Assembly and Characterization of a First Functional 2S Module for the CMS Phase-2 Upgrade at LHC

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1. Introduction

The main goal of physics is to get a deeper understanding of nature and the universe. The fundamental properties and composition of matter are studied in the field of particle physics, where complex experiments in the form of particle accelerators and detectors have achieved great success in testing the Standard Model of Physics. Just recently in 2012 experimental evidence for the Higgs Boson was provided after its theoretical postulation in 1964. This discovery was achieved at the largest and most powerful particle accelerator in existence, the Large Hadron Collider (LHC), which is situated at CERN (Conseil européen pour la recherche nucléaire) close to Geneva.

The LHC consists of a 27 km long accelerator ring, in which proton beams travel in opposite orbital directions with a center-of-mass energy of 14 TeV, close to the speed of light. At dedicated points, the two beams are crossed, which results in collisions of the protons. In order to draw conclusions about the underlying physical principals of the interactions, these events are recorded by particle detectors installed around the collision points.

One of the largest detectors at CERN is the Compact Muon Solenoid (CMS), which consists of different subdetectors to achieve high sensitivity to various particles to investigate a broad field of theories. An essential component of CMS is the tracking detector also called tracker. It is equipped with about 15000 silicon modules to precisely measure the path of charged particles close to the collision point. More details concerning the LHC and the CMS experiment are given in Chapter 2.

Despite the success of the Standard Model, there are several aspects, which at this point cannot be explained by it like the matter-antimatter asymmetry, dark matter or the non-zero mass of neutrinos. In order to further explore these phenomena, more data recorded at higher collision energies are required to increase the statistics and thereby the precision of the measurements.

For this purpose, the LHC will be upgraded to the High Luminosity LHC between 2024 and 2026, whereby the instantaneous luminosity will increase to $5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$, which is five times above the LHC’s design value. This will result in up to 200 simultaneous collisions of the protons, whose decay products need to be differentiated in the detector. In addition to that, the annual luminosity is supposed to increase to about 300 fb$^{-1}$. In the whole, this creates challenging demands on the detector systems, for example higher radiation tolerances and an increase of granularity to ensure a sufficient tracking performance.

Since the current tracker will not comply with these requirements, it will be replaced by an entirely new system as part of the Phase-2 Upgrade. In this context, two new types of silicon modules are being developed, which for the first time feed information from the tracker to the Level-1 trigger system to cope with the increased amount of data. In particular, 7680 of the so-called 2S modules will be installed in the tracker. Each module consists of a variety of components, like two silicon strip sensors, read-out electronics, and power-electronics. This allows the module to detect and process hits of particles, and to communicate them to the detector back-end. More details regarding the Phase-2 Upgrade and the 2S modules are presented in Chapter 3 of this thesis.

The production of the 2S modules will take place at several institutes in Europe, the United States, India, and Pakistan. One of the assembly centers is RWTH Aachen University, where 1000 2S modules will be built. However, prior to the production phase in 2022, intensive research is required to ensure that the modules can be assembled according
1. Introduction

to strict mechanical and electrical specifications for their operation in the detector. This thesis presents investigations of the tooling and the assembly procedure used at RWTH Aachen University in conjunction with the construction of the first functional module prototype of this assembly center. In this context, isolation strips need to be glued on the backside of the sensor, which requires an accurate execution to allow for a sufficient performance of the module. For this purpose, a dispensing gantry was commissioned, whereby an evaluation scheme was developed in order to assess the optimal parameters of the gantry. This will be presented in Chapter 4 together with a discussion about the challenges of this assembly step arising from the viscosity behavior of the glue during series production.

In Chapter 5, the assembly of the module prototype is described. For this purpose, the nominal assembly procedure is explained for each component. This is followed by a presentation of the modifications made to the tooling, either to improve the precision or the process of the assembly. Then, the experiences gained during the assembly of the module prototype are described, and the results in the form of mechanical properties are presented. Since the silicon sensors are the most sensitive and expensive components of the 2S module, a check of their intactness is of particular interest. For this purpose, leakage current measurements were carried out after each assembly step. The setup together with the results of this study are presented in Chapter 6.

Furthermore, noise measurements were carried out with the module after various assembly steps. These served the purpose of checking the performance of the readout electronics and the quality of the wire bonds, which connect the sensors with the readout system. Additionally, the noise of the fully assembled module was compared with the target value. The setup to conduct these measurements and the obtained results are presented in Chapter 7.

To finalize this thesis, Chapter 8 summarizes the obtained results and gives a brief outlook with regard to further module assembly activities.
2. The Large Hadron Collider and the Compact Muon Solenoid experiment

In particle physics, collider experiments are developed for the purpose of accelerating particles nearly to the speed of light and colliding them with each other. Through the analysis of the decay products, statistical statements can be made about the respective interactions to study the elementary structure of matter.

The world’s most powerful particle accelerator is the Large Hadron Collider (LHC), a circular synchrotron located at CERN, the European Organization for Nuclear Research near Geneva [1]. Since its commissioning in September 2008, many facets of the standard model have already been investigated and confirmed with its help. The discovery of the Higgs boson in July 2012 [2, 3] represents the biggest success so far, which was accomplished by CMS and ATLAS, the two largest experiments at CERN.

In the next sections, the LHC together with the CMS experiment is explained in more detail. Thereby, the following measures will be used to characterize the accelerator stages and the detector. The center of mass $\sqrt{s}$ of the colliding particles relates to the total energy provided for the collision. The instantaneous luminosity $\mathcal{L}$ relates to the rate of potential particle collisions per surface unit\(^1\). The integrated luminosity $L$, which is the time integral of $\mathcal{L}$, is a measure for the number of collected data and is expressed in units of inverse femtobarns.

2.1. The Large Hadron Collider

In order to be accelerated by the LHC, the particles require a minimum of speed, which is achieved by passing them through a cascade of pre-accelerators. A schematic overview of the various stages is depicted in Fig. 2.1. For simplification, the acceleration process is explained in the following for protons, but it refers equally to lead ions.

As a first step, the protons are extracted from hydrogen gas with an electric field and fed into the LINAC 2 (LINear ACcelerator), where they are accelerated to about $\sqrt{s} = 50$ MeV. Subsequently, they pass through two circular accelerators, the PS booster and the PS (Proton Synchrotron). Thereby, they are accelerated to an energy of 25 GeV, which corresponds to 99.93% of the speed of light. The last stage prior to the LHC is the SPS (Super Proton Synchrotron) in which the protons reach an energy of 450 GeV. During these different acceleration stages, the protons are separated into bunches which contain about $10^{11}$ protons each. Up to 2808 of these bunches are then filled into each of the two LHC beam pipes, where they circulate in opposite directions in the accelerator ring.

The ring of the LHC has a circumference of 26.7 km and is divided into eight sections, each consisting of an arched and a straight subsection. The former part is responsible for bending the particle beam on its circular trajectory by the Lorentz force which is realized by 1232 dipole magnets made out of Niobium-titanium coils [5]. These are operated at a temperature of 1.9 K to achieve a superconducting state. This allows for currents of 11 kA generating a magnetic field of 8.3 T which is directed upwards or downwards depending on the respective beam pipe.

\(^1\)The luminosity connects the cross-section $\sigma$ of certain decay process with the rate $\dot{N}$ of this processes by $\dot{N} = \mathcal{L} \cdot \sigma$. More information regarding the luminosity can be found in Ref. [4].
2. The Large Hadron Collider and the Compact Muon Solenoid experiment

![LHC Diagram](image)

Figure 2.1.: The LHC and its pre-accelerators in a schematic representation [6].

In the straight section of the ring, the so-called cavities are installed, which generate an alternating electric field to accelerate the particles to an energy of up to 7 TeV. In addition to that, 392 quadrupole magnets are used to concentrate the bunches on a cross-sectional size of up to $16 \times 16 \mu m^2$ right before the collision point, where the two beams are crossed and the particles collide. However, due to the small size of the protons, most of them pass each other or scatter elastically, which is not of interest for the experiment. Only 25 of the $10^{11}$ particles per bunch collide inelastically on average, assuming an instantaneous luminosity of $1 \cdot 10^{34} cm^{-2} s^{-1}$. The collision takes place at the so-called bunch crossing rate of 40 MHz.

To record collisions and to reconstruct the underlying physical processes, particle detectors are installed around the crossing points of the beams. At the LHC, the largest detectors are ALICE, ATLAS, CMS, and LHCb. ALICE (A Large Ion Collider Experiment) concentrates mainly on the generation and investigation of high temperature and energy density states that existed shortly after the Big Bang. For this purpose, lead ion collisions are analyzed at ALICE. LHCb is specialized in the search for asymmetries between matter and antimatter, for which it investigates decays, wherein b-quark are involved. ATLAS (A Toroidal LHC Apparatus) and CMS were both constructed as multi-purpose detectors to study a wide range of physics. Besides reviewing the Standard Model, they also search for new particles as proposed for example by supersymmetry. In the following, the CMS detector will be explained in more detail.

2.2. The CMS detector

The CMS detector is installed 100 m underground at the LHC interaction point 5 near the village of Cessy in France [7]. It has a radius of 7.5 m, a length of 28.7 m and a weight of about 14000 t, which makes it the heaviest experiment at the LHC. The detector is segmented into different layers or rather subdetectors as shown in the sketch in Fig. 2.2. The different subdetectors are arranged in cylindrical layers around the collision point and typically consist of a tubular barrel and two endcaps. The innermost layer is the tracking detector, also known as the tracker, which is divided into the inner pixel and the outer strip detector. Both of these systems are responsible for the precise measurement of the trajectory and the transversal momentum $p_T$ of the particle.
The CMS detector

Figure 2.2.: Schematic view of the CMS detector showing its subdetectors [8].

The silicon pixel detector

In the barrel of the pixel detector (BPix) 1184 pixel sensor modules are installed. It has a length of 548.8 mm and a radial distance $r$ of 30 mm to 160 mm from the collision point\(^2\). The forward region of the pixel system (FPix) is equipped with 672 modules that are mounted on each of the two endcaps. The particular location of the modules in the tracker is indicated in Fig. 2.3 with green bars. Each module is equipped with a sensor providing 66560 pixels with a pixel size of about $100 \times 150 \mu \text{m}^2$. Concerning the whole pixel detector, this amounts to about 125 million pixels covering an area of roughly $2 \text{m}^2$. Due to the high granularity of this subdetector, it is particularly suitable for the reconstruction of secondary vertices.

The silicon strip detector

In the outer tracker, modules with silicon strip sensors are installed. As indicated in Fig. 2.3 this part of the detector is divided into four partitions occupying a radial distance ranging from 20 cm up to 1.2 m. The part closest to the collision point is the inner barrel (TIB), which is accompanied by the inner discs (TID). The outer ‘shell’ of the tracker consists of the outer barrel (TOB) and the endcaps (TEC).

The strip sensors have a size of about $10 \times 10 \text{cm}^2$, strip lengths of 10 cm and a strip-to-strip distance, also called pitch, ranging from 80 $\mu \text{m}$ to 183 $\mu \text{m}$. The exact properties vary greatly between the individual modules depending on their location in the tracker. In total,

\(^2\)The CMS coordinate system is right-handed with its origin in the collision point. The $x$-axis pointing towards the center of the LHC, the $y$-axis pointing vertically upwards and the $z$-axis pointing along the anticlockwise LHC beam. The radial coordinate in the $x$-$y$ plane is measured by $r$ and the polar angle $\theta$ is defined in the $r$-$z$ plane. The azimuthal angle $\phi$ is measured from the positive $x$-axis in the $x$-$y$ plane. The pseudorapidity $\eta$ is calculated by $\eta = -\ln[\tan(\theta/2)]$ [7].
2. The Large Hadron Collider and the Compact Muon Solenoid experiment

Figure 2.3.: Schematic view of one quarter of the current CMS tracker in the $r$-$z$ plane. The pixel detector is shown in green while single and back to back mounted strip modules are depicted as red and blue segments [9].

29 versions with 15 different sensor variants in rectangular and trapezoidal geometry exist to optimize the geometrical coverage of the detector. In order to obtain a better three-dimensional reconstruction of the particle traces, some modules are mounted back-to-back to each other with a twist of 100 mrad. These modules are indicated as blue bars in Fig. 2.3 in contrast to the ordinary modules, which have a red color. In the whole 15148 modules are installed in the tracker, making it the largest silicon detector in the world with an active sensor area of 198 m$^2$.

The calorimeters

In the next layer starting at a radial distance of 1.2 m the calorimeters are installed, which measure the energy of incident particles by absorbing them. The electromagnetic calorimeter, ECAL for short, detects the energy of particles that interact via the electromagnetic interaction, like electrons or photons. For this detector type, crystalline lead tungstate (PbWO$_4$) is used to convert the kinetic energy of the particles into photons by scintillation. The photons are subsequently detected by avalanche photodiodes (APDs). In order to obtain a spatial resolution, the ECAL is divided into about 75000 individual segments. Hadrons like neutrons or pions, however, penetrate the crystals almost unimpeded and need to be detected by a separate hadronic calorimeter (HCAL), which is installed at a detector radius ranging from 1.8 m to 2.9 m. In the HCAL, the hadrons lose their energy by inelastic interaction with brass plates that are embedded in plastic scintillators to detect the resulting hadronic showers. In total, about 70000 of these scintillator tiles are installed in this subdetector.

The magnet

The next component of the CMS detector is the magnet, which is a solenoid coil with a length of 13 m and a diameter of 6 m. It is made out of aluminum reinforced Niobium-titanium wires and is operated at a temperature of about 4.5 K to reach its superconducting state. This enables currents of 19.4 kA flowing through the coil, resulting in a homogeneous magnetic field of 3.8 T. This field forces charged particles inside the detector onto a circular path due to the Lorentz force, whereby the radius of the curvature is used to determine the momentum and charge of the particle.
The muon chambers

The last layer of the CMS detector consists of the muon chambers, which start at a radius of 3.2 m. These are composed of the Drift Tubes (DT), Cathode Strip Chambers (CSC), and Resistive Plate Chambers (RPC) to detect the hardly interacting muons. The chambers themselves are enclosed in a 12500 t heavy iron return yoke, which is magnetized by the solenoid. This results in a Lorentz force acting on the muons. However, the muon trace is bent in the opposite direction as in the tracker since the yoke catches the outer magnetic field lines of the solenoid.

The trigger system

Another crucial component of CMS, which is not depicted in Fig. 2.2, is the trigger system. It is responsible for filtering out the physically interesting events at the bunch crossing frequency of 40 MHz. For this purpose, a hardware-based level-1 trigger is used to perform a first filtering with a maximum output rate of 100 kHz of temporarily stored events. Afterward, the data are processed by the software-based high-level trigger (HLT), whose algorithms analyze the events in more detail. It features an output rate of about 300 Hz, resulting in a fractional amount of data that is stored permanently.
3. The High Luminosity LHC, the Phase-2 Upgrade and the 2S module

3.1. The High Luminosity LHC

In order to investigate further aspects of the Standard Model, higher collision energies and frequencies are necessary to increase the probability of finding physically interesting events. At LHC this is achieved through various upgrade phases, in which the accelerator is equipped with improved components. A detailed schedule of these phases can be found in Appendix A.1.

During the first upgrade phase in 2015, the instantaneous luminosity was increased to $2 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$ by halving the bunch distance to 25 ns, while the center of mass was increased from 8 TeV to 13 TeV. In this still ongoing operation phase, called Run 2, the LHC has so far delivered an integrated luminosity of about 140 fb$^{-1}$ [10]. The next upgrade phase will take place from 2019 to 2020 during the Long Shutdown 2 of the LHC, whereupon the beam energy will rise to 14 TeV. Furthermore, the bunches will contain more particles to further increase the instantaneous luminosity. By that, it is planned to achieve an integrated luminosity of over 300 fb$^{-1}$ until the next, approximately two-year operation pause in 2024. During this Long Shutdown 3, the LHC will be prepared for its operation as High Luminosity LHC (HL-LHC), where it is planned to reach an instantaneous luminosity of $5-7.5 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$. In order to achieve this performance, which exceeds the original target luminosity by a factor of at least 5, various components need to be upgraded [12]. For example, the beam focusing inner triplet quadrupole magnets need to be replaced, as they reach their radiation tolerance. Thereby, a different superconducting material, Nb$_3$Sn, will be used. To increase the instantaneous luminosity, crab cavities will be installed to raise the overlap of the bunches at the collision point [12]. In the whole, it is expected to achieve an integrated luminosity of 3000 fb$^{-1}$ until the HL-LHC ends its operation scheduled in 2035.

3.2. The CMS Phase-2 Upgrade

3.2.1. The Phase-2 tracker

In order to exploit the strong increase in the instantaneous luminosity, CMS conducts the so-called Phase-2 upgrade, which represents a comprehensive revision of the entire detector. In this context, the tracker will be replaced by a new system for its operation at the HL-LHC. This requires an increased radiation tolerance of all components to withstand fluences of up to $9.6 \cdot 10^{14} \text{n}_{eq}/\text{cm}^{-2}$ in the inner layers of the outer tracker [11]. In addition to that, a higher channel density of the tracker is required to keep the channel occupancy below a percent (permille) level for the outer (inner) tracker. This is necessary to enable a sufficient tracking performance during high levels of pileup$^1$ of up to 140 (200) for an average instantaneous luminosity of $5 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$ ($7.5 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$). For this purpose, the so-called PS and 2S modules are being developed for the outer tracker.

$^1$This corresponds to the number of simultaneous particle collisions per bunch crossing.
The arrangement of the modules is depicted in Fig. 3.1, where the upper right quarter of the future tracker is shown in the r-z plane.

Figure 3.1.: Sketch of one quarter of the CMS Phase-2 tracker [11]. The different segments of the outer tracker are indicated together with the PS and 2S modules marked as blue and red lines, respectively. The modules of the pixel detector are indicated as green and yellow lines.

The PS modules are mounted in the inner layers of the barrel (TBPS) and in the end caps (TEDD) at a radial distance ranging from 200 mm to 600 mm. In the outer tracker a total of 5616 PS modules is installed, which are each equipped with two sensors mounted back-to-back with a certain distance from each other. The sensor on the front side of the module facing towards the collision point is a macro pixel sensor (P in PS) with a pixel size of approximately $1.5 \times 0.1 \text{mm}^2$. On the module back side, a strip sensor (S in PS) is mounted, which has a strip size of $25 \times 0.1 \text{mm}^2$. The total size of each sensor is about $5 \times 10 \text{cm}^2$. A schematic representation of the PS modules can be found in Appendix A.2.

The 7680 2S modules are installed in the outer tracker barrel (TB2S) and TEDD at radial distances between 600 mm and 1200 mm. In contrast to the PS modules, the 2S modules are equipped with two equal strip sensors on the front and backside, which have an active size of about $10 \times 10 \text{cm}^2$ and a strip pitch of 90 $\mu\text{m}$.

3.2.2. The $p_T$ module concept

Another important aspect of the Phase-2 Upgrade concerns the Level-1 trigger since the recognition of potentially interesting events becomes more challenging for the selection algorithms with the increased luminosity. Therefore, a new Level-1 trigger system is installed, which for the first time includes information from the tracker in its calculations to improve the discrimination power. For this purpose, the aforementioned 2S and PS modules are equipped with two sensors, which enables each module to evaluate the transverse momentum of incident particles individually. The measuring concept is illustrated in Fig. 3.2, which shows the cross-section of a 2S module, together with the trajectories of two particles with different transverse momenta.

In the first step of this $p_T$-evaluation, the module detects the hits of the particles in the sensor pair, which are indicated by blue colored strips in the picture. Subsequently, the readout logic uses the hits in the sensor passed first as a reference to calculate a selection window in the second sensor, indicated by the green blocks. Due to the bending of the particles' trajectories caused by the Lorentz force, only particles which exceed a certain $p_T$ threshold fall into this window. This is indicated by the left trajectory in Fig. 3.2.

For this mechanism to work at a bunch crossing rate of 40 MHz, a selection window corresponding to a $p_T$ of 2 GeV is chosen, which reduces the data sent to the trigger by roughly one order of magnitude.
Figure 3.2.: Illustration of the stub mechanism. The two particles originate from the common interaction point below the sensor pair. The blue blocks indicate the hit signals in the strip, whereas the green blocks correspond to the $p_T$ window [11].

If the readout logic finds the hit in the second sensor to be inside this window, it generates a so-called stub, which is the relevant information for the Level-1 trigger. The trigger then analyzes the stubs received from all the PS and 2S modules and transmits a trigger signal to the front-end, if certain particle signatures are found. This induces the full readout of the modules that sent the hit data stored in front-end pipelines to the back-end for further processing. The full readout is expected to happen at a rate of about 750 kHz. Since the strip window is made up of only a few strips, it is fine-adjusted in its width and offset by the readout logic depending on the place of installation of the respective module in the tracker. To reduce geometrical inefficiencies of the stub finding the PS modules in the high $|\eta|$ region of the barrel are slightly tilted, as shown in Fig. 3.1 of the detector layout.

In addition to that, the precise assembly of the sensors is of essential importance for the correct functioning of this mechanism. Therefore, the margins for sensor displacements amount to only a few hundredths of a millimeter, which is the reason for using a special assembly method, which will be explained in Chapter 4. Another essential parameter of the stub mechanism is the spacing of the two sensors. On the one side, a larger spacing results in larger window sizes and therefore higher resolutions of the $p_T$ cut since more strips are involved. On the other side, it increases the chance of accidental combinations of hits originating from different particles, especially near the collision point. Furthermore, it needs to be considered that spacers with a larger spacing have a higher impact on the material budget and that a large number of spacer variants is unfavorable for serial production. As a compromise of these arguments, the PS module is designed with a 1.6 mm, 2.6 mm, and 4.0 mm spacing, whereas the 2S module features a 1.8 mm and 4.0 mm spacing.

### 3.3. The 2S module

A first overview of the 2S module is given in the CAD drawing depicted in Fig. 3.3, which shows the assembled module on the left and an exploded view on the right side. The module design is optimized in regard to installation space and weight in order to increase the ‘density’ of modules in the tracker and to reduce the material budget. This results in a module size of about $145 \text{ mm} \times 125 \text{ mm} \times 18 \text{ mm}$ and a weight of 37 g [11].

**Silicon strip sensors**

The two silicon strip sensors need to fulfill special demands regarding the radiation hard-ness to comply with the HL-LHC operating conditions. Therefore, n-in-p doped silicon is used as sensor material, since its charge collection efficiency does not decrease as strongly
3. The High Luminosity LHC, the Phase-2 Upgrade and the 2S module

Figure 3.3.: 3D view of the assembled 2S module on the left and exploded view of the individual module components on the right [11].

...after irradiation in comparison with p-in-n doped silicon, which has been used so far [13]. The sensor thickness is currently under investigation but will be in the range of 200 µm and 320 µm. Depending on the thickness, the depletion voltage\(^3\) for unirradiated sensors is targeted between 150 V and 300 V. A picture of a prototype sensor is shown on the left side of Fig. 3.4.

The sensors are divided into two halves, each featuring 1016 strips with a length of 5 cm, resulting in an active sensor area of about 10\(\times\)10 cm\(^2\). The strips have a pitch of 90 µm and a width of 22.5 µm. They are capacitively coupled to prevent the leakage current from flowing into the readout electronics.

For this purpose, a coupling SiO\(_2\) layer is introduced between the doped silicon strips and the aluminum strips. P-stop structures are implemented to provide sufficient interstrip isolation. Furthermore, the strip area is surrounded by multiple rings. The outermost ring is the edge shaper, a highly p-doped area, which protects the sensor from damage originating from wafer dicing. The next ring is the so-called guard ring, which shapes the electric field of the active sensor area to realize a defined homogeneous potential for all strips. The innermost ring is the bias ring, which distributes the ground potential of the sensor via polysilicon resistors to the DC pads and the doped strips. AC pads beside are used to connect the aluminum strips to the readout electronics via wire bonds. In addition to that, the sensor features characteristic patterns, so-called markers, in the sensor corners, which are used as reference points for alignment measurements.

**HV pigtails**

The depletion voltage of up to 600 V for irradiated sensors is applied with small flex circuits, denoted as ‘pigtails’ in the following, which are glued on the sensor backside. Since a non-conductive epoxy glue is used for that, wire bonds are attached to the gold pad of the pigtails and the aluminum coated sensor backside to establish an electrical connection between the two parts. A picture of the pigtails is shown in Fig. 3.4 beside the sensor, where the tail on the right side refers to the bottom sensor of the module and the tail on the left to the top sensor. The latter is also equipped with a thermistor to monitor the sensor temperature.

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\(^3\)The strips are connected to the ground potential and the sensor backplane to the negative potential to deplete the n-in-p type sensor. In the following, positive values are quoted for the depletion voltage.
HV Kapton strips

In order to protect the sensitive electronics of the module against the sensor bias voltage, polyimide strips are applied to the sensor backside for isolation. In Fig. 3.4 the strips are shown on the right side. They are made from a 25 µm thin Kapton MT foil with a dielectric strength of around 0.2 kV/µm, which provides sufficient isolation and thermal conductivity for dissipating the heat from the sensors. Each sensor is equipped with three strips according to the three spacers, whereas the centrally placed strip differs in its length depending on the version of the module. In Chapter 4 the gluing and positioning procedure for these Kapton strips will be explained.

AlCF-bridges

To keep the sensors apart, three spacers are used for each module, which are called 'bridges' in general and 'stub bridge' when referring in particular to the short, center bridge. The sets for the 1.8 mm and 4 mm module are depicted on the left and right side of Fig. 3.5, respectively. They show a substantial difference in their design, which is necessary to reduce their mass and maintain their strength. Besides the spacing itself, the bridges fulfill three other tasks. First, they provide the support structure for the rest of the module. For this purpose, they feature tabs on each side to apply the hybrids\(^4\), which will be explained in the next section. Second, they provide the holes to mount the module onto the cooling and support structure of the tracker. And third, they are used to position the module during the assembly. In order to fulfill these tasks, the bridges are manufactured out of an Aluminum Carbon Fiber (AlCF) composite material. This provides enough mechanical strength together with good thermal conductivity to remove heat sufficiently from the module.

Another point to consider is the coefficient of thermal expansion (CTE) of the material to prevent mechanical stress arising from the large difference of assembly temperature (20°C) and operating temperature (−30°C) of the module.

\(^4\)From the mechanical point of view, the stub bridge is not necessary, but it provides an important cooling contact for the Service Hybrid.
For this purpose, the fiber orientation of the AlCF is chosen in a way to realize a CTE of 4 \text{ ppm/}^\circ\text{C} to match it with the CTE of 3 \text{ ppm/}^\circ\text{C} of silicon, which results in a differential expansion of 5 \mu\text{m} over the total length of the sensor [11].

![AlCF-bridges for the 4 mm (left) and 1.8 mm (right) type of the 2S module.](image)

**Front-end hybrid**

In order to process the signals generated in the sensors, the so-called front-end hybrids (FEH) are used, which are glued onto the previously mentioned tabs of the bridges at both lateral sides of the sensor. A preliminary version of an FEH is shown on the left side of Fig. 3.6. It consists of a high density, four-layer polyimide circuit that is laminated onto a 500 \mu\text{m} thick carbon fiber stiffener. An overlapping part of the flex circuit is folded over a spacer, which has the same height as the AlCF bridges. In this way, the bond pads on the FEH and the sensor are leveled both for the top and bottom side of the module. Due to the existence of two module variants, two different FEH versions are required, which differ in the thickness of the spacer accordingly. For precise manufacturing of this fold-over part, alignment holes are used. A cross-section of the module with focus on the fold-over is shown on the right of Fig 3.6. The electrical connection of the sensor strips and the FEHs is established with wire bonds that are cast in an encapsulant in order to protect them from handling damages and resonant vibrations in the magnetic field of CMS [11].

![Prototype FEH with 1.8 mm sensor spacing photographed from the top and bottom side (left) and a cross-sectional view of the fold-over area of 4 mm FEH module (right) [11].](image)
For the readout of the sensor, the FEHs are equipped with eight CMS Binary Chips (CBC), which are also depicted in Fig. 3.6. These are 130nm CMOS chips with 254 channels each, which are used to read out 127 strips both of the top and bottom sensors. More information regarding the binary readout can be found in Chapter 7 in conjunction with the description of noise measurements. Besides the hit detection, the CBCs also perform the stub identification by correlating the hits in the top and bottom sensor. For this purpose, the CBCs exchange data with adjacent chips to consider particle trajectories that span across two chips. The data, which consists of 1 bit of hit information and 5 bits of stub information, are subsequently sent out to the Concentrator Integrated Circuit (CIC). This is a 65nm CMOS chip, which formats the data from the eight CBCs into packets and transmits them to the Service Hybrid. As this chip is still under development, the current FEHs are equipped with a fine pitch connector, in the following called FEH tail, to access and power the CBCs directly, which can also be seen in Fig. 3.6.

Service hybrid

Every module is equipped with a Service Hybrid (SEH), which is responsible for the power supply and the data transmission to the back-end. It is made from a flexible polyimide circuit with four layers, which is laminated onto a CF stiffener of 500 µm thickness. For the data transmission, the SEH is equipped with a Low-power Gigabit Transceiver (LpGBT), which merges the data from the two CICs and serializes them for the back-end. It also controls the front-end chips via I²C communication, distributes the clocks as well as the trigger signals. The SEH is also equipped with a Versatile Transceiver plus (VTRx), which converts the data from (to) the LpGBT into optical (electrical) signals. The optical signals are subsequently transmitted to (and received from) the back-end via an optical fiber. To connect the SEH with the FEHs it features lateral ‘tails’ with connectors underneath, which are plugged into the connectors of the FEH. To compensate the two different FEH positions resulting from the 1.8 mm and 4 mm sensor spacing, two different versions of the SEH exist, which differ in the length of the tails. Figure 3.7 shows the current prototype of the hybrid from the top and bottom side. It is equipped with a preliminary connector for the VTRx and the GBTx, an ancestor of the LpGTB, mounted on an extension board of the SEH. The indicated precision holes will later be used in the assembly process.

Figure 3.7.: Prototype SEH shown from the top (left) and bottom side (right).
In order to power the components of the module, the SEH uses two step-down DC-DC buck converters to reduce power losses. The first conversion stage, the bPOL12V\textsuperscript{5}, is fed by an 11 V line from the back-end and transforms this voltage to 2.55 V, as required by the laser of the VTRx. The second stage, the bPOL2V5, converts the voltage further down to 1.25 V to power the 16 CBCs, the two CICs, the LpGBT and the VTRx. In total, this amounts to about 5.4 W of power for a single module by assuming a conversion efficiency of 66\% for the DC-DC converter chain. Furthermore, the SEH is used to route the high voltage coming from the back-end to connectors on its bottom side, into which the pigtails are plugged. The depletion voltage of the sensors is expected to reach a level of 600 V for modules in the inner part of the TB2S after 3000 fb\textsuperscript{-1}. This adds up another 1 W to the total power usage of the module arising from the increase of the leakage currents of irradiated sensors.

**Cooling**

The whole Outer Tracker (including the PS modules) is expected to consume up to 100 kW of power, which will be dissipated as heat by the electrical components. To remove this heat a two-phase CO\textsubscript{2} cooling system is used, which provides a coolant temperature of −35 °C. This sufficiently prevents the modules from a thermal runaway\textsuperscript{6}, which is expected to set in between −21.6 °C and −23.4 °C depending on the module position [11].

### 3.4. Module production at the Aachen assembly center

Presently, several module components are being developed in the context of the prototyping phase, which will continue until the end of 2020. After that, the preproduction phase takes place until the middle of 2021, in which the first modules with the final components are assembled. This is finally followed by the series production phase, lasting until the end of 2023, where the 7680 2S modules (and 5616 PS modules) will be produced. The production itself will take place in several institutes located in Belgium, Germany, India, Pakistan and the USA. RWTH Aachen University, as one of the German assembly centers, will contribute about 1000 2S modules for the experiment. There it is targeted to assemble about five modules per day, resulting in a total production duration of about one year, leaving enough time to compensate for delays. After the assembly, a variety of functionality tests are carried out for each module, including thermal cycling between the lab and operating temperature. This is the so-called burn-in, which qualifies the modules for their later use in the detector. But before the series production can take place, the assembly procedures and the tooling must be developed and tested, which is the main subject of this thesis.

\textsuperscript{5}In ‘bPOL’ b stands for buck and POL for point-of-load.

\textsuperscript{6}Thermal runaway describes a situation, in which the module temperature increases in a self-feeding process due to the exponential temperature dependency of the sensor leakage current.
4. Dispensing studies

As described in the previous chapter, the method used to permanently attach the components of the module with each other is gluing. For an accurate deposition and dosing of the adhesives, a dispensing gantry is used multiple times in the assembly process either for the gluing of parts or the encapsulation of wire bonds. In this context, especially the gluing of the Kapton strips onto the backside of the sensors is an important step, which must be executed accurately to ensure the performance of the module.

In the first section of this chapter, the gantry used for this task will be described together with the assembly process of the Kapton strips. In the next section, an evaluation procedure is presented, which was used to optimize the parameters of the gantry for this assembly step. Then, the gluing of the Kapton strips to the functional sensors is briefly described, followed by an assessment of the achieved glue layer. The chapter subsequently closes with a discussion about the relevance of the glue processing time in regard to series production.

4.1. The Kapton strip assembly

The gluing of the Kapton strips onto the sensor backsides is a delicate task since the thickness of the glue layer has a significant influence on the thermal heat flow between the sensors and the AlCF spacer. This results from the similar values of the thermal conductivity of epoxy glues of about 0.3 W/m-K [14] in comparison with 0.46 W/m-K of Kapton MT strips [15]. In order to comply with a simulated thermal runaway temperature of about −22°C [11], the glue layer needs to be thinner than 20 µm. In addition to that, simulations conducted by Stefan Meier from KIT indicate that every further reduction of the glue layer by 3 µm reduces the thermal runaway temperature by 0.1 K [16]. Therefore, the glue layers need to be as small as possible. This also implies that the entrapment of air must be prevented due to its comparably small thermal conductivity of 0.03 W/m-K [17].

Figure 4.1.: Nominal dimensions and positions of the Kapton strips in reference to a sensor. The sensor is centered with its lower left corner in the coordinate system.
4. Dispensing studies

Therefore, the glue must cover the interface between the strips and the sensor sufficiently. To illustrate this, Fig. 4.1 shows the sensor backside in gray and the Kapton strips in orange, together with the dimensions of the respective parts. The ideal coverage is characterized by a complete wetting of the strip-sensor interface as indicated by the hatched areas. At the same time, any excess glue must be avoided, since it could creep around the nearby sensor edge and reach the strip side. There it could lead to a significant increase in the leakage current of the sensor, resulting in higher power dissipation and increased noise. The dispensing gantry, which is used to realize a precise deposition and dosing of the glue, is presented in the following.

4.2. The dispensing setup

4.2.1. The dispensing gantry and its commissioning

The dispensing gantry consists of two main components: the volumetric dispenser Nordson Ultimus IV [18] and the desktop robot Nordson E4V [19], both depicted in Fig. 4.2. The dispenser is responsible for the accurate dispensing of the glue, which is achieved by a motor, which is connected to a plunger via a hydraulic link. This plunger pushes a piston through a syringe, which increases the pressure in the chamber and finally presses the glue outwards through a tip. These components are shown in more detail on the right side of Fig. 4.2. The piston, syringe, and tip are disposable products, which are thrown away after usage.

The robot is responsible for the precise positioning of the tip above the workpieces. It is also shown in Fig. 4.2 together with a coordinate system describing the directions of its movements. The motions in the x- and z-direction are executed by the arm of the robot, which has a travel range of 350 mm and 100 mm, respectively. This arm is equipped with a holder for the syringe and a camera to film workpieces that are placed on the table underneath. The table provides the movements in the y-direction and features a travel range of 400 mm.

Figure 4.2.: The Dispensing gantry consists of a dispenser and a robot, which is operated with a computer (left). The coordinate system is indicated on the stand of the robot. On the robotic arm, various components are mounted (right). The tip detector underneath is mounted on the robotic table.

The stub bridge strip in Fig. 4.1 refers to the 4 mm version of the module. These were used for the following evaluations and the assembly of the 1.8 mm prototype module since the 1.8 mm strips were not available in a stamp cut cut quality.
The dispensing setup

The robot is connected to a computer that runs the DispenseMotion software, which distinguishes between two classes of commands. The first class refers to dispensing commands, which are used to program a sequence of dots and lines, in the following called ‘pattern’. In this work, the Dispense Dot, the Line Start and the Line Stop commands were used, which specify the coordinates of the dots and lines to be dispensed. The second class includes setup commands to alter the parameters of the robot like the thickness of the dots and lines, which will be explained in more detail in Section 4.3.2. It should be noted that the dispenser and the robot are independent devices. The sole ‘communication’ is a 24V DC signal, which is sent from the robot to the dispenser and initializes the release of glue for the duration of the signal.

In order to fix the workpieces on the y-table, it is equipped with three bolts\(^2\). In addition to that, it features a so-called Tip Detector Sensor to calibrate the position of the tip, which is required since the tips are manually screwed into the thread of the syringe. As a consequence, depending on the applied torque and force, the position of the tips can vary by about 100 \(\mu\)m in all three dimensions. To compensate these deviations, the robot can perform two kinds of calibrations. In the case of the \(z\)-position, the robot lowers the tips onto the Tip Detector sensor. This device consists of a small spring-loaded table with a sensor underneath and measures the force originating from the tip pressing onto the table. The robot subsequently compares the forces measured for certain \(z\)-coordinates of the robotic arm with previous calibrations and adapts the \(z\)-coordinates of the gluing patterns accordingly. After that, the robot calibrates the \(x\)- and \(y\)-coordinates of the tip, for which it dispenses a small dot of glue at a predefined location. Then it takes a picture of this dot with the camera and calculates the shift of this dot with respect to a reference picture. Then, the robot adapts the \(x\)- and \(y\)-coordinates of the respective pattern.

To evaluate the precision of this calibration procedure, 15 calibration runs were conducted in succession, whereby the tip was left in its initial position. The corrected \(z\)-coordinate varied by 15 \(\mu\)m, which is sufficient for the purpose of this thesis. In the \(x\)- and \(y\)-direction instead, the image recognition showed an unstable behavior, which was caused by the lack of contrast between the dot and the underlying surface due to the transparency of the glue. In this context, also the reflectivity of the glue was a problem since slight variations in the glue surface caused different reflections of the environment. Additionally, the low viscosity of the glue resulted in irregularly dispensed dots, which lead to an insufficient matching of the dot with the reference picture. Due to these effects, the tip calibration in the \(x\)- and \(y\)-direction showed variations of 100 \(\mu\)m. Both calibration routines were used for the following measurements, but calibrations in the \(x\)-\(y\)-, were manually checked and repeated, if necessary.

Another feature is the compensation of dislocations of the workpiece. For that, similar to the \(x\)-\(y\)-calibration, the camera approaches predefined points of the workpiece, compares its surface with reference pictures and performs adjustments to the coordinates of the pattern. The precision of the process was analyzed repeating a calibration run 15 times with a workpiece, which was fixed on the \(y\)-table. As the performance of the pattern recognition highly depends on the ‘uniqueness’ of the reference pictures, small markers in the form of crosses were engraved into the workpiece. In this way, the variation of the calibration was reduced to about \(\pm 15\mu\)m. These variations can mainly be traced back to the camera, as one pixel of it depicts an area of about 25 \(\times\) 25 \(\mu\)m\(^2\) of the workpiece. Since this calibration procedure takes several seconds per calibration point and introduces further uncertainties, it was evaluated if this calibration is necessary at all. For that, the workpiece was pushed multiple times against the three stopper bolts. The variation of its position was subsequently measured with the robot camera, which was placed at a fixed point above the workpiece. As these displacements were consistently smaller than 10 \(\mu\)m,

\(^2\)The bolts can be seen in Fig. 4.4

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most of the following tests were conducted by relying just on a manual positioning to save

time and to exclude miscalibrations.

While operating the gantry, it has been observed that the movements of the robotic arm
can bend the hydraulic link of the dispenser, which results in irregularities in the gluing

pattern. Therefore, the dispenser was placed on top of the arm in order to avoid relative

movements of the dispenser. This however compensates only motions in the $x$-direction

since the top of the arm does not perform movements in the $z$-direction, which are pro-

vided by a separate motor in the arm. Movements in the $y$-direction are provided by the

$y$-table and are therefore independent of the dispenser.

4.2.2. The glue

The glue, which is used for all assembly steps in this thesis excluding the encapsulation

of the wire bonds, is the Polytec EP 601-LV [20]. This glue is also foreseen for the series

production of the 2S modules, as it is radiation hard, electronics-grade, and does not
degenerate the Kapton strips. It is a transparent, two-component epoxy with a ratio of

resin to harder of 100:35 and a pot life of 4 hours. In the course of this thesis, the glue

was prepared by dripping respective amounts with a pipette into a glue pot and weighing
them with a precision balance\textsuperscript{3}. For the mixture of the components a vacuum mixer\textsuperscript{4} was
used. In the mixed state, the glue has a nominal viscosity of 240 mPa\cdot s, which increases
during the curing process through polymerization of the resin and hardener. This aspect is
discussed at the end of this chapter in more detail. The time frame in which the viscosity
remains almost constant is about one hour. This was taken into account for the tests
described in the following by mixing new portions after the glue exceeded this time frame.

4.2.3. The Kapton strip application procedure

The primary function of the Kapton strips is to ensure sufficient protection of the bridges
against the high voltage, which is applied to the sensor backside. Since the displacement
margins of the strips are just about 200 $\mu$m small, a multi-step procedure involving three
jigs is used to position the strips with a sufficient precision.

In the first step, the sensor is placed in the sensor positioning jig, which is shown in the first
and second picture of Fig. 4.3\textsuperscript{.} Thereby, the strip side of the sensor is facing downwards
laying on a PTFE-surface\textsuperscript{5}, which features a precisely milled bed to place the sensor in
a defined position. By attaching a vacuum pump\textsuperscript{6} to the jig, the sensor is subsequently
fixed in the jig. Then, the Kapton strips are placed in the strip positioning jig, which is
an aluminum plate that features precisely milled beds for the strips. On top of this jig, the
strip transfer jig is placed, as depicted in the third picture of Fig. 4.3\textsuperscript{.} The strips are
subsequently fixed onto the strip transfer jig by applying a vacuum.

In the next step, the glue is applied using the dispensing gantry. This was initially carried
out by depositing the glue directly on the sensor and subsequently placing the Kapton
strips on top. However, this procedure has two main disadvantages. First, it has been
observed that the glue can spread irregularly over time on the aluminum-coated backside
of a sensor, resulting in irregular glue layers when the strips are positioned. A picture
showing this behavior can be found in Appendix B.1\textsuperscript{.} These irregularities can result from
dust, residuals from manufacturing, or handling. However, an intense cleaning of the
surface should be avoided to minimize the risk of damaging the sensors. Additionally, the
height difference between the tip and the sensors during the gluing procedure measures

\textsuperscript{3}KERN EW220-3N \textsuperscript{[26].}

\textsuperscript{4}Amann Girrbach Smartmix X2 \textsuperscript{[22].}

\textsuperscript{5}PTFE stands for Polytetrafluoroethylene, which is colloquially referred to as Teflon.

\textsuperscript{6}Vacuumbrand ME1 \textsuperscript{[24].}
The dispensing setup

Figure 4.3.: Overview of the Kapton positioning procedure showing: 1.) bare strip positioning and sensor positioning jigs, 2.) Kapton strips and sensors placed in the jigs, 3.) transfer jig placed on top of the strip placement jig, 4.) transfer jig turned around with strips fixed to it, 5.) strip transfer jig placed on top of the sensor positioning jig, 6.) Kapton strips precisely positioned on the backside of the sensor.

just about 100 µm. A wrong tip calibration or dirt under the sensor positioning jig can further reduce this height. In the worst case, this distance is so small that the tip crashes into the sensor and destroys it. To circumvent this problem, a new approach has been successfully tested, where the glue is deposited on the Kapton strips. This provides more stability regarding an irregular spreading of the glue since the strips are easier to clean and it eliminates the risk of destroying the sensor. Since this method worked out without any problems, it is used for every gluing activity in this thesis that involves Kapton strips.

To deposit the glue on the Kapton strips, the strip transfer jig is placed onto the y-table of the gantry. After carrying out the dispensing program, the transfer jig is dismounted, turned around and placed on top of the sensor positioning jig to apply the strips, as depicted in the sixth picture of Fig. 4.3. Four metal blocks with a total weight of 1 kg are added on top of the transfer jig to achieve a thin glue layer between the strips and sensor. The total pressure on the strips amounts to 5 kPa. Prior to a curing phase of typically 24 hours, the vacuum is deactivated to prevent the strips from forming hollows, which would result in buckles of the glue layer. After that, the weights and the transfer jig are removed, and the sensor can be used for the further assembly. This procedure ensures a precise placement of the Kapton strips to comply with the small margins for displacements. A discussion of the precision achieved with this process is presented in Chapter 5.

4.3. Pattern and parameter evaluation

For the gluing of Kapton the strips onto the sensors no specifications or recommendations concerning the dispensing program exist yet. Therefore, a comprehensive evaluation was carried out to find a pattern and parameters that comply with the requirements on the glue layer with respect to thickness and coverage. In addition to that, the dispensing program should yield consistent results and a fast execution of the dispensing program to comply with series production conditions.

The strips can be cleaned for example in a microwave bath or by careful wiping with a cloth and isopropyl alcohol.

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4. Dispensing studies

**Evaluation setup**

For the evaluation of the pattern the glue was applied to a set of Kapton strips, as it can be seen on the left side of Fig. 4.4. Then, the strips were placed with the strip transfer jig on a sensor, and after a certain wait time the coverage was assessed. Instead of silicon sensors, so-called glass sensors were typically used for this task, which have approximately the nominal dimensions of a sensor. Besides that, some tests were conducted with dummy sensors, which have the same mechanical dimensions as the later serial sensor but do not provide an electrical readout due to missing doping. However, for the later-described calibration of the gantry, it was not approach was not sufficient just to deposit glue on sensors. Instead, multiple patterns had to be dispensed side by side to compare them directly. For this purpose, a test plate depicted on the right side of Fig. 4.4 was used, which consists of an aluminum plate covered with a glass plate to obtain a smooth, flat and easy to clean surface.

![Figure 4.4: The glue is applied directly on the strips, fixed by the strip transfer jig to evaluate the wetting of a certain pattern (left). To evaluate the parameters, a set of different lines is dispensed on a test plate to compare the results side by side (right).](image)

Prior to the execution of each dispensing program, several short lines were dispensed on the test plate to flush the tip and to build up an operating pressure in the syringe. Eventual curing phases took place at room temperature.

**4.3.1. Pattern evaluation**

The pattern tested first consisted of a simple line of glue, which was centrally dispensed on each of the three Kapton strips. The wetting achieved with these lines is exemplarily shown on the left side of Fig. 4.5. The strip has a good wetting in the center area, but large parts in the corners remain unwetted. Further variations of the position, length and the thickness of the line did not significantly improve the wetting or resulted in leaks of the glue. Then, the line pattern was extended with small dots placed in each corner of the strips, as shown on the right side of Fig. 4.5, yielding a significantly better wetting. At the same time, this increased the parameter space in regard to the position and thickness of the dots. To simplify the evaluation of sufficient parameters that cover the strip sufficiently, this task was split up into two aspects. First, the wetting of the main area of the strip should be optimized by varying the thickness of the line, with the so-called Line Speed parameter of the robot. Second, the wetting of the corner areas should be adjusted by the position of dots. For that, the thickness of the dots was set to a predefined value\(^8\).

\(^8\)The dot thickness was not chosen as a free parameter due to an insufficient reproducibility of the dots at certain sizes
Pattern and parameter evaluation

Figure 4.5.: Wetting of the long Kapton strips achieved by a line (left) and a line combined with four dots located in the corners of the strip (right). The unwetted areas are colored orange.

Basic values for the parameters and the pattern could be found by using known good values. But in order to achieve consistent results, a more systematic approach was required. For this purpose, the optimization procedure illustrated by the flow chart shown in Fig. 4.6 was developed, which displays besides the tip diameter all relevant parameters used for the dispenser and the robot. The influence of the parameters on each other is indicated by the arrows. In this sense, the procedure begins with the evaluation of the tip diameter and then follows the arrows to optimize the dispenser- and robot-related parameters. In this way, the alteration of a parameter does not affect the optimal setting of others further up in the flow chart.

Figure 4.6.: Flow chart of the parameter evaluation. The optimization order reads from the top to bottom. The dependencies of the parameters are indicated by arrows.
4. Dispensing studies

4.3.2. Parameter evaluation

Tip diameter

In the first step of the evaluation, the diameter of the tip that is screwed on the syringe was evaluated. For this purpose, a set of lines and dots was deposited on the test plate with eight different tips of the 'General Purpose' series of Nordson EFD [25]. They have a length of 12.7 mm and inner diameters ranging from to 0.25 mm to 1.54 mm. It was observed that the tip diameter determines on the one side the expanse or 'resolution' of a dot but also its height due to the surface tension of the low viscosity glue. Therefore, it occurred that more glue than originally defined was deposited at a first dot of a pattern. For the subsequent dot however this fraction of glue was missing and therefore resulted in a smaller dot. Because of these inconsistencies, tips with diameters larger than 1 mm were excluded for the further tests.

For small diameter tips an additional surface tension effect was observed. Once the glue reached the edge of the tip, it was energetically more favorable for a fraction of glue to flow around the tip, where it formed a drop. This drop slipped off when the subsequent dot or line was dispensed, resulting in irregularities in the gluing pattern. Therefore, the tip with an inner diameter of 0.84 mm was selected since it was the smallest or rather best-resolving tip, which did not show the effects mentioned above. This type of tip was used for all subsequent gluing activities involving the Polytec EP 601-LV.

Dispense Rate

In the next step, the Dispense Rate parameter of the dispenser was optimized. It relates to the velocity of the plunger in the syringe during the dispensing process and therefore determines the thickness of the dots and lines. To get a reasonable value, a couple of lines were dispensed with different dispense rates ranging from 0.0001 cm$^3$/s to 0.01 cm$^3$/s. For a meaningful comparison of the result, the Line Speed parameter, which describes the moving speed of the robot, was adapted accordingly to maintain the thickness of the lines at a constant level. Inaccuracies were observed with increasing dispense rates that may result from larger compressions of the glue during the dispensing process [18]. After all, a value of 0.001 cm$^3$/s was chosen for the further evaluation, according to the suggestion by the manufacturer [18].

Pullback

Then, the Pullback of the dispenser was calibrated. This parameter describes the automatic retraction of the piston in the syringe after dispensing a line or dot in order to generate a vacuum, which stops the glue from flowing out of the tip. In addition to that, it keeps the glue in the needle to prevent dripping. The optimal value was evaluated by positioning the tip in the air and dispensing a small dot of glue as shown in Fig. 4.7. The glue then formed a small drop around the tip. After a wait time of about 30 seconds, the Pullback value was either increased if the drop was growing due to an insufficient vacuum, or reduced if the vacuum was so strong that the drop was shrinking since the glue was sucked into the tip.

The optimal value for the Pullback in combination with the used glue, tip and Dispense Rate was found to be between 95 and 105. For the further evaluation a value of 100 was chosen, which performed well for consecutively dispensed dots. Although, it was observed that after depositing the glue lines on the long Kapton strips, the glue was more retracted in the tip than it was the case after dispensing dots or short lines. By that, the tip was not sufficiently 'filled' for the next dot or line, causing irregularities.
Pattern and parameter evaluation

Figure 4.7.: Evolution of the dot size. Depending on the Pullback parameter, the dot gets soaked in (left), has a constant size (middle) or grows (right).

However, this could be compensated for the pattern under consideration by dispensing this dot twice in a row. Therefore, this behavior was not further analyzed.

**Line Speed**

Then, the parameters of the robot were evaluated starting with the *Line Speed*, which was used as a free parameter to determine the wetting of the center area of the strip. The corresponding optimization was carried out by applying lines with a certain Line Speed on the Kapton strips and placing them with the procedure described in Section 4.2.3 onto a glass sensor. First, some rapid tests were conducted to get familiar with the technique, whereby the weights were removed after 10 min. The degree of wetting was subsequently examined with a microscope$^9$. Depending on the results, the Line Speed was adapted to either increase the wetting or reduce the overspill of the glue. After stable results were achieved, runs with a curing time of 24 hours were conducted and yielded an appropriate wetting for a Line Speed of 10 mm/s. However, after the bars of the strip transfer jig were milled down to ‘refresh’ their surface, this value was not sufficient anymore and resulted in large overspill. The reason for this behavior could not be conclusively clarified, but it is assumed that the bars had an uneven surface. This may have concentrated the pressure of the weight plate to a small area of the Kapton strips, which allowed the glue to cumulate at areas with lower pressures. After further evaluations with the refreshed jig, the optimal Line Speed was evaluated to be 27 mm/s for the long bridge and 23 mm/s for the stub bridge.

**Valve On Time**

The thickness of the dots was optimized with the *Valve On Time* parameter, which is exclusively available for dots and describes the length of the DC signal sent from the robot to the dispenser. Since the concept of the pattern relies on the variation of the dot position to adjust the wetting of the corners, the goal of this evaluation was to find a setting, which yields a sufficiently reproducible dot size. A set of dots with Valve-On-Times increasing in their value in steps of 0.05 s was printed on the test plate. The size of the dots was subsequently measured under a microscope. The optimal value was determined to be 0.4 s since this was the lowest value, providing a sufficient reproducibility.

$^9$Keyence VHX-900F [23].
4. Dispensing studies

**z-coordinates**

Directly linked with the Line Speed and the Valve On Time are the *z-coordinates* of the gluing pattern. In particular, this relates to the distance between the tip and the workpiece $d_{tw}$. If this distance is set too small, the tip moves through the glue layer, resulting in inaccuracies. In the opposite case, if the tip-workpiece distance is too large, the adhesive is not directly flowing from the tip to the surface. Instead, the glue forms a growing drop around the tip, which falls off after it is too heavy to be held back by its surface tension.

Since $d_{tw}$ is not a parameter of the robot, its configuration must be carried out indirectly via the *z*-coordinates of the patterns in the reference system of the robot. For this purpose, the tip-workpiece distance was measured by moving the tip close above the test plate. Then, the test plate was carefully moved underneath, while the tip was slowly lowered onto the plate. At full contact the plate could not be easily moved anymore due to the contact pressure of the tip. The corresponding *z*-coordinate was subsequently set as the workpiece height in the coordinate system of the robot. The same procedure was later repeated with the Kapton transfer jig in order to evaluate the *z*-coordinates of the final dispensing program.

Then, a set of lines and dots was deposited on the test plate starting with *z*-coordinates corresponding to a tip-workpiece distance $d_{tw} = 200 \, \mu m$ and then reducing this distance further in steps of 10 $\mu m$. The resulting pattern is shown on the left side of Fig. 4.8. The height of the first line showing a uniform body corresponds to $d_{tw} = 130 \, \mu m$ with a Line Speed of $27 \, mm/s$. For tip-workpiece distances smaller than $50 \, \mu m$ the tip drove through the glue. The final pattern was programmed with *z*-coordinates that equal a tip-workpiece distance of $100 \, \mu m$ to allow for uncertainties of tip calibration.

![Gluing pattern dispensed on the test plate to evaluate the z-coordinates. The height between plate and tip decreases from 200\,\mu m in step sizes of 10\,\mu m from the left to the right.](image)

**Pre-move Delay**

The *Pre-move Delay* parameter is exclusively available for lines and corresponds to a wait time of the robot. This is used to prevent a systematic shortening of lines, due to an intrinsic start delay of the dispenser. This delay is caused by the fact that the plunger requires some time to drive out of its ‘retraction’ position, which is used to build up the vacuum. To evaluate a sufficient value, a set of lines was dispensed on the test plate with a stepwise increase of the delay of 0.05s. The resulting pattern is depicted on the right side of Fig. 4.9. It shows that the glue is deposited ‘earlier’ with an increasing delay time. However, at large values the lines show blobs caused by the robot standing still while the dispenser is already depositing glue. The optimal value for the Pre-move Delay was determined from the first line showing a track with the full length, which corresponded to 0.3s for the final pattern. To pronounce this effect, the Line Speed may be increased.
Pattern and parameter evaluation

Figure 4.9.: Gluing pattern dispensed on the test plate to optimize the delay. The delay of the dispenser increases from 0 seconds in step sizes of 0.05 seconds from the left to the right.

Shutoff Distance

The other, line specific parameter is the *Shutoff Distance*, which stops the robot from sending out a dispensing signal at a given distance prior to the stop coordinate of the line. This is used to prevent blobs at the end of lines, which are caused by the fact that the plunger needs some retraction time until it generates a sufficient vacuum to stop the release of glue. Examples of small blobs can be seen at the lower end of the lines shown in Fig. 4.8 and 4.9.

The Shutoff Distance is evaluated similarly to the Pre-move Delay. Again, a set of lines was deposited onto the test plate with increasing Shutoff Distances in step sizes of 0.5 mm. The optimal value was determined from the line that achieved as the last a full track, yielding a Shutoff Distance of 1 mm for the final pattern.

Results of the parameter evaluation

To summarize the results of the evaluations, all values obtained are listed in Tab. 4.1. These were subsequently used to glue the Kapton strips to the functional sensors of the module prototype.

<table>
<thead>
<tr>
<th>Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pullback (steps)</td>
<td>100</td>
</tr>
<tr>
<td>Dispense Rate (cm³/s)</td>
<td>0.001</td>
</tr>
<tr>
<td>Valve On Time (s)</td>
<td>0.4</td>
</tr>
<tr>
<td>Pre-move Delay (s)</td>
<td>0.3</td>
</tr>
<tr>
<td>Shutoff Distance (mm)</td>
<td>1</td>
</tr>
<tr>
<td>Tip-workpiece Distance (mm)</td>
<td>0.1</td>
</tr>
<tr>
<td>Stub bridge Line Speed (mm/s)</td>
<td>23</td>
</tr>
<tr>
<td>Long bridge Line Speed (mm/s)</td>
<td>27</td>
</tr>
</tbody>
</table>

Table 4.1.: Dispenser and robot settings found with the parameter evaluation.

4.3.3. Position evaluation

After these settings were found, the last step of the procedure existed in the evaluation of the coordinates of the dots as well as the start and stop points of the lines. For this purpose, a preliminary pattern was dispensed on Kapton strips that were subsequently placed on a glass sensor. This procedure was repeated with different dot and line positions until a sufficient wetting in the corner areas was achieved. The final pattern was then used...
4. Dispensing studies

to glue a set of Kapton strips on two dummy sensors to test the procedure. After the glue had cured, a large local overspill depicted in Fig. 4.10 was observed. During further test runs, this feature occurred in a similar extends, regardless of which glass sensors or Kapton strips were used. Since the overspill was not observed after exchanging the strip transfer jig, it is assumed that a residual or dent in the strip transfer jig caused this problem. This underlines the importance of keeping the jigs clean and protecting them from scratches.

![Image](image.png)

Figure 4.10.: Punctual overspill at a Kapton strip applied to a dummy sensor.

Results of the position evaluation

The final pattern resulting from this evaluation is visualized in Fig. 4.11. The exact coordinates of the dots, as well as the start and stop points of the lines are listed in Appendix B.1. The two red dots labeled as 'double points' were dispensed twice in order to compensate for the Pullback effect, which occurred after dispensing large lines, as mentioned earlier in Sect. 4.3.2. The path of the tip is indicated by the gray line. With series production in mind, this path was chosen to reduce the total dispense time of the pattern, which is 40s for the configuration shown in Fig. 4.11.

4.4. Kapton strip gluing of the 2S module prototype

After the presentation of the evaluation procedure and the final pattern, the assembly of the strips onto the prototype sensors is described in the following. Prior to the gluing, all strips were examined for holes and wrinkles with a microscope. Then, the strips were cleaned with isopropyl alcohol and applied according to the previously described procedure. Compressed air was used to remove dust that landed on the strip during the transfer process. The gluing of the two sensors was carried out on two days in succession. After lifting the jigs, the strips were examined for entrapped air as well as overspill and piecewise photographed with the microscope. The corresponding pictures of the strip with the worst results are depicted in Fig. 4.12. It shows the ends of the strip enlarged at the top and a collage of the merged pictures of the strip at the bottom. In these pictures, areas with entrapped air are marked red.

The strip features a small number of bubbles and a negligible overspill. In order to measure the size of the entrapped air, the corresponding areas were measured in terms of pixels with an image editing program. This area was then set in relation to the entire strip, which yields a wetting of more than 99.9%.

Adobe Photoshop CS6 28.

28

28
Figure 4.11.: The final pattern to glue the Kapton HV strips onto the sensor backside. The sensor is shown in gray together with the Kapton strips in orange. The lines, dots and the path of the tip are indicated separately. The coordinates of the dots, line start and line stop points are listed in Appendix B.1.

Figure 4.12.: Pictures of a Kapton strip glued onto the backside of a functional sensor. The corner areas of both sides are fully wetted with a negligible overspill (top left and right). A few small air bubbles are trapped in the glue layer marked red (bottom).
Similar results were obtained for all other strips. However, bubbles smaller than 20 \( \mu m \) are not resolved by these pictures. But since at most 10 (2) of such bubbles were observed for every long (short) strip during an examination with the microscope. Since these bubbles account for a fraction of less than 0.001\%, this measuring uncertainty is negligible.

In order to derive the thickness of the glue layer, the gluing pattern was dispensed 20 times on a glass plate and cumulatively weighed. By using the density of the glue and the area of the strip-sensor interface, which was measured in a CAD software\(^{11}\), a glue layer thickness of 8.5 \( \mu m \) was obtained. These results are listed in Tab. 4.2 together with the corresponding specifications.

<table>
<thead>
<tr>
<th>Wetting</th>
<th>Layer thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement</td>
<td>&gt; 99.9%</td>
</tr>
<tr>
<td>Specifications</td>
<td>&gt; 90%</td>
</tr>
</tbody>
</table>

Table 4.2.: Measured and specified values for the wetting and thickness of the glue layer.

The values achieved for the wetting and the glue layer thickness are well compatible with the requirements. In particular, the wetting exceeds the specifications by nearly 10\%. Due to this large ’safety margin’, it can be assumed that the wetting of future strip assemblies will also comply with the specifications.

Furthermore, the achieved glue layer thickness is about 60\% smaller than the specified value. This would reduce the thermal runaway temperature of the modules by nearly 0.5 K \(^{16}\), if a similar layer can be achieved during series production. In summary it can be said that satisfying results were obtained, which also reflect the performance of the parameter choice and the corresponding evaluation process.

### 4.5. Gluing during series production

In the studies presented so far, only a single sensor was glued at a time. But during series production about ten sensors need to be equipped with Kapton strips every day. At a rough estimate, this will take about 30 to 60 min considering the handling time of the jigs. During this processing time, the viscosity of the glue changes due to the incipient polymerization of the resin and the hardener. This causes the glue to lose its ’compatibility’ with the fine adjusted parameters of the gantry. For example, higher viscosities require higher Pullback values to generate a stronger vacuum in order to prevent the glue from oozing \(^{18}\).

Since the encapsulation of the wire bonds is also performed with the dispensing gantry, this incompatibility problem refers equally to the encapsulant. In order to investigate the relevance of this problem for the both adhesives in more detail, a study described in the following was carried out.

#### 4.5.1. Viscosity behavior

In this study the flow of the adhesives was measured after time to assess a time frame, in which the parameters of the gantry are still applicable. Besides the Polytec EP 601-LV, the encapsulant Sylgard 186 \(^{21}\) was used, which is the specified adhesive for the encapsulation of bond wires \(^{30}\). For the measurements, the setup depicted in Fig. 4.13 was used.

\(^{11}\)Autodesk Inventor Professional 2018 \(^{27}\).
The setup consists of a shortened syringe, which is mounted on a support arm. After the glue is filled in the syringe, it flows through a tip into the pot underneath, which is placed on a precision balance. The balance is then used to calculate a 'mass flow' by measuring the weight of the glue, which poured in the pot during a measuring time of one minute. This value is subsequently converted to a volume flow, \( V \), with the respective glue density\(^\text{12}\). This measurement was repeated 36 times with a 1.5 min pause in between. This pause was necessary, to refill glue in order to achieve a constant column of glue or rather pressure in the syringe. For the measurement of the more viscous Sylgard 186, the tip connector of the syringe was cut off and the hole in the syringe was enlarged to a diameter of about 6 mm to achieve a sufficient flow. The uncertainties originate from variations of the measurement time of about 2 seconds resulting in a relative uncertainty of 3% on the measured flow. The results of both measurements are shown in Fig. 4.14. The \( x \)-axis refers to the time after the glue mixer finished the respective mixing program. In case of the Polytec EP 601-LV glue, the flow remains approximately on a stable level within the first 15 minutes, whereupon it slowly decreases. After about 25 minutes the flow decreases consistently with about 125 mg/min. Due to these measurements, it can be stated that the parameters of the dispensing gantry are applicable for a time frame of at least 15 min, which complies with the experiences made in the course of this thesis. However, no significant changes in the performance of the parameters have been observed even 60 min after mixing the glue. Therefore, it is assumed that the parameters yield sufficient results for a whole batch of ten sensors to be glued during series production. In contrast to that, the Sylgard 186 encapsulant shows a substantial decrease right from the start, which flattens out after time. This behavior is unfavorable for series production and complicates an estimation of a specific processing time limit for the glue. To circumvent this strong initial change, it could be imagined to let the mixed encapsulant rest for a while before its usage to get more consistent gluing results. But since the initial viscosity is

\(^{12}\)The density of Polytec EP 601-LV is 1.15 g/cm\(^3\) and the density of Sylgard 186 equals 1.12 g/cm\(^3\).
4. Dispensing studies

Figure 4.14.: Measurement of the flow of the Polytec EP 601-LV and the Sylgard 186 against the time after the glue mixing finished.

already as large as 66700 mPa·s, the encapsulant may become too viscous to flow through the 'lattice' of wire bonds. In this case, the encapsulation would form just a cover resting on the bonds instead of fully enclosing them. Therefore the encapsulation needs to be applied shortly after mixing. In this context, it is useful to have a process to quickly transfer the encapsulant from the mixing pot to the syringe. Since the Sylgard 186 cannot be just poured into the syringe due to its high viscosity, a tool presented in the following has been developed to address this problem.

4.5.2. Filling technique for Sylgard 186

The tool relies on the concept of filling the syringe through the tip by sucking the encapsulation in with a vacuum. For this purpose, an external vacuum pump is attached with a hose to hose connector, which is screwed into a syringe cap plugged onto the syringe. However, shortly after activating the vacuum, the encapsulation forms a hollow in the pot due to its high viscosity, which leads to air being sucked in, as illustrated in the first picture on the left side of Fig. 4.15. To get rid of large bubbles, a further vacuum treatment is required, which prolongs the process. However, small bubbles are likely to remain in the adhesive reducing the protection of the wire bonds.

To avoid this behavior, a stamp is attached to the tip, which compresses the glue ensuring a sufficient reflow. The stamp is made from Sylgard 186, which cured in the mixing pot. In this way, the stamp fits precisely into the pot and thus seals the encapsulant against the entrapment of air. The required 'lubrication' of the stamp is automatically provided by the encapsulant. Furthermore, the mechanism is self-sealing as the stamp sucks itself against the bottom after the pot is emptied and therefore prevents the tip from drawing air. Test runs with a vacuum of -0.6 bar and a tip with an inner diameter of 2 mm and a length of 25 mm have shown that a 30 cm³ syringe can be entirely filled within less than a minute accelerating the handling time significantly for series production.

In order to prove the reliability of this tool over a longer period of time, further tests are required. In particular, it has been observed that the silicone of the first prototype stamp torn open at the hole, where the tip is inserted, which caused air being sucked in. This could be prevented by molding a tip or a bushing directly into the stamp to circumvent any weak points in the material.

\[ \text{The wire bonds have a thickness of } 28 \mu\text{m resulting in a gap size of the lattice of } 62 \mu\text{m due to the pitch of } 90 \mu\text{m.} \]
Figure 4.15.: Filling mechanism of Sylgard 186. 1.) the encapsulant forms a hollow surface in the pot resulting in air being sucked in, 2.) a stamp attached at the tip compresses the glue and ensures reflow, 3.) photography of the tool.
5. Assembly of the functional module

In this chapter, the assembly of the first functional module prototype in the Aachen assembly center is presented. Each assembly step is explained in its individual section, which is divided into three subsections. In the first one, the formal assembly process developed by CERN is described together with the jigs that are used to align and assemble the individual components. The jigs used in this thesis rely on designs from CERN and feature minor modifications to comply with the manufacturing techniques of the workshop in Aachen.

In order to test the procedures and jigs, a dummy module was built in preparation of the assembly of the module prototype. Since this test run revealed several potentials for improvements, various modifications were made to the jigs and the assembly process, which are described in the second subsection. These modified jigs were subsequently used for the assembly of the module prototype. The gained experiences and the achieved results are presented in the third part, which closes the respective section. After each assembly step of the module prototype, the leakage current of the sensors and the noise of the CBCs was measured. The results of these measurements are discussed separately in Chapter 6 and 7.

5.1. Sensors size deviation

The two functional sensors used for the module prototype are made from Float-Zone (FZ) silicon with a physical thickness of 320 µm. Their active size was reduced by a thermal treatment called deep diffusion to 200 µm. A laser dicing method was used to cut the sensors out of the respective wafers. Since this method does not allow to cut through aluminum coated surfaces, the sensors were diced beyond their nominal edges. This causes an additional edge of silicon surrounding the sensors, as it can be seen in Fig. 5.1. This increases the physical sensor size by 130 µm in the direction parallel and 65 µm in the direction perpendicular to the strips.\(^1\)

Besides that, several buckles with a size of 30 µm were observed at each edge of the sensors, as shown on the right side of Fig. 5.1. Since the edges are used for the alignment, the additional silicon frame, as well as the buckles, caused a displacement of the sensors from their nominal position. As a consequence, some of the following measurements show a systematic shift, which will be pointed out in the respective sections.

5.2. The assembly of the HV bias pigtails

The first step of the module assembly procedure is the assembly of the pigtails to the backside of the sensors. For this purpose, a multistep procedure is used, which includes gluing, wire bonding and encapsulation, to achieve a reliable electrical connection between the pigtails and the sensor backside. Furthermore, a precise alignment of the pigtails is required, since they need to be plugged into the SEH in a later assembly step.

\(^1\)The uniform width of the silicon frame shown in Fig. 5.1 results from the fact that the sensors were ordered 65 µm smaller in the direction perpendicular to the strips compared to the nominal dimensions.
5. Assembly of the functional module

5.1. Features of the functional sensors

The sensors are surrounded by a frame of blank silicon (left). The edge of the sensors shows buckles with a size of 30 \( \mu \text{m} \) (right).

5.2. Jig and assembly procedure

To assemble the pigtails, the sensors are placed in the sensor positioning jigs with the strip side facing downwards. Then, the jigs are mounted on the \( y \)-table of the dispensing gantry and dots of the Polytec EP 601-LV glue are applied to the sensor backside at the designated positions of the bond pads and the thermistor of the pigtails. Next, the pigtails are picked up with a tweezer and inserted in corresponding beds, which are milled into the PTFE surface of the jig. This is shown on the left side of Fig. 5.2. Since the beds have an open side facing towards the sensor, the pigtails are floating in their vertical position and need to be pushed manually against the lower bed edge for a precise positioning. This step is important since the pigtails must sufficiently protrude over the sensor edge to ensure that they can be plugged into the SEH later on.

After checking the placement of the pigtails under a microscope, a vacuum is applied to the sensor positioning jig to fix the sensor and the pigtail in their position. Then, a weight block is placed on the pigtail, as shown on the right side of Fig. 5.2, to improve the spread of the glue. In this configuration, the jigs are left for a 24-hour long curing phase.

After this period, the weights are lifted and the sensors, still within the jigs, are moved to the wire bonding machine. To establish an electrical connection between the pigtail and sensor backside wire bonds are placed on the gold pad of the pigtails and the sensor backside. A more detailed description of the wire bonding process can be found in Section 5.7 in the context of the bonding of the sensor strips.

After that, the jigs are moved back to the dispensing gantry, where the wire bonds are encapsulated with the Sylgard 186 encapsulant [21].

5.2.2. Modifications of the jig

During the test run with the dummy sensors it was observed that the sensor positioning jigs relied on an old version of the pigtail with a different connector placement. To compensate this, the beds in the jigs were manually enlarged, whereby the nominal position of the bond pads moved by 1 mm. This resulted in an according shift of the bond pads with respect to the 'feet' of the weight blocks, which then covered partly the bond pad and partly the sensor. To prevent the feet from sticking on the sensor in case glue leaks out of the gluing gap, they were narrowed, as it can be seen in the detail view on the right side of Fig. 5.2.
The assembly of the HV bias pigtails

Figure 5.2.: Assembly of a pigtails on a sensor. The pigtails is positioned within their bed, which is milled into the Teflon surface of the sensor positioning jig (left). An aluminum block is placed on the tail to spread the glue under the bond pad (right). The detailed view shows the narrowed food weighting the bond pad.

5.2.3. Assembly of the pigtails to the functional sensors

The assembly of the pigtails was carried out as previously explained. However, the vacuum could be not applied during the curing phase since the pigtail and the sensor share the same vacuum system in the jig. And as the sensors did not fit correctly in their bed due to their oversize, it was not possible to generate a sufficient vacuum. Furthermore, the pulsation of the vacuum pump caused vibrations resulting in a lateral movement of the pigtail. This smeared the glue of the bottom sensor pigtail, as depicted in Fig. 5.3.

Figure 5.3.: Pigtails of the top sensor (left) and bottom sensor (right) after wire bonding.

5.2.4. Bonding and encapsulation of the pigtails

Subsequently, the wire bonding of the pigtails was conducted by Tim Ziemons [29]. A pull test was performed with the first three bonds in order to check the strength of their welds. Each bond yielded a corrected value of 9.8 g, which complies with the specifications of at least 8 g [30]. Then, the wire bonds were applied in a vertical row starting at the top of the left (right) side of the top (bottom) bond pad. The bonding at the upper half of the pads was carried out without any problems.

\[^2\text{Vacuubrand ME 1 [24].}\]
At the lower half, however, the pads showed vibrations, when the wedge of the bonding machine applied pressure to it. Since the wedge requires a certain counterpressure to generate a sufficient welt, the other bonds were applied above the first row of bonds in the stiff half of the pad. In total 15 bonds were placed on the top sensor and 19 on the bottom sensor, which complies with the specification of a minimum amount of 10 and a maximum amount of 20 bonds sensor. Subsequently, the electrical contact between the pigtails and the sensor backside was verified with an ohmmeter.

Since these movements were observed for both pigtails, it is conceivable that not enough glue was used. Another explanation is that the pigtails weights did not generate enough contact pressure to spread the glue sufficiently. This theory is supported by the observation that the weights did not fully cover the lower parts of the gold pads due to the change of the pigtails position, as shown in Fig. 5.2. This problem needs to be further investigated if it occurs during subsequent assemblies.

The bonds were encapsulated with the dispensing gantry and the Sylgard 186, as shown in Fig. 5.4. Multiple dots were applied until every bond was covered, requiring 10mg of encapsulation for every sensor. After that, an ohmmeter was used to verify that the sensors still have an electrical connection to the pigtails.

Figure 5.4.: Encapsulation of the wire bonds with the dispensing gantry.

5.3. The assembly of the Kapton HV strips

The next assembly step is the gluing of the Kapton strips, which was already described in the previous chapter. However, an important aspect of this step, which was just briefly mentioned, is the precise placement of the strips to ensure that the bridges are sufficiently isolated from the sensors. Therefore, a distance of at least 500 µm is required between any point of the sensor backside and the AlCF-bridges. Together with the nominal positions of the strips illustrated in Fig. 5.5, this yields margins for displacements of about 200 µm; a derivation of the exact values can be found in Appendix C.1. In order to comply with such small margins, the strips are applied by using the placement and positioning jigs, as described previously in Chapter 4. To assess the performance of this process, the jigs were evaluated to ensure that the strips of the module prototype can be placed with a sufficient precision.
5.3.1. Evaluation of the strip application process

Strip and sensor placement jigs

The misalignments arising from the sensor and strip positioning jigs were assessed, by measuring the dimensions of the beds with a coordinate measuring machine\(^3\). Both jigs did not show significant deviations from their design within a measurement accuracy of 5\(\mu\)m. It should be pointed out that the beds of the sensor positioning jigs are designed 35\(\mu\)m (25\(\mu\)m) larger at both edges parallel (perpendicular) to the sensor strips than the nominal sensor dimensions. This simplifies the removal of the sensor out of the jig, but it also allows for displacements of the sensor, which affect the alignment precision of the Kapton strips. To exclude systematic displacements of the strips, the positions of the sensor and strip beds were measured and compared, whereby no significant differences were observed.

Strip transfer jig

Then, the misalignments caused by picking up, transferring and placing the strips with the strip transfer jig were measured. Prior to the further discussion, it should be noted that the strip and sensor positioning jigs are equipped with three positioning bolts to insert the transfer jig. Corresponding to that, the transfer jig features three holes, as depicted in Fig. 5.6. These holes have a diameter, which is 250\(\mu\)m larger than the bolts to allow for smooth insertion of the jig. At the same time, this clearance results in respective inaccuracies. Therefore, spring plungers are used to constrain the horizontal and vertical freedom of the jig. A cutaway model of a plunger is shown on the right side of Fig. 5.6.

\(^{3}\text{Mitutoyo Euro-M544.}\)
5. Assembly of the functional module

Figure 5.6.: Jigs for the Kapton strip assembly. The strip and sensor positioning jigs feature three positioning bolts (left). The strip transfer jig is equipped with spring plungers to constraint the clearance of the holes. The spring plungers are hollow screws with a spring inside, which preloads a pressure pin (right).

To evaluate the achievable precision of the strip transfer process, a set of strips was applied 30 times to a glass sensor with the previously described procedure. Instead of glue, dish soap was dispensed on the strips to fix them temporarily. After removing the transfer jig, the shifts of the left strip and the stub strip were measured with a microscope at the reference locations 1, 2 and 3 defined in Fig. 5.5. Measurements of the right strip were omitted since they were assumed to behave symmetric to the shifts of the left strip.

Figure 5.7.: Distributions of Kapton strip shifts. The upper (lower) row of plots shows the shifts of the strips in the horizontal (vertical) direction. Each column presents the measurements of a specific reference location. The transparent histograms represent the distribution of the displacements using the original and modified jig. The bin size is 20 µm, and the specifications are indicated, if they fall into the displayed range.
The assembly of the Kapton HV strips

The results of the measurements carried out with this 'unmodified jig' are shown as red colored histograms in Fig. 5.7. Thereby, the measurements conducted at a certain reference location are shown in a separate column. The horizontal and vertical displacements are given in the top or bottom row respectively. Each histogram is centered to its mean value, since only the variation of the shift is assessed in this part of the evaluation. The measurements that were taken at reference location 1 depicted in the left column show just small deviations. This is caused by the spring plunger denoted as '2b' in Fig. 5.6, which constrains the movements. The measurements taken at the reference locations 2 and 3 show a significantly larger variation, which can be seen in the middle and left column of Fig. 5.7. Although the measurements meet the specifications, there is a proportion that is close to the limits of 150 \( \mu \text{m} \) for horizontal shifts at reference point 2. This is caused by a missing constraint in the horizontal direction since just the single spring plunger '2c' is installed in the lower area of the jig. Therefore, the two additional spring plungers '3a' and '3b' were introduced at the marked areas in order to restrict the movement of the jig in the horizontal direction. Subsequently, the same measurement procedure as previously described was carried out.

The results are shown in Fig. 5.7 with the blue bins denoted as 'modified jig'. The fluctuations in the horizontal direction are significantly smaller for the values measured at reference location 2 and 3 with margins of at least 75 \( \mu \text{m} \) to the specification. These results were assumed to be sufficient for the assembly of the module prototype so that further modifications were omitted. However, it should be noted that the installation of the additional spring plungers considerably increased the friction with the positioning bolts of the positioning jigs. Therefore, a careful adjustment of the spring plungers is necessary to achieve sufficient guidance and, at the same time, to allow for a smooth lowering and lifting of the transfer jig.

**Vacuum strength and pickup of electrostatic charge**

Two additional aspects were considered to improve the assembly of the strips. First, the strength of the vacuum applied to the strip transfer jig was adjusted to hold the strips securely in place. At the same time, the vacuum was kept at a level weak enough to prevent the strip from forming wells, which could result in entrapping air or the formation of buckles in the glue layer. Both effects would reduce the thermal conductivity of the glue joint between strip and AlCF-bridge. Therefore, a negative pressure of \(-0.1\text{bar}\) was chosen for the assembly of the module prototype. For series production, however, it is suggested to increase this value to make the transfer process more secure. To circumvent the aforementioned problems, the suction holes of later jigs could be moved to positions that are not overlapping with the AlCF-bridges. Since the strip transfer jig is used to build both module types, the position needs to be independent of the bridge type. Figure 5.8 shows the overlaid footprints of a 4 mm and 1.8 mm long AlCF-bridge together with a Kapton strip underneath. The yellow areas, where the Kapton strip is visible, correspond to suitable locations for the suction holes.

The second aspect of improving the assembly process refers to the electrostatic charge up of the sensor positioning jig and the Kapton strips, which was observed after cleaning the parts with tissues and isopropyl alcohol. This complicated the assembly process, since the sensor and the strips adhered to the surfaces. Therefore, an anti-static ionizing bar was used in order to discharge the jigs and strips.

\[\text{Fraser 3024 F 31}].\]
5. Assembly of the functional module

Figure 5.8.: Sketch of an overlaid 1.8 mm and 4 mm AlCF-bridge. The yellow area represents a Kapton strip underneath the bridges. The circles correspond to feasible locations for suction holes.

To summarize the results of this jig evaluation, it can be stated that on the one hand the sensors and strip can be placed precisely in the two positioning jigs. On the other hand, the strip transfer jig provides a stable way to transfer the strips onto the sensor. Therefore, it can be assumed that the presented jigs and the according process provide sufficient precision to comply with the specifications.

5.3.2. Assembly of the Kapton strips

During the assembly of the dummy sensors it was observed that the strips varied in their width and length, which resulted in a bad fit in the strip positioning jig. Therefore, several strips were measured and tested for the assembly of the module prototype. From this set, four long strips were chosen that had a nominal width of 9.7 mm and a length of 95.420 mm, which is 140 µm smaller than specified. The stub bridge strips had approximately the nominal size. Besides these measurements, the beds of the sensor positioning jig were enlarged at the top and the left edge to provide space for the larger functional sensors. To compensate for the various size deviations, the components were placed in a specific way into the jigs to enable a sufficient isolation. In particular, the sensors were pushed to the lower right corner of the bed in the sensor positioning jig, and the long Kapton strips were pushed to the upper edges of beds in the strip positioning jig. This orientation scheme allowed for a sufficient overlap of the strips. However, it also changed their expected positions. A derivation of these values can be found in Appendix C.2. The subsequent gluing of the Kapton strips was conducted as described in the previous chapter. After the glue had cured, the positions of the strips were examined with a microscope by measuring the distance between the edges of the sensor and Kapton strips. The uncertainty of these measurements amounts to 3 µm, due to the optics of the microscope with multiple measurements.

The results are shown in Tab. 5.1 together with the expected values in parenthesis. The specifications refer to the ideal positions of the strips. An explicit calculation of the specifications can be found in Appendix C.1. Thereby, the superscripted and subscripted values represent the upper and lower limits, to comply with the specifications. The upper limits of \( d_y \) at reference point 3 are left blank since the module prototype was built with the long, 4 mm stub bridge strips, yielding a theoretical boundary of about 15 mm, which does not have a practical relevance.

Most of the strips are placed with deviations smaller than 30 µm from the expectations. The largest deviation of 84 µm occurs at reference point 2 for the top sensor. This complies with the evaluation measurement described in Section 5.3.1, where a maximal displacement of 75 µm was measured at this lower left corner of the sensor.

\[ \text{The strips were manufactured 130} \, \mu\text{m shorter. They showed an additional shortage individual to the strip ranging from 10} \, \mu\text{m to up to} \, 100 \, \mu\text{m depending on the strip.} \]

\[ \text{Keyence VHX-900F [23].} \]
Table 5.1.: Distances between Kapton strip and sensor edges of the module prototype. The expected values are given in parenthesis. The specifications represent the ideal values together with the upper and lower limits, which still allow for a sufficient isolation.

Furthermore, all strips are well within the specifications, which is why it can be assumed that the position of the strips is sufficient to isolate the AlCF-bridges against the bias voltage of the sensors. Based on these results, a similar grade of precision is expected for future assemblies.

5.4. The assembly of the bare module

The next step is the gluing of the sensors to the AlCF-bridges, which decides about the suitability of a module for the Level-1 trigger. For that, special demands are placed on the alignment of the sensors relative to each other. The specified margins allow for a rotational displacement of 400 μrad and a parallel (perpendicular) displacement of 100 μm (50 μm) with respect to the strip direction [11]. On the one hand, this requires special tooling to realize a precise positioning of the sensors. On the other hand, a measuring system is needed to check the sensor alignment with sufficient precision. In the following, both of these aspects will be described in more detail.

5.4.1. Jig and assembly procedure

For the assembly of the AlCF-bridges to the sensors the sensor gluing jig is used, which is depicted on the left side of Fig. 5.9. In the first step of the assembly process, the bottom sensor is placed on the vacuum bed of the jig with the strip side facing downwards. Two spring pushers are used to push the sensor towards the three precision bolts. The spring pushers are subsequently locked in a preloaded position with splints to hold the sensor in place. The sensor is then fixed by attaching a vacuum to the jig that sucks the sensor onto the PTFE-surface of the bed. After that, the spring pushers are moved back into their initial position.

In the next step, the glue is painted on the glue transfer jig, which consists of an aluminum bar with the length of the long AlCF-bridges. By placing the bridges on an area which is painted with glue, they are wetted just at the surfaces that will be in contact with the sensors. This procedure is shown on the right side of Fig. 5.9. The bridges are subsequently turned around to apply the glue also on the backside and then placed onto positioning pins in the sensor gluing jig.
5. Assembly of the functional module

Figure 5.9.: Assembly of the bare module. The sensor gluing jig uses spring pushers, precision bolts and pins to precisely glue the sensors and the bridges together (left). The glue is applied to the bridges by placing them on the glue application jig (right).

After the bridges are installed, the top sensor is placed on top with the strip side facing upwards. The spring pushers are preloaded and remain in this position to permanently push the top sensor towards the precision bolts. Subsequently, a weight plate is placed onto this sensor-bridge-sandwich. This weight plate is equipped with PTFE-strips underneath, to protect the sensor from scratches. The strips are located at the positions corresponding to the AICF-bridges to achieve a defined glue layer. After a curing phase of 24 hours, the weight plate is removed, and the spring pistons are retracted. The positioning pins of the bridges are then pulled out, and the vacuum is deactivated. In the last step the so-called bare module is removed from the jig.

5.4.2. Modifications of the sensor gluing jig

During the assembly of the dummy module three problems had been observed, which were solved with the following modifications made to the sensor gluing jig. First, the original positioning pins of the AICF-bridges were replaced by h6-tolerance pins, which offer a tolerance range of 0 to $-6 \mu m$. This prevents the pins from getting stuck in the jig or the bridges. At the same time, this tolerance also results in an equal loss of positioning precision of the AICF-bridges, but since they have a specified displacement margin of $50 \mu m$, this loss is acceptable.

The next modification refers to the weight plate, which has been equipped with an additional PTFE-strip at the side, where spring pusher '2b' is located. This strip serves as vertical support to prevent an upwards bending of the sensor, which may be caused by the spring pusher since it moves slightly upwards in its housing when it is locked in its position with the splint. This movement leverages to the sensor, bending it upwards and inducing additional stress in the module. A picture of the modified weight plate is shown in Appendix C.3.

The last modification concerns the pins that limit the lateral movement of the stub bridge in the jig. Initially, there was a clearance of $370 \mu m$ between the pins and the bridge, allowing for displacements of the bridge that considerably reduced the overlap of the stub.
The assembly of the bare module

bridge strip. A graphic illustration of this problem can be found in Appendix C.4. As a solution, custom pins were made, which feature a larger diameter at the part that protrudes out of the jig to fill the clearance.

5.4.3. Assembly of the prototype bare module

Prior to the assembly of the prototype bare module, the AlCF-bridges were examined for sharp edges that could damage the Kapton strips. Additionally, it was ensured that the bridges are flat so that they have complete contact with the sensors along their whole length. The subsequent assembly of the bare module was carried out as described before, using the Polytec EP 601-LV glue. The glue layer was estimated by weighting the individual components before the assembly and the assembled bare module afterward, which yielded a weight difference of 40 mg. This value corresponds to an average glue layer thickness of 38 μm between the bridges and the Kapton strips, which complies with the specifications of a maximum value of 50 μm. However, it is assumed that the real layer is thinner, since the glue locally flowed out of the glue gap.

5.4.4. Double sided metrology of the bare module

To check whether the sensor alignment of bare modules complies with the specifications, the so-called double sided metrology (DSM) method is used at the Aachen assembly center. This method together with the setup shown in Fig. 5.10 was developed by Marius Preuten [32].

![Figure 5.10.](image)

Figure 5.10.: Double sided metrology setup. The module is mounted on an x-y-rotation-stage (left) and filmed with cameras mounted above and below the module (right). The lower camera is mounted in a similar position as indicated by the reflection of the upper camera.

The setup consists of two cameras mounted above and below an x-y-stage with an integrated rotary unit. These cameras take pictures of the top and bottom sensor of the module [11]. In principle, it is sufficient to compare just two pictures taken from the top and the bottom sensor to calculate their relative displacement. But due to vibrations and temperature variations it is not possible to sufficiently calibrate the cameras to each other for a longer period of time. Therefore, the rotational axis of the x-y-stage is used to generate reference points to match the cameras. For that, a corner of the module is photographed from both sides while the module is slowly rotated. A software subsequently identifies the marker in the corner of the sensor and calculates its position on each of the
5. Assembly of the functional module

taken pictures. According to the rotational movement, all these positions lie on a circular path. Then, a circle is fitted to these positions, whose center corresponds to the rotational axis of the stage. Since the two cameras share this rotational axis due to the experimental setup, these center points are equal for both cameras. With this information, the relative shift of the cameras to each other can be determined. In order to calculate their twist, a second reference point is necessary. Therefore this procedure is repeated for at least a second corner of the module. In order to increase the precision of the measurement, typically four reference points namely the four sensor corners are used. The two rectangles spanned by the four reference points of the two sensors, are matched to each other with a fit. This finally yields the values for the vertical, horizontal and rotational displacements of the sensors relative to each other.

Results of the measurement

The result of the measurement of the functional module is listed in Tab. 5.2 together with the specified values. It can be seen that the displacements of the module are well within the specifications. Since previous modules yielded similar results, it can be assumed that the jig still provides sufficient precision, although it was manufactured two and a half years prior to this measurement. This also means that the aluminum alloy of the jig does not suffer from significant corrosions or distortions over longer periods of time.

<table>
<thead>
<tr>
<th>Displacement</th>
<th>Rotational (µrad)</th>
<th>Perp. to strips (µm)</th>
<th>Par. to strips (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module prototype</td>
<td>15.9</td>
<td>5.56</td>
<td>8.01</td>
</tr>
<tr>
<td>Specifications</td>
<td>&lt;400</td>
<td>&lt;50</td>
<td>&lt;100</td>
</tr>
</tbody>
</table>

Table 5.2.: Sensor displacements of the module prototype. The values describe the misalignments of the top sensor with respect to the bottom sensor.

5.5. The module carrier jig

After dismounting the bare module from the sensor gluing jig, it is moved to the module carrier jig, shown in Fig. 5.11. This jig consists of an aluminum frame, in which the module can be mounted for a secure transportation and handling. Plexiglas plates can be attached at the top and bottom to protect the sensors against contamination and damage.

5.5.1. Isolation test of the module prototype

Besides transportation, the carrier jig was used to perform a high voltage test in order to verify that the Kapton strips provide the expected isolation. For this purpose, the high output of a high voltage power supply\(^7\) was connected with cables to the pigtails via adapter boards\(^8\). The ground output was attached to a cable soldered to a ring cable lug, which was screwed on the module carrier, as depicted in Fig. 5.11. The electrical contact between the ring lug and the three AlCF-bridges was verified with an ohmmeter. A voltage of \(-1000\) V was applied to the pigtails, which yielded a stable resistance of about 1 GΩ. This validates the assumption made in Section 5.3.1 that the Kapton strips are placed sufficiently precise to isolate the bridges against the sensor bias voltage.

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\(^7\)Keithley 2410 [33].

\(^8\)The adapter boards were manufactured by KIT in Karlsruhe.
5.6. The assembly of the hybrids

The next step of the module assembly is the gluing of the front-end and service hybrids to the tabs of the Al-CF bridges. The challenge of this step is to achieve a precise alignment of the FEHs to the sensors for a convenient wire bonding. Furthermore, the position of the FEHs and the SEH must be matched to ensure that the hybrids can be connected to each other. In addition to that, a thin glue layer between the hybrids and the tabs is important to transport the generated heat effectively to the cooling pipes. The specified maximal thickness of the layer is 50 µm.

5.6.1. Jig and assembly procedure

For the assembly of the hybrids, the *hybrid gluing jig* is used, which is shown as a CAD model in Fig. 5.12. First, the bare module is plugged onto alignments pins. Then, the dispensing gantry is used to apply a dot of glue onto each tab of the AICF-bridges at the dedicated position of the FEHs. Subsequently, the FEHs are placed on the tabs of the AICF-bridge, and two 100 µm thick Kapton strips are vertically inserted between the FEHs and the sensor edges. These strips protect the fold-overs of the FEH from the sharp-edged sensors during the next step, where the FEHs are pushed towards the bare module by engaging the spring pushers. The position of the FEHs is manually adjusted so that the bond pads of the hybrids line up with the sensor strips to within one pitch (90 µm), which is checked under a microscope. Next, the SEH is assembled by applying a dot of glue onto each tab of the AICF-bridges at the dedicated position of the SEH. The hybrid is subsequently plugged with its alignments holes on two positioning pins in the jig to align it with the bare module. Then, three weight bars are lowered onto the hybrids and the spring pushers are released from the FEHs. After a curing period of 24 hours, the weight bars are lifted, and the tails of the SEH are plugged into the FEHs. Then the alignment pins are removed together with the 100 µm Kapton strips, and the module can be dismounted from the hybrid gluing jig. As the last step, the module is transferred to the carrier with the bottom sensor facing upwards to reach the pigtails and plug them into the SEH.
5. Assembly of the functional module

Figure 5.12.: CAD model of the hybrid gluing jig. The FEHs are pushed with spring pushers against the sensor edges with Kapton foils in between. Weight bars are used to achieve a defined glue layer.

5.6.2. Modifications of the hybrid gluing jig

The problem associated with this assembly approach is that misalignments of the sensors are transferred to the FEHs due to their floating position relative to the bridges. But as the SEH is glued at a defined position, the hybrid alignment is over-constrained. Therefore, any shifts of the FEHs need to be compensated by the tails of the SEH. Since these consist of a 250 µm thick PCB with four 17 µm thick copper layers, a study was carried out to evaluate the flexibility of the SEH tails and the feasibility of this assembly approach.

Flexibility study of the SEH tails

For this study, two test boards were used, which are depicted in Fig. 5.13. The left board replicates a 1.8 mm FEH, into which the right board was plugged, which substitutes the SEH with the respective tail. The FEH board was fixed onto a support bar, which was screwed to the microscope plate of a microscope\(^9\). These screws were additionally equipped with nuts to restrict lateral movements of the SEH board. To measure the force required to compensate a dislocation of the FEH, a spring balance was attached to the SEH board with a hook to bend the SEH tail. By pulling the spring balance, the tail was compressed. The corresponding weight was subsequently read off and multiplied with the gravitational constant to yield the force. The respective uncertainty is composed of two linearly added components. The first component is a 3 g uncertainty caused by reading off the 10 g scale of the spring balance\(^{10}\). The second component originates from an inelastic bending of the tail during each measurement, which distorted further measurements. To correct this behavior, the tail was bent back into its initial shape after every measurement, which caused variations of 5%, assessed with multiple measurements. The displacement of the SEH board was measured with the microscope with the aforementioned uncertainty of

\(^9\)Keyence VHX-900F [23];
\(^{10}\)It is assumed that the real weight is equally distributed in the scale interval.
The assembly of the hybrids

3 µm, which was also assessed with multiple measurements. This measuring procedure was subsequently repeated with the spring balance turned around to pull the SEH board away from the FEH board to ‘stretch’ the tail.

Figure 5.13.: Measurement of the SEH tail flexibility. The setup consists of two hybrid boards that are pushed together and pulled apart with a spring balance (left). The force was measured with a SEH board featuring a nominal and a slitted tail (right).

The results are displayed in Fig. 5.13 as the curve labeled as ‘Nominal tail’. It can be seen that the applied force is linearly and symmetrically increasing in the compression and stretching direction. For the assembly, this means that a force of about 5 N needs to be applied on each of the tails of the SEH to compensate a FEH misalignment along the sensor strips of 75 µm. This is a realistic displacement of the two connectors considering besides the sensor and FEH misalignment also manufacturing-related displacements of the male and female connector on the hybrids. On the one side, this complicates the assembly, since the tail needs to be bent with a considerable force to plug the SEH tail into the FEH. On the other side, this induces a significant and permanent amount of stress in the module and increases the chance of the tail unplugging itself at some point in time, which is not an abstract scenario in regard to an operating period of about ten years.

Therefore, different approaches were investigated in order to increase the flexibility of the tail. For example, two slots each 300 µm wide were cut into the SEH, which reduced the total width of the tail (5.6 mm) by about 10%. The corresponding measurement is shown in Fig. 5.13 as the curve labeled as ‘Slitted tail’. This curve also shows a linear and symmetric increase in the force but with an approximately 10% smaller slope compared to the previous measurement. This indicates a linear relation between the width and the flexibility of the tail. However, since the tail can hardly be narrowed even further, this slitting approach is not sufficient to increase the flexibility to a required extent. Solutions such as replacing the copper layers by meshes are not expected to have the necessary impact. In addition to that, it should be noted that the shifts of the FEHs perpendicular to the sensor strips have not been taken into account in this evaluation, which further increases the required force.

In summary, it seems questionable whether the SEH tails provide enough flexibility to allow for the ‘floating’ alignment of the FEHs due to the large stress. This assessment also applies to the 4 mm version of the module, although a slightly higher flexibility is expected due to the longer and more extensive curvature of the tail.
5. Assembly of the functional module

Figure 5.14.: The alternative design of the SEH tail features a loop (left). The measurement of this looped tail is shown together with the values of the nominal tail design (right).

In order to connect the SEH in a less mechanically demanding way, two other approaches were investigated. The first one exists in a redesign of the tail to increase its flexibility. The design under consideration is as a loop that connects to the opposite side of the SEH connector, as shown in the CAD sketch on the left side of Fig. 5.14. To test this design, an SEH board was used, whose tail was cut and bent until the shape of the design-loop was achieved. For the corresponding tests two different loop diameters, $d_l$, of 3.5 mm and 5.5 mm were investigated. These values correspond to the largest possible diameters for the 1.8 mm and 4 mm module respectively, whereby the limitations arise from the installation space in the tracker. The measurements were conducted in the same way as in the previous study. The corresponding results are displayed on the right side of Fig. 5.14. It can be seen that the flexibility increased by more than one order of magnitude compared to the nominal tail design. Extrapolating the first measurement points yields that less than 0.15 N are necessary to compensate an FEH dislocation of 75 µm compared to the 5 N obtained with the nominal tail design. By assuming that similar forces are necessary to dislocate the tail in the perpendicular direction, this approach results in a significant reduction of the mechanical stress for the module. Therefore, it is suggested to consider this design in the later SEH hybrid.

The second approach to reduce the stress between the SEH and FEH connection relies on the concept of assembling the FEHs at defined positions matched with the SEH. By that, a bending of the tails would not be necessary. Furthermore, this would simplify the assembly process of the FEHs, as the 100 µm Kapton spacer and the spring pushers could be omitted. In addition to that, a manual check of the bond pad alignment would not be required, presuming that the FEHs could be aligned precise enough.

However, this approach has some implications in regard to the assembly that should be briefly discussed. First, dislocations of the sensors must now be compensated by the wire bonds. But since the bonding machine automatically compensates changes in the sensor and FEH bond pad alignment of up to a few hundred microns, this implication does not further affect the assembly process [29]. Second, there must be a gap of a few hundred microns between the FEH fold over and the sensor edge in order to compensate for displacements of the sensors in the direction parallel to the strips. This gap also allows for inaccuracies of the bending of the fold over and the positioning of the alignment holes. But since the encapsulation of the wire bonds is applied above this gap, it must be ensured that the glue does not flow through the gap between sensor and fold-over.
For this purpose, a test structure was made by Tim Ziemons \[29\] to check whether the encapsulant is viscous enough to remain on the top side of the module or if it flows through the gap to the bottom sensor. The structure consists of a slitted bar, on which two gold covered strips were glued to replicate the row of bond pads on an FEH and sensor. Onto these strips, a line of 200 bonds with a length of about 4.5 mm and a nominal pitch of 90 µm was placed to imitate the wire bonds on a real module. After the application of the Sylgard 186 on top of the wire bonds and a subsequent curing phase of 24 hours, the test structure was photographed from the front side, as shown in Fig. 5.15. A lamp was used to illuminate the structure from behind. The picture shows that the slit is clear, meaning that the encapsulant completely remained at the wire bonds. Therefore, it can be assumed that the encapsulant is viscous enough not to flow through a gap of a few hundred microns between the fold over and the sensor edge.

![Test structure with wire bonds to assess the behavior of the encapsulant.](image)

This leads to the conclusion that the assembly of the FEHs at predefined positions is a feasible concept. To translate it into practice, the alignment holes of the FEH were used and according to that four holes were drilled into the hybrid gluing jig. These were placed at the nominal positions of the alignment holes of the 1.8 mm FEH with a lateral offset of 500 µm pointing away from the respective sensor edge. This offset considers imperfections of the FEH and allows the jig to assemble the 1.8 mm and 4 mm module version since the latter features a more spacious fold over.

The jig used in the course of this thesis is shown in Fig. 5.16, whereby the module prototype is placed in the jig together with the two FEHs. The left FEH is already positioned with the pins; the right hybrid rests on two ramps, whose purpose will be explained in the next section.

### Constraining the FEH placement

The ramps are used to guide the FEHs directly to their nominal position on the tabs of the bridges. This eliminates the need for readjustments of the FEHs, which are required in the original assembly procedure when placing the FEHs manually on the AlCF tabs and pushing them to the sensor edge. This movement of the FEHs results in smearing of the glue layer between the tabs and the FEH, reducing the quality of the thermal connection between the two components. Additionally, it increases the chance of glue leaking out of the gluing gap. This is unfavorable since outgassing could condense on the sensor and thus cause an increase of the leakage current. To circumvent these problems, the ramps depicted in Fig. 5.17 were developed, to constrain the hybrids to a defined path to their target position.
5. Assembly of the functional module

Figure 5.16.: Assembly of the FEHs to the module prototype in the hybrid gluing jig. For this step, the FEHs pushed along the trajectory defined by the ramps underneath. Guides beside prevented lateral shifts. The FEHs were fixed with alignment pins.

Figure 5.17.: Path of the FEHs with the ramps as constraint. In this ideal CAD model the FEH touches the glued tabs of the AlCF-bridges in the same moment, when it has reached its nominal position minimizing the smearing of glue (left).

In their resting position, the FEH is slightly tilted since the points of contact with the ramp are the edge of the CF stiffener and the edge of the fold-over PCB. This ensures that the bond pads of the hybrid are not rubbed off or contaminated when the FEH slides on the ramps. By pushing the hybrid towards the sensors, the FEHs rotate in a horizontal orientation, since the slope of the ramp is matched with the FEH geometry. The trajectory of the FEH ends directly at its nominal position where it is subsequently fixed with the alignment pins. In this way, no further adjustments of its position are required. During this gliding process the lateral movement of the FEH is constrained with lateral guides placed beside the AlCF-bridges, as depicted in Fig. 5.16.

In the course of this thesis, a set of ramps was produced with an acrylic-resin 3D printer featuring an accuracy of about 100 µm. The ramps were attached with an offset of 300 µm pointing away from the sensor edge to allow for the inaccuracies of the printer and additional manufacturing tolerances of the FEHs. Due to that, the FEHs touch the bridges slightly before they reach their target position.

It should be noted that the 4 mm FEHs require ramps with a steeper slope due to their larger thickness. Sketches with the dimensions of both types of ramps can be found in Appendix C.5. For series production, however, it is conceivable to design the ramps with holes and pins to plug them onto the hybrid gluing jig. In this way, it is avoided to manufacture and use different jigs depending on the module type to be assembled.
5.6.3. Assembly of the FEH

After the test run with the dummy module, the weight bars were equipped with further cut outs to consider the SMD parts of the FEH. Furthermore, the FEHs were examined under a microscope, whereby cracks in the isolation layer of the fold over were found. In order to protect the exposed shield layer, small pieces of Kapton tape were applied. Since particles with a size of a few hundred microns were observed in the Polytec TC 437, which is the intended glue for this step, the Polytec EP 601-LV was used instead to ensure a sufficient glue joint. For the assembly of the FEHs, a dot with a weight of 1mg was dispensed on each tab of the AlCF-bridges, which equals a glue layer thickness of 5 µm.

Then the assembly was carried out with the procedure mentioned in Section 5.6.1. Instead of using spring pushers, the FEHs were placed on the ramps and then moved by hand to their nominal position. Subsequently, the alignment pins were inserted, and the adapted weight bars were applied for a curing phase of 24 hours. The assembly of the SEH was conducted at the end of the whole module building process and is therefore described in the last part of this chapter in Section 5.9.

After the glue had cured, the alignment of the FEHs was measured with the microscope by measuring the distance between the ground pads and the sensor edge on the top side of the module. The results are shown in Table 5.3 in terms of deviations from the nominal values in the parallel (Δx) and perpendicular (Δy) direction to the strips. The read-off uncertainty is 3 µm. The numbering of the module corners refers to the definition introduced in Section 5.3.

<table>
<thead>
<tr>
<th>Ref. point</th>
<th>Δx (µm)</th>
<th>Δy (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-140</td>
<td>-37</td>
</tr>
<tr>
<td>2</td>
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<td>-72</td>
</tr>
<tr>
<td>5</td>
<td>44</td>
<td>-82</td>
</tr>
</tbody>
</table>

Table 5.3: Deviation of the FEH position from the expectation.

From the table it can be seen that all measurements deviate considerably from the expectation. In general, these deviations are caused by an inaccurate gluing of the PCB onto the CF-stiffeners during manufacturing, which is carried out with a precision of about 100 µm [34]. This was validated by an inspection of the alignment holes of the FEHs. Besides that, the gap between the left FEH and the left sensor edge is considerably smaller than at the right side. This can be attributed to the size deviation of the sensor, which reduces the distance by 130 µm. But since a variety of other assembly inaccuracies conglomerate in this measurement (for example the misalignment of the top sensor and the drilling precision of the holes in the jig) a more detailed discussion is waived at this point.

To summarize this section, it can be said that the positioning of the FEHs at a defined location is mechanically feasible and simplifies the FEH assembly due to omitting the Kapton spacers and the spring pusher mechanism. However, with this approach the alignment of the FEHs is mainly determined by their manufacturing accuracy. Since the imprecisions can amount to about 100 µm, this solution alone may not be sufficient to reduce the stress between SEH and FEH. Therefore it is suggested to use the defined positioning of the FEHs together with the loop-shaped tails of the SEH in order to achieve a reliable and straightforward assembly.
5. Assembly of the functional module

5.7. The wire bonding

The next step of the assembly process is the connection of the sensor strips with the readout chips on the FEH, which is performed with the wedge bonding technique. The main challenge of this task is the evaluation of optimal parameters of the bonding process in order to reliably connect all 4064 channels of the module.

5.7.1. Jig and bonding procedure

For this step, the wire bonding jig was designed, which is shown in Fig. 5.18. It features alignment pins, onto which the AlCF-bridges of the module are plugged. For fixation, six rubber feet connected to vacuum are used to suck the bottom sensor onto a plastic covered surface of the jig. Subsequently, two bars underneath the FEHs are raised with a screw mechanism, until they touch the bottom side of the respective FEH to provide counterpressure for the wire bonding machine. Then, the bonding machine calibrates the position of the bond pads on the FEH and the sensor, by identifying characteristic features on the surfaces of both components with a camera. After that, the wedge of the bond machine positions the end of a 28 µm thick aluminum bond wire above the first to be bonded gold pad of the FEH. By pressing the wire onto the pad and applying an ultrasonic vibration, both materials are welded together. Subsequently, the wedge moves from the FEH pad to the strip pad. During that, a clamp that fixes the bond wire is opened to span the wire from pad to pad. Next, the clamp is closed, and the wedge repeats the bonding procedure to weld the wire onto the AC pad of the strip. As the last step, the wedge performs a tear-off movement to break off the wire. This process is subsequently carried out for all strips. Additionally, the ground pads of the FEH are bonded to the bias ring in order to enable the AC coupled readout. After finishing the bonding of the top sensor, the module is turned around to repeat the procedure with the bottom sensor.

Figure 5.18.: Wire bonding jig. The module is positioned with two alignment pins and fixed with vacuum suction cups. The FEHs are support with bars that can be leveled with screws.
5.7.2. Wire bonding of the module prototype

Prior to the bonding of the module prototype, the FEHs were carefully cleaned with isopropyl alcohol. Then the bias pads of the FEHs were bonded to the bias ring of the sensor with three wire bonds in each corner, according to the specifications. This was followed by a measurement of the I-V curves to assess the influence of the FEH ground loop. After that, the channels of the FEHs were bonded to the sensor strips\(^{11}\). This was first carried out with the dummy module to optimize the bonding parameters and positions. These settings were then used for the wire bonding of the module prototype. At first, just 20 wire bonds were placed in order to perform a pull test to assess the performance of the parameters\(^{12}\). The test of these 20 bonds yielded a corrected mean of 12.7 g (> 8 g), a root-mean-square value of 4% (<10%) and did not show any lift offs (<20%). The specifications given in the brackets comply well with the measured values. Therefore, these settings were used to bond all strips of the functional module. The results are listed in Tab. 5.4, whereby the first column describes the number of bonds per FEH per sensor that were applied in the first attempt. The second row refers to bonds, which were successfully placed in a second attempt with slightly varied bond parameters. The last column describes the number of channels of the sensor that remain unconnected after these two attempts. The bonding itself was conducted by Tim Ziemons [29].

<table>
<thead>
<tr>
<th>FEH</th>
<th>Sensor</th>
<th>1st attempt bonded</th>
<th>2nd attempt bonded</th>
<th>2nd attempt unbonded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left FEH</td>
<td>Top sensor</td>
<td>1015</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Bottom sensor</td>
<td>1016</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Right FEH</td>
<td>Top sensor</td>
<td>1011</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Bottom sensor</td>
<td>211</td>
<td>10</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 5.4.: Amount of wire bonds applied to the module prototype. The first and second column list the amount of bonds, which were successfully applied at the first or second attempt. The last column refers to channels that remain unbonded after the second attempt.

The table shows that all channels of the left FEH were initially bonded except for one channel, for which the machine did not reach a sufficient wire deformation in the first attempt. This is typically caused by entrapped air in the glue layer under the gold pad of the FEH. A picture of a row of wire bonds applied to the top sensor is depicted on the left side of Fig. 5.19.

The bonding of the channels on the right FEH revealed more problems. On the top sensor it was not possible to create a sufficient weld on two pads of the FEH despite a manual correction of the parameters and bond locations. On the bottom side, the proportion of bonds that suffered from this problem was so large that it was decided to cancel the assembly on this side after 244 channels in order to investigate the cause of this behavior. A contamination by a fingerprint was ruled out since this problem did not occur locally but unsystematically spread.

By investigating the surface of the FEH pads with a microscope, small droplets of a clear liquid surrounding the FEH pads were observed, as depicted on the right side of Fig. 5.19. It can be ruled out that the contamination took place during the assembly of the module since the FEHs had not been in direct contact with any glues, apart from their assembly on the AlCF-tabs.

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\(^{11}\) For that a F&K Delvotec G5 62000 wire bonding machine was used.

\(^{12}\) The tests were performed with a Dage Series 3000 pull tester.
5. Assembly of the functional module

Figure 5.19.: Wire bonding of the module prototype. The top side of the right FEH was bonded without disruptions and yielded a uniform row of wires (left). The bond pads on the bottom side of the right FEH were locally contaminated with residuals (right).

In addition to that, the left FEH did not show any residuals and could be bonded without any issues. It is conceivable that the contamination may have occurred during the production of the FEH, where an epoxy glue is used near the lower bonds to manufacture the fold over.

To summarize this step, it can be said that one FEH has been successfully bonded to the sensors, enabling the full readout of the left half of the module, which will be subject of Chapter 7. Regarding the other 'half' of the module, it could be considered to remove the residuals with acetone and try to bond the remaining channels.

5.8. The encapsulation of the wire bonds

The next step in the assembly process is the encapsulation of the wire bonds. For this task the Sylgard 186 encapsulant is used, which provides a high viscosity of 66700 mPa·s to prevent the adhesive from spreading over the sensor surface. To ensure sufficient protection, it is required that all wire bonds are entirely coated with the encapsulant.

5.8.1. Encapsulation procedure

For the encapsulation the module is installed in the carrier jig, which is mounted on the table of the dispensing gantry with adapter plates. Then, the encapsulation is applied to the left and right row of bonds, which connect the top sensor with the left and right FEH. This includes the bonds, which are applied to the strips, as well as the bias ring of the sensor. After a curing phase of 24 hours, the module is installed upside down in the carrier to encapsulate the bonds of the bottom sensor. This is followed by another 24-hour curing phase to dry the encapsulation on the bottom side. Due to the curing time of in total 48 hours, the encapsulation of the bond wires is the most time-consuming assembly step.

5.8.2. Encapsulation of the module

In contrast to the nominal procedure using adapter plates, the module carrier was placed directly on the y-table and positioned with the three stopper bolts. The encapsulation was applied in a spiral pattern, as shown in Fig. 5.20. This pattern was previously tested.
with the test plate and later with the dummy module. For the application, a conically shaped, light green tip with a minimum inner diameter of 0.84 mm was used, together with a Dispense Rate of 0.005 cm³/s and a Line Speed of 5.5 mm/s. The distance between tip and bond wires was set to approximately 1 mm. With these settings, the two rows of bonds on the top sensor were covered with 0.55 g of encapsulant each. Most of the bonds were initially covered; punctual holes in the layer were filled by dispensing additional dots on the respective areas. The only macroscopic air bubble with a diameter of about 1 mm was removed by puncturing it with a tweezer.

Figure 5.20.: Encapsulation of the module prototype. The encapsulant was applied using the dispensing gantry (left). The dispensing pattern consisted of a single, spiral shaped line (right).

The subsequent curing phase was reduced from 24 hours to four hours. After that, the module was turned around, and the encapsulant was applied on the left, fully bonded row of the bottom sensor. In this orientation with the ‘precured’ glue facing downwards, the module was subsequently left for the nominal 24 hour curing phase. After that, the module was photographed from the front, as depicted in Fig. 5.21, to examine the impact of this procedure on the shape of the layer.

Figure 5.21.: Front view of the module. The thickness of the encapsulation layer on the top and bottom side of the module is measured with respect to the surface of the respective sensor.

From the figure, it can be seen that the encapsulation layer on the top side of the module measures 1041 µm and the layer on the bottom side 1088 µm. Both values can be assumed as compatible, since the height of the layers varied by about 100 µm along the whole edge of the FEH. Therefore, a pre-curing phase of 4 hours is sufficient for the encapsulant to get viscous enough in order to retain its shape regardless of the module orientation. This
means that the duration of this assembly step can be reduced by one day, which equals about 10% of the total assembly time of the module.

5.9. The assembly of the service hybrid

The last assembly step in the course of this thesis existed in the assembly of the SEH. Since in the nominal procedure this step was already explained in Section 5.6.1, this section concentrates on the assembly of the SEH to the dummy module and the module prototype.

5.9.1. SEH assembly of the module

The dummy module was used to test the general procedure with a non-functional SEH. For this test run, dots with a weight of 1 mg of Polytec EP 601-LV were applied on each of the three tabs of the AlCF-bridges. This amount equals an average glue layer thickness of 5 µm, which is well within the specifications of 50 µm [30]. But due to this large margin and since no excess was visible at the SEH edges after curing, this could also indicate a lack of glue. Therefore, it should be considered to increase the value for further assemblies. In case of the functional module, a rectangular piece of adhesive tape was applied to each tab of the bridges to allow for an exchange of the SEH with a newer or modified version. The assembly is depicted on the left side of Fig. 5.22.

![Figure 5.22.: Assembly of the SEH. The SEH is assembled to the module prototype by plugging it onto the alignment pins (left). The HV pigtails are plugged into the backside of the SEH (right).](image)

The last step of the assembly existed in the connection of the pigtails with the SEH. For that, the module was removed from the hybrid gluing jig and mounted upside down in the carrier. The pigtails were then plugged into SEH connector. The electrical connection between the high voltage circuit of the SEH and the sensor backside was subsequently validated by probing the parts with an ohmmeter. A picture with the connected pigtails is shown on the right side of Fig. 5.22. Since the SEH was also used during the subsequent electrical tests to route the bias voltage to the sensors, it can be stated that this is the first time that a 2S module is assembled and operated in such a configuration.
5.10. The 2S module prototype

The final module, mounted in the carrier, is shown in Fig. 5.23. To summarize this chapter it can be stated that several optimization potentials were recognized and implemented through modifying the jigs or the assembly process. This has ultimately paid off, as the 2S module prototype complies well with the mechanical specifications.

Figure 5.23.: The fully assembled 2S module prototype mounted in the carrier jig.
6. Measurements of the leakage current

Besides the previously discussed mechanical aspects, the sensors must also meet electrical requirements for the later operation in the detector. Many of them relate to the leakage current, as it directly affects the performance of a module in two ways. On the one hand, the leakage currents can generate noise affecting the detection efficiency of the module. On the other hand, the sensor is a significant contributor to the amount of heat dissipated by the module. Since the leakage current reacts sensitive to damages and contaminations, it is also a measure of the quality of the modules and the assembly procedure. Therefore, the leakage current of the two sensors assembled to the module prototype was measured after each assembly step. After a brief theoretical introduction, the measuring setup and the results are presented.

6.1. Theoretical background

In a simple model, the sensor of the 2S module can be approximated by a reverse biased p-n junction with the surface $A$ and the thickness $D$. To increase the width $w$ of its initial space charge region (SCR), a depletion voltage $V$ is applied to the junction. The relation between $w$ and $V$ is given by [36]:

$$w = \sqrt{\frac{2\epsilon_0 \epsilon_{Si} V}{q_e N_A}}, \quad (6.1)$$

with the free space permittivity $\epsilon_0$, the dielectric constant of silicon $\epsilon_{Si}$ and the electron electric charge $q_e$. The doping concentration of the junction is approximated by the acceptor concentration $N_A$ of the bulk [37].

The amount of electron-hole pairs generated when a particle crosses the sensor is maximized by using the whole sensor volume as SCR. For that, the 'full depletion voltage' $V_{FD}$ needs to be applied to the sensor, which is calculated by solving Equ. 6.1 for $V$ and inserting $D$ as width. This yields:

$$V_{FD} = \frac{D^2 q_e N_A}{2\epsilon_0 \epsilon_{Si}}. \quad (6.2)$$

In this model the p-n junction can also be seen as a parallel plate capacitor with the bulk capacitance $C_{bulk}$ and the width $w$. This is represented by Equ. 6.3 [35], where $C_{bulk}$ decreases hyperbolically in $w$ until the whole bulk is depleted:

$$C_{bulk} = \begin{cases} 
\frac{\epsilon_0 \epsilon_{Si} A}{\omega} = A \cdot \sqrt{\frac{\epsilon_0 \epsilon_{Si} q_e N_A}{2V}}, & V \leq V_{FD} \\
A \cdot \frac{\epsilon_0 \epsilon_{Si}}{D} = const., & V > V_{FD}
\end{cases} \quad (6.3)$$

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6. Measurements of the leakage current

The leakage current of a diode

The p-n junction operated in reverse bias produces a leakage current \( I \), which originates from two sources. The first source arises from minority charge carriers that are located at the outside but close to the SCR. With a sufficiently large diffusion length, they can reach the electric field of the SCR, where the charge carriers are attracted to the voltage source. However, in the considered voltage and temperature ranges of the following measurements, this so-called ‘diffusion current’ can be neglected [37]. The second contribution is the ‘generation current’, denoted as \( I_{\text{gen}}(T) \). It is caused by the thermal generation of electron-hole pairs inside the SCR, which are immediately separated by the electric field. The extent of this effect depends on the SCR volume and is the dominating contribution to the total leakage current. Therefore, \( I \) can be approximated by \( I_{\text{gen}} \) with [35]:

\[
I(T) \approx I_{\text{gen}}(T) = \frac{\omega A g_{e} \sigma N_{t}}{2} \cdot n_{i}(T) \cdot v_{th}(T).
\]

(6.4)

The impurity state concentration near the middle of the band gap is denoted as \( N_{t} \) and the charge carrier cross-section as \( \sigma \). The equation also contains the thermal velocity \( v_{th} \) and the intrinsic charge carrier concentration \( n_{i} \). By combining Equ. 6.1 and 6.4, the relation \( I \propto \omega \propto \sqrt{V} \) is obtained, which is valid until the p-n junction is fully depleted at \( V_{FD} \). If the voltage is further increased, the current starts to increase strongly above a certain point. This is caused by the multiplication of charge carriers during their collision with the lattice, leading to a destructive avalanche called breakdown [37]. These features result in a characteristic curve when measuring the leakage current against the applied voltage, which will be called \( I-V \) curve in the following.

Another property of the leakage current is its strong temperature dependence, which arises from \( n_{i}(T) \) and \( v_{th}(T) \) in Equ. 6.4. The relation describing this behavior is given by [37]:

\[
I(T) \propto T^{2} \cdot \exp \left( -\frac{E_{g}}{2k_{B}T} \right),
\]

(6.5)

where \( k_{B} \) is the Boltzmann constant and \( E_{g} \) the energy gap between the conduction and valence band.

6.2. Setup for the leakage current measurement

The probe station

The leakage current measurements of the assembled silicon sensors were carried out with a probe station\(^1\) shown in Fig. 6.1. It is housed in a light-tight box, which shields the samples from light to avoid photoelectric currents distorting the measurements. The sensors are placed on a sample holder, the so-called chuck, which is connected to vacuum to fix the sensors. The chuck is mounted on a \( x-y-z \) stage and can be moved with an external controller or computer software. Beside the chuck, an environmental sensor\(^2\) is placed to monitor the humidity and temperature. To lower the humidity, the probe station can be flooded with dry air.

The sensors are contacted with a tungsten needle, which has a tip radius of 7 \( \mu \text{m} \). It is installed in the arm of a positioner\(^3\) which allows for a precise, three-dimensional movement of the needle by actuating micrometer screws. The positioner can be fixed to the platen of the probe station with a vacuum. A microscope, which can also be moved by the control panel or the software, is used to observe the contacting procedure.

\(^1\)Cascade Microtech PA200

\(^2\)IST LabKit HYT module [38] equipped with an HYT 271 sensor [39].

\(^3\)Cascade Microtech 5
Setup for the leakage current measurement

Figure 6.1.: Setup for the leakage current measurement. The probe station is placed in a light-tight box, which can be closed with a hut. Nearby is the power supply, the chuck and microscope controller and a monitor showing the measuring LabVIEW program.

A high voltage power supply\(^4\) is used to apply the (negative) bias voltage to the sensors. Its 'high' output is connected via cables either to the chuck or a module component depending on the assembly step to be investigated. More details regarding the connections are described in the next part. The 'low' output is always attached to the needle positioner. The current is measured with the 'high accuracy' setting of the power supply, whereby its compliance setting is used to limit the current to 7 µA. A GPIB cable connects the power supply with a computer that runs the measuring program, which was created with LabVIEW \(^{[40]}\). It initializes the power supply, starts and records the measurement. The program is inspired by a script from Jakob Wehner \(^{[41]}\).

The electrical connection of the module

The first measurement of the sensor leakage current was conducted by placing the bare sensors with their backside on the chuck, as depicted on the left side of Fig. 6.2. The voltage was applied via a cable to the chuck; the ground connection was established by contacting the bias ring of the sensor. After the Kapton strips were glued to the sensor backside, the voltage was applied by placing two aluminum spacers between the chuck and the sensor. Once the HV-pigtails were assembled, the spacers were isolated with Kapton tape and a cable attached to the pigtails was used to route the voltage to the sensors. After the bare module had been built, the carrier jig was used to fix the module. The carrier itself was mounted on the chuck with an adapter plate and adhesive tape. In this setup, the voltage cable was applied only to the sensor to be measured. The bottom sensor was contacted by installing the module upside down in the carrier. Once the FEHs were glued and bonded to the bias rings, the sensors were grounded by contacting the HV ground pads of the right FEH. After the assembly of the SEH, the voltage was applied via a cable attached to the SEH. This configuration is depicted on the right side of Fig. 6.2.

\(^4\)Keithley 2410 \(^{[33]}\).
6. Measurements of the leakage current

Since the path of the current changed between nearly each assembly step due to additional components or different cables, comparing measurements were conducted. For that, the voltage and ground connection were applied identically to the respective previous measurement. For example, after bonding the bias ring to the FEHS, the ground was applied not only through the FEH ground circuit (actual measurement) but also by contacting the bias ring of the sensor (comparing measurement). Since no significant deviations between the comparing and the actual measurements were observed, influences on the I-V curves arising from new circuits could be ruled out. Besides that, the probe station was flooded with dry air for each measurement, since a high sensitivity of the sensors to humidity was observed. A relative humidity level of around 8% was chosen as the target value. To maintain this level, the dry air valve required readjustments to react on leaks of the probe station. This resulted in variations of 0.5% in units of relative humidity.

Figure 6.2.: Measurement of the leakage current. A bare sensor was measured by fixing it on the chuck, which routes the voltage to the sensor backside. A needle probing the bias ring was used to ground the sensor (left). In case of the assembled module prototype the voltage was applied through the SEH and the needle was placed on a ground pad of the FEH underneath the SEH tail (right).

6.3. Results of the measurement

The I-V curves of the top sensor, which were measured during the assembly of the module prototype, are shown on the left side of Fig. 6.3. For a better readability, the values of V and I are displayed in absolute values. Both sensors show the characteristic, root-function-like increase for voltages of up to 150 V. After that, I flattens, indicating the full depletion of the sensors. At about 400 V the leakage current increases in its slope indicating the start of the breakdown phase.

It can also be seen that the variations in the ambient temperature affected the I-V curves. This is especially noticeable for the sixth I-V curve recorded after the bonding of the bias rings. This curve was measured during a maintenance shut down of the air conditioner, which caused the significantly higher temperature of about 25°C.

In order to make the I-V more comparable for the further discussion, the uncertainty $\sigma_I$ or rather the shift caused by the temperature deviations was estimated. For this purpose the following equation [37], derived from Equ. 6.5, was used:

$$\sigma_I = I(T_0) - I_{\text{Bulk}}(T) \left( \frac{T_0}{T} \right)^2 \exp \left( -\frac{E_g}{2k_B} \left( \frac{T - T_0}{T \cdot T_0} \right) \right).$$

This equation only refers to bulk leakage currents $I_{\text{Bulk}}$. The measured 'total' leakage currents $I$ however are also comprised of surface leakage currents $I_{\text{Surf}}$. 
Results of the measurement

Figure 6.3: I-V curves of the top sensor measured after each assembly step of the module prototype with the ambient temperature indicated in parenthesis (left). The linear fit applied to the 'Bare sensor' I-V curve of the top sensor considers the currents measured between 200 V and 350 V (right). The contribution of \( I_{\text{Surf}} \) is indicated for 350 V.

These surface leakage currents are not \([42]\) (or much less \([35]\)) temperature dependent. To estimate their contribution to the 'total' leakage current, it was used they depend linearly on the bias voltage since they obey ohm law \([42]\). This causes the linear increase of the measured currents for voltages in the depleted regime prior to the start of the breakdown phase. According to that, a linear fit was applied to the I-V curves between 200 V and 350 V with the coefficients \( \alpha \) and \( \beta \):

\[
I_{\text{Fit}} = \alpha \cdot V + \beta \tag{6.7}
\]

This fit is exemplarily shown on the right side of Fig. 6.3 for the first I-V curve of the top sensor. The optimized coefficient \( \alpha \) was subsequently used as 'surface resistance' to estimate \( I_{\text{Bulk}} \), as difference of \( I \) and \( I_{\text{Surf}} \):

\[
I_{\text{Bulk}} = I - I_{\text{Surf}} = I - \alpha \cdot V . \tag{6.8}
\]

The corresponding \( I_{\text{Bulk}} \) curve is exemplarily shown for the 'bare sensor' measurement of the top sensor on the right side of Fig. 6.3. The obtained values for \( I_{\text{Bulk}} \) were subsequently used to calculate the values for \( \sigma_I \) with Eqn. 6.6 at a baseline temperature \( T_0 \) of 22.2°C. Since the ambient temperature either increased or reduced the I-V curve, \( \sigma_I \) is used as single-sided uncertainty. It is either positive or negative, depending on whether the measurement was conducted at a temperature below or above \( T_0 \).

6.3.1. Discussion of the I-V curves

The I-V curves with their according uncertainties are shown in Fig. 6.4 in a detailed view. For a better readability, the uncertainties are shown as bands. The I-V curves of the top sensor, depicted on the left side of Fig. 6.4, can be divided into two groups. The first group contains the measurements carried out with the bare sensor, the assembled pigtails, and the glued Kapton strips. Considering the uncertainties, it can be assumed that the leakage currents of these three measurements are compatible with each other. This in turn means that these assembly steps did not significantly influence the sensor.

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6. Measurements of the leakage current

After the assembly of the bare module, however, the leakage current increased by a factor of about 1.6. Since this behavior has already been observed by other working groups [16, 30], it is conceivable that this is not caused by individual handling faults. Instead, it could result from outgassings of the glue that condense on the surface of the top sensor, which is not fully covered by the weight plate during the curing phase. This theory could be checked by using fans during the next assemblies to blow eventual outgassings away from the sensor.

The $I$-$V$ curves of the subsequent assembly steps have a similar level considering the uncertainties. Therefore, it can be assumed that in principle neither the gluing of the FEHs nor the bonding, the encapsulation and the application of the SEH had a significant impact on the top sensor.

The bottom sensor deviates from this behavior in two aspects. First, the $I$-$V$ curve corresponding to the bare module does not differ from the preceding measurements. This supports the theory of outgassings since the strip side of the bottom sensor faces the PTFE-surface of the sensor gluing jig and is therefore covered against outgassings. Second, the $I$-$V$ curve measured after the assembly of the FEHs shows a significant increase. During an optical inspection, no signs of damages or contaminations of the sensor surface were found. Therefore, this increase is not understood and needs to be further investigated if it also occurs by other modules.

The next assembly step consisted in the bonding of the bias ring. This measurement is not depicted since it would exceed the plot range. In addition to that, it was waived to calculate an uncertainty due to the large extrapolation range. Hence, it is not possible to judge whether the subsequent increase in the $I$-$V$ curves is caused by the wire bonding of the bias ring or the strips. However, the second option is more likely, since the bonding of the bottom channels was accompanied by contamination problems of the FEH, as described in Chapter 5. During this process, several bond wires have been removed with a tweezer, which resulted in contaminations and slight scratches to the sensor surface. The subsequent encapsulation of the wire bonds (only on the left sensor side) and the assembly of the SEH did not cause a further increase in the leakage current.

It can be summarized that slight increases in the leakage current were observed after certain assembly steps. But since these measurements did not reveal a severe damaging of the sensors, the jigs and the assembly processes are assessed as applicable for the preproduction phase.
7. Measurement of the readout noise

Besides the leakage current also the noise level is an important measure to assess the performance of the module. It is especially suitable for checking the intactness of the bonds and the readout system. Since both of these aspects are of particular interest for the module assembly, noise measurements with the module prototype were performed between various assembly steps. The measuring setup and the results are presented in the following after a brief theoretical introduction.

7.1. Theoretical background

Noise is often specified in units of the Equivalent Noise Charge (ENC) representing the number of electrons generating the noise [35]. In the case of the module prototype, the dominating noise contribution is caused by the load capacitance of the (unirradiated) sensors. It is calculated by [35]:

\[ ENC \approx a + b \cdot C_{\text{strip}} . \]  

(7.1)

The variables \(a\) and \(b\) are specified by the preamplifier of the readout system, and the parameter \(C_{\text{strip}}\) refers to the total strip capacitance of the sensor. Thereby, \(C_{\text{strip}}\) is composed of two components [35]:

\[ C_{\text{strip}} = C_{\text{int}} + C_{\text{back}} . \]  

(7.2)

The first component, \(C_{\text{int}}\), relates to the interstrip capacitance; the second component, \(C_{\text{back}}\), describes the capacitance between the strip and the sensor backplane. In the following \(C_{\text{back}}\) is approximated by the bulk capacity \(C_{\text{bulk}}\) of the sensor divided by the number of strips:

\[ C_{\text{back}} \approx C_{\text{bulk}}/2032 . \]  

(7.3)

The interstrip capacitance is calculated by the following formula derived by theory [37]:

\[ \frac{C_{\text{int}}}{l} = (0.03 + 1.62 \frac{w + 20 \mu m}{p}) \text{ pF/cm} . \]  

(7.4)

This formula describes the interstrip capacitance per cm length \(l\) of the strip and depends on the ratio of the width \(w\) and pitch \(p\) of the strips. To cross-check the values of the total strip capacitance resulting by these formulas, the following equation is used [43]:

\[ \frac{C_{\text{strip}}}{l} = (0.8 + 1.7 \frac{w}{p}) \text{ pF/cm} . \]  

(7.5)

It applies to a depleted sensor of a thickness \(d\) with \(0.1 < w/p < 0.6\) and \(0.2 < p/d < 0.8\).
7. Measurement of the readout noise

7.2. Noise measurement with the CBC2

Binary readout scheme of the CBC2

The two FEHs, which were assembled to the prototype module, are so-called 8CBC2 hybrids. They are equipped with eight CBCs of the second generation (CBC2), which provide the basic functionalities to readout the strips of the sensor. The CBCs use an analog front-end design, depicted in Fig. 7.1, which provides a binary hit detection, briefly explained in the following.

![Analog front-end of the CBC2 chip](image)

Figure 7.1.: Analog front-end of the CBC2 chip [44]. Each readout channel consists of a pre- and postamplifier, as well as a comparator. The parameters $V_{\text{Plus}}$ and $V_{\text{Offset}}$ determine the DC baseline of the signal, while the $V_{\text{cth}}$ parameter refers to the threshold of the comparator.

After a particle crosses the SCR of a sensor, the generated electron-hole pairs are immi-

nently separated by the bias voltage. The resulting current is integrated and preamplified to a voltage pulse by the first stage of the CBC. A subsequent shaper filters this pulse and transmits it to the post-amplifier. This stage shifts the baseline voltage of all strips to a global value. This shift is specified by an 8-bit I$^2$C register denoted as $V_{\text{Plus}}$. A channel-specific adjustment of the baseline is provided by the $V_{\text{Offset}}$ register. In the last stage, the pulse is forwarded to a comparator, which compares the incoming pulse with a global threshold specified in the $V_{\text{cth}}$ register. Since the pulses after the post-amplifier stage are negative going, low $V_{\text{cth}}$ values correspond to high physical thresholds. If in this sense a pulse falls below the DAC threshold, the comparator generates a binary hit signal for the logic circuit of the chip.

The S-curve measurement

In reality, the DC baseline is superimposed by Gaussian noise of the electrical components, as sketched on the left side of Fig. 7.2 [37]. This results in noise pulses being incorrectly identified as hits if they reach the threshold of the DAC. By reducing the threshold, this behavior can be suppressed, but it also excludes weak signals of real particles from being identified. Therefore, a precise assessment of the noise level and a reasonable setting of the threshold is required.

For this purpose, a threshold scan is performed, whereby the threshold is ramped up while measuring the so-called occupancy $\epsilon$ of each channel is measured. The occupancy equals the ratio of hits per $N$ triggered readouts. By starting at low $V_{\text{cth}}$ values, the obtained occupancies are small since just a fraction of the fluctuations ‘reach’ the threshold as it is depicted on the left side of Fig. 7.2.
Figure 7.2.: The noise is a Gaussian distributed fluctuation in the amplitude of the DC baseline (left) [37]. S-curves of 20 channels measured for a CBC on a bare FEH (right).

At higher $V_{\text{cth}}$ values, the noise reaches this limit more often until the occupancy equals one if the amplitude of the noise consistently exceeds the threshold. By conducting this scan for a whole range of $V_{\text{cth}}$ values the so-called S-curve is derived. This is exemplarily shown on the right side of Fig. 7.2 with 20 S-curves recorded with a CBC on a ‘bare’ FEH not assembled to a module. Since this S-curve is obtained by a temporal integration over Gaussian distributed noise pulses, its distribution follows an error function [37]. This property is used to calculate the noise level $w$, defined as the width of the distribution, by fitting the error function to the measured occupancies:

$$
\epsilon = \frac{1}{2} \text{erf} \left( \frac{V_{\text{cth}} - P}{\sqrt{2\sigma}} \right) + \frac{1}{2}.
$$

(7.6)

Besides $w$ this equation also includes the pedestal $P$ of the S-curve, which equals the $V_{\text{cth}}$ value that yields an occupancy of 0.5.

### 7.3. Setup for noise measurement

The setup to measure the noise of the module is depicted in Fig. 7.3. At the front-end, an aluminum box is used to shield the module from light and electromagnetic fields. The box can be flushed with dry air, whereby the humidity and temperature are monitored with an environmental sensor\(^1\). The module itself is mounted upside down in its carrier jig to connect the FEHs with test boards\(^2\). Support bars on the carrier fix the tails of the FEHs and pieces of ESD-safe plastic foam provide support for the boards. The test boards power the CBCs and transmit the data from the hybrid to the back-end (and vice versa) via VHDCI cables. The back-end consists of an FPGA Mezzanine Card (FMC) mounted on an FC7 evaluation board [45], which is plugged into a µTCA crate\(^3\). This board represents the main readout unit, which will also be used for the module testing during series production. Besides the readout, it also configures the registers of the CBCs via I2C communication and provides trigger and clock signals. The board is operated with the d19c firmware of the CMS collaboration, which is controlled with the Ph2_ACF middleware via an Ethernet connection between a computer and the crate.

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1. IST LabKit HYT module [38] equipped with an HYT 271 sensor [39].
2. Just one hybrid was read out at a time in the course of this thesis since a simultaneous readout of both hybrids significantly increased the noise.
3. ELMA MicroTCA.4 6-slot crate [46].
A power supply provides the various low voltages (−5.0 V, 5 V, 3.3 V, 1.2 V) to the test boards and chips. More information regarding the powering scheme can be found in Ref. [48]. A high voltage supply is connected with its 'high' output to the pigtailed (or the SEH, depending on the assembly progress) to bias the sensors with −300 V during the noise measurement. The 'low' output is connected to a dedicated ground connector of the low voltage power supply, which acts as reference ground for the setup. Also the µTCA crate, the aluminum box, and the carrier jig are connected to this port to allow for a common grounding of all components. In addition to that, a significant reduction of the noise has been observed after connecting the carrier jig with the grounded mounting holes of the test boards with screws. This preliminary grounding scheme achieved the best results in the course of the measurements. But it may be further optimized, for example by grounding the FEHs for example directly to the SEH.

The measurements are carried out with the previously mentioned Ph2_ACF software, which contains a set of procedures to test the module. Prior to every noise measurement, the Calibration routine is carried out to achieve a uniform response behavior of the channels to incoming signals. This is realized by setting the $V_{cth}$ value of each CBC to a target value. Subsequently, the global $V_{Plus}$ is varied until the channels of a CBC in their entirety yield an occupancy of 50%. After this value is found and applied to the post amplifier, the channels are individually fine-tuned to an occupancy of 50% by adjusting the strip-specific VOffset value. Subsequently, the PedeNoise routine is executed, which performs the threshold scan. In contrast to the default settings, the number of triggers per $V_{cth}$ value is changed from 50 to 2000 events for each $V_{cth}$ step to reduce the variations of the measurement. To reduce crosstalk between simultaneously measured channels, the software had to be adapted so that just every eighth strip is measured simultaneously. After the measurements are completed, the software stores the obtained S-curves and computes the noise for each channel. This is realized by approximating the derivative of the S-curve with difference quotients and calculating the RMS this distribution.

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4Rhode & Schwarz HMP4040 [47].
5Keithley 2410 [33].
6The original setting measured every sixteenth pair of top and bottom strips simultaneously.
Results of the noise measurement

Offline calculation of the noise

In the course of the measurements, it was observed that some chips showed instabilities at high occupancies, as shown in Fig. 7.4, which warped the noise calculations of the software. Therefore, the noise was calculated offline by applying S-curve fits according to Equ. 7.6 to the measured occupancies. The range of the fit was adapted individually to the strip to exclude these instabilities. The uncertainty on the occupancy was assessed with multiple measurements. For that, the FEH was measured five times prior to the assembly. This yielded five values for the occupancy \( \epsilon_{i,j} \) measured for each channel \( i \) and each \( V_{\text{cth}} \) value \( j \). The standard deviation of these five values was used as uncertainty \( \sigma_{\epsilon_{i,j}} \) for the fit to weight the data. These uncertainties are indicated in Fig. 7.4 as error bars. After the FEHs were wire bonded to the strips, new multiple measurements were performed and the values for \( \sigma_{\epsilon_{i,j}} \) were updated.

Figure 7.4.: Single S-curve showing an instability at a high occupancy level. The uncertainties on the occupancies are obtained by multiple measurements.

The total noise \( \mu \) of the hybrid was calculated by averaging the noise of all 2032 channels. To estimate the uncertainty on this value, the total noise of the multiple measurements mentioned before was computed. The standard deviation of these values was subsequently used as uncertainty \( \sigma_{\mu} \). This uncertainty was also updated, by a new value obtained with the new multiple measurements, once the strips were bonded to the FEH.

7.4. Results of the noise measurement

7.4.1. The noise for different assembly stages

The results of the noise measurements after different assembly steps are displayed in Fig. 7.5, where the left plot refers to the left FEH and the right plot to the right FEH. In case of the left FEH, the histograms can be distinguished into two groups. The first group includes the measurements carried out prior to the bonding of the sensor strips, which peak at about 1.4 \( V_{\text{cth}} \) units. Considering the uncertainties, the measurements are compatible with each other, meaning that neither the gluing of the FEH on the module nor the bonding of the bias ring influenced the noise behavior of the module. The second group of measurements, embracing the bonding of the channels and the subsequent encapsulation of the module, show an increase of the noise from 1.4 to 2.5 \( V_{\text{cth}} \) units. This behavior results from the capacitance of the sensor that couples to the readout electronics through the wire bonds.
7. Measurement of the readout noise

Figure 7.5.: Noise of the left FEH (left) and right FEH (right) of the module prototype. The noise measurement of each assembly step is shown as translucent, colored histogram. The values of the right FEH separated by semicolons refer to the left and right peak respectively.

Furthermore, it can be stated that all channels are sufficiently bonded since every channel shows a noise of at least $2 V_{th}$ units. This also holds for the last measurement, meaning that not a single bond was not destroyed during the encapsulation process. However, a small increase in the noise is noticeable. Since it barely exceeds the measurement uncertainty, it is not clear if this increase results from the encapsulation. Therefore, special attention should be paid during the assembly of further modules whether this feature occurs again.

On the right side of Fig. 7.5 the results of the right FEH are displayed. Similar to the left FEH, the histograms that correspond to the first three assembly steps are well compatible with each other. The noise is 5% smaller than for the left FEH, however the width of the distribution is wider. After the bonding of the strips, also for this FEH a significant increase in noise can be seen. But in contrast to the left FEH, the distribution features a second, lower peak. This results from the 795 channels on the bottom side and the two on the top side of the hybrid, which could not be bonded, as described in Chapter 5. However, this result shows that all bonded channels have a sufficient electrical contact with the bond pads, which was also maintained after the encapsulation. Therefore, it can be concluded that all 4064 strips of the module show reasonable values for the noise, meaning that no bonds or channels in the readout electronic were destroyed during the assembly process. This again underlines the suitability of the assembly procedure and the jigs for the preproduction phase.

7.4.2. The noise in ENC units

With the left FEH of the fully assembled module prototype another study was carried out to investigate the noise of the module in dependence of the applied bias voltage. In addition to that, the noise should be compared with the target noise level of $1000 e^{-}$ [11]. For this purpose, the measured noise values $\mu$ were converted from $V_{th}$ units to ENC units. Since the conversion factors of the particular CBC2s were not measured, the upper and lower boundary of these values was estimated. For that the lowest (322 $e^{-}/V_{th}$ [49]) and highest (404 $e^{-}/V_{th}$ [50]) values, which have been found by measurements of other CBC2s, were used. By multiplying the measured noise values with these two factors, two noise-voltage curves were obtained, which are depicted in Fig. 7.6. The range in between these values is assumed as uncertainty and is indicated as blue band. Besides that, the expected noise level was estimated with Equ. 7.1. Thereby, the coefficient $a = 500 e^{-}$ and $b = 64 e^{-}/V_{th}$ were used, which have been determined by previous measurements [50].

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The values for the backplane capacitance $C_{\text{back}}$ were obtained as function of the voltage by averaging the $C-V$ curves of the top and bottom sensor recorded by the manufacturer [51]. Since the interstrip capacitance of the sensors was not measured, Eq. 7.4 was used for that. The strips have a width of 22.2 $\mu$m, a pitch of 90 $\mu$m and length of 5 cm according to the 2S sensor design [11]. Furthermore, Eq. 7.5 was used to cross-check these values by calculating a total strip capacitance. This yields the two other curves depicted in Fig. 7.6, which are labeled according to the used formulas.

Figure 7.6.: Noise of the left FEH. The measured values are converted to ENC units, labeled according to the conversion factors. The area between the curves is tinted blue to indicate the estimated uncertainty range. The expected noise is labeled corresponding to the used formulas.

The curves of the measured noise reproduce the hyperbolic slope arising from the relation $C_{\text{bulk}} \propto 1/\sqrt{V}$ according to Eqn. 6.3. At a voltage of 180 V the curves level off indicating that the sensors are fully depleted. This complies with the behavior observed in Chapter 6, where the $I-V$ curves were assessed. For higher voltages, the measured noise settles at levels between $818 e^-$ and $1026 e^-$. The value of the expected noise calculated with Equ.7.5 is $892 e^-$. The curve computed using Equ.7.4 deviates less than a half percent from this value for voltages of 180 V and higher.

On the one hand, these curves show a good compatibility of the measured and expected values underlining the dominating role of the capacitance for the total noise. On the other hand, it cannot be ruled out that the total noise of the module exceeds the target value of 1000 $e^-$. To reduce the uncertainties, it is suggested to carry out calibrations with the internal test pulses of the chips to determine the $e^-/V_{\text{ch}}$-conversion factors. In addition to that, a more elaborated grounding scheme could be used to achieve a lower noise level. And finally, a precise measurement of the interstrip capacitance of (other) 2S sensors could be used to cross-check further measurements.

Finally, it should be noted that these results are compatible with noise levels obtained with module prototypes built and tested at CERN and KIT [11, 16]. This makes it conceivable that the high noise level originates from the components in the first place, meaning that the assembly itself was sufficient.
8. Summary and Outlook

In the course of the High Luminosity upgrade of the LHC, the luminosity will increase by a factor of 5-7 with respect to the LHC’s design value. This results in higher demands on the detector in regard to radiation resistance and data processing. For this purpose, CMS will be equipped with a new tracker, relying on a new module type, which contributes as first of its kind information to the Level-1 trigger by identifying particles with high transverse momentum. These modules consist of various components, which require a precise assembly to achieve sufficient performance.

In the course of this thesis, the assembly of the first functional 2S module prototype of the Aachen assembly center was performed and investigated. In the first step, the pigtails were assembled to the sensor, which was followed by the application of the Kapton strips. For the precise deposition of the glue, a dispensing gantry was used. An evaluation scheme was developed to assess the optimal parameters of the gantry and the pattern of the glue applied on the strips. In case of the module prototype, this yielded a wetting of the Kapton-sensor interface of more than 99.9% for each strip while avoiding overspill. Besides the gluing of the Kapton strips, also their alignment was investigated in more detail to ensure sufficient isolation of the module components against the bias voltage of the sensors. The positioning accuracy of the jigs used to apply the strips was significantly increased, which allowed for a sufficiently precise placement of the strips on the functional sensors of the module prototype. After the bare module was assembled, the alignment of the sensors was checked with the Double Sided Metrology method, which yielded shifts one order of magnitude smaller than the specifications.

In preparation for the assembly of the FEHs, the flexibility of the SEH tails was found to be insufficient for the current assembly method, where the FEHs are aligned with respect to the edges of the sensor. To address this issue, a loop-shaped design of the tail was investigated and yielded a significant increase of the flexibility. In addition to that, an alternative assembly approach was developed relying on a defined positioning of the FEH by using alignment holes in the PCB. These were found as the dominating source for inaccuracies. Furthermore, ramps were designed to simplify the assembly procedure and to avoid smearing of the glue during the lowering of the FEHs. The subsequent wire bonding of the FEHs to the bias ring and the strips of the sensors yielded in general satisfying results. However, on the bottom side of the right FEH, the wire could not be welded to about 10% of the bond pads. During an inspection, residuals near the pads were observed, which are likely to have caused the problem. Therefore, it is suggested to clean the hybrid with acetone and to retry the bonding. For the subsequent encapsulation of the wire bonds, the dispensing gantry was used. In this context, a reduction of the curing time of the encapsulation from 20 to 4 hours was successfully tested, which has the potential to reduce the total assembly time of a module by about 10%. In the last assembly step, a functional SEH prototype was attached to the module and connected with the HV pigtails to use its circuit for the application of the bias voltage. This is the first time that a 2S module is operated in a configuration that uses an SEH to supply the bias voltage to the sensors.

After each assembly step, the sensor leakage current was measured to investigate the condition of the sensors. Thereby, the temperature-induced uncertainty was estimated to better relate the results to each other. The total increase of the leakage current during
the assembly amounts to 50% and 60% in case of the top and bottom sensor, respectively. This increase occurred at different assembly steps for reasons to be further investigated. However, all curves remained in a reasonable range in the order of µA for depletion voltages of up to 800 V. Therefore, it can be stated that the sensors have not been considerably soiled or damaged during the assembly process.

In addition to the leakage current, the noise of the module was measured after various assembly steps by performing readouts of the 8CBC2 hybrids with the FC7 board in combination with the Ph2_ACF software. A noticeable but expected increase of the noise after bonding the sensor strips to the FEH was observed for both hybrids, which resulted from the additional load capacitance introduced by the strips. In the whole all 4064 strips of the module show reasonable values, meaning that all bonded channels remained connected even after their encapsulation. Furthermore, the noise was converted from $V_{\text{cth}}$ units of the comparator to $\text{ENC}$ units, but due to a considerable uncertainty on the conversion factor it could not be ruled out that the total noise of the module slightly exceeds the target value. However, the noise level is compatible with measurements made at other institutes, which makes it likely that the noise results from the components in the first place and not from a fault in the assembly. In addition to that, a revision of the grounding scheme is expected to reduce the noise level further.

In the whole, it can be summarized that various optimization potentials were recognized and implemented by modifying the jigs and the assembly process. This has ultimately paid off, as the 2S module prototype built in the course of this thesis complies with the specifications except for the bonding and the noise. This qualifies the module for further testing like the detection of particles, which would be the natural next step on a short-term basis. For this purpose, a radioactive source could be used to generate signals in the sensors. Of particular interest would be the functionality test of the stub mechanism to see the feasibility of the $p_T$ module concept. In the long term, the experiences gained in the framework of this thesis will be very valuable for the upcoming preproduction phase, during which another 20 modules will be built.
Bibliography


[16] Stefan Meier, private communication, KIT, Karlsruhe.


[29] Tim Ziemons, ongoing doctorate, RWTH Aachen University, Aachen.


[34] Mark Kovacs, private communication, CERN, Geneva.


A. First Appendix

A.1. The LHC upgrade schedule

Figure A.1.: Schedule of the different upgrade phases from the LHC to the HL-LHC [52].
A. First Appendix

A.2. The PS module

Figure A.2.: The PS module of the Outer Tracker. The assembled module is shown on top, together with an exploded view on the bottom [11].

1: PS-s sensor
2: PS-p sensor
3: Macro-pixel ASICs
4: Al-CF spacer
5: Front-end hybrid
6: Power hybrid
7: Opto hybrid
8: CFRP support
9: CFRP baseplate
10: High voltage tab
11: Temperature sensor
12: Kapton HV isolators
B. Second Appendix

B.1. Dissolution of glue

After depositing glue on the aluminum-coated backside of the sensor, it has been observed that the glue forms irregularities over time. This is shown in Fig. B.1, which causes local overspills when lowering the strips onto the sensor. A cleaning of the sensor with isopropyl alcohol prior to the strip assembly did not considerably changed this behavior.

![Irregular spread of Polytec EP 601-LV glue on the backside of a silicon sensor evolving over time.](image)

Figure B.1.: Irregular spread of the Polytec EP 601-LV glue on the backside of a silicon sensor evolving over time.

B.2. Coordinates of the gluing pattern

Table B.1 summarizes the position of all points. The reference system is placed at the lower left corner of a sensor with a nominal size of 102.700 mm width and 94.183 mm length. The Kapton strips are placed according to their specifications, shown in Section 5.5.

<table>
<thead>
<tr>
<th>Point</th>
<th>Left bridge x (mm)</th>
<th>y (mm)</th>
<th>Stub bridge</th>
<th>Right bridge x (mm)</th>
<th>y (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.20</td>
<td>7.60</td>
<td>7</td>
<td>51.35</td>
<td>7.60</td>
</tr>
<tr>
<td>2</td>
<td>5.20</td>
<td>86.59</td>
<td>8</td>
<td>51.35</td>
<td>9.41</td>
</tr>
<tr>
<td>3</td>
<td>7.50</td>
<td>90.59</td>
<td>9</td>
<td>54.00</td>
<td>13.41</td>
</tr>
<tr>
<td>4</td>
<td>2.50</td>
<td>90.59</td>
<td>10</td>
<td>48.70</td>
<td>13.41</td>
</tr>
<tr>
<td>5</td>
<td>2.50</td>
<td>3.60</td>
<td>11</td>
<td>48.70</td>
<td>3.60</td>
</tr>
<tr>
<td>6</td>
<td>7.50</td>
<td>3.60</td>
<td>12</td>
<td>54.00</td>
<td>3.60</td>
</tr>
</tbody>
</table>

Table B.1.: Coordinates of the glue dots as well as the start and stop points of the glue lines with respect to the lower left corner of a nominal sized 2S sensor.
C. Third appendix

C.1. Calculations of the Kapton strip displacement margins

To derive the displacement margins of the Kapton strips, Fig. 5.5 is used. In the following discussion, the position of the strips is described with the variables $d_x$ and $d_y$. These reflect the distance between the Kapton strip edge and the corresponding silicon sensor edge in the horizontal and vertical direction. For simplification, these distances are measured in absolute values. The displacement margins of the strips are described with upper and lower boundaries, which are denoted as $\delta^+_x$ and $\delta^-_x$ as well as $\delta^+_y$ and $\delta^-_y$.

The displacement margins are determined by the isolation condition, which requires a minimum overlap of 500 $\mu$m of the strips in reference to the bridge (sensor) edge in the horizontal (vertical) direction. Besides that, misalignments of the bridges and the sensors during the bare module assembly need to be considered, which reduce the margins. For the bridges a maximal deviation from their nominal position of 50 $\mu$m is assumed. This allows for manufacturing inaccuracies of the bridges and the alignment holes in the jig as well as imprecisions caused by the h6-tolerance pins. The maximal displacement of the sensors from their nominal position is specified with 100 $\mu$m. For the later evaluation it should be emphasized that the strips are already glued on the sensors during that step.

Displacement margins of the long strips

To discuss the derivation of the margins, the example of reference point 5 is used, which was defined in Fig. 5.5. The upper boundary $\delta^+_x$ is obtained by calculating the largest 'allowed' shift of the strip to the left side of the overlaying bridge. For that, the minimum overlap of 500 $\mu$m and the maximum displacement of the sensor and bridge of 100 $\mu$m and 50 $\mu$m are subtracted from the nominal overlap of 800 $\mu$m to the right side of the bridge. This yields an upper boundary for the horizontal displacement with respect to the sensor edge of $\delta^+_x = 150 \mu$m. The values for the lower boundaries $\delta^-_x$ are in general obtained in the same way, by computing the maximum allowed displacement of the strip to the right. This yields a value of $\delta^-_x = 350 \mu$m due to the larger overlap of the strip to the left side of the bridge. However, an additional constraint is given as the strip must not overlap with the sensor in the horizontal direction. This would influence the precision of the bare module assembly described in Section 5.4, since the sensor edge is positioned by pushing it against a stopper. Therefore, the maximum allowed displacement is limited to 150 $\mu$m.

The vertical displacement margins $\delta^+_y$ and $\delta^-_y$ are computed similarly. However, in this case the misalignments of the bridge and the sensor do not contribute to the calculation since only the overlap of the Kapton strip with respect to the sensor edge is the relevant measure for the isolation. The values used for the calculations together with the resulting displacement margins are summarized in Tab. C.1.

Due to the symmetric positioning of the Kapton strips, the obtained margins also refer to the other reference points 1, 2, and 4 of the sensor; the stub bridge strip at reference point 3 is considered separately in the following.
Table C.1.: Calculation of the displacement margins of the long strip at reference point 5. The asterisk indicates that the value was obtained by considering that the strip must not overlap with the sensor in the horizontal direction.

<table>
<thead>
<tr>
<th>Margin to be calculated:</th>
<th>$\delta^+_x$</th>
<th>$\delta^-_x$</th>
<th>$\delta^+_y$</th>
<th>$\delta^-_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal strip overlap (µm)</td>
<td>800</td>
<td>1000</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>Minimum strip overlap (µm)</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Sensor displacement (µm)</td>
<td>100</td>
<td>100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bridge displacement (µm)</td>
<td>50</td>
<td>50</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Displacement margin (µm)</td>
<td>150</td>
<td>150*</td>
<td>200</td>
<td>200</td>
</tr>
</tbody>
</table>

Table C.2.: Calculation of the displacement margins of the stub bridge strip.

The displacement margins of the stub bridge strip are calculated similarly to margins of the long strip. The strip has a larger overlap with the bridge to its left, right and top side. But, the top side of the stub bridge strip does not overlap with the sensor. This means that misalignments of the bridges and the sensor need to be considered to obtain $\delta^+_y$. The resulting value thereby refers to the 1.8mm version of the stub bridge strip. The values for the calculation and the according results are listed in Tab. C.2.

Table C.3.: Calculation of the ideal displacement margins with sensor size corrections.

The displacement margins derived in this section are valid for the 1.8 mm as well as the 4.0 mm 2S module baseline design from November 2017. The following part, however, refers explicitly to the sensors, Kapton strips and jigs used for this thesis.

Sensor size corrections

The previously determined values rely on sensors with nominal dimension. However, the sensors assembled in the course of this thesis deviate from their nominal size by 130 µm in the horizontal and 65 µm in the vertical direction. This results in a shift of the Kapton strips with respect to the bridges during the bare module assembly. Therefore, the ideal position of the Kapton strips, as well as the displacement margins, need to be adjusted. Since the bottom (top) sensor is aligned with its lower and right (lower and left) edge, this adaptation refers to the reference points 1, 2 (3, 4, 5). At these points, the position of the strip needs to be increased by 130 µm in the $x$-direction. As a consequence, the value of $\delta^-_x$ is increased accordingly. In the $y$-direction instead, all values can be maintained since only the overlap of the Kapton strip with the sensor is relevant for the isolation, which was determined during the gluing of the strip.

In Tab. C.3 the adapted values are listed, which represent an ideal placement of the strips. The superscripts and subscripts refer to the adjusted displacement margins. Thereby, the...
upper boundaries of the stub bridge strip (reference point 3) are given in brackets, since the calculated values refer to the stub bridge strips of the 1.8 mm module. For the module prototype however about 15 mm longer stub bridge strips of the 4 mm module were used, which yields an 15 mm larger boundary that is without relevance in practice.

<table>
<thead>
<tr>
<th>Ref. point</th>
<th>Top Sensor</th>
<th>Bottom Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$d_x$ (µm)</td>
<td>$d_y$ (µm)</td>
</tr>
<tr>
<td>1</td>
<td>150$^{+150}_{-150}$</td>
<td>700$^{+200}_{-200}$</td>
</tr>
<tr>
<td>2</td>
<td>150$^{+150}_{-150}$</td>
<td>700$^{+200}_{-200}$</td>
</tr>
<tr>
<td>3</td>
<td>46480$^{+350}_{-350}$</td>
<td>700$^{+350}_{-200}$</td>
</tr>
<tr>
<td>4</td>
<td>280$^{+150}_{-280}$</td>
<td>700$^{+200}_{-200}$</td>
</tr>
<tr>
<td>5</td>
<td>280$^{+150}_{-280}$</td>
<td>700$^{+200}_{-200}$</td>
</tr>
</tbody>
</table>

Table C.3.: Ideal positions of the Kapton strips with respect to the edges of the sensor. The superscripts and subscripts describe the displacement margins of the strips.

### C.2. Calculation of the expected Kapton strip positions

The expected positions of the Kapton strips need to be adapted, due to the size deviations of the components and the orientation scheme to compensate for them. This should be explained with the following example. At reference point 2, $d_x$ is increased by 130 µm, since the larger sensor is aligned at the right edge of the jig. This results in a larger distance of the strip and the sensor edge, due to the size deviation of the sensor. But as the sensor touches the jig with the buckles in its edge, the distance between the Kapton strip and the sensor edge is increased by another 30 µm. However, since the jig is manufactured 25 µm larger, the position of the sensor in the jig is shifted to the right, which in turn reduces $d_x$ by 25 µm. In the whole, this yields a total change of the Kapton edge position in the horizontal direction of $\Delta d_x = 135$ µm. These values and the values of the other reference points are listed in Tab. C.4. The change of the Kapton edge position in the vertical direction is considered separately in the following.

<table>
<thead>
<tr>
<th>Reference point</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor dimensions (µm)</td>
<td>+130</td>
<td>+130</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sensor buckles (µm)</td>
<td>+30</td>
<td>+30</td>
<td>-30</td>
<td>-30</td>
<td>-30</td>
</tr>
<tr>
<td>Jig dimensions (µm)</td>
<td>-25</td>
<td>-25</td>
<td>+25</td>
<td>+25</td>
<td>+25</td>
</tr>
<tr>
<td>Strip dimensions (µm)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta d_x$ (µm)</td>
<td>+135</td>
<td>+135</td>
<td>-5</td>
<td>-5</td>
<td>-5</td>
</tr>
</tbody>
</table>

Table C.4.: Calculation of the horizontal change in the Kapton strip position.

To calculate the changes in the expected positions in the vertical direction, the example of reference point 2 should be used again. Here, $d_y$ is reduced by 30 µm since the sensor is
aligned with the buckles in its edge to the jig. Therefore, the nominal edge is positioned 30 \( \mu m \) further apart from the jig, reducing the overlap of the Kapton strips with the sensor at the bottom edge. Since the jig is manufactured 35 \( \mu m \) larger at its bottom edge, this increases \( d_x \) accordingly by 35 \( \mu m \). The last component of this calculation is contributed by the long strips, which are aligned at the top edge of the strip positioning jig. Since they are 140 \( \mu m \) shorter than specified, this shortening reduces the overlap at the bottom edge of the sensor. In the whole, this yields a total change of the Kapton edge position in the vertical direction of \( \Delta d_x = -135 \mu m \). These values are listed in Tab. C.5 together with the values of other reference points.

<table>
<thead>
<tr>
<th>Reference point</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor dimensions (( \mu m ))</td>
<td>-65</td>
<td>-</td>
<td>-65</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sensor buckles (( \mu m ))</td>
<td>+30</td>
<td>-30</td>
<td>-30</td>
<td>+30</td>
<td>-30</td>
</tr>
<tr>
<td>Jig dimensions (( \mu m ))</td>
<td>-35</td>
<td>+35</td>
<td>+35</td>
<td>-35</td>
<td>+35</td>
</tr>
<tr>
<td>Strip dimensions (( \mu m ))</td>
<td>-</td>
<td>-140</td>
<td>-</td>
<td>-</td>
<td>-140</td>
</tr>
<tr>
<td>( \Delta d_y ) (( \mu m ))</td>
<td>-70</td>
<td>-135</td>
<td>+5</td>
<td>-70</td>
<td>-135</td>
</tr>
</tbody>
</table>

Table C.5.: Calculation of the vertical change in the Kapton strip positions.

By combing the values calculated for \( \Delta d_x \) and \( \Delta d_y \) with the nominal values for \( d_x \) and \( d_y \) (given in Fig. 5.5), the adapted, expected values are obtained. They are listed in Tab. C.6 and refer equally to the top as well as to the bottom sensor since the dimensions and the orientation of components in the positioning jigs was the same.

<table>
<thead>
<tr>
<th>Reference point:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_x ) (( \mu m ))</td>
<td>285</td>
<td>285</td>
<td>46345</td>
<td>145</td>
<td>145</td>
</tr>
<tr>
<td>( d_y ) (( \mu m ))</td>
<td>630</td>
<td>565</td>
<td>695</td>
<td>630</td>
<td>565</td>
</tr>
</tbody>
</table>

Table C.6.: Expected positions of the Kapton strips with respect to the edges of the sensor.

C.3. Modified weight plate

The weight plate is equipped with PTFE-strips on its backside in order apply pressure on the three areas of the top sensor, which are in contact with the three AlCF-bridges during the bare module assembly. At the same time these strips protect the surface of the top sensor from scratches. To prevent the sensor from bending upwards due to the fixation of the spring pusher, an additional strip was applied, which acts as vertical spacer. The weight plate with all four strips is depicted in Fig. C.1.

C.4. Stub bridge clearance

During the assembly of the bare dummy module a clearance of 370 \( \mu m \) was measured between the stub bridge and its lateral pins, which limit the lateral movement of the bridge. This was also observed in the CAD drawing of the sensor gluing jig, as shown
in Fig. C.2. The top left side of the figure shows a CAD drawing of a 1.8 mm module inserted in the jig. The gap between the unprotected sensor and the stub bridge measures 1000 µm. If the stub bridge is tilted until it touches its lateral alignment pin, this gap is reduced to 700 µm, as shown on the bottom left side of Fig. C.2. In case of a 4 mm module depicted on the right side, the longer stub bridge acts as a lever, which further reduces the gap to 275 µm. This compromises the protection of the bridge against the high voltage of the sensor, which requires a gap of at least 500 µm. Therefore, custom pins were manufactured to compensate this clearance.

Figure C.2.: Clearance of the stub bridge in the sensor gluing jig. The gap between the stub bridge and the sensor amounts to 1000 µm, both for the 1.8 mm module (top, left) and the 4 mm module (top, right). The clearance between the lateral alignment pins and the stub bridge reduces the gap between sensor backplane and bridge to 700 µm in case of the 1.8 mm module (bottom, left) and to 275 µm for the 4 mm module (bottom, right).
C.5. Drawings of the FEH ramps

In Fig. C.3 the ramps are depicted, which are mounted on the hybrid gluing jig to guide the FEHs to the tabs of the AlCF-bridges. On the left side, a ramp for a 4 mm module is shown, the right side displays a ramp for a 1.8 mm module. The two versions differ in the angle of the ramp, to consider the different thicknesses of the FEHs types. Both drawings feature a stopper at the back to securely place the hybrids in their initial assembly position.

Figure C.3.: Ramp used to guide the FEHs to a 1.8 mm (4 mm) module on the left (right).
Zum Abschluss möchte ich noch denjenigen Mitmenschen meinen Dank aussprechen, die mich während dieser Arbeit begleitet haben.


