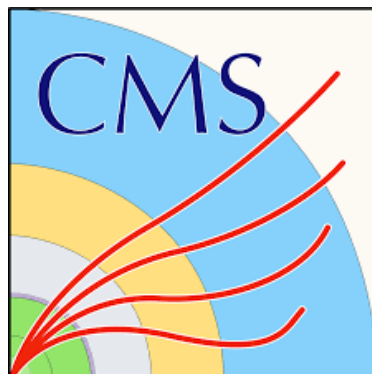




American University Of The Middle East



Coupling Muon Solenoid (CMS) Gas Electron Multiplier (GEM) & Voltage Divider Project

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Abstract

The European Organization for Nuclear Research (CERN) is home to the Large Hadron Collider (LHC) which is a 27km ultra-high-vacuum ring that is 100 meters underground. The LHC uses an electric field to accelerate two opposing proton beams to near the speed of light; a network of superconducting electromagnets keep the particles confined in the circular accelerator. To further investigate the laws of physics and convert the large energy into fundamental particle mass, the opposing proton beams collide. The LHC will increase its luminosity, essentially increasing the number of particles produced following a collision of two proton bunch crossings; the increase of luminosity requires improved momentum resolution. To study the physics of the LHC, four experiments are installed around the circumference: ATLAS, ALICE, CMS and LHCb. The Compact Muon Solenoid is general-purpose detector that records new data every 25 ns. To upgrade the CMS, the new Gas Electron Multiplier stations GE1/1, GE2/1 and ME0 are developed and installed. The GEM detectors amplify the electrons that are a product of the muon ionization, thus making it easier to detect muons by differentiating it from noise. The amplification occurs as a result of the capacitance of the GEM foils. Gas Electron Multiplier foils are two copper sheets with dielectric kapton in between them. GEM foils have 70 micron holes with 140 micron distributions. The potential difference introduced to the foils induces an electric field. With three GEM foils, the amplification of the electrons reaches a factor of 8000. The ME0 will also improve PT resolution (transverse momentum) while simultaneously reducing neutron background noise. To ensure that the modules are of acceptable standards, Quality Control tests are done. Quality Control 1 and 2 involve checking on the GEM foil's health, while Quality Control 3 and 4 check the module's Gas Leakage as well as the Intrinsic Noise respectively. To improve on the gas leak tests, the PS7 NPA500B001G pressure sensor is introduced and calibrated for precision and accuracy. The PS7 NPA500B001G sensor is also much smaller and lighter than the older SensorTechnics CTEM9100GQ4 pressure sensor. This will make it easier to design a portable Quality Control 3 in the future. To improve on the intrinsic noise test, a new printed circuit board is designed for the convenient installation of the voltage divider piece. Soldering the voltage divider piece onto the module causes the piece to break, it can sometimes damage the module itself. This PCB will allow for wires to be soldered on to the module instead of soldering the voltage divider piece directly on the module.

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1 Introduction

CERN is a particle physics research facility based in Switzerland and France. It is home to a range of physicists, engineers, computer scientists and mathematicians. CERN houses the Large Hadron Collider (LHC), a particle accelerator that studies the fundamental particles that make up the universe and the interactions between them within the facilities of CERN. This is an essential part of studying particle physics and testing to discover new particles. It is used to understand the physics of the Higgs Boson and to investigate the Standard Model by conducting collisions between particles. It accelerates two opposing proton beams before colliding them. The beams collide at four points across CERN where experiments are installed: ALICE, ATLAS, CMS and LHCb. CERN accelerates science in general; it is the birthplace of the World Wide Web and it found many improvements to medical imaging techniques and cancer therapy.



Figure 1: Large Hadron Collider ALICE, ATLAS, CMS and LHCb.

2 Large Hadron Collider

2.1 Proton Beam Collision

The LHC is a 27-kilometer ring structure enclosing an Ultra-High-Vacuum. The LHC can be operated with two types of particle beams: proton beams and lead ion beams (1). The superconducting electromagnets and the electric field of the LHC accelerate the two opposing proton beams to a speed close to the speed of light (2)(the protons cycle the LHC ring 11,000 times in 1 second = 2.97×10^8 m/s roughly). The superconducting electromagnets confine the charged particles within the LHC circumference. The Large Hadron Collider operates at 8.3 Tesla (2) - which is 166,000 times more powerful than Earth's magnetic field.

The superconducting electromagnets are kept at 1.9 Kelvin (2)- a temperature lower than that of deep space. This is essential for the magnets to become superconductive. Current in a superconductive material circulates with no resistance and therefore no heat dissipation, essentially yielding higher currents that induce a higher and more potent magnetic field. A Helium mass of 135 tonnes is required to refrigerate the electromagnets of the Large Hadron Collider to the required temperature. Since the size of the protons makes it nearly impossible to have the two exclusive protons collide in the LHC, two pairs of opposing proton bunches with 100 billion protons will collide at about the speed of light (2). For this reason, it is important to focus the two beams with the aforementioned electromagnets to increase the chance of proton collisions yielding rare particles (2).

The LHC tube has a vacuum (10^{-10} to 10^{-11} mBar) lower than the surface of the moon to ensure the beams accelerate effectively as the proton beam does not collide with gasses in their path. When the protons collide, physicists can recreate the same conditions as a few millionth of a second after the Big Bang 14 Billion years ago (2); the proton collision kinetic energy is converted into mass and later decays into other fundamental particles(3). The post-collision temperature also reaches a temperature of a trillion degrees centigrade (2) (even higher than the core of the Sun).



Figure 2: Large Hadron Collider dipole magnets.

2.2 Compact Muon Solenoid

The Compact Muon Solenoid (CMS) is one of the four experiment sites on the Large Hadron Collider (LHC). The area of operation is in Cessy, France. The CMS aims to record particle collisions occurring at 40 Mega Hertz (1)- it records new data every 25 nanoseconds. Whereas it can only record 1000 full particle events every second (4), thus it must select the most interesting and noteworthy particle interactions with the help of the trigger system. The ME0 will sit alongside the GE1/1 in the nose of the Coupling Muon Solenoid endcap. The GE2/1 will sit on the other side of the first disk of Muon Chambers (4).

It utilizes Gas Electron Multiplier (GEM) amplification technology in the ME0, GE1/1 AND GE2/1 boards respectively. The Compact Muon Solenoid has a magnetic field 80,000 times more powerful than Earth's magnetic field. It operates at 4 Tesla and weighs 12,500 Tonnes (4).

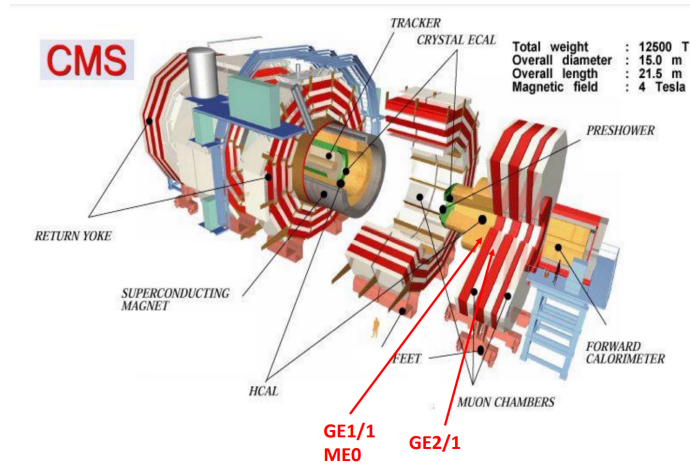


Figure 3: Compact Muon Solenoid.

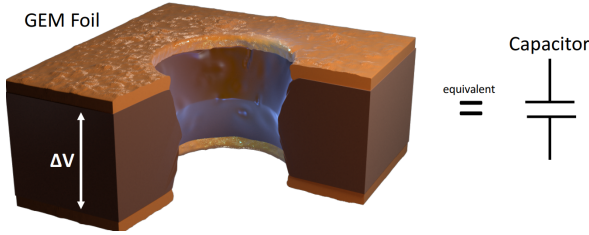
2.2.1 Gas Detection

The GEM is essentially a gas detector that uses Argon:CO₂ (70:30) in between the cathode and the anode in it's modules(5). When the muons pass the Argon gas, they will ionize into an electron and positive ion pair. The ionized Argon will emit Ultra-Violet photons that can cause secondary

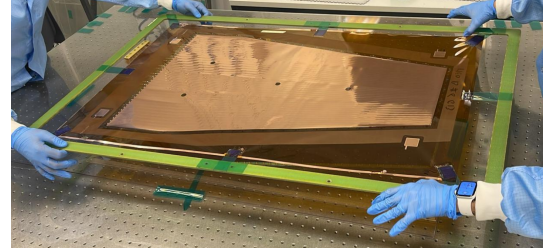
avalanches as well as a loss of proportionality (5), thus the second CO₂ gas is required to absorb the created energy in a non ionizing process in order to prevent noise and distortion. Carbon Dioxide will act as a quenching agent in the gas detecting mixture (5).

2.2.2 Gas Electron Multiplier (GEM)

The GEM foils are made of two external sheets of copper and a dielectric (kapton) in between them. When a voltage is introduced, the GEM foils behave like a capacitor chamber with an induced electric field; three GEM foils are used for the amplification (6). The voltage must induce a constant electric field of 80kV/cm to continue getting the same amplification gain(6). Essentially, each GEM foil will multiply each electron by a factor of 20. With three GEM foils, the gain will be 8000. The GEM foils have many 70 micron diameter holes in them with 140 micron spacing. When the muon ionizes in the gas and produces electrons and positive ions. Due to the induced electric field, the positive ions move toward the drift cathode; the electrons moves toward the readout anode and go through the GEM foils. When this happens, the electrons are exposed to an electric field that will create an electron avalanche; this amplification makes it easier to detect the charges in the readout. The moving electron charge will induce a current on the readout of the GEM detector, which will create a signal from the readout on the conductive strip (6).



(a) Microscopic Hole in Gas Electron Multiplier.



(b) Individual GEM Foil.

Figure 4: Gas Electron Multiplier Foil

2.3 CMS Upgrade

There are three other types of Gas Detectors. Cathode Strip Chamber (CSC), Drift Tube (DT) and the Resistive Plate Chamber (RPC) (1).

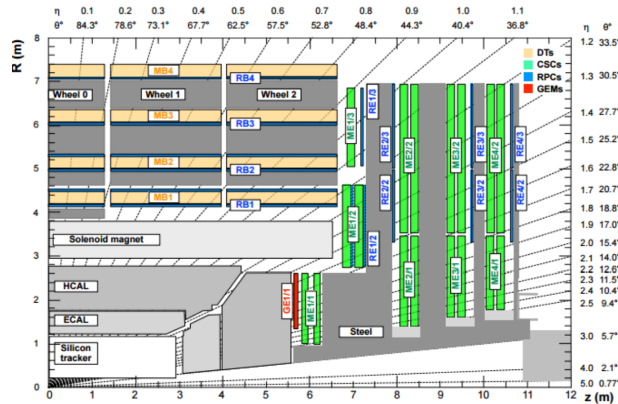


Figure 5: Muon system with RPC, CSC and DTs.

The LHC will increase its luminosity to an approximate particle rate of $5kHZ/cm^2$ (1). This increase in luminosity will increase the produced particles at each proton beam collision; the momentum resolution must thus also be improved which will keep the DAQ at 100kHz following LV1 (1)(7). The Drift Tubes are placed in the central barrel part of the CMS; the Cathode Strip Chamber is installed

in the endcap section of the CMS. The Resistive Plate Chamber was initially supposed to be installed in both the endcap and the central barrel part of the Coupling Muon Solenoid. Return yokes separate the layers and induce a magnetic field of 2T in the muon tracker(1). However, since the LHC will increase it's luminosity to an approximate particle rate of $5kHZ/cm^2$ (which is too high for the RPC capabilities), the RPC detector has been rendered obsolete and has been abandoned as a result. The GE1/1 project aims to rectify this issue. The better adapted GE1/1 will replace the unused area of the RPC. The GE1/1 project aims to improve the impulsion determination of the muons(1). The GE1/1 project also aims to offer a redundancy of detection to ensure that if other detectors start to degrade, the system continues operating at a high efficiency(1).

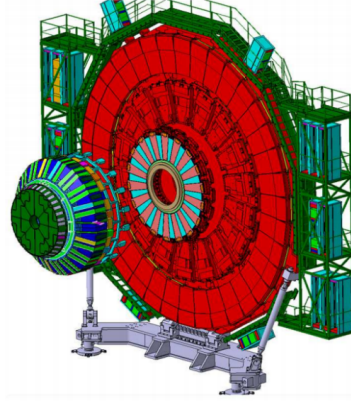


Figure 6: The first CMS endcap station that is equipped with 18 short (blue) and 18 long (pink) triple-GEM detectors in it's inner ring (1).

2.4 GEM Board Modules

2.4.1 ME0

The ME0 sits at the very front end of the CMS, thus it is exposed to the highest level of radiation when compared to the other boards (4)(8). The ME0 will improve muon detection as it will improve spatial resolution and granularity. The ME0 will also improve the transverse momentum of the muons and reduce neutron background noise (9).

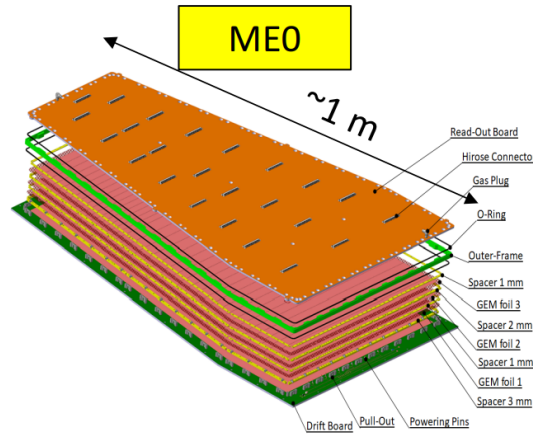


Figure 7: ME0 Module Dimensions.

Six layers of triple GEM are stacked upon each other rather than two with chambers spanning 20°

in phi. For the ME0, 6 chambers per stack are required, with 18 stacks per endcap, there are two endcaps. It has an eta range of $2.4 < |n| < 2.8$ (4).

2.4.2 GE1/1

The GE1/1 is slightly larger than the ME0. The GE1/1 is not as exposed to radiation when compared to the ME0.

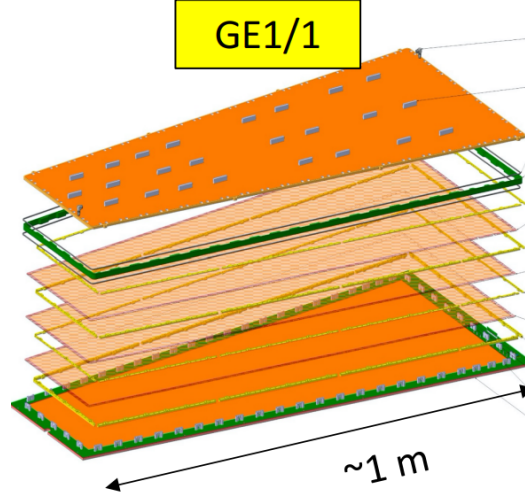


Figure 8: GE1/1 Module Dimensions.

The GE1/1 has 36 super-chambers per endcap (super-chambers are two triple GEM detectors mounted back to back), it thus has 72 triple GEM detectors and 144 layers (4). Each chamber spans 10° in phi. The GE1/1 covers the eta region $1.6 < |n| < 2.1$ (4).

2.4.3 GE2/1

The GE2/1 is the largest board out of the three. It has 18 staggered super chambers per endcap, it thus has 36 triple GEM detectors per endcap and 72 layers of triple GEM detectors (4).

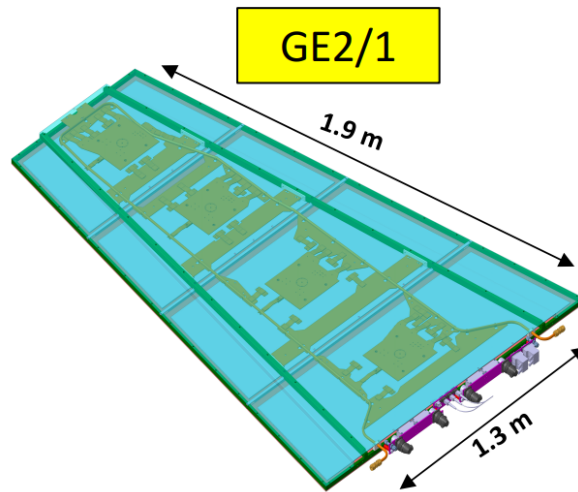


Figure 9: GE2/1 Module Dimensions.

Each GE2/1 chamber span 20° in phi. The GE2/1 covers the eta region $1.55 < |n| < 2.45$ (4). The GE2/1 has four segments and four Optohybrids.

2.5 Board Layers

The electron avalanche amplification makes it easier to detect the charge from the readout. The amplification also makes it easier to differentiate between the useful signals and the unwanted noise (6).

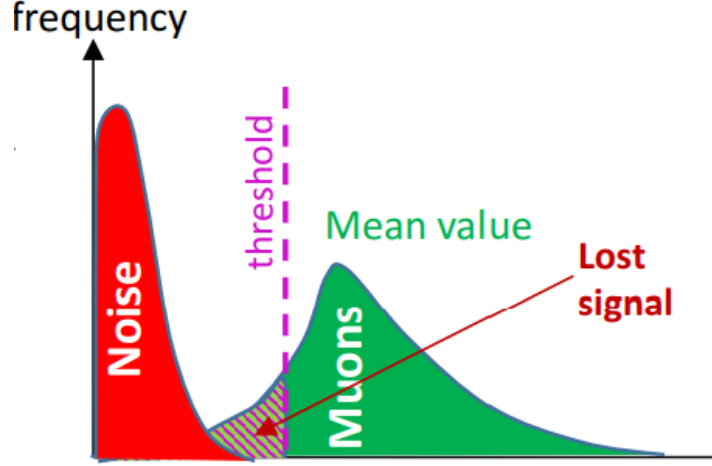


Figure 10: Low amplification can cause muon signals to be lost in noise.

2.5.1 Frontend board

The front end of the board is where the 24 VFAT ASICs of the ME0 and GE1 are housed. The ASIC amplifies, digitizes and shapes the data signals (8). The Optohybrid (OH) then transmits the data from the front end to the backend via optical fibers via the GEM Electronics Board (GEB) (7). Furthermore, the ASIC uses 128 channels per VFAT to decide whether the signals are interesting (above the threshold) or not (below the threshold) (8).

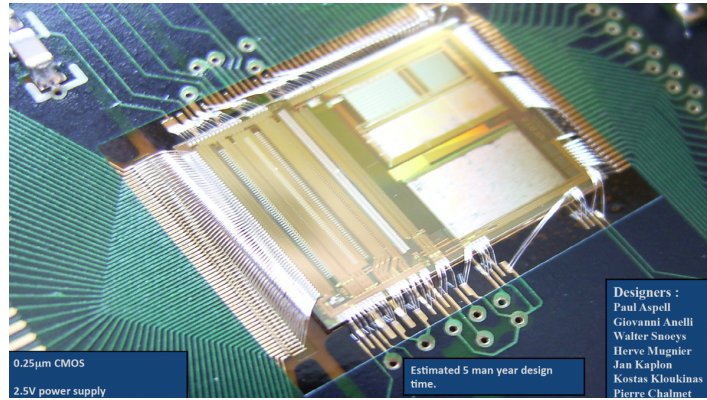


Figure 11: 24 VFAT ASICs sit on the GE1/1 and the ME0.

The different detectors and modules along with the control signals must be synchronized by a 40MHz clock. This is accomplished with the Timing & Control Distribution System (TCDS)(7). After the Level 1 trigger, the rate goes from 40MHz to 100kHz. The bunch counter zero will signal the start of a proton bunch orbit. The Level 1 trigger chooses the most interesting proton bunch crosses (proton beam collisions). When a Level-1 Accept (L1A) is sent, the full detector is read out. The data is then sent to the Data Acquisition System which processes the reconstruction of the signals and reads the

data in high resolution. Further signal filtration is done at the High Level Trigger. After the HLT data is sent outside of the Coupling Muon Solenoid at 1000Hz where it can be stored. This is because CMS can only record 1000 full events per second (4); all other data is lost(7).

2.5.2 Backend Board

The backend puts together and processes all the data and then sends it to the Data Acquisition System (DAQ) where the data is reconstructed and read out with high resolution (7). It does this over optical links such that the backend of the board has access to the CMS Central services (Timing Control Distribution System, L1 Trigger, L1 Accept and the Digital Acquisition System). The backend can communicate with the frontend and vice versa (7) (8).

The backend of the board provides the 40MHz clock to the frontend of the board. The backend of the board sends Level 1 Accept signals to the VFAT ASICs while also controlling the FPGAs of the OptoHybrids of the frontend. On the GE1/1 and the GE2/1, the FPGA on the Optohybrid processes data of single layer hit clusters (7). Though on the ME0, the processing of 6 layer track segments is done on the backend of the board (7); this is because the ME0 has no FPGA on it's Optohybrid due to high radiation exposure.



Figure 12: The backend of the GE1/1 module.

3 ME0 Module Assembly

The first step is to remove the dust from the plastic outline with a dust roll remover. A vacuum cleaner must also remove the dust from the individual internal frames). The internal frame must have no spikes; they must be properly cut and the borders of the frames must be properly shaped.

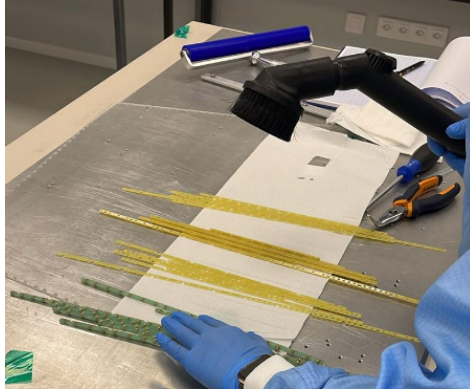
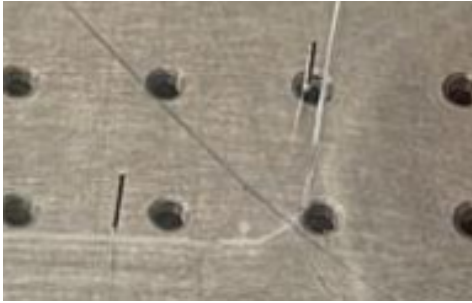
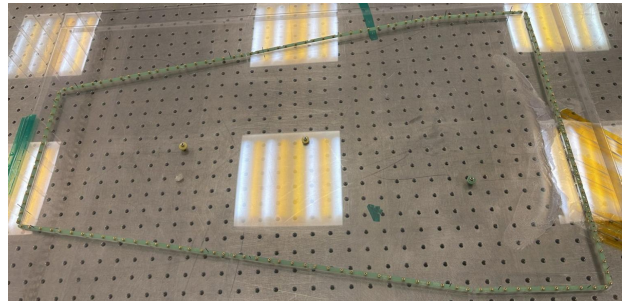


Figure 13: Removing the dust from the internal frames with a vacuum cleaner.

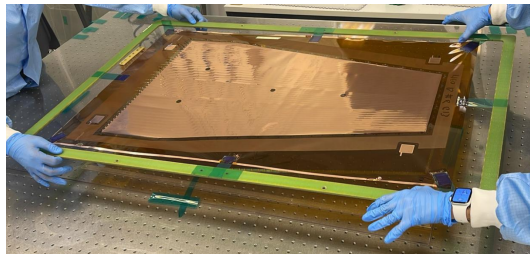
The internal frames are then connected and aligned; guiding pins are added onto the internal frames to allow for perfect alignment of the coming layers of the board.



(a) Adding the guiding pins to the table.



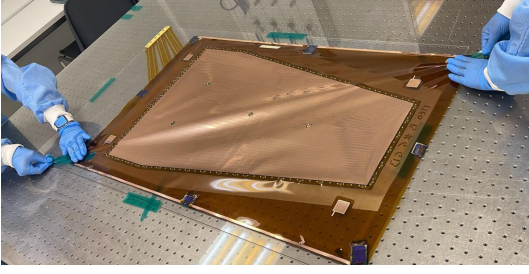
(b) The internal frames are aligned on the outline.



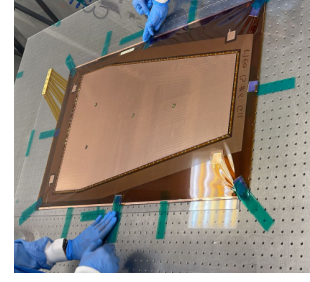
(c) Placing the first GEM foil on the 3mm internal frame.

Figure 14: Aligning all the GEM layers.

The first layer of internal frames is 3mm; the order of the internal frames is 3,1,2,1 which specifies the spacing between the three GEM layers. The first layer of Gas Electron Multiplier foil is then aligned on top of the 3mm internal frames. The foil must also harmonize with the guiding pins for alignment reasons. The next step is for two people to flatten the GEM foil at opposing ends of the foil. The tightening takes place at both corner pairs; the three segments of the vertical height; and the the middle part of the horizontal width of the board.



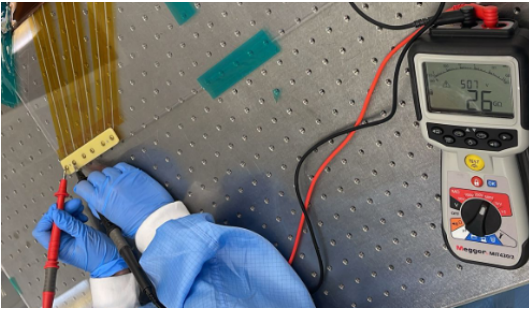
(a) Flattening the GEM foil to ensure it is uniformly distributed



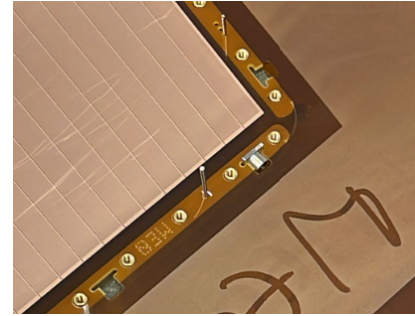
(b) Flattening tape is added to six opposing ends

Figure 15: Flattening & Evening GEM foils correctly

Then the GEM foil is tested with a voltmeter. A 500V electromotive force is induced, if the resistance of the GEM foil is above 20 Giga-Ohms, the GEM foil is operational. If however the GEM is less than 20 Giga-Ohms or it reaches the Mega-Ohm scale, then the foil could be contaminated with dust. The dust can be burnt off when the voltmeter readings are being conducted. At the end of each test, discharging the foils with the negative black probe is essential to minimize static discharge effect. The frame is then cut off of the GEM with a razor. The tightening tape is also visible at 6 opposing pairs on the board. The previous steps are repeated for two more foils and 3 more internal frames (1,2,1) (8). On the second GEM, T-nuts are added onto the edges of the second foil which will later help with the stretching of the foils. The wider side of the Tnut is on the surface and the shorter side of Tnut goes in the foil.



(a) Checking the health of GEM 1.



(b) Tnut installation.

Figure 16: Assessment & Preparation

The internal frames have dots that allow the frames to be ordered in the correct sequence. There are 8 segments of the internal frame which are ordered sequentially, this can be seen in the figure below.

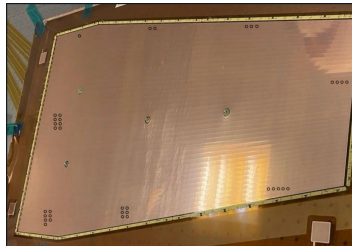
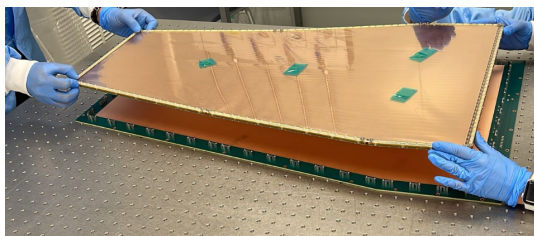


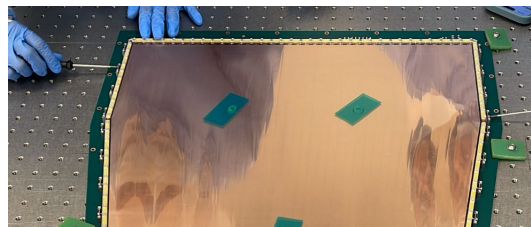
Figure 17: The sequence of internal frame dots from 1 to 8.

Once all of three of the GEM foils and their gaps are properly assembled, a protective plastic cover is

also added on top of GEM 3 in-case an object accidentally impacts the foils. The GEMs will then be lifted and attached onto the drift cathode. This is a critical step since the people carrying the GEMs must minimize the static discharge effect which can ruin the microscopic holes of the GEM foils. If the wholes become too damaged with time, the amplifying effect can be corrupted.



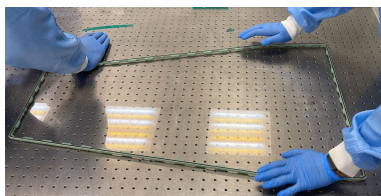
(a) Attaching the GEM foils onto the Drift.



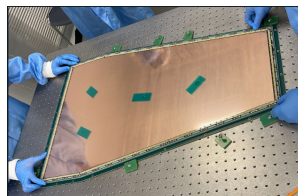
(b) Stretching of the board done at opposite end.

Figure 18: Static discharge must be minimized

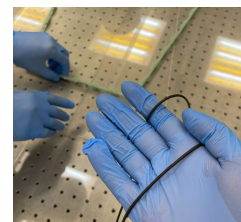
Now the stretching of the GEMs will be done with the help of the T-nuts that were previously installed. Stretching involves adding the screws to the side, but not tightening them at first. Once all the screws are positioned along the edges of the board, the tightening of the screws happens simultaneously at two opposite ends as seen in the figure. This ensures that both ends of the GEM are tightened. This leaves the foils with a mirroring effect. The next part is preparing the external frame. The O-ring is first cleaned with sticky paper and ethanol to remove any contaminating dust. The external frame is also cleaned with sticky paper. The O-ring is added to minimize the gas leakage effect. Whereas often times a problem with either the external frame or the O-ring can cause the gas to leak. The O-ring is flattened inside the external ring to minimize gas leakage.



(a) Flattening the O-ring inside the external frame.



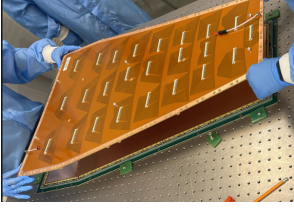
(b) Attaching the external frame.



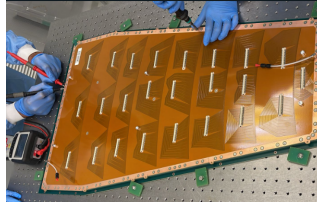
(c) The O-ring and the external frame.

Figure 19: Preparing the external frame

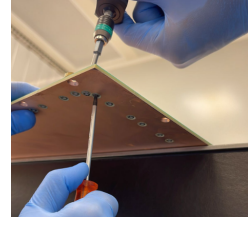
The protective layer is then removed to allow the external frame to be attached on the GEM foils. The GEMs are tested again with a voltmeter. The next step is attaching the Readout Anode to the rest of the GEM board. Pushing the readout atop the external frame inside will stabilize the board. The Readout will then be screwed atop the board and above the third and last GEM foil. For this reason, as the Readout is being screwed in, the third GEM foil must be monitored with a voltmeter. The screws must not be over torqued. If the voltmeter stays above 20-Giga-Ohms, the lab faculty can keep screwing in the Readout. If however there is a drop in the resistance and it reaches the Mega-Ohm scale, then the lab faculty must stop screwing in the Readout until the resistance rises back up to the Giga-Ohm scale. This process ensures that GEM 3 does not get damaged. If anything feels loose, it can be tightened from the top and the bottom simultaneously. Below the cylinder is being tightened since one of the stretching nails wouldn't go in.



(a) Attaching the external frame to the GEM foils.



(b) Monitoring GEM 3 as the Readout is screwed in.



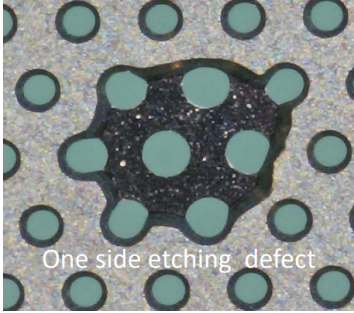
(c) Tightening the cylinder.

Figure 20: Final Steps.

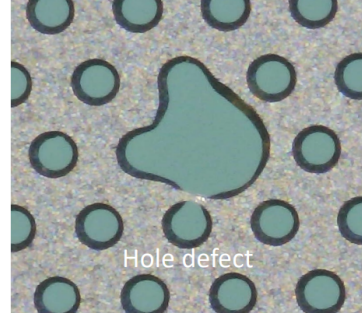
4 Quality Control

4.1 QC1 GEM Foil Visual Inspection

Since the holes are in the micro-scale (70 micron), an optical microscope can be used to observe the GEM foil holes. The readout holes are the PI(polyimide); the test also inspects the Cu(copper) layers hole size (10).



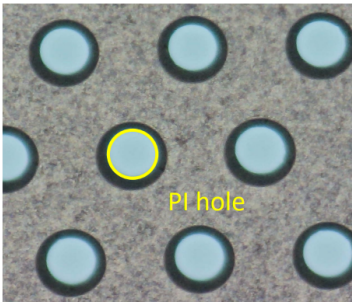
(a) Etching defect.



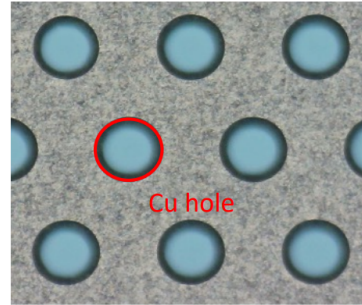
(b) Hole defect.

Figure 21: Types of defects on GEM foils.

The two types of defects are the etching defect on one of the sides of the foil, in addition to the hole defects. The polyimide and copper hole sizes are critical to the gain, they must thus be monitored closely. If less than 10 holes are detected, the test is still successful. If however more than 10 holes are deformed, the test is not successful (10).



(a) Polyimide Hole.

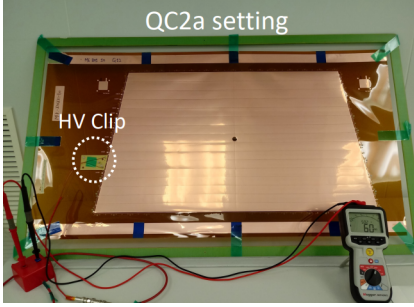


(b) Copper Hole.

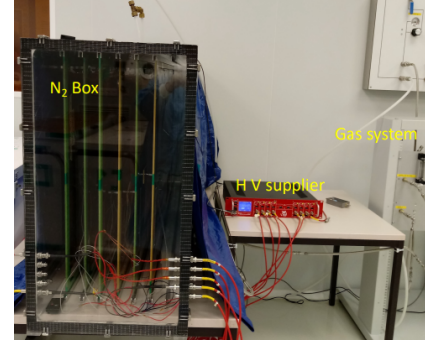
Figure 22: Polyimide and Copper holes on GEM foil.

4.2 QC2 High Voltage stability and Leakage Current check

The second quality control test assesses the health of the GEM foils. The first part of the test QC2a will see that 500V with an impedance greater than 10 Giga-Ohms is induced onto the foils. The number of sparks is then counted and recorded. Sparks often indicate the presence of foreign parasitic impedance like dust particles or other contamination sources. Sparks are counted for 30 seconds, if sparks continue the test can count for each minute for 5 minutes. If the sparks persist, counting is done for up to 10 minutes. The foils that pass QC2a are stored inside a Nitrogen flushed box and can then move to QC2b (10).



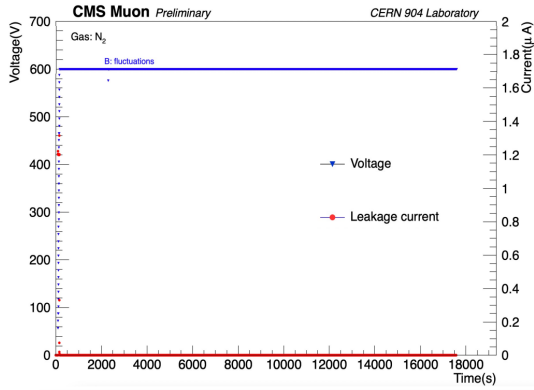
(a) Applying 500V with Impedance greater than 10 Giga-ohms.



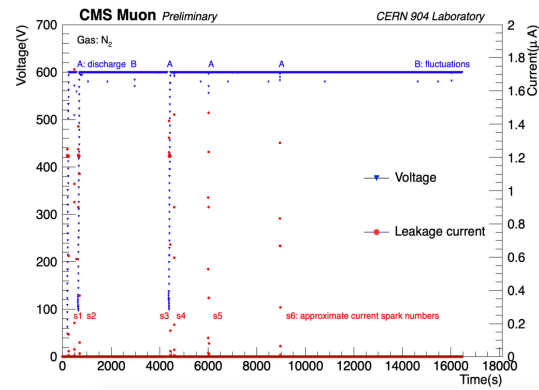
(b) Nitrogen Chamber of QC2b.

Figure 23: Quality Control 2a & 2b settings.

Quality Control Test 2b flushes the foil chamber with Nitrogen gas with 100 L/h. This is done until the humidity within the chamber reaches less than 7%. Following this, a larger 600V is applied for 90 minutes; the current range must be less than 20 micro amperes (leakage current $< 20\mu A$). If the first part of QC2b passes, 600V is applied for 14 hours, if the leakage current is less than 2 micro amperes (leakage current $< 2\mu A$) and the number of sparks is less than or equal to 3 ($N \leq 3$) the test is successful. In the plot below, the failed GEM foil is damaging itself as it discharges, making the foil unstable. When the foil is stable, voltage fluctuation & current sparks cease and the test is successful (10).



(a) QC2 Pass.



(b) QC2 Fail.

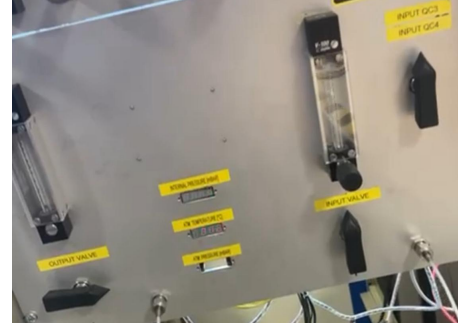
Figure 24: QC2 pass & fail plots.

4.3 QC3 Gas Leak Test

The Compact Muon Solenoid is a gas detector. Thus, the gas leak test must be conducted to ensure no leakage of gas occurs. The board is flushed with CO₂ for one hour. This can be done by turning on the output and input valves (setting them both from horizontal to vertical alignment) as seen below. The flow-meter is also opened. After an hour, the output gas valve is closed (10). We need to wait for the internal pressure to reach 26.5mBar before the input gas valve is also closed along with the flow-meter above the input valve.



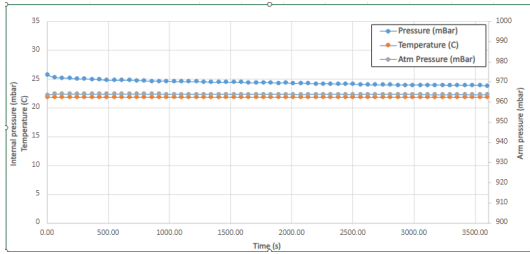
(a) Flush module with CO₂ for an hour.



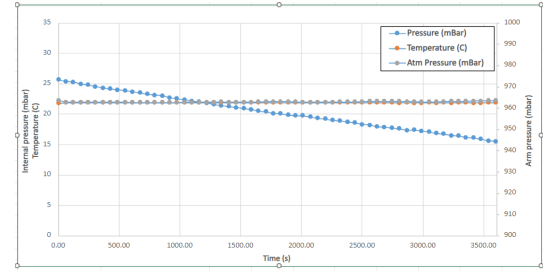
(b) Closing the output valve.

Figure 25: The steps of Quality Control 3.

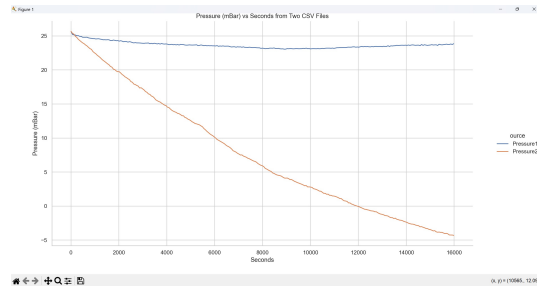
Following these steps, the test can commence. The test can either pass or fail. If the test succeeds, the pressure will hold and remain relatively constant. In the passing test, the pressure starts at 25.68mBar and in 15983 seconds it reaches 23.86mBar. Whereas if a test fails, the internal pressure of the module will visibly go down and dwindle. In the failing test, it also starts at 25.68mBar and then after 15983 seconds it reaches -4.31mBar. This can be seen in the figures below.



(a) The pressure is remaining constant in the passing test.



(b) The pressure drops straight away in the failing test.



(c) Plotting the pressure data of the two CSV files on Seaborne.

Figure 26: Comparison of internal pressure behavior in passing and failing tests.

4.4 QC4 Intrinsic noise test

This test is done to measure the intrinsic noise of the module with the high voltage linearity and compares it with the divider current. This test assesses the health of the GEM foils via the eight pins on the edge of the module for the (Drift, 3mm, GEM1, 1mm, GEM2, 2mm, GEM3, 1mm). Below displays a linear voltage vs divider current (10).

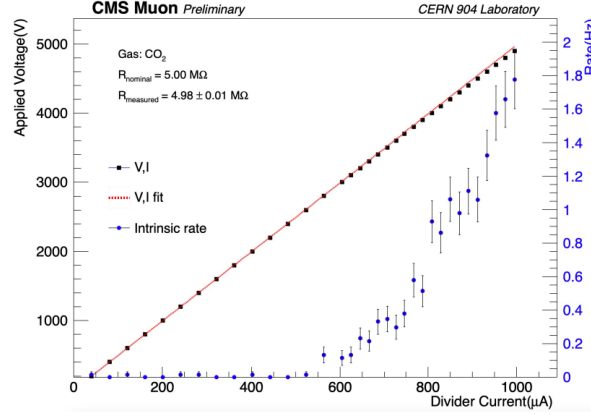


Figure 27: Linear High Voltage vs. Current Divider plot.

If the High Voltage vs Divider Current plot is not linear, that can indicate the presence of foreign wasteful impedance's - like dust - on the GEM foils (10). To make the QC4 easier for Voltage detection, the Voltage Divider PCB was designed.

5 Projects

5.1 Voltage Divider Project (QC4 Aid)

On the ME0 board, there are 8 pins on the bottom of the structure. Each of the pins must be measured with a voltmeter to determine the health and function of each of the GEM foils. The previously designed component was an impractical and fragile one; the old voltage divider kept on breaking.

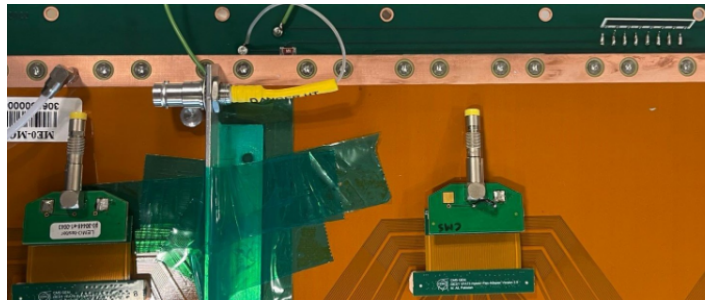
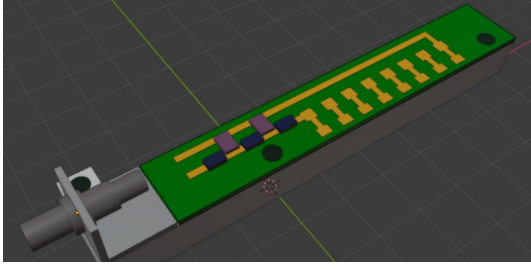
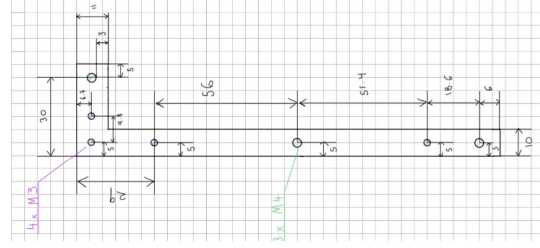


Figure 28: The frail original design for the voltage of the Module.

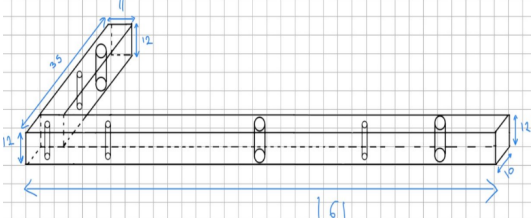
My task and job at the CERN 904 lab, is to design and print a voltage divider that will be able to do the voltage dividing job while sitting on the ME0 edges. The prototype will be attached to the ME0 with wires such that they may be replaced if they are to break. The first step of the design is to design the large L shaped slab that will sit on the ME0 board. There must be a three-dimensional and two-dimensional design for the L shaped slab.



(a) The concept design for the new Voltage Divider PCB.



(b) Two-Dimensional technical drawing of the L-shape.



(c) Three-Dimensional technical drawing of the L-shape.



(d) Technical drawing for the Printed Circuit Board.

Figure 29: The steps of Quality Control 3.

The next step is designing the Printed Circuit Board on the Circuit Maker software. It is also very important to have precise and correct measurements for both the PCB and the L-shaped slab; the location of the screw holes of both designs must align perfectly and without issue. The PCB will be ordered and built at PCB Way.

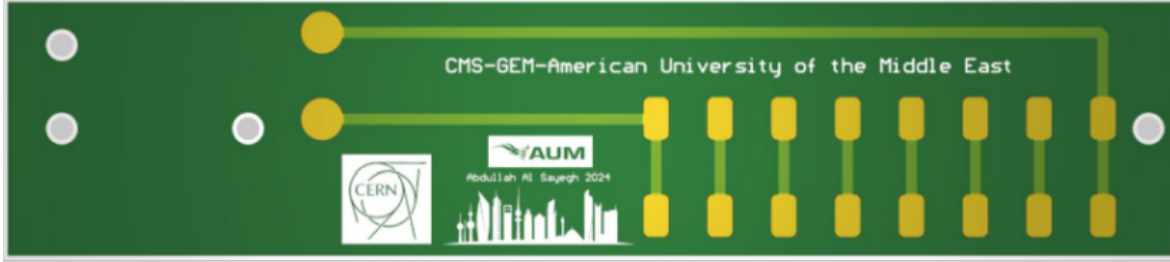


Figure 30: Final Printed Circuit Board design on Circuit-Maker.

5.2 Pressure Sensor Calibration (QC3 Update)

The previously installed sensor on the QC3 (SensorTechnics CTEM9100GQ4) had been giving inaccurate readings; the pressure of the modules was rising instead of minutely falling. As a result of this, I had been tasked with calibrating a new sensor (PS7 NPA500B001G) in addition to replacing the old seven segment displays with LCD screens. The new PS7 NPA500B001G is much lighter than the older sensor; picking a lighter sensor is the first step in designing a portable QC3. To calibrate the sensor, a U-pressure-tube (filled with brown dyed water) is used. The equation we will use for the brown dye water is:

- Pressure (Pascals)=density(kg/m^3) * height(m)*gravity($9.81\text{m}/\text{s}^2$).
- $99.8658 \text{ Pa}=0.998658 \text{ mBar}=1018(\text{kg}/\text{m}^3) * 10^{-2}(\text{m})*9.81(\text{m}/\text{s}^2)$.

We will consider a 1cm height difference between the two water levels to equal to 0.998658 mBar while calibrating the new sensor. The sensor will have one tube open to the room pressure and another tube to apply variable pressure.

We then convert the ADC value to a voltage value with the equation:

- $\text{ADC (bits)} * \frac{\text{Maximum Processed Voltage}}{2^N \text{ of bits}} = \text{ADC (bits)} * \frac{5V}{2^{10} \text{ bits}} = \text{ADC (bits)} * \frac{5V}{1024 \text{ bits}}$

We get the new voltage value in milli-Volts and calculate the average value each second. We then induce no pressure on the sensor so that the two water levels are equal to each other and record the milli-Volt value. Next we increase the distance between the two water levels with increments of 1cm (which corresponds to 0.998658 mBar). We go up to a 20cm difference between the water levels. The next step is to plot the milli-Volt values against their corresponding mBar values. The slope equation we get will be used to calibrate and convert the voltage to an accurate pressure reading.

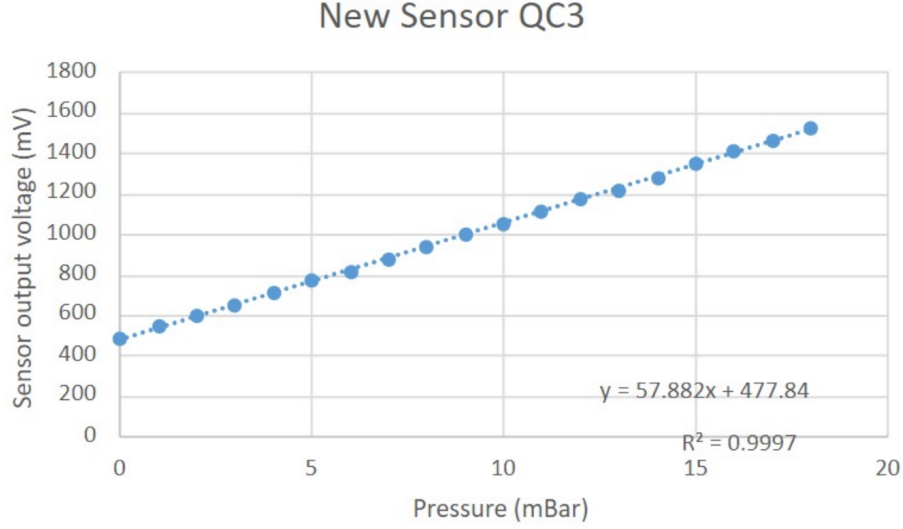
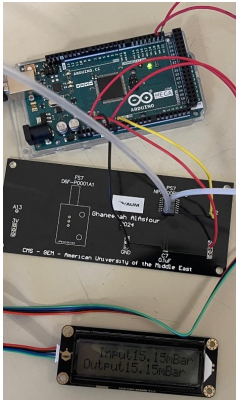


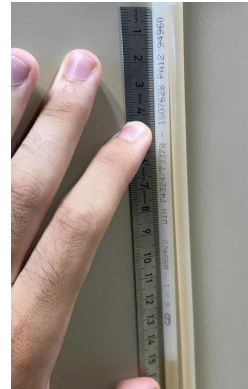
Figure 31: Plotting the voltage against the corresponding pressure.

The y-value represents the voltage in milli-Volts, while the x-value represents the pressure in mBar. So to get the pressure, we solve to get x.

- $x = \frac{y - 477.84}{57.882}$



(a) The pressure is 15.15 mBar.



(b) The height difference is about 15.2 cm.

Figure 32: Testing the accuracy of the pressure calibration.

Following this, the derived equation is used to write the properly calibrated Arduino code. To test that the pressure sensor is working, the pressure readings on the new LCD screens are compared the the

height difference of the two water levels. As seen in the two figures above, the system is rather precise. The height difference is 15.2cm approximately, the pressure reading is 15.15mBar. This reading can also be read and recorded on a text file log. To test, random numbers were recorded on Excel as well. For both the txt file and Excel, new data is logged each minute for one hour.

```

Python 3.12.4 (tags/v3.12.4:8e8a4ba, Jun 6 2024, 19:30:16) [MSC v.1940 64 bit (AMD64)] on win32
Type "help", "copyright", "credits" or "license()" for more information.
>>>
= RESTART: C:/Users/ABDULLAH/Downloads/Project_main_3Disp_V2_Debug1/savetext.py
DATA,TIME,1,15.10,0.00,0.00,
DATA,TIME,62,15.15,0.00,0.00,
DATA,TIME,123,15.17,0.00,0.00,
DATA,TIME,184,15.18,0.00,0.00,
DATA,TIME,245,15.18,0.00,0.00,
DATA,TIME,306,15.18,0.00,0.00,
DATA,TIME,367,15.18,0.00,0.00,
DATA,TIME,428,15.18,0.00,0.00,
DATA,TIME,489,15.18,0.00,0.00,
DATA,TIME,550,6.93,0.00,0.00,
DATA,TIME,611,6.93,0.00,0.00,
DATA,TIME,672,20.99,0.00,0.00,
DATA,TIME,733,21.03,0.00,0.00,
DATA,TIME,794,21.02,0.00,0.00,
DATA,TIME,855,8.44,0.00,0.00,

```

Figure 33: Recording the data onto a .txt file.

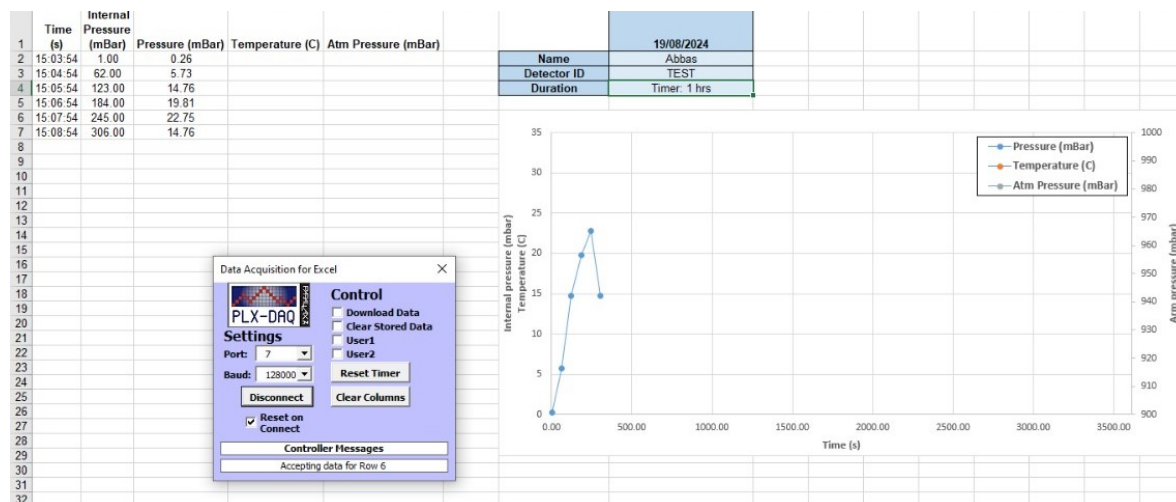


Figure 34: Inducing a range of random pressures and recording the values on MS Excel.

6 Conclusion

6.1 CERN Summer Student Program

Being a part of the CERN Summer Student Program was an immense privilege and honor. It was delightful to meet a range of different people with many various backgrounds and majors. Working at the Gas Electron Multiplier 904 Lab was especially useful. Witnessing physicists, engineers and computer scientists come together to work on the Gas Electron Multiplier is surreal. I especially appreciated the freedom to work on many different projects throughout my time at the 904 lab. For this reason, I developed numerous new skills and gained significant valuable experiences during my time at the 904 lab. Other than the projects I was assigned, I took part in the assembly of the ME0 module. I also worked on drift and readout board preparation.



Figure 35: CERN Globe of Science and Innovation.

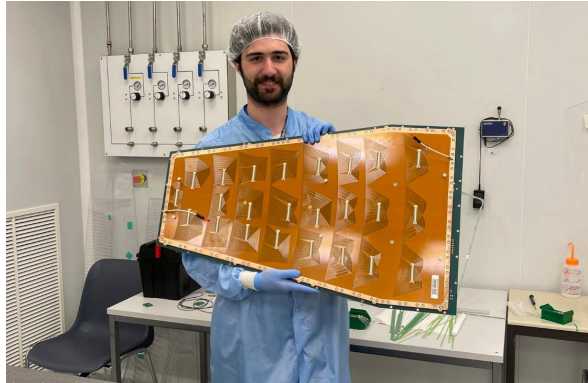


Figure 36: My first ME0 module.

6.2 Acknowledgment & Thanks

I would like to thank CERN for enrolling me in the prestigious Summer Student Program and the 904 GEM team for guiding me throughout my time working at CERN. I also give thanks to Dr. Bilal Jabakhanji and Dr. Bilel Neji as well as the American University of the Middle East for nominating me for the Summer Student Program.

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