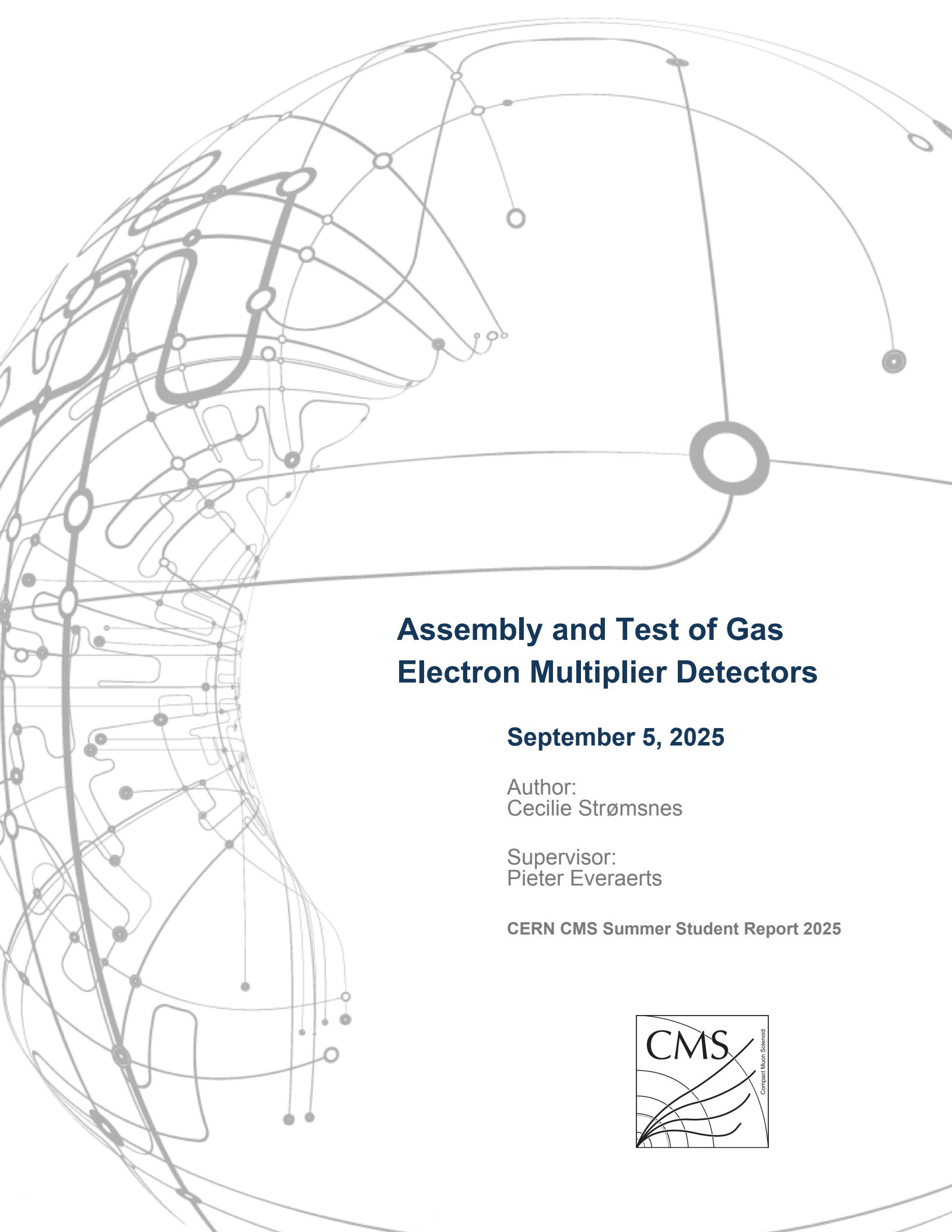


The background of the entire page is a complex, abstract network of thin, grey lines and dots, resembling particle tracks or a web. The lines are of varying thickness and curvature, with some forming loops and others extending straight out. Small circles of different sizes are scattered throughout, some acting as nodes where lines intersect or terminate. The overall effect is one of dynamic, interconnected movement.

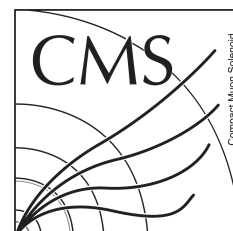
# **Assembly and Test of Gas Electron Multiplier Detectors**

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**CERN CMS Summer Student Report 2025**



## Abstract

This report summarizes my experience as a summer student at CERN, where I contributed to the assembly and quality control of GEM detectors for the CMS experiment. My tasks included hands-on work with detector modules, such as soldering, mounting electronics, installing gas systems, and conducting quality control tests.

Through this experience, I gained valuable insights into how large-scale particle physics experiments ensure the reliability of their detectors. I developed practical skills in electronics assembly, inspection techniques, and systematic testing procedures. Additionally, I came to appreciate the importance of precision, cleanliness, and teamwork in a high-tech research environment.

My work directly contributed to the preparation of GEM detectors that will be installed in the CMS, enhancing muon detection in the forward endcap region.



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# 1 Introduction

The Large Hadron Collider (LHC) at CERN is the world's largest and most powerful particle accelerator. It features a 27 km circular tunnel in which two counter-rotating proton beams are accelerated to energies of up to 6.8 TeV per beam. Superconducting magnets generate a magnetic field of 8.3 T to guide the beams, which collide at four interaction points designated for the main experiments: ATLAS, CMS, ALICE, and LHCb [1].



Figure 1: Map of the Large Hadron Collider (LHC), showing the four main experiments.

The Compact Muon Solenoid (CMS) is one of two general-purpose detectors, alongside ATLAS. It is designed to test the Standard Model of particle physics and search for new physics, such as the Higgs boson and potential candidates for dark matter. Built around a powerful superconducting solenoid magnet, CMS allows for precise momentum measurements of charged particles. This detector is among the largest ever constructed, measuring 15 meters in height, 15 meters in width, and 21 meters in length, with a total mass of approximately 14,000 tonnes [2].

## 2 Compact Muon Solenoid (CMS)

The name Compact Muon Solenoid (CMS) comes from three defining features of the detector [3]:

- **Compact:** CMS has a smaller diameter than ATLAS, but it is denser and heavier, to make sure it stops all of the photons, electrons, and hadrons fully and measures the energy.
- **Muon:** Muons are highly penetrating particles that are produced in various interesting processes, such as the decay of heavy particles. Detecting them with precision is one of the central goals of the CMS experiment.
- **Solenoid:** The detector is built around a powerful 3.8 T superconducting solenoid magnet, which bends the paths of charged particles to measure their momentum with high accuracy.

CMS has an onion-like structure consisting of multiple layers of sub-detectors, each optimized for detecting different types of particles. A transverse slice of the CMS detector is shown in Figure 2.

In CMS, different types of particles are detected by different sub-detectors. Photons are detected in the electromagnetic calorimeter (ECAL). Electrons and positrons leave tracks in the inner tracker and also deposit energy in the ECAL. Charged hadrons are detected by both the tracker and the hadronic calorimeter (HCAL), while neutral hadrons interact solely within the HCAL. Muons can penetrate the calorimeters and are measured in both the tracker and the muon chambers. Neutrinos and hypothetical supersymmetric particles (SUSY) are not detected directly; instead, their presence is inferred from missing transverse momentum.

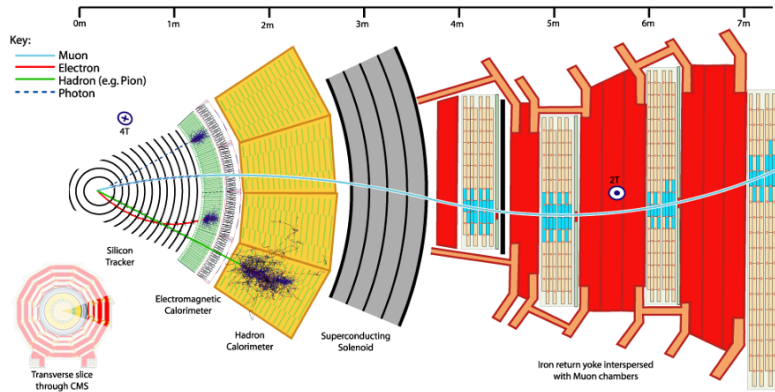


Figure 2: Transverse slice of CMS, showing all the different sub-detectors and how the different particles interact.

### 3 Gas Electron Multiplier (GEM) Detectors

Gas Electron Multipliers (GEMs) are gaseous particle detectors used in the CMS muon system, particularly in the forward endcap region where radiation levels and particle rates are very high. Their purpose is to extend muon coverage, improve bending-angle measurements, and enhance trigger efficiency. GEMs operate by amplifying ionization signals in thin Kapton foils perforated with microscopic holes, which concentrate the electric field and enable controlled avalanche multiplication [4].

The detection process can be summarized as the following steps:

1. **Ionization:** A charged particle traverses the detector's gas mixture ( $Ar/CO_2$ , 70/30), producing primary electron-ion pairs.
2. **Drift:** The freed electrons drift under the applied electric field toward the GEM foils.
3. **Avalanche multiplication:** Inside the microscopic GEM holes, strong electric fields accelerate the electrons, causing them to collide with gas atoms and create secondary ionization.
4. **Cascade amplification:** The process repeats in multiple GEM foils (3 in CMS), with each foil multiplying the electron population by a factor of  $10^3 - 10^4$ .
5. **Signal formation:** The resulting avalanche ( $10^6$  electrons per initial ionization) drifts to the readout anode, where the motion of charges induces a detectable electrical signal.
6. **Ion back-drift:** The much heavier positive ions created in the avalanches drift slowly in the opposite direction, but the GEM structure suppresses their flow back into the drift region, reducing detector noise and prolonging stability [5].

#### 3.1 Triple GEM detectors

A Triple-GEM detector is constructed by stacking three individual GEM foils between a drift cathode and a readout anode. This configuration creates three amplification stages in a cascade, resulting in a high overall gain. This high gain improves performance in managing discharges and ensures

stable operation in high-rate environments, making it ideal for applications in the CMS endcap [6].

Some of the key structural features in the Triple-GEM detector are:

- Each GEM foil is a thin, copper-clad polymer sheet featuring a dense and regular array of microscopic holes, approximately 50 to 100 per  $mm^2$ . These holes concentrate the electric field and enable controlled electron avalanching.
- A triple-layer configuration increases gain and reduces discharge risk compared to single foil setups.
- The GEM chamber within the CMS consists of two printed circuit boards (PCBs) that define the volume of gas. Three GEM foils are stacked between these PCBs and enclosed within an argon ( $AR$ ) and carbon dioxide ( $CO_2$ ) gas mixture. When ionization electrons drift towards the foils, they gain enough energy to initiate avalanches, which ultimately affect the readout signal [4].

## 4 Assembly

### 4.1 Electronics Overview

The GEM detectors require specialized front-end electronics to process signals, manage communication, and distribute power. The key components are:

- **VFAT:** Application-Specific Integrated Circuit (ASIC) that amplifies, shapes, digitizes, and transmits signals from the GEM strips. Provides both fast trigger data and detailed tacking readout.
- **OptoHybrid:** Communication hub that concentrates signals from six VFATs and forwards them via optical links. Also manages slow/fast control signals.
- **GEB (GEM Electronics Board):** Printed circuit board that hosts VFAT chips, distributes power, routes signals through the OptoHybrid, and provides electrical shielding.
- **bPols:** On-board power converters that regulate and deliver the precise low voltages required by the electronics [7].

### 4.2 Assembly of GEM Layers

For the layer assembly, many steps are involved. These steps are described here in a step-by-step manner:

#### Step 1: Module preparation

When getting the module ready, we need to ensure that the gas inlets and outlets are properly connected and that the surface of the detector is cleaned of dust using a vacuum cleaner or a brush. After that, we will do a Megger check (Mega-ohm insulation meter), where we measure the impedance at 250V between all electrodes. The Megger test can be seen in Figure 3.

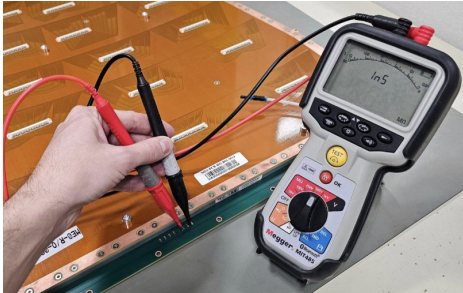


Figure 3: Megger test, measuring insulation resistance between electrodes at 250 V.

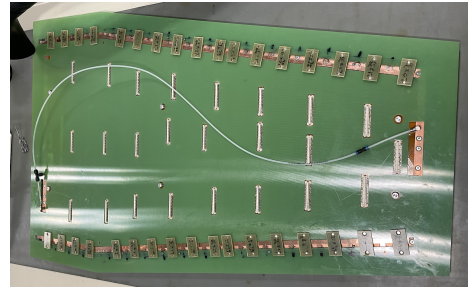


Figure 4: Soldering copper bars onto PCB. In this image, the compression bridges are also included.

### Step 2: Soldering copper bars

For the next step, we need to solder copper bars onto the PCB to provide an improved grounding to the readout board. After the copper bars are placed, we put magnetic compression bridges on top to keep the copper slats in place. This is shown in Figure 4. Then the soldering job begins. The soldering is complete when there is a smooth and shiny finish to the soldering. After the compression bridges are removed, we perform a stress test by pulling the copper slat up. Lastly, the copper slats should be cleaned with isopropanol.

### Step 3: Aluminium frame assembly

Next, we need to mount the aluminium frame around the module. This consists of a lot of aluminium bars that are screwed together around the module from the bottom of the drift. The frame is seen in Figure 5. In this step, we also add the grounding block and patch panel fixation in the wide end of the module.

### Step 4: Spacers installation

Then we need to add spacers between each row of the HRS connectors. All the spacers are secured using Kapton tape. This is done to lower noise, due to the extra space between the readout board and the GEM electronic board. This can be seen in Figure 6.

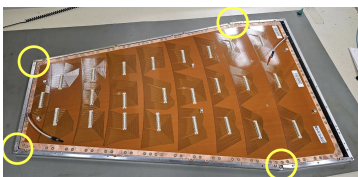


Figure 5: Aluminium frame assembly.

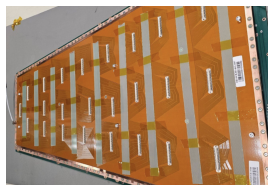


Figure 6: Spacers taped between each HRS connector.

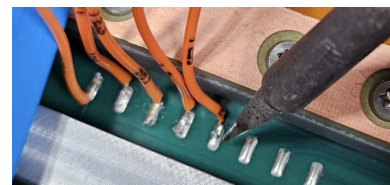


Figure 7: Soldering of HV pads onto drift board.

### Step 5: HV filter installation

The next step is to add the HV (high voltage) filters. For this, we get a pre-mounted HV filter. We need to modify it by stripping a part of the outer layer, so the internal layers are exposed. We cut unused wires away and connect a grounding wire to the HV cables using shield wire. Then the HV filter has to be fixed to the patch panel. After fixation, the preparation of the wires is done, stripping



the wires and soldering the tips. The HV pads on the module are also pre-soldered on the drift board. This way, it is easier to solder the wires afterwards. The soldering can be seen in Figure 7. Lastly, we need to seal, using a Polyurethane spray and a soft brush to apply a thick layer all over the HV pads on the drift board.

### Step 6: Adding the electronics

The next step is rather long. And can be labeled into sub-steps.

#### *GEB (GEM Electronic Board) mounting:*

First, we need to mount the wide GEB on the module/detector, making sure it goes underneath the wires of the HV filter. Then it should be screwed onto the board. Then the narrow GEB is mounted, and the shield lines will be insulated with Kapton tape. The narrow and wide GEBs are shown in Figure 8, and after installation, are shown in Figure 9.

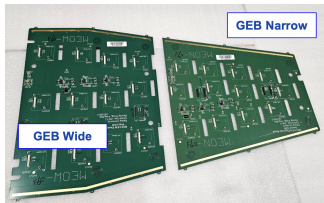


Figure 8: Narrow and wide GEBs.

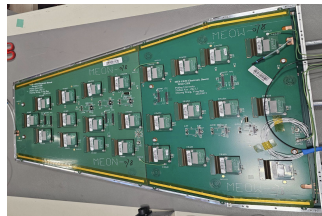


Figure 9: GEBs installation and insulation.

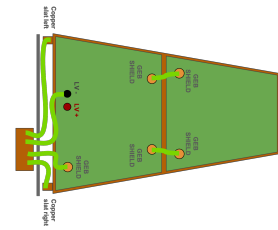


Figure 10: Mapping of the grounding on the module.

#### *Securing HV wires:*

We need to arrange the HV wires in a loop and secure them with Kapton tape.

#### *Grounding cables:*

We have 6 grounding cables around the module that need to be attached. Most of them need to be pre-soldered on the ends, and some need an eyelet end. A map of schematic of the grounding is shown in Figure 10.

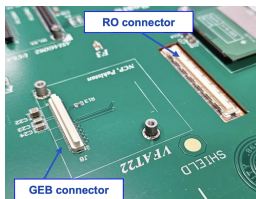


Figure 11: VFAT connector.



Figure 12: VFAT.

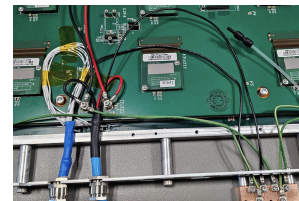


Figure 13: Final result after mounting LV cables.

#### *VFAT mounting:*

The next part is to mount the VFATs. Here we place each VFAT card in its dedicated slot. The card is first connected to the GEB connector and then to the RO connector as shown in Figure 11. The flexible thermal strap of the VFATs is then pressed to make a wave going downward towards the GEB as seen in Figure 12. Then the VFATs will be screwed in place.

#### *LV cables:*

Next, the LV (Low Voltage) cables need to be attached. These are easier than HV, as you just have to screw them in using eyelets. The final result after attaching the LV cables is shown in Figure 13.

#### *Optohybrids:*

Next, we add the optohybrids. For this, we need optohybrid cooling, thermal pads, and the optohybrids themselves. The cooling pads are attached to the cooling unit, as shown in Figure 14.

Then we need to mount the 4 optohybrids and add thermal pads on the lpGBT chip as well, as shown in Figure 15. On each optohybrid, there is a fiber cable coming from the VTRx+ transceiver [7] that needs to be routed to the patch panel. The fibers should follow the F-connectors and be secured with Kapton tape. The routing of the optical fibers is shown in Figure 16.

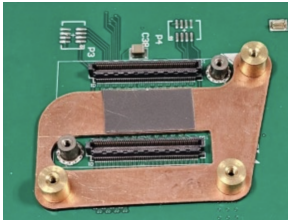


Figure 14: Cooling element with thermal pads.

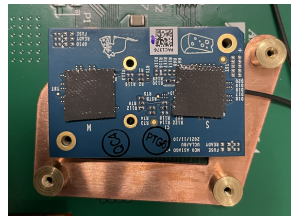


Figure 15: Optohybrid installation.

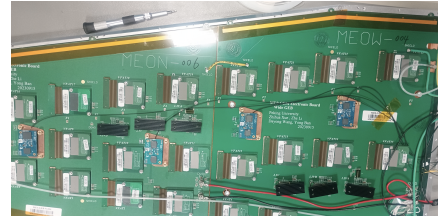


Figure 16: Optic fiber routing.

#### *bPols:*

The last step of the electronics assembly is to add the bPols to the GEBs. There are 3 types: 1.2A, 1.2D, and 2.5V. Once these are installed, we need to add thermal pads on top and also a heat sink before moving on to the QC7, as shown in Figures 17 and 18.

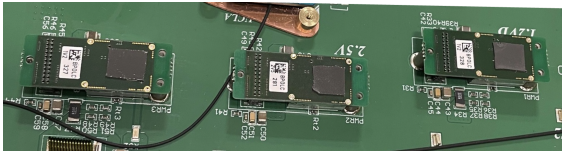


Figure 17: Installation of bPols with thermal .

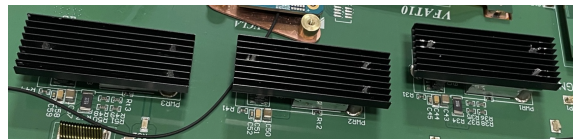


Figure 18: Adding heat sinks to the bPols before QC7.

### **Step 7: QC7**

The next step after the assembly of the electronics is to do the QC7. This is described in Section 5.3.

### **Step 8: Gas pipes and cooling**

After the first QC7 is done, we need to add the gas pipes and cooling to the layer. Before starting, we have to clean the gas pipes using an air gun. After this, we attach the two pipes and ensure that they are secured with Kapton tape and that the pipe is close to the VFATs so that they will not be squished by the cooling afterward. This is shown in Figure 19.

Next, we have to install the cooling system. Here, we have to be careful not to squeeze the gas pipes, wires, or optical cables. The cooling system will be screwed onto the bPols, optohybrids, and other attachment points as shown in Figure 20.

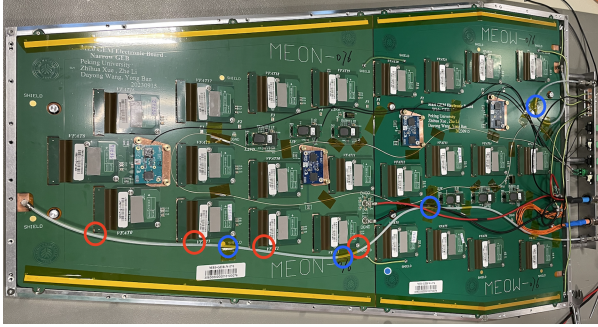


Figure 19: Gas pipe installation. Red circles indicate that the gas pipe is lying close to the VFATs. Blue circles indicate where the gas pipes are secured with Kapton tape.

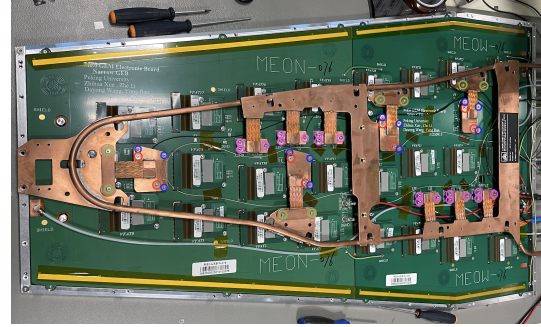


Figure 20: Cooling system installation. Red circles indicate optohybrid screws, blue indicate optohybrid cooling screws, pink indicate bPol screws, and green indicate attachment points.

The cooling system is also attached to each end of the aluminium frame. When the cooling system is secured, we make the QC7 again.

#### Step 9: Second QC7

This step is the same as step 7.

#### Step 10: Leak test

After we have ensured that the QC7 test is still successful after attaching the cooling system, we need to perform a gas leak test. This test will be done multiple times in the whole assembly process, and will be described in Section 5.2 for the whole stack. But it is the same principle for each layer.

#### Step 11: Chimney

The last step for the layer assembly is to attach the chimney. The chimney acts as a cover for the whole layer to protect it from getting damaged and dirty. It also closes the Faraday cage and keeps external noise sources out.

### 4.3 Assembly of GEM Stacks

After individual GEM layers have been assembled, they are integrated into a complete detector stack consisting of six layers. The stack is mounted onto a baseplate that provides mechanical stability and organizes the routing of power, signal, and grounding cables. The baseplate can be seen in Figure 21. When installing the stack, each layer must be secured to the baseplate, and all the wires need to be guided and pulled through the different trays and brackets.

Out of each layer, we have different cables: an orange high-voltage cable for powering GEM foils, a blue low-voltage cable for electronics, and a yellow-and-green grounding cable for safety and noise suppression. An overview of these can be seen in Figure 22.



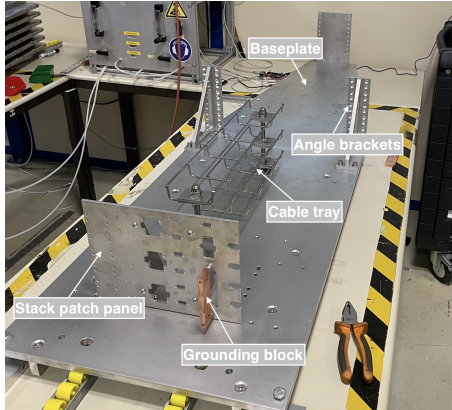


Figure 21: Baseplate used to install the 6 layers into a stack.

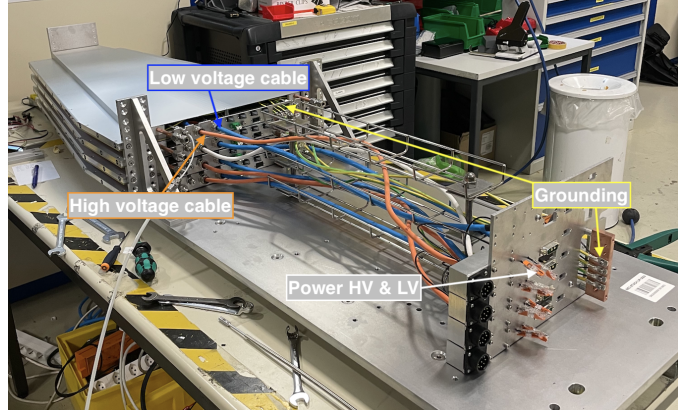


Figure 22: Stack showing low-voltage, high-voltage, and grounding cables.

Cables are routed through designated trays and brackets to minimize stress on connectors and avoid interference between HV, LV, and ground lines. The high-voltage cable has a box on the end that needs to be attached to the stack patch panel. Similarly, the low-voltage cable has a connection at the end of the cable that should also be connected. And the grounding cable needs to be screwed in place at the grounding block. This can be seen in Figures 23, 24, and 25.

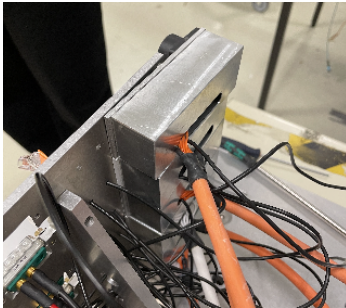


Figure 23: High-voltage cable box from stack.

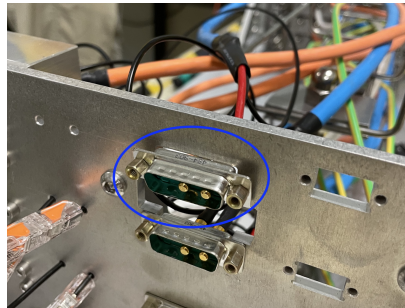


Figure 24: Low-voltage cable from stack.

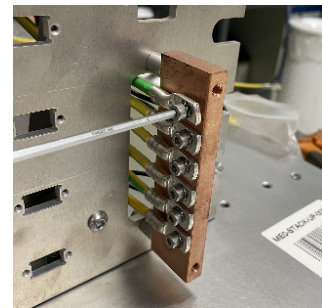


Figure 25: Grounding cable from stack.

When all the power outlet wires and cables from each layer have been routed and secured, the stack patch panel should look like Figure 26.

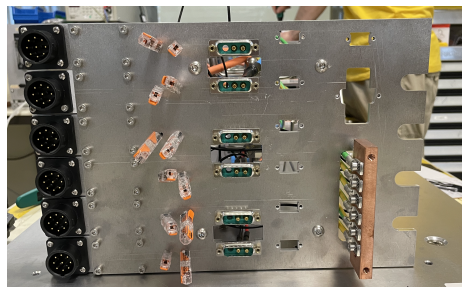


Figure 26: Stack patch panel after implementing all layers with cables and wires.

## 5 Quality Control Tests

### 5.1 QC1: Layer Inspection

The first quality control step is performed on each GEM layer before it is integrated. QC1 consists of three tests: a short-circuit test, a visual inspection, and a microscopic inspection. These tests ensure that there are no electrical shorts, mechanical damage, or microscopic defects that could compromise detector performance.

#### 5.1.1 Short-Circuit Test Between Strip and Ground

The short-circuit test is performed to ensure that no unintended electrical connection exists between the readout strips and the ground plane. Such shorts would prevent correct signal readout and compromise detector performance.

The test requires a multimeter and an HRS connector (Figure 27). The multimeter is connected between the ground contact of the HRS connector and the adjacent readout strips, as shown in Figure 28. If the measured resistance is close to zero, a short circuit is present. If the measured resistance is significantly above zero, the strip is properly isolated. Each readout board (ROB) contains 24 VFATs, and the procedure is repeated for each corresponding connector.



Figure 27: Multimeter and HRS connector used for short-circuit testing.



Figure 28: Short-circuit test setup, with the multimeter measuring resistance between strips and ground.

#### 5.1.2 Visual Inspection

The visual inspection is carried out to identify any surface damage or contamination that could affect the detector. The ROB is coated with a thin insulating layer, which is fragile and can be damaged during handling. Scratches, dust, or misalignments are potential issues that must be identified.

During the test, a full image of each ROB is taken, and areas of interest are documented with close-up photographs if defects are found. This step helps catch visible problems before proceeding to more detailed microscopic analysis.

### 5.1.3 Microscopic Inspection

The microscopic inspection ensures that no fine dust particles, copper debris, or other microscopic defects are present on the ROB. Such contaminants could cause electrical discharges or degrade detector performance.

For this test, a microscope with bright illumination and an imaging program is used, as seen in Figure 29. Eight predefined inspection areas are examined on each ROB, as shown in Figure 30.

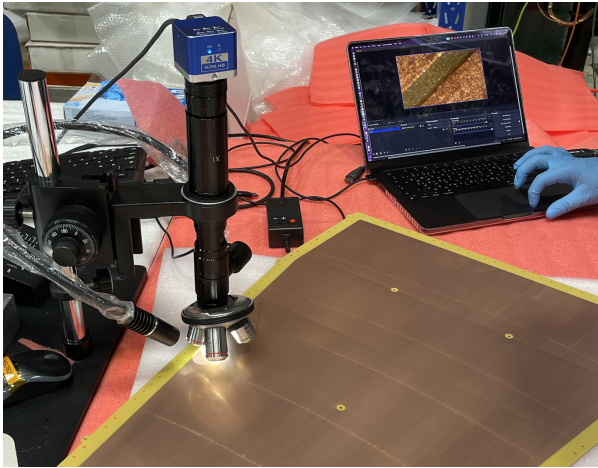


Figure 29: Setup for microscopic inspection of ROB.

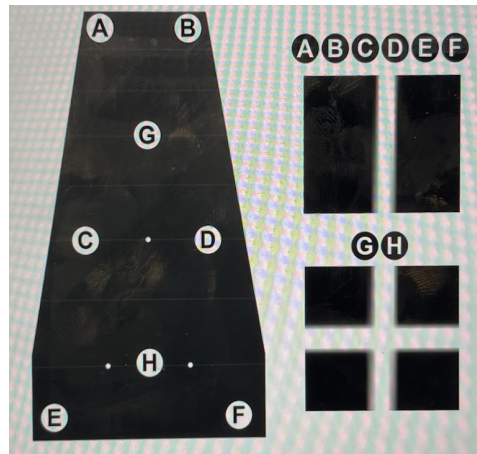


Figure 30: Inspection map of the TOB, indicating eight locations to be examined.

To do the test, we must:

- 1) Position the microscope at spot A on the ROB.
- 2) Focus on the alignment mark (line or cross).
- 3) Switch off the bright light and adjust focus to inspect the dark region for dust particles.
- 4) Switch the bright light back on, and refocus if necessary to make small particles shimmer.
- 5) Repeat for all inspection areas A-H.

If dust or debris is detected, the affected area is documented with images and cleaned before retesting. Examples of the microscopic images are presented in Section 6.1.

## 5.2 QC3: Gas Leak Test

After each layer has been installed in the stack, a gas leak test is performed to ensure the chamber is gas-tight before proceeding with the next layer. Leak testing is essential, since even small leaks can compromise detector performance.

The test procedure is as follows:

- 1) Attach the supply pipe (ingoing flow) to the chamber.
- 2) Secure the supply pipe and verify that the outflow is closed.
- 3) Open the supply valve.



- 4) Pressurize the chamber to 30 mbar, as indicated on the pressure meter.
- 5) Monitor the pressure after 30 minutes using the online QC3 interface.

The acceptance criterion is that the overpressure loss must not exceed 10% within one hour. If the pressure loss is greater, the chamber fails the test and must be rechecked for leaks.

The setup can be seen in Figure 31.

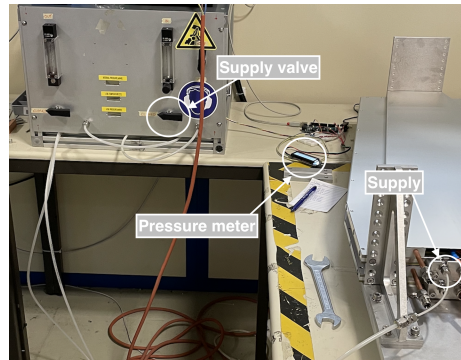


Figure 31: Setup for gas leak test of stack.

### 5.3 QC7: Electronics Test

The QC7 test verifies the correct functionality of the front-end electronics after assembly. For this test, low-voltage power is supplied from an external power supply, distributed by the GEM Electronics Board (GEB), and regulated by bPol converters.

The QC7 procedure is controlled via a web interface. To begin, the user enters the module name, the four OptoHybrid (ASIAGOs) numbers, and the number on the wide and narrow ends of the GEB. The software then generated a YAML configuration file, which initializes the electronics, and pushed the configuration to the front-end.

Once the system is configured, a series of automated scans is performed to evaluate the electronics:

- GBT phase scan: Synchronizes data transmission through the GBT links.
- DAC scan: Verifies digital-to-analog converter functionality.
- VFAT reset: Checks communication and reset response of VFAT chips.
- FED monitoring: Reads parameters from the Front-End Driver for performance monitoring.
- S-bit scan: Checks the trigger outputs from the VFATs.
- S-curves: Measures channel response to injected charge.
- Threshold scan: Determines noise levels and uniformity across channels.

The outcome of these tests ensures that all VFATs, Optohybrids, and readout electronics operate correctly before integration into the full system. The results can be seen in Section 6.3.

## 6 Results

### 6.1 QC1 Results

The QC1 test was performed as described in Section 5.1. Here, we present the results for one of the tested Read-Out Boards, number 0008.

#### 6.1.1 Short-Circuit Test Results

The short-circuit test confirmed that ROB 0008 met the required isolation between strips and ground. All VFAT connectors showed resistances within the acceptable range, with no values close to zero. Figure 32 illustrates the VFAT layout on the ROB, and Figure 33 summarizes the measured results.

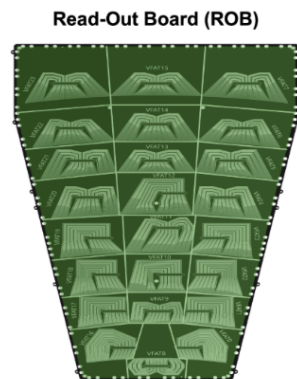


Figure 32: Read-Out Board (ROB) layout showing the placement of VFAT connectors.

| Module      | MED-PCB-RO-006-0008 |
|-------------|---------------------|
| VFAT Number | Status              |
| VFIAT00     | Passed O.L.         |
| VFIAT01     | Passed O.L.         |
| VFIAT02     | Passed O.L.         |
| VFIAT03     | Passed 380 M ohm    |
| VFIAT04     | Passed 200 M ohm    |
| VFIAT05     | Passed O.L.         |
| VFIAT06     | Passed O.L.         |
| VFIAT07     | Passed O.L.         |
| VFIAT08     | Passed O.L.         |
| VFIAT09     | Passed O.L.         |
| VFIAT10     | Passed O.L.         |
| VFIAT11     | Passed 278 M ohm    |
| VFIAT12     | Passed 170 M ohm    |
| VFIAT13     | Passed 440 M ohm    |
| VFIAT14     | Passed O.L.         |
| VFIAT15     | Passed O.L.         |
| VFIAT16     | Passed O.L.         |
| VFIAT17     | Passed O.L.         |
| VFIAT18     | Passed O.L.         |
| VFIAT19     | Passed 315 M ohm    |
| VFIAT20     | Passed 315 M ohm    |
| VFIAT21     | Passed 380 M ohm    |
| VFIAT22     | Passed O.L.         |
| VFIAT23     | Passed O.L.         |

Figure 33: Results of the QC1 short-circuit test for ROB 0008, demonstrating that all VFATs passed within the required resistance range.

#### 6.1.2 Visual Inspection Results

The visual inspection of ROB 0008 showed no major defects. Only a few minor surface scratches were observed, but these were within acceptable limits and were not expected to impact performance.

#### 6.1.3 Microscopic Inspection Results

The microscopic inspection of ROB 0008 detected small amounts of dust, but the level was within expected tolerances and did not indicate contamination that would compromise the detector. Figures 34 and 35 show the microscopic images of position G in dark mode (without bright light) and in bright mode, respectively.



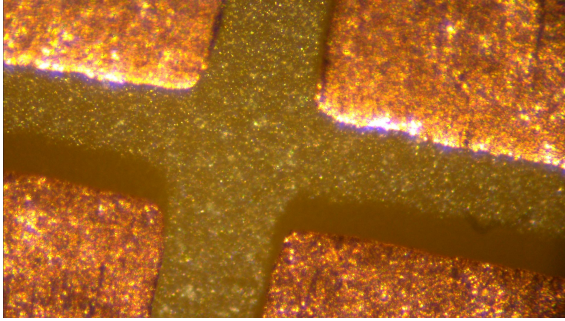


Figure 34: Microscopic inspection of ROB 0008 at position G in dark mode, showing minor dust particles.

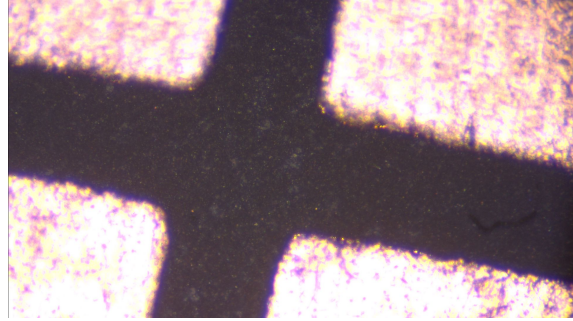


Figure 35: Microscopic inspection of ROB 0008 at position G in bright mode.

## 6.2 QC3 Results

The QC3 test verifies the gas tightness of the chambers after installation in the stack. The test was performed for stack 0003, specifically for layers 4, 5, and 6. The measured pressure as a function of time is shown in Figure 36.

The pressure dropped by approximately 1.2 mbar over 30 minutes, corresponding to about 7.5% per hour. Since the acceptance criterion requires the pressure drop to remain below 10% per hour, this chamber successfully passed the QC3 test.

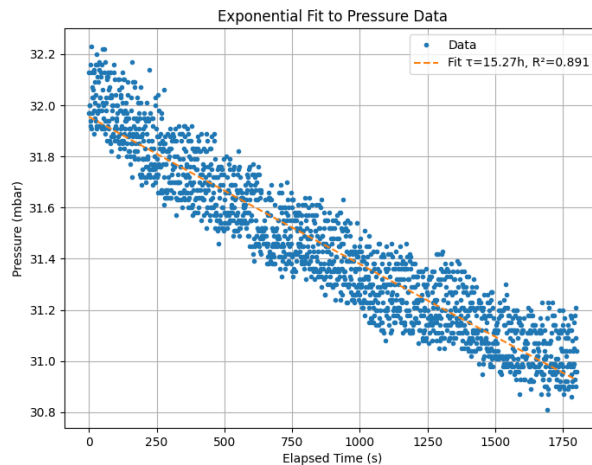


Figure 36: QC3 result for stack 0003, layers 4–6. The pressure decreased by 1.2 mbar over 30 minutes, corresponding to a leak rate of 7.5%/hour.

## 6.3 QC7 Results

The QC7 test was described in Section 5.3. Here, we present results for module 0069, covering the main electronics validation scans

### GBT Phase Scan Results:

The GBT phase scan verifies synchronization of the high-speed data links between the OptoHybrids and the back-end electronics. Figure 37 shows the scan for module 0069. The majority of VFATs display stable synchronization (green values), with no more than two channels failing per chip, which is expected.

### DAC Scan Results:

The DAC scan evaluates the functionality of the digital-to-analog converters on the VFAT chips. Smooth curves are expected; deviations may indicate grounding or noise issues. Figure 38 shows the DAC scan for VFAT 9 of module 0069, which behaved within the expected range. Adjusting the DACs to their optimal settings is a method of calibrating the chip.

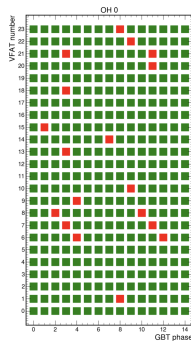


Figure 37: QC7 GBT phase scan result for module 0069. Green indicates synchronized channels; red indicates errors.

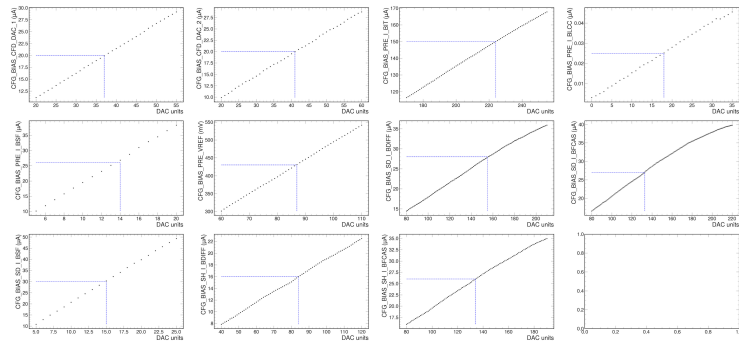


Figure 38: QC7 DAC scan for VFAT 9 on module 0069, showing smooth behavior within the expected range.

### S-bit Rate Scan results

The S-bit scan tests the trigger outputs of the VFATs. A correct scan should display a smoothly falling distribution as the threshold increases. Figure 39 shows the S-bit scan result for VFAT 9 of module 0069, which showed the expected behavior.

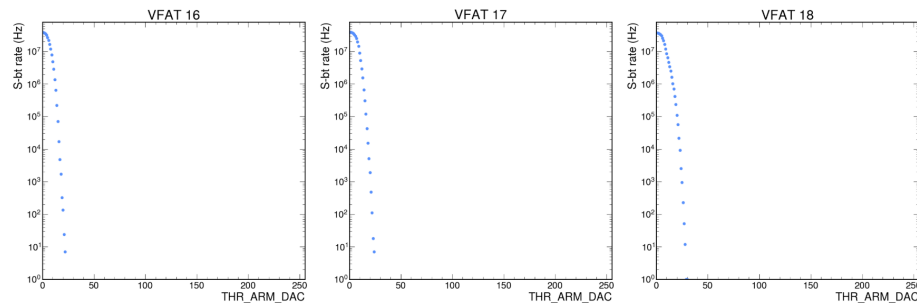


Figure 39: QC7 S-bit rate scan for VFAT 16, 17, and 18 on module 0069, showing the expected decrease.

### S-curve Scan Results

The S-curve scan measures the noise behavior of each VFAT channel. Ideally, no dead, disconnected, or excessively noisy channels should be present. Figure 40 shows the S-curve for the eta-1 region of module 0069, with most channels behaving correctly. Figure 41 shows an example of a dead channel, indicated by the flat white line.

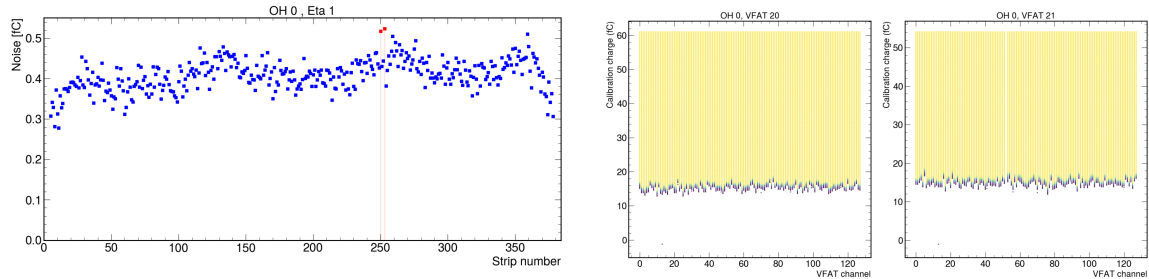


Figure 40: QC7 S-curve scan for the eta-1 region of module 0069, showing normal channel behavior. Figure 41: QC7 S-curve scan highlighting a dead VFAT channel (white line).

### Threshold Scan Results

The threshold scan characterizes the noise and uniformity of all VFAT channels by measuring their response as a function of threshold. Figure 42 shows the threshold scan for VFAT 9 of module 0069. The channels are distributed within the expected range, indicating stable and uniform behavior.

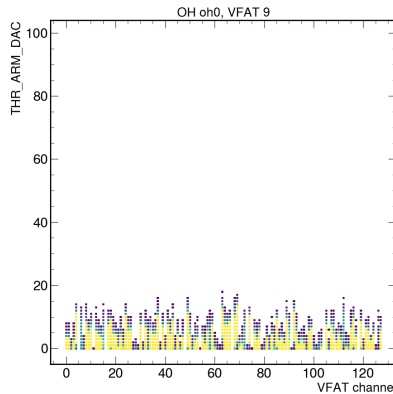


Figure 42: QC7 threshold scan result for VFAT 9 on module 0069, showing uniform channel response across all 128 channels.

## 7 Discussion

### 7.1 QC1 Discussion

In the QC1 test, we can detect issues early, since it's done before any further assembly steps.

- **Short-circuit test:**

If the test is not passed, it will indicate an electrical short between a readout strip and ground. If shorts are detected, the layer must be rejected, and in some cases returned to the manufacturer for modification or replacement.

- **Visual inspection:**

A common problem is contamination of the surface, such as dust and scratches on the protective coating. Minor contamination can often be cleaned, but in cases where the damage has affected the coating itself, the module may have to be sent back to the manufacturer.

- **Microscopic inspection:**

Under the microscope, dust particles can frequently be observed. Some of this can be removed by cleaning, but persistent contamination may compromise detector stability by increasing the risk of discharges. In that case, the affected board cannot be used.

Overall, the QC1 proved effective in identifying problems at an early stage. While many problems can be corrected with cleaning, serious damage and defects might require the module to be sent back to the supplier.

### 7.2 QC3 Discussion

The QC3 test ensures that each chamber is gas-tight before and after assembly. A failure in this test can arise from genuine gas leaks and environmental factors.

- **Gas leaks:**

The most common issue will be mechanical, such as loose fittings, damaged gas inlets, or forgotten sealing washers. In most cases, these leaks can be corrected by tightening connections or replacing faulty components. Some more persistent leaks may require reassembly or replacement of defective parts.

Another issue could arise from sensor and environmental effects. Variations in laboratory conditions - such as doors opening or temperature fluctuations - can influence pressure readings, which may falsely suggest a gas leak during testing. Additionally, sensor drift can affect the results. To minimize these effects, it is important to monitor external pressure simultaneously and interpret the results with consideration of the surrounding environment.

Overall, QC3 is a critical step in ensuring the reliability of the detectors. This is why it is performed multiple times during the assembly of layers and stacks. While most leak issues can often be addressed locally through adjustments, systematic monitoring of external conditions is essential to differentiate between genuine leaks and environmental noise.

### 7.3 QC7 Discussion

The QC7 test validates the functionality of the front-end electronics after installation. Several types of problems were encountered during these tests, ranging from defective components to assembly-related issues.

- **Defective VFATs:**

Individual VFAT chips may occasionally fail during testing. When this happens, the affected VFAT can be swapped with a functioning VFAT, and the test will be run again. If the issue follows the VFAT, the faulty chip will be removed and either replaced or modified to determine if it can be saved.

- **bPol converters:**

Issues occurred when bPols were installed incorrectly or subjected to mechanical stress. Over-tightening screws during installation occasionally resulted in failures. Proper mounting is crucial to prevent these problems.

- **Grounding cables:**

Improper cable lengths caused the grounding cables to not fit under the protective chimney. This issue was resolved by carefully re-soldering the cables, allowing them to fit precisely under the chimney.

- **Loose or damaged components:**

Small components like resistors sometimes detach due to poor soldering. These components are repaired by re-soldering and conducting a careful inspection before retesting.

- **Dead channels:**

VFAT channels sometimes appeared non-functional/dead during scans, often due to shorts to ground pins. Such defects could not always be fixed and occasionally required the affected chip to be discarded.

QC7 emphasized the sensitivity of the electronics and the significance of precise mechanical assembly. While most issues could be addressed through re-soldering, replacement, or adjustments, QC7 guaranteed that only fully functional electronics were integrated into the final detector system.



## 8 Conclusion

The assembly and testing of GEM detectors for CMS followed a systematic procedure that included several key steps: preparation, soldering, installation, gas connections, and electronics mounting, among others. At each stage, from individual components to layers and then to stacks, various quality control measures were implemented to ensure that only functional and reliable layers advanced to the subsequent steps.

Quality control processes included several key verifications. QC1 ensured the integrity of the detection layers by checking for electrical shorts, surface damage, and microscopic contamination. QC3 confirmed that the chambers were leak-tight, which is essential for the stable operation of the gas system. Finally, QC7 validated the functionality of the front-end electronics, identifying and correcting issues such as defective VFATs, bPol problems, and grounding issues.

The combined results indicated that the quality control procedures were effective. Although minor defects, such as dust, scratches, poor soldering, and faulty components, were occasionally observed, most issues could be addressed locally through cleaning or modifications. More significant problems, such as persistent shorts or defective components, were resolved by rejecting or returning the affected modules.

In summary, the quality control method ensured that only high-quality GEM layers were incorporated into the final stacks, resulting in reliable performance for later integration into the CMS muon system.

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