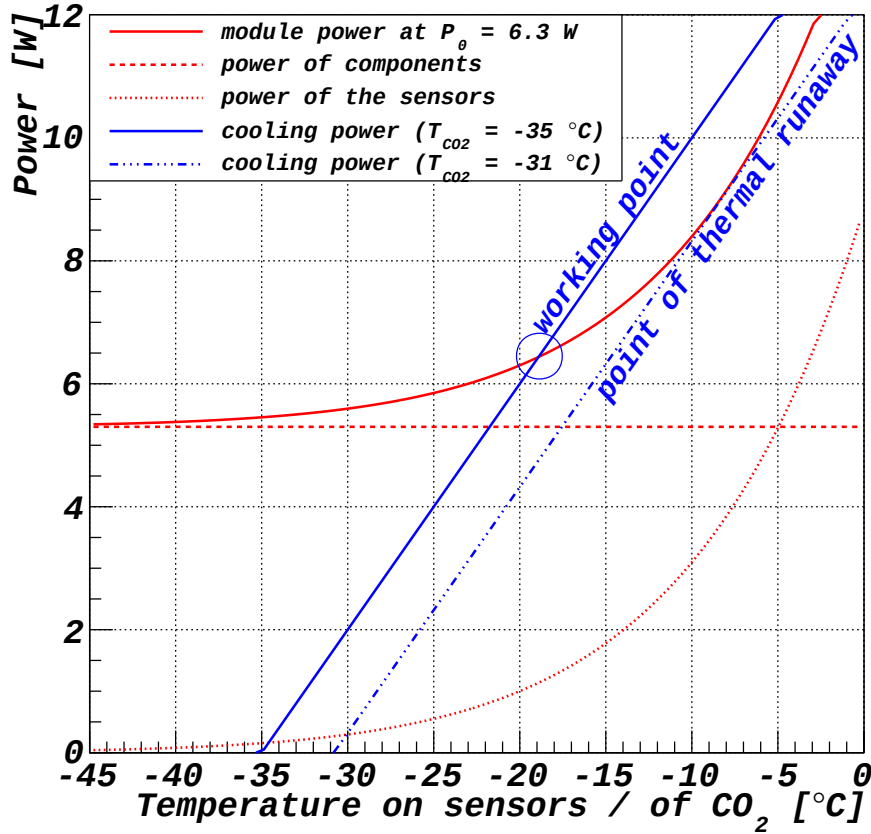


Figure 6.9.: Illustration of the thermal runaway effect with power and temperatures close to the expected values for the 2S modules. The dashed red line shows the power of the hybrids and the dotted line shows the power of the sensors in dependence of the sensor temperature. The red solid curve shows the nominal power of the full 2S module, which is the sum of the power of the sensors and the hybrids. The blue lines show possible cooling powers. The coolant temperature can be read at the intersection of the temperature axis with the cooling power lines. In this illustration, a stable working point of the system at a sensor temperature of  $-19^{\circ}\text{C}$  would be possible at e.g. a coolant temperature of  $-35^{\circ}\text{C}$ . No stable working point would be possible at a coolant temperature of  $-31^{\circ}\text{C}$  and the thermal runaway would occur at a sensor temperature of  $-8^{\circ}\text{C}$ .



## 7. Thermal Measurements with the 2S Module

A good understanding of the thermal properties of the 2S module is crucial for the operation and the longevity of the Phase-2 tracker. The Phase-2 tracker is planned to be operated until an integrated luminosity of  $3000 \text{ fb}^{-1}$  or, in other scenarios under discussion, even  $4000 \text{ fb}^{-1}$ . The 2S modules have to be operated until the end of the lifetime of the detector despite of the high radiation level they will be exposed to.

The effect of the rise of the leakage current because of radiation damage and the effect of thermal runaway have to be carefully estimated in order to make reliable projections for the lifetime of the detector. Thermal finite element models (FE models) are developed within the scope of this thesis and used to simulate the thermal behavior and the thermal runaway of the 2S modules. The Heat Transfer Module of COMSOL<sup>®</sup> Multiphysics [62, 63] is used for the FE models. The results from the FE models published in the Phase-2 Tracker Upgrade TDR [5] are cross-checked with the FE models in this thesis. The models incorporate a large number of theoretical and experimental assumptions: on the leakage current of the sensor, on the power of other active components on the modules, on thermal conductivities of the materials and thermal interfaces, and on the heat transfer to the cooling system.

The assumptions have to be confirmed experimentally and, if necessary, have to be revised in the finite element model. For this thesis a setup was developed which provides the opportunity to make well defined thermal measurements with thermal dummy 2S modules and an evaporative  $\text{CO}_2$  cooling system with an operating temperature close to the nominal operational temperature in the Phase-2 tracker. The connection to the cooling system is realized with inserts in a design comparable to the configuration in the TEDDs. The measurements are performed in a custom-built test box which makes it possible to accurately control the ambient temperature during the measurements. With well defined and well known ambient conditions it is possible to minimize the heat exchange between the thermal test device and the ambient and a comparison with finite element simulations is possible. With this concept the thermal performance of the cooling system, its mechanics, and the module design can be tested. On the other hand it is possible to estimate the magnitude of the thermal interaction between the module and the ambient.

The concept of this method is described in more detail in Section 7.2 and the measurement setup is described in Section 7.3. The thermal analysis is divided into two categories. Firstly, the thermal behavior of the mechanics and the cooling structure is characterized in Section 7.4. Secondly, the thermal behavior of the 2S module is measured and analysed. The thermal dummy modules built are presented in Section 7.5 and the finite element models are presented in Section 7.6. The measurement of a bare 2S module without hybrids is presented in Section 7.7 and the measurement with a fully assembled 2S module with hybrids is presented in Section 7.8. In both sections appropriate finite element model are compared with the thermal measurements. The the concept of thermal runaway of the 2S module and the attempt to measure it is presented in Sections 7.9 and 7.10. A detailed finite element simulation of the thermal runaway i presented in Seciton 7.11. The thermal runaway of the 2S modules in the TEDD2S subdetector for different scnearii is discussed in Section 7.12. A short comment on the thermal design of the 2S module is given in Section 7.13. The measurement of the thermal behavior when switching the module power on or off is presented in Appendix D. A study on the thermal contact between the spacers and the inserts in dependence on the torque applied to the screws is presented in Appendix E.

### 7.1. Thermal Design of the 2S Module

The most crucial point in the thermal design of the 2S module is the proper cooling of the silicon sensors. The 2S module design realizes an optimized thermal decoupling of the sensor from the other heat producing components. The sensors are glued to the AlCF spacers, through which the heat is removed and dissipated to the module screwing points. The heat fluxes from the SEH and the FEH do not share a common path with the sensor heat flux within the 2S module. Their heat is removed through the spacers from the opposite side of the screwing point, which makes the heat fluxes thermally rather independent. The only thermally conductive coupling between the sensors and the FEHs is the connection through the wirebonds and the encapsulation material, which is unavoidable. In the mounting points the module heat flux is merged and directed into the cooling blocks or inserts. The heat load of the module is not necessarily distributed equally to the inserts. The mean temperature on the top surface of the inserts or the temperature of the spacers at the screwing points can be defined as the baseline temperature of the 2S module entity.

### 7.2. Concept of the Measurement Program

Most thermal test setups and tests follow the same idea for the measurement procedure. A test device produces a power  $P$  which is removed by a cooling system at a given temperature  $T_{\text{cooling}}$  and the temperature  $T$  of the test device is measured. The curves

$$P(T) = \lambda_{\text{cooling}} (T - T_{\text{cooling}}) \quad (7.1)$$

or

$$T(P) = \alpha_{\text{cooling}} P + T_{\text{cooling}} \quad (7.2)$$

are recorded and it is possible to determine the effective thermal conductivity,  $\lambda_{\text{cooling}}$ , or the thermal resistance,  $\alpha_{\text{cooling}} = 1/\lambda_{\text{cooling}}$ , of the system from the data. In most practical cases these curves can be recorded relatively easily and the parameters  $\alpha_{\text{cooling}}$  or  $\lambda_{\text{cooling}}$  can be extracted. In test setups, heat load can be applied easily to the test device with an electrical power  $P$  where techniques like e.g. heating resistors or heating foils are common. The actual execution of temperature measurements is also not very difficult as resistive temperature devices (e.g. PT100 sensors or NTC thermistors) are commonly available and the measured resistance can be converted to a temperature value  $T$  with given calibration curves. Assuming no measurement errors, the thermal properties of the system would be fully described by Equation 7.1 or 7.2. However, a substantial and reliable analysis of the recorded data requires a detailed understanding of the setup and the potential measurement errors related to it. Many sources of measurement errors can be specified. Many of them are related to effects of heat exchange between the test device and the ambient. This quantity is not included in Equations 7.1 and 7.2, but plays a significant role in the thermal behavior of typical test setups. This is discussed in the following.

#### 7.2.1. Heat Exchange with the Ambient

Figure 7.1 (top) shows a simplified schematic of a possible test setup. A test device indicated by the red line produces a known and constant heat load  $P$ . The device is coupled thermally to two outer systems, the cooling system and the ambient, through the thermal conductivities  $\lambda_{\text{cooling}}$  and  $\lambda_{\text{ambient}}$ , respectively. The temperature of the cooling system be  $T_{\text{cooling}}$  and the temperature of the ambient be  $T_{\text{ambient}}$ . In a stationary situation the test device is at a constant temperature  $T$ . The heat fluxes  $P_{\text{ambient}}$  and  $P_{\text{cooling}}$  from the test device to the outer systems

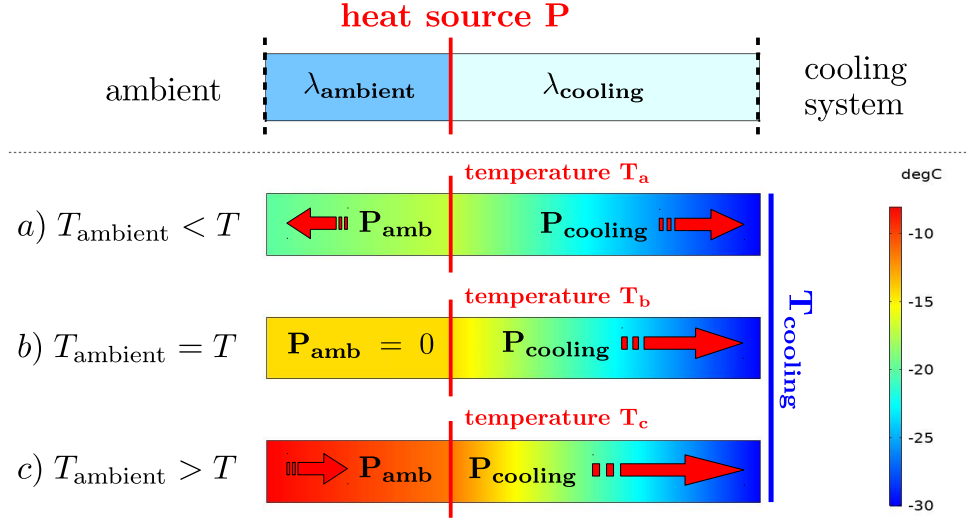


Figure 7.1.: Illustration of the temperature distribution and the heat flux in a simplified geometric model. On top, a mechanical structure is sketched with thermal coupling to a cooling system and to the ambient. On bottom, the temperature distribution and the heat fluxes in the system are illustrated for different ambient temperatures. The red line indicates the position of heat source with power  $P$  and the temperature measurement with value  $T$ .

are given by

$$P_{\text{ambient}} = \lambda_{\text{ambient}} (T - T_{\text{ambient}}) \quad (7.3)$$

$$(7.4)$$

and

$$P_{\text{cooling}} = \lambda_{\text{cooling}} (T - T_{\text{cooling}}). \quad (7.5)$$

Here, the sign convention is chosen such that positive values denote heat flowing from the test device to the outer system, and negative values denote heat flowing from the outer system to the test device. By using the equation of continuity both values sum up to the full power  $P$  of the test device:

$$P_{\text{ambient}} + P_{\text{cooling}} = P = \underbrace{\lambda_{\text{ambient}} (T - T_{\text{ambient}})}_{\text{= heat exchange with the ambient}} + \underbrace{\lambda_{\text{cooling}} (T - T_{\text{cooling}})}_{\text{= heat removed by cooling system}}. \quad (7.6)$$

This splitted notation of the heat fluxes from the test device to the outer systems can be used for detailed analyses of the thermal properties of the test setup. Figure 7.1 (bottom) schematically shows three different realistic scenarios for relative values of  $T$  and  $T_{\text{ambient}}$ . The temperature  $T$  of the test device is measured at the position where the test device produces the heat load  $P$ . The temperature  $T_{\text{cooling}}$  of the cooling system is constant ( $-30^\circ\text{C}$  in the case shown) and it is assumed that it is always the coldest temperature in the whole setup. For all three cases a heat flux  $P_{\text{cooling}}$  from the heat source to the cooling system occurs. The magnitude of  $P_{\text{cooling}}$  and the value of  $T$  vary depending on the ambient temperature  $T_{\text{ambient}}$ . Also, the heat flux  $P_{\text{amb}}$  between the test device and the ambient behaves differently. The thermal resistance of the test device  $\alpha_{\text{cooling}} = (T - T_{\text{cooling}})/P$  is evaluated differently depending on the ambient conditions. Three cases can be distinguished qualitatively as follows, under the assumption that only Equation 7.2 would be used for the analysis.

Case a)  $T_{\text{ambient}} < T$ ,  $P_{\text{cooling}} < P$ : The ambient temperature is lower than the device temperature. A heat flux from the test device to the ambient occurs. The actual heat which flows from the test device to the cooling system is overestimated. The thermal resistance  $\alpha_{\text{cooling}}$  of the device is underestimated.

Case b)  $T_{\text{ambient}} = T$ ,  $P_{\text{cooling}} = P$ : The case of thermal equilibrium between ambient and test device is illustrated. The ambient temperature is equal to the device temperature, and the heat flux from the device to the cooling system is equal to the heat load produced by the device. No heat exchange occurs between the ambient and the device. The thermal resistance  $\alpha_{\text{cooling}}$  of the device is estimated correctly.

Case c)  $T_{\text{ambient}} > T$ ,  $P_{\text{cooling}} > P$ : The ambient temperature is higher than the device temperature. A heat flux from the ambient to the device occurs. The actual heat which flows from the test device to the cooling system is underestimated. The thermal resistance  $\alpha_{\text{cooling}}$  of the device is overestimated.

The three cases show how the impact from the ambient can produce errors in thermal measurements. Understanding these impacts is a crucial step for making meaningful thermal measurements. For the characterization of the thermal properties of a test device it is advantageous to produce a thermal equilibrium between the device and the ambient because then correct descriptions of the device are possible.

### 7.2.2. Measurement of the Thermal Resistance

As described above, a common method for making thermal measurements is to measure the temperature of the device in dependence on the device power, i.e. measuring the function  $T(P)$ . The relation  $\Delta T / \Delta P \propto \alpha$  is usually sufficiently linear and the factor of proportionality  $\alpha$  can be obtained by fitting a linear function to the data. Solving Equation 7.6 for  $T$  yields

$$T(P) = \frac{P + \lambda_{\text{ambient}} T_{\text{ambient}} + \lambda_{\text{cooling}} T_{\text{cooling}}}{\lambda_{\text{ambient}} + \lambda_{\text{cooling}}}, \quad (7.7)$$

which is a linear function of the form  $T(P) = \alpha P + T_0$  with the measured factor of proportionality  $\alpha$  and a temperature  $T_0$ , which is the temperature for no device power. The slope of Equation 7.7 can be compared with the slope of Equation 7.2, yielding

$$\Delta T \propto \frac{1}{\lambda_{\text{ambient}} + \lambda_{\text{cooling}}} P < \frac{1}{\lambda_{\text{cooling}}} P. \quad (7.8)$$

In the simplified model discussed here with two thermal resistances, Equation 7.8 can be rewritten as

$$\Delta T \propto \frac{1}{\frac{1}{\alpha_{\text{ambient}}} + \frac{1}{\alpha_{\text{cooling}}}} P < \alpha_{\text{cooling}} P. \quad (7.9)$$

From this equation it is obvious that the thermal resistance of a system  $\alpha_{\text{cooling}} = \frac{T - T_{\text{cooling}}}{P_{\text{cooling}}}$  in general cannot be accessed with this measurement method when there is a coupling to the ambient with a finite thermal resistance  $\alpha_{\text{ambient}}$ .

Setting the device temperature  $T$  equal to the ambient temperature  $T_{\text{ambient}}$  in Equations 7.6 or 7.7 (i.e.  $T = T_{\text{ambient}}$ ) leads to the desired form

$$T(P) = \alpha_{\text{cooling}} P + T_{\text{cooling}}. \quad (7.10)$$

This scenario corresponds to the case b) in the example above and the measurement of  $\alpha_{\text{cooling}}$  is possible.



Figure 7.2 illustrates the approach for the measurement and the determination of the actual thermal resistance  $\alpha_{\text{cooling}}$  used in this thesis. The curve shown in Equation 7.7 is recorded for different ambient temperatures  $T_{\text{amb}} > T_{\text{cooling}}$ . At each ambient temperature it is measured by increasing the device power with proper step sizes in a reasonable range. The temperature  $T(P)$  of the test device is recorded for each power step. By interpolation of the data points, the point  $T_i(P_i) = T_{\text{ambient},i}$  is determined for each ambient temperature  $T_{\text{ambient},i}$ . From the points obtained, a new data series  $T_{\text{equil}}(P)$  is generated which follows also a linear behavior and which is by construction the measurement of Equation 7.10. By fitting a linear function to this data series the thermal resistance  $\alpha_{\text{cooling}}$  of the test device can be determined.

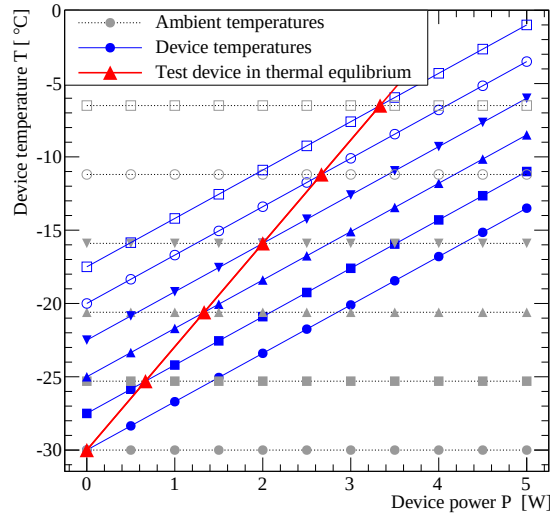


Figure 7.2.: Illustration of the measurement of the thermal resistance of a mechanical test device which is in contact with the ambient. The horizontal gray lines indicate the ambient temperatures  $T_{\text{ambient},i}$ . The blue data points are the measured device temperatures versus the device power for the corresponding ambient temperature. The red points are the points which fulfill the condition  $T_i = T_{\text{ambient},i}$ . The resulting red curve is the constructed data series from which the thermal resistance can be determined.

### 7.3. Measurement Setup

Within the scope of this thesis a test setup for thermal measurements with the 2S module has been developed, constructed, and commissioned. The concept and design of the thermal measurement setup for 2S modules is driven by the idea described in the previous section. It is important to individually control both important temperatures,  $T_{\text{cooling}}$  and  $T_{\text{ambient}}$ . The test setup has to be operated with a two-phase  $\text{CO}_2$  cooling system at temperatures in the order of the nominal cooling temperature of  $-35^\circ\text{C}$  of the Phase-2 tracker in order to produce realistic thermal properties of the  $\text{CO}_2$ . The ambient temperature of the measurement setup has to be controlled precisely down to temperatures in this order of magnitude. The setup has to be equipped with 2S module cooling positions which are mechanically well comparable with the cooling situation in the future Phase-2 tracker.

A schematical drawing of the system design is shown in Figure 7.3. A photograph of the full system is shown in Figure 7.4. A two-phase  $\text{CO}_2$  cooling circuit serves three positions for 2S modules in the test setup region. The cooling positions are located in a module cooling box. In its inner volume defined ambient temperatures can be produced with a second silicon oil based cooling circuit.

A Hameg HMP 4040 power supply was used to power the thermal test devices [64]. The following

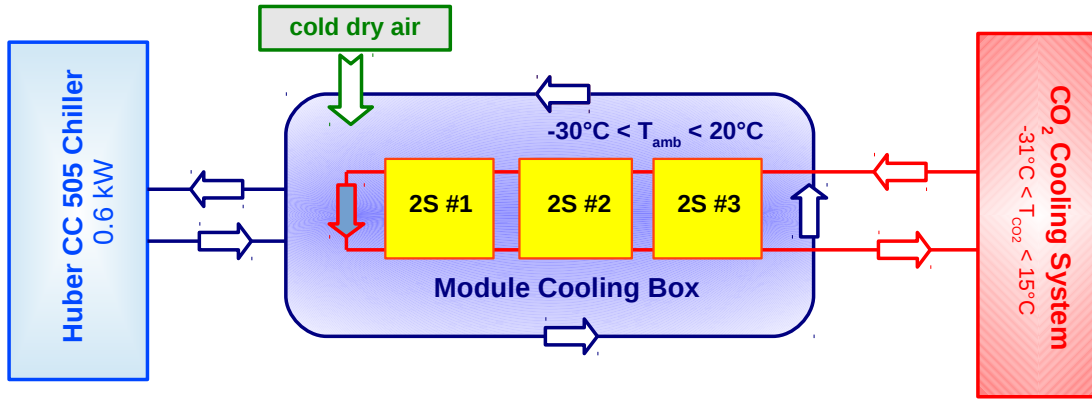


Figure 7.3.: Sketch of the concept and design of the thermal measurement setup for the 2S modules. Three cooling positions for 2S modules (yellow) are connected to the cooling pipes of a two-phase CO<sub>2</sub> cooling system (red). The cooling positions are located in an ambient volume (dark blue) whose temperature is controlled with an external chiller (light blue). The volume is flooded with tempered cold dry air (green).

sections describe the measurement setup.

### 7.3.1. CO<sub>2</sub> Cooling System

The CO<sub>2</sub> cooling system used for the measurements presented in this chapter are performed with the custom evaporative CO<sub>2</sub> cooling system in the laboratory of this working group [65]. The CO<sub>2</sub> cooling system is based on the 2PACL method described in Section 4.10.1. The system uses a 3.8 L expansion vessel [66] as the accumulator of the system and a pump [67] for the circulation of the CO<sub>2</sub>. CO<sub>2</sub> temperatures down to  $-31^{\circ}\text{C}$  at mass flows of 60 g/min can be reached. The temperatures of the accumulator and the subcooling part in front of the pump are controlled with Huber unistat 815 [68] cooling machines. The mass flow is measured with the flowmeter RHE 07 [69]. The NTC temperature sensors [70] of the system and of the test device are read out with the Keithley Model 2701 [71]. The controlling and readout of the devices is implemented with LabView [72]. The same LabView program provides also a graphical user interface for the system.

### 7.3.2. Module Cooling Box

The module cooling box is used to produce a defined ambient temperature in its inner volume. It is a custom design cooling box developed and produced at this institute. It has an outer (inner) extent of about  $113\text{ cm} \times 24\text{ cm} \times 18\text{ cm}$  ( $96\text{ cm} \times 16\text{ cm} \times 12\text{ cm}$ ). Its long faces are constructed out of ITEM profiles [73]. As a second entity the top face is integrated as a cover which can be opened with a handle through hinges. The hollow lateral cross sections of the ITEM profile are used as tube channels for silicon oil as cooling liquid [74]. A Huber cc 505 with a cooling power of 600 W at  $-20^{\circ}\text{C}$  is used as chiller for this circuit [75]. The silicon oil flows through the three long faces and the cover of the box. At the front faces custom made endpieces are mounted which divert the silicon oil to the adjacent channel in the ITEM profile. The connection between the cover and the three other walls is implemented with a flexible tube. Insulating blocks are inserted at the small front side walls for the termination of the inner volume. One side provides a hole to pass cables through. In the grooves of the inner bottom wall dry air supply channels are implemented in order to avoid condensation of the air humidity at cold temperatures. The dry air flows some distance parallel to the wall in order to reach the temperature of the walls and then enters the inner

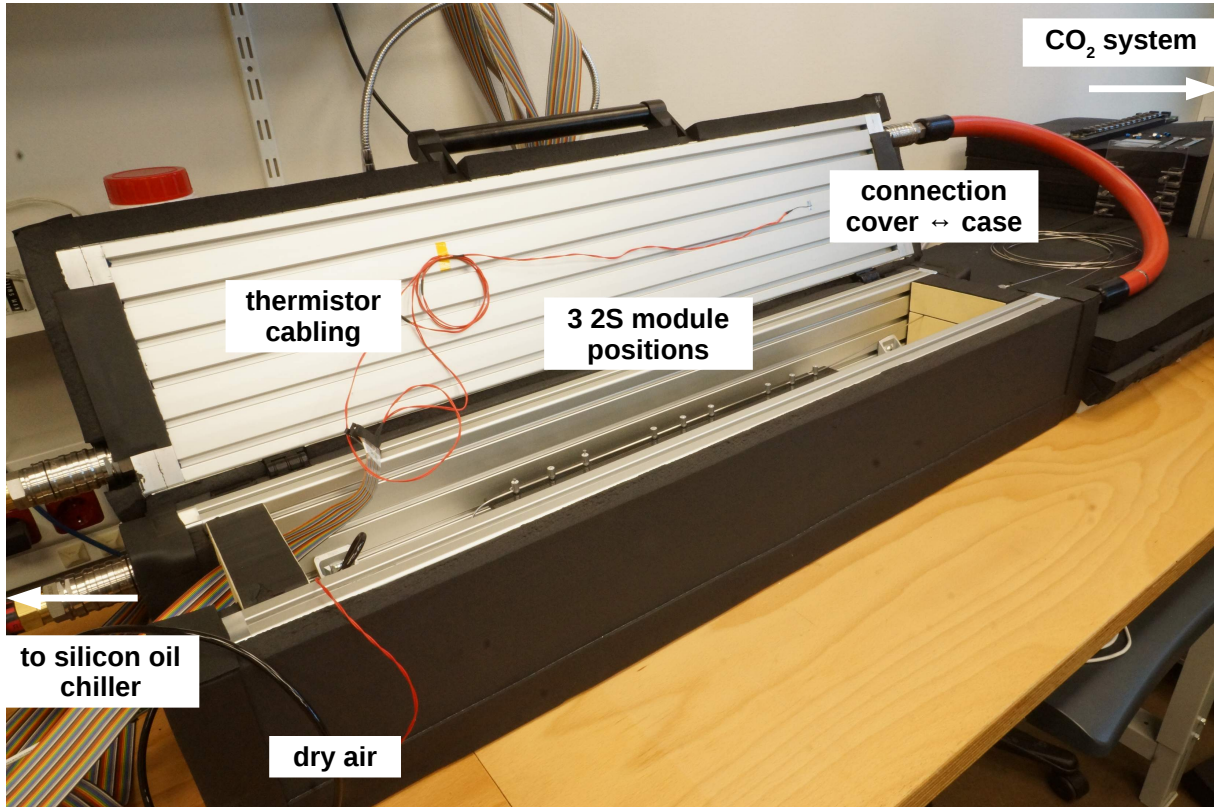


Figure 7.4.: Photograph of the 2S module thermal measurement setup. The cooling box is custom made and constructed out of ITEM profiles. The inlet and outlet of the silicon oil chiller are connected on the left. The silicon oil runs through the walls of the box and its cover. The connection between box and cover is on the right side. The inlet and outlet of the CO<sub>2</sub> system are connected on the right side. The CO<sub>2</sub> system itself is not shown on the photograph. The carbon fiber plate with the three 2S module positions is integrated in the box. The black dry air tube and some thermistor cablings are also visible.

box volume. The outer wall surfaces are completely insulated with about 2 cm thick Armaflex insulating mats. The inner wall surfaces are blank aluminum in order to have the optimal thermal contact between wall and inner air volume. The temperature of the air volume is completely dominated by the wall temperature. Temperatures down to  $-31^{\circ}\text{C}$  can be achieved in the bath of the chiller. The actual temperature achieved in the cooling box volume is usually 1 or 2 K higher.

### 7.3.3. Module Positions and Cooling Inserts

A CFRP plate is installed in the module cooling box as mechanical support for the module cooling inserts and the cooling pipe. Three 2S module positions are present in the module cooling box. Each module position contains five cooling inserts leading to a total number of 15 inserts in the box. A photograph of the cooling inserts is shown in Figure 7.5 (left). The cooling inserts are built similarly to the design of the 2S inserts in the TEDDs. However small changes are made for internal construction reasons. Figure 7.5 (right) shows a photograph of one insert used in this setup and Figures A.1 and A.3 in Appendix A show the technical drawings of the cooling insert. The cylindrical inserts are made out of the aluminum alloy Aluminum 7075-T651 with a thermal conductivity of  $130\text{ W/m/K}$  [76]. They have a diameter of 8 mm. The insert is constructed out of two parts, a top part and a bottom part. The bottom part has a height of about 4 mm and it is positioned on the base plate and fixed with a screw. The top part is glued on top of the bottom

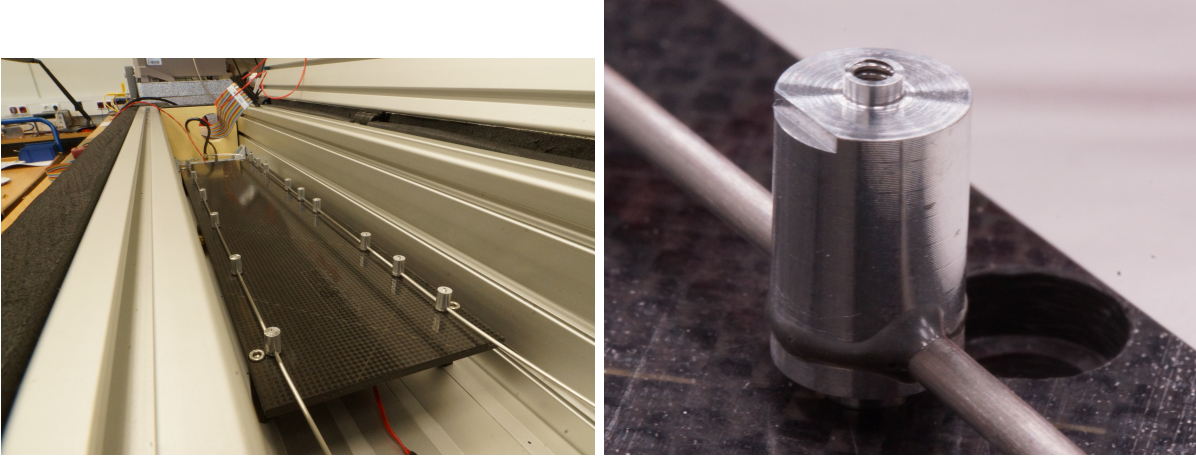


Figure 7.5.: Left: the carbon fiber plate with the cooling inserts as it is installed in the inner volume of the box. Right: a TEDD-like cooling insert in the thermal test setup for the 2S modules.

part. Together the top and bottom part of the insert embrace the cooling pipe. The distance between the center of the cooling pipe and the top surface of the inserts is approximately 1 cm. The screwing point and cooling contact for the 2S module is on the top surface of the inserts where they have a nipple protruding about 2 mm with a diameter of 2.5 mm. The nipples do not only serve as positioning pins for the 2S modules, but they also provide some additional thread length in order to apply enough torque for the contact pressure between module and insert. Steel screws with an M2 thread with a length of 3 mm and a washer are used.

All cooling positions are served by a common cooling pipe which enters and leaves the module cooling box at the same side. A stainless steel pipe with 2.2 mm outer diameter and 100  $\mu\text{m}$  wall thickness is used. The cooling pipe has the same specifications as the cooling pipe in the Phase-2 Outer Tracker. A dedicated assembly procedure was utilized which made both thin glue layers and sufficient positioning accuracy of the inserts possible. The glue used was the 3M Scotch-Weld Epoxy Adhesive 2216 [77]. It was chosen because of its relatively good thermal conductivity of 0.4 W/m/K and its elasticity under thermal cycling conditions. From the specifications of the mechanics, glue layer thicknesses of about 20  $\mu\text{m}$  were produced. However it is not possible to confirm this specification by a measurement.

The 2S module design utilizes Kapton high voltage isolation strips between AlCF spacers and sensor backplane. The specification of the 700  $\mu\text{m}$  Kapton strip overhang from the sensor backplane is in conflict with the cylindrical TEDD cooling insert design. The Kapton strip overhang would be trapped between the AlCF spacers and the cooling insert, which would lead to a worse cooling contact. The design of the TEDD inserts is adjusted by machining a proper cut-out on the upper edge of the TEDD cooling insert. In this setup a cut-out with a cross-section of 1 mm  $\times$  1 mm was implemented as visible in Figure 7.5 (right).

Two temperature sensors are connected to the bottom and the top wall of the box, respectively. The mean value of the temperatures measured with them is used as the reference ambient temperature of the whole setup. The air temperature, the humidity, and the dew point are measured with a LabKit hygrometer [78]. The air temperature measured with the LabKit device and the temperature sensors at the wall of the box are compatible within less than 1 K. The distribution of five thermistors on the carbon fiber base plate and the thermistors on each insert is shown in Figure 7.6. The mean of the temperature values of the base plate thermistors is referred to as the base plate temperature. Each insert is equipped with a thermistor which is fixed with copper tape. This makes an individual temperature measurement for each insert possible. The base plate and the cooling inserts are insulated in order to minimize the thermal



impact of the ambient to these components. The insulation can be seen in Figure 7.7. The carbon fiber base plate is insulated with 13 mm thick Armaflex on the bottom and with Armaflex tape on the top side. The barrel of the inserts is insulated with Armaflex tape. The applied insulation enables very reliable temperature measurements on these components.

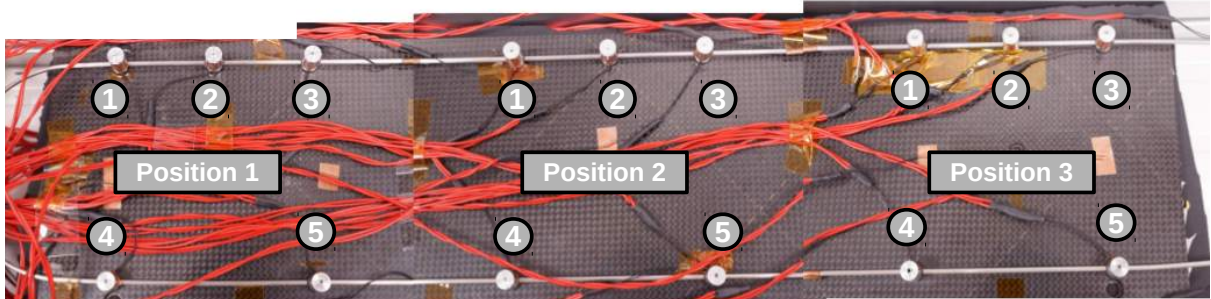


Figure 7.6.: The temperature sensors connected to the fifteen cooling inserts of the three module cooling positions and the thermistors for the carbon fiber base plate.

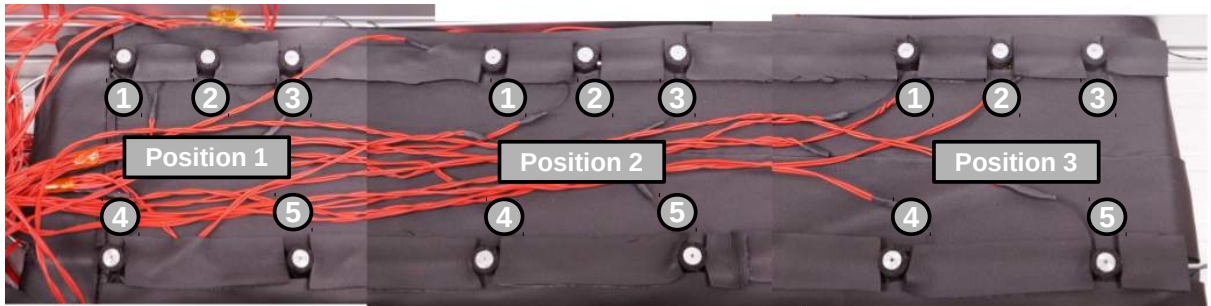


Figure 7.7.: The cooling inserts and the carbon fiber base plate are insulated with Armaflex in order to minimize the impact of the ambient to these components.

## 7.4. Thermal Characterization of the Mechanics

The characterization of the thermal properties of the mechanics is done independently from the measurements with the 2S dummy modules. With this method it is possible to understand thermal effects which are only related to the setup, but not to the 2S modules themselves. This section firstly describes the thermal behavior of the carbon fiber base plate and the cooling inserts in dependence on the ambient temperature. Secondly, the thermal properties of the individual cooling inserts are analyzed and compared to a Finite Element model of the inserts.

### 7.4.1. Thermal Behavior of the Setup Structure

Despite the insulation of the carbon fiber base plate and the inserts, there is still an impact from the ambient to these components. When the ambient temperature of the module cooling box is higher than the temperature  $T_{\text{cooling}}$ , a heat flux from the ambient to the carbon fiber base plate occurs. As the cooling inserts have a tight connection to the base plate by screws, a heat flux from the base plate to the inserts occurs, which is removed by the cooling system. This heat flux raises the temperature of the cooling inserts. The behavior of the temperatures can be described quantitatively and a function which corrects for these effects in further measurements can be given. However, a quantitative value of the heat flux itself cannot be obtained. The dependence of the temperatures of the carbon fiber base plate and the inserts on the ambient temperature is shown in Figure 7.8. It was measured with the following procedure. The module

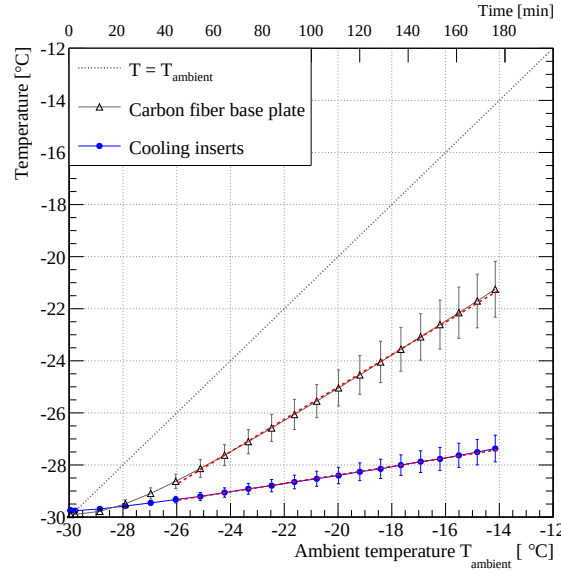


Figure 7.8.: Temperature dependence of the inserts (blue dots) and the carbon fiber base plate (black triangles) on the ambient temperature, along with linear fits shown (red dashed lines). The  $\text{CO}_2$  temperature is set to  $-30^\circ\text{C}$ .

cooling box and the  $\text{CO}_2$  cooling system were cooled down to  $-30^\circ\text{C}$  to a stationary situation. Then, the cooling machine for the module cooling box was turned off. The module cooling box heated up continuously and very slowly from  $-30^\circ\text{C}$  to  $-14^\circ\text{C}$  within about 3 hours. With this method a quasi-stationary equilibrium was produced. As the carbon fiber plate and the inserts are relatively well insulated from the cooling box wall and the ambient temperature, their response in terms of temperature rise takes about 30 to 45 minutes. After that time, the carbon fiber plate and the insert temperatures follow the ambient temperature linearly. This time is also a typical waiting time during measurements after having changed the ambient temperature. Thus this measurement can be used as calibration method.

The carbon fiber base plate is colder than the ambient temperature, but it is warmer than the  $\text{CO}_2$  temperature. The effect of heat fluxes described above occurs and the insert temperatures rise. The insert temperatures are at a value between the base plate temperature and the  $\text{CO}_2$  cooling temperature. For ambient temperatures between  $-26^\circ\text{C}$  and  $-14^\circ\text{C}$  (45 and 180 minutes) a linear function  $T_{\text{component}}(T_{\text{ambient}})$  is fitted to both data series. The fitted functions are corrected for the delay in order to meet the relation  $T_{\text{component}}(T_{\text{cooling}}) = T_{\text{cooling}}$ . The temperature difference  $\Delta T_{\text{component}}^{\text{ambient}}$  in dependence on the ambient temperature  $T_{\text{ambient}}$  is given by

$$\Delta T_{\text{base plate}}^{\text{ambient}}(T_{\text{ambient}}) = 0.62 (T_{\text{ambient}} - T_{\text{cooling}}) \quad (7.11)$$

for the base plate and by

$$\Delta T_{\text{insert}}^{\text{ambient}}(T_{\text{ambient}}) = 0.16 (T_{\text{ambient}} - T_{\text{cooling}}) \quad (7.12)$$

for the cooling inserts, where the index 'ambient' indicates that the temperature difference is only caused by the ambient. The measurement shows that already the variation of the ambient temperature in the setup has a significant impact on the thermal behavior of the cooling structure. A reliable estimation of the magnitude of the heat fluxes is not possible with the measured data as no information on power is obtained from the data. Data have to be corrected for these effects in further measurements in this thesis in order to obtain a pure thermal description of the mechanics. This is done by subtracting the temperature offset obtained from Equation 7.12 from

measurement data. The corrected temperature data can then be compared to results from FE simulations.

#### 7.4.2. Thermal Characterization of the Inserts

As it was observed that each insert is different in terms of thermal behavior, the insert are characterized individually and compared to a dedicated Finite Element Model. This is important for the correct implementation of the insert characteristics into the thermal Finite Element model of the 2S module. The only property in which the inserts are expected to vary is the glue thickness. A dedicated heating device was built in order to apply heat load to individual inserts. A  $10\ \Omega$  Caddock MP915 heating resistor was glued to a 2S module 1.8 mm aluminum stump bridge [79]. During the measurements, two temperature sensors were attached to the stump bridge which are used for cross-check measurements. A photograph of the device can be seen in Figure 7.9. For the measurements, the heating device was screwed to the inserts. For each insert

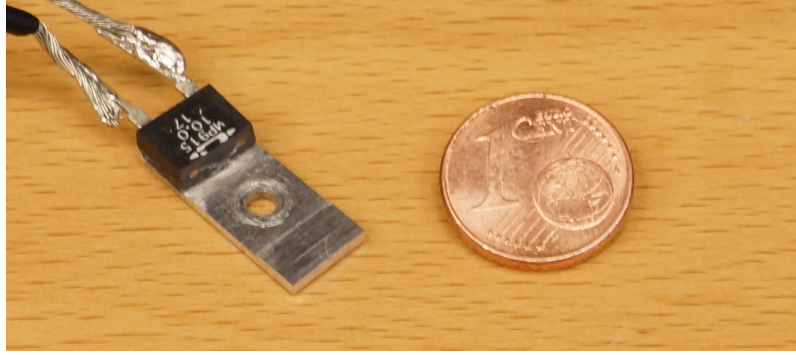


Figure 7.9.: Heating device for the thermal characterization of the inserts. A 2S module 1.8 mm aluminum stump bridge is equipped with a heating resistor. The two temperature sensors, which were attached during measurement for cross-checks, are not shown.

the same heating device was used. Heat loads between 0 W and 1.5 W in steps of 0.1 W were applied and the temperature of the insert was measured at each power step. The measurements were performed at a  $\text{CO}_2$  temperature and an ambient temperature of  $+15\ ^\circ\text{C}$ . The results of the measurement are shown in Figure 7.10. The measurements show a linear behavior in the

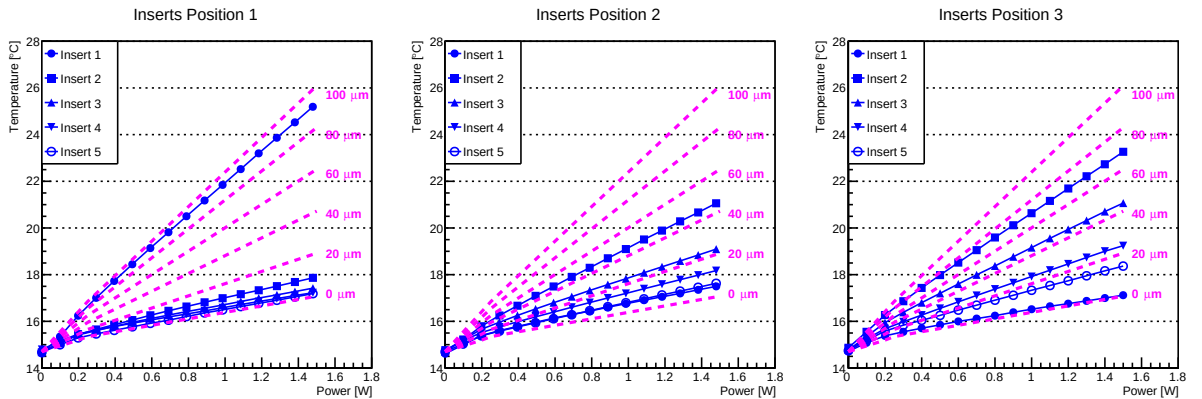


Figure 7.10.: Result of the measurement for the thermal characterization of the inserts. The three plots refer to the inserts on the three 2S module positions. The blue dots represent the insert temperatures plotted versus the applied heat load. The dashed pink lines show the FE simulated insert temperatures for glue thicknesses of 0, 20, 40, 60, 80, and  $100\ \mu\text{m}$ , with a heat flux dependent  $\text{CO}_2$  heat transfer coefficient implemented.

low power region between 0 W and 0.2 W. In the transition region between 0.2 W and 0.4 W the slope of the data decreases. It is again constant for values above 0.4 W which is probably related to the change of the boiling behavior of the CO<sub>2</sub> at higher heat flux densities. This effect was observed also in earlier cooling block characterization tests, done in this institute [80]. The measured data series show relatively large deviations from each other. A linear function is fitted to each data series in the range between 0.4 W and 1.4 W in order to roughly estimate the thermal resistance of the inserts in this power regime. The average thermal resistance of the inserts is  $\alpha_{\text{inserts}, +15^\circ\text{C}} = 2.67 \pm 1.65 \text{ K/W}$ , where the uncertainty is the standard deviation of the data. This result is used to compare the measured thermal resistances of the inserts with the FE model.

A Finite Element model of the insert without the heating device was generated. It is shown in Figure 7.11. The literature values for all the materials used are incorporated. A glue thickness

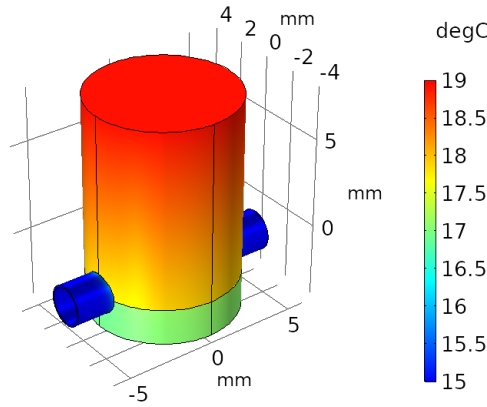


Figure 7.11.: Thermal Finite Element simulation of the 2S insert. The temperature is color coded. The heat flux of 1.3 W is removed by the CO<sub>2</sub> in the pipe. The average temperature of the upper insert barrel is 3.4 K higher than the CO<sub>2</sub> temperature of +15 °C.

of 20  $\mu\text{m}$  between the top and the bottom part of the insert and between both insert parts and the cooling pipe is assumed. For the CO<sub>2</sub>, a temperature of +15 °C and a heat transfer coefficient of 25 kW/m<sup>2</sup>/K is assumed. A total heat flux of 1.3 W is applied to the top surface of the insert. As the thermistor has approximately the length of the insert cylinder height, the average temperature of the upper barrel of the insert model is evaluated. The value is 18.4 °C, which is 3.4 K higher than the CO<sub>2</sub> temperature. The thermal resistance of the FE model is then calculated to be  $\alpha_{\text{inserts}}^{\text{FE}} = 2.62 \text{ K/W}$ , which is very well compatible with the measured average thermal resistances for power values greater than 0.4 W.

In the FE model the glue thickness is varied between 0  $\mu\text{m}$  and 100  $\mu\text{m}$  in steps of 20  $\mu\text{m}$  and the simulation is calculated for heat fluxes between 0 W and 1.5 W. In the transition region and in the low power region the heat transfer coefficient of the CO<sub>2</sub> is modelled with a heat flux dependent model in order to describe the data. The model for these regions is not used for further analyses. The resulting curves are shown in Figure 7.10 with the magenta lines with the corresponding glue thicknesses written next to the lines. From the simulated curves with various glue thicknesses a glue thickness is assigned to each insert by interpolation with a granularity of 5  $\mu\text{m}$ . The assigned glue thicknesses are listed in Table 7.1.

As a simplified description, it is assumed that the glue layer thickness in one insert is uniform, which is not necessarily the real case. However, a more accurate characterization of the glue junction is not possible as the glue junction and its inner structure cannot be measured with reasonable technical effort. Thus, in the following sections, the glue thickness assigned to one insert will be distributed uniformly over the outer surface of the pipe and the connection between



the top and the bottom part. With this method the thermal characteristics of the inserts will be implemented in the FE model of the 2S module. Note that the thermal resistance of the inserts, measured and evaluated at a CO<sub>2</sub> temperature of +15 °C in this section, might change with CO<sub>2</sub> temperature.

Table 7.1.: Assigned glue thicknesses for the 15 inserts as determined from the comparison between data and simulation. The glue thicknesses are given with an accuracy of  $\pm 5 \mu\text{m}$ .

| Insert number | Position 1        | Position 2       | Position 3       |
|---------------|-------------------|------------------|------------------|
| 1             | 100 $\mu\text{m}$ | 10 $\mu\text{m}$ | 0 $\mu\text{m}$  |
| 2             | 10 $\mu\text{m}$  | 50 $\mu\text{m}$ | 75 $\mu\text{m}$ |
| 3             | 5 $\mu\text{m}$   | 25 $\mu\text{m}$ | 45 $\mu\text{m}$ |
| 4             | 5 $\mu\text{m}$   | 15 $\mu\text{m}$ | 25 $\mu\text{m}$ |
| 5             | 5 $\mu\text{m}$   | 10 $\mu\text{m}$ | 20 $\mu\text{m}$ |
| Average       | 25 $\mu\text{m}$  | 20 $\mu\text{m}$ | 35 $\mu\text{m}$ |

## 7.5. 2S Thermal Dummy Modules

Two 2S thermal dummy modules have been built for the thermal measurements. One dummy module was only used as bare module, which means that it has not been equipped with hybrids. The other dummy module was firstly measured without hybrids and later equipped with two dummy front-end hybrids and one dummy service hybrid. The assembly procedure followed the guidelines for the 2S module assembly as they were available in the collaboration at the time of assembly. The assembly procedure of 2S modules was exercised and co-developed in this institute [81].

### 7.5.1. 2S Thermal Dummy Bare Modules

The bare modules of both thermal dummy modules were built with 4.0 mm AlCF spacers, Kapton MT strips, and thermal dummy sensors. The thermal dummy sensors are 320  $\mu\text{m}$  thick silicon strip sensors with an aluminum backplane and a strip aluminum mask on the top plane. These sensors have no physical functionality for particle detection. The front plane mask is modified such that all strips are connected electrically to the high-voltage bias ring. The resistivity of the bulk of the sensors is chosen such that the electrical resistance between the front plane and the backplane is in the order of  $5\,\Omega$ . With this implementation it is possible to connect electrically to the front plane bias ring and the backplane, and to produce current through the bulk of sensor by applying a low voltage between front and back plane. The heat load is then produced directly in the volume of the sensors and no external heating devices (e.g. foils, resistors) have to be used. Figure 7.12 shows the two thermal dummy modules, thermal dummy 1 and thermal dummy 2, placed in the module cooling box. The electrical connection to the sensors is implemented differently. For thermal dummy 1, pin headers have been glued to the sensor planes. On the front plane, electrical contact with the bias ring was produced. The contact to the guard ring was isolated. The electrically conductive glue EPO-TEK H20E-LC was used [82]. Low-voltage cables can be connected with plugs to the pin headers. For thermal dummy 2, 2S module high voltage pigtailed are glued to the sensor planes, one on the backplane, and two on the front plane for redundancy. The front plane connectors are connected in parallel. The electrical connection to the backplane and the bias ring was made with wirebonds, which are encapsulated in order to protect them. Custom made adapter boards from KIT, Karlsruhe, have been used for establishing the plugging connection. For the bare modules the temperature measurements were performed approximately at the central position of each sensor quadrant, as shown in Figure 7.12. The average of the four temperature measurements on the top (bottom) sensor is referred to as the mean top (bottom) sensor temperature or simply the top (bottom) sensor temperature sensor. Additionally, temperature sensors were placed on the top side of the spacers, close to the screwing points. The positions, color codes, and indices of the thermistors used are illustrated in Figure B.1 in Appendix B.

### 7.5.2. 2S Thermal Dummy Full Module

The 2S thermal dummy module 2 was equipped with two thermal dummy 2S 4.0 mm Front-end Hybrids (FEHs) and one thermal dummy Service Hybrid (SEH). A photograph of the fully equipped 2S thermal Dummy module 2 is shown in Figure 7.13. The thermal dummy FEHs were folded over in-house and glued to the 2S 4.0 mm AlCF FEH spacers. The FEHs were equipped with eight  $10\,\Omega$  Caddock MP915 heating resistors [79]. These resistors have a ceramic surface on the bottom side, where the heat produced is fully removed, which is advantageous for the use in this thermal test setup. Each resistor was cut to approximately fit the footprint of a CBC. The cutting did not affect the electrical properties of the resistors. Eight resistors were glued with the ceramic face to the FEHs on the position of the CBCs and then connected in series with

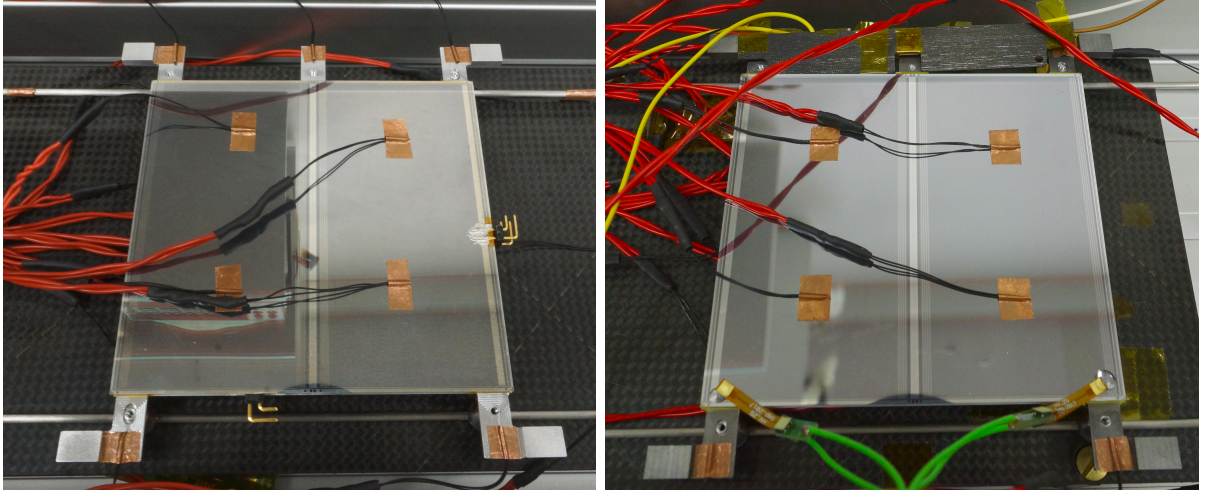


Figure 7.12.: Left: 2S thermal dummy module 1. The electrical connection to the dummy sensors is implemented with pin headers. The connection cables are not shown. Right: 2S thermal dummy module 2. The electrical connection to the dummy sensors is implemented with the 2S high voltage pigtail cables, at two connection points for redundancy. The connector to the backplane is located under the CFRP board on the top and cannot be seen .

solder joints.

The dummy thermal SEH is a flex PCB of the SEH version v2 developed in this institute. It was folded over and laminated to a K13C2U carbon fiber stiffener received from the CMS Tracker FNAL group. The thermal dummy SEH was equipped with two heating resistors of the same type like used for the FEHs. One heating resistor was glued on the side of the SEH where the optical transmitting and receiving part would be located, and the other heating resistor was placed on the side of the SEH where the DC-DC converters would sit.

The module was firstly measured equipped with the hybrids, but the sensors not yet wirebonded to the FEHs. Afterwards, the top sensor was wirebonded to the FEHs and the wirebonds were encapsulated. For technical reasons it was not possible to wirebond the bottom sensor to the FEHs. The module was measured a second time with the sensors wirebonded to the FEHs and the wirebond encapsulation present.

The positions, color codes, and indices of the thermistors used are illustrated in Figure B.1 in Appendix B.

## 7.6. Finite Element Models of the 2S Thermal Dummy Modules

The thermal measurements of the 2S 4.0 mm modules are compared and cross-checked with thermal Finite Element (FE) analyses of the 2S modules which were developed within the scope of this thesis. The models are built, studied, and analyzed with the Finite Element Software COMSOL<sup>®</sup> Multiphysics using the Heat Transfer Module. The mechanical composition of the FE model is partly imported from technical drawings of the 2S module components and partly self-designed. The models are simplified by e.g. avoiding tiny structures, but without neglecting important thermal properties. Two thermal FE models have been developed in the scope of this thesis, one of the 2S bare module and one of the 2S full module, which are described in the following sections. If not mentioned differently, the right-handed coordinate system in the FE models is chosen such that the  $x$ -axis runs along the strip direction of the sensor, the  $y$ -axis runs perpendicular to the  $x$ -axis in the strip-plane pointing from the service hybrid to the direction of the sensors, and the  $z$ -axis is perpendicular to both sensor planes, pointing upwards. The parameters used in the FE models are listed in Table C.1 in Appendix C.

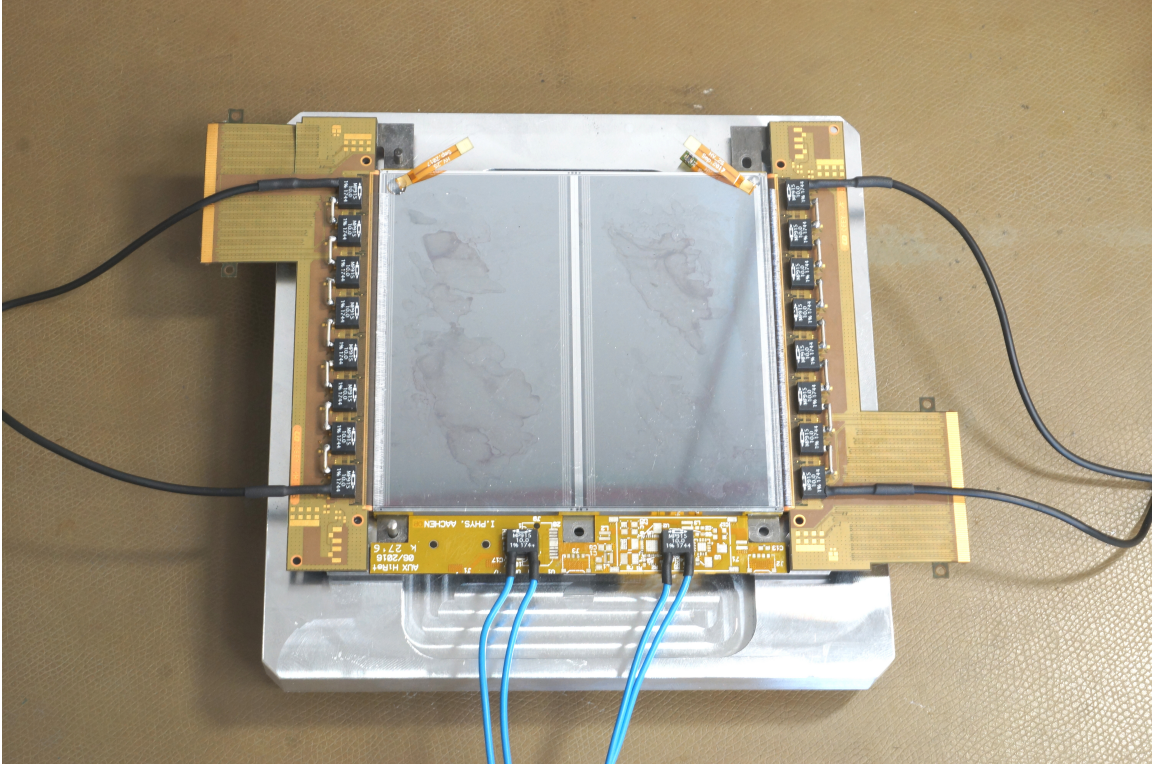


Figure 7.13.: The 2S thermal dummy full module. One can see the thermal dummy top sensor with the two connectors for the low voltage, the two thermal dummy FEHs with the eight heating resistors simulating the CBCs, and the thermal dummy SEH with the two resistors simulating the opto-part and DC-DC converter part of the 2S service hybrid.

### 7.6.1. Thermal Finite Element Model of the 2S Bare Module

The FE model of the 2S 4.0 mm bare module features only the silicon sensors and the AICF spacers as geometric entities. The bare module model is placed on five cooling inserts. An image with a transparent view of the bare module FE model is shown in Figure 7.14 (left) and an example of the result of the thermal simulation is shown in Figure 7.15 (left). The silicon sensors have an extent of  $103 \text{ mm} \times 94 \text{ mm}$  in  $x$  and  $y$  and a thickness of  $320 \mu\text{m}$ . The thermal conductivity of silicon is taken from the COMSOL material library as  $k_{\text{silicon}} = 130 \text{ W/m/K}$ . The 2S 4.0 mm AICF spacers are imported from technical drawings. An anisotropic thermal conductivity of  $\mathcal{K}_{\text{AICF}} = \{k_{xx}, k_{yy}, k_{zz}\}_{\text{AICF}} = \{120, 230, 230\} \text{ W/m/K}$  is assigned to the AICF material. The glue layers and the Kapton HV isolator strips are not modelled as geometric entities, but implemented with the Thin Layer feature of the COMSOL<sup>®</sup> Heat Transfer Module. Both glue layers, surrounding the Kapton strips, are assumed to have a thickness of  $d_{\text{glue}} = 20 \mu\text{m}$ . The thickness of the Kapton strips is taken from their specifications as  $d_{\text{Kapton}} = 25 \mu\text{m}$ . Thus, the Thin Layer is implemented with a thickness of  $d_{\text{glue, Kapton, glue}} = 65 \mu\text{m}$ . For simplification, its thermal conductivity is assumed to be isotropic as  $\lambda_{\text{glue, Kapton, glue}} = 0.26 \text{ W/m/K}$ . This value is calculated from the harmonic average of the thermal conductivities of the materials weighted with their thickness. The contact surface between the AICF spacers and the aluminum inserts is modelled with the Thermal Contact feature of the COMSOL<sup>®</sup> Heat Transfer module with a heat transfer coefficient of  $h_{\text{spacer, insert}} = 10\,000 \text{ W/m}^2/\text{K}$ . This value was firstly motivated from Ref. [48]. Within this thesis the value could be confirmed with measurements as described in Appendix E. The screw, the thread, and the washer are not implemented. The cooling inserts are modelled as described in Section 7.4.2.

The total heat input from the 2S module and from the ambient is directly related with the heat flux density at the CO<sub>2</sub> cooling pipe. The properties of the heat removal process in the two-phase CO<sub>2</sub> are directly affected by the heat flux density as the boiling behavior changes. The cooling pipe contact surface of one insert to the CO<sub>2</sub> is given by

$$A_{\text{cooling contact}}^{\text{insert}} = l_{\text{contact}} \cdot C_{\text{pipe, inner}} = l_{\text{contact}} \cdot \pi \cdot d_{\text{pipe, inner}} = 50 \text{ mm}^2,$$

with the insert diameter  $l_{\text{contact}} = 8 \text{ mm}$  and the inner cooling pipe diameter  $d_{\text{pipe, inner}} = 2.0 \text{ mm}$  (inner cooling pipe circumference  $C_{\text{pipe, inner}} = 6.3 \text{ mm}$ ). The total cooling contact surface to the CO<sub>2</sub> for one 2S module,  $A_{\text{cooling contact}}^{\text{2S module}}$ , is then given by

$$A_{\text{cooling contact}}^{\text{2S module}} = 5 \cdot A_{\text{cooling contact}}^{\text{insert}} = 250 \text{ mm}^2,$$

as it is connected to five inserts. With 2S module powers of  $P_{\text{2S module, low}} \approx 1.5 \text{ W}$  and  $P_{\text{2S module, high}} \approx 6 \text{ W}$ , as they are used in the measurements for this thesis, typical heat flux densities at the inner surface of the cooling pipes are

$$\dot{q} = \frac{P_{\text{2S module, low}}}{A_{\text{cooling contact}}^{\text{2S module}}} = \frac{1.5 \text{ W}}{250 \text{ mm}^2} = 6 \text{ kW/m}^2$$

and

$$\dot{q} = \frac{P_{\text{2S module, high}}}{A_{\text{cooling contact}}^{\text{2S module}}} = \frac{6 \text{ W}}{250 \text{ mm}^2} = 24 \text{ kW/m}^2.$$

Ref. [35] presents measurements of the heat transfer coefficient of two-phase CO<sub>2</sub> at a temperature of  $-30^\circ\text{C}$  and a mass flow of  $G = 300 \text{ kg/m}^2/\text{s}$  for heat flux densities of  $\dot{q} = 7.5 \text{ kW/m}^2$  and  $\dot{q} = 29.8 \text{ kW/m}^2$ . This value for  $G$  is compatible with the CO<sub>2</sub> mass flow in the measurements for this thesis,

$$\Phi = 1 \frac{\text{g}}{\text{s}} \approx G \cdot A_{\text{cooling pipe}}^{\text{cross section}} = 300 \frac{\text{kg}}{\text{m}^2\text{s}} \cdot 3.14 \text{ mm}^2 = 0.94 \frac{\text{g}}{\text{s}},$$

with the inner cross section of the cooling pipe,  $A_{\text{cooling pipe}}^{\text{cross section}} = \pi \cdot (\frac{1}{2}d_{\text{pipe, inner}})^2 = 3.14 \text{ mm}^2$ . For low vapor qualities  $x$  one obtains a CO<sub>2</sub> heat transfer coefficient of  $5 \text{ kW/m}^2/\text{K}$  ( $10 \text{ kW/m}^2/\text{K}$ ) for a heat flux density of  $7.5 \text{ kW/m}^2$  ( $29.8 \text{ kW/m}^2$ ) from Ref. [35]. Thus in the FE simulations of the 2S module, a heat transfer coefficient of either  $5 \text{ kW/m}^2/\text{K}$  or  $10 \text{ kW/m}^2/\text{K}$  is assumed for the CO<sub>2</sub> at a temperature of  $-30^\circ\text{C}$ , depending on whether the total heat input to the CO<sub>2</sub> is closer to  $7.5 \text{ kW/m}^2$  or to  $29.8 \text{ kW/m}^2$ . A detailed discussion of the effect of the heat transfer coefficient for the cooling inserts is given in Section 7.11.1.

For both silicon sensors, the heat production of the sensors is implemented individually with the Heat Source feature in the full sensor volume. With the Heat Source feature the power consumption in a geometric domain (i.e. a component) can be modeled. Typical implementations are the definition of a fixed heat load or heat load density, but the heat load can also be defined as a function of other variables in the model, like e.g. temperature. For the comparison with the dummy module measurements the Heat Source feature with the fixed heat load values is implemented to the sensors. For the simulations of the thermal runaway a temperature dependent heat load is implemented to the sensors of the 2S full module model. The FE model of the 2S full module is described in the following section.

### 7.6.2. Thermal Finite Element Model of the 2S Full Module

The thermal finite element model of the 2S 4.0 mm full module is an expansion from the 2S bare module FE model. An image of the full FE model is shown in Figure 7.14 (right) and



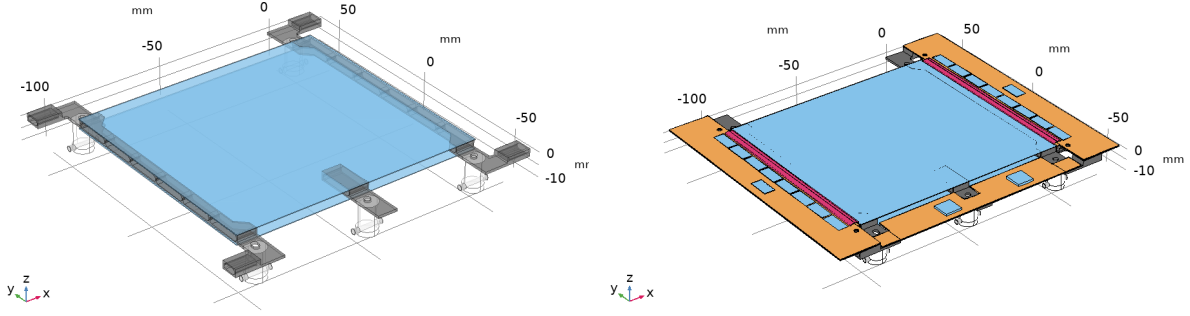


Figure 7.14.: Left: finite element model of the 2S bare module mounted on the cooling inserts. Right: finite element Model of the 2S module with front-end hybrids and a service hybrid.

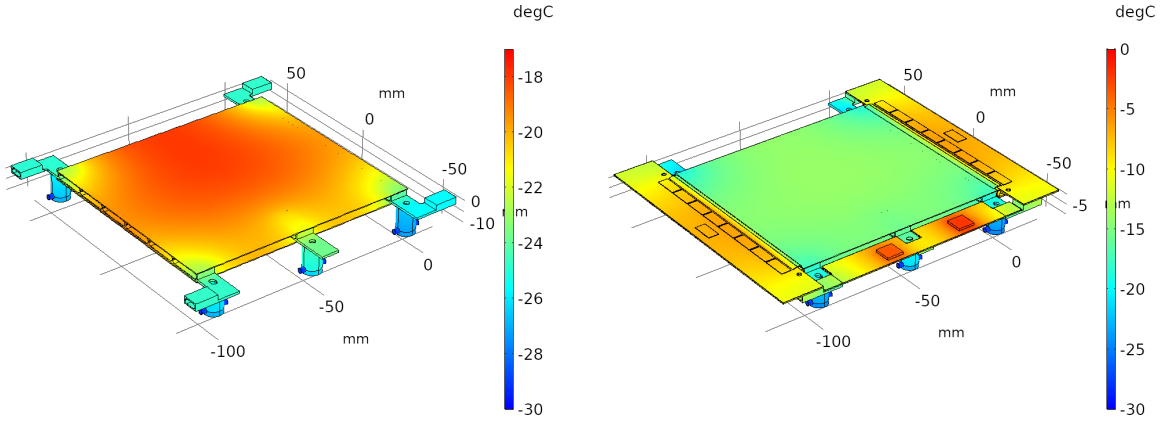


Figure 7.15.: Left: thermal finite element simulation of the 2S bare module with a sensor power of 1.15 W each. Right: thermal finite element simulation of the 2S module with front-end hybrids and a service hybrid with nominal 2S module power values. Both simulations are for a CO<sub>2</sub> cooling temperature of -30 °C. The surface temperatures are color coded.

an example of the result of the thermal simulation is shown in Figure 7.15 (right). Simplified models of the FEHs and the SEH are added to the model. The wirebonds are modelled more coarsely with an effective model in order to avoid too much complexity of the model. The geometric entities of the FEHs and the SEH are imported from technical drawings and simplified. Only the major components are kept in the model which are the hybrid PCBs, the carbon fiber stiffeners, the components producing heat, and, for the FEHs, the AlCF spacers. The material for the PCBs of the FEHs and the SEH is modelled as an isotropic material with a thermal conductivity of  $\lambda_{\text{PCB}} = 49 \text{ W/m/K}$ . This value is calculated from an assumption on the relative amount of copper traces and the organic PCB material (e.g. polyimide) in the PCB, using the weighted harmonic mean of their thermal conductivities. The detailed layout of the hybrids is not modelled, in order to minimize the complexity of the model. An anisotropic thermal conductivity of  $\mathcal{K}_{\text{CF}, \text{K13D2U}} = \{k_{xx}, k_{yy}, k_{zz}\}_{\text{CF}, \text{K13D2U}} = \{250, 250, 0.5\} \text{ W/m/K}$  is assigned to the K13D2U stiffeners of the FEHs [42]. The value is calculated from assumptions on the carbon fiber matrix, which include the orientation and number of prepreg plies, and the mass ratio of carbon fiber filaments and epoxy material. For the K13C2U stiffener of the SEH a worse thermal conductivity of  $\mathcal{K}_{\text{CF}, \text{K13C2U}} = \{k_{xx}, k_{yy}, k_{zz}\}_{\text{CF}, \text{K13C2U}} = \{167, 167, 0.3\} \text{ W/m/K}$  is implemented [51]. The layers of the lamination between the carbon fiber PCB stiffeners and the PCBs are not modelled. The hybrid stiffeners are connected to the spacers through the Thin Layer feature with a thickness of  $d_{\text{glue}} = 20 \mu\text{m}$  and a thermal conductivity of  $k_{\text{glue}} = 0.2 \text{ W/m/K}$ . Eight blocks with the extents and positions of the CBC chips are implemented on each FEH,

respectively. On the SEH two blocks are implemented at the positions of the heating resistors. On all three hybrids these blocks are used as heating devices with the Heat Source feature. The material assigned to the blocks is silicon.

In order to avoid very small structures in the FE model, the wirebonds and their encapsulation material are implemented as an effective model. The implemented geometry of the wirebonds is shown in Figure 7.16. A bow with a thickness of  $d_{\text{WB}}^{\text{FE}} = 250 \mu\text{m}$ , a width of  $w_{\text{WB}}^{\text{FE}} = w_{\text{WB}} = 100 \text{ mm}$ , and a length of  $l_{\text{WB}}^{\text{FE}} = l_{\text{WB}} = 5 \text{ mm}$  is chosen for the geometry of the effective wirebond model. The thermal conductivity assigned to the wirebond model has to be derived from assumptions on the extents and the thermal conductivities of the wirebonds and the encapsulation material. The thermal conductivity is chosen in a way that the thermal resistance of the wirebond model is compatible with the expectation from the real geometry. In the following it is explained how the thermal conductivity assigned to the model is derived.

One row of wirebonds consist of about 1000 wirebonds. Each wirebond has a radius of  $r_{\text{WB}} = 12.5 \mu\text{m}$  and a length of  $l_{\text{WB}} = 5.0 \text{ mm}$ . The total effective cross section of one wirebond row is then  $A_{\text{WB, row}} = 1000 \pi r_{\text{WB}}^2 = 0.5 \text{ mm}^2$ . The material of the bond wires is an aluminum-silicon alloy with a small amount of silicon (approx. 1%). The thermal conductivity of this material is assumed to be  $k_{\text{WB}} \approx 200 \text{ W/m/K}$ . The effective thermal conductivity of one wirebond row is then given by

$$\lambda_{\text{WB, row}} = k_{\text{WB}} \frac{A_{\text{WB, row}}}{l_{\text{WB}}} = 20 \frac{\text{mW}}{\text{K}}.$$

In addition to the wirebonds also the encapsulation material contributes to the thermal contact between FEH and sensor. The encapsulation material Sylgard 186 is implemented, with a thermal conductivity of  $k_{\text{Sylgard 186}} = 0.2 \text{ W/m/K}$  [83]. For simplicity the encapsulation is modeled as a cuboid with a width of  $w_{\text{encaps}} = 100 \text{ mm}$ , a height of  $h_{\text{encaps}} = 2 \text{ mm}$ , and a length of  $l_{\text{encaps}} = 5 \text{ mm}$ . This yields an effective cross section of

$$A_{\text{encaps}} = w_{\text{encaps}} h_{\text{encaps}} = 200 \text{ mm}^2.$$

The effective thermal conductivity for the encapsulation material is then calculated to

$$\lambda_{\text{encaps}} = k_{\text{Sylgard 186}} A_{\text{encaps}} / l_{\text{encaps}} = 8 \frac{\text{mW}}{\text{K}} \left( = \frac{2}{5} \lambda_{\text{wb, row}} \right). \quad (7.13)$$

The effective thermal conductivities of the wirebonds and the encapsulation material can be added to

$$\lambda_{\text{WB, encaps}} = \lambda_{\text{WB}} + \lambda_{\text{encaps}} = 28 \frac{\text{mW}}{\text{K}}. \quad (7.14)$$

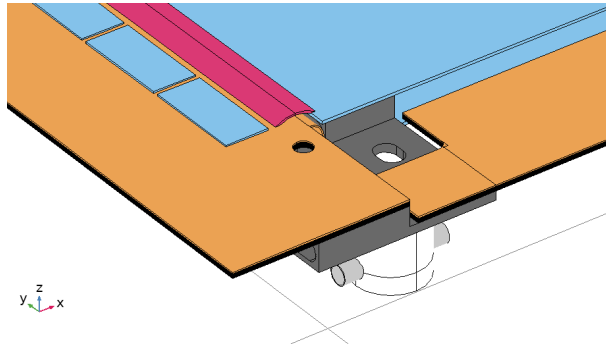


Figure 7.16.: Image of the effective wirebond model (magenta) in the FE model of the 2S module. The wirebonds are modelled as a bow from the FEH to the sensors.

The effective cross section of the bow geometry in the FE model is  $A_{\text{WB, row}}^{\text{FE}} = d_{\text{WB}}^{\text{FE}} w_{\text{WB}}^{\text{FE}} = 250 \mu\text{m} \cdot 100 \text{ mm} = 25 \text{ mm}^2$ . The specific thermal conductivity which has to be assigned to the specific wirebond geometry in the FE model is given by

$$k_{\text{WB,encaps}}^{\text{FE}} = \lambda_{\text{WB,encaps}} \frac{l_{\text{WB,encaps}}^{\text{FE}}}{A_{\text{WB,encaps}}^{\text{FE}}} = 5.6 \frac{\text{W}}{\text{mK}}. \quad (7.15)$$

## 7.7. Thermal Measurements and Analysis of the 2S Dummy Bare Modules

The 2S Thermal Dummy Module 1, which is a bare module, was measured with the method described in Section 7.2.2, which determines the state of thermal equilibrium in order to know the point at which the generated sensor power is fully removed. In the following it is demonstrated that this method works very well and stably. The temperatures measured with this method have to be corrected for the constant offset described in Section 7.4.1 by using Equation 7.12. After this correction the thermal resistances of the mechanics are obtained. The first part of this section concentrates on this measurement and discusses the measured effects in detail. The second part of this section presents a nearly equivalent measurement method, which takes less time and which is therefore advantageous for taking a larger set of data. The results are compared to results from FE simulations.

### 7.7.1. Thermal Measurement of 2S Thermal Dummy Bare Module 1

The 2S thermal dummy module 1 was measured on cooling position 2 in the module cooling box. The measurements were performed at a nominal  $\text{CO}_2$  temperature of  $-30^\circ\text{C}$  and a  $\text{CO}_2$  mass flow of  $60 \text{ g/s}$  for five different ambient temperatures of  $T_{\text{ambient}} = -27.9, -26.1, -22.7, -19.8$ , and  $-16.8^\circ\text{C}$ . For each ambient temperature the power of both sensors was ramped up in steps of  $0.25 \text{ W}$  per sensor, which is equivalent to a power ramping step of  $0.5 \text{ W}$  for the whole bare module. The temperatures were measured on four components, namely with four thermistors on the top sensor, four thermistors on the bottom sensor, and one thermistor per spacer screwing point and insert. The temperatures for each power step were recorded after the system had reached a sufficiently stable state, which takes approximately six minutes. Figure 7.17 shows the averaged temperature data of the bottom and the top sensor for the five different measurement series at different ambient temperatures plotted versus the power  $P$  of both sensors. The five measurement series are referred as the raw data series. The taken data series represent the measurement of the function in Equation 7.7. The state of thermal equilibrium between the sensor and the ambient is given by the points where the average sensor temperature and the ambient temperature are equal. For both sensors and for each measurement series, this point is determined by finding the intersection point between the two temperature curves  $T_{\text{sensor}}$  and  $T_{\text{ambient}}$  by linear interpolation between the data points. The resulting curves  $T_{\text{equil}}^{\text{top}}$  ( $T_{\text{equil}}^{\text{bottom}}$ ) are plotted in red (orange) for the top (bottom) sensor. They are also shown in Figure 7.18 with the open markers. A linear function is fitted to the thermal equilibrium curves in order to determine the pseudo thermal resistances  $\alpha_{\text{equil}}^{\text{top}}$  of the raw data and  $\alpha_{\text{equil}}^{\text{bottom}}$ , which do not yet have the constant offset correction. The fit results are given as

$$T_{\text{equil}}^{\text{top}} = (\alpha_{\text{equil}}^{\text{top}} \pm \sigma_{\alpha, \text{top}}) P + T_0^{\text{top}} = (5.57 \pm 0.30 \text{ K/W}) P - 29.2^\circ\text{C} \quad (7.16)$$

$$T_{\text{equil}}^{\text{bottom}} = (\alpha_{\text{equil}}^{\text{bottom}} \pm \sigma_{\alpha, \text{bottom}}) P + T_0^{\text{bottom}} = (5.25 \pm 0.48 \text{ K/W}) P - 29.2^\circ\text{C}, \quad (7.17)$$

where  $\sigma_{\alpha, \text{top/bottom}}$  is the uncertainty on the fit parameter  $\alpha_{\text{equil}}^{\text{top/bottom}}$ . The data series of the top and bottom sensor in thermal equilibrium have the same temperature values on the  $y$ -axis,



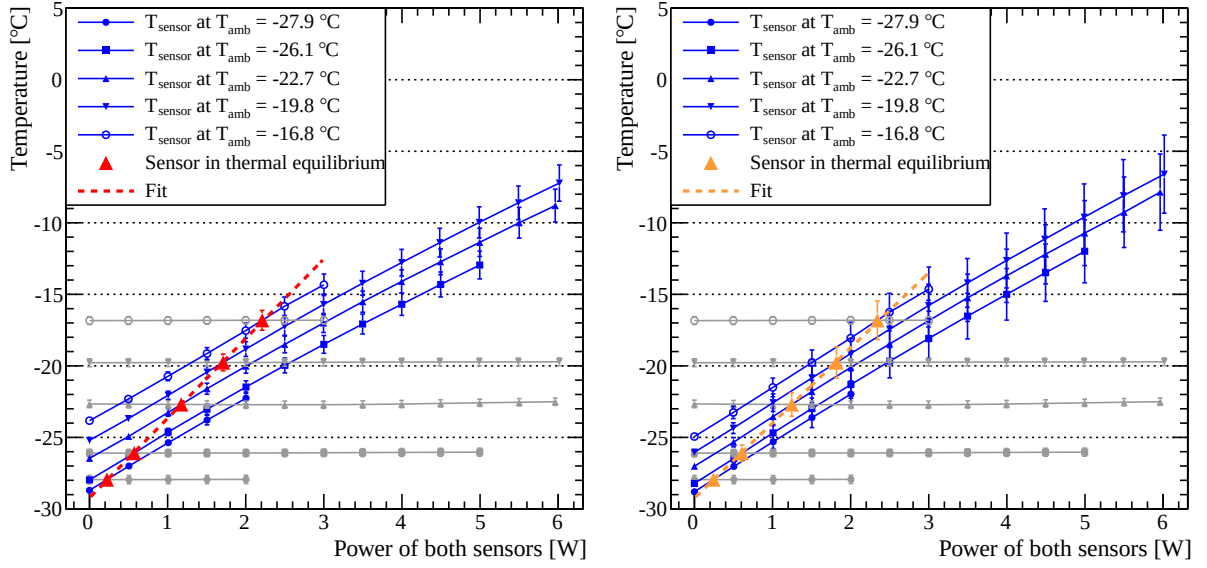


Figure 7.17.: Mean temperatures of the top sensor (left) and the bottom sensor (right) for the measurement series at different ambient temperatures. The error bars on the data points denote the standard deviation of the four temperature measurements per sensor. The ambient temperatures, shown with the standard deviation of their four measurement points, are plotted in gray. The extracted curves in thermal equilibrium  $T_{\text{equil}}^{\text{top}}$  ( $T_{\text{equil}}^{\text{bottom}}$ ) are plotted in red (orange) for the top (bottom) sensor.

by construction. However the power values for the state of the thermal equilibrium differs. The bottom sensor reaches the thermal equilibrium at approximately 10 % higher power values than the top sensor. The power values for the thermal equilibrium of both sensors are averaged and defined as the power  $P_{\text{equil}} = (P_{\text{equil}}^{\text{top}} + P_{\text{equil}}^{\text{bottom}})/2$ . At the position of  $P_{\text{equil}}$  the average temperatures of the spacers and the inserts are evaluated for each ambient temperature by linear interpolation of the data points. The curves for the spacers and inserts are shown in Figure 7.18 with the open markers in green and blue, respectively. The fitted linear functions to the non-corrected curves are given by

$$T_{\text{equil}}^{\text{spacers}} = (\alpha_{\text{equil}}^{\text{spacers}} \pm \sigma_{\alpha, \text{spacers}}) P + T_0^{\text{spacers}} = (3.05 \pm 0.07 \text{ K/W}) P - 29.2^\circ \text{C} \quad (7.18)$$

$$T_{\text{equil}}^{\text{inserts}} = (\alpha_{\text{equil}}^{\text{inserts}} \pm \sigma_{\alpha, \text{inserts}}) P + T_0^{\text{inserts}} = (2.43 \pm 0.09 \text{ K/W}) P - 29.2^\circ \text{C}. \quad (7.19)$$

The raw data are corrected for the temperature offset provoked by the impact of the ambient. The measured dependence of the insert temperature  $T_{\text{insert}}^0$  on the ambient temperature  $T_{\text{ambient}}$ , given in Equation 7.12, is subtracted from the temperature values in the thermal equilibrium state for each component:

$$T_{\text{corr}}^{\text{component}} = T_{\text{equil}}^{\text{component}} - \Delta T_{\text{inserts}}^{\text{ambient}}(T_{\text{ambient}}) = T_{\text{equil}}^{\text{component}} - 0.16 (T_{\text{ambient}} - T_{\text{cooling}}), \quad (7.20)$$

where the index 'component' refers to the components top sensor, bottom sensor, spacers, or inserts. The corrected temperatures  $T_{\text{corr}}^{\text{component}}$  of the top sensor, the bottom sensor, the spacers, and the inserts, are plotted in Figure 7.18 with the full markers. Linear functions are fitted to the corrected temperature data and the results from the fits are given by the four equations

$$T_{\text{corr}}^{\text{top}} = (\alpha_{\text{corr}}^{\text{top}} \pm \sigma_{\alpha, \text{top}}) P + T_0^{\text{top}} = (4.34 \pm 0.30 \text{ K/W}) P - 29.2^\circ \text{C}, \quad (7.21)$$

$$T_{\text{corr}}^{\text{bottom}} = (\alpha_{\text{corr}}^{\text{bottom}} \pm \sigma_{\alpha, \text{bottom}}) P + T_0^{\text{bottom}} = (4.10 \pm 0.48 \text{ K/W}) P - 29.2^\circ \text{C}, \quad (7.22)$$

$$T_{\text{corr}}^{\text{spacers}} = (\alpha_{\text{corr}}^{\text{spacers}} \pm \sigma_{\alpha, \text{spacers}}) P + T_0^{\text{spacers}} = (1.87 \pm 0.07 \text{ K/W}) P - 29.2^\circ \text{C}, \quad (7.23)$$

$$T_{\text{corr}}^{\text{inserts}} = (\alpha_{\text{corr}}^{\text{inserts}} \pm \sigma_{\alpha, \text{inserts}}) P + T_0^{\text{inserts}} = (1.25 \pm 0.09 \text{ K/W}) P - 29.2^\circ \text{C}. \quad (7.24)$$

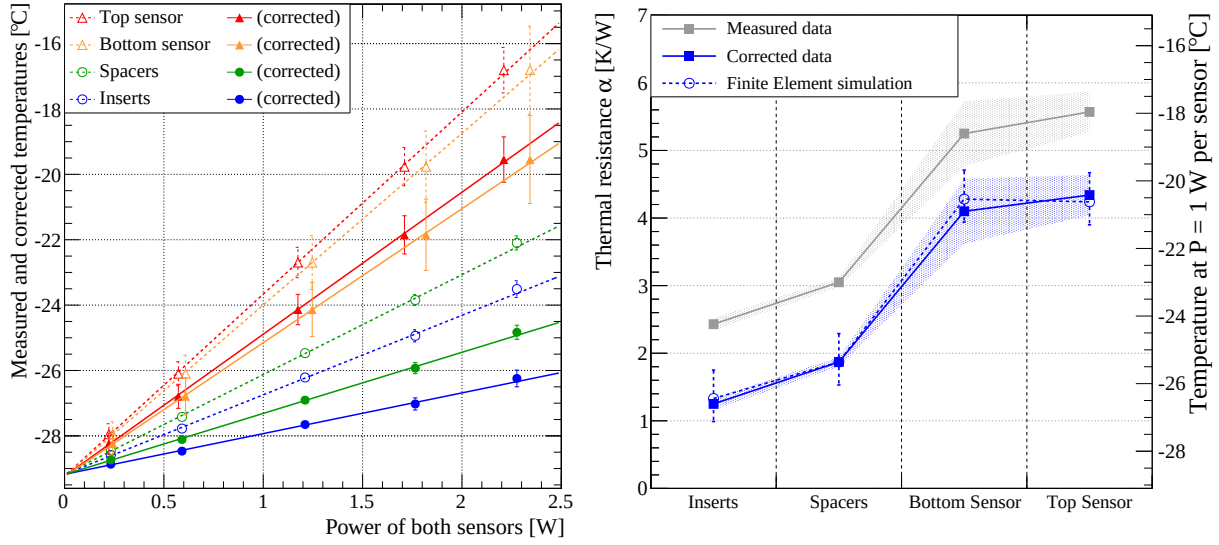


Figure 7.18.: Left: measured temperatures in thermal equilibrium and offset corrected temperatures for the bare module at a  $\text{CO}_2$  temperature of  $29.2^\circ\text{C}$ . The full (open) markers show the corrected (raw) data and the solid (dashed) lines show the linear fit to the data. Right: extracted thermal resistances from the fits to the data for the four measured parts of the module and mechanics. The full blue (gray) line shows the corrected (raw) thermal resistances. The blue error band shows the uncertainties extracted from the linear fit. The dashed blue line shows the thermal resistances extracted from the FE simulation, with the error band showing the standard deviation of the averaged data points.

These equations describe the thermal characteristics of the raw mechanical system of the  $\text{CO}_2$  cooling, the cooling inserts, and the bare module, corrected for all ambient effects. The values for the  $\alpha_{\text{corr}}^{\text{component}}$  are listed in Table 7.2 and plotted in Figure 7.18 (right). The measurement uncertainties in the fitted data are the standard deviations of all thermistor data per component, and are relatively large. The  $\chi^2/ndf$  values of the fits are very low. The relative uncertainties on the fit parameters  $\alpha_i$  are in the order of 4 to 12 % for the corrected data. The uncertainties of the measured and corrected data are shown with a band in Figure 7.18 (right).

One should note that in the equations given the power  $P$  refers to the power of both bare module sensors and not to the actual heat removed by one cooling point along one screw point and one insert. The values for  $\alpha_{\text{corr}}^{\text{component}} = \Delta T_{\text{corr}}^{\text{component}} / \Delta P$  have to be understood in this context. The actual heat removed along one cooling point cannot be determined from this measurement. The simplest assumption one can make is that the heat is removed equally among the five cooling points. With that assumption the thermal resistances of the spacers and inserts can be normalized to a fifth of the bare module power:

$$\alpha_{\text{spacer}} = \frac{\Delta T_{\text{corr}}^{\text{spacers}}}{\Delta P/5} = 5 \cdot \alpha_{\text{corr}}^{\text{spacer}} = 9.4 \text{ K/W} \quad (7.25)$$

$$\alpha_{\text{insert}} = \frac{\Delta T_{\text{corr}}^{\text{inserts}}}{\Delta P/5} = 5 \cdot \alpha_{\text{corr}}^{\text{insert}} = 6.2 \text{ K/W} . \quad (7.26)$$

The thermal resistance of the screw contact  $\alpha_{\text{screw point}}$  between spacers and inserts can then be calculated as

$$\alpha_{\text{screw point}} = \alpha^{\text{spacer}} - \alpha^{\text{insert}} = 3.2 \text{ K/W} \quad (7.27)$$

with respect to the power which flows through one cooling contact. With the radius of the inserts ( $r_{\text{insert}} = 4 \text{ mm}$ ) and the radius of the screw point nipple ( $r_{\text{nipple}} = 1.25 \text{ mm}$ ) the contact surface between a spacer and an insert at the screwing point is calculated to  $A_{\text{contact}} = \pi (r_{\text{insert}}^2 - r_{\text{nipple}}^2) =$

4.5 mm<sup>2</sup>. The heat transfer coefficient for the contact surface is calculated as

$$\text{htc}_{\text{screw point}} = \frac{1}{\alpha_{\text{screw point}} \cdot A_{\text{contact}}} = 6.9 \text{ kW/m}^2/\text{K}.$$

This value is obtained from the bare module measurements at a coolant temperature of  $-30^\circ\text{C}$ . A more detailed analysis of the heat transfer coefficient between spacers and inserts was performed at a coolant temperature of  $0^\circ\text{C}$ . This measurement is presented in Appendix E. The value of  $\text{htc}_{\text{screw point}} = 6.9 \text{ kW/m}^2/\text{K}$  presented above is about 20 % lower than the value of  $8.5 \text{ kW/m}^2/\text{K}$  measured in Appendix E while the average values of the thermal resistances  $\alpha_{\text{screw point}}$  are rather compatible. The reason for this is the more accurate determination of  $\text{htc}_{\text{screw point}}$  in Appendix E.

With the measured thermal resistances  $\alpha_{\text{corr}}^{\text{top}}$  and  $\alpha_{\text{corr}}^{\text{bottom}}$ , the thermal coupling between the ambient and the sensors,  $\lambda_{\text{ambient}}$ , can be estimated quantitatively from the raw data series using Equation 7.7. A linear function is fitted to the raw data series for every ambient temperature in Figure 7.17. The extracted slope from that fit is the value

$$\alpha_{\text{raw}}^{\text{top/bottom}} = \frac{1}{\frac{1}{\alpha_{\text{ambient}}} + \frac{1}{\alpha_{\text{cooling, corr}}}} = \frac{1}{\lambda_{\text{ambient}} + \lambda_{\text{cooling, corr}}}. \quad (7.28)$$

From that equation the thermal coupling  $\lambda_{\text{ambient}}$  can be calculated, as the values for  $\lambda_{\text{cooling, corr}} = 1/\alpha_{\text{cooling, corr}}$  are available from the measurement presented above:

$$\lambda_{\text{ambient}}^{\text{top/bottom}} = \frac{1}{\alpha_{\text{raw}}^{\text{top/bottom}}} - \frac{1}{\alpha_{\text{cooling, corr}}^{\text{top/bottom}}}. \quad (7.29)$$

Table 7.3 lists the fitted values  $\alpha_{\text{raw}}^{\text{top/bottom}}$  and the extracted values for  $\lambda_{\text{ambient}}^{\text{top/bottom}}$  for the five different ambient temperatures. The average of the fitted values for  $\alpha_{\text{raw}}^{\text{top}}$  ( $\alpha_{\text{raw}}^{\text{bottom}}$ ) is 3.15 K/W (3.39 K/W), which yields an average thermal coupling of  $\lambda_{\text{ambient}}^{\text{top}} = 81 \text{ mW/K}$  ( $\lambda_{\text{ambient}}^{\text{bottom}} = 58 \text{ mW/K}$ ). The values for the thermal coupling are quite large. Practically, the thermal impact from the ambient onto the sensors is not entirely negligible on the scale of the module power. For the top sensor a temperature difference of 5 K between sensor and ambient would mean a heat exchange of roughly 400 mW with the ambient. The value for this heat exchange is on the same scale as the sensor power after full irradiation. The thermal coupling of the bottom sensor to the ambient is measured approximately 25% lower than for the top sensor. In the measurement setup the bottom sensor faces downwards and has a clearance of about 15 mm to the base plate, which is colder than the ambient. The thermal convection in that constrained space might possibly be less than for the top sensor. However the measured value of  $\lambda_{\text{ambient}}^{\text{bottom}} = 58 \text{ mW/K}$  is still in the same order of magnitude as the value for the top sensor.

Table 7.2.: Table with the raw and corrected values for the thermal resistance  $\alpha$  of the measured components. The data are compared to the thermal resistances  $\alpha_{\text{FE model}}$  obtained from the FE model. The uncertainties  $\sigma_{\alpha, \text{component}}$  from the fit to the the corrected data are also listed.

| Component     | $\alpha_{\text{equil}}[\text{K/W}]$ | $\alpha_{\text{corrected}}[\text{K/W}]$ | $\sigma_{\alpha, \text{component}}[\text{K/W}]$ | $\alpha_{\text{FE model}}[\text{K/W}]$ |
|---------------|-------------------------------------|-----------------------------------------|-------------------------------------------------|----------------------------------------|
| Top sensor    | 5.6                                 | 4.3                                     | 0.3                                             | 4.3                                    |
| Bottom sensor | 5.3                                 | 4.1                                     | 0.5                                             | 4.3                                    |
| Spacers       | 3.1                                 | 1.9                                     | 0.1                                             | 1.7                                    |
| Inserts       | 2.4                                 | 1.3                                     | 0.1                                             | 1.2                                    |

## 7.7. Thermal Measurements and Analysis of the 2S Dummy Bare Modules

Table 7.3.: Values for the fitted overall thermal resistance  $\alpha_{\text{raw}}^{\text{top/bottom}}$  of the 2S sensors, and the thermal coupling between top/bottom sensor and the ambient  $\lambda_{\text{ambient}}^{\text{top/bottom}}$  for the five different ambient temperatures. The last line lists the average values of  $\alpha_{\text{raw}}^{\text{top/bottom}}$  and  $\lambda_{\text{ambient}}^{\text{top/bottom}}$ .

| $T_{\text{ambient}} [^{\circ}\text{C}]$ | $\alpha_{\text{raw}}^{\text{top}} [\text{K/W}]$ | $\lambda_{\text{ambient}}^{\text{top}} [\text{mW/K}]$ | $\alpha_{\text{raw}}^{\text{bottom}} [\text{K/W}]$ | $\lambda_{\text{ambient}}^{\text{bottom}} [\text{mW/K}]$ |
|-----------------------------------------|-------------------------------------------------|-------------------------------------------------------|----------------------------------------------------|----------------------------------------------------------|
| -27.9                                   | 3.28                                            | 68                                                    | 3.46                                               | 52                                                       |
| -26.1                                   | 3.14                                            | 81                                                    | 3.38                                               | 59                                                       |
| -22.7                                   | 3.09                                            | 87                                                    | 3.33                                               | 63                                                       |
| -19.8                                   | 3.10                                            | 86                                                    | 3.35                                               | 61                                                       |
| -16.8                                   | 3.15                                            | 81                                                    | 3.44                                               | 53                                                       |
| Average                                 | 3.15                                            | 81                                                    | 3.39                                               | 58                                                       |

### 7.7.2. Finite Element Simulation of the Bare Module and Comparison with the Measurement

The measurement results discussed in the previous section are compared with the results from the FE model described in Section 7.6.1. The glue thicknesses of the inserts in the FE model are configured for each module cooling position as described in Section 7.4.2. The ratio of the sensor power is chosen to be  $P_{\text{bottom}}/P_{\text{top}} = 1.1$ , in order to account for the fact that the thermal equilibrium states of the sensors are reached at different power values. Except for the CO<sub>2</sub> cooling system with a heat transfer coefficient of 5000 W/m<sup>2</sup>/K, the model does not interact thermally with the outer world. The thermal simulation is run with a given heat load and a given CO<sub>2</sub> temperature. The differences between the sensor temperatures and the CO<sub>2</sub> temperature are evaluated from the result of the FE simulation. The temperature values are extracted at the positions where the actual temperature sensors are placed. The mean thermal resistance

$$\alpha_{\text{FE model}} = \frac{1}{N_{\text{thermistor}}} \sum_i \alpha_{i,\text{FE}}^{\text{component}}$$

is calculated. The simulated values for the  $\alpha_{\text{FE model}}$  are listed in Table 7.2 and shown in Figure 7.18 (right). The simulated values deviate less than 5 % from the measured values for the sensors and the inserts, and by 10 % for the spacers. They are in good agreement with the data within the measurement uncertainties. This shows that the thermal FE model describes the 2S bare module very well. The individual thermal resistances at every thermistor position in the data and in the FE model is shown in Figure 7.19. The data are described by the simulation with an accuracy of 20 % or better for all data points. The measurement shows that the 2S thermal bare module is described qualitatively and quantitatively very well by the FE simulation, not only on average, but also at the single temperature measurement points.

The thermal path between sensor and CO<sub>2</sub> is described with assumptions of values for many parameters in the FE model. In the simulation five parameters are varied in a certain range in order to evaluate their impact on the thermal performance of the 2S bare module. The following parameters are varied between a minimum and a maximum value around their nominal value:

- thickness of the glue-Kapton-glue layer,  $d_{\text{glue-Kapton-glue}}$ , between spacers and sensors by  $\pm 20 \mu\text{m}$
- in-plane and through-plane thermal conductivity of the AlCF material,  $k_{\text{AlCF},\parallel}$  and  $k_{\text{AlCF},\perp}$ , by 25 %
- heat transfer coefficient between spacers and inserts,  $h_{\text{spacers, inserts}}$ , by 25 %
- CO<sub>2</sub> heat transfer coefficient,  $h_{\text{CO}_2}$ , between 3.75 kW/m<sup>2</sup>/K and 10.0 kW/m<sup>2</sup>/K
- thickness of the glue layers of the inserts,  $d_{\text{glue, insert}}$ , by 50 %
- the linear combination of the CO<sub>2</sub> heat transfer coefficient and the insert glue thickness with the variation mentioned above.

The influence of the parameter variations on the thermal resistance of the 2S bare module is shown in Figure 7.20. The variation of  $d_{\text{glue-Kapton-glue}}$  affects the thermal resistances of the full structure by less than 2 *unit*%. The thermal resistance of the silicon sensor varies at maximum by 4 % and 8 % under variation of  $h_{\text{spacers, inserts}}$  and  $k_{\text{AlCF}}$ , respectively. This illustrates the thermally stable design of the 2S module itself, and in particular the low-resistance connection between the 2S silicon sensor and the module mounting points. The variation of  $d_{\text{glue, insert}}$  results in a change of 5 % of the thermal resistance of the 2S bare module. The variation of  $h_{\text{CO}_2}$  to 10 kW/m<sup>2</sup>/K (3.5 kW/m<sup>2</sup>/K) results in a 9 % lower (5 % higher) thermal resistance. The variation of  $d_{\text{glue, insert}}$  and  $h_{\text{CO}_2}$  at the same time leads to changes of 11 % to 13 % of the thermal resistance of the 2S sensor. For the last two parameters the change of the thermal resistance of the 2S sensors is provoked only by the properties of the cooling structure while the first three parameters are (also) related to the layout of the 2S module. The overall relative change of the thermal resistance of the 2S sensors under variation of all five parameters can be calculated to be 11 to 12 %. This value is obtained by calculating the square root of the quadratic sum of the individual relative changes.

In the layout and assembly process of the TEDDs the thermal properties of the detector are defined at different stages of the construction procedure. The thickness and quality of the connection between the silicon sensor and spacers  $d_{\text{glue-Kapton-glue}}$  is the only thermal property which can be controlled during the 2S module assembly process. The thermal conductivity of the AlCF material  $k_{\text{AlCF}}$  will be defined by the final material which will be delivered from the supplier. The thermal contact between module and cooling structure  $h_{\text{spacers, inserts}}$ , and the glue layer thickness of the inserts  $d_{\text{glue, insert}}$  will mainly be defined by the layout and the construction of the TEDDs. The CO<sub>2</sub> heat transfer coefficient  $h_{\text{CO}_2}$  is a property of the CO<sub>2</sub> cooling system and may depend on e.g. mass flow and temperature.

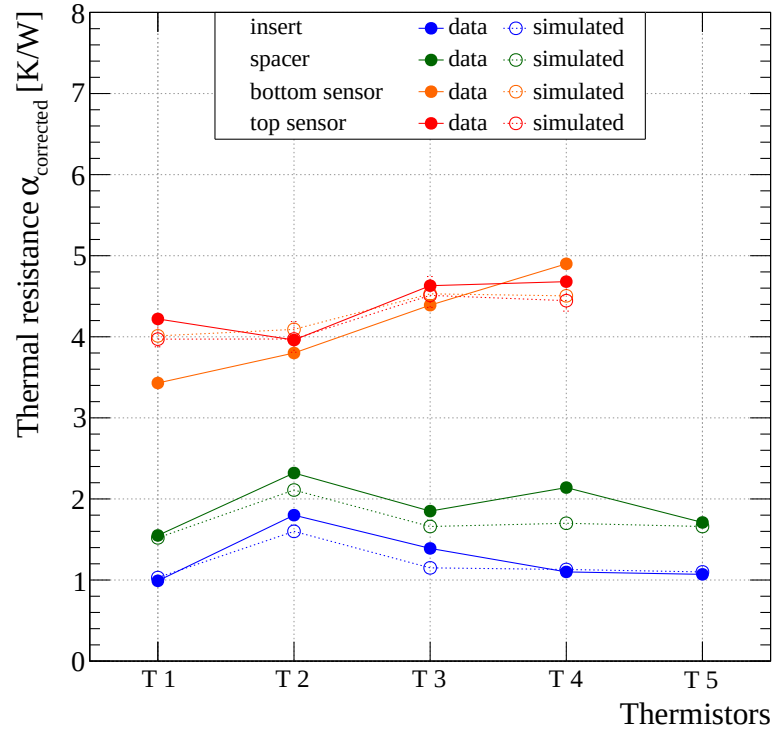


Figure 7.19.: Corrected thermal resistances for the individual measurement positions for the bare module in comparison to the FE simulation. The thermal resistances refer to the full sensor power of the bare module.

## 7.7. Thermal Measurements and Analysis of the 2S Dummy Bare Modules

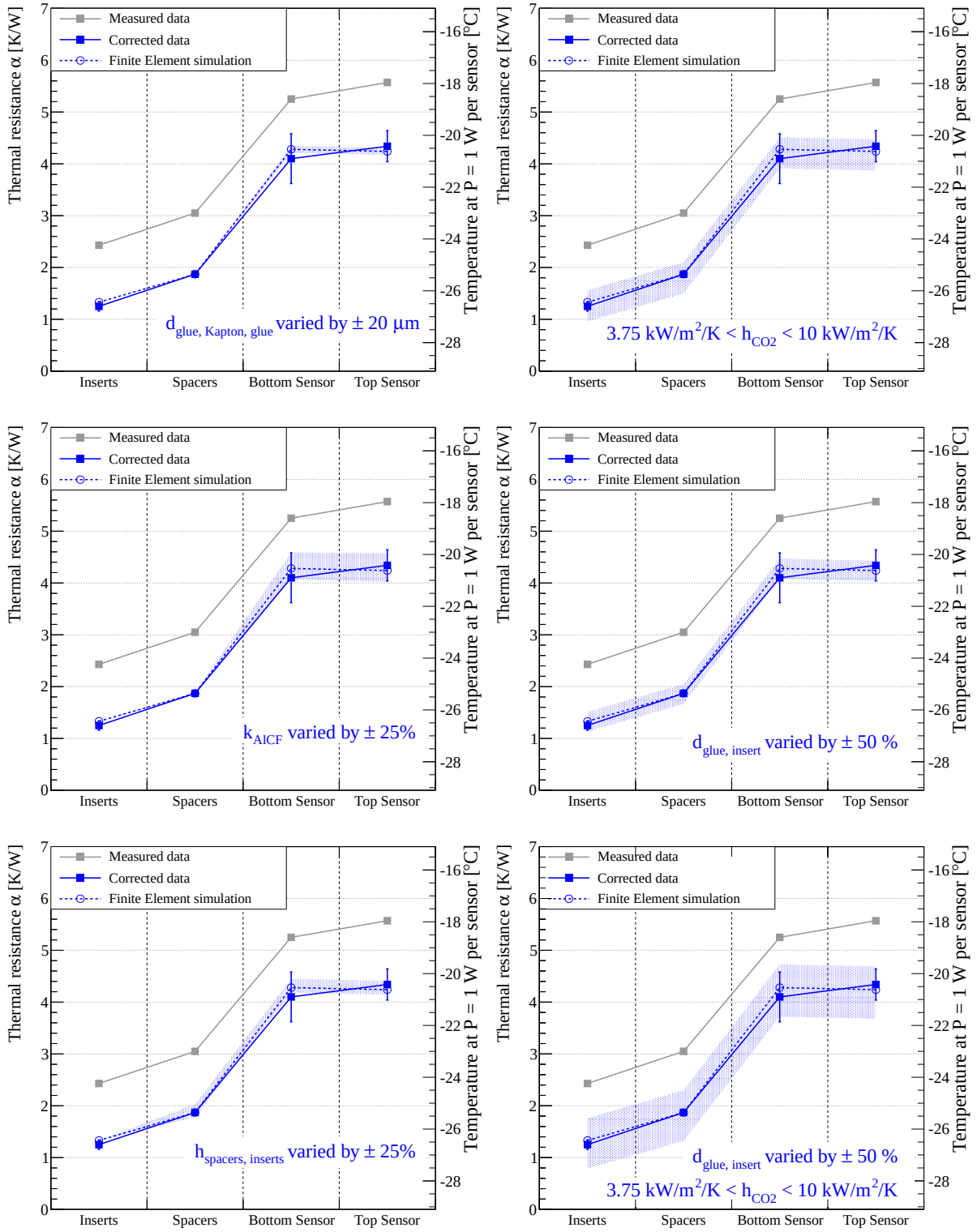


Figure 7.20.: Measured and simulated thermal resistances for the 2S bare module at a  $\text{CO}_2$  temperature of  $29.2^\circ\text{C}$  as shown in Figure 7.18 (right). The blue band around the FE simulation values shows the change of the thermal resistances of the bare module components under variation of certain FE simulation parameters. The FE simulation parameters varied are: the thickness of the glue-Kapton-glue layer between spacers and sensors (top left), the in-plane and through-plane thermal conductivity of the AlCF material (center left), the heat transfer coefficient between spacers and inserts (bottom left), the  $\text{CO}_2$  heat transfer coefficient (top right), the insert glue thickness (center right), and the combination of the  $\text{CO}_2$  heat transfer coefficient and the insert glue thickness (bottom right). The scale of the parameter variation is written in the corresponding plot.

### 7.7.3. Thermal Measurements with Both 2S Thermal Dummy Bare Modules

The measurement of the thermal behavior of the bare modules was performed with both thermal dummy modules on every cooling position. A slightly different procedure than described above was utilized. Instead of ramping up the power of the sensors and determining the thermal equilibrium from the data with the interpolation method, the thermal equilibrium is produced directly during the measurement. The mean temperatures of the ambient and the sensors is monitored and the power of the sensors is set manually to a value such that the mean sensor and ambient temperatures are the same within their standard deviations. The correction from Equation 7.20 is applied to the data like described above and the corrected thermal resistances  $\alpha_{\text{corr}} = \Delta T_{\text{corr}} / \Delta P_{\text{bare module}}$  are calculated. The thermal resistances of top sensor, bottom sensor, spacers, and inserts are shown in Figure 7.21. The data are compared to the FE simulation for every cooling position individually. The models for the three cooling positions differ only in the glue thicknesses of the inserts. The shape of the temperature distribution on the inserts and the spacers is described very well with the simulation. This would not have been possible without the adjustment of the glue thicknesses of the inserts. For the inserts and the spacers almost all measurement points are described by the simulation with an accuracy better than 20%. The data point for Position 1 Insert 4 is measured higher for both modules, which is probably caused by a malfunction of this specific thermistor. This measurement value is excluded for the calculation of the average values. The measurement value for Position 2 Module 2 Spacer 5 is not shown as the thermistor lost contact during the measurement and its data cannot be used. The average thermal resistances of the measurements are listed in Table 7.4 together with the values from the FE simulation.

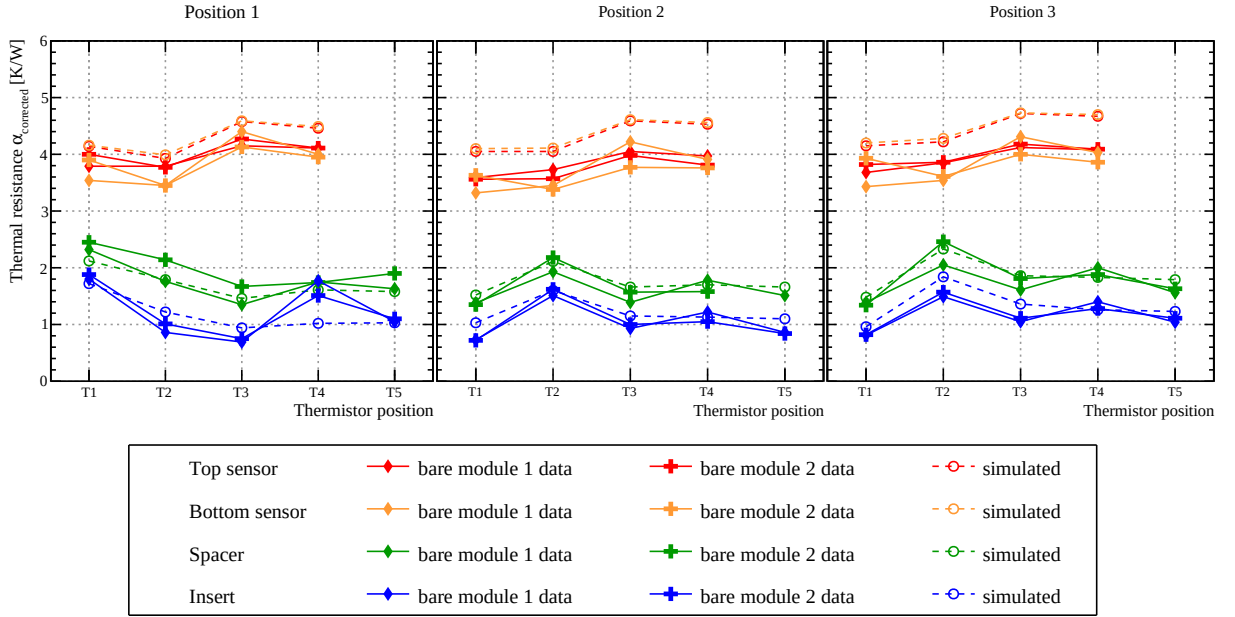


Figure 7.21.: Measured thermal resistances for the single measurement points of the two 2S bare modules on the three module positions. The thermal resistances are compared to the FE simulation.

## 7.8. Thermal Measurements and Simulation of the 2S Dummy Full Module

The full thermal dummy 2S module is measured and analyzed thermally in order to develop a description and an understanding of the thermal behavior of a full 2S module. The thermal

## 7.8. Thermal Measurements and Simulation of the 2S Dummy Full Module

Table 7.4.: Overview on the measured thermal resistances for the two 2S bare modules on the three measurement positions. The values are compared to the FE model for the corresponding cooling position.

| Measurement | Component     | Thermal resistance $\alpha_{\text{corrected}}$ [K/W] |            |            | Mean of all positions<br>$\bar{\alpha}$ [K/W] |
|-------------|---------------|------------------------------------------------------|------------|------------|-----------------------------------------------|
|             |               | Position 1                                           | Position 2 | Position 3 |                                               |
| Module 1    | Top sensor    | 3.96                                                 | 3.84       | 3.92       | 3.91                                          |
|             | Bottom sensor | 3.85                                                 | 3.73       | 3.83       | 3.80                                          |
|             | Spacers       | 1.74                                                 | 1.58       | 1.67       | 1.68                                          |
|             | Inserts       | 1.10                                                 | 1.04       | 1.14       | 1.10                                          |
| Module 2    | Top sensor    | 4.04                                                 | 3.75       | 3.99       | 3.93                                          |
|             | Bottom sensor | 3.86                                                 | 3.65       | 3.85       | 3.79                                          |
|             | Spacers       | 1.97                                                 | 1.85       | 1.81       | 1.87                                          |
|             | Inserts       | 1.19                                                 | 1.02       | 1.17       | 1.12                                          |
| FE model    | Top sensor    | 4.28                                                 | 4.31       | 4.44       | 4.34                                          |
|             | Bottom sensor | 4.31                                                 | 4.35       | 4.48       | 4.38                                          |
|             | Spacers       | 1.71                                                 | 1.73       | 1.86       | 1.77                                          |
|             | Inserts       | 1.19                                                 | 1.20       | 1.33       | 1.24                                          |

measurements and analyses of the full 2S dummy module equipped with a dummy service hybrid and two dummy front-end hybrids is performed in three steps. Firstly, the module is measured in the thermal equilibrium state. This measurement procedure is comparable to the measurement procedure with the bare module presented in the previous section. However, the description in terms of thermal resistances becomes more unclear in case of the full 2S module because of the complex geometry of the module. This part of the measurement series is the main validation of the assumptions on thermal interfaces and materials used in the finite element model. Secondly, the module is powered with realistic heat loads on sensors and hybrids. In this state higher temperature gradients occur on the module. While the heat fluxes on the module can be treated with the FE simulation, the heat exchange with the ambient is estimated from data and implemented in the FE model. This measurement gives an insight into the thermal behavior of the module under possibly realistic conditions. Thirdly, the module is wirebonded from the top sensor to the front-end hybrids and the wirebonds are encapsulated. The measurement with realistic heat loads is then repeated. It is expected from the FE simulation that a significant amount of heat (in the order of 0.2 W) flows from the warmer front-end hybrids to the top sensor through the wirebonds and the encapsulation material. The top sensor will be warmed up from that heat flux. An estimation of the magnitude of this heat flux and a comparison to the wirebond model in the FE simulation is presented. For all measurements, the full dummy module is positioned at the Cooling Position 2 and cooled with a CO<sub>2</sub> mass flow of 60 g/min at a CO<sub>2</sub> temperature of  $-29.8^{\circ}\text{C}$  in the pipes.

A photograph of the full thermal dummy module positioned in the cooling box is shown in Figure 7.22. For this measurement the top sensor is equipped with nine thermistors at the positions shown in the photograph. The bottom sensor is equipped with six thermistors with identical positions to the top sensor situation whereas the central three thermistors are omitted. The service hybrid is equipped with five thermistors on the top side of the hybrid. Three of them are positioned over the glue contacts to the spacers, and two of them are positioned next to the heating resistors in the center between the glue contacts. Each front-end hybrid is equipped symmetrically with four thermistors of which two are positioned in the corners over the glue contacts to the spacers and two are positioned in central positions.



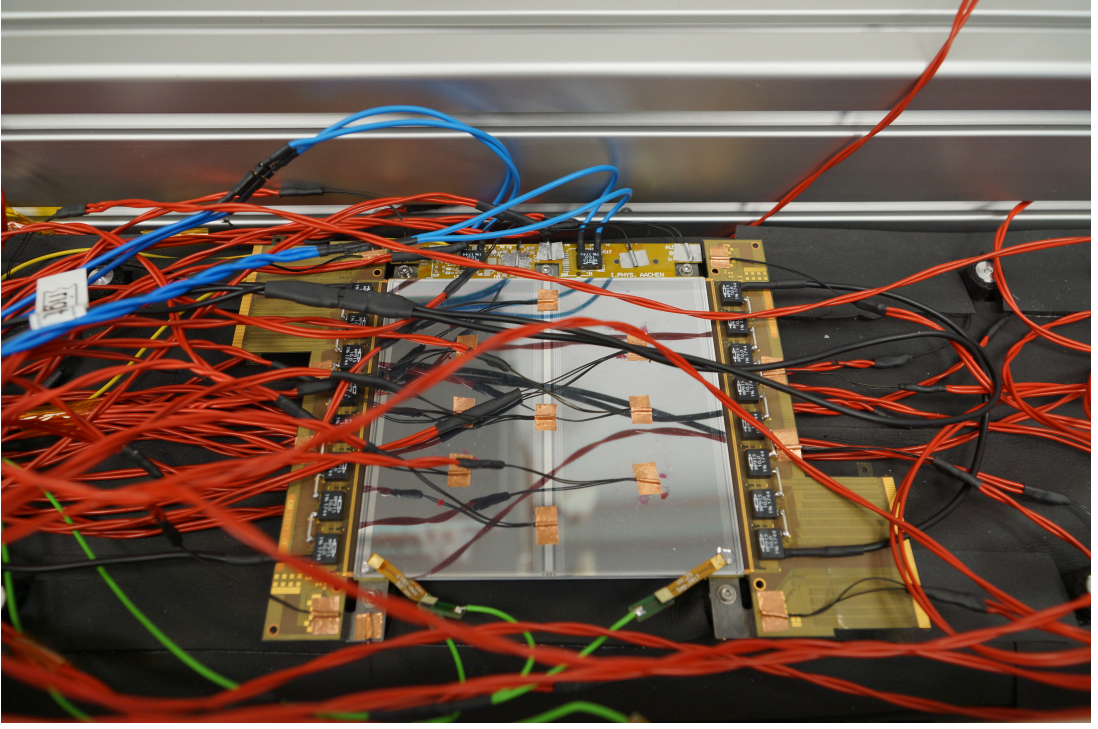


Figure 7.22.: The full 2S dummy module placed in the module cooling box. The top sensor is equipped with nine thermistors, each front-end hybrid is equipped with four thermistors, and the service hybrid is equipped with five thermistors. The bottom sensor, which is equipped with six thermistors, is not visible. Four of five spacer thermistors are also not visible. The electrical connections of the service hybrid, the right front-end hybrid and the top sensor are shown. The ground connection of the sensors is located under the service hybrid and cannot be seen.

### 7.8.1. The Full 2S Module in Thermal Equilibrium

For the measurement of the module in thermal equilibrium an ambient temperature of  $-21.0^{\circ}\text{C}$  is produced in the module cooling box volume. The heat loads are chosen such that active components have on average the temperature of the ambient. The power for the top (bottom) sensor is set to  $0.74\text{ W}$  ( $0.73\text{ W}$ ), each FE hybrid is powered with  $0.4\text{ W}$ , and the service hybrid is powered with  $0.8\text{ W}$ , where the power is distributed equally to both heating resistors. The values sum up to a full module power of  $3.1\text{ W}$ . These values are not realistic for the operation of the 2S module. The temperature distribution on the module and the inserts is shown in Figure 7.23. For the analysis and the comparison with the FE model, all temperature values are offset corrected with the function from Equation 7.20. In the following the corrected values are referred to as measured values. The resulting temperature distributions on the top and bottom sensor and the hybrids are shown in Figure 7.24. Table 7.5 lists the averaged measured and simulated temperature values  $\bar{T}$  of all components of the full thermal dummy module in thermal equilibrium. The data are compared to the simulated values from the FE model, in which the nominal heat loads mentioned above were applied to the components. The heat transfer coefficient of the  $\text{CO}_2$  is increased to  $10\text{ kW/m}^2/\text{K}$  because of the higher heat fluxes, following the discussion in Section 7.6.1 on the heat transfer coefficient. The FE model describes the measured temperature dependence of the inserts very well.

simulated value is  $0.3\text{ K/W}$  higher than simulated for the bare module. The higher value obtained from the simulation results from the fact that the additional heat flux from the hybrids raises the temperature at the point where the thermistor is located. Thus a temperature gradient from the measurement point to the insert contact occurs. The measured mean temperature

values for the two sensors and the three hybrids are all between  $-23.0^{\circ}\text{C}$  and  $-22.5^{\circ}\text{C}$  and the simulated mean values are between  $-22.0^{\circ}\text{C}$  and  $-21.4^{\circ}\text{C}$ . On average, this corresponds to a measured (simulated) temperature difference of 7.1 K (8.2 K) between the components and the  $\text{CO}_2$  temperature. The simulated values are on average 1.1 K higher than the measured values. This deviation includes already the mismatch of 0.6 K between data and simulation from the spacers. The values for data and simulation are compatible within 15 %. The origin of the deviation remains unclear. The discrepancy between data and FE simulation is well compatible with the discrepancies observed in the measurements with the bare modules.

The offset corrected temperature data of the single thermistors are plotted in Figure 7.24 and compared to the simulated values. The chosen heat transfer coefficient of the  $\text{CO}_2$  in the FE model gives a very good description of the temperatures of the components.

The measurement indicates that most of the mechanical properties of the components are implemented sufficiently well in the FE model and that also the heat loads are estimated correctly in the FE model. The deviations observed might possibly originate from the mismodeling of some thermal interfaces between the components and the inserts, e.g. slightly wrong assumptions the anisotropic thermal conductivity of the AlCF material of the spacers. At this point no changes based on such speculations are applied to the FE model. Instead it can be stated that the thermal properties of the full 2S module are in good agreement with the FE simulation, to a precision of or even better than 20 %.

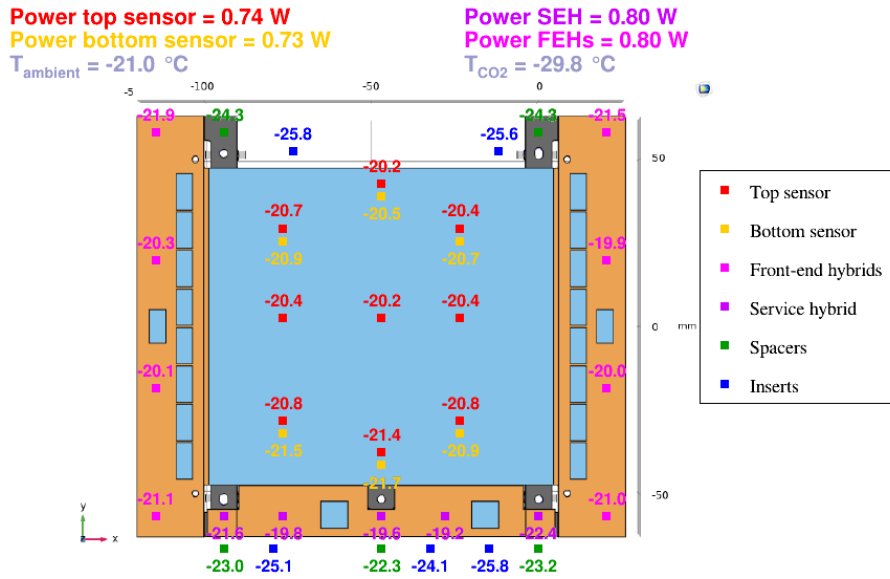


Figure 7.23.: Temperatures measured on the full 2S dummy module in the thermal equilibrium measurement. The power of the components are listed on top. The yellow numbers refer to the temperatures on the bottom sensor, which is not shown. Temperature values are given in  $^{\circ}\text{C}$ .

### 7.8.2. The Full 2S Module with Realistic Heat Loads

In this measurement the thermal dummy 2S full module is powered with realistic heat loads, as they are expected for the operation in the detector. The power for each front-end hybrid is set to 1.4 W and the service hybrid power to 2.5 W. The sensor power is chosen such that it roughly fits the estimated values for the expected sensor power of a 2S 4.0 mm module after an integrated luminosity of  $3000 \text{ fb}^{-1}$ . The power values set in the measurements are 0.49 W for the top sensor and 0.48 W for the bottom sensor. The overall nominal module power is 6.3 W in this measurement. The measurements are performed at ambient temperatures of  $-29.9^{\circ}\text{C}$ ,

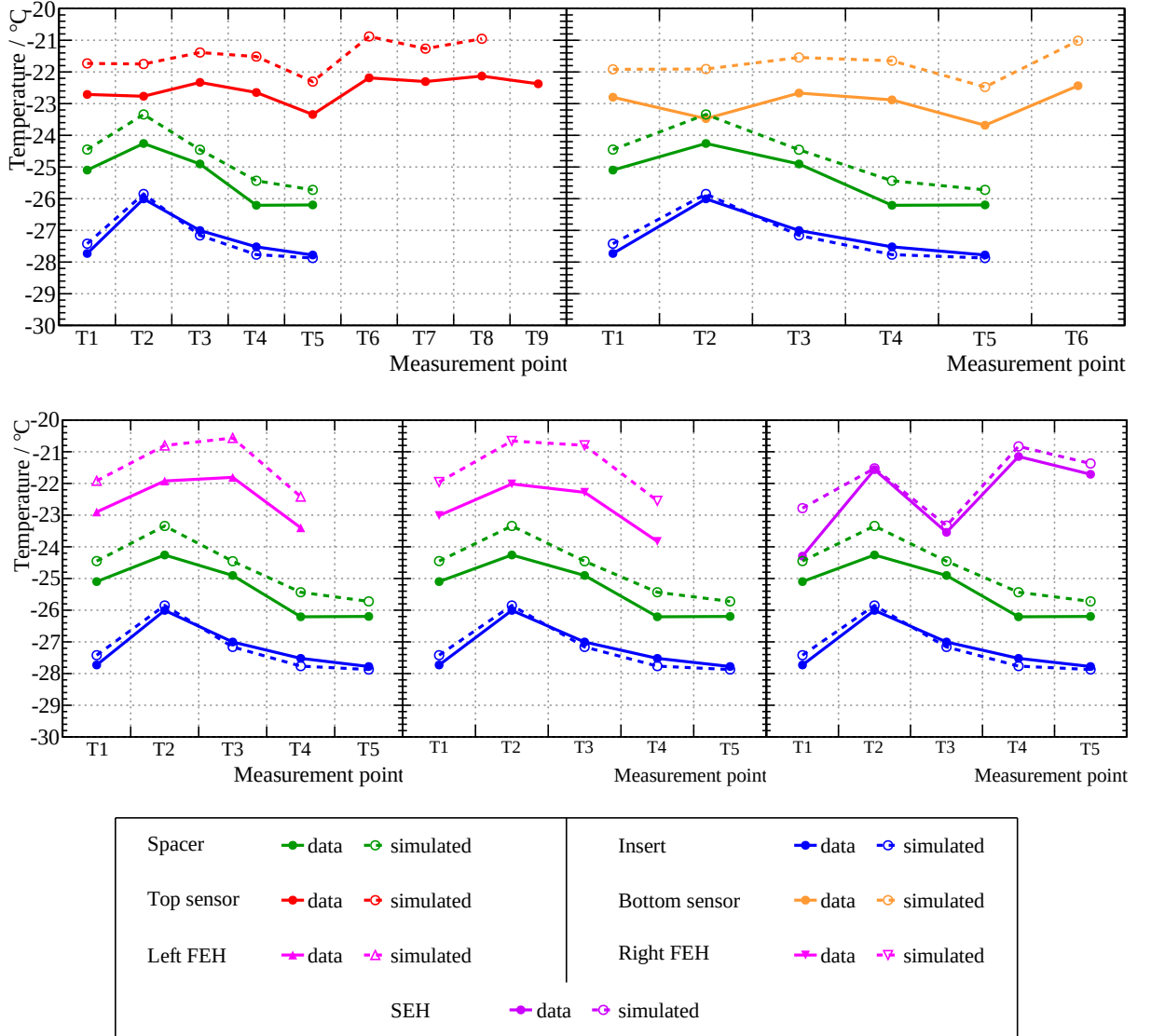


Figure 7.24.: Corrected temperature values for the single measurement points from the measurement of the 2S full dummy module in thermal equilibrium. The data are compared to the Finite Element simulation.

$-19.7^{\circ}\text{C}$ , and  $-13.0^{\circ}\text{C}$ . All heat loads and the  $\text{CO}_2$  temperature are kept constant during these measurements. The temperature distribution on the module is shown in Figure 7.25 for the ambient temperature of  $-19.7^{\circ}\text{C}$ . The average temperature of the front-end hybrids is  $-13.5^{\circ}\text{C}$  and the average temperature of the service hybrid is  $-12.6^{\circ}\text{C}$ . The average temperatures of the top (bottom) sensor is  $-18.7^{\circ}\text{C}$  ( $-19.0^{\circ}\text{C}$ ). The average values of the measured components are plotted versus the ambient temperature in Figure 7.26 for constant power values. The temperatures rise linearly with the ambient temperature. The measured temperatures are corrected with the usual method. The corrected temperatures are also plotted in Figure 7.26. The corrected insert temperatures stay constant for the different ambient temperatures. A possible explanation of this effect is that the heat input from the module and from the ambient to the  $\text{CO}_2$  through the inserts becomes larger with higher ambient temperatures, and this may lead to a change of the heat transfer coefficient of the  $\text{CO}_2$ . The effective thermal resistance of the inserts would be reduced by this effect. This effect is not investigated further.

## 7.8. Thermal Measurements and Simulation of the 2S Dummy Full Module

Table 7.5.: Average values of the measured, corrected, and FE simulated temperature values of the individual components for the measurement of the 2S full module in thermal equilibrium. The temperature differences to the CO<sub>2</sub> temperature are also given.

| Component       | $\bar{T}_{\text{data}} [^{\circ}\text{C}]$ | $\Delta\bar{T}_{\text{CO}_2} [\text{K}]$ | $\bar{T}_{\text{data}}^{\text{corr}} [^{\circ}\text{C}]$ | $\Delta\bar{T}_{\text{CO}_2} [\text{K}]$ | $\bar{T}_{\text{FE model}} [^{\circ}\text{C}]$ | $\Delta\bar{T}_{\text{CO}_2} [\text{K}]$ |
|-----------------|--------------------------------------------|------------------------------------------|----------------------------------------------------------|------------------------------------------|------------------------------------------------|------------------------------------------|
| Inserts         | -25.3                                      | 4.5                                      | -27.2                                                    | 2.6                                      | -27.2                                          | 2.6                                      |
| Spacers         | -23.4                                      | 6.4                                      | -25.3                                                    | 4.5                                      | -24.7                                          | 5.1                                      |
| Top sensor      | -20.6                                      | 9.2                                      | -22.5                                                    | 7.3                                      | -21.5                                          | 8.4                                      |
| Bottom sensor   | -21.0                                      | 8.8                                      | -23.0                                                    | 6.8                                      | -21.8                                          | 8.0                                      |
| Right FEH       | -20.6                                      | 9.2                                      | -22.5                                                    | 7.3                                      | -21.4                                          | 8.4                                      |
| Left FEH        | -20.8                                      | 9.0                                      | -22.8                                                    | 7.0                                      | -21.5                                          | 8.3                                      |
| SEH             | -20.5                                      | 9.3                                      | -22.5                                                    | 7.3                                      | -22.0                                          | 7.8                                      |
| CO <sub>2</sub> | -29.8                                      | —                                        | -29.8                                                    | —                                        | -29.8                                          | —                                        |
| Ambient         | -21.0                                      | 8.8                                      | —                                                        | —                                        | —                                              | —                                        |

Figure 7.27 shows the average corrected temperature values per component for the measurement at  $T_{\text{amb}} = -20^{\circ}\text{C}$  and the corresponding FE simulation values. It is evident that the measured and simulated values are not compatible with each other, i.e. for the spacers and hybrids. The temperatures of the front-end hybrids are simulated about 8 K higher than in the measurement. The reason for this is the interaction of the module components with the ambient. The magnitude of the heat exchange with the ambient is estimated as follows. To the three data points of each component in Figure 7.26 a linear function

$$T_{\text{component}}(T_{\text{amb}}) = m T_{\text{amb}} + T_0 \quad (7.30)$$

is fitted. The temperature at which the component would be in thermal equilibrium with the ambient is determined by finding the fixed point of the fitted function,  $T_{\text{equil}}$ , which is defined by the condition  $T_{\text{component}}(T_{\text{equil}}) = T_{\text{equil}}$ . This point exists for the sensors at an ambient temperature of approximately  $-19^{\circ}\text{C}$ . For the hybrids the equilibrium point is at approximately  $-8^{\circ}\text{C}$ , which is out of the measured temperature range. It is assumed that at these equilibrium points the respective components would have zero heat exchange with the ambient, respectively. For temperatures lower (higher) than their respective thermal equilibrium temperature, the sensors are cooled (heated) by the ambient and the actual heat removed by the cooling system is lower (higher) than the nominal sensor power. The hybrids are always colder than the ambient. They always lose heat to the ambient and the actual heat removed by the cooling system is always lower than the nominal hybrid power. From the estimation of the actual heat loads of the single components the total actual module power removed with the cooling system can be estimated. The corrected temperatures  $T_{\text{equil}}^{\text{corr}}$  at the equilibrium points are computed for each component. For each component a pseudo thermal resistance  $\tilde{\alpha}$  is defined as

$$\tilde{\alpha}_{\text{component}} = \frac{T_{\text{equil}}^{\text{corr}} - T_{\text{CO}_2}}{P_{\text{component}}^{\text{nominal}}},$$

where  $P_{\text{component}}^{\text{nominal}}$  is the nominal heat load for each component as supplied with the power supply. The expression “pseudo” indicates that the value for  $\tilde{\alpha}$  is also affected by the heat loads from the other components. With the corrected temperatures, the actual heat load of the component with respect to the CO<sub>2</sub> system can be estimated for each ambient temperature by evaluating

$$P_{\text{component}} = \frac{T_{\text{corr}} - T_{\text{CO}_2}}{\tilde{\alpha}_{\text{component}}}.$$

The values of  $P_{\text{component}}$  are listed in Table 7.6. Qualitatively they show the expected behavior of the interaction of the components with the ambient. In the measurement at an ambient

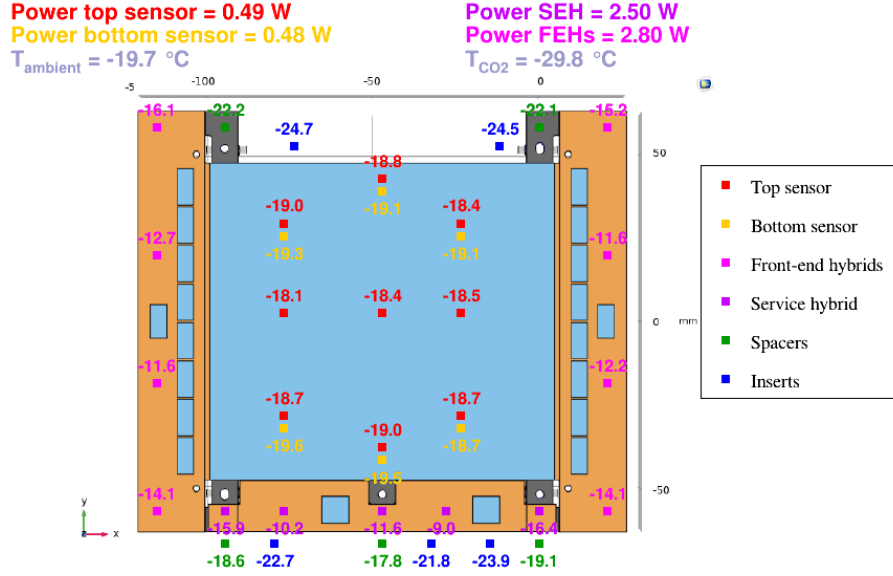


Figure 7.25.: Temperatures measured on the full 2S dummy module in the measurement with realistic heat loads at an ambient temperature of  $-19.7^{\circ}\text{C}$ . The nominal power of the components is listed on top. The yellow numbers refer to the temperatures on the bottom sensor, which is not shown. Temperature values are given in  $^{\circ}\text{C}$ .

temperature  $T_{\text{amb}} = -30^{\circ}\text{C}$  only 3.5 W of the module power is removed by the cooling system. This corresponds to 56 % of the whole module power. The remaining 2.8 W are dissipated to the ambient. For the measurement at  $T_{\text{amb}} = -13^{\circ}\text{C}$ , 5.8 W are removed by the cooling system which corresponds to 93 % of the whole nominal module power. In the FE simulation, the ambient corrected power values for the ambient temperature of  $-20^{\circ}\text{C}$  obtained from the procedure explained above are used. The simulated temperatures are compared to the measured temperature data at the ambient temperature of  $-20^{\circ}\text{C}$ . This is shown in Figure 7.27. The values from data and simulation are compatible to better than 20 % for each component, which is a better description of the thermal behavior due to the adjusted power values. The temperatures of the hybrids is overestimated by about 3 K. Using only 80 % of the front-end hybrid power in the FE model gives a very accurate description of the measured temperatures. This approach was motivated by further investigations of measurement errors. The temperature of the front-end hybrids was measured on four positions on the hybrid PCB, as indicated in Figure 7.25. Two thermistors are positioned at the corners of the hybrids and two thermistors are positioned

Table 7.6.: Extracted actual powers of the 2S full dummy module components which are removed by the  $\text{CO}_2$  cooling system, listed for the measurement at the three different ambient temperatures. The values are listed for the measurement with and without wirebonds. The difference between the listed power and the nominal power  $P_{\text{nominal}}$  is dissipated to the ambient.

| Component     | $P_{\text{nominal}}$ | $P(T_{\text{amb}} = -30^{\circ}\text{C})[\text{W}]$ |      | $P(T_{\text{amb}} = -20^{\circ}\text{C})[\text{W}]$ |      | $P(T_{\text{amb}} = -13^{\circ}\text{C})[\text{W}]$ |      |
|---------------|----------------------|-----------------------------------------------------|------|-----------------------------------------------------|------|-----------------------------------------------------|------|
|               |                      | no WB                                               | WB   | no WB                                               | WB   | no WB                                               | WB   |
| Top sensor    | 0.49                 | 0.28                                                | 0.29 | 0.45                                                | 0.44 | 0.56                                                | 0.57 |
| Bottom sensor | 0.48                 | 0.32                                                | 0.33 | 0.46                                                | 0.46 | 0.57                                                | 0.59 |
| Left FEH      | 1.40                 | 0.68                                                | 0.73 | 0.96                                                | 1.05 | 1.19                                                | 1.37 |
| Right FEH     | 1.40                 | 0.69                                                | 0.76 | 0.98                                                | 1.08 | 1.17                                                | 1.35 |
| SEH           | 2.50                 | 1.55                                                | 1.26 | 1.95                                                | 1.70 | 2.29                                                | 2.05 |
| Full Module   | 6.3                  | 3.5                                                 | 3.4  | 4.8                                                 | 4.7  | 5.8                                                 | 5.9  |

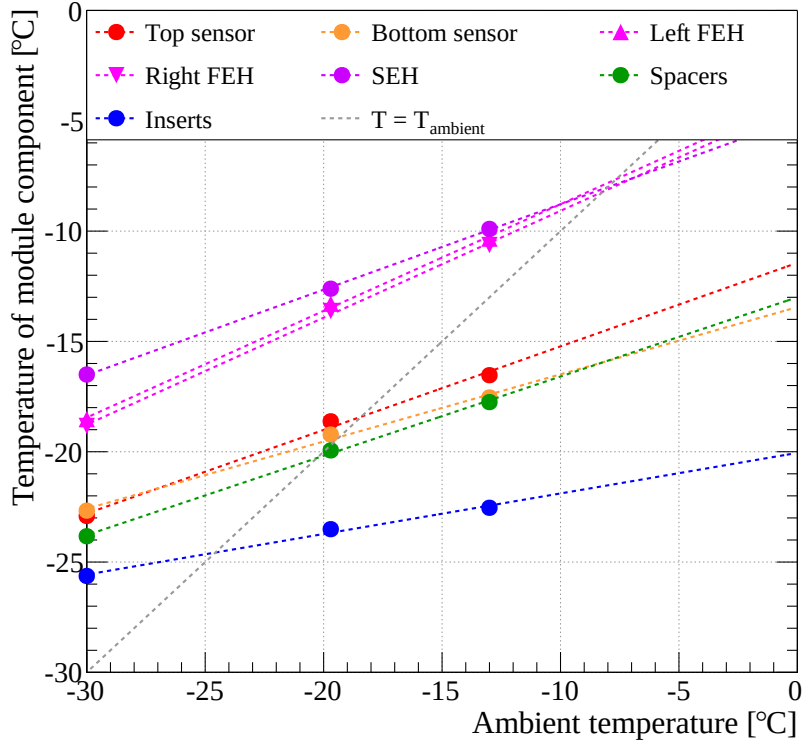


Figure 7.26.: Measured and corrected average temperatures of the measurement with the 2S full dummy module with realistic heat loads versus the ambient temperature. The curves with the full markers and solid lines show the values for the corrected data with the color of the corresponding component.

equidistantly on the hybrid PCB. No thermistor is positioned at the center of the hybrid PCB where the highest hybrid temperature is expected. The heat flows from the center to edges of the hybrid. The heat flow becomes linearly higher towards the hybrid edges as the power of the CBCs is added to the overall heat flux. The linearly rising heat flux leads to a parabolic temperature distribution on the FEHs, with the maximum in the center. In the analysis presented above the maximum value of the FEH temperature profile is not taken into account because no thermistor was positioned there. This leads to an underestimation of the mean hybrid temperature. A parabolic fit is applied to the measured hybrid temperatures plotted versus their  $y$ -position. From this fit, the mean value of the fitted temperature distributions is calculated for each front-end hybrid. The difference between the mean temperature differences calculated from the fitted function and the  $\text{CO}_2$  temperature is about 25 % higher than for the mean value calculated from the thermistor measurements. The analysis procedure for the heat loss correction explained above is repeated for the values obtained from the fit function. For doing this, the mean temperature differences between the FEH hybrid and the  $\text{CO}_2$  were multiplied with a factor 1.25. The same analysis procedure for the heat removed by the  $\text{CO}_2$  was applied by using the condition of thermal equilibrium etc. This analysis indicated that the factor of 1.25 directly affected the front-end hybrid power removed by the cooling system. It was 80 % of the original estimation of the heat loss corrected power.

The sensor temperatures are modelled very well with the FE model and no serious deviations between data and simulation occurred for all simulation scenarios. The deviations between data and simulation are smaller than 1 K for all power cases considered. The good simulation is due to the fact that the thermal coupling of the sensor to the inserts through the spacers is relatively independent from the heat fluxes stemming from the hybrids. Like for the bare module measurement, this indicates that the thermal coupling of the sensor to the cooling system is



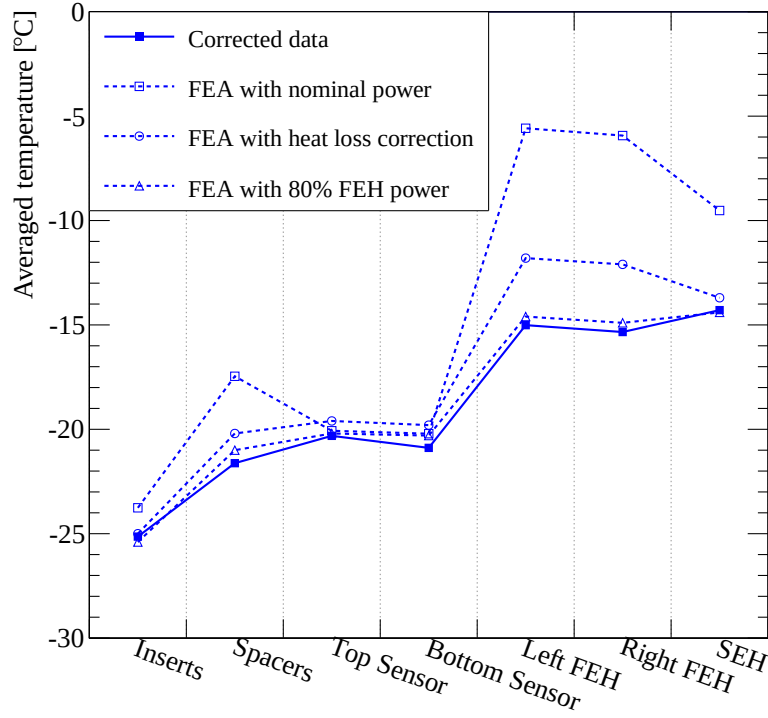


Figure 7.27.: Average temperatures of the components of the 2S full dummy module without wirebonds with realistic heat loads from the measurement at the ambient temperature of  $-19.7^{\circ}\text{C}$ .

described very well with the FE model.

### 7.8.3. The Full 2S Module with Wirebonds

As seen in the previous section, the thermal design of the 2S module is chosen such that the sensors are cooled very well, with minimized interference with the hybrids. However the situation changes once the sensor is in thermal contact with the front-end hybrids through the wirebonds and their encapsulation. The top sensor of the full 2S thermal dummy module has been wirebonded to the FEHs and the wirebonds were encapsulated with Sylgard 86. The measurement with the wirebonds is performed in the same way as the measurement described in the previous section, but at slightly different ambient temperatures. The average offset corrected temperatures of the components with wirebonds are plotted in Figure 7.28 together with the measured data without wirebonds. The linear functions fitted to the data are also plotted in Figure 7.28. The temperatures of the inserts and the spacers are compatible with the measurement without wirebonds. The front-end hybrids are about 1 K colder in the case with wirebonds than in the case without wirebonds. Both sensors are about 1 to 2 K warmer in the case with wirebonds than in the case without wirebonds. The service hybrid is approximately at the same temperature for both cases. The dependence of the temperatures on the ambient is identical for the front-end hybrids. The temperature of the sensors and the service hybrid has a dependence on the ambient temperature with a higher slope than for the case without wirebonds. The analysis of the temperatures and the actual power of the components of the module with wirebonds is done in the same way as for the measurement without wirebonds. The estimated power removed by the cooling system is listed in Table 7.6. Figure 7.29 shows the measured temperature in comparison with the FE simulation, where the simplified model of the wirebonds is implemented, with the three power scenarios of the nominal power, with the heat loss corrected power, and with 80 % power of the heat loss corrected power. Again the simulation scenario

with the full nominal module power does not describe the thermal behavior of the module. The simulation scenario with 80 % of the actual front-end hybrid heat load gives a proper description the thermal behavior. The overall module power removed by the cooling system is compatible with the values from the measurement without wirebonds. However the heat load coming from the service hybrid is 0.2 to 0.3 W smaller than for the case without wirebonds, and the one coming from the front-end hybrids is about 0.1 W larger for each front-end hybrid.

The corrected mean temperatures of the components evaluated from the fitted linear function (Equation 7.30) at an ambient temperature of  $-20^{\circ}\text{C}$  are plotted in Figure 7.30 and compared to the measurement without wirebonds. The effect of the wirebonds is clearly visible. In the wirebond case the front-end hybrids are 1 to 1.5 K colder than in the case without wirebonds while the wirebonded top sensor is 0.8 K warmer. This verifies the assumption that heat flows from the front-end hybrids to the top sensor. The temperatures of the other components are nearly unaffected by the wirebonds. The simulation with the simplified wirebond model describes the temperature drop of the front-end hybrids, because of the heat flux through the wirebonds to the sensor, in good accuracy. Also the temperature rise of the top sensor is modelled with very good accuracy.

The magnitude of the heat flux from the front-end hybrids through the wirebonds is estimated with the thermal resistance of the sensor obtained in the bare module measurements described in Section 7.7. For the top sensor the thermal resistance  $\alpha_{\text{raw}}^{\text{top}} = 3.2 \text{ K/W}$  was measured, which describes the temperature behavior of the top sensor when in contact with the ambient. With the temperature rise of 0.8 K in the wirebond case with respect to the non-wirebond case, it can be estimated that an additional heat flux of

$$P_{\text{wirebond}}^{\text{top}} = \frac{0.8 \text{ K}}{\alpha_{\text{raw}}^{\text{top}}} = 0.25 \text{ W} \quad (7.31)$$

flows from the front-end hybrids to the top sensor. The magnitude of the heat flux from the front-end hybrids to the sensor through the wirebonds can also be extracted from the simulation. It is evaluated to be 0.17 W per front-end hybrid for the given power situation. The FE simulation values sum up to a total additional heat flux to the sensor of 0.34 W. The values for the measured and simulated values are in the same order of magnitude and are compatible within 50 %, which is already a good result. It confirms that the simplified wirebond model in the simulation gives a sufficient description of the complex wirebond and encapsulation material geometry. It is important to note that the additional heat flux to the sensor through the wirebonds is in the same order of magnitude like the actual sensor power generated by the high-voltage leakage current after full irradiation.



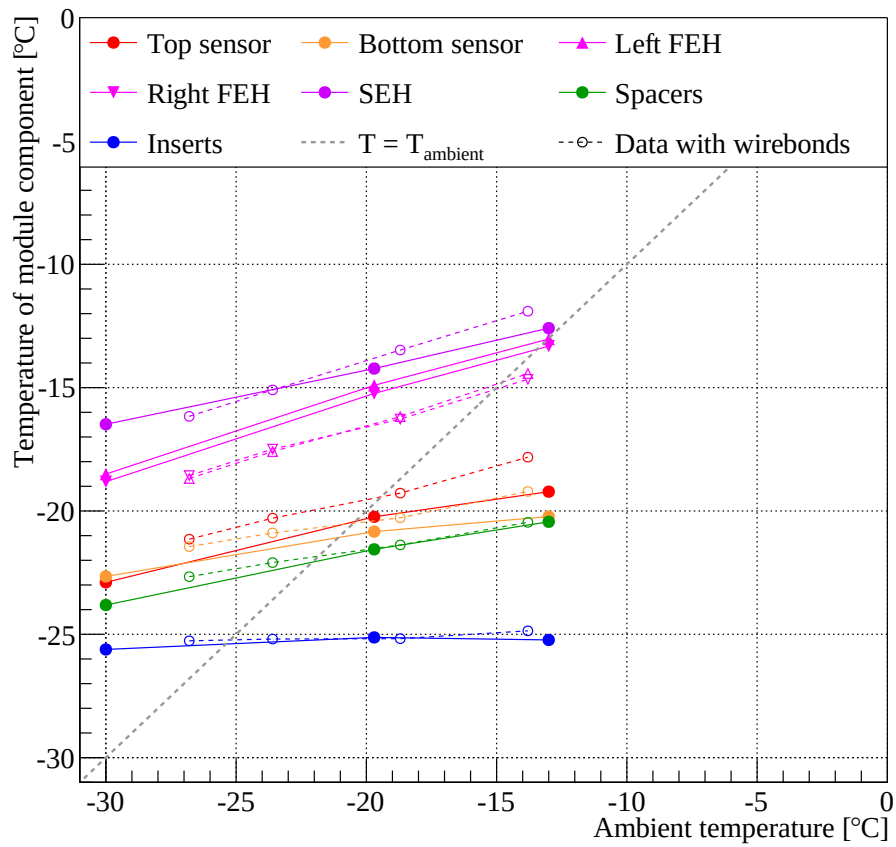


Figure 7.28.: Corrected average temperatures of the measurement with the 2S full dummy module with realistic heat loads versus the ambient temperature. The curves with the open markers and dashed lines show the values for the data with wirebonds with the color of the corresponding component.

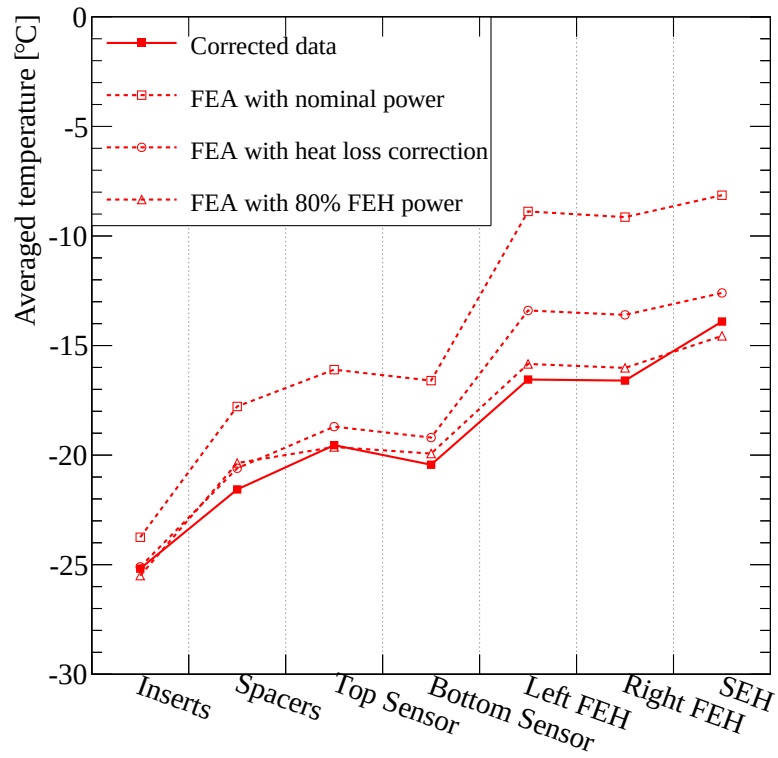


Figure 7.29.: Average temperatures of the components of the 2S full dummy module with wirebonds with realistic heat loads from the interpolated data at the ambient temperature of  $-19.7^{\circ}\text{C}$ .

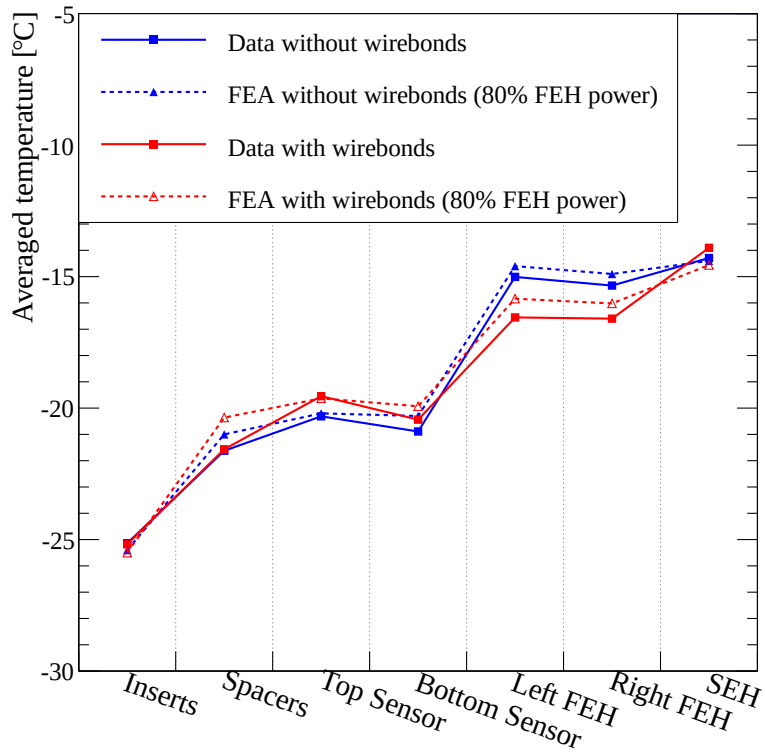


Figure 7.30.: Average temperatures of the components of the 2S full dummy module without (with) wirebonds with realistic heat loads from the measured (interpolated) data at the ambient temperature of  $-19.7^{\circ}\text{C}$ .

## 7.9. Thermal Runaway of the 2S Modules

The high voltage leakage current of the silicon sensor scales non-linearly with the temperature, which can lead to the effect of thermal runaway, i.e. the sensor heats itself up in an uncontrolled way. The leakage current scales also with the radiation damage. This effect depends on the position of the module in the detector. As the sensor power is the product of the high voltage times the leakage current, the sensor power is also proportional to the high voltage. The thermal runaway is characterized by the point of the sensor power and temperature, and the CO<sub>2</sub> cooling temperature, at which the sensor starts heating up in an uncontrolled way and the cooling power of the mechanics cannot stop the self-heating. Given that the sensor power and the mechanics are determined, the point of thermal runaway can be defined as the CO<sub>2</sub> temperature at which the thermal runaway starts. The maximum expected CO<sub>2</sub> temperature in the detector is  $-33^{\circ}\text{C}$ . The collaboration aims to design the 2S module for a point of thermal runaway with 3 K margin to  $-33^{\circ}\text{C}$  in order to ensure a fully operational detector over the full HL-LHC period.

The effect of thermal runaway has to be carefully studied and analyzed, as it can strongly limit the longevity of the detector. Unfortunately, the measurement of the thermal runaway with real modules is not possible in this early stage of module prototyping. The main reason for that is that only a few functional 2S modules are available in the collaboration and none of them has been radiated to the expected fluences. FE models are utilized to estimate the thermal runaway. These models produce exact numerical solutions for the mechanical and thermal boundaries implemented. However it is hard to quantitatively implement real ambient effects into these models as they might (or will) occur in the real detector.

The project of this thesis provides the rare opportunity to make an attempt to demonstrate the effect of thermal runaway with the 2S dummy module. This measurement is presented in Section 7.10. The finite element model for the thermal runaway, which were developed in the scope of this thesis, are presented in Section 7.11 and compared to the results from the Technical Design Report from 2017 [5]. This FE model serves as an independent cross-check of the FE result from the TDR.

### 7.9.1. Sensor Power and FE Model

An important part of the study of the thermal runaway is a good estimation of the sensor power. The leakage current is directly proportional to the active sensor volume. The active sensor volume is the zone where the sensor is depleted and electron-hole pairs are produced when a charged particle passes through. The collected charge is proportional to the active sensor volume. Therefore (among other issues) the active sensor volume is an important and critical parameter in the layout of the whole detector. For a long time, it was the baseline design in the collaboration to utilize sensors with a total thickness of  $320\text{ }\mu\text{m}$  and an active thickness of  $200\text{ }\mu\text{m}$  (the ddFZ200 design). Since this design was not supported anymore from the supplier side, it was decided to utilize sensors with a total thickness of  $320\text{ }\mu\text{m}$  and an active thickness of  $290\text{ }\mu\text{m}$  (the FZ290 design). In the meantime also sensors with an active thickness of  $240\text{ }\mu\text{m}$  were under discussion. The active thickness of the sensors has a direct impact on the thermal behavior of the module as it directly affects the sensor leakage current. The simulation of the thermal runaway is made with the full thermal model of the 2S module, which is nearly identical to the model used before in this thesis. However in this FE model, the heat load of the sensor is now generated temperature-dependently. It is scaled with the Boltzmann distribution (Equation 6.17) for each finite element of the active sensor volume  $V_{\text{sensor, active}}$ . This feature can be implemented in COMSOL Multiphysics with the Heat Source feature where the power density, i.e. power  $p_i$

per finite element volume  $i$ , is set to

$$p_i(T_i) = \frac{P_0}{V_{\text{sensor, active}}} \left( \frac{T_i}{T_0} \right)^2 \exp \left( - \frac{\Delta E}{2k_B} \left( \frac{1}{T_i} - \frac{1}{T_0} \right) \right). \quad (7.32)$$

The reference power  $P_0$  of the active sensor volume is calculated as described in Section 6.4.2. The reference for an active sensor thickness of  $320 \mu\text{m}$  is given by

$$P_0 = P(T_{\text{sensor}} = +20^\circ\text{C}) = U_{\text{bias}} \cdot I_{\text{leakage}}(\Phi, V_{\text{sensor}}) = U_{\text{bias}} \cdot \alpha_{\text{damage}} \cdot \Phi \cdot V_{\text{sensor}} \quad (7.33)$$

$$= 600 \text{ V} \cdot 5.35 \cdot 10^{-17} \frac{\text{A}}{\text{cm neq}} \cdot 3.0 \cdot 10^{14} \frac{\text{neq}}{\text{cm}^2} \cdot 1935 \text{ mm}^3 = 22.4 \text{ W} \quad (7.34)$$

where the values for  $U_{\text{bias}}$ ,  $\alpha_{\text{damage}}$  and  $\Phi$  are taken from the Technical Design Report [5]. For a reference temperature of  $-20^\circ\text{C}$  the calculated power value corresponds to a power of

$$P(T_{\text{sensor}, 200 \mu\text{m}} = -20^\circ\text{C}) = 0.32 \text{ W} \quad (7.35)$$

for a sensor with an active thickness of  $200 \mu\text{m}$ . With the analog calculation one obtains

$$P(T_{\text{sensor}, 290 \mu\text{m}} = -20^\circ\text{C}) = 0.46 \text{ W} \quad (7.36)$$

for a sensor with an active thickness of  $290 \mu\text{m}$ . These values refer to a 2S 4.0 mm module in the TEDDs after an integrated luminosity of  $3000 \text{ fb}^{-1}$  and to a high voltage of 600 V, which is the standard reference in the following sections. More values for the 2S 4.0 mm module sensor power are listed in Table 6.2. For the service hybrid and the front-end hybrids the standard power values listed in Table 6.1 are implemented into the models.

## 7.10. Measurement of the Thermal Runaway with the 2S Full Dummy Module

In this section the attempt to measure the thermal runaway of the full 2S dummy module is presented. The measurement is designed such that the  $\text{CO}_2$  cooling temperature, the ambient temperature and the sensor powers are varied until a proper working point is reached. The working point is defined by the condition that the power and the mean temperature of one sensor satisfy the Boltzmann function (Equation 6.17). The nominal  $\text{CO}_2$  temperature is increased in steps of 1 K starting from  $-31^\circ\text{C}$ . For each  $\text{CO}_2$  temperature the sensor power (scaled with the Boltzmann function) and the ambient temperature are varied in an iterative procedure such that the mean temperatures of the sensors and the ambient eventually are equal. This method produces the state of thermal equilibrium between the sensors and the ambient, and the temperature dependent leakage current is modelled in the dummy 2S sensors. The situation with the dummy sensors is slightly different to the actual situation in real irradiated silicon sensors. When the temperature distribution on a real irradiated sensor becomes inhomogeneous, the leakage current distribution and thus the heat generation is also distributed inhomogeneously. At points with higher (lower) temperatures the leakage current density will be higher (lower). This leakage current distribution affects again the temperature distribution on the sensor. This recursive effect is taken into account in the thermal simulations. The 2S dummy sensors used in this measurement are Ohmic resistors. It is assumed that the leakage current density in their volume is distributed homogeneously, which can lead to slight differences in the thermal behavior compared to the simulation. Nevertheless, the results of the measurement presented in the following can be used as an estimator of how well the measured and simulated thermal runaway curves agree. In the measurement a high voltage power consumption of 400 mW at a constant sensor temperature of  $-20^\circ\text{C}$  is assumed. This value is chosen as it reflects the coarse

mean value of the different values of the expected power consumption for various possible active sensor thicknesses after an integrated luminosity of  $3000 \text{ fb}^{-1}$  and a high voltage of 600 V. The overall front-end hybrid power was set to 2.8 W and the service hybrid power was set to 2.5 W. The  $\text{CO}_2$  cooling system used in the setup is not capable of working at cooling temperatures of below  $-31^\circ\text{C}$ . Thus, the minimal possible cooling temperature of  $-31^\circ\text{C}$  was chosen as the starting point of the measurement. This  $\text{CO}_2$  temperature is below the expected  $\text{CO}_2$  temperature at which the thermal runaway will occur for the chosen reference sensor power. Two further measurement points at nominal  $\text{CO}_2$  temperatures of  $-30^\circ\text{C}$  and  $-29^\circ\text{C}$  were recorded. Figure 7.31 (left) shows the measured values of the full module power plotted versus the average sensor temperature. The gray curve shows the sum of the overall hybrid power of 5.3 W and the temperature dependent power of one sensor, i.e. the Boltzmann curve. The three measurement curves close to the Boltzmann curve show the measured points of the average ambient temperature, and the mean bottom and top sensor temperature. The first (second, third) data point per graph refers to the first (second, third) measurement at the  $\text{CO}_2$  temperature of  $-31^\circ\text{C}$  ( $-30^\circ\text{C}$ ,  $-29^\circ\text{C}$ ). Blue boxes indicate which data points belong together. For all three measurement points it was possible to find a point where the average of the ambient temperature and both sensor temperatures were equal within less than 1.5 K. The three ambient temperatures were  $-17.2^\circ\text{C}$ ,  $-15.8^\circ\text{C}$  and  $-13.1^\circ\text{C}$ . These ambient temperatures are 14 K to 16 K higher than the corresponding  $\text{CO}_2$  temperatures. At the third measurement point the powers of each sensor approached 1 W. It was decided to not exceed a sensor power of 1 W, as this would require that a current higher than 500 mA would be drawn through the thin Kapton HV connector cables. In order not to risk to burn the Kapton tails, higher currents were avoided. Nevertheless the data can be used as an estimation of the thermal runaway. The end of the measurement at a sensor power of about 1 W is compatible with the FE simulation where the thermal runaway is simulated to happen at sensor powers of 1 W. The measured data points are plotted in Figure 7.31 (right) in the representation which is chosen in the Phase-2 Tracker Technical Design report. The difference between sensor temperature and the  $\text{CO}_2$  temperature is plotted on the  $y$ -axis, and the  $\text{CO}_2$  temperature on the  $x$ -axis. With the coarse definition that the thermal runaway appears when the power exceeds 1 W per sensor, the measurement would indicate a thermal runaway at a  $\text{CO}_2$  temperature at  $-29^\circ\text{C}$ . The measured data can be understood as a fiducial thermal runaway in the given thermal setup, which is affected by unavoidable impacts from the ambient. Although thermal impacts from the ambient cannot be eliminated in the real detector, the thermal characteristics might be different in the real detector. The measured data are offset corrected in order to compare with the simulation. As this function corrects for the reference cooling temperature, i.e. the baseline cooling temperature offset, the  $\text{CO}_2$  temperature has to be corrected in this case. The corrected data points are plotted in Figure 7.31 (right). They show a thermal runaway at a  $\text{CO}_2$  temperature slightly lower than  $-25^\circ\text{C}$ .

The non-corrected measured data points include two unavoidable thermal interactions with the ambient which have a big influence on the measurement. These thermal interactions are firstly the temperature offset caused by the heat impact from the ambient, and secondly the heat loss of the front-end hybrids to the ambient. The measurement thus demonstrates how the thermal runaway curve of the 2S modules behaves in this specific test setup. The offset corrected data show how the thermal runaway would look like if the temperature offset could be completely avoided. However, the corrected data are not corrected for the thermal interaction between hybrids and ambient.

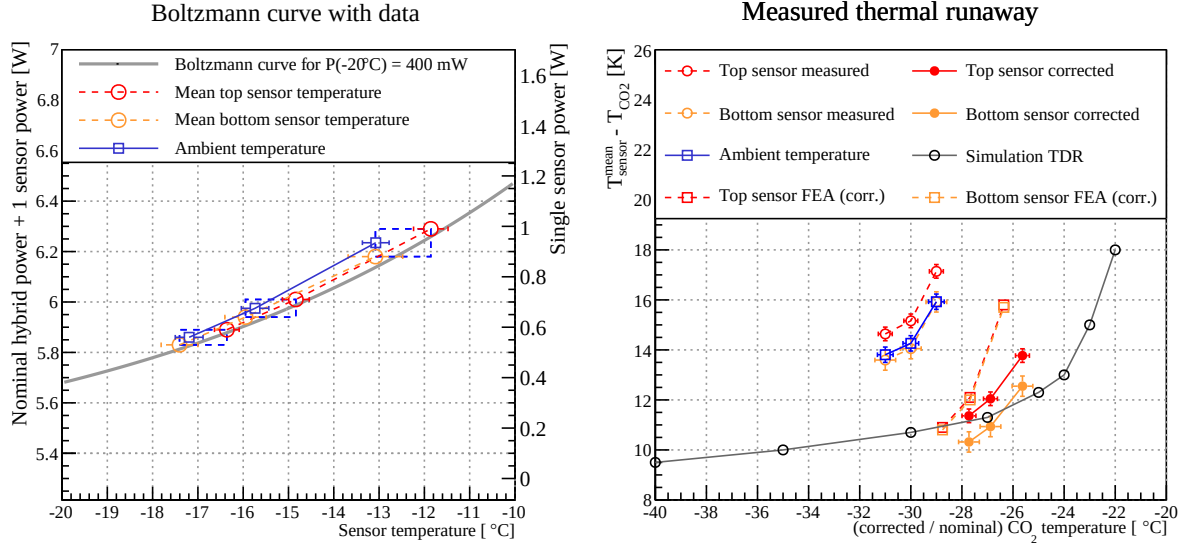


Figure 7.31.: Left: average hybrid power plus the single sensor power (left axis) and single sensor power (right axis) of the top sensor and the bottom sensor in the measurement for the thermal runaway of the 2S module plotted versus the corresponding sensor temperature. The blue boxes indicate which data points belong together. The grey dashed line shows the sensor power expected from Equation 6.23. Right: the temperature difference between the sensors and the CO<sub>2</sub> coolant plotted versus the CO<sub>2</sub> temperature. The thermal runaway simulation from the Technical Design Report is plotted as reference [5].

## 7.11. Thermal Runaway in the FE Simulations and Comparison with the TDR

The simulated thermal runaway curve that was presented in the Technical Design Report [5, 48] is shown in Figure 7.32. The thermal runaway occurs at a CO<sub>2</sub> temperature of about  $-22^\circ\text{C}$  with a good margin to the maximum expected CO<sub>2</sub> temperature of  $T_{\text{CO}_2} = -33^\circ\text{C}$ . Within the scope of this thesis an FE model of the 2S module was developed in parallel as a cross-check of the TDR-model. This model is referred to as the TDR-like model. The main boundary conditions of the TDR-model with an active sensor thickness of  $200 \mu\text{m}$  were implemented into this FE model and the result of the thermal runaway simulation is plotted in Figure 7.32. The thermal runaway occurs at a CO<sub>2</sub> temperature of  $-24^\circ\text{C}$  with a good margin to  $T_{\text{CO}_2} = -33^\circ\text{C}$ . The results of these FE models can be declared as compatible with each other despite the small differences in their outcomes. There still exist differences between the models which can lead to those different results. However it had not been the aim to produce two identical models, but to cross-check the results. The model from the TDR was developed with the ANSYS® Thermal Electric software [84] while the model in this thesis was developed with the COMSOL® Heat Transfer Module. The models are based on the same mechanical model of the 2S module, but modifications were made independently, like e.g. the simplification of the hybrids or the wirebonds. Under these aspects, the important message of the comparison is that the two independently constructed models give fairly the same result.

### 7.11.1. Insert Variants

The thermal FE model described above utilized a cooling insert geometry which is not purely cylindrical, but has an extended contact surface to the cooling pipe with a length of 12 mm, the so-called foot, as seen in Figures 6.8, 7.33 (right), and A.3 and A.4 in Appendix A. Furthermore a thermal conductivity of  $240 \text{ W/m/K}$  was used for the insert material which is the literature value

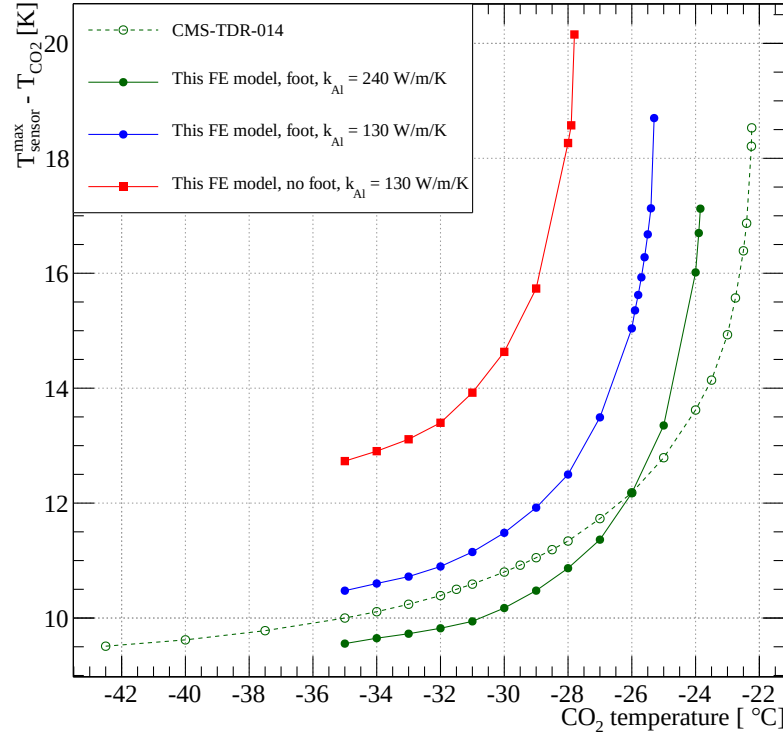


Figure 7.32.: Comparison between the FE simulations developed in this thesis and the one presented in the TDR [5]. The simulations are made for an active sensor thickness of  $200\text{ }\mu\text{m}$  and a reference sensor power of  $P(-20\text{ }^{\circ}\text{C}) = 0.32\text{ W}$ .

for pure aluminum. Most aluminum alloys used for machining have significantly lower thermal conductivities. The purely cylindrical insert design with a thermal conductivity of  $130\text{ W/m/K}$  was used in the thermal test setup measurements and simulations in this thesis. Figure 7.33 shows a comparison of the thermal FE simulations of three different versions of the cooling insert, which differ in the parameters described above. A heat flux of  $1\text{ W}$  was applied to the top surface of the inserts and a  $\text{CO}_2$  heat transfer coefficient of  $5\text{ kW/m}^2/\text{K}$  was applied to the inner pipe walls. The extended cooling contact and the good thermal conductivity lead to a significant better thermal performance than a purely cylindrical design. The insert with the foot and high thermal conductivity has a thermal resistance of  $5.0\text{ K/W}$  which is about  $40\%$  lower compared to the cylindrical insert with the thermal conductivity of  $130\text{ W/m/K}$  which has a thermal resistance of  $7.9\text{ K/W}$ . The insert with  $k_{\text{Al}} = 130\text{ W/m/K}$  and the long cooling pipe contact has a thermal resistance of  $5.7\text{ K}$ , which is in between the other two values. An overview of the results of the thermal simulations of the inserts is given in Table 7.7.

As described in Section 7.6.1, the heat transfer coefficient of the  $\text{CO}_2$  is heat flux dependent. The value of  $5\text{ kW/m}^2/\text{K}$  is a conservative estimate which is chosen in order to be coherent with the FE simulation in the TDR and in order to avoid an overestimation of the capability of the  $\text{CO}_2$  cooling system. In the following, an FE simulation with a heat transfer coefficient (htc) of  $10\text{ kW/m}^2/\text{K}$  and with a heat flux dependent htc is performed for the insert variants 1) and 2) from Figure 7.33. The two reference values for the htc obtained from Ref. [35] are  $5\text{ kW/m}^2/\text{K}$  for a heat flux density  $7.5\text{ kW/m}^2$ , and  $10\text{ kW/m}^2/\text{K}$  for  $29.8\text{ kW/m}^2$ . As a simplified approach, it is assumed that the htc depends linearly on the heat flux density  $\dot{q}$ . However the actual behavior of the htc might follow a more complex function. A linear function for the heat transfer

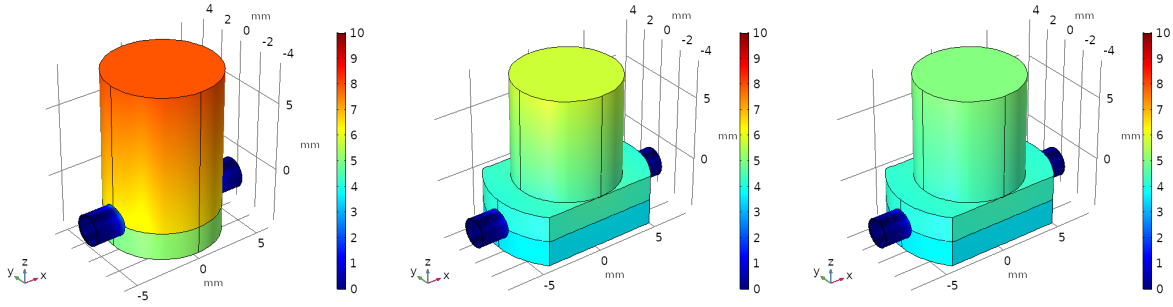


Figure 7.33.: Overview on the insert models implemented into the FE models in this thesis. Left: the purely cylindrical insert with a thermal conductivity of  $k_{Al} = 130 \text{ W/m/K}$  (1). Middle: insert with the 12 mm long foot and  $k_{Al} = 130 \text{ W/m/K}$  (2). Right: insert with the 12 mm long foot and  $k_{Al} = 240 \text{ W/m/K}$  (3).

Table 7.7.: Results of the thermal simulation of the three insert variants shown in Figure 7.33 and the results of the thermal runaway simulation of the 2S 4.0 mm module with  $d_{\text{active}} = 200 \mu\text{m}$  with these insert variants. The thermal conductivity  $k_{Al}$  refers to the thermal conductivity of the aluminum alloy the insert is made of. The thermal resistance  $\alpha_{\text{insert}}$  denotes the thermal resistance between  $\text{CO}_2$  and the top surface of the insert. The indices refer to the indices given in the caption of Figure 7.33.  $\Delta T(-35^\circ\text{C})$  denotes the difference between the maximum sensor temperature and the  $\text{CO}_2$  temperature at a  $\text{CO}_2$  temperature of  $-35^\circ\text{C}$ .  $T_{\text{thermal runaway}}$  denotes the  $\text{CO}_2$  temperature where the thermal runaway occurs, i.e. the highest  $\text{CO}_2$  temperature for which the FE model could be numerically solved.

| Index | $k_{Al}$  | Pipe contact length | $\alpha_{\text{insert}}$ | $\Delta T(-35^\circ\text{C})$ | $T_{\text{thermal runaway}}$ |
|-------|-----------|---------------------|--------------------------|-------------------------------|------------------------------|
| 1     | 130 W/m/K | 8 mm                | 7.9 K/W                  | 12.7 K                        | $-27.8^\circ\text{C}$        |
| 2     | 130 W/m/K | 12 mm               | 5.7 K/W                  | 10.5 K                        | $-25.3^\circ\text{C}$        |
| 3     | 240 W/m/K | 12 mm               | 5.0 K/W                  | 9.6 K                         | $-23.8^\circ\text{C}$        |

coefficients is derived based on these two reference points:

$$\text{htc}_{\text{CO}_2}^{\text{local}} = \frac{1}{4.464 \text{ K}} \cdot \dot{q} + 3.318 \text{ kW/m}^2/\text{K}. \quad (7.37)$$

In the FE model, this relation is applied to the inner walls of the cooling pipe. The htc is then evaluated locally (per boundary mesh) and the thermal simulation of the insert is solved iteratively. As another approach,  $\dot{q}$  in Equation 7.37 is normalized to the inner pipe surface which is embraced by the no-foot and the foot cooling insert, respectively. With the total heat load,  $P_{\text{insert}}$ , the heat transfer coefficients are expressed as

$$\text{htc}_{\text{CO}_2}^{\text{no foot}} = \frac{3318}{\text{m}^2\text{K}} \cdot P_{\text{insert}} + 4461 \text{ W/m}^2/\text{K} \quad (7.38)$$

and

$$\text{htc}_{\text{CO}_2}^{\text{foot}} = \frac{2974}{\text{m}^2\text{K}} \cdot P_{\text{insert}} + 4461 \text{ W/m}^2/\text{K}. \quad (7.39)$$

This value is then applied uniformly to the inner wall of the cooling pipe in the FE model. Figure 7.34 shows the thermal resistances evaluated from the FE simulations. The red and blue shaded areas indicate the simulation results with a constant htc between 5 and  $10 \text{ kW/m}^2/\text{K}$ , for the two insert variants, respectively. In the simulations with the heat flux dependent htc, the thermal resistances are not constant, but decrease for higher power values. The two htc models applied differ slightly for low power values, but level out at approximately the same value for higher power values, which are the ones relevant in the case of the 2S module. For a power of  $P_{\text{insert}} = 1.2 \text{ W}$ , which for five inserts corresponds to a 2S module power of 6 W, the thermal resistance  $\alpha_{\text{insert}}$  is 6.4 K/W for the no-foot insert and 5.0 K/W for the foot insert. These values are 23 % and 14 % lower than the corresponding values in Table 7.7.



In the following the thermal runaway of the 2S modules is discussed with the conservative assumption that the  $\text{CO}_2$  heat transfer coefficient is  $5 \text{ kW/m}^2/\text{K}$ . The non-conservative approach with higher heat transfer coefficients and lower thermal resistances of the cooling inserts is being under study by the time of writing this thesis.

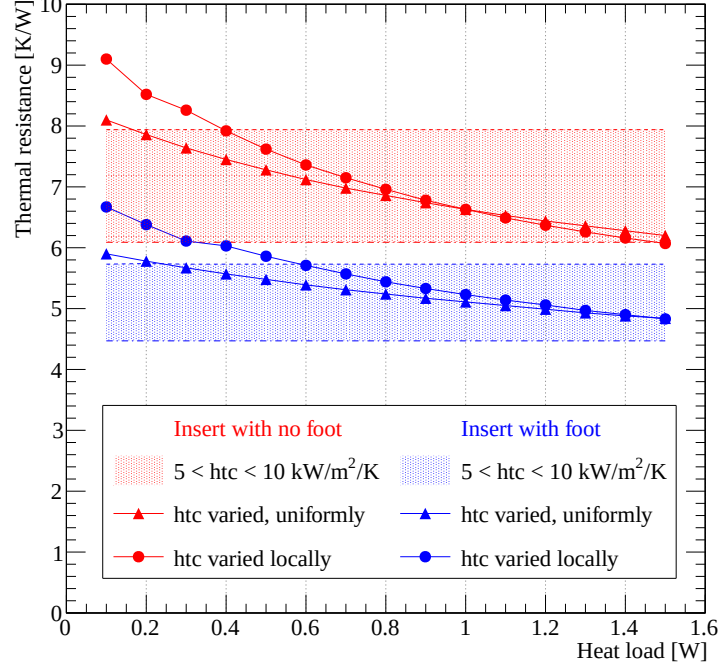


Figure 7.34.: FE simulated thermal resistances of the insert variants 1) (red) and 2) (blue) from Figure 7.33 plotted versus the heat load with various assumptions on the  $\text{CO}_2$  heat transfer coefficient. The shaded areas indicate the region with a constant heat transfer coefficient between 5 and  $10 \text{ kW/m}^2/\text{K}$ , respectively. Triangles refer to a uniform, but heat load dependent htc in the cooling pipe. Circles refer to a heat transfer coefficient which depends on the actual local heat flux density in the cooling pipe.

### 7.11.2. Thermal Runaway with Insert Variants

The simulation of the thermal runaway is repeated with the other two insert models implemented into the FE model. The resulting curves are plotted in Figure 7.32. The difference in the thermal behavior of the sensor temperature is clearly visible. The baseline difference between the top sensor temperature and the  $\text{CO}_2$  temperature at a  $\text{CO}_2$  temperature of  $-35^\circ\text{C}$ ,  $\Delta T(-35^\circ\text{C})$ , varies between 9.6 K and 12.7 K among the three insert models. Also the thermal runaway behavior depends clearly on the insert model. For the insert version with the foot and  $k_{A1} = 130 \text{ W/m/K}$  the thermal runaway occurs at a  $\text{CO}_2$  temperature of  $\approx -25^\circ\text{C}$  and for the cylindrical insert the thermal runaway occurs at a  $\text{CO}_2$  temperature of  $\approx -28^\circ\text{C}$ . With the cylindrical insert the thermal runaway occurs at a  $\text{CO}_2$  temperature which is 4 K lower than in the TDR-like model and 6 K lower than in the TDR-model. The margin to the maximum expected  $\text{CO}_2$  temperature of  $-33^\circ\text{C}$  is only 5 K. The results mentioned above are also listed in Table 7.7.

### 7.11.3. Results with Active Sensor Thickness $d_{\text{active}} = 290 \mu\text{m}$

The thermal runaway simulations with the three different insert models are repeated for the case of an active sensor thickness of  $d_{\text{active}} = 290 \mu\text{m}$ . The results are plotted in Figure 7.35, together with the results from the previous section, and they are listed in Table 7.8. At the lowest simulated  $\text{CO}_2$  temperatures of  $-40^\circ\text{C}$ , at which also the sensors have temperatures far

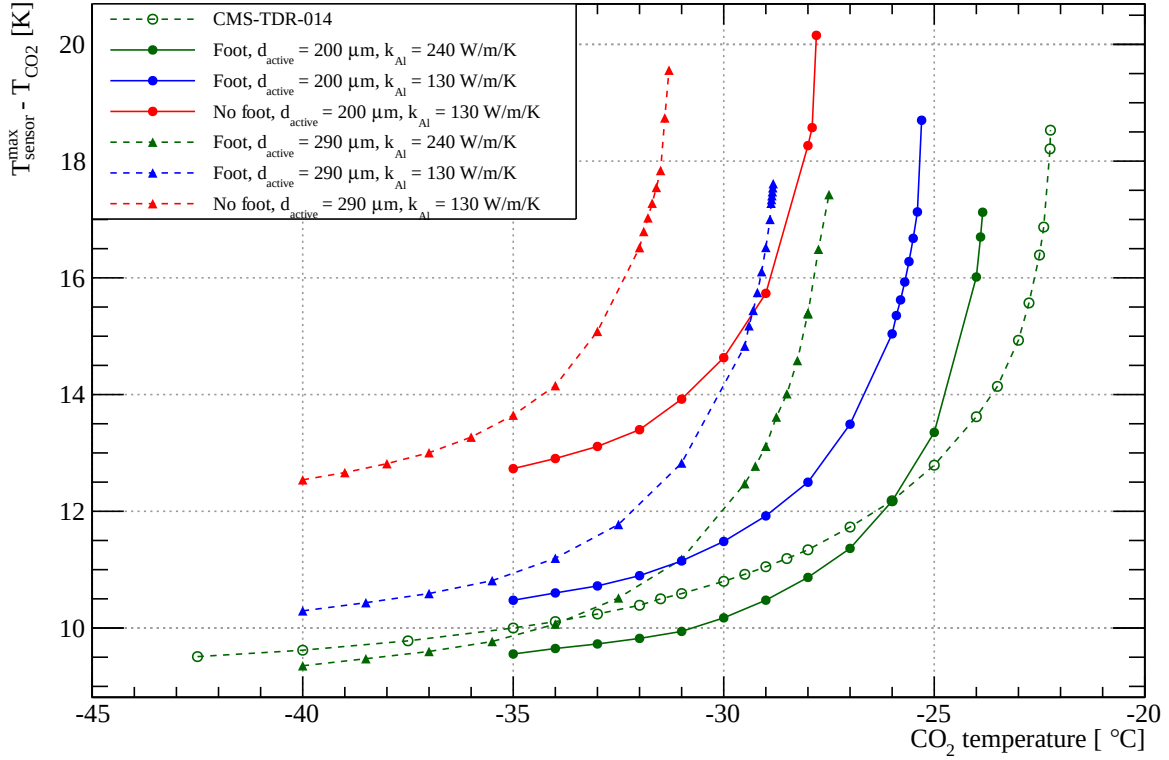


Figure 7.35.: Comparison between the FE simulations developed in this thesis and the one presented in the TDR [5]. The thermal runaway curves for all three insert variants and for the active sensor thicknesses of  $200\ \mu\text{m}$  and  $290\ \mu\text{m}$  are shown.

below  $-20\ ^\circ\text{C}$  and thus have a negligible power, the sensor temperatures level out at the same temperature difference between sensor and  $\text{CO}_2$ , like for the corresponding  $d_{\text{active}} = 200\ \mu\text{m}$  case. The temperature difference  $\Delta T(-35\ ^\circ\text{C})$  is higher than for the  $d_{\text{active}} = 200\ \mu\text{m}$  case, which is expected because of the higher sensor power. In the two models with the foot inserts the maximum sensor temperature is about  $0.5\ \text{K}$  higher than for the  $d_{\text{active}} = 200\ \mu\text{m}$  case. For the model with the cylindrical insert the maximum sensor temperature is about  $1\ \text{K}$  higher than for the  $d_{\text{active}} = 200\ \mu\text{m}$  case. This is due to the worse thermal resistance of the sensor to the cooling system and the non-linear rise of the sensor power with temperature. For all insert variants the thermal runaway occurs at about  $3.5\ \text{K}$  lower  $\text{CO}_2$  temperatures in the  $d_{\text{active}} = 290\ \mu\text{m}$  case than in the corresponding  $d_{\text{active}} = 200\ \mu\text{m}$  case. In particular, the thermal runaway with the cylindrical insert in the  $d_{\text{active}} = 290\ \mu\text{m}$  case occurs at a  $\text{CO}_2$  temperature of  $-31.3\ ^\circ\text{C}$  with a margin of only  $1.7\ \text{K}$  to the maximum expected  $\text{CO}_2$  temperature of  $-33\ ^\circ\text{C}$ . This margin would be unacceptable for the detector design if one requires a margin of  $3\ \text{K}$  for the  $\text{CO}_2$  temperature of the thermal runaway to the maximum expected  $\text{CO}_2$  temperature of  $-33\ ^\circ\text{C}$ . A more detailed discussion of the assumptions on the 2S module power and possible thermal runaway scenarii in TEDDs is presented in the following section.

Table 7.8.: Results of the thermal simulation of the three insert variants shown in Figure 7.33 and the results of the thermal runaway simulation of the 2S 4.0 mm module with these insert variants. The thermal conductivity  $k_{\text{Al}}$  refers to the thermal conductivity of the aluminum alloy the insert is made of. The thermal resistance  $\alpha_{\text{insert}}$  denotes the thermal resistance between  $\text{CO}_2$  and the top surface of the insert. The indices refer to the indices given in the caption of Figure 7.33.  $\Delta T(-35^\circ\text{C})$  denotes the difference between the maximum sensor temperature and the  $\text{CO}_2$  temperature at a  $\text{CO}_2$  temperature of  $-35^\circ\text{C}$ .  $T_{\text{thermal runaway}}$  denotes the  $\text{CO}_2$  temperature where the thermal runaway occurs, i.e. the highest  $\text{CO}_2$  temperature for which the FE model could be numerically solved.

| Index | $k_{\text{Al}}$ | Pipe contact length | $\alpha_{\text{insert}}$ | $\Delta T(-35^\circ\text{C})$ | $T_{\text{thermal runaway}}$ |
|-------|-----------------|---------------------|--------------------------|-------------------------------|------------------------------|
| 1     | 130 W/m/K       | 8 mm                | 7.9 K/W                  | 13.5 K                        | $-31.3^\circ\text{C}$        |
| 2     | 130 W/m/K       | 12 mm               | 5.7 K/W                  | 11.0 K                        | $-28.8^\circ\text{C}$        |
| 3     | 240 W/m/K       | 12 mm               | 5.0 K/W                  | 9.8 K                         | $-27.5^\circ\text{C}$        |

## 7.12. Discussion

This section presents a more detailed discussion and an analysis of the expected thermal runaway of the 2S modules in the TEDD. It is presented how many of the 2S modules are actually affected in dependence on various power and  $\text{CO}_2$  temperature scenarii. The thermal runaway point of the 2S modules depends highly on the 2S sensor power. The estimation of the sensor power is made with assumptions on many parameters, of which the most important ones are listed in Table 7.9 and occur in the following equation

$$P_{\text{sensor}}(T_{\text{sensor}}) = U_{\text{bias}} \Phi \alpha_{\text{damage}} A_{\text{sensor}} d_{\text{sensor, active}} \left( \frac{T_{\text{sensor}}}{T_0} \right)^2 \exp \left( - \frac{\Delta E}{2k_{\text{B}}} \left( \frac{1}{T_{\text{sensor}}} - \frac{1}{T_0} \right) \right), \quad (7.40)$$

i.e. the damage constant  $\alpha_{\text{damage}}$ , the integrated luminosity  $\mathcal{L}_{\text{int}}$ , the particle flux  $\Phi$ , and the active sensor volume  $V_{\text{sensor, active}}$ .

### 7.12.1. Overview on Models in the Collaboration

During modelling the tracker detector and designing the 2S module, the values of nearly all parameters were continuously updated or differed among various working groups in the collaboration. Table 7.9 compares the values of the parameters mentioned above as they were used in three working group projects related to this thesis. The whole CMS Phase-2 Tracker detector was modelled and designed based on tkLayout, a 3D modeling and performance estimation tool for silicon trackers [85, 86]. Nearly all relevant parameters are taken from tkLayout results. However, the values used in the FE simulations for the Technical Design Report [5] differ slightly from the most recent tkLayout values. In the TDR the damage constant  $\alpha_{\text{damage}}$  was estimated 25 % higher than in tkLayout. This was motivated by measurements which indicated that the value of  $\alpha_{\text{damage}}$  is higher for silicon strip sensors than for simple silicon diodes [5]. The TDR value for the maximum flux  $\Phi$  was assumed to  $3.0 \cdot 10^{14} \text{ neq/cm}^2$ . In tkLayout the particle flux is estimated based on FLUKA, a fully integrated particle physics MonteCarlo simulation package [87]. In the recent versions of tkLayout the maximum expected particle flux has changed with respect to the TDR to  $3.7 \cdot 10^{14} \text{ neq/cm}^2$ . However the average particle flux in the TEDDs from tkLayout is 17 % lower than the TDR value. The active sensor volume in tkLayout is assumed to be 5 % lower than in the TDR. This is because in the TDR the full sensor extent in  $x$ - $y$ -direction multiplied by the active sensor thickness is assumed to be the active sensor volume. The values used in this thesis were chosen according to the TDR from 2017 and Ref. [48]. For following discussion the tkLayout model OT616.IT16 is taken as the reference tkLayout model [88]. In the followig, the word 'TEDD' refers only to the TEDD2S subdetector.

### 7.12.2. Thermal Runaway in Dependence on Reference Power

As described in the previous section, many parameters define the estimation of the 2S module sensor power after irradiation. In order to simplify the number of combinations of parameter variations in the long factor in front of the temperature dependent term in Equation 7.40, an effective reference power

$$P_{\text{ref, eff}} = U_{\text{bias}} \Phi \alpha_{\text{damage}} A_{\text{sensor}} d_{\text{sensor, active}}$$

at  $T_0 = -20^\circ\text{C}$  sensor power is introduced. Equation 7.40 then reads

$$P_{\text{sensor}}(T_{\text{sensor}}) = P_{\text{ref, eff}} \cdot \left( \frac{T_{\text{sensor}}}{T_0} \right)^2 \exp \left( - \frac{\Delta E}{2k_B} \left( \frac{1}{T_{\text{sensor}}} - \frac{1}{T_0} \right) \right). \quad (7.41)$$

In the FE simulation of the thermal runaway of the 2S module the value of  $P_{\text{ref, eff}}$  is varied and the evolution of the actual sensor power with increasing  $P_{\text{ref, eff}}$  is studied. This simulation is performed for the maximum expected  $\text{CO}_2$  temperature of  $-33^\circ\text{C}$  and the minimum expected  $\text{CO}_2$  temperature of  $-35^\circ\text{C}$ . A  $\text{CO}_2$  temperature of  $-30^\circ\text{C}$  which represents the 3K safety margin is also simulated. Additionally, a fourth simulation is performed with a  $\text{CO}_2$  temperature of  $-37.5^\circ\text{C}$  in order to evaluate how a hypothetical lower  $\text{CO}_2$  cooling temperature would affect the point of thermal runaway. The simulation is made for the configuration with the purely cylindrical inserts, as they were used for this thesis with a  $\text{CO}_2$  heat transfer coefficient of  $5\text{ kW/m}^2/\text{K}$  (Figure 7.33, left), and for the inserts with the enhanced contact surface to the cooling pipe (Figure 7.33, center) with the same parameters as in the case before. The value of  $5\text{ kW/m}^2/\text{K}$  for the  $\text{CO}_2$  heat transfer coefficient is a conservative assumption. The result of the FE simulations is shown in Figure 7.36, showing the actual power,  $P_{\text{sensor}}$ , of one 2S sensor plotted versus the reference power  $P_{\text{ref, eff}}$ . Figure 7.36 (top) shows the cylindrical insert case and Figure 7.36 (bottom) shows the foot-insert case. The endpoint of the curves defines the limit of the reference power,  $P_{\text{ref, eff}}^{\text{runaway}}$ , at which the sensor enters the thermal runaway, and at which the 2S module would not be operational anymore. For the simulation with the cylindrical insert this lower limit is determined with an accuracy of 10 mW and for the simulation with the foot-insert is determined with an accuracy of 100 mW. For a  $\text{CO}_2$  temperature of  $-35^\circ\text{C}$  ( $-33^\circ\text{C}$ ) the 2S module enters thermal runaway at  $P_{\text{ref, eff}}^{\text{runaway}} = 0.70\text{ W}$  ( $P_{\text{ref, eff}}^{\text{runaway}} = 0.55\text{ W}$ ). At a  $\text{CO}_2$  temperature of  $-30^\circ\text{C}$  the thermal runaway would occur at  $P_{\text{ref, eff}} = 0.40\text{ W}$ . The implementation of the 2S foot-insert improves the situation significantly. The results of the thermal runaway power  $P_{\text{ref, eff}}^{\text{runaway}}$  for the four  $\text{CO}_2$  temperatures and the two insert configurations are summarized in Table 7.10.

Table 7.9.: Overview on the parameters which are relevant for the power consumption of the 2S sensors in the TEDD2S after irradiation as they are used in the detector modeling software tkLayout, in the FE simulations presented in the Technical Design Report, and in this thesis. The values for the active sensor volume assume an active sensor thickness of  $290\text{ }\mu\text{m}$ .

| Parameter                                                                 | tkLayout             | TDR                                 | this work            |
|---------------------------------------------------------------------------|----------------------|-------------------------------------|----------------------|
| Damage constant $\alpha_{\text{damage}}(+20^\circ\text{C}) [\text{A/cm}]$ | $4.28 \cdot 10^{17}$ | $5.35 \cdot 10^{17}$                | $5.35 \cdot 10^{17}$ |
| Int. luminosity $\mathcal{L}_{\text{int}} [\text{fb}^{-1}]$               | 3000                 | 3000 to 4000                        | 3000                 |
| Average particle flux $\langle \Phi \rangle [\text{neq/cm}^2]$            | $2.5 \cdot 10^{14}$  | $2.2 \text{ to } 3.0 \cdot 10^{14}$ | $3.0 \cdot 10^{14}$  |
| Maximum particle flux $\Phi_{\text{max}} [\text{neq/cm}^2]$               | $3.7 \cdot 10^{14}$  | $3.0 \cdot 10^{14}$                 | $3.0 \cdot 10^{14}$  |
| High voltage $ U_{\text{bias}}  [\text{V}]$                               | 600                  | 600 to 800                          | 600                  |
| Active sensor volume $[\text{mm}^3]$                                      | 2671                 | 2806                                | 2806                 |

Table 7.10.: Values of  $P_{\text{ref, eff}}^{\text{runaway}}$ , the reference power at which the 2S module enters thermal runaway for different CO<sub>2</sub> temperatures and two different cooling insert configurations.

| CO <sub>2</sub> temperature | $P_{\text{ref, eff}}^{\text{runaway}}$ [W] (cylindrical insert) | $P_{\text{ref, eff}}^{\text{runaway}}$ [W] (foot-insert) |
|-----------------------------|-----------------------------------------------------------------|----------------------------------------------------------|
| −30 °C                      | 0.40                                                            | 0.6                                                      |
| −33 °C                      | 0.55                                                            | 0.8                                                      |
| −35 °C                      | 0.70                                                            | 1.0                                                      |
| −37.5 °C                    | 0.87                                                            | 1.4                                                      |

### 7.12.3. Possible HL-LHC Scenarii

Figure 7.37 shows the schematical drawing of one quadrant of the Phase-2 Tracker in the  $r$ - $z$ -plane, with a superimposed map of the particle flux in the TEDD2S subdetector after an integrated luminosity of  $3000 \text{ fb}^{-1}$ . The same map is shown as a standalone plot in Figure 7.38. The particle flux and thus the radiation damage of the modules is dominated by the position in the pseudo-rapidity  $|\eta|$  rather than by the radial distance to the interaction point. The radiation damage is the highest for the 2S modules in the forward TEDD in regions with high  $|\eta|$ . The highest particle flux of  $3.7 \cdot 10^{14} \text{ neq/cm}^2$  is expected in Ring 11 in the fifth double-disk ( $r \approx 700 \text{ mm}$  and  $z \approx 2650 \text{ mm}$ ). The lowest particle flux of  $1.9 \cdot 10^{14} \text{ neq/cm}^2$  is expected in Ring 15 in the first double-disk ( $r \approx 1050 \text{ mm}$  and  $z \approx 1300 \text{ mm}$ ).

With Equation 7.40 the expected reference power at  $-20^\circ\text{C}$  of the 2S silicon sensors can be calculated. At this point the choice of the parameters is the critical point. As still no baseline parameter set is defined in the collaboration, four different scenarii are introduced for the purpose of this thesis. The scenarii are defined such that realistic variations of the most important quantities which influence the sensor power are covered, namely the radiation damage constant  $\alpha_{\text{damage}}$ , the high voltage  $|U_{\text{bias}}|$ , and the integrated luminosity  $\mathcal{L}_{\text{int}}$ . An overview of the four scenarii is given in Table 7.11. The calculated reference power for the 2S module sensors after full irradiation differs by a factor of

$$\frac{\alpha_{\text{damage, tkLayout-scenario}}}{\alpha_{\text{damage, Scenario 1}}} \cdot \frac{|U_{\text{bias, Scenario 2 a)}}{|U_{\text{bias, Scenario 1}}|} \cdot \frac{\mathcal{L}_{\text{int, Scenario 2 b)}}{\mathcal{L}_{\text{int, Scenario 2 a)}} = \frac{5.35}{4.28} \cdot \frac{800}{600} \cdot \frac{4000}{3000} = 2.22$$

between the tkLayout-scenario and Scenario 2 b). This is one of the biggest uncertainties of the thermal design of the TEDD2S subdetector. The fixed definition of baseline values for these quantities will be an important issue in the collaboration as then the design parameters of the detector are clear. A map with the single sensor reference power values for Scenario 1 is shown in Figure 7.39. This map was calculated using the particle flux values shown in Figure 7.38. The other values are taken from the last column in Table 7.9. The reference power values per sensor range from 0.54 W in the region with the highest particle flux to 0.28 W in the region with the lowest particle flux. The maps of the reference power values for the other three scenarii are shown in Figure F.1 in Appendix F. Figure F.2 in Appendix F shows a map of the number of 2S modules in the TEDD. Overall 1596 2S modules are installed in one TEDD. Rings with lower radii contain less 2S modules than rings with higher radii. With the number of modules given, histograms of the expected reference powers can be created. The reference power histograms for the four scenarii in Table 7.11 are shown in Figure 7.40. With the information on the thermal runaway power  $P_{\text{ref, eff}}^{\text{runaway}}$  from the previous Section 7.12.2 for different CO<sub>2</sub> temperatures and with the sensor power estimation in the TEDD, it is possible to predict the thermal runaway of the TEDD 2S modules. In the following the thermal runaway of the 2S modules is discussed with respect to integrated luminosity, the four scenarii defined above and CO<sub>2</sub> temperature.

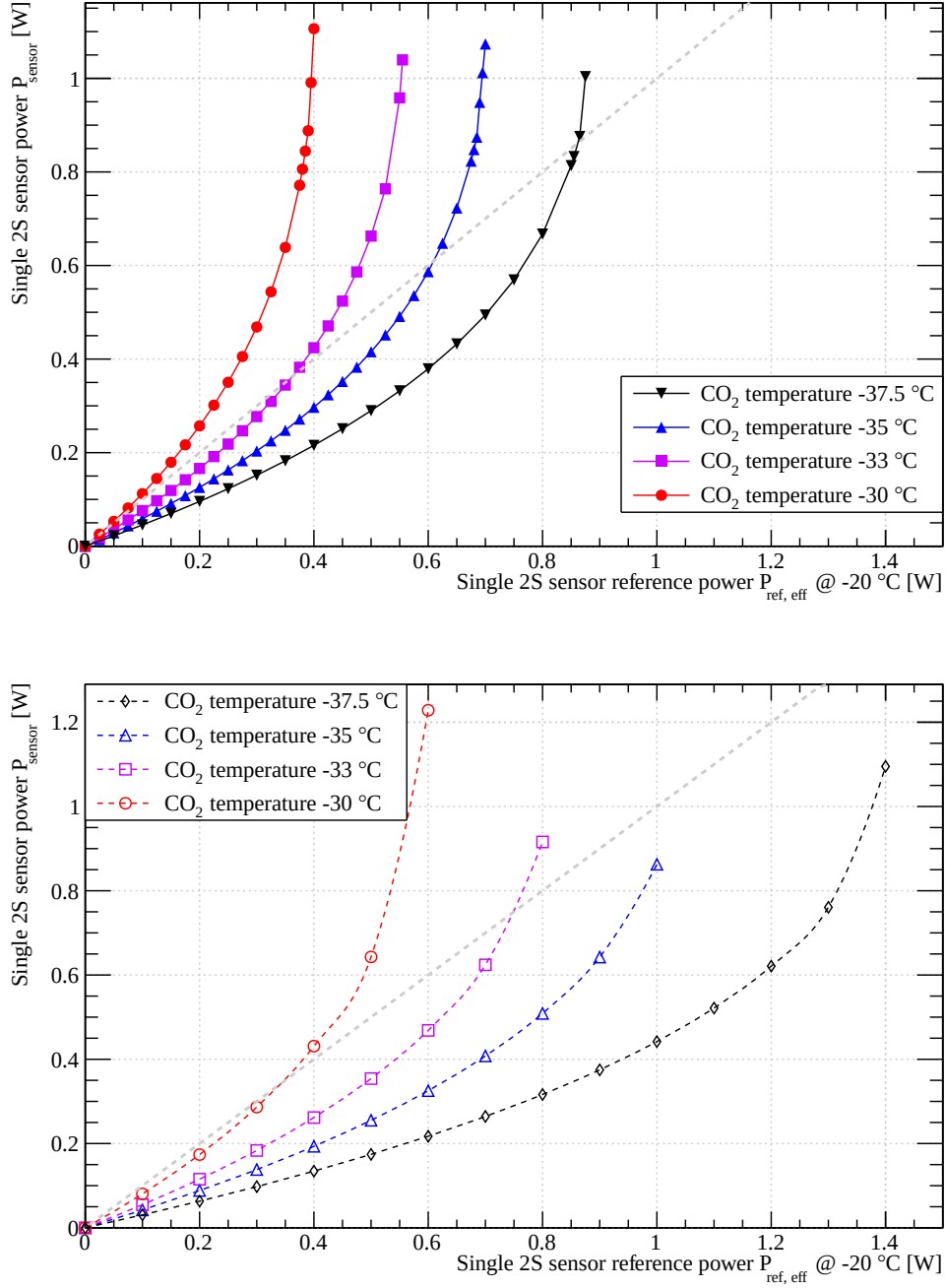


Figure 7.36.: FE simulated power values of the 2S module for different  $\text{CO}_2$  temperatures with a sweep of the reference power  $P_{\text{ref, eff}}(-20\text{ }^{\circ}\text{C})$ , as defined in Equation 7.41. The top plot shows the configuration with the purely cylindrical insert without foot and the bottom plot the configuration with the insert with the enhanced contact surface to the cooling pipe, the 'foot'. With higher  $P_{\text{ref, eff}}(-20\text{ }^{\circ}\text{C})$  the self-heating of the sensors increases, leading eventually to thermal runaway. The gray dashed line shows the function  $P_{\text{sensor}} = P_{\text{ref, eff}}$ .

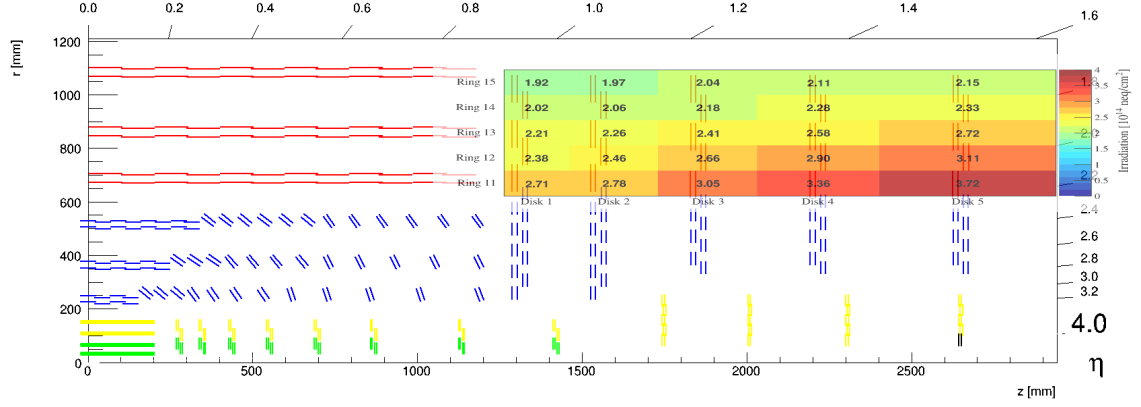


Figure 7.37.: Schematic drawing of one quadrant of the Phase-2 Tracker in the  $r$ - $z$ -plane with a map of the particle flux in the TEDD2S subdetector superimposed.

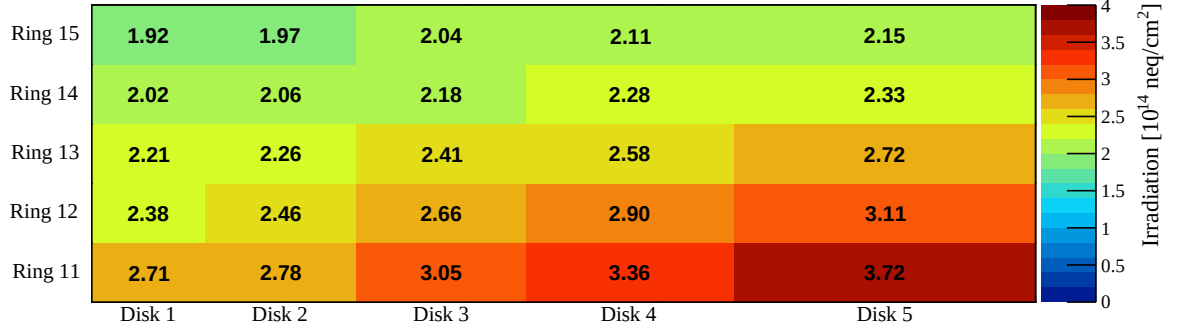


Figure 7.38.: Map of the particle flux in the TEDD2S after  $3000 \text{ fb}^{-1}$  taken from Ref. [88]. The nomenclature for the TEDD2S rings starts from 11 taking into account the ten TEDDPS rings at the inner radii.

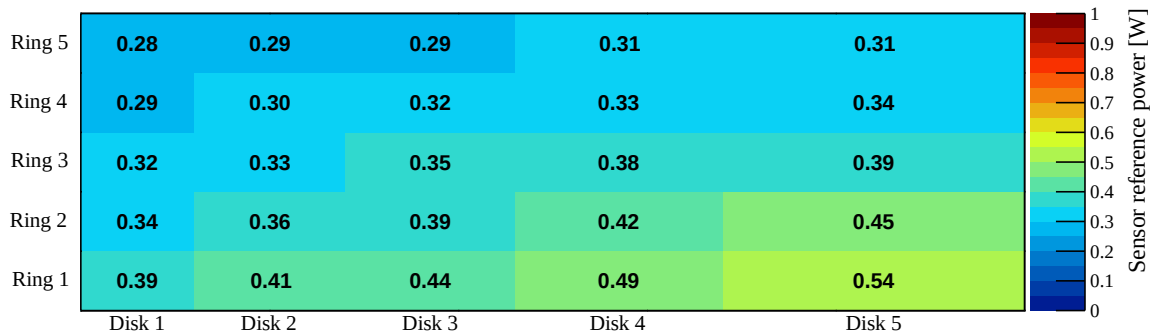


Figure 7.39.: Power consumption of a single 2S module sensor in the TEDD at the reference temperature of  $-20^\circ\text{C}$  for the Scenario 1 in Table 7.11.

The analysis is based on the following principle. The reference power,  $P_{\text{ref, eff}}$ , of a 2S sensor is calculated in a certain scenario in dependence on the integrated luminosity. The module position in the TEDD and the corresponding irradiation is taken into account, as e.g. indicated in Figure 7.39. Once the value of  $P_{\text{ref, eff}}$  has exceeded the value of  $P_{\text{ref, eff}}^{\text{runaway}}$  for a given  $\text{CO}_2$  temperature, the sensor enters thermal runaway and the module is inoperational. In the following this will

## 2S Sensor Power in one TEDD @ -20 °C

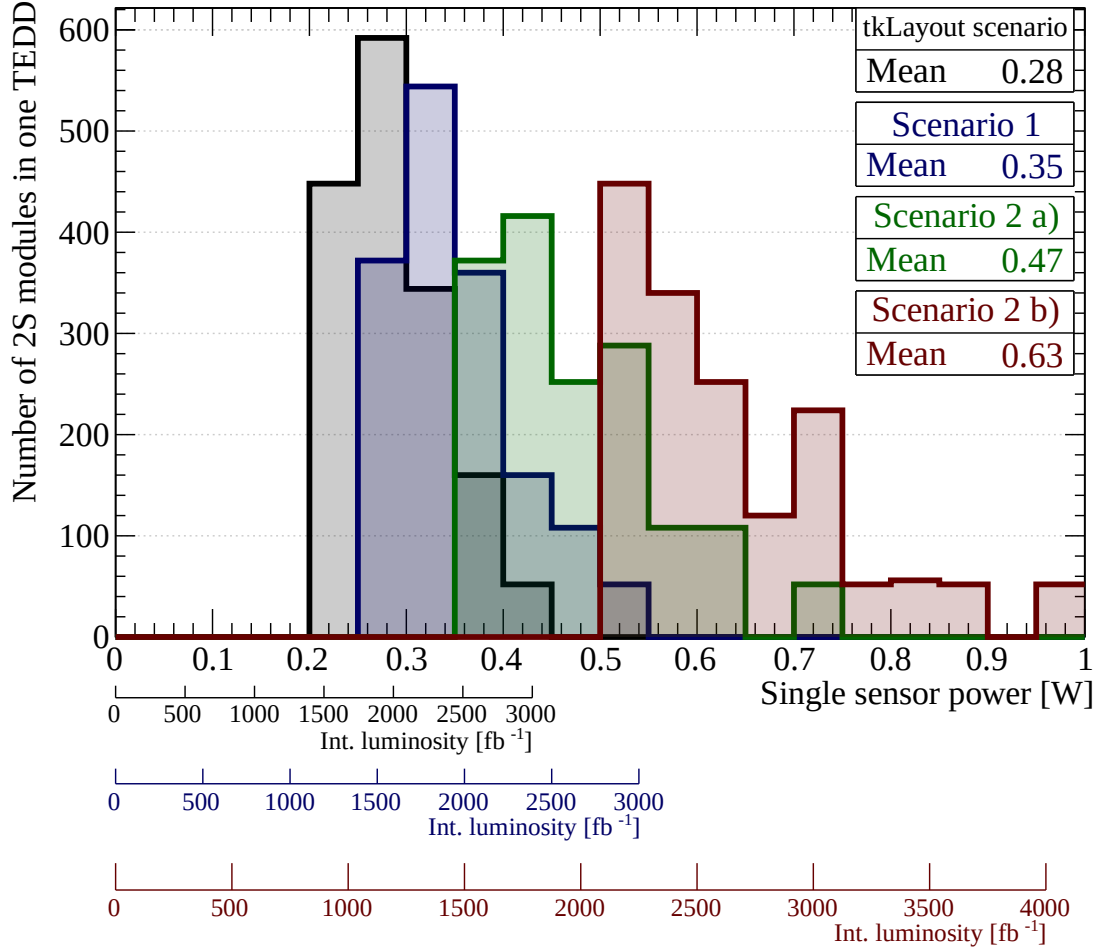


Figure 7.40.: Expected reference powers for the four scenarii defined in Table 7.11. The lower three  $x$ -axes shows the integrated luminosity for the modules which experience the highest particle flux, for the tkLayout-scenario and Scenario 1, and Scenario 2 b). The end point of each axis is defined by the reference power the modules with the highest particle flux will have after the final integrated luminosity.

be called 'lost module'. The integrated luminosity,  $\mathcal{L}_{\text{int}}^{\text{runaway}}$ , at which the module is lost, is calculated for each position in the TEDD. This value depends directly on the chosen scenario, the position in the TEDD, and the  $\text{CO}_2$  temperature. Figure 7.41 shows a map of the distribution of  $\mathcal{L}_{\text{int}}^{\text{runaway}}$  in the TEDD for Scenario 1 and a  $\text{CO}_2$  temperature of  $-33^\circ\text{C}$ . This is a possibly realistic scenario for the operation of the Phase-2 Tracker at HL-LHC. In this scenario the first modules would be lost in Disk 5 Ring 11 after  $\simeq 3100\text{fb}^{-1}$ . This is a higher integrated luminosity than the original design value of HL-LHC. The next module position lost is in Disk 4 Ring 11 after  $\simeq 3400\text{fb}^{-1}$ . Up to an integrated luminosity of  $4000\text{fb}^{-1}$  three other module positions are lost. Taking into account the number of 2S modules per ring (Figure F.2 in Appendix F) 268 of 1596 2S modules are lost per TEDD after an integrated luminosity of  $4000\text{fb}^{-1}$ . This corresponds to 17%.



Table 7.11.: Four scenarii of parameter sets defined in this thesis for the estimation of the silicon sensor power. The scenarii differ in the value for the damage constant  $\alpha_{\text{damage}}$ , the bias voltage  $U_{\text{bias}}$ , and the integrated luminosity  $\mathcal{L}_{\text{int}}$ .

| Scenario      | $\alpha_{\text{damage}}$          | $ U_{\text{bias}} $ | $\mathcal{L}_{\text{int}}$ | Description                                                                             |
|---------------|-----------------------------------|---------------------|----------------------------|-----------------------------------------------------------------------------------------|
| tkLayout      | $4.28 \cdot 10^{17} \text{ A/cm}$ | 600 V               | $3000 \text{ fb}^{-1}$     | Parameters as assumed in detector modeling software tkLayout                            |
| Scenario 1    | $5.35 \cdot 10^{17} \text{ A/cm}$ | 600 V               | $3000 \text{ fb}^{-1}$     | 25 % higher radiation damage constant for silicon strip sensors than for silicon diodes |
| Scenario 2 a) | $5.35 \cdot 10^{17} \text{ A/cm}$ | 800 V               | $3000 \text{ fb}^{-1}$     | High voltage increased by 33 %, possibly necessary for full depletion                   |
| Scenario 2 b) | $5.35 \cdot 10^{17} \text{ A/cm}$ | 800 V               | $4000 \text{ fb}^{-1}$     | Like Scenario 2 a), but with $\mathcal{L}_{\text{int}} = 4000 \text{ fb}^{-1}$          |

### Estimation of Thermal Runaway with the Cylindrical Insert

The simulated number of operational 2S modules in the TEDD2S subdetector at  $\text{CO}_2$  temperatures of  $-30^\circ\text{C}$ ,  $-33^\circ\text{C}$ ,  $-35^\circ\text{C}$ , and  $-37.5^\circ\text{C}$  for three different scenarii is plotted in Figure 7.42. These FE simulations show the case with the purely cylindrical insert. For the tkLayout-Scenario the operation of the 2S modules in the TEDD would be possible up to an integrated luminosity of  $4000 \text{ fb}^{-1}$  for the  $\text{CO}_2$  temperatures of  $-33^\circ\text{C}$  or lower, except for a small loss of 52 modules at  $-33^\circ\text{C}$  after about  $3800 \text{ fb}^{-1}$ . At  $-30^\circ\text{C}$  the loss of modules starts at  $2800 \text{ fb}^{-1}$ , and after  $4000 \text{ fb}^{-1}$  about 35 % of the 2S modules would be lost.

For Scenario 1 the operation of the 2S modules would be possible until  $4000 \text{ fb}^{-1}$  for a  $\text{CO}_2$  temperature of  $-35^\circ\text{C}$ , except for a small loss of 52 modules after  $3900 \text{ fb}^{-1}$  at  $-35^\circ\text{C}$ . At a  $\text{CO}_2$  temperature of  $-30^\circ\text{C}$  the loss of 2S modules starts at  $2200 \text{ fb}^{-1}$  and 77 % of the 2S modules in the TEDDs (1224 per TEDD) will be lost after  $4000 \text{ fb}^{-1}$ . For Scenario 2 at a  $\text{CO}_2$  temperature of  $-35^\circ\text{C}$  ( $-33^\circ\text{C}$ ), the loss of 2S modules starts after  $2900 \text{ fb}^{-1}$  ( $2300 \text{ fb}^{-1}$ ). After  $4000 \text{ fb}^{-1}$ , 21 % (72 %) of the modules would be lost. At a  $\text{CO}_2$  temperature of  $-30^\circ\text{C}$  all 2S modules in the TEDD would be lost already after  $4000 \text{ fb}^{-1}$ .

The detailed maps of thermal runaway corresponding to Figure 7.42 are shown in Figures F.3 to F.5 in Appendix F.

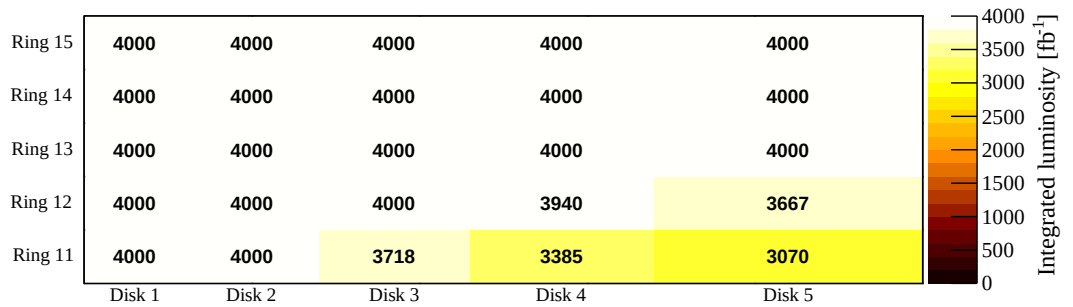


Figure 7.41.: Map of the integrated luminosity,  $\mathcal{L}_{\text{int}}^{\text{runaway}}$ , in the TEDD for Scenario 1 and a  $\text{CO}_2$  temperature of  $-33^\circ\text{C}$ . The numbers written at the 2S module position denote  $\mathcal{L}_{\text{int}}^{\text{runaway}}$  (in units of  $\text{fb}^{-1}$ ) of the 2S modules at the specific position.

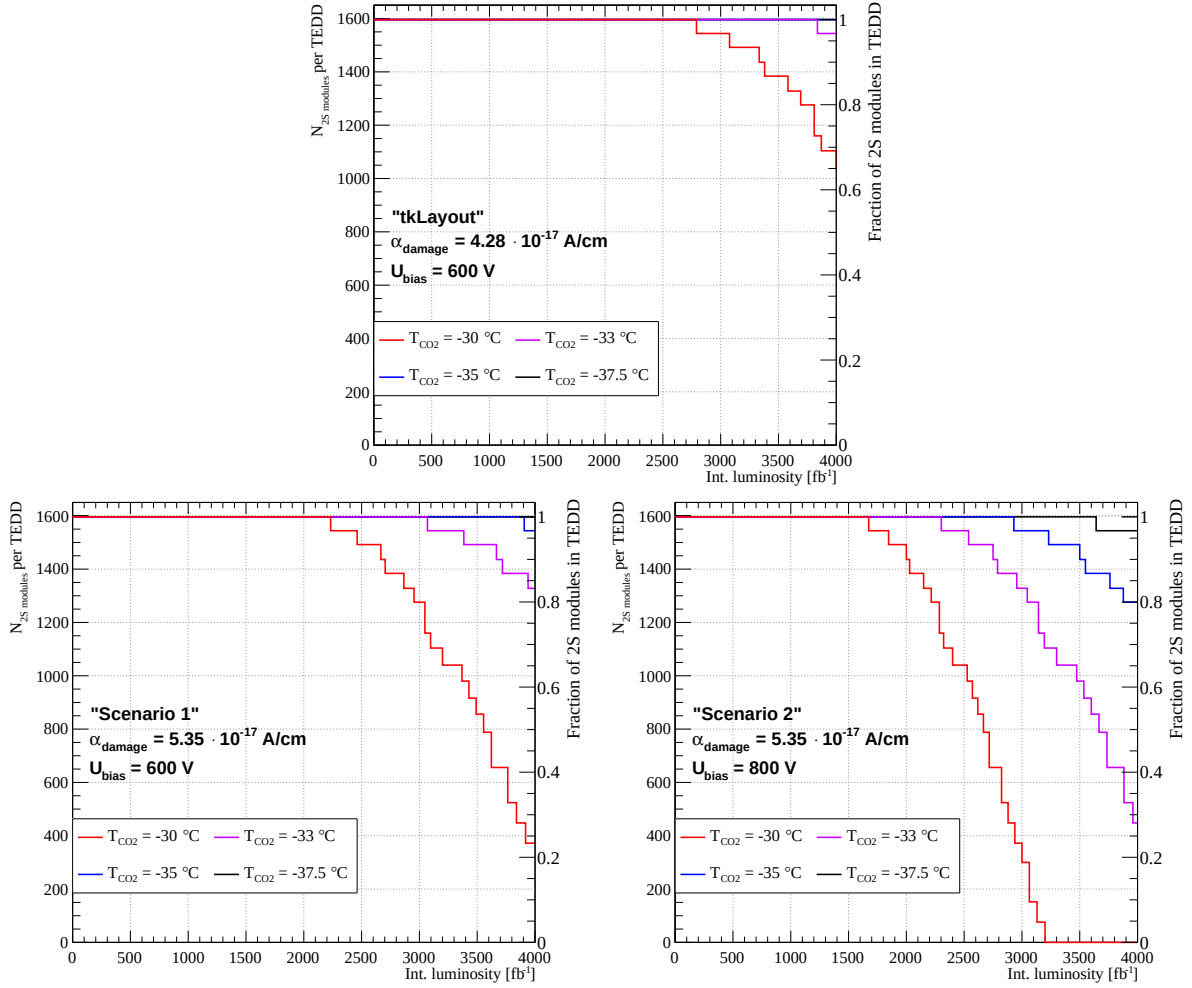


Figure 7.42.: Number of operational modules in one TEDD2S subdetector plotted against the integrated luminosity for four different CO<sub>2</sub> temperatures in the tkLayout-Scenario (top), Scenario 1 (bottom left), and Scenario 2 (bottom right). The simulations are made with the purely cylindrical cooling inserts. Modules are lost because they enter thermal runaway.

### Estimation of Thermal Runaway with the Foot-Insert

In the FE simulation, the situation in terms of thermal runaway is improved significantly with the foot-insert. Like before, the same heat transfer coefficient of  $5 \text{ kW/m}^2/\text{K}$  was used for the  $\text{CO}_2$  in the simulation. In the tkLayout-Scenario no module enters thermal runaway before  $4000 \text{ fb}^{-1}$ . For the Scenario 1, modules are lost only for a  $\text{CO}_2$  temperature of  $-30^\circ\text{C}$ . Here thermal runaway starts after  $3300 \text{ fb}^{-1}$  and 6 % of the 2S modules in the TEDD would be lost. The same situation would arise in Scenario 2 at a  $\text{CO}_2$  temperature of  $-33^\circ\text{C}$  (for this analysis the thermal runaway power  $P_{\text{ref, eff}}^{\text{runaway}}$  is only determined with an accuracy of  $0.1 \text{ W}$ , leading to the exact same result here). At a  $\text{CO}_2$  temperature of  $-30^\circ\text{C}$  in Scenario 2 the thermal runaway would start  $2500 \text{ fb}^{-1}$  for the first modules. After  $4000 \text{ fb}^{-1}$ , the fraction of lost 2S modules would 46 %.

The detailed maps of thermal runaway corresponding to Figure 7.43 are shown in Figures F.6 to F.8 in Appendix F.

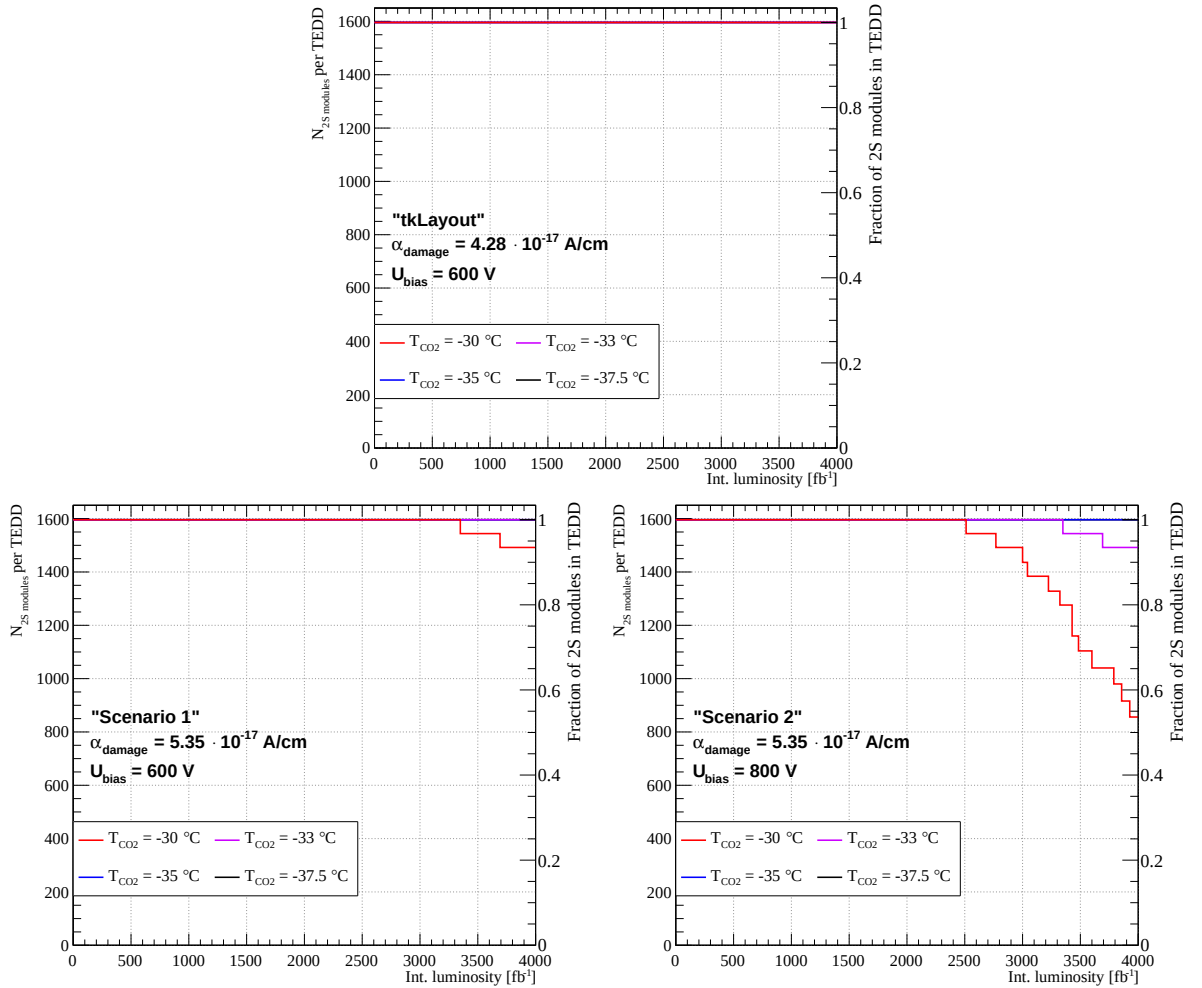


Figure 7.43.: Number of operational modules in one TEDD2S subdetector plotted against the integrated luminosity for four different  $\text{CO}_2$  temperatures in the tkLayout-Scenario (top), Scenario 1 (bottom left), and Scenario 2 (bottom right). The simulations are made with the cooling inserts with the foot. Modules are lost because they enter thermal runaway.

### 7.13. Comment of the Thermal Layout of the 2S Module

The 2S module is thermally quite well designed. The thermal paths of the sensor power and the hybrid power towards the module mounting point are distinct, except for the thermal bridge from FEH to sensors through the wirebonds. This design is also quite elegant as only few assembly steps are needed for the 2S module. With the distinct thermal paths the temperature gradients of the sensors to the mounting points is nearly independent from the hybrid power. However, the same base temperature is defined at the points where the heat flows starts sharing a common thermal path - which is right at the mounting points. This base temperature has direct impact on the sensor temperature and thus on its power production. The temperature difference between the mounting points and the cooling liquid is then fully determined by the thermal resistance of the cooling structure and the total heat flux from the 2S module. The thermal resistance involves the screw connection of the 2S modules, the cooling insert, the length and glue thickness of the contact to the cooling pipe, the cooling pipe itself, and the transition to the CO<sub>2</sub>. These components and thermal interfaces can be considered as the bottleneck of the thermal performance of the 2S module. These interfaces are more or less related to the mechanical design of the detector support structure, but not to the 2S module design itself. CMS has chosen to follow the concept of individual 2S modules which are individually mounted to the support structure with screws, but not glued. Under this aspect the current solution for the 2S modules has still to be considered as one of the best possible, despite of the relative critical thermal performance estimated. The material budget of the module and the support structure is kept as low as possible and the 2S module assembly can be kept as simple as possible. More advanced 2S module designs which somehow would make separate thermal paths of the hybrid power and the sensor power possible would require more complicated module designs, or even totally different module concepts.

A very critical parameter for the power consumption of the 2S sensors is the high voltage  $U_{\text{bias}}$ . Current estimates expect that the 2S sensor will be fully operational in terms of sensor depletion at a bias voltage of 600 V for the whole HL-LHC period [89]. The 800 V scenario can probably be avoided. This would significantly help to avoid thermal runaway, as described in the previous section for Scenario 1.

The temperature gradient between coolant and 2S module is directly affected by the total heat flux defined by all components on the 2S module. The heat flux produced by the low-voltage power components is the dominating part of the overall 2S module. The fractions of the overall 2S module are approximately  $5.4 \text{ W} / 6.4 \text{ W} = 84 \%$  low voltage power, and  $1.0 \text{ W} / 6.4 \text{ W} = 16 \%$  sensor power after  $3000 \text{ fb}^{-1}$  and  $-20^\circ\text{C}$ . Assuming an approximate overall efficiency of  $0.8 \cdot 0.8 = 0.64$  for the DC-DC converters, the low-voltage ( $= 5.4 \text{ W}$ ) is composed of  $1.8 \text{ W}$  because of the DC-DC converters, and  $3.6 \text{ W}$  from the low-voltage components powered by the DC-DC converters. That means that about a third of the low-voltage power and about a fourth of the full 2S module power is produced by the DC-DC converters. In terms of thermal performance, this additional contribution of the DC-DC converters is disadvantageous as it leads to higher thermal gradients in the detector support structure, and thus to higher sensor temperatures. However, the on-module DC-DC converters have also advantageous properties since they make a lower overall power consumption of the detector possible. They also make it possible to use thinner current cables in order to reduce the material budget of the detector. For this reason they can be still considered as an elegant choice for the 2S module design.

## 8. Thermal Characterization of the Phase-1 BPIX Detector

The CMS Phase-1 Pixel Detector is cooled with an evaporative CO<sub>2</sub> cooling system. In the two-phase state a falling temperature gradient occurs along a cooling loop because of the pressure drop in the pipe. Hence, the temperatures of the pixel modules vary depending on their position on the cooling loop. As the leakage current of the silicon sensors of the pixel modules is temperature dependent, it varies also depending on the position on the cooling loop. The temperature distribution on the cooling loop was measured with a thermal mock-up of BPIX Layer 2. The observed leakage current distribution in the real BPIX detector could be explained with the temperature distribution on the CO<sub>2</sub> cooling pipes.

This chapter presents the setup of the thermal mock-up, the measurements and results, and the comparison with the leakage currents in the real detector. The temperature distribution is measured in dependence of the CO<sub>2</sub> mass flow and the module power.

### 8.1. The BPIX Mock-up

The BPIX thermal mock-up is a BPIX Layer 2 half-shell which can be used for testing the thermal behavior of the BPIX detector. In terms of mechanics, i.e. cooling pipes and carbon fiber ladders, it is identical to the real existing Phase-1 BPIX half-shells, which are installed in CMS. It consists of 14 ladders and two cooling loops. The mock-up is equipped with 112 thermal dummy pixel modules with temperature sensors and a powering functionality. The setup is located in the BPIX clean room at LHC Point 5 in Cessy, France. The mock-up is installed in a freezer and connected to a LUKASZ CO<sub>2</sub> cooling system [90]. The following sections describe the features of the mock-up in more detail.

#### 8.1.1. History of the Mock-up

Although the BPIX thermal mock-up is a Phase-1 Pixel Detector project, the final commissioning of the setup and the measurements were performed in 2018, about one and a half year after the installation of the Phase-1 Pixel Detector into CMS. The mechanics of the BPIX thermal mock-up was originally built as a spare for the existing Layer 2 half-shells. Like for the whole BPIX detector, the pipe structure was manufactured at the University of Zurich, Switzerland, and the production and gluing of the carbon fiber ladders was performed at Paul-Scherrer-Institut, Villigen, Switzerland. As at Karlsruhe Institute of Technology (KIT), Germany, material from the BPIX module production was left over, it was decided to construct a thermal mock-up out of the existing Layer 2 half-shell. The Layer 2 mechanics was shipped to KIT and equipped with thermal dummy modules built out of the left-over components. The Master thesis by Johanna Renner [91] describes the characterization of the dummy modules and the installation of the modules into the mock-up. The mock-up was then transported to CERN LHC Point 5 in Cessy, France, where the final commissioning of the mock-up took place, which was done within the scope of this thesis. The final commissioning comprised the electrical connection of the power supplies, the software development for the temperature read-out, the installation of the preheating section, and the start of the operation with the cooling system. A photograph of the fully commissioned setup in the BPIX clean room at Point 5 is shown in Figure 8.1.

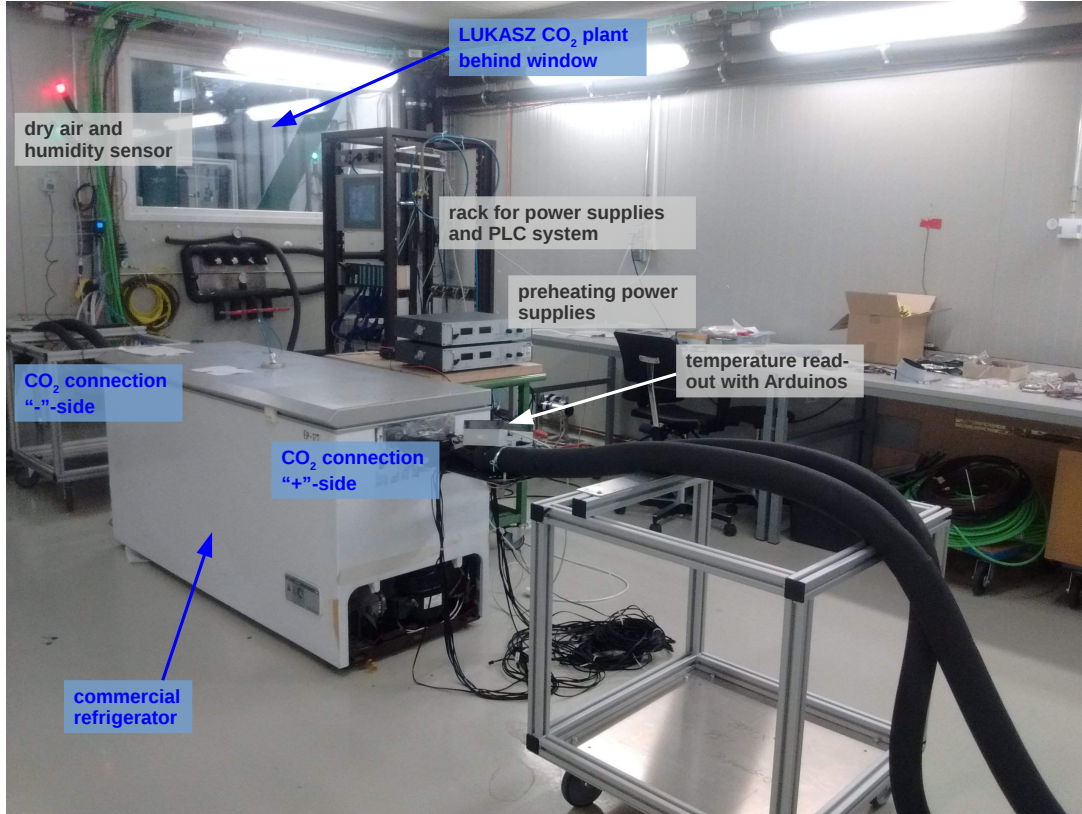


Figure 8.1.: Photograph of the setup in the BPIX clean room at Point 5 in Cessy in summer 2018. The BPIX mock-up is installed in the commercial refrigerator.

### 8.1.2. Mechanical Support and Mounting in a Freezer

For stability, transport and handling reasons the mock-up is mounted in an ITEM support frame which also provides mounting points and patch panels for the power cable connections and the temperature sensor wires. As the nominal CO<sub>2</sub> temperature of the BPIX cooling system is  $-22^{\circ}\text{C}$ , the tests with the mock-up cannot be performed at room temperature, but have to take place in a controlled and cooled ambient. Therefore, the mock-up is installed in a commercial freezer which can be controlled to produce stable temperatures at  $-16^{\circ}\text{C}$  and lower. When turned on and controlled to the maximum temperature, the refrigerator produces ambient temperatures of about  $-16 \pm 1^{\circ}\text{C}$ , which in the following is used as the standard ambient condition in the measurement series. The freezer is flooded with dry air and the relative humidity and the ambient temperature are monitored.

### 8.1.3. LUKASZ CO<sub>2</sub> Plant

The mock-up was connected to a LUKASZ (Light Use Cooling Appliance for Surface Zones) CO<sub>2</sub> cooling system at Point 5. The LUKASZ is based on the Integrated 2-Phase Accumulator Controlled Loop concept [36]. The system provides two evaporative CO<sub>2</sub> cooling branches which each serve local user boxes, the so-called master and slave box, which in this thesis are referred to as plus-loop and minus-loop, respectively. Both loops are operated at a common temperature, which is set centrally in the accumulator volume in the LUKASZ plant. The LUKASZ system is designed for operating temperatures between  $-30^{\circ}\text{C}$  and  $+18^{\circ}\text{C}$ . The total cooling power depends on the CO<sub>2</sub> temperature and is higher than 2 kW. The CO<sub>2</sub> mass flow can be set individually for each cooling loop. The system is capable to provide a maximum CO<sub>2</sub> flow of

10 g/s per cooling loop. However the actual possible maximum flow depends also on the connected setup. Because of different pipe lengths and characteristics, different positions in the room, etc. the cooling loops do not behave exactly identically, but show slight differences in their behavior.

#### 8.1.4. BPIX Mock-up Mechanics

A schematical view of the mock-up is shown Figure 8.2. It contains 14 carbon fiber ladders, of which seven are facing to the inner side, where the beam line would be (Inner Ladders I-1 to I-7), and seven are facing to the outside (Outer Ladders O-1 to O-7). Inner and outer ladders are mounted alternately. Two cooling loops run through the mock-up, where one loop is connected from the positive  $z$ -side (plus-loop) and the other one from the negative  $z$ -side (minus-loop). The plus-loop then serves the seven ladders from I-1 to I-4, and the minus-loop serves six ladders O-7 to I-5. The ladder O-4 is served by both cooling loops. Both cooling loops leave the detector after having served ladder O-4. While connecting the mock-up to the CO<sub>2</sub> system at Point 5, a technical drawing of the connection scheme was misinterpreted. Therefore, the CO<sub>2</sub> flow direction in the cooling loops of the real BPIX detector is in the opposite direction with respect to the cooling loop scheme explained above. Figure 8.2 shows the CO<sub>2</sub> flow direction as it was for all measurements with the mock-up. However, the measurements made with this configuration are still sufficiently meaningful as the effects observed do not depend on the flow direction of the cooling liquid. It is possible to transform and analyse the measured data in a way that a comparison to real BPIX detector data is possible without significantly increased uncertainties.

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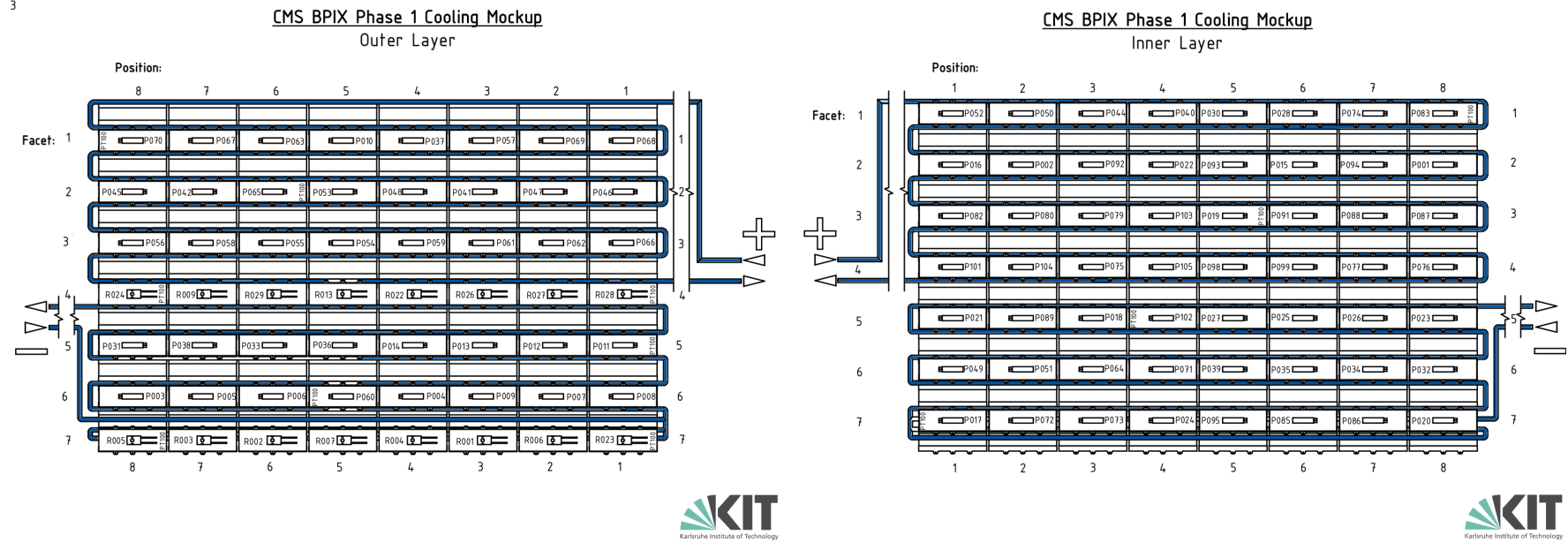


Figure 8.2.: Module positions and cooling pipe routing (colored blue) in the BPIX mock-up Outer (left) and Inner (right) layer. The heating resistor modules are placed on Outer Ladder 1 and 4. Arrows indicate the inlet and outlet of the coolant. [44]



### 8.1.5. Thermal Dummy Modules

Each ladder is equipped with eight thermal dummy modules, resulting in a sum of 112 modules for the entire mock-up. A photograph of examples of dummy modules is shown in Figure 8.3. All dummy modules are made out of a bare silicon piece with the dimensions of the pixel module sensors. The dummy sensors are glued to the base strips. The heating functionality of the dummy modules is implemented in two different ways. There are 96 modules equipped with PCB heaters which are glued on top and cover the full sensor area. The electrical resistance of the heating foil is approximately  $20\,\Omega$ . The other 16 modules are each equipped with a  $20\,\Omega$  heating resistor positioned at the center of the dummy sensor. For both types of modules the temperature is measured with one-wire temperature sensors [92]. For each PCB heater module, one temperature sensor is used and the sensor is glued to the center of the dummy sensor. The temperature sensors have direct contact to the silicon through a cut-out in the heating foil. For the heating resistor modules the sensors are glued very close to the long edge roughly 2 cm away from the sensor center, as visible in Figure 8.3. Thermal simulations indicate that the temperature distribution on the dummy sensors with heat load is different between the PCB heater modules and the heating resistor modules, as the thermal hot spot is very point-like for the heating resistor modules [91]. In the measurements presented in the following an additional uncertainty of 1 K is thus assumed for the temperature measurement of the heating resistor modules. The one-wire temperature sensors are connected to custom interface boards and read out with Arduinos boards [93]. The temperature calibration of the one-wire sensors had already been done at KIT [91]. Twelve modules are equipped with an additional PT100 temperature sensor, which can be used for interlocking the power in case of too high temperature.

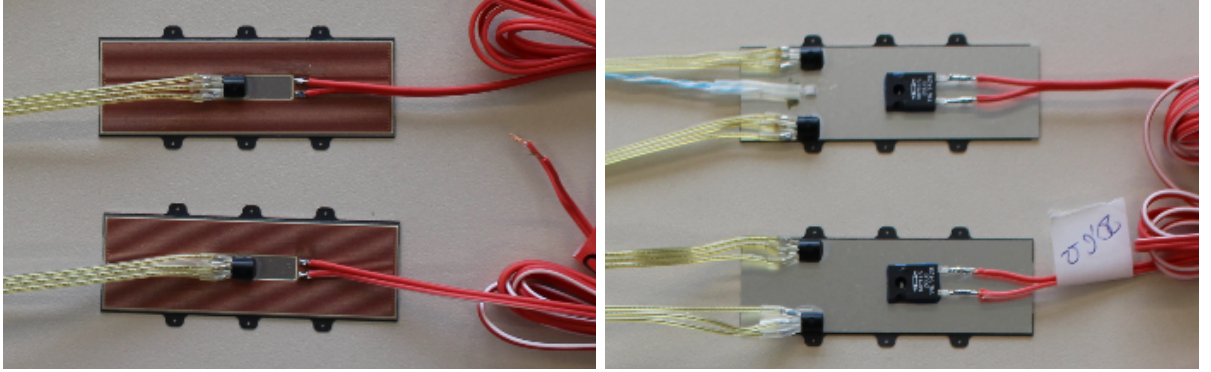


Figure 8.3.: Thermal dummy silicon modules with PCB heaters (left) and with a heating resistor (right). The one-wire temperature sensors (black, with yellow cables) are glued to the silicon. The temperature measurement is made with one (two) one-wire sensor (sensors) for the PCB heater (heating resistor) modules. The heating resistor module on top is equipped with one PT100 temperature sensor. [91]

### 8.1.6. Power Supplies and PLC System

The dummy modules are powered with Delta Power Supplies [94]. Two power supplies are connected to 48 heating foil modules each and one power supply is connected to the 16 heating resistor modules. Overall 28 power cables are used and at each power cable four modules are connected in parallel. The current dependent power losses on the power cables are known from a dedicated calibration procedure, which was conducted during the commissioning at Point 5. The dummy module powers are corrected for these losses. The power supplies are integrated in a PLC (Programmable Logic Controller) rack. The PLC reads also the PT100 interlock thermistors on eight dummy modules, and was programmed to interlock the power supplies at module temperatures above  $30\,^{\circ}\text{C}$ .

### 8.1.7. Preheating Section

A preheating section is installed at the inlet of both cooling loops, behind the capillaries. A schematics is shown in Figure 8.4. The preheating sections are used to apply heat load to the  $\text{CO}_2$  before it enters the detector part. With this technique one can heat up the  $\text{CO}_2$  in order to ensure that it enters the detector in the two-phase state. One preheating section is approximately 60 cm long. On both ends of the sections the ground potential is connected and in the center of the line the positive voltage is connected. The electrical connection is made with custom made brass blocks. The preheating sections have a resistance of  $0.11\ \Omega$  and  $0.12\ \Omega$ . For each preheating line, a low-voltage Delta Power Supply [94], which can provide currents up to 45 A, is used. Preheating powers up to 200 W are possible.

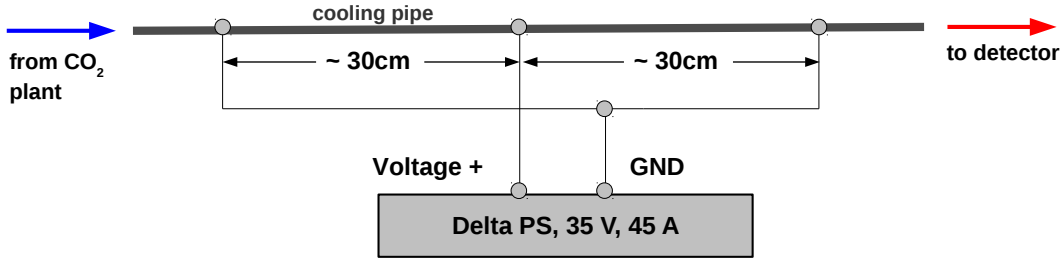


Figure 8.4.: Schematics of the preheating section installed at the inlets of both cooling loops. The connection to the pipes is realized with custom made brass blocks which embrace the pipe.

## 8.2. Measurements with the BPIX Mock-up

### 8.2.1. Temperatures with Module Power

The temperature measurements with the BPIX mock-up were performed with the intent to imitate the conditions in the real BPIX detector as closely as possible. The main focus was put on measurements with the nominal BPIX operating conditions in terms of  $\text{CO}_2$  temperature,  $\text{CO}_2$  mass flow, and detector power. In particular, the nominal  $\text{CO}_2$  temperature in the LUKASZ accumulator volume is set to  $-22.5\ ^\circ\text{C}$  and the  $\text{CO}_2$  mass flow is set to  $2.5\ \text{g/s}$ . The module power is generally chosen such that they were compatible with the estimated module power during collisions in August 2018, namely 3.1 W. The standard preheating power was chosen to be 30 W per preheating section, to emulate the estimated inefficiency losses of the DC-DC converters in the real BPIX supply tube. However, the preheating power was not necessary for the production of the two-phase state of the  $\text{CO}_2$  at temperatures of  $-22.5\ ^\circ\text{C}$ . It was observed that the  $\text{CO}_2$  enters the detector volume already in the two-phase state without preheating power, as a significant amount of heat is collected in the supply pipes from the  $\text{CO}_2$  plant to the detector. All measurements are performed at the standard ambient temperature of  $-16 \pm 1\ ^\circ\text{C}$ . Figure 8.5 shows the measured module temperatures in the mock-up with the standard measurement parameters described above.

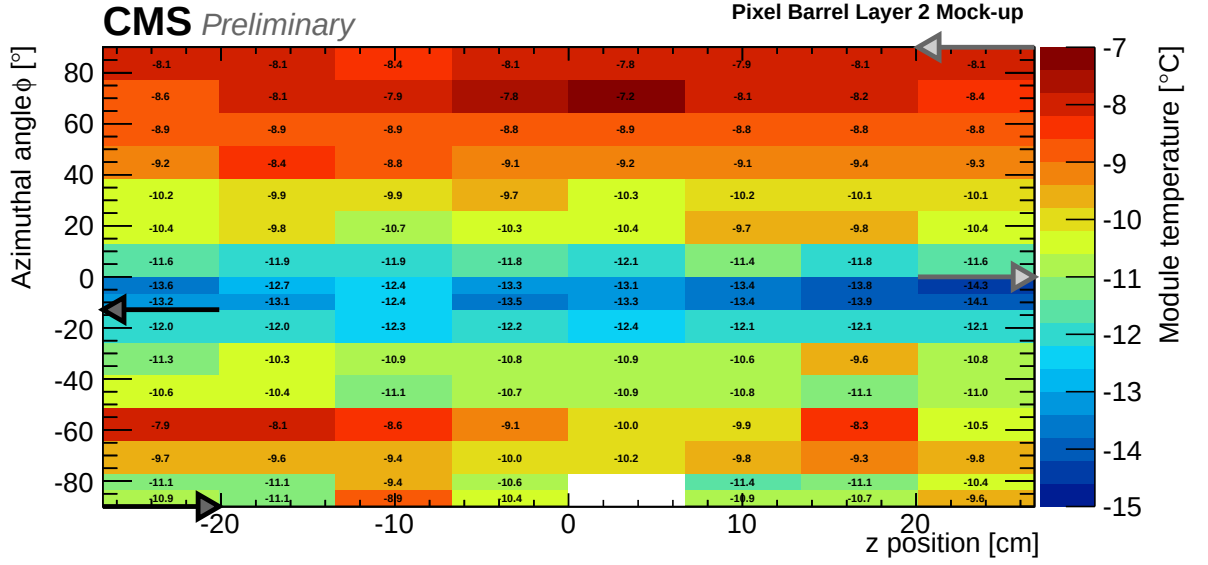


Figure 8.5.: Temperature distribution on the dummy modules in the thermal mock-up with standard measurement parameters. Individual bins denote one dummy module. The binning in  $\phi$  represents the 14 ladders. The temperature is color coded. The white bin indicates a broken module. The heat resistor dummy modules are divided into two parts in order to display the temperatures measured by both temperature sensors. The light (dark) arrows denote the inlet and outlet of the plus (minus) cooling loop.

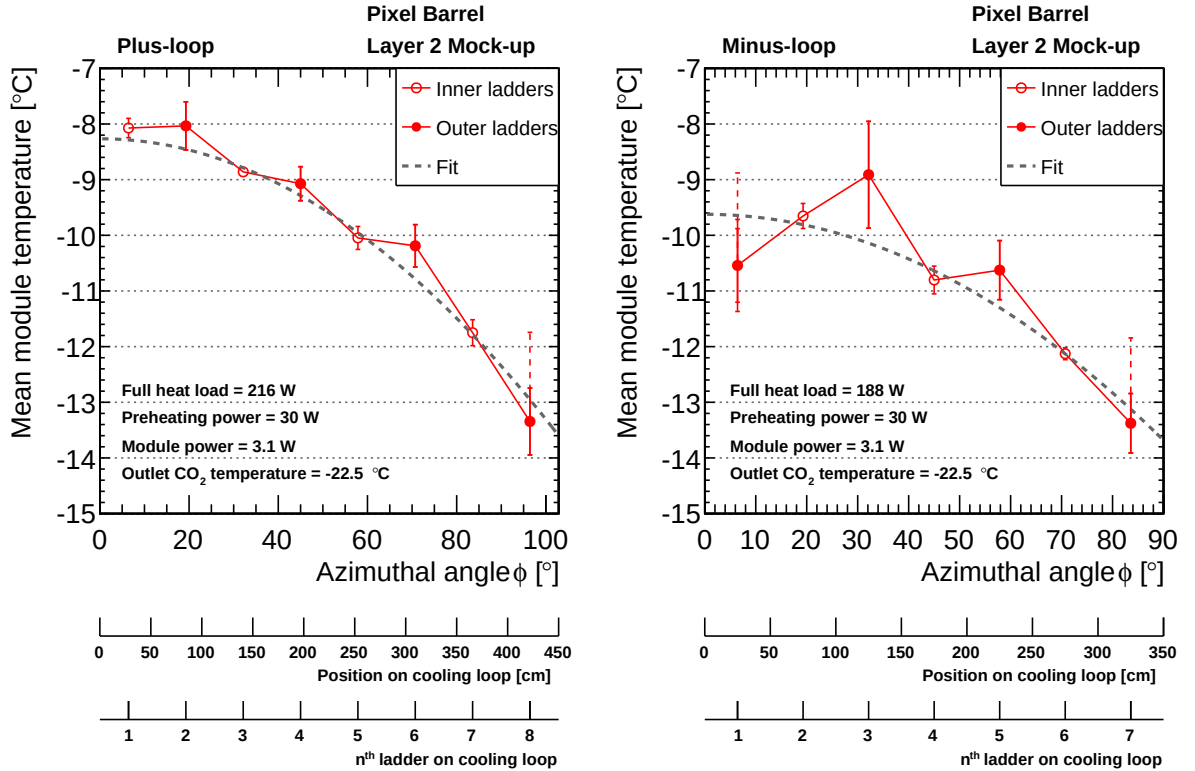


Figure 8.6.: Distribution of the mean module temperatures versus the azimuthal angle  $\phi$ . The second  $x$ -axis indicates the averaged position on the cooling loop in terms of length. The third  $x$ -axis indicates the ladder index on the cooling loop. The dashed gray line shows the fitted parabolas.

The mean value of the module temperatures in the mock-up is  $-10.5 \pm 1.7^\circ\text{C}$ , where the uncertainty is the standard deviation of the distribution. However the mean value of the module temperatures is  $-9.9 \pm 1.8^\circ\text{C}$  on the plus cooling loop and  $-11.0 \pm 1.5^\circ\text{C}$  on the minus cooling loop. The difference of these mean values can be explained with the differences between the two cooling loops. The temperature values in the mock-up are not distributed randomly, but decrease along the cooling loops in the  $\text{CO}_2$  flow direction. The temperatures are the highest on the modules which are located on the ladders directly after the inlet of the cooling loop and are the lowest towards the outlet. Figure 8.6 shows the temperature distribution of the mean module temperature per ladder along  $\phi$ , where  $\phi = 0^\circ$  ( $\phi \approx 90^\circ$ ) denotes the inlet (outlet) of the cooling loop. The red dotted error bar of the three data points represents the uncertainty of 1 K on the temperature measurement with the heating resistor modules, which will be not mentioned explicitly in the following analyses. The temperature distribution along  $\phi$  is very smooth for the plus cooling loop. A small step-like behavior can be observed in the curve. An outer ladder (second, fourth, and sixth data point) shows a smaller temperature drop with respect to the preceeding inner ladder than an inner ladder to the preceeding outer ladder. The statistical fluctuations (i.e. the RMS) are also higher for the outer ladders. The effect is not understood. Possible causes could e.g. be different convective behavior between inner and outer ladders or mechanical differences between inner and outer ladders. The temperature distribution on the minus loop is not as smooth as on the plus loop. A group of modules at around  $\phi \approx -60^\circ$  on the negative  $z$ -side (Outer Ladder 2) in Figure 8.5 is significantly warmer than all the other modules. The last module on the ladder is the warmest and the adjacent modules are successively colder towards the center of the ladder. One single module on the same ladder is also significantly warmer than the surrounding modules. The effect is not understood. By varying many measurement parameters such as  $\text{CO}_2$  temperature,  $\text{CO}_2$  flow, preheating and module power, it was systematically confirmed that the effect does not disappear. It is assumed that the effect is related to a mechanical property of the mock-up at this position, which cannot be specified in more detail.

A temperature difference of 5.3 K (2.9 K) is measured between inlet and outlet for the plus (minus) cooling loop. The corresponding average value is 4.1 K. The mean temperature of the modules on the last ladder of the cooling loops (Outer Ladder 4 at  $\phi \approx -5^\circ$ ) is  $-13.3^\circ\text{C}$ . Empirically the temperature distribution can be described with a parabola

$$T_{\pm}(\phi) = a_{\pm} \phi^2 + T_{\text{inlet},\pm} \quad (8.1)$$

which is fitted to the data, shown as the gray curve in Figure 8.6. The values of the fitted parameters are extracted to be

$$T_+(\phi) = (-4.8 \cdot 10^{-4} \phi^2 - 8.3)^\circ\text{C} \quad (8.2)$$

$$T_-(\phi) = (-5.1 \cdot 10^{-4} \phi^2 - 9.5)^\circ\text{C}, \quad (8.3)$$

and

$$T_{\text{mean}}(\phi) = (-5.0 \cdot 10^{-4} \phi^2 - 8.9)^\circ\text{C} \quad (8.4)$$

where the angle  $\phi$  is measured in units of degree ( $^\circ$ ). The curve  $T_{\text{Layer } 2}^{\text{mean}}(\phi) = (T_+(\phi) + T_-(\phi))/2$  is the average of the fitted functions of both cooling lines. It can be assumed that the temperature distribution of the modules represents the temperature distribution of the  $\text{CO}_2$  in the cooling pipes, except for a constant temperature offset. The ladders have contact to the cooling loops on two grooves and the pipes are bent over at the end of the ladder with a u-piece. The position of the u-piece coincides with the average cooling contact position of the respective ladder. Assuming that the temperature drop along one cooling line is sufficiently linear along one ladder, it can be

deducted that the average temperature of the cooling liquid is the same as the temperature of the cooling liquid in the u-piece. Thus, the measured temperature differences can be translated into a temperature distribution in dependence on the position on the cooling loop. These positions are indicated in Figure 8.6 with the additional  $x$ -axis and the additional cooling loop axis showing the ladder index. The parabola functions from the fits versus the  $x$ -position on the cooling loop can be found in Appendix G.1.

### 8.2.2. Temperatures without Module Power

The same measurement and analysis as presented above is repeated, but without module power. This measurement serves as a reference measurement for the measurement with module power. The temperature distribution without module power is investigated and the effect of the module heat load of about 200 W per cooling loop on the CO<sub>2</sub> properties can be elaborated. The temperature distribution is shown in Figures 8.7 and 8.8. The mean temperature is  $-18.4^\circ\text{C}$  for the plus cooling line, and  $-18.9^\circ\text{C}$  for the minus cooling line. The temperature tends to fall towards the outlet of the mockup, indicating that the CO<sub>2</sub> is in the two-phase state. The temperature values of the modules are significantly higher than the outlet temperature at the accumulator of the LUKASZ CO<sub>2</sub> plant. The temperature of the modules at the outlet of the cooling loop is  $-19.2^\circ\text{C}$ , which is 3.2 K higher than the accumulator temperature. It is rather unlikely that this temperature difference is due to large pressure drops on the return lines, as the return lines have a significantly larger cross section than the mock-up pipes and the mass velocity is significantly lower than in the mock-up, leading to less pressure drop. A better explanation for the higher temperatures could be the impact of the ambient to the modules. The ambient temperature is at  $\approx -15^\circ\text{C}$  and thus higher than the CO<sub>2</sub> temperature. A heat flux from the ambient to the modules, which is then removed from the cooling system, increases the module temperatures. The temperature distribution does not follow a smooth shape and higher temperatures are measured for the outer ladders. It is plausible that the ambient has more impact on the ladders facing to the outside of the mock-up than to the ones facing to the inside. Like in the previous section a parabola  $T_{\pm}(\phi) = a_{\pm} \phi^2 + T_{\text{inlet},\pm}$  is fitted to the temperature distributions and the fitted functions are

$$T_+(\phi) = (-1.7 \cdot 10^{-4} \phi^2 - 17.8)^\circ\text{C} \quad (8.5)$$

$$T_-(\phi) = (-1.6 \cdot 10^{-4} \phi^2 - 18.4)^\circ\text{C}, \quad (8.6)$$

and

$$T_{\text{mean}}^{\text{no power}}(\phi) = (-1.6 \cdot 10^{-4} \phi^2 - 18.1)^\circ\text{C}. \quad (8.7)$$

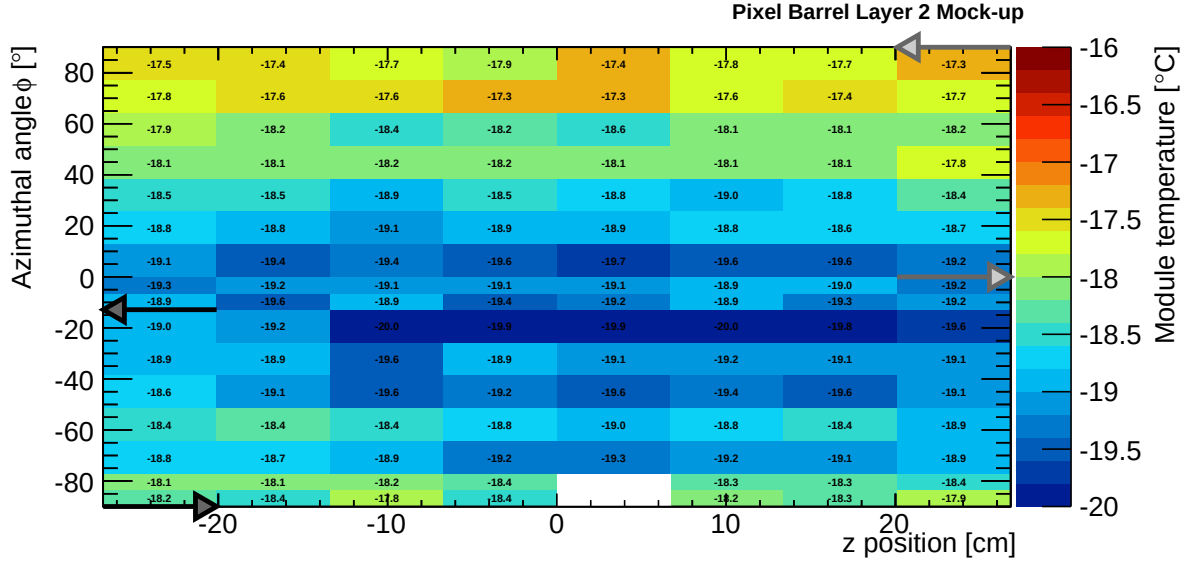


Figure 8.7.: Two-dimensional view of the temperature distribution in the thermal mock-up without module power and with 30 W preheating power. Individual bins denote one dummy module. The binning in  $\phi$  represents the 14 ladders. The temperature is color coded. The white bin indicates a broken module. The heat resistor dummy modules are divided into two parts in order to display the temperatures measured by both temperature sensors. The light (dark) arrows denote the inlet and outlet of the plus (minus) cooling loop.

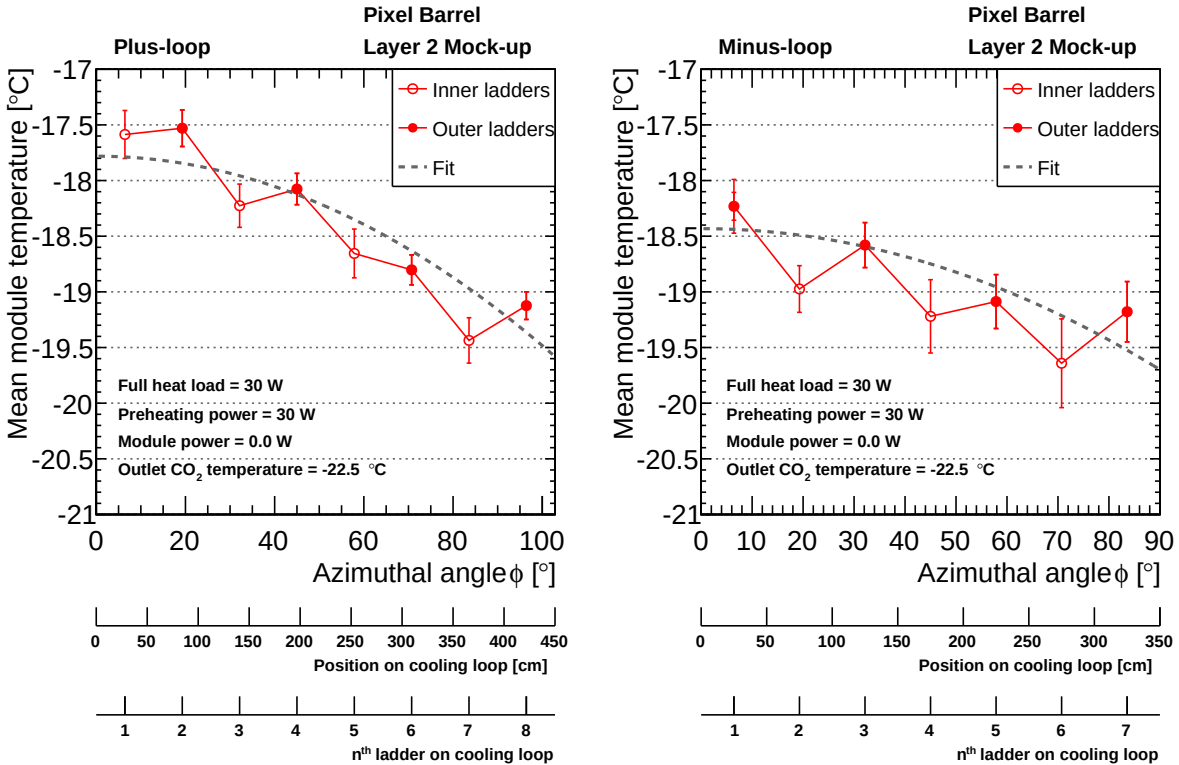


Figure 8.8.: Temperature distribution in the thermal mock-up without module power and with 30 W preheating power. The second  $x$ -axis indicates the averaged position on the cooling loop in terms of length. The third  $x$ -axis indicates the ladder index on the cooling loop.

### 8.2.3. Variation of the Module Power

In order to measure the thermal behavior of the BPIX detector for the power estimated for the end of its planned operation (i.e. for  $\mathcal{L}_{\text{int}} \approx 500 \text{ fb}^{-1}$ ) and beyond, the module power is increased stepwise from 2.7 W up to 4.8 W. Overall five measurements were performed at module powers between these power values. The power values correspond to full heat loads between 192 W and 318 W (168 W and 275 W) for the plus (minus) loop. The temperature distributions for these measurements are shown in Figure 8.9. The measurements were performed under the standard conditions explained in Section 8.2.1. For both cooling lines, the maximum module temperatures are in the order of  $-10^\circ\text{C}$  for module powers of 2.7 W. They rise to temperatures in the order of  $-4^\circ\text{C}$  for the highest module power of 4.8 W. The lowest module temperatures per measurement are increased from around  $-14^\circ\text{C}$  to  $-10^\circ\text{C}$ . The overall temperature difference between the modules in the mock-up is then increased by approximately 2 K, from 4 K to 6 K. The temperature distributions can again be described with the parabolic shapes of  $T_P = a_P \phi^2 + T_{\text{max}}$ . The fitted functions are shown in Figure 8.9 as dashed curves. The averaged functions of the fitted functions from both cooling loops are given by

$$T_{2.7\text{W}}(\phi) = (-4.7 \cdot 10^{-4} \phi^2 - 10.0)^\circ\text{C} \quad (8.8)$$

$$T_{3.1\text{W}}(\phi) = (-5.0 \cdot 10^{-4} \phi^2 - 8.9)^\circ\text{C} \quad (8.9)$$

$$T_{3.5\text{W}}(\phi) = (-5.2 \cdot 10^{-4} \phi^2 - 8.0)^\circ\text{C} \quad (8.10)$$

$$T_{4.2\text{W}}(\phi) = (-5.6 \cdot 10^{-4} \phi^2 - 6.1)^\circ\text{C} \quad (8.11)$$

$$T_{4.8\text{W}}(\phi) = (-5.7 \cdot 10^{-4} \phi^2 - 4.4)^\circ\text{C} \quad (8.12)$$

where  $\phi$  is measured in units of degree ( $^\circ$ ). The fitted functions for the individual cooling loops are listed in Appendix G.1. The maximum module temperature  $T_{\text{inlet}}$  extracted from the fit is increased by 5.6 K from  $-10.0^\circ\text{C}$  to  $-4.4^\circ\text{C}$ . The differences between the maximum module temperatures in both cooling loops are extracted from the fits to be 1.4 K, where the plus loop has the higher temperature. This is in good agreement with the observation made before that the minus loop is colder than the plus loop. The negative parameter  $a_P$  is a measure for the falling behavior of the temperature distribution and larger absolute values correspond to a higher temperature gradient between the ladders. The absolute values for  $a_P$  are larger for higher module powers, i.e., the temperature gradients between the ladders are larger for higher module powers. In particular, this means that the module temperatures are not simply increased by a constant offset, but that also effects related to the two-phase  $\text{CO}_2$  cooling play a role. A higher temperature drop in the two-phase  $\text{CO}_2$  is equivalent to a higher pressure drop along the cooling loops. A possible explanation for the higher pressure drop is the difference of the vapor quality at lower and higher module powers. At a temperature of  $-20.0^\circ\text{C}$  the evaporation enthalpy of the two-phase  $\text{CO}_2$  is approximately  $H_{\text{evap}} = 440 \text{ J/g}$ . At a given  $\text{CO}_2$  mass flow of  $\Phi_{\text{CO}_2}$  and a given heat load the difference of the vapor quality  $\Delta x$  between inlet and outlet of the cooling loops can be calculated. For a module power of 2.7 W (4.8 W) the heat load on the plus cooling loop coming from the modules is  $P_{2.7\text{W}} = 162 \text{ W}$  ( $P_{4.8\text{W}} = 288 \text{ W}$ ). The values for  $\Delta x$  are then

$$\Delta x_{2.7\text{W}} = \frac{1}{H_{\text{evap}} \cdot \Phi_{\text{CO}_2}} P_{2.7\text{W}} = 0.15 = 15\% \quad (8.13)$$

and

$$\Delta x_{4.8\text{W}} = \frac{1}{H_{\text{evap}} \cdot \Phi_{\text{CO}_2}} P_{4.8\text{W}} = 0.26 = 26\%. \quad (8.14)$$

These values denote the change of the vapor quality in the active BPIX mock-up volume excluding the preheating power. The values are increased to  $\Delta x_{2.7\text{W}} = 17\%$  and  $\Delta x_{4.8\text{W}} = 29\%$  when

taking into account the preheating power of 30 W. As the vapor quality at the inlet of the preheating section remains unknown, the values of  $\Delta x$  give a lower limit on the vapor quality at the outlet of the mock-up.

For each ladder the average thermal resistance  $\alpha = \Delta T / \Delta P$  of the modules is determined. The mean module temperature per ladder is plotted versus the module power, as shown in Figure 8.10. The thermal resistance  $\alpha$  is determined by fitting a linear function to the data points for each ladder. The values for  $\alpha$  are extracted from the slope of the fit function. They are shown in Figure 8.11. In this figure the graphs are superimposed such that the outlet of the cooling loops coincides at  $\approx 90^\circ$ . The difference of the thermal resistances between the ladders on the plus and the minus cooling loop is negligible, except for two ladders. For Outer Ladder 2 the thermal resistance is measured about 10 % higher than for the opposite ladder Outer Ladder 6. This is due to the group of modules on Outer Ladder 2 which is known to have a worse thermal contact to the cooling system. The measured value for Outer Ladder 1 is about 20 % lower higher than for the opposite ladder Outer Ladder 7. This is due to the heating resistor modules on which the temperature distribution is not uniform and where the temperature is not measured at the warmest point of the module. The significantly lower thermal resistance on the modules on Outer Ladder 4 are due to the same reason, i.e. the heating resistor modules. The values mentioned above are excluded for the calculation of the mean thermal resistance. For the remaining values, the mean thermal resistance between the pixel module sensor and the  $\text{CO}_2$  is calculated to be  $\bar{\alpha} = 2.6 \text{ K/W}$ . This value is in good agreement with the values measured in [41].

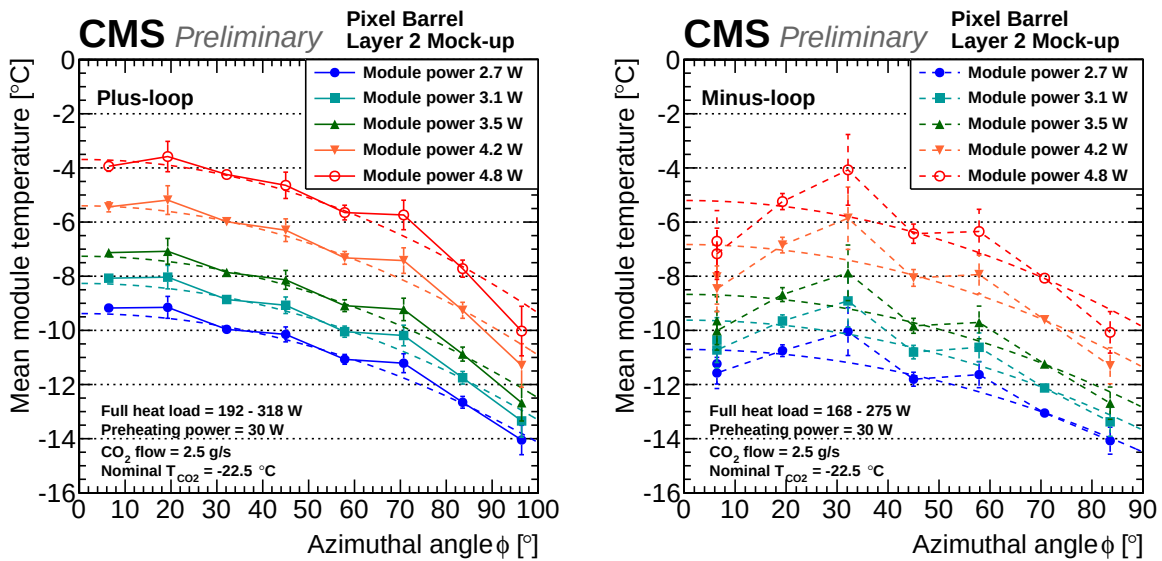


Figure 8.9.: Average module temperatures versus  $\phi$  for various module power values. The dashed line shows the parabolic fits to the data.



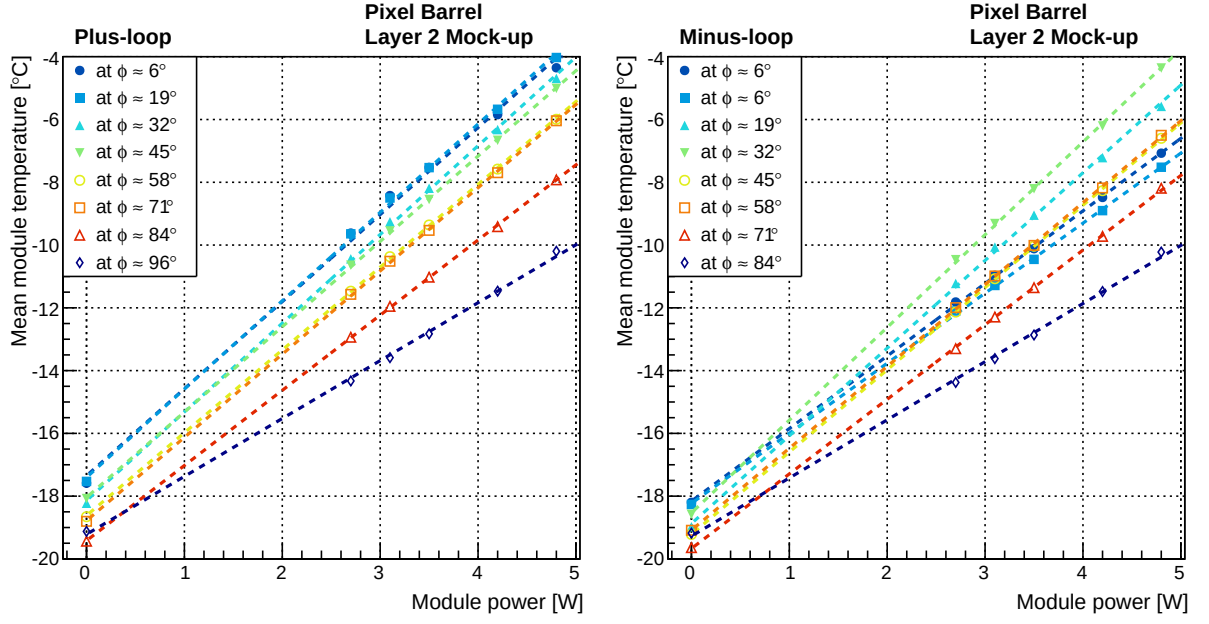


Figure 8.10.: Temperatures of the thermal dummy modules averaged by ladders at the given  $\phi$  position plotted versus the single module power. The dashed lines show the linear fits to the data for the extraction of the thermal resistances.

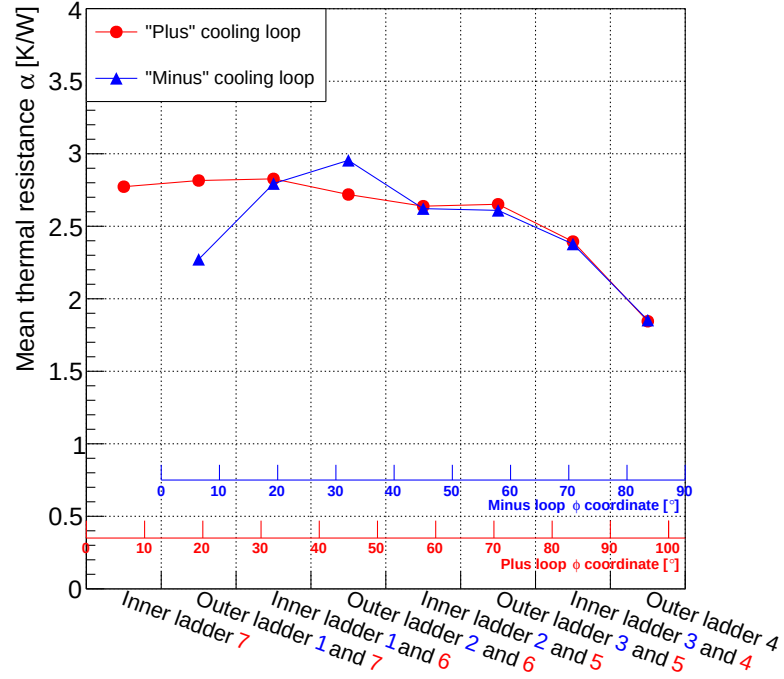


Figure 8.11.: Thermal resistances of the thermal dummy modules averaged by ladders plotted versus ladders and versus  $\phi$ . The red (blue)  $\phi$  axis and the red (blue) numbers in the ladder indices refer to the plus (minus) cooling loop.

8.2.4. Variation of the CO<sub>2</sub> Mass Flow

As the temperature drop along the cooling loop is due to the pressure drop in the two-phase CO<sub>2</sub>, the overall temperature gradient in the mock-up can be reduced by lowering the CO<sub>2</sub> mass flow. With less mass flow, the velocity of the CO<sub>2</sub> is lower, and thus less pressure drop occurs. At the standard parameter configuration of the mock-up the CO<sub>2</sub> mass flow was reduced from  $\Phi = 2.5$  g/s to  $\Phi = 2.0$  g/s and  $\Phi = 1.8$  g/s and the module temperatures were measured. The temperature distributions averaged per ladder are shown in Figure 8.12. The temperature difference in the mock-up decreases for lower mass flow values, which is the expected behavior. The parabolic functions  $T_\Phi = a_\Phi \phi^2 + T_{\max}$  are fitted to the measured curves and plotted as dashed lines in Figure 8.12. The fitted functions are averaged for the two cooling loops. They are:

$$T_{2.5 \text{ g/s}}(\phi) = (-5.0 \cdot 10^{-4} \phi^2 - 8.9)^\circ\text{C} \quad (8.15)$$

$$T_{2.0 \text{ g/s}}(\phi) = (-4.5 \cdot 10^{-4} \phi^2 - 9.5)^\circ\text{C} \quad (8.16)$$

$$T_{1.8 \text{ g/s}}(\phi) = (-4.0 \cdot 10^{-4} \phi^2 - 10.0)^\circ\text{C} . \quad (8.17)$$

The module temperatures at the outlet remain nearly stable for the three measurement series. The maximum module temperatures at the inlet extracted from the fit decrease by 1.1 K, from  $-8.9^\circ\text{C}$  to  $-10.0^\circ\text{C}$ . As expected the parabolas  $T_\Phi$  become more flat with decreasing flow. This is also confirmed in the fit parameters  $a_\Phi$ , which have smaller absolute values for the measurements with less flow. The temperature difference between inlet and outlet extracted from the fits becomes lower and is 4.0 K for the 2.5 g/s case, 3.2 K for the 2.0 g/s case, and 2.6 K for the 1.5 g/s case.

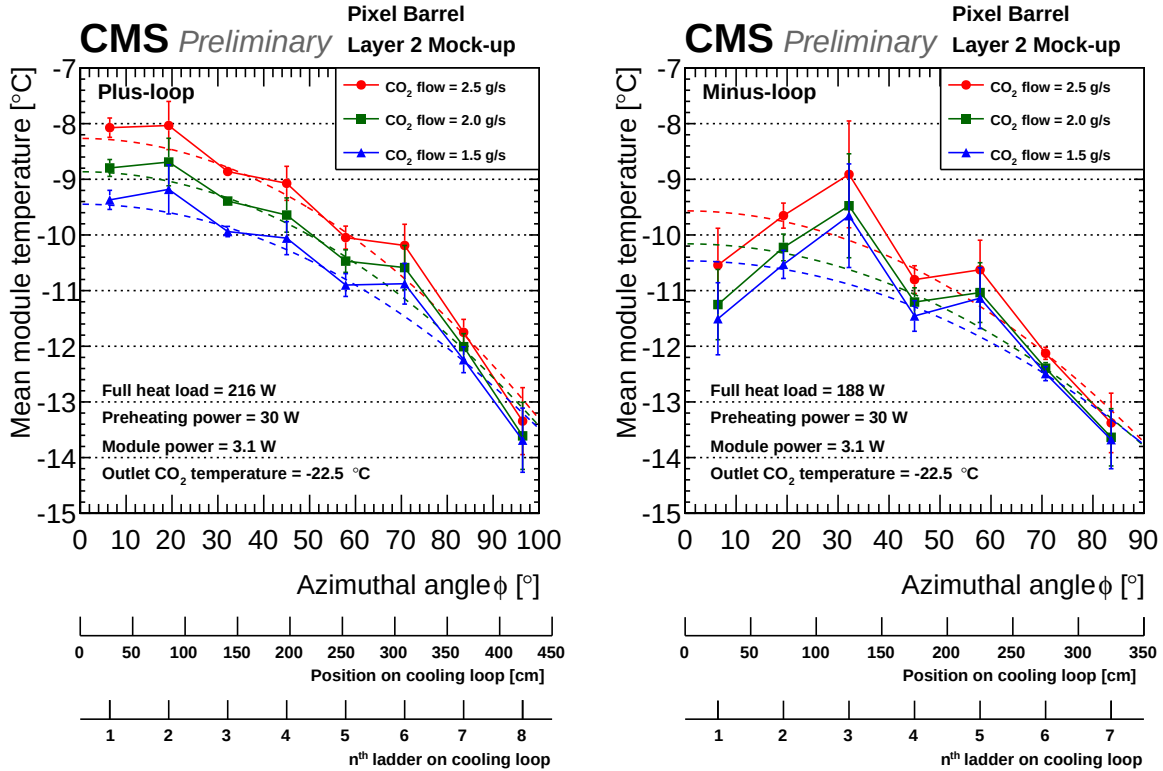


Figure 8.12.: Average module temperatures versus  $\phi$  for different CO<sub>2</sub> mass flows.

### 8.2.5. Estimation of the BPIX Leakage Currents

The temperature distribution, as measured in the mock-up, will have a significant impact on the temperature dependent leakage current in the real existing detector, which scales with the Boltzmann distribution:

$$I_{\text{leakage}}(T) = I_{\text{leak},0} \left( \frac{T}{T_0} \right)^2 \exp \left( - \frac{\Delta E}{2k_B} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right) \quad (8.18)$$

with a given leakage current  $I_{\text{leak},0}$  at a reference temperature  $T_0$ . This leakage current is proportional to the radiation the modules have been exposed to. For the following, the leakage current factor is defined as

$$f(T) = \frac{I_{\text{leakage}}(T)}{I_{\text{leak},0}}.$$

In particular for comparison with BPIX detector data, the leakage current factor of the power sectors at an inlet and an outlet of a cooling will be used:

$$f_{\text{max}} = \frac{I_{\text{leakage}}^{\text{max}}}{I_{\text{leakage}}^{\text{min}}}.$$

The radiation damage of one pixel module depends on the position in the detector, predominantly on the BPIX layer. For the following analysis, the reference module temperature  $T_0$  in the Boltzmann distribution is set as  $T_0 = T_{\text{mean}}(90^\circ) = -12.8^\circ\text{C}$  at the position  $\phi = 90^\circ$ , which refers to the approximate outlet position for a Layer 2 cooling loop. At this position the coldest module per cooling loop is located and the leakage current factor is 1. If the temperature is a function of the position in the detector, e.g. in dependence on the azimuthal position  $\phi$ , Equation 8.18 becomes

$$\frac{I_{\text{leakage}}(T(\phi))}{I_{\text{leak},0}} \propto \left( \frac{T(\phi)}{T_0} \right)^2 \exp \left( - \frac{\Delta E}{2k_B} \left( \frac{1}{T(\phi)} - \frac{1}{T_0} \right) \right), \quad (8.19)$$

where  $T(\phi)$  are the fitted temperature distributions described in the previous sections. At the temperatures relevant in the Phase-1 pixel detector, the leakage current is increased by a factor of 2 when the temperature  $T$  is increased by about 7 K with respect to  $T_0$ . With the fitted function  $T_{\text{mean}}(\phi)$  in Equation 8.7 the relative leakage current distribution in BPIX Layer 2 can be estimated. Figure 8.13 shows the estimated leakage current distribution  $I_{\text{leakage}}(T(\phi))/I_{\text{leak},0}$ . The red curve represents the temperature distribution  $T_{\text{mean}}(\phi)$ . The continuous distribution of the leakage current factor  $I_{\text{leakage}}(T(\phi))/I_{\text{leak},0}$  is derived from the temperature distribution by using Equation 8.19. For smaller values of  $\phi$  the leakage current factor increases non-linearly in dependence of the module temperature and reaches values up to 1.56.

However, the continuous treatment does not reflect the actual situation in the real BPIX detector. Here, modules from multiple ladders are merged to common power sectors. For the common high voltage power sectors only the overall leakage current can be obtained and no information on the leakage current of individual modules or ladders is available. Thus, the leakage current in one power sector is the sum of the leakage currents of all pixel modules in the power sector. As the leakage currents of the pixel modules are temperature dependent, the leakage current in one power sector is given by

$$\frac{I_{\text{leak}}^{\text{power sector}}}{I_0} = \frac{1}{I_0} \sum_{\text{modules}} I_{\text{leak}}^{\text{module}} = \sum_{\text{modules}} \left( \frac{T_{\text{module}}}{T_0} \right)^2 \exp \left( - \frac{\Delta E}{2k_B} \left( \frac{1}{T_{\text{module}}} - \frac{1}{T_0} \right) \right) \quad (8.20)$$

where the sum runs over all modules in the power sector. The estimated leakage current factor in the power sectors for a Layer 2 cooling loop is shown in Figure 8.13 as the blue dashed line.

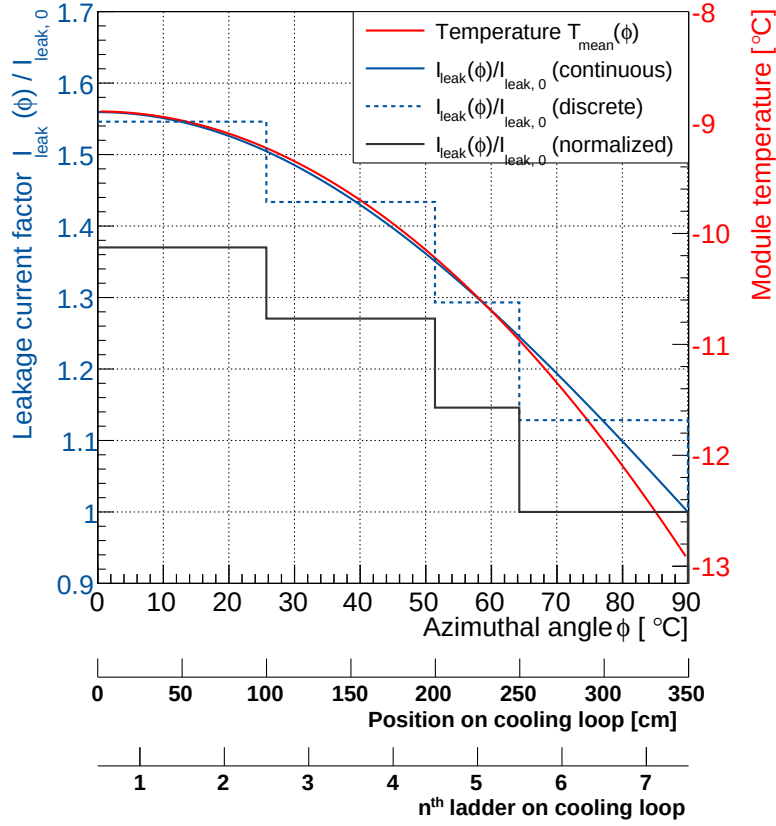


Figure 8.13.: Estimated leakage current factors based on the fit function  $T_{\text{mean}}(\phi)$ . The red curve shows the temperature distribution  $T_{\text{mean}}(\phi)$  obtained from the fit to the mock-up data (Equation 8.7). The solid blue curve shows the calculated continuous leakage current factor distribution  $I_{\text{leak}}(\phi)/I_{\text{leak},0}$ . The dashed blue curve shows the same distribution binned to the BPIX power sectors. The gray line shows the binned distribution scaled to  $I_{\text{leak}}(90^\circ)/I_{\text{leak},0} = 1$ . The second  $x$ -axis indicates the averaged position on the cooling loop in terms of length. The third  $x$ -axis indicates the ladder index on the cooling loop.

In order to take the leakage current of the power sector at the end of a cooling loop as reference, the leakage current factor distribution is divided by the value of the last bin of the histogram. The expected leakage current factors normalized to the lowest leakage current factor is shown as the gray solid line. Leakage current factors up to 1.37 are expected for a Layer 2 cooling loop because of the temperature distribution in the detector.

### 8.3. Measurements in the BPIX Detector

The temperatures and high voltage leakage currents of the BPIX detector are measured in a stable and standard operating state during LHC collisions. The relevant beam and detector conditions are listed in Table 8.1.

#### 8.3.1. Power Consumption in BPIX

The power of the pixel modules can be divided into the high voltage power consumption of the silicon pixel sensors and the low voltage power consumption of the readout chips, as described in Section 5.5. For the low voltage power, Layer 1 and Layer 4, and Layer 2 and Layer 3 modules are connected to the same power sector, respectively. In particular this implies that the low voltage power consumption from a given power sector cannot be resolved accurately into the actual power consumption in a specific layer. Coarse assumptions have to be made taking into

Table 8.1.: Relevant LHC beam and CMS detector conditions for the measured leakage currents referred to in this section. The integrated luminosity refers to the approximate value the Phase-1 pixel detector had been exposed to.

| Quantity                 | Value                                            |
|--------------------------|--------------------------------------------------|
| Data and time            | 20 <sup>th</sup> Aug 2018, 05:00 am              |
| LHC fill                 | 7069                                             |
| Instantaneous luminosity | $1.3 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1}$ |
| Integrated luminosity    | $\approx 80 \text{fb}^{-1}$                      |
| CMS run number           | 321475                                           |

account that the digital low voltage power consumption is slightly higher for modules located closer to the interaction point as the particle hit rate is higher at lower radii. For the low voltage channels only input voltage and input current are known and the full input power is given by  $P_{LV} = U_{LV} \cdot I_{LV}$ . The values  $U_{LV}$  and  $I_{LV}$  are however converted by the DC-DC converters. The efficiency of the DC-DC-converters was measured to be  $\eta = 80\%$  [40]. The power loss from the inefficiency of the DC-DC converters is used as the preheating power for the CO<sub>2</sub> cooling lines. The power of one pixel module is the sum of the high voltage power of the sensor and the power consumption of the readout chips. With these assumptions, the power of one pixel module in Layer 2 and 3 is estimated to be approximately 2.6 W.

### 8.3.2. Preheating in the BPIX Detector

The preheating power in the BPIX detector can be calculated from the inefficiencies of the DC-DC converters. The resulting power loss of the DC-DC converters is removed by the preheating section of the CO<sub>2</sub> cooling system. A pair of analog and digital DC-DC converters is mounted with the backside of their PCB to a cooling bridge. The cooling bridge is clamped to two CO<sub>2</sub> cooling lines and the heat load of the DC-DC converters is guided through the cooling bridges into cooling pipe. The preheating power for the CO<sub>2</sub> cooling system is dominated by the DC-DC converters. The heat load of the DC-DC converters is calculated with the assumptions that the inefficiency of the DC-DC converters is 20%, that the heat load is distributed equally through the bridges to the cooling loops and that this heat load is removed completely by the preheating section. The averaged calculated preheating power for the cooling loops of each layer is listed in Table 8.2. The preheating powers for Layer 1, 2, and 4 are around 35 W which corresponds to the power loss of 13 DC-DC converter pairs. The cooling line for Layer 3 is routed two times more along different DC-DC busboards and thus the preheating power for these cooling lines is a factor two larger than for the other layers.

### 8.3.3. Temperatures in BPIX with Module Power

In the active BPIX detector PT100 temperature sensors are glued on the backside of the carbon fiber ladders on three positions per cooling loop. The sensors are located at the inlet, the

Table 8.2.: Average preheating power per cooling loop per layer in BPIX. [95]

| Layer | Preheating power |
|-------|------------------|
| 1     | 35.0 W           |
| 2     | 34.7 W           |
| 3     | 70.2 W           |
| 4     | 35.4 W           |

middle, and the outlet, respectively. At some positions it was not possible to install a sensor, for reasons of limited space. At these positions no temperature measurement is available. A profound understanding of the cooling behavior cannot be obtained from every cooling loop as many uncertainties remain, e.g. on the fixture of the temperature sensors and the impact from the ambient. The temperature distribution is shown in Figure 8.14 for the two-half-shells of BPIX Layer 4. In each plot the temperature at the inlet, the middle, and the return is shown. BPIX Layer 4 has eight cooling loops and the  $x$ -axes in the plots cover a  $\phi$ -range of  $45^\circ$ . The data points for the inlet and the return lines are adjusted in order to represent the actual angular position in the detector. For the eight cooling lines, a similar behavior is observed for the temperature distribution. An average temperature drop of 3.5 K is measured between inlet and return, which is compatible with the mean value of 4.1 K measured with the mock-up in Section 8.2.1. For Layer 4, the length of one cooling loop and the number of attached ladders is identical to Layer 2. However, the  $\phi$ -coverage of one loop in Layer 4 is half compared to the one for Layer 2. The function  $T_{\text{Layer 4}}^{\text{mean}}(\phi)$  can be obtained from the function  $T_{\text{Layer 2}}^{\text{mean}}(\phi)$  by applying the transformation  $\phi \rightarrow \phi/2$ . The curve  $T_{\text{Layer 4}}^{\text{mean}}(\phi)$  is drawn into the plots with the temperature offset  $T_{\text{inlet}}$  from Equation 8.1 fitted to the temperature data for each cooling loop individually. The fitted temperature offset is on average  $\bar{T}_0 = -9.7^\circ\text{C}$ . The temperature distribution measured with the Layer 2 mock-up is compatible with the temperature distributions measured in BPIX Layer 4. However, the actual pixel module temperature in BPIX remains unknown. It can be assumed that the temperature of the modules is a few degrees (e.g. 2 to 5 K) higher than the temperatures measured on the carbon fiber ladders.

The analysis described above is also performed for Layer 2, where not every temperature measurement seems to give a reasonable value. The temperature distribution in Layer 2 is shown in Figure 8.15. For the cooling loops L2D1MN and L2D2PF, three measurement points are available. The temperature drop along the cooling loop between inlet and outlet is evident and the average temperature difference is 5.4 K. This value is 2 K higher than the mean temperature difference obtained in Section 8.2.1, but it is still compatible within the uncertainties. The mean curve  $T_{\text{Layer 2}}^{\text{mean}}(\phi)$  is compared to the BPIX measurement. The discrepancy between mock-up data and BPIX data is larger than for the Layer 4 data. A comparison with the mock-up measurements only from the plus cooling loop delivers a better agreement with the BPIX Layer 2 data. For the cooling loops L2PD2PN and L2D2MF no temperature sensors are available for the measurement positions at the inlet. The temperature value measured at the middle of the cooling loop L2D2MF is not compatible with the data measured with the mock-up. It also deviates strongly from the other measurements in BPIX Layer 2 at the middle position. However the temperature value of  $\approx -14^\circ\text{C}$  at the return point is in good agreement with the return of L2D1MN which is the identical cooling loop in the opposite half-shell. It is likely that the measurement value in the middle of L2D2MF is a measurement error and does not represent the actual temperature on that position.

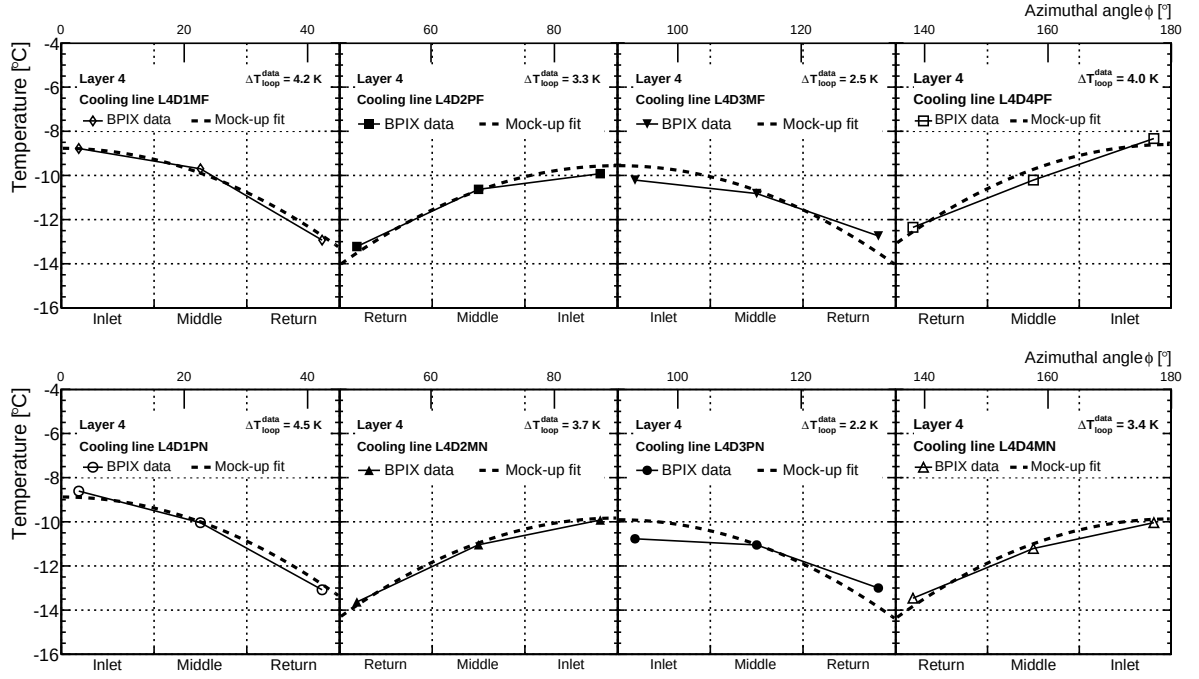


Figure 8.14.: Temperatures measured in BPIX Layer 4. The cooling line is given in the plot and the  $x$ -axes show the position of the temperature sensor. The upper plots refer to BPIX BO and the lower plots refer to BPIX BI. The dashed line shows the parabola from the mock-up studies shifted by a fitted temperature offset. The  $\Delta T_{\text{loop}}^{\text{data}}$ -values refer to the measured temperature difference between inlet and outlet in BPIX.

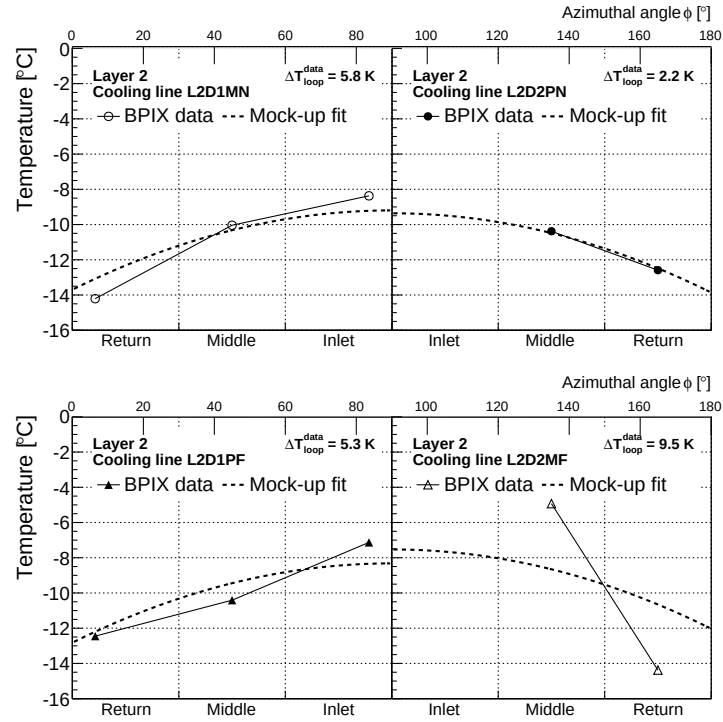


Figure 8.15.: Temperatures measured in BPIX Layer 2. The cooling line is given in the plot and the  $x$ -axis shows the position of the temperature sensor. The upper plot refers to BPIX BO and the lower plots refer to BPIX BI.

## 8.3.4. Temperatures in BPIX without Module Power

When the BPIX detector is in standby mode, no power is consumed in the detector. Nevertheless the cooling system might be running at nominal conditions with a  $\text{CO}_2$  mass flow of 2.5 g/s and a nominal temperature  $-22^\circ\text{C}$ . From the theoretical design of the cooling system the liquid  $\text{CO}_2$  should then remove no heat from the active detector components and run through the detector at the constant nominal temperature. The  $\text{CO}_2$  two-phase state should not be produced since there is no heat input. In an ideally insulated mechanics all detector parts would then be at the cooling temperature of  $-22^\circ\text{C}$ , as there are no heat fluxes and temperature gradients present in the detector mechanics. For such a standby state, the temperatures of the carbon fiber ladders in the BPIX detector are evaluated, and as an example the temperatures measured in Layer 4 are shown in Figure 8.16. The mean temperature is  $-17.5^\circ\text{C}$ , which is 4.5 K higher than the nominal cooling temperature. An effect which would lead to such a result would be an ambient in BPIX which is significantly warmer than the cooling liquid. This would result in a heat flux from the ambient air to the surfaces in the detector, which is then removed by the cooling system. This could possibly produce the two-phase state in the detector. The measured temperature distribution in BPIX during standby mode is not flat or rising towards the return, but tends to fall towards the return. This clearly indicates that the  $\text{CO}_2$  is not in a liquid state, but in two-phase state where the temperature falls with the pressure drop. A liquid cooling medium would stay at constant temperature if it collected no heat, or its temperature would rise if it removed heat from the system. The function which was fitted to the mock-up data to the measurement without module power (Equation 8.7) is drawn to the temperature distribution in Figure 8.16, with the transformation  $\phi \rightarrow \phi/2$  and the individual fit of  $T_{\text{inlet}}$  applied. The measured temperatures in BPIX without detector power are described very well with the temperature distribution obtained from the mock-up. This indicates that the  $\text{CO}_2$  cooling system of BPIX receives also without operational power of the detector a significant heat input from the ambient in the detector or on the transfer lines.

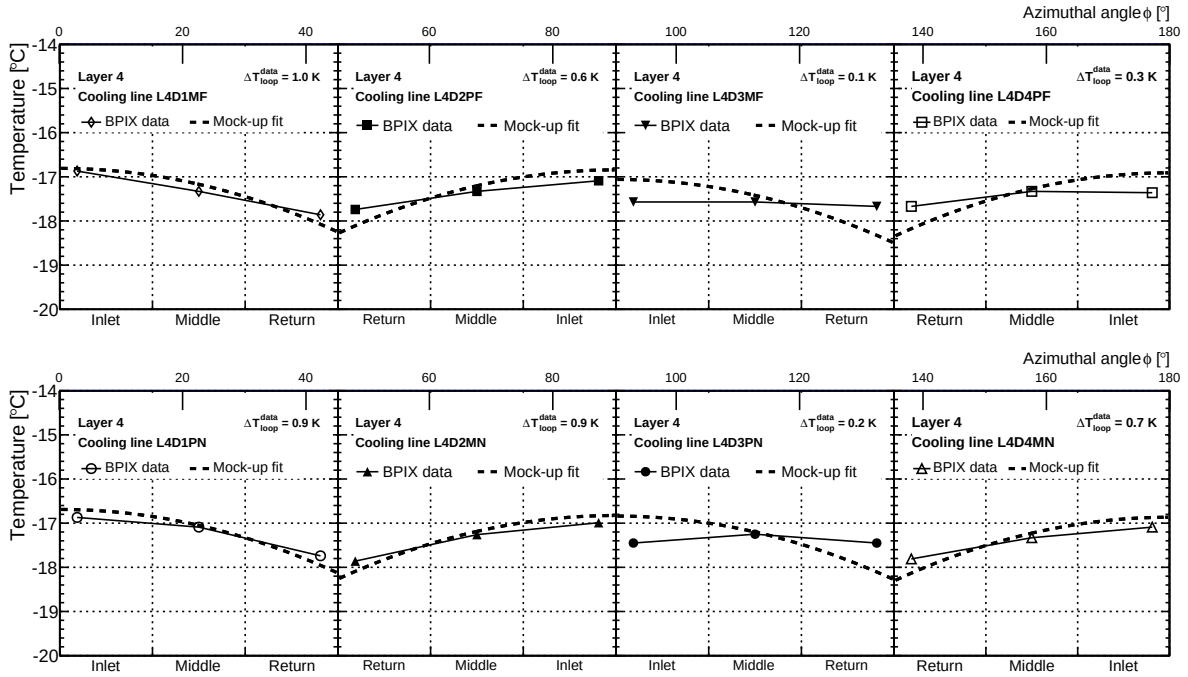


Figure 8.16.: Temperatures measured in BPIX Layer 4 without module power with the detector in standby mode. The cooling line is given in the plot and the  $x$ -axes show the position of the temperature sensor. The upper plots refer to BPIX BO and the lower plots refer to BPIX BI.



### 8.3.5. Sensor Leakage Currents in BPIX

During the operation of the BPIX Phase-1 detector, it was observed that the high voltage leakage currents drawn by the different power sectors varied significantly. The stable operation of the detector was still possible despite of the non-uniform leakage current distribution. Nevertheless it was necessary to understand the origin of the observed non-uniformities in detail. The most probable explanation is the temperature distribution in the detector due to the CO<sub>2</sub> cooling. For the detector operating conditions mentioned above the leakage current distribution in BPIX is shown in a two-dimensional representation in Figure 8.17, with a segmentation into the power sectors. The leakage current is normalized to the number of active modules for each power sector. The leakage current per module per sector is plotted in Figure 8.18 in a one-dimensional representation, where each data point shows the averaged  $\phi$  positions of the modules in the corresponding power sector. In Figure 8.17 adjacent arrows of the same style denote the same cooling loop. The arrows pointing to the inner (outer) of the plot indicate the inlet (return) of the cooling loop. In Figure 8.18 each arrow denotes the CO<sub>2</sub> flow direction in one cooling line. For Layer 2 and 4 it is evident that the leakage currents have the lowest values at the outlet of the cooling loops and the highest values at the inlet of the cooling loops. This observation is well compatible with the temperature measurements in the BPIX detector presented in the previous sections, and with the measurements with the BPIX mock-up. Table 8.3 shows the maximum and minimum normalized leakage currents  $I_{\text{leakage}}^{\text{max}}$  and  $I_{\text{leakage}}^{\text{min}}$  per cooling loop and the ratio  $r_{\text{leak}} = I_{\text{leakage}}^{\text{max}}/I_{\text{leakage}}^{\text{min}}$ . The estimation of the expected leakage current factors is explained in Section 8.2.5. For Layer 2 and 4 the discrete normalized distribution of the leakage current factor in Figure 8.13 is evaluated at 90°, which relates to the corresponding number of ladders per cooling loop for these two layers. The comparison between the predictions from the mock-up measurements and the leakage current distribution in the BPIX detector indicates clearly that the leakage current distribution is generated by the temperature distribution of the two-phase CO<sub>2</sub> cooling system.

The effect cannot be observed that clearly in Layer 1 and 3. In Layer 1, the power sector allocation does not follow the ladder structure of the Layer 1 half-shells (Figure 5.7) and the cooling loops are shorter than for Layer 2 and 4. For Layer 3 the cooling loops are also shorter than for Layer 2 and 4 and the distribution of inlets and outlets of the cooling loops does not follow the same system as for Layer 2 and 4. Thus, here the leakage current factor is estimated from by evaluating the discrete normalized leakage current in Figure 8.13 at -45°. This is a very coarse assumption in order to account for the more uniform temperature and leakage current distributions in Layer 1 and 3.

Table 8.3.: Maximum leakage currents  $I_{\text{leakage}}^{\text{max}}$  and minimum leakage currents  $I_{\text{leakage}}^{\text{min}}$  per BPIX cooling loop normalized to the number of modules per power sector. The unit of the current values in this table is  $\mu\text{A}$ . The leakage current factor  $I_{\text{leakage}}^{\text{max}}/I_{\text{leakage}}^{\text{min}}$  is compared with the expectation from the mock-up measurements.

| Layer   | Barrel plus side                  |                                   |                                                                   | Barrel minus side                 |                                   |                                                                   | Expected<br>$I_{\text{leakage}}^{\text{max}}/I_{\text{leakage}}^{\text{min}}$ |
|---------|-----------------------------------|-----------------------------------|-------------------------------------------------------------------|-----------------------------------|-----------------------------------|-------------------------------------------------------------------|-------------------------------------------------------------------------------|
|         | $I_{\text{leakage}}^{\text{max}}$ | $I_{\text{leakage}}^{\text{min}}$ | $I_{\text{leakage}}^{\text{max}}/I_{\text{leakage}}^{\text{min}}$ | $I_{\text{leakage}}^{\text{max}}$ | $I_{\text{leakage}}^{\text{min}}$ | $I_{\text{leakage}}^{\text{max}}/I_{\text{leakage}}^{\text{min}}$ |                                                                               |
| Layer 1 | 608                               | 504                               | 1.22                                                              | 610                               | 482                               | 1.28                                                              | 1.27                                                                          |
| Layer 2 | 302                               | 207                               | 1.46                                                              | 288                               | 206                               | 1.40                                                              | 1.37                                                                          |
| Layer 3 | 103                               | 92                                | 1.14                                                              | 100                               | 88                                | 1.14                                                              | 1.27                                                                          |
| Layer 4 | 71                                | 52                                | 1.37                                                              | 66                                | 53                                | 1.25                                                              | 1.37                                                                          |

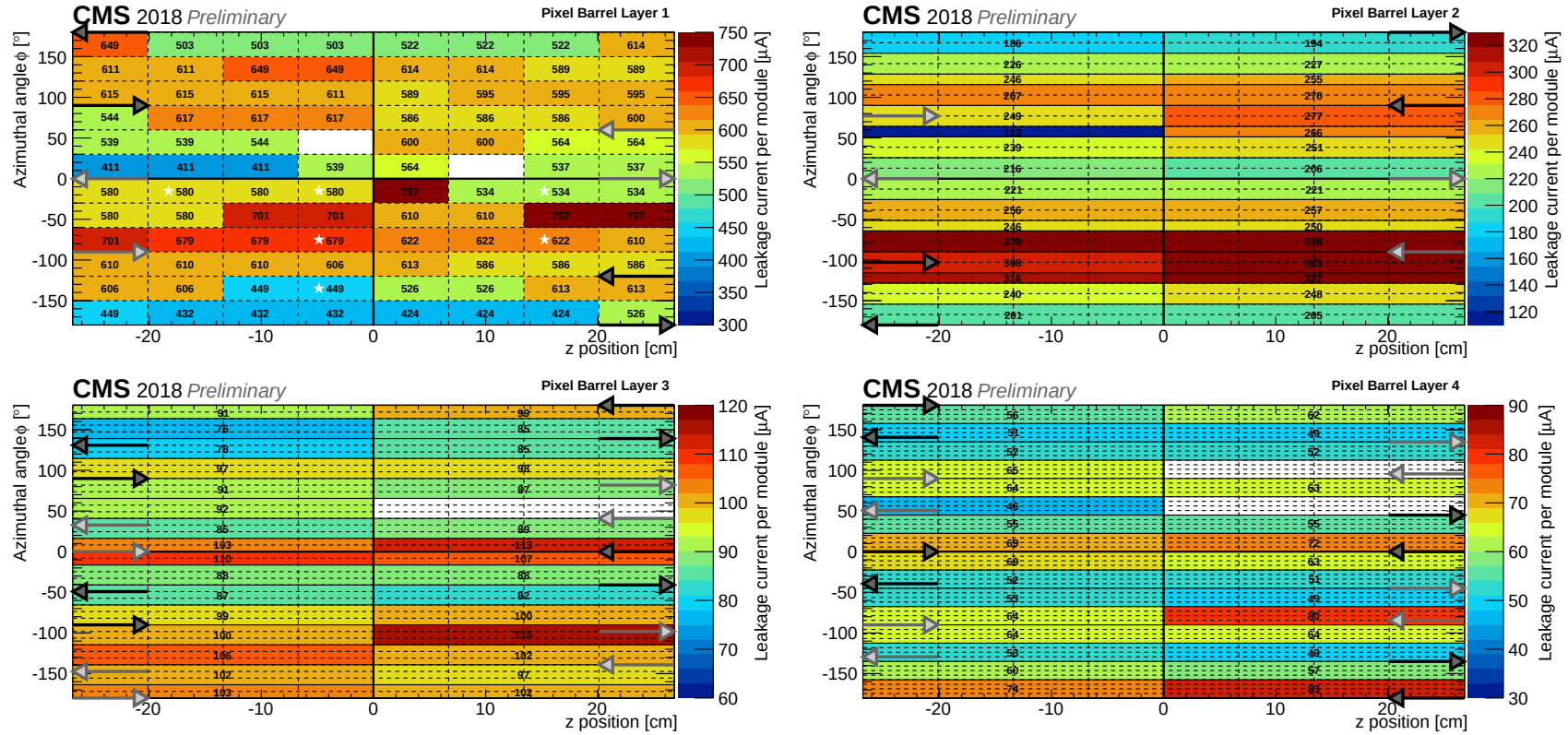


Figure 8.17.: Two-dimensional representation of the sensor leakage currents normalized to the number of modules per power sector in BPIX Layer 1 (top left), Layer 2 (top right), Layer 3 (bottom left), and Layer 4 (bottom right). Inlet and outlet of the cooling lines are indicated with arrows.

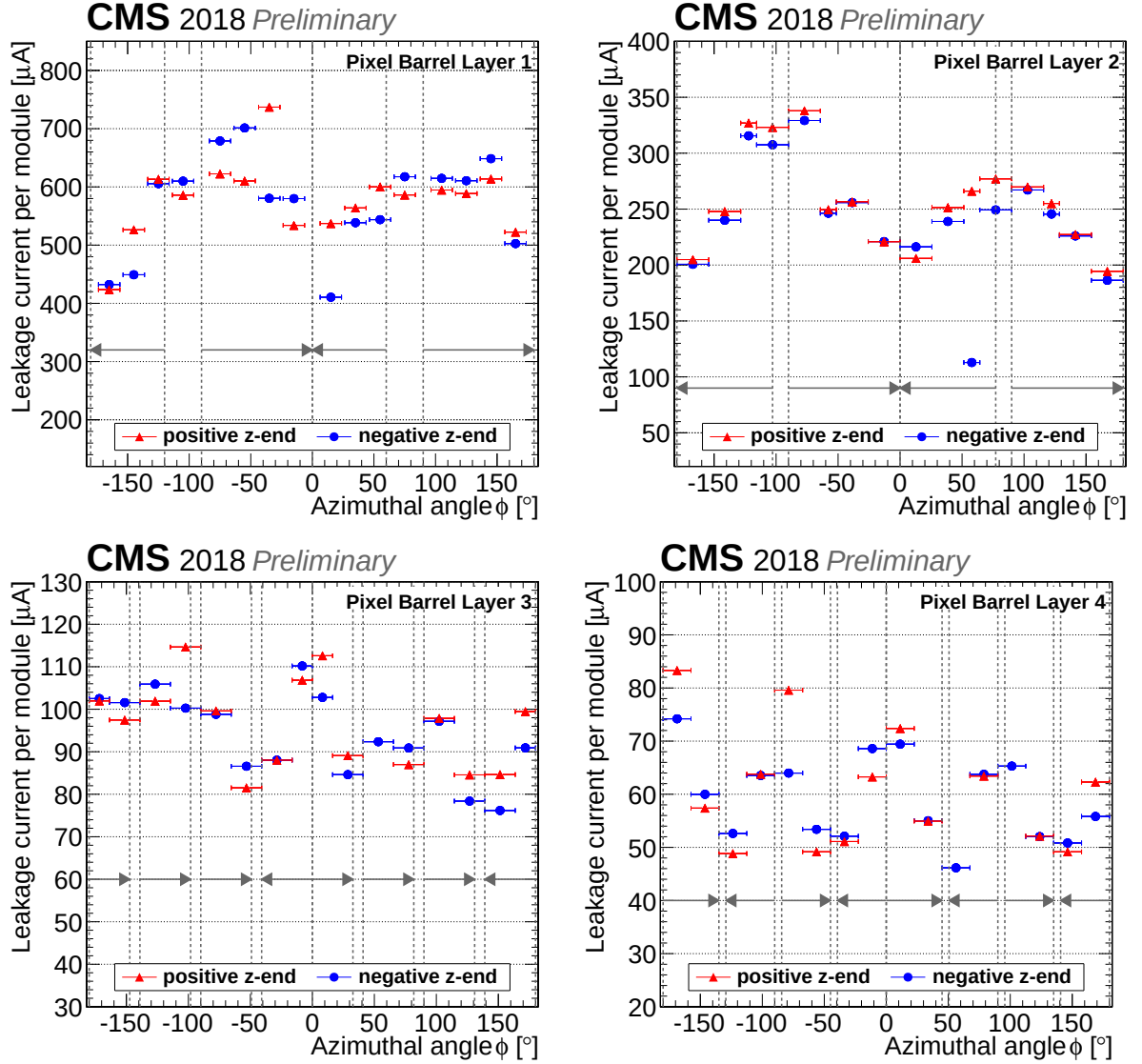


Figure 8.18.: One-dimensional representation of the sensor leakage currents normalized to the number of modules per power sector in BPIX Layer 1 (top left), Layer 2 (top right), Layer 3 (bottom left), and Layer 4 (bottom right). The arrows point from the  $\phi$ -position where a cooling loop enters the detector, to the  $\phi$ -position where it leaves the detector. The dashed lines indicate the  $\phi$ -position of the inlets and outlets of the cooling loops. For Layer 2-4 the horizontal error bars denote the phi range of the power sector. For Layer 1 the error bars are chosen to indicate the standard deviation of the  $\phi$ -width of one ladder which is  $30^\circ/\sqrt{12}$ .

8.3.6. Reduction of the CO<sub>2</sub> Mass Flow in BPIX

In the previous section it was shown that the temperature gradients in the detector can be reduced by reducing the CO<sub>2</sub> mass flow. Based on these measurements, the CO<sub>2</sub> mass flow was reduced from 2.5 g/s to 2.0 g/s and then to 1.8 g/s per cooling loop, in September and October 2018. The temperatures in BPIX measured on the backside of the carbon fiber ladders before and after the flow reduction are shown for Layer 2 in Figure 8.19. For the cooling line L2D1MN

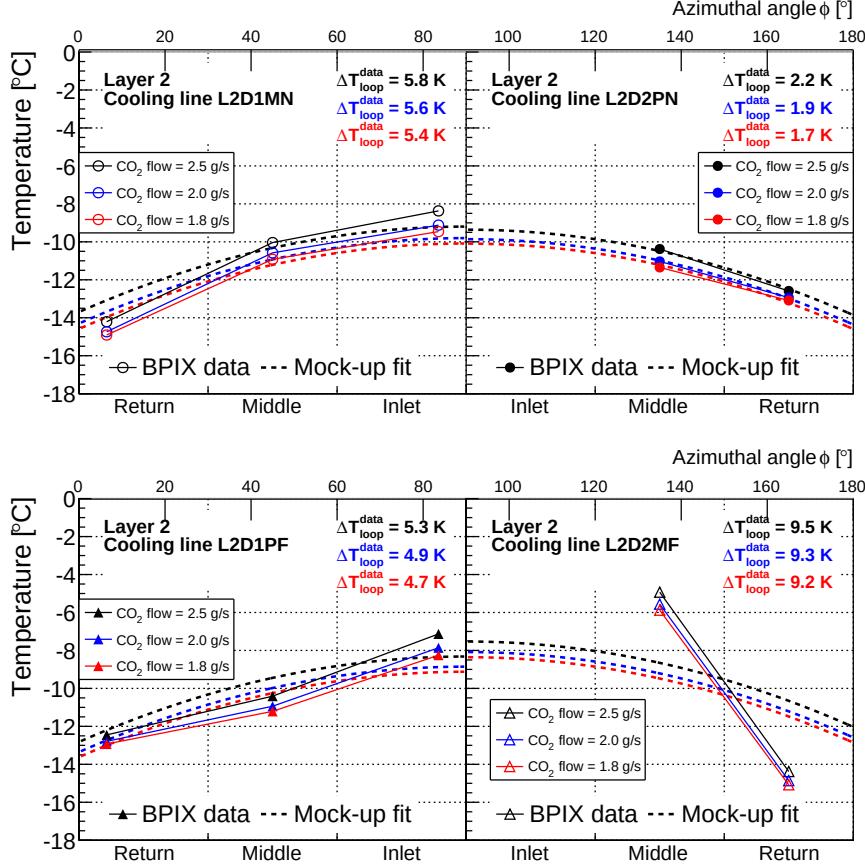


Figure 8.19.: Temperatures measured in BPIX Layer 2 with reduction of the CO<sub>2</sub> mass flow. The black curves corresponds to a CO<sub>2</sub> mass flow of 2.5 g/s, the blue curve to 2.0 g/s, and the red curve to 1.8 g/s. The cooling line is written in the plot and the  $x$ -axis shows the position of the temperature sensor. The upper plot refers to BPIX BO and the lower plots refer to BPIX BI.

(L2D1PF), the temperature difference along the cooling loop is lowered from 5.8 K to 5.4 K (from 5.3 K to 4.7 K), which is a reduction of the temperature difference of 0.5 K whereas 0.8 K were expected from the mock-up measurements. The measurements with the mock-up and the measurements in BPIX are in good agreement. For two cooling lines in Layer 2, respectively no measurement points are available at the inlet of the cooling loop. No analyses can be made for these loops. Table 8.4 gives an overview on the average temperature differences for BPIX Layers 1-4 for the various CO<sub>2</sub> mass flows. The effect can also be observed for Layer 3 and 4 where the temperature difference along the cooling loop became also smaller after the reduction of the CO<sub>2</sub> mass flow.

The analysis of the flow change and the consequent change of the temperature distribution is expected to also affect the leakage current distribution. However, the absolute leakage current distribution depends also on other effects (i.e. radiation damage and annealing time). These effects overlay the change of the leakage distributions. This makes a significant and accurate

Table 8.4.: Average temperature differences along the cooling loops for Layers 1-4 for different CO<sub>2</sub> mass flows in BPIX.

| Date       | CO <sub>2</sub> mass flow | $\Delta T$ (Layer 1) | $\Delta T$ (Layer 2) | $\Delta T$ (Layer 3) | $\Delta T$ (Layer 4) |
|------------|---------------------------|----------------------|----------------------|----------------------|----------------------|
| 2018/9/9   | 2.5 g/s                   | 2.2 K                | 5.6 K                | 2.1 K                | 3.5 K                |
| 2018/10/4  | 2.0 g/s                   | 2.2 K                | 5.3 K                | 1.9 K                | 3.3 K                |
| 2018/10/23 | 1.8 g/s                   | 2.2 K                | 5.1 K                | 1.9 K                | 3.2 K                |

study of the leakage currents in correlation with the detector temperatures nearly impossible.

## 8.4. Discussion

The measurements and studies with the thermal mock-up could give the confirmation that the leakage current distribution in the BPIX detector is fully dominated by the temperature distribution because of the CO<sub>2</sub> cooling loops. After the start of operation of the Phase-1 pixel detector, the inhomogenous leakage current distribution appeared. Although it was assumed that this is due to the temperature distribution because of the CO<sub>2</sub> cooling, no proof could be given. With the mock-up measurements it could be clearly shown that the CO<sub>2</sub> cooling can cause this effect. The measured values in BPIX and the expected values from the mock-up measurement agree very well for the leakage current factors, and in particular also quantitatively. At this order of magnitude with leakage current factors of about 1.4, no other effects seem to occur in the BPIX detector, like e.g. sectors with worse thermal contact, parasitic currents, or inhomogenous radiation damage.

In order to operate the detector more uniformly, it was predicted with the BPIX mock-up that the temperature gradients in the detector can be reduced by lowering the CO<sub>2</sub> mass flow. Based on this prediction, the CO<sub>2</sub> mass flow was lowered in the detector in September and October 2018, and the lower temperature gradients in the detector could be observed.

The measurements with the mock-up are also interesting for future detector projects which will incorporate a CO<sub>2</sub> cooling concept. The mock-up studies provide measurements and data with a test prototype on a realistic detector scale, with realistic heat loads in the detector and realistic cooling conditions.



## 9. Summary and Conclusion

This thesis focussed on measurements and analyses of the thermal properties of two CMS Tracker Upgrade subdetector parts, the Phase-1 Barrel Pixel Detector and the Phase-2 Tracker 2S modules. Both detectors use an evaporative CO<sub>2</sub> cooling system. The operating temperatures of the detector cooling systems are far below room temperature and the freezing point of water in order to mitigate radiation damage of the silicon sensors and to reduce their temperature dependent power. The low temperatures require more advanced thermal test setups. The test setup for the 2S modules was successfully developed, constructed, commissioned, and operated during the work on this thesis. The Phase-1 Barrel pixel detector setup was partially commissioned and operated at CERN Point 5 in Cessy, France, during the work on this thesis. Both test setups featured evaporative CO<sub>2</sub> cooling systems, controlled ambient volumes, and realistic detector mechanics, which in common makes them suited for meaningful measurements for the CMS Tracker Collaboration.

### 9.1. Summary of the Part on the Phase-2 2S Module

The 2S module for the CMS Phase-2 tracker is a device with five components producing heat that are assembled in a complex mechanical arrangement. One of the crucial points is the thermal performance of the module and particularly the thermal connection of the sensor to the cooling system. In the scope of this thesis thermal dummy modules were assembled which are mechanically as similar as possible to the real 2S modules. The dummy sensors of the modules, whose bulk resistivity was chosen especially for thermal tests, could be operated as ohmic resistors with a low voltage supply. With this method the heat production in the actual silicon sensor volume was ensured. The dummy hybrids were built from prototype flex hybrids with realistic spacers and stiffeners. The heat was produced on the hybrids with heating resistors that were glued on the approximate positions where the ASICs would sit.

A thermal test setup was developed and constructed. Three cooling positions for 2S modules were available in the test setup. The cooling inserts were almost identical to the cooling inserts in the TEDD. The inserts were connected to a two-phase CO<sub>2</sub> cooling system which could be operated down to a nominal temperature of  $-31^{\circ}\text{C}$ . The test setup was installed in a custom-built cooling box. The inner volume of the cooling box could be cooled down to  $-30^{\circ}\text{C}$ . A stable and well defined ambient temperature could be produced in the inner volume of the box.

A complete thermal Finite Element model of the 2S module on the TEDD cooling structure was developed with COMSOL<sup>®</sup> Multiphysics. The model was used to simulate the thermal performance of the 2S module. The results of the thermal measurements were compared to the results from the FE simulation. This was an important cross-check procedure. The FE model could also be used to simulate the thermal runaway of the 2S module by implementing a temperature dependent heat source in the silicon sensors.

The test setup and its thermal characteristics were understood and analyzed in detail. The unavoidable heat input into the CO<sub>2</sub> cooling system lead to a temperature raise of the inserts. This offset had to be corrected for in further analyses. The effect leads also to systematically higher module temperatures than predicted in thermal FE simulations, showing that the idealistic FE model does not describe reality well.

The measurements with the 2S module were firstly conducted with bare modules that were not equipped with hybrids. The principle of the measurement was to produce a thermal equilibrium between the powered sensors and the controllable ambient temperature in order to minimize

the heat exchange between the sensors and the ambient. The thermal resistance of the top (bottom) sensor was measured to be 4.3 K/W (4.1 K/W) with respect to the power of both sensors. This value was well compatible with the predictions from the Finite Element simulations. In further measurements the thermal characteristics of the bare 2S module could be confirmed to be compatible with the FE model on all three module positions available. The mechanical assumptions implemented in the bare module finite element model could be confirmed with measurements. The thermal coupling of the top (bottom) sensor to the ambient could be determined to be 81 mW/K (58 mW/K) in this setup. The average thermal resistance of the cooling insert (spacer) was determined to be 6.2 K/W (9.4 K/W) with respect to the heat removed through the specific insert. By using the contact surface between spacer and insert, the heat transfer coefficient between spacer and insert from the contact pressure can be calculated to be 7 kW/m<sup>2</sup>/K.

From the measurement with the 2S dummy module equipped with the dummy hybrids the mechanical assumptions implemented in the FE model could be confirmed by exploiting again the principle of thermal equilibrium. However in the measurement with realistic sensor and hybrid heat loads a significant heat loss from the hybrid to the sensor could be observed depending on the ambient temperature. At an ambient temperature of  $-20^{\circ}\text{C}$  the heat loss was in the order of 400 to 500 mW, which corresponds to about 20 to 30 % of the full hybrid power. It could be shown that adjusting the heat loads in the FE models gave also a proper description of this observation. It could also be observed that a significant amount of heat flows from the front-end hybrids through the wirebonds and the encapsulation material to the sensor. At the nominal heat loads this amount could be quantified to 125 mW per front-end hybrid and sensor, summing up to total of 250 mW per sensor. This value is compatible with the value extracted from the FE simulation with a properly simplified model of the wirebond geometry.

An attempt was made to demonstrate the effect of thermal runaway with the dummy module. Ambient temperature and sensor power, which was scaled with the Boltzmann distribution in dependence on the sensor temperature, were iteratively adjusted until they converged at an acceptable working point in terms of the principle of thermal equilibrium. The module could be operated up to a CO<sub>2</sub> temperature of  $-29^{\circ}\text{C}$ . However, this measurement is affected by ambient effects. Correcting for these effects implies a thermal runaway at a 3 K higher CO<sub>2</sub> temperature of  $-26^{\circ}\text{C}$ .

The thermal runaway simulation which was presented in the Technical Design Report of the Phase-2 Tracker Upgrade [5] was cross-checked with the FE simulations developed for this thesis. These thermal runaway results could be confirmed within 2 K for an integrated luminosity of 3000 fb<sup>-1</sup> and a high voltage of 600 V. The FE simulations assumed a cooling insert with an enlarged contact surface to the cooling pipe. Both models predict a thermal runaway at a CO<sub>2</sub> temperature about 10 K higher than the maximum estimated CO<sub>2</sub> temperature of  $-33^{\circ}\text{C}$ . The estimation of the thermal runaway with the insert geometry used for the thermal tests (with no enlarged contact surface) yields a thermal runaway at a CO<sub>2</sub> temperature of about  $-28^{\circ}\text{C}$ . Recently, the collaboration decided to utilize silicon sensors with an active thickness of 290  $\mu\text{m}$ , which leads to a higher power consumption of the sensors. Thermal runaway simulations for this sensor thickness and for the insert geometry used in this thesis predict a thermal runaway at a CO<sub>2</sub> temperature of about  $-31^{\circ}\text{C}$ . The final insert geometry in the TEDDs needs to be discussed in the collaboration. This thesis has given important insights into the thermal properties of the 2S module and can reasonably contribute to this discussion.

The power estimation of the 2S sensors does not only depend on the active sensor thickness, but also on many other parameters, like e.g. radiation damage, particle flux, high voltage, etc. These parameters may also be multiplied with safety factors. It will be an important step in the collaboration to fix the assumptions on these parameters. In this thesis various scenarii have



been discussed with different assumptions on various parameters. The thermal runaway was simulated for each scenario. With the scenario of a high voltage of 600 V and a radiation damage constant of  $\alpha_{\text{damage}} = 5.35 \cdot 10^{17} \text{ neq/cm}^2$ , which was the base line scenario in the collaboration for a long time, the 2S modules in the TEDD could be operated at the maximum expected  $\text{CO}_2$  temperature of  $-33^\circ\text{C}$  up to an integrated luminosity of  $4000 \text{ fb}^{-1}$ , with less than 10 % entering thermal runaway after  $3000 \text{ fb}^{-1}$ . However, for a  $\text{CO}_2$  temperature of  $-30^\circ\text{C}$ , which represents the 3 K margin, the thermal runaway of the 2S modules would start at  $2200 \text{ fb}^{-1}$  and after  $4000 \text{ fb}^{-1}$  the fraction of lost 2S modules in the TEDD would amount to nearly 80 %. For the 800 V and a  $\text{CO}_2$  temperature of  $-33^\circ\text{C}$  the situation looks very similar like in the 600 V and  $T_{\text{CO}_2} = -30^\circ\text{C}$  case. In the 800 V and at a  $\text{CO}_2$  temperature of  $-35^\circ\text{C}$  the thermal runaway of 2S modules would start after  $2900 \text{ fb}^{-1}$  and about 20 % of the 2S modules were lost after  $4000 \text{ fb}^{-1}$ . The reduction of the  $\text{CO}_2$  temperature to nominally  $-37.5^\circ\text{C}$  would make an entire operation up to  $4000 \text{ fb}^{-1}$  possible, except for about 5 % of the 2S modules.

All these estimation are based on FE models which do not interact with the ambient. Potential heat losses from the hybrids to the ambient or heat fluxes from the ambient to the sensors are not considered. The influences from the ambient might heavily effect the thermal behavior and the thermal runaway point of the 2S modules. The simulations of the thermal runaway for the two insert variants are made with a conservative assumption of a  $\text{CO}_2$  heat transfer coefficient of  $5 \text{ kW/m}^2/\text{K}$ . The configuration with the foot-insert then theoretically improves the situation of thermal runaway. Less conservative analyses of the thermal runaway with a higher  $\text{CO}_2$  heat transfer coefficient and with a linearly heat flux dependent  $\text{CO}_2$  heat transfer coefficient are being under study. Simulations of the thermal resistance of the inserts indicate that the cylindrical insert behaves under these conditions similar to the foot-insert with the conservative heat transfer coefficient. Despite the lower heat flux densities in the cooling pipe contacts, the foot-insert performs still better than the cylindrical insert.

## 9.2. Summary of the Part on the Phase-1 Barrel Pixel Detector

The thermal behavior of the CMS Phase-1 BPIX detector has been analyzed with a thermal mock-up of one BPIX Layer 2 half-shell whose mechanics is identical to the real BPIX detector. Dummy modules were used to simulate the pixel modules and their heat loads. It was measured that the temperature of the  $\text{CO}_2$  drops along the cooling line by about 4 to 5 K because of the pressure drop in the pipes. This effect leads to a characteristic temperature distribution in the detector. The temperature distribution was measured for different module power settings and different  $\text{CO}_2$  mass flows. With the former measurement it was shown that not only the module temperatures become higher for higher module power values, but also that the temperature distribution in the detector becomes steeper with higher module power. The average thermal resistance  $\alpha$  of the pixel modules could be determined to be  $\alpha = 2.7 \text{ K/W}$ . This value is in good agreement with older measurements. By reducing the  $\text{CO}_2$  mass flow from  $2.5 \text{ g/s}$  to  $1.8 \text{ g/s}$  the overall temperature difference in the detector can be reduced by about 1.5 K, leading to a more homogeneous temperature distribution in the detector. With the measurements done the expected temperature dependent high voltage leakage current distribution can be determined. Factors of 1.4 are expected between the leakage currents in the power sectors along the cooling lines.

The measurements with the mock-up are compared to actual temperature and leakage current measurements in the BPIX detector. The temperatures in the BPIX detector are measured with thermistors on the backside of the carbon fiber ladders at the inlet, middle, and outlet of each cooling loop. These values are expected to be different from the module temperatures only by a constant temperature offset, but not in shape. For Layer 2 and Layer 4 the measured temperatures in BPIX are compatible with the measurements in the mock-up. Layer 1 and 3

have different arrangements of cooling lines and power sectors and cannot be directly compared to the mock-up measurements. However they seem to show similar effects, but less pronounced. The leakage current distribution in BPIX is measured and compared to the position of the inlets and outlets of the cooling loops. It is obvious that power sectors with higher leakage currents are located towards the inlet of the cooling loops and power sectors with lower leakage currents towards the outlet. This is compatible with the expectation from the mock-up measurements and also the factors between the leakage currents at the inlet and at the outlet are compatible with the expectation of 1.4.

The reduction of the mass flow in BPIX lead to lower temperatures at the backsides of the carbon fiber ladders. The value of the temperature drop is in good agreement with the expectation from the mock-up measurements.

The measurements with the mock-up could show that the effect of the leakage current distribution is caused by the temperature distribution determined by the CO<sub>2</sub> cooling system. Other effects like e.g. inhomogenous radiation damage, localized parasitic current, worse mechanical structure could be excluded. This was an important result for the pixel detector operation.

### 9.3. Conclusion

Measurements of the 2S module were made with optimized and realistic thermal dummy modules, and a good control, description and understanding of all dominating thermal effects in the entire test setup. In an extensive and involved measurement program, it was shown that the assumptions for the mechanics of the 2S modules made in the FE models could be confirmed with measurements under defined ambient conditions. The thermal design and performance of the 2S modules, which for many years was nearly only based on thermal simulations, could be now confirmed with thermal measurements. Ambient effects affecting both the modules and the test setup could be described and mostly quantified. These effects have significant impact on the thermal performance of the 2S module. It has to be noted that such effects can of course also occur in the real detector. The extrapolation of the results measured on this setup to the real detector geometry and mechanics (where modules sit back-to-back and the hybrids radiate heat to an nearby sensor, etc.) seems very difficult. Measurements in larger test setup structures will be needed to fully characterize the thermal situation in the real detector system.

The work for the thermal characterization of the 2S modules benefited highly from the interplay of thermal measurements, the CO<sub>2</sub> cooling system, the FE simulation program, and the 2S module assembly procedure, which was everything in-house at 1. Physikalisches Institut of RWTH Aachen University.

The thermal runaway estimation in the TEDD2S subdetector depends on many parameters which have to be reasonably estimated, with some safety margin. The detailed analysis of various scenarios showed that the 2S module design is critical under variation of many parameters. Another interesting discussion will be if a loss of about e.g. 10 % of 2S modules in the TEDD would be perhaps an acceptable scenario.

The BPIX mock-up test setup gave the rare opportunity to conduct thermal measurements with real detector mechanics and nearly realistic dummy modules - not only on a scale of a few test samples, but on a large, detector-like scale. Although the BPIX detector was already in operation by the time of the measurements, the test results gave important insights into the thermal behavior of the BPIX detector. The relatively high temperature gradients in the CO<sub>2</sub> cooling pipes lead to temperature differences of the pixel module sensors of 5 K, which results in a relative difference of the high-voltage leakage currents in the order of 1.5. The measurements showed that the relative leakage current distribution in the BPIX detector is produced by the temperature distribution in CO<sub>2</sub> cooling pipes. This observation would not have been possible without the BPIX mock-up measurement. All other sources which would have caused such effects could be excluded with these results. It could be shown with the mock-up measurements that a reduction of the CO<sub>2</sub> mass flow leads to lower temperature gradients in the detector. Based on this measurement the CO<sub>2</sub> mass flow was reduced in the BPIX detector and the same observation could be made.

The measurements and the results with the mock-up can also be interpreted as input for future developments of CO<sub>2</sub> cooling structures in pixel detectors, like e.g. the Phase-2 Inner Tracker. For the CMS Tracker collaboration, the setup has been and remains a unique opportunity to perform such cooling test measurements.



# Appendix



## A. Technical Drawings of the Cooling Inserts

This appendix lists the technical drawings of the cooling insert design that was used in the test setup for the thermal measurements with the 2S module. The geometry of the assembled inserts (top and bottom) part is identical to the baseline design in the collaboration. The actual geometry of the individual top and bottom part of the insert and how they are jointed differs slightly among this design, the design at the TEDD assembly center DESY, and the design at the TEDD assembly centers (Lyon/Brussels).

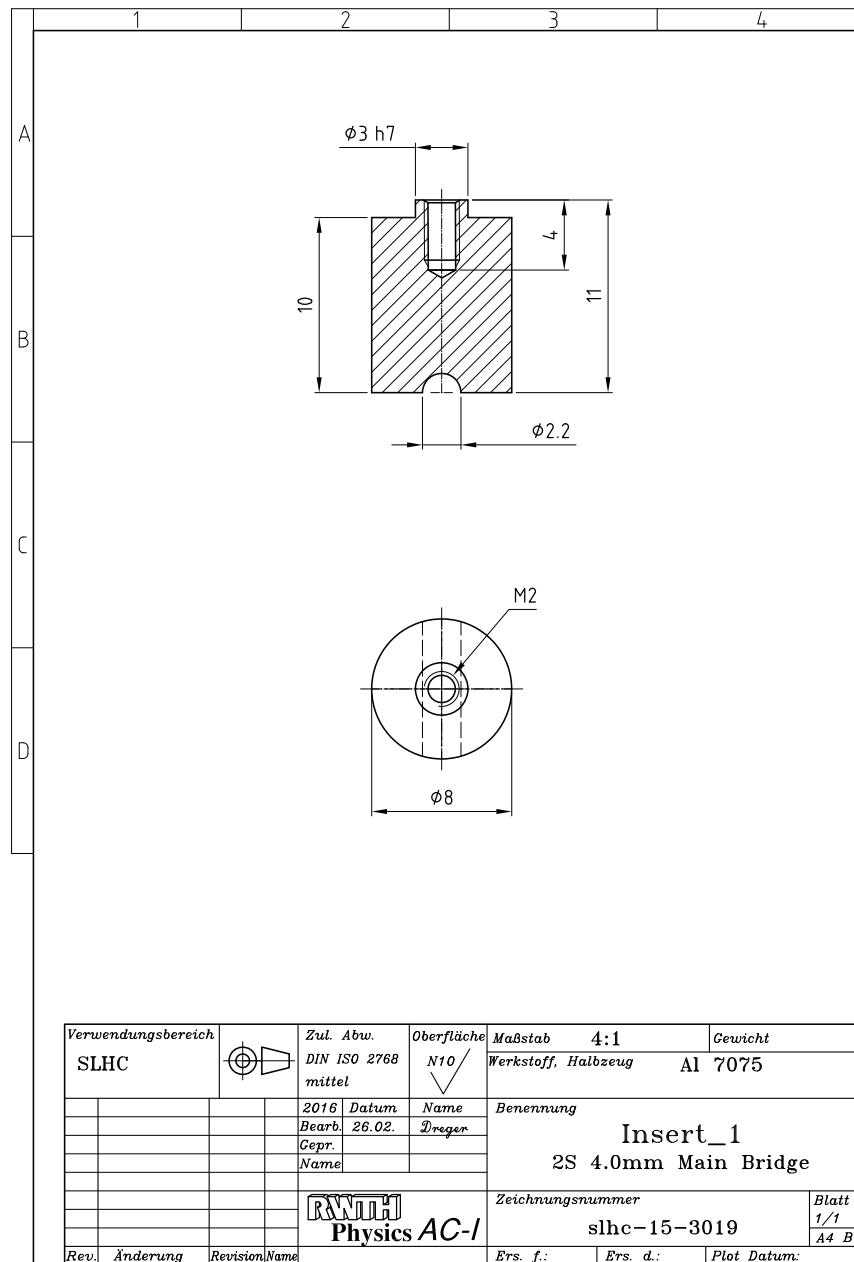


Figure A.1.: Technical drawing of the top part of the TEDD 2S module cooling insert with purely cylindrical design. This insert design was used in the test setup for the thermal measurements with the 2S module.

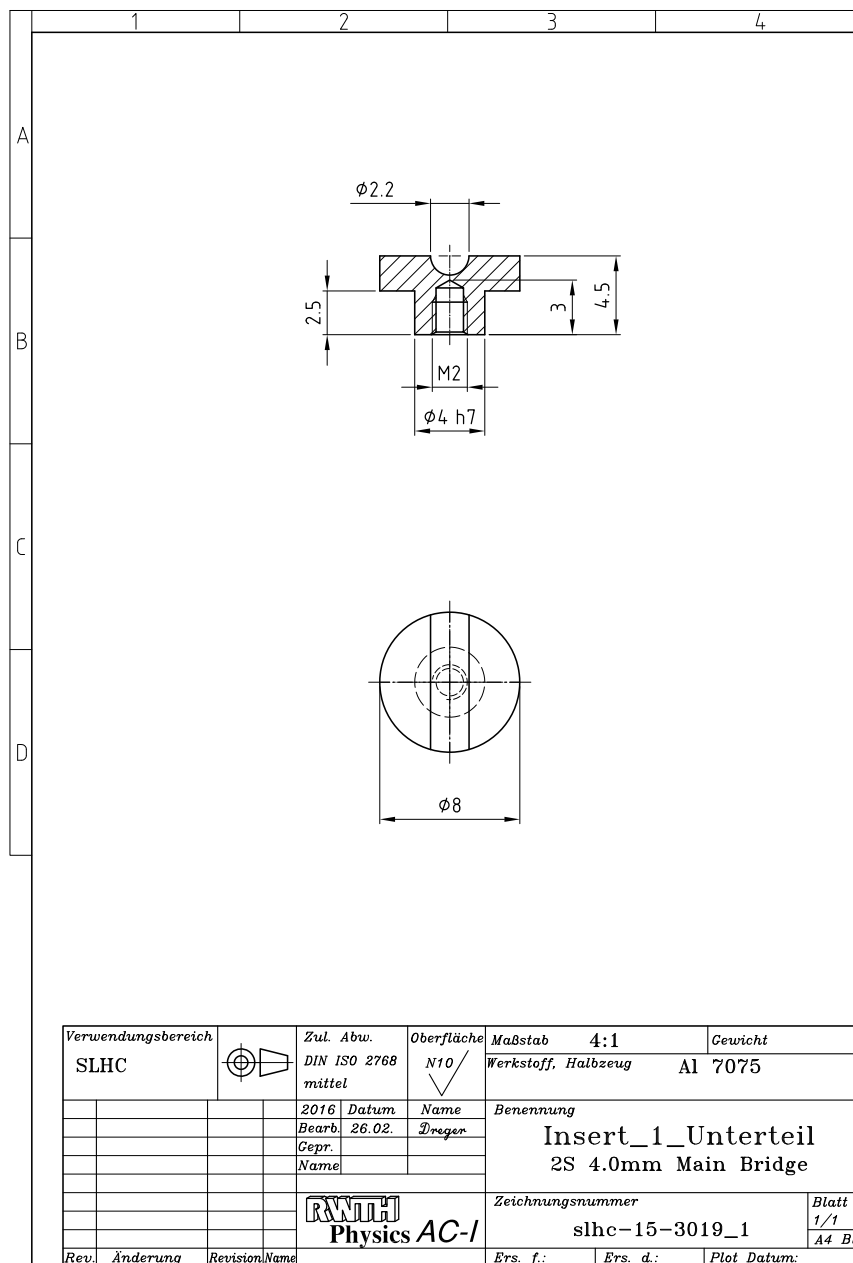


Figure A.2.: Technical drawing of the bottom part of the TEDD 2S module cooling insert with purely cylindrical design. This insert design was used in the test setup for the thermal measurements with the 2S module.







## B. Thermistor Positions for the 2S Modules

Figure B.1 shows the coarse positions, color codes, and the indices of the thermistors on the 2S thermal dummy modules. Blue markers refer to the thermistors glued to the inserts. The green markers refer to the thermistors glued to the spacers close to the screwing point. For the bare module measurements all hybrid thermistors and all sensor thermistors with index greater than 4 are not used.

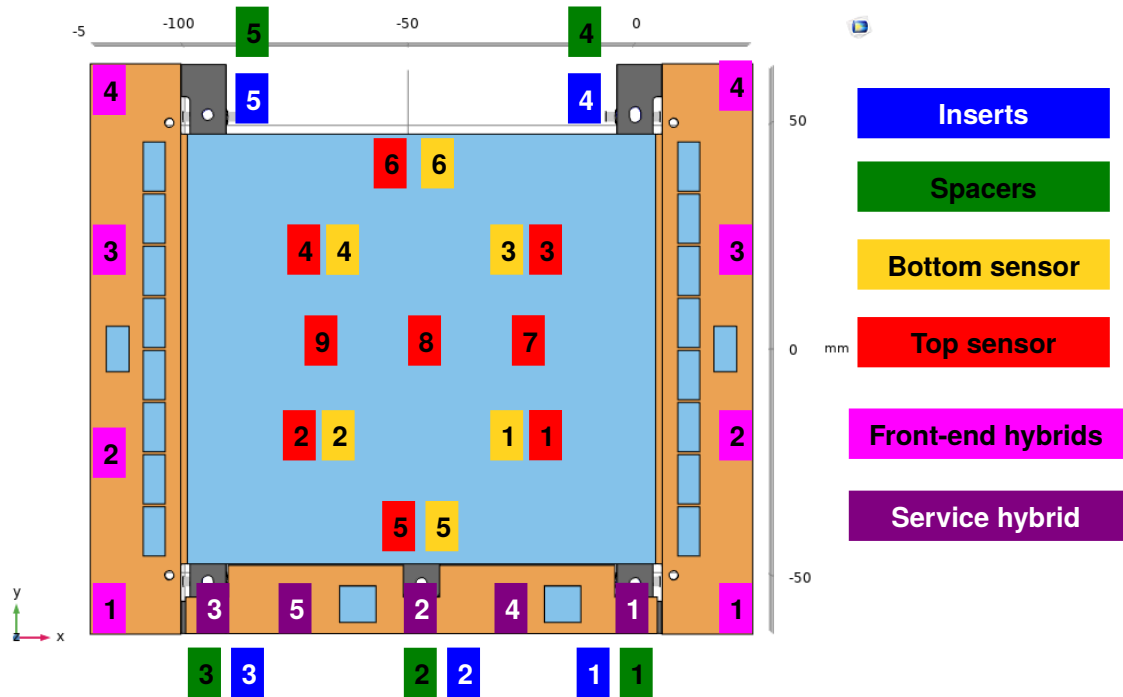


Figure B.1: Coarse positions, color codes, and indices of the thermistors on the 2S thermal dummy module. The orange thermistors are positioned on the bottom sensor, which is not shown, at the same  $xy$ -position.



## C. Parameters of the Thermal FE Simulation for the 2S Module

Table C.1.: Table of the parameters used in the thermal FE models and simulations.

| Quantity                                    | Description                                               | Value                                  |
|---------------------------------------------|-----------------------------------------------------------|----------------------------------------|
| Silicon sensors                             |                                                           |                                        |
| $k_{\text{Si}}$                             | Thermal conductivity of silicon                           | 130 W/m/K                              |
| $d_{\text{sensor}}$                         | Total thickness of the silicon sensor                     | 320 $\mu\text{m}$                      |
| $d_{\text{sensor, active}}$                 | Active thickness of the silicon sensor                    | 200 $\mu\text{m}$ or 290 $\mu\text{m}$ |
| Glue-Kapton-glue layer                      |                                                           |                                        |
| $k_{\text{glue-Kapton-glue}}$               | Thermal conductivity of the glue-Kapton-glue layer        | 0.3 W/m/K                              |
| $d_{\text{glue-Kapton-glue}}$               | Thickness of the glue-Kapton-glue layer                   | 65 $\mu\text{m}$                       |
| Aluminum carbon fiber spacers               |                                                           |                                        |
| $k_{\text{AlCF},\parallel}$                 | Thermal conductivity in the carbon fiber plane            | 230 W/m/K                              |
| $k_{\text{AlCF},\perp}$                     | Thermal conductivity through the carbon fiber plane       | 120 W/m/K                              |
| Thermal contact between inserts and spacers |                                                           |                                        |
| $h_{\text{spacers, inserts}}$               | Heat transfer coefficient between spacers and insert      | 10 kW/m <sup>2</sup> /K                |
| Inserts and cooling pipes                   |                                                           |                                        |
| $k_{\text{insert}}$                         | Thermal conductivity of Al 7075-T651                      | 130 W/m/K                              |
| $k_{\text{glue, insert}}$                   | Thermal conductivity of the glue                          |                                        |
|                                             | in test setup model                                       | 0.4 W/m/K                              |
|                                             | in thermal runaway model                                  | 0.2 W/m/K                              |
| $k_{\text{stainless steel}}$                | Thermal conductivity of stainless steel                   | 12 W/m/K                               |
| $d_{\text{glue, insert}}$                   | Thickness of the glue between insert and cooling pipe     | 20 $\mu\text{m}$                       |
| $d_{\text{wall}}$                           | Wall Thickness of the cooling pipe                        | 100 $\mu\text{m}$                      |
| $r_{\text{inner wall}}$                     | Inner radius of the cooling pipe                          | 1 mm                                   |
| $h_{\text{CO}_2}$                           | Heat transfer coefficient for the 2-phase CO <sub>2</sub> |                                        |
|                                             | lowest value                                              | 5 kW/m <sup>2</sup> /K                 |
|                                             | highest value                                             | 10 kW/m <sup>2</sup> /K                |
| Hybrids                                     |                                                           |                                        |
| $k_{\text{PCB}}$                            | Thermal conductivity of flex PCBs (FEH and SEH)           | 49 W/m/K                               |
| $k_{\text{K13D2U},\parallel}$               | Thermal conductivity in the carbon fiber plane            | 250 W/m/K                              |
| $k_{\text{K13D2U},\perp}$                   | Thermal conductivity through the carbon fiber plane       | 0.5 W/m/K                              |
| $k_{\text{K13C2U},\parallel}$               | Thermal conductivity in the carbon fiber plane            | 188 W/m/K                              |
| $k_{\text{K13C2U},\perp}$                   | Thermal conductivity through the carbon fiber plane       | 0.4 W/m/K                              |

Table C.2.: Table of the power values used in the FE Simulation.

| Quantity                                      | Description                                                  | Value  |
|-----------------------------------------------|--------------------------------------------------------------|--------|
| $P_{\text{sensor, 4.0mm}}(-20^\circ\text{C})$ | Power of one sensor for the 2S module at $-20^\circ\text{C}$ |        |
|                                               | with active sensor thickness of $200\ \mu\text{m}$           | 0.32 W |
|                                               | with active sensor thickness of $290\ \mu\text{m}$           | 0.46 W |
| $P_{\text{DC-DC (BPOL12V)}}$                  | Inefficiency of the first-stage DC-DC-converter              | 0.9 W  |
| $P_{\text{DC-DC (BPOL2V5)}}$                  | Inefficiency of the second stage DC-DC-converter             | 0.9 W  |
| $P_{\text{opto-part}}$                        | Heat load of the VTRX+ and LpGBT                             | 0.80 W |
| $P_{16\ \text{CBCs}}$                         | Power of 16 CBC ASICs                                        | 2.20 W |
| $P_{2\ \text{CICs}}$                          | Power of 2 CIC ASICs                                         | 0.40 W |

## D. Temperature Behavior during Power Switching

The behavior of the 2S module when being turned on and off is interesting in order to estimate the thermal stress the module is exposed to due to the spontaneously changing heat load and the following temperature changes. In order to measure the behavior of the temperature change, the full 2S module is cooled at a nominal CO<sub>2</sub> temperature of  $-30^{\circ}\text{C}$  and an ambient temperature of  $-13^{\circ}\text{C}$  with all powers off. Then the powers of all components are switched on at once with nominal values and the temperatures of the module are measured versus time. Once the module has reached stable temperatures, the powers are switched off again at once. The evolution of the average temperatures with time during the turn-on and turn-off are plotted in Figures D.1 and D.2 on the left side, respectively. In both cases, the temperature changes immediately after the power switch with a relatively high rate and the temperatures eventually level out a stationary temperature. In the turn-on case, a relatively stable temperature situation is reached after approximately 2.5 minutes, and in the turnoff case after approximately 4.5 minutes. For each component, the average temperature change rate  $\dot{T} = \Delta T_{\text{component}} / \Delta t$  is computed and plotted in Figures D.1 and D.2 for the turn-on and the turn-off, respectively. For the front-end hybrids, both sensors, spacers, and inserts the absolute values of the temperature change rate is below 7 K/min in both cases, the turn-on and turn-off case. The average temperature change rate of the service hybrid is significantly higher than for the other components. Its average maximum value is 17 K/min, whereas individual points on the service hybrid have even higher values. The temperature change rate at the single measurement points on the service hybrid is shown in Figure D.4. The absolute values of the temperature change rate stays below 13 K/min for the three measurement points 1, 2, and 3, located over the glue connection to the spacers. For the two measurement points 4 and 5 in between, the maximum absolute values of the temperature change rate exceed 20 K/min, with up to 25 K/min at measurement point 4 because of their relatively large distance to the cooling points and the low heat capacity of the service hybrid.

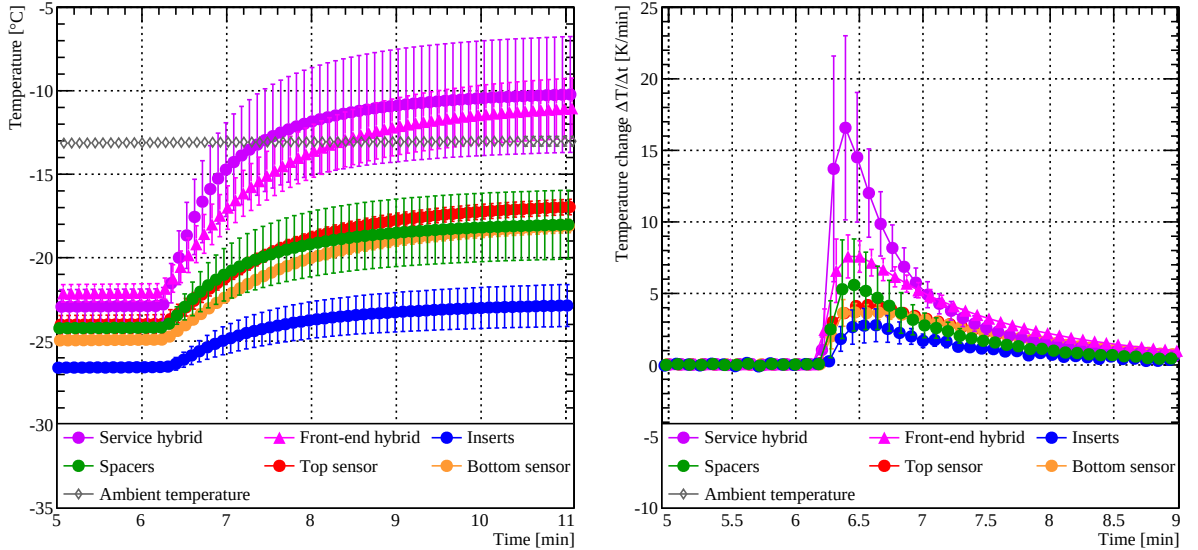


Figure D.1.: Left: evolution of the average temperatures of the components during power turn-on. Right: average temperature change rate  $\dot{T} = \Delta T_{\text{component}} / \Delta t$  during the power turn-on process. The error bars show the standard deviation of the temperatures on each component.

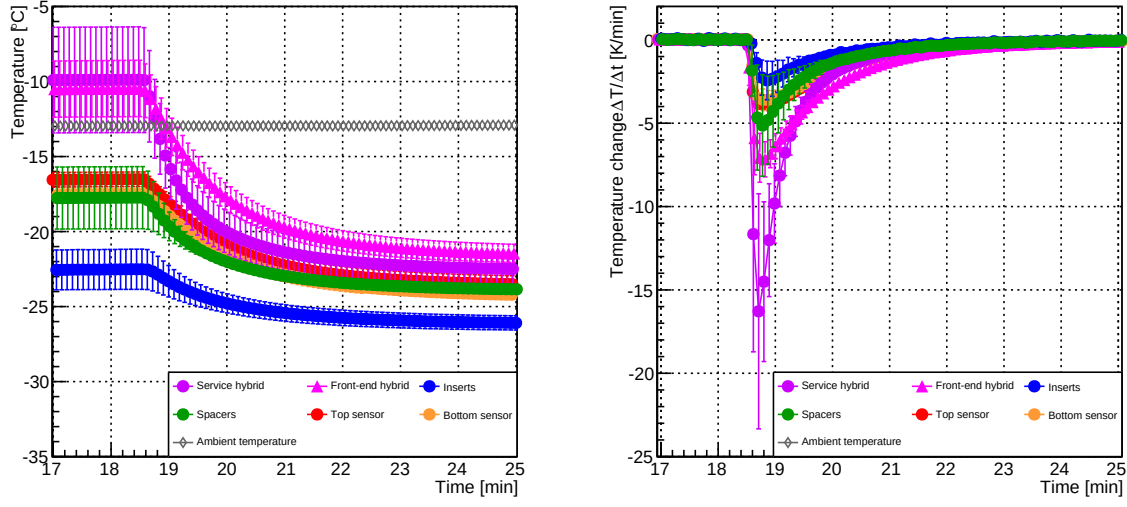


Figure D.2.: Left: evolution of the average temperatures of the components during power turn-off. Right: average temperature change rate  $\dot{T} = \Delta T_{\text{component}} / \Delta t$  during the power turn-off process. The error bars show the standard deviation of the temperatures on each component.

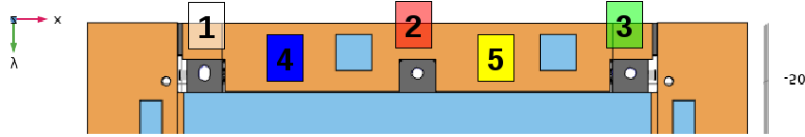


Figure D.3.: Temperature measurement points on the service hybrid.

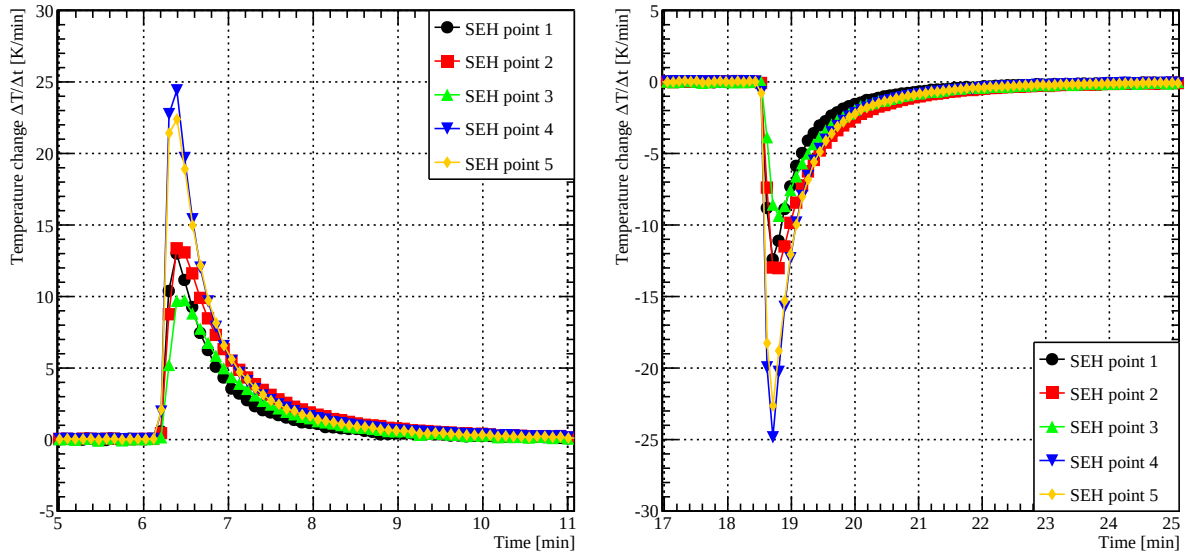


Figure D.4.: Left: temperature change rate at the single measurement points of the service hybrid during power turn-on. Right: temperature change rate of the single measurement points of the service hybrid during power turn-off. The position of the measurement points is shown in Figure D.3.



## E. Thermal Contact between Spacers and Inserts

The thermal resistance and the heat transfer coefficient between the spacers and the 2S inserts at the 2S module mounting points was measured with the 2S dummy bare module 1. The screw connection between the inserts and the spacers is made with a M2 screw with a thread length of 3 mm and an Allen key screw head. The measurements were done on inserts without the additional cut-out. Two measurement series were recorded, one with a washer for the screw and one in the unrealistic scenario without a washer. The measurements were performed at a CO<sub>2</sub> temperature of 0 °C. The power of each sensor was in the order of 0.7 W. Each measurement point was taken in the state of thermal equilibrium with the ambient. The first measurement point was taken at a torque of 1 cNm and the torque of the screw was increased step-wise in steps of 2 cNm up to 15 cNm. As the thermal contact of the module to the cooling system got better with higher screw torque, the power of the module  $P_{\text{module}^{\text{torque}}}$  had to be adjusted after each step to stay in thermal equilibrium with the ambient. For the analysis of the thermal resistance, it was assumed that the power of the module is equally distributed amongst the five cooling inserts. The thermal resistance  $\alpha_{\text{screw point}}$  of one mounting point is then calculated for each torque applied as

$$\alpha_{\text{screw point}} = \frac{1}{5} \sum_{i=1}^5 \frac{T_{\text{spacer},i} - T_{\text{insert},i}}{P_{\text{module}^{\text{torque}}}/5} \quad (\text{E.1})$$

where  $T_{\text{spacer},i}$  and  $T_{\text{insert},i}$  are the temperatures of the five inserts and the five spacer screwing points. The measured values are shown in Figure E.1 (left). For the measurement with the washers the thermal resistances start at approximately 5 K/W for low torque values and improve steadily until they level out at values of 2.6 K/W for torques higher than 9 cNm. The value measured at a torque of 9 cNm,  $\alpha_{\text{screw point}} = 3.1 \text{ K/W}$ , is well compatible with the value listed in Equation 7.27. The thermal resistance without any washer is worse by a factor of about 2 or higher. The average heat transfer coefficient of the screw connection  $\text{htc}_{\text{screw point}}$  is calculated by taking into account the area of the contact surface  $A_{\text{contact}}$  which is given by the full cross section of the cylindrical insert with radius  $r_{\text{insert}} = 4 \text{ mm}$ , where the cross sectional area with radius  $r_{\text{nipple}} = 1.25 \text{ mm}$  of the insert nipples is subtracted:

$$A_{\text{contact}} = \pi (r_{\text{insert}}^2 - r_{\text{nipple}}^2) = 4.5 \text{ mm}^2. \quad (\text{E.2})$$

This value is about 10 % smaller for the screw points with the long hole in the spacer, which is accounted for in the calculation. The average value  $\text{htc}_{\text{screw point}}$  is then calculated as

$$\text{htc}_{\text{screw point}} = \frac{1}{5} \sum_{i=1}^5 \frac{P_{\text{module}^{\text{torque}}}/5}{A_{\text{contact},i} \cdot (T_{\text{spacer},i} - T_{\text{insert},i})}. \quad (\text{E.3})$$

The measured values are shown in Figure E.1 (right). For the measurement with the washers the heat transfer coefficient levels out at values slightly larger than  $\text{htc}_{\text{screw point}} = 10 \text{ kW/m}^2/\text{K}$ . At the standard value for the torque of 9 cNm used in this thesis the heat transfer coefficient is

$$\text{htc}_{\text{screw point}}(9 \text{ cNm}) = 8.5 \text{ kW/m}^2/\text{K}.$$

The heat transfer coefficient of the measurement without washers is significantly lower. The value of  $\text{htc}_{\text{screw point}} = 10 \text{ kW/m}^2/\text{K}$  is the value which was used in all FE simulations for the 2S module presented in this thesis.

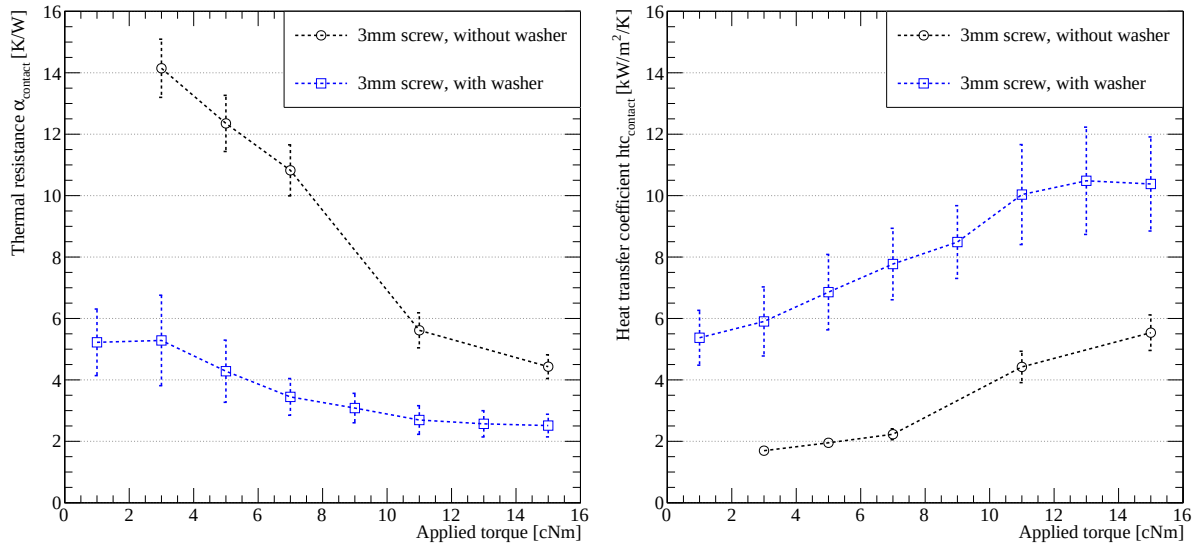


Figure E.1.: Left: measured average thermal resistance between inserts and spacers versus the applied torque to the screws. Right: average heat transfer coefficient between inserts and spacers calculated from the thermal resistances (left) taking into account the contact surface between insert and spacer. The error bars denote the RMS of the measurements.

## F. Additional Plots with Maps of the TEDD

### Reference Powers

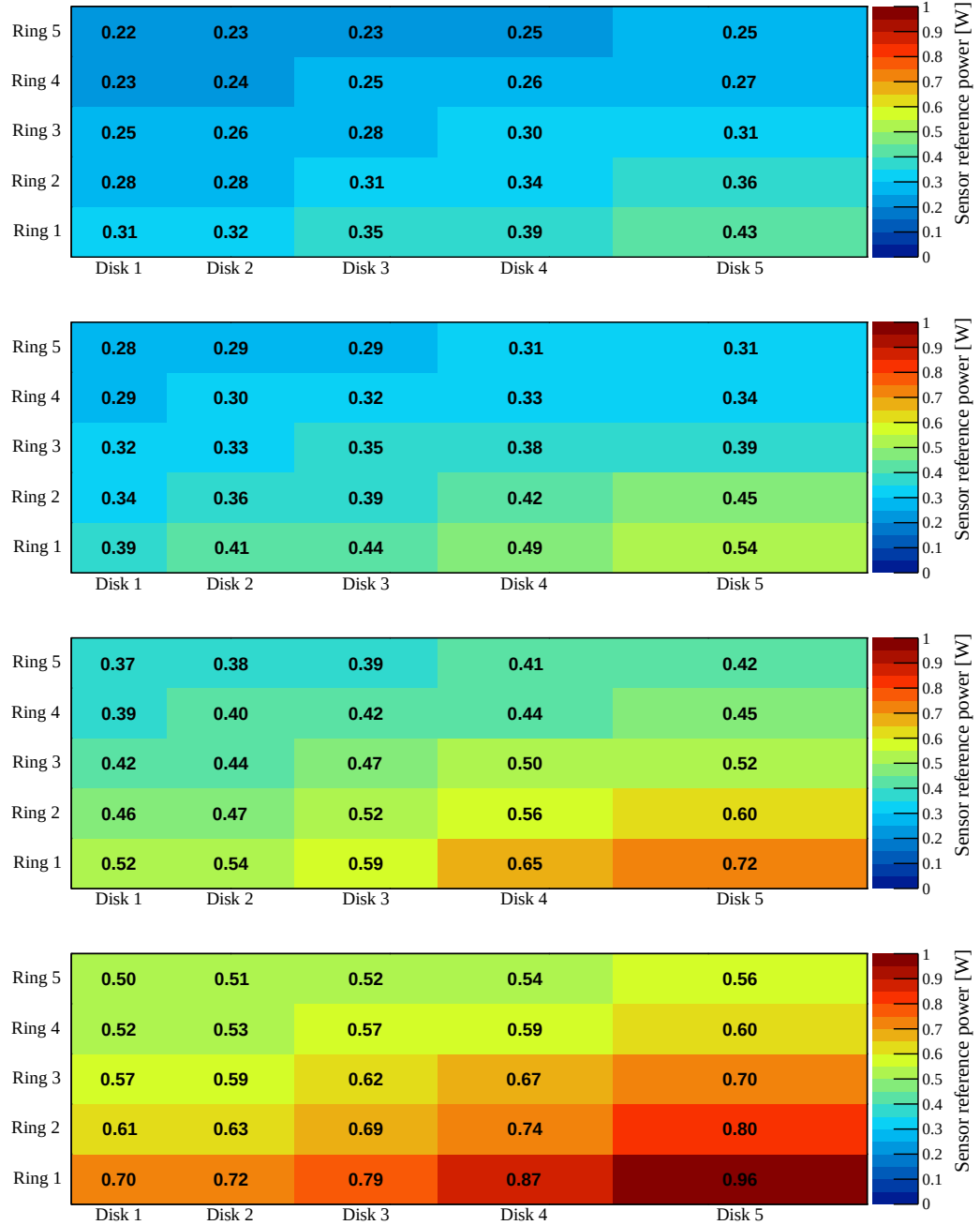


Figure F.1.: Calculated reference powers in the TEDD for the four scenarii described in Section 7.12.3. The figures refer from top to bottom to the tkLayout-scenario, Scenario 1, Scenario 2 a), and Scenario 2 b).

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|         |           |           |           |           |           |
|---------|-----------|-----------|-----------|-----------|-----------|
| Ring 15 | <b>76</b> | <b>76</b> | <b>76</b> | <b>76</b> | <b>76</b> |
| Ring 14 | <b>72</b> | <b>72</b> | <b>68</b> | <b>68</b> | <b>68</b> |
| Ring 13 | <b>64</b> | <b>64</b> | <b>64</b> | <b>64</b> | <b>64</b> |
| Ring 12 | <b>60</b> | <b>60</b> | <b>56</b> | <b>56</b> | <b>56</b> |
| Ring 11 | <b>52</b> | <b>52</b> | <b>52</b> | <b>52</b> | <b>52</b> |
|         | Disk 1    | Disk 2    | Disk 3    | Disk 4    | Disk 5    |

Figure F.2.: Number of 2S modules per TEDD ring. The first and second double-disk have a slightly different geometry than the third, fourth, and fifth, and thus the number of modules is slightly different between the double-disks. The overall number of 2S modules in one TEDD is 1596.

## Thermal Runaway Maps for tkLayout-Scenario with the Cylindrical Insert

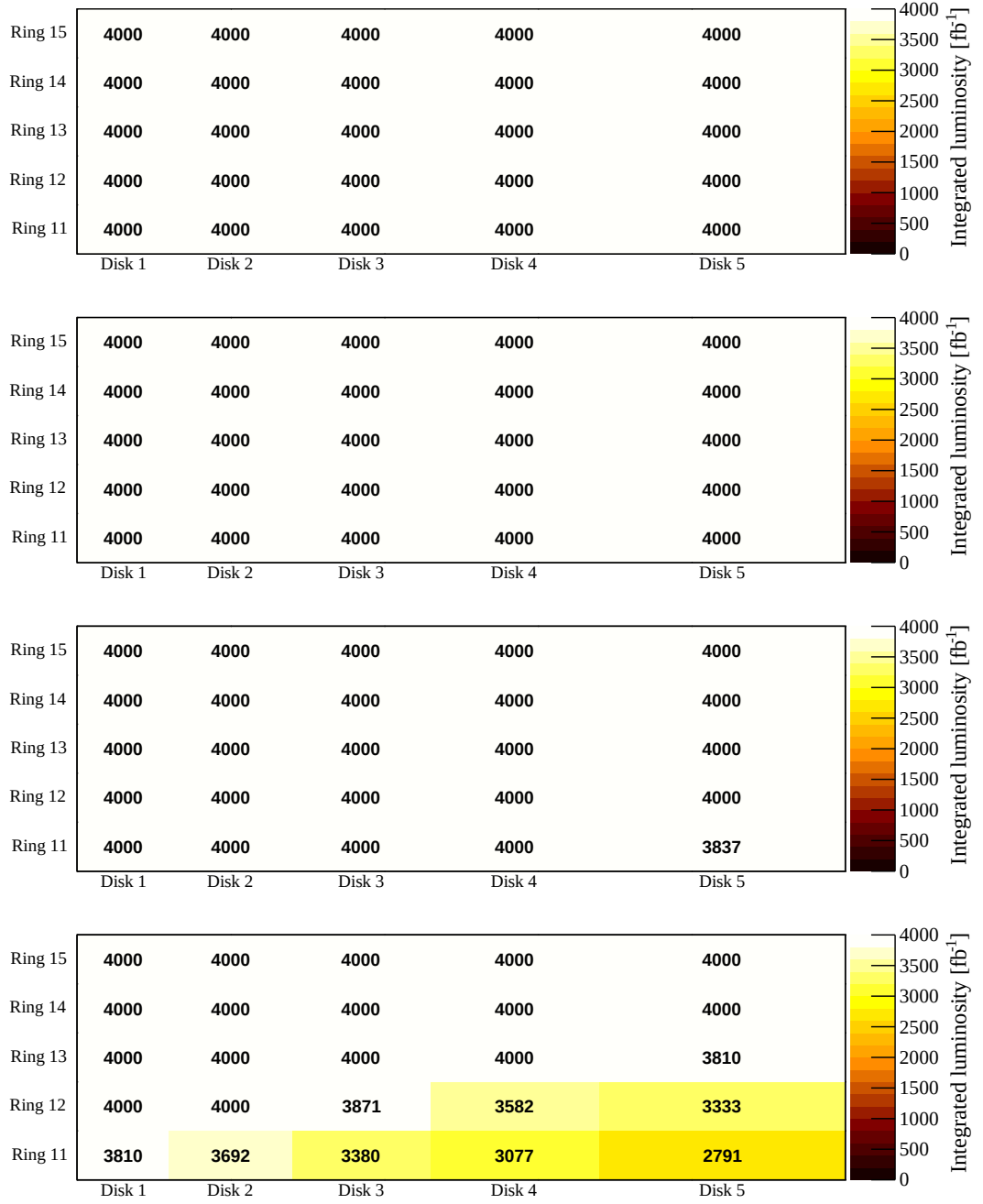


Figure F.3.: Thermal runaway maps of the TEDD2S subdetector with the integrated luminosity  $\mathcal{L}_{\text{int}}^{\text{runaway}}$  per module position for the tk-Layout-Scenario described in Section 7.12.3. The plots refer from top to bottom to CO<sub>2</sub> temperatures of -37.5 °C, -35 °C, -33 °C, and -30 °C.

## Thermal Runaway Maps for Scenario 1 with the Cylindrical Insert

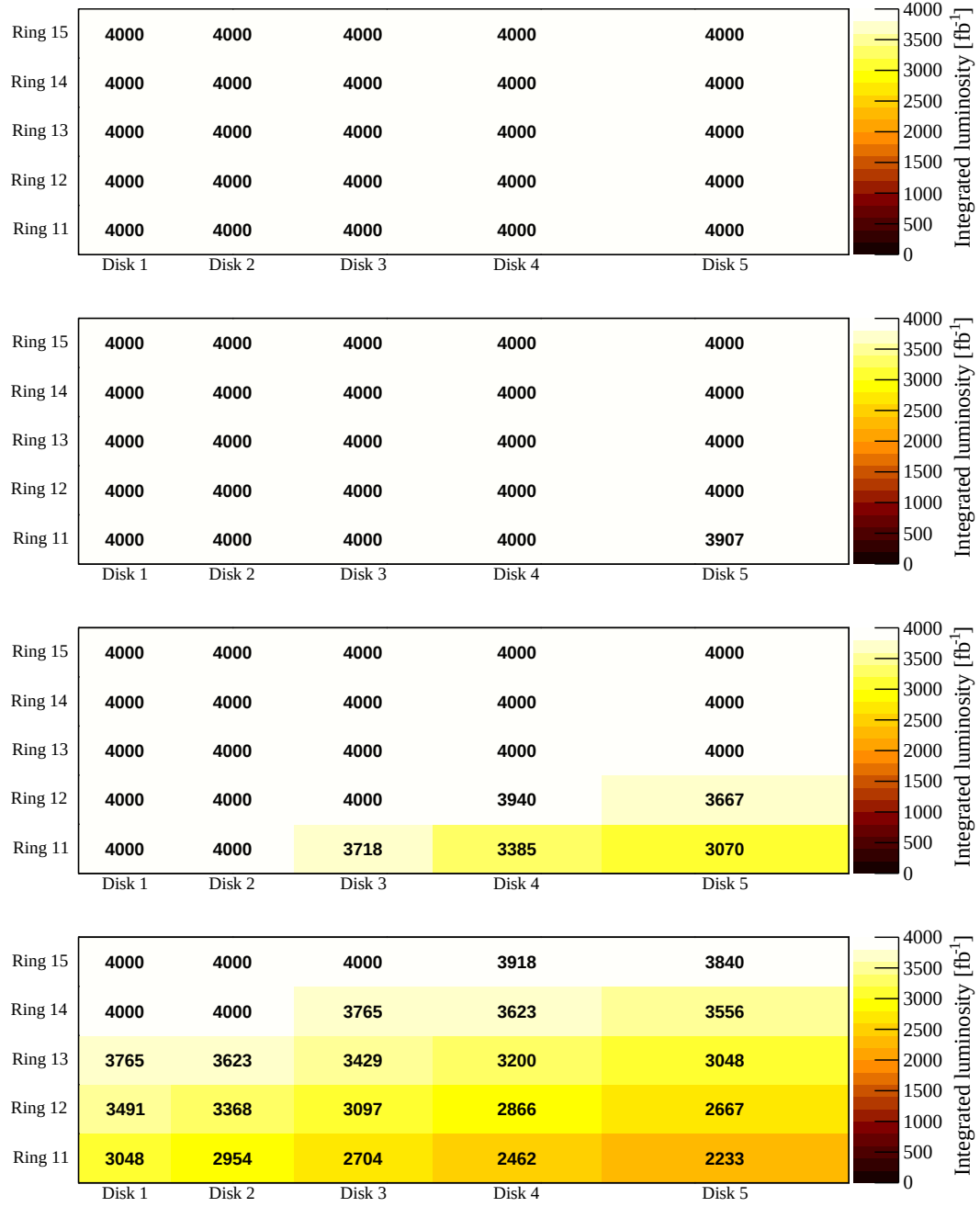


Figure F.4.: Thermal runaway maps of the TEDD2S subdetector with the integrated luminosity  $\mathcal{L}_{\text{int}}^{\text{runaway}}$  per module position for the Scenario 1 described in Section 7.12.3. The plots refer from top to bottom to CO<sub>2</sub> temperatures of -37.5 °C, -35 °C, -33 °C, and -30 °C.

## Thermal Runaway Maps for Scenario 2 with the Cylindrical Insert

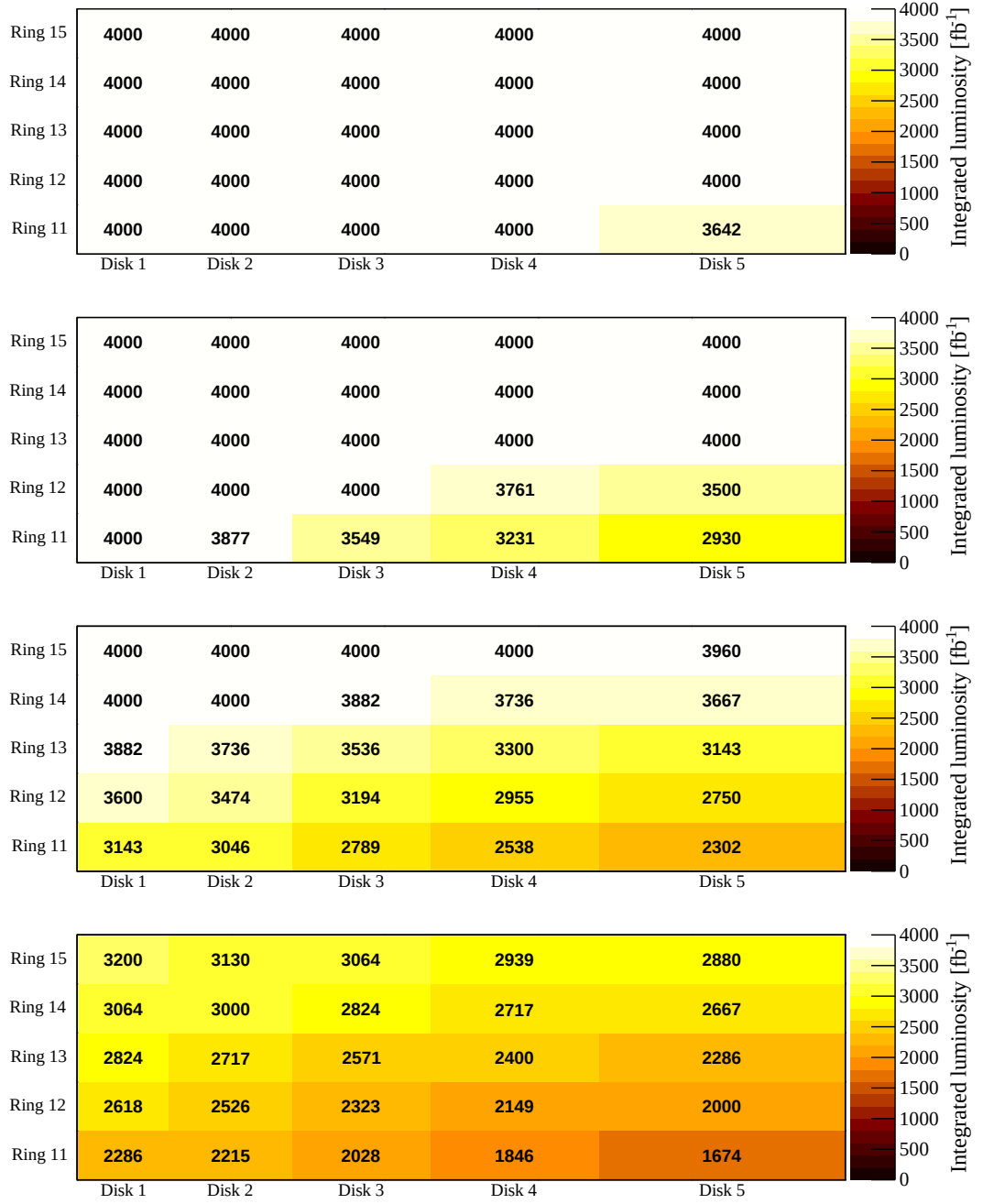


Figure F.5.: Thermal runaway maps of the TEDD2S subdetector with the integrated luminosity  $\mathcal{L}_{\text{int}}^{\text{runaway}}$  per module position for the Scenario 2 described in Section 7.12.3. The plots refer from top to bottom to CO<sub>2</sub> temperatures of  $-37.5^\circ\text{C}$ ,  $-35^\circ\text{C}$ ,  $-33^\circ\text{C}$ , and  $-30^\circ\text{C}$ .

## Thermal Runaway Maps for tkLayout-Scenario with the Foot-Insert

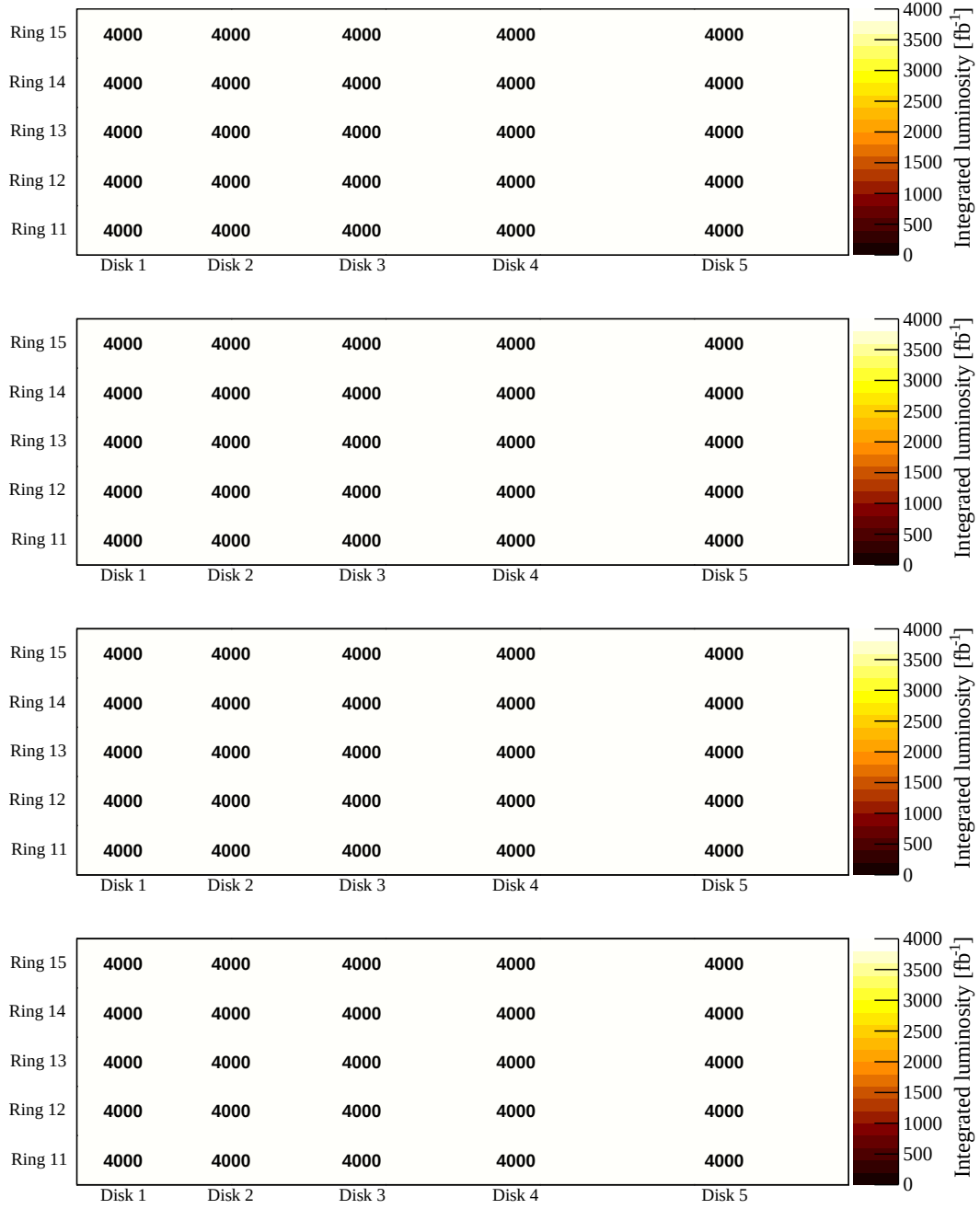


Figure F.6.: Thermal runaway maps of the TEDD2S subdetector with the integrated luminosity  $\mathcal{L}_{\text{int}}^{\text{runaway}}$  per module position for the tk-Layout-Scenario described in Section 7.12.3. The plots refer from top to bottom to  $\text{CO}_2$  temperatures of  $-37.5^\circ\text{C}$ ,  $-35^\circ\text{C}$ ,  $-33^\circ\text{C}$ , and  $-30^\circ\text{C}$ .



## Thermal Runaway Maps for Scenario 1 with the Foot-Insert

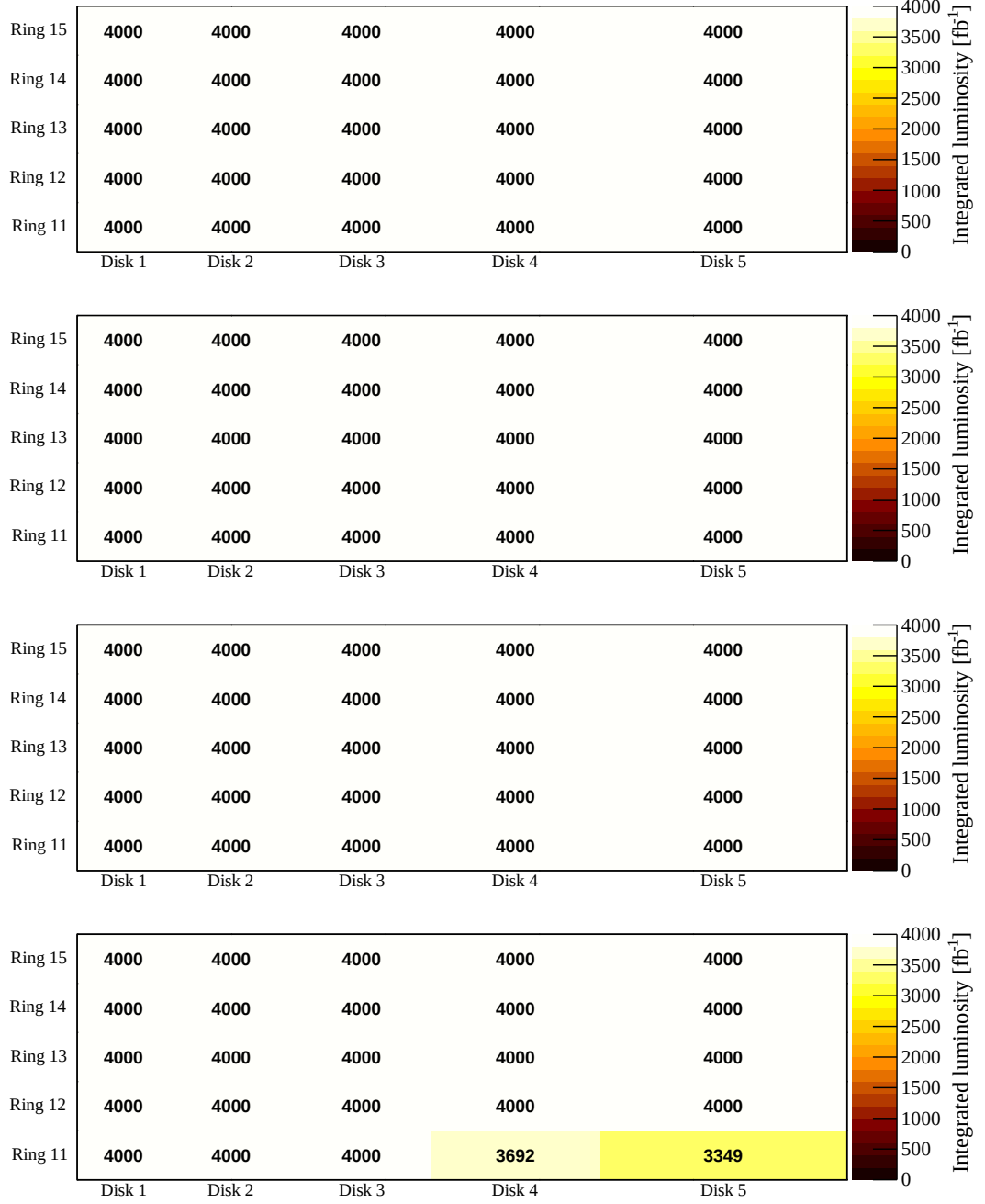


Figure F.7.: Thermal runaway maps of the TEDD2S subdetector with the integrated luminosity  $\mathcal{L}_{\text{int}}^{\text{runaway}}$  per module position for the Scenario 1 described in Section 7.12.3. The plots refer from top to bottom to CO<sub>2</sub> temperatures of -37.5 °C, -35 °C, -33 °C, and -30 °C.

## Thermal Runaway Maps for Scenario 2 with the Foot-Insert

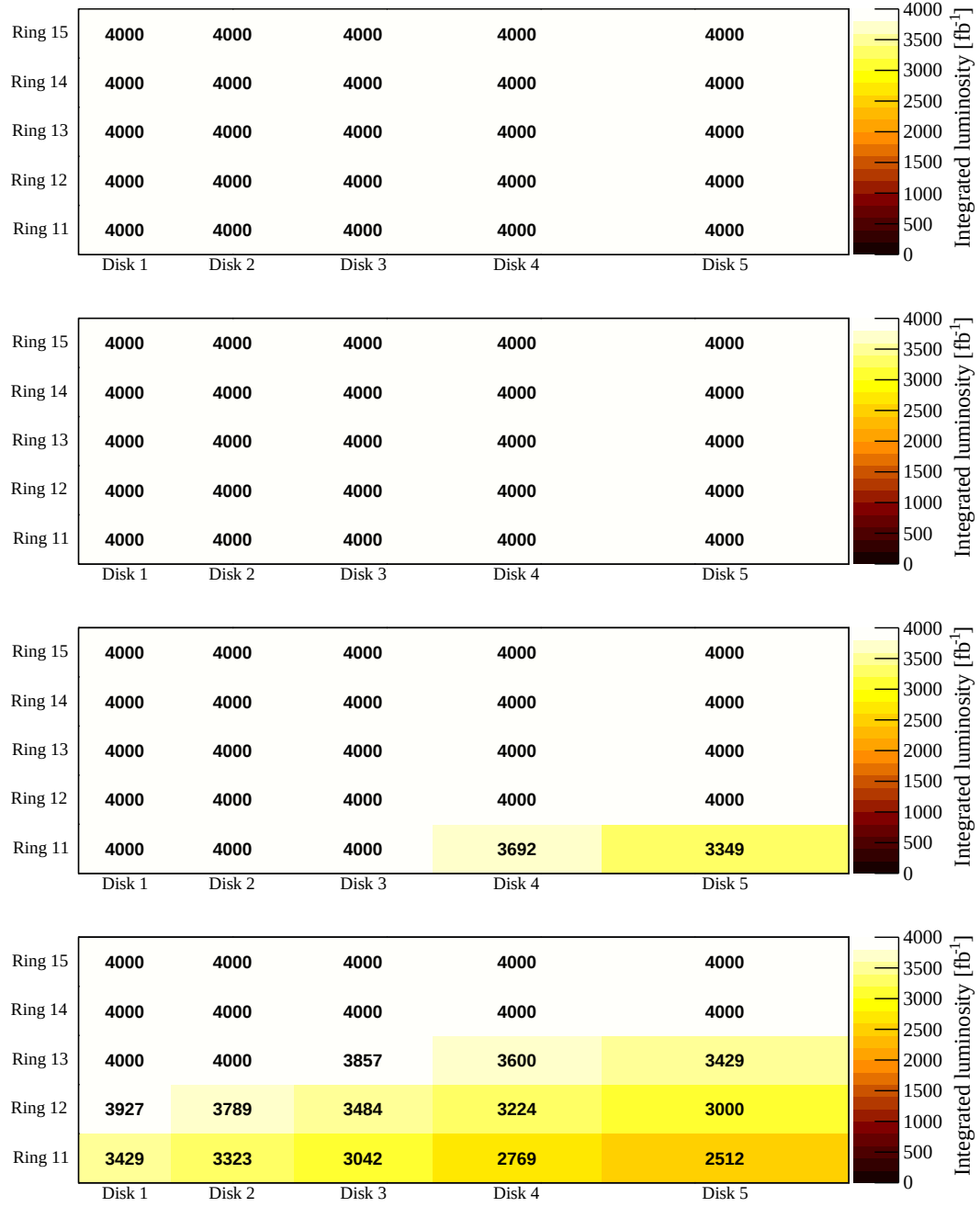


Figure F.8.: Thermal runaway maps of the TEDD2S subdetector with the integrated luminosity  $\mathcal{L}_{\text{int}}^{\text{runaway}}$  per module position for the Scenario 2 described in Section 7.12.3. The plots refer from top to bottom to CO<sub>2</sub> temperatures of -37.5 °C, -35 °C, -33 °C, and -30 °C.

## G. More BPIX Data and Plots

### G.1. Formulas from the Module Power Variation

The fitted parabolic functions in Figure 8.9 are given by

$$T_{2.7W}^+(\phi) = (-4.8 \cdot 10^{-4} \phi^2 - 9.4) ^\circ\text{C} \quad (\text{G.1})$$

$$T_{3.1W}^+(\phi) = (-5.0 \cdot 10^{-4} \phi^2 - 8.3) ^\circ\text{C} \quad (\text{G.2})$$

$$T_{3.5W}^+(\phi) = (-5.2 \cdot 10^{-4} \phi^2 - 7.3) ^\circ\text{C} \quad (\text{G.3})$$

$$T_{4.2W}^+(\phi) = (-5.5 \cdot 10^{-4} \phi^2 - 5.4) ^\circ\text{C} \quad (\text{G.4})$$

$$T_{4.8W}^+(\phi) = (-5.7 \cdot 10^{-4} \phi^2 - 3.7) ^\circ\text{C}, \quad (\text{G.5})$$

for the plus loop and by

$$T_{2.7W}^-(\phi) = (-4.7 \cdot 10^{-4} \phi^2 - 10.7) ^\circ\text{C} \quad (\text{G.6})$$

$$T_{3.1W}^-(\phi) = (-5.0 \cdot 10^{-4} \phi^2 - 9.6) ^\circ\text{C} \quad (\text{G.7})$$

$$T_{3.5W}^-(\phi) = (-5.2 \cdot 10^{-4} \phi^2 - 8.7) ^\circ\text{C} \quad (\text{G.8})$$

$$T_{4.2W}^-(\phi) = (-5.6 \cdot 10^{-4} \phi^2 - 6.8) ^\circ\text{C} \quad (\text{G.9})$$

$$T_{4.8W}^-(\phi) = (-5.8 \cdot 10^{-4} \phi^2 - 5.2) ^\circ\text{C}, \quad (\text{G.10})$$

for the minus loop where  $\phi$  is measured in units of  $^\circ$ . The fitted functions in units of cm are given by

$$T^+(x) = (-2.5 \cdot 10^{-5} x^2 - 8.1) ^\circ\text{C} \quad (\text{G.11})$$

$$T^-(x) = (-2.4 \cdot 10^{-5} x^2 - 9.5) ^\circ\text{C} \quad (\text{G.12})$$

$$T^{\text{mean}}(x) = (-2.5 \cdot 10^{-5} x^2 - 8.8) ^\circ\text{C} \quad (\text{G.13})$$

where  $x$  is the position on the cooling loop in units of cm.

## G.2. Leakage Current Values in BPIX

This section gives an overview of the leakage currents of BPIX which are plotted in Figure 8.17. The values were recorded at the time and the conditions which are listed in Table 8.1.

Table G.1.: Maximum leakage currents  $I_{\text{leakage}}^{\text{max}}$  and minimum leakage currents  $I_{\text{leakage}}^{\text{min}}$  per BPIX cooling loop normalized to the number of modules per power sector. The mean values are also given per BPIX layer. Fields without entries (—) refer to inactive power sectors which were out of operation.

| Layer               | Cooling loop | Barrel plus side                  |                                   |                                                                   | Barrel minus side                 |                                   |                                                                   |
|---------------------|--------------|-----------------------------------|-----------------------------------|-------------------------------------------------------------------|-----------------------------------|-----------------------------------|-------------------------------------------------------------------|
|                     |              | $I_{\text{leakage}}^{\text{max}}$ | $I_{\text{leakage}}^{\text{min}}$ | $I_{\text{leakage}}^{\text{max}}/I_{\text{leakage}}^{\text{min}}$ | $I_{\text{leakage}}^{\text{max}}$ | $I_{\text{leakage}}^{\text{max}}$ | $I_{\text{leakage}}^{\text{max}}/I_{\text{leakage}}^{\text{min}}$ |
| Layer 1             | L1D2PF       | 613                               | 424                               | 1.45                                                              | 606                               | 432                               | 1.40                                                              |
|                     | L1D1MF       | 622                               | 534                               | 1.16                                                              | 679                               | 580                               | 1.17                                                              |
|                     | L1D1PN       | 595                               | 522                               | 1.14                                                              | 615                               | 503                               | 1.22                                                              |
|                     | L1D2MN       | 600                               | 537                               | 1.12                                                              | 539                               | 411                               | 1.31                                                              |
| Mean values Layer 1 |              | 608                               | 504                               | 1.22                                                              | 610                               | 482                               | 1.28                                                              |
| Layer 2             | L2D2MF       | 323                               | 205                               | 1.58                                                              | 308                               | 201                               | 1.53                                                              |
|                     | L2D1PF       | 338                               | 221                               | 1.53                                                              | 329                               | 221                               | 1.49                                                              |
|                     | L2D1MN       | 277                               | 206                               | 1.34                                                              | 249                               | 216                               | 1.15                                                              |
|                     | L2D2PN       | 270                               | 194                               | 1.39                                                              | 267                               | 186                               | 1.44                                                              |
| Mean values Layer 2 |              | 302                               | 207                               | 1.46                                                              | 288                               | 206                               | 1.40                                                              |
| Layer 3             | L3D4MF       | 102                               | 97                                | 1.05                                                              | 103                               | 102                               | 1.01                                                              |
|                     | L3D2MN       | 100                               | 82                                | 1.22                                                              | 99                                | 87                                | 1.14                                                              |
|                     | L3D1MN       | 113                               | 89                                | 1.27                                                              | 103                               | 85                                | 1.21                                                              |
|                     | L3D3MN       | 98                                | 85                                | 1.15                                                              | 97                                | 78                                | 1.24                                                              |
|                     | L3D3PF       | 102                               | 115                               | 0.89                                                              | 106                               | 100                               | 1.06                                                              |
|                     | L3D1PF       | 107                               | 88                                | 1.22                                                              | 110                               | 88                                | 1.25                                                              |
|                     | L3D2PN       | —                                 | —                                 | —                                                                 | 92                                | 91                                | 1.01                                                              |
|                     | L3D4PN       | 99                                | 85                                | 1.16                                                              | 91                                | 76                                | 1.20                                                              |
| Mean values Layer 3 |              | 103                               | 92                                | 1.14                                                              | 100                               | 88                                | 1.14                                                              |
| Layer 4             | L4D1MF       | 63                                | 51                                | 1.24                                                              | 69                                | 52                                | 1.33                                                              |
|                     | L4D2PF       | 80                                | 49                                | 1.63                                                              | 64                                | 53                                | 1.21                                                              |
|                     | L4D3MF       | 64                                | 49                                | 1.31                                                              | 64                                | 53                                | 1.21                                                              |
|                     | L4D4PF       | 83                                | 57                                | 1.46                                                              | 74                                | 60                                | 1.23                                                              |
|                     | L4D1PN       | 72                                | 55                                | 1.31                                                              | 69                                | 55                                | 1.25                                                              |
|                     | L4D2MN       | —                                 | —                                 | —                                                                 | 64                                | 46                                | 1.39                                                              |
|                     | L4D3PN       | —                                 | —                                 | —                                                                 | 65                                | 52                                | 1.25                                                              |
|                     | L4D4MN       | 62                                | 49                                | 1.27                                                              | 56                                | 51                                | 1.10                                                              |
| Mean values Layer 4 |              | 71                                | 52                                | 1.37                                                              | 66                                | 53                                | 1.25                                                              |

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