Characterization of triple-GEM detectors for application in future hadronic calorimeters

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ABSTRACT

This report contains my work experience regarding the activities as a Non-Member State Summer Student from June, 16th to August, 8th 2025 working in the Gas Detector Development Lab (GDD) at CERN. Over the course of these weeks, I had a hands-on-work experience working on the assembly of MPGD prototypes and set up of a cosmic stand using triple-GEM detectors with double layer of readout strips, that will be used in the tracking system in the context of an *R&D* on a calorimeter with MPGD for future collider experiments, alongside my direct supervisor Anna Stamerra and the rest of the team. At the end of the program, I gained invaluable researching experience and skills on experimental physics, instrumentation and data analysis applied to gaseous detectors and MPGD technologies. Furthermore, I participated in a test beam campaign to test one of these detectors, by integrating it in the setup, collecting data and to the preliminary phase of the data analysis.

1.- Introduction

The gaseous detectors are radiation detection instruments designed to point out the presence of ionizing particles such as protons (p), electrons (e), muons (μ) through the measure of their respective physical properties such as momentum, trajectory or charge, which could be determined if a system of these detectors are used. Their main functioning principle is to use the ionizing effect produced by the incoming particle onto a gas-filled volume. The charged particle, passing through the gas, loses a small fraction of its energy producing various collateral effects, such as the ionization of the gas atoms or molecules. The resulting electrons and ions, moving in an external electrical field, cause a current flow which can be measured.

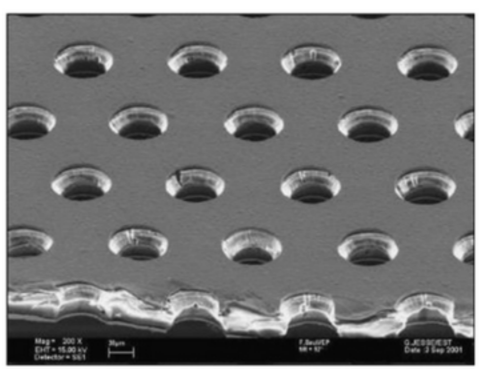

Figure 1. Electron microscope picture of a section of typical GEM electrode, 50 mm thick. The holes pitch and diameter are 140 and 70 mm, respectively. [1]

The Gas Electron Multiplier (GEM) is a thin polymer foil, metal-coated on both sides and pierced with a high density of holes, typically 50 ˘ 100 mm^2 (Figure 1). Inserted between a drift and a charge collection electrode, and with the application of appropriate potentials, applied between the two sides of the foil a high field is established within the GEM holes; electrons released in the upper region drift towards the holes and acquire sufficient energy to cause ionizing collisions with the molecules of the gas filling the structure. A sizeable fraction of the electrons produced in the avalanche's front leave the multiplication region and transfer into the lower section of the structure, where they can be collected by an electrode, or injected into a second multiplying region. Unlike other gaseous counters, the (negative) signal on the GEM's anode is generated only by the movement of electrons, without a contribution from the slow positive ions, making the device potentially very fast and minimizing space charge problems. Moreover, the low field gap between the multiplying stage and the collection electrodes reduces the probability of the propagation of a discharge to the fragile front-end readout electronics.

Further research and experimentation on this new technology led to the creation of Multi-GEM structures. As mentioned in the work *"The gas electron multiplier (GEM): Operating principles and applications" (Sauli, Fabio. 2015*, A unique feature of GEM devices is that the fraction of amplified electrons transferring to the gas gap following a first electrode can be injected and multiplied in a second foil, and again in a cascade of GEM electrodes; structures of up to five multipliers have been successfully studied. The noticeable advantage of multiple structures is that the overall gain needed for detection can be attained with each of the electrodes operated at much lower voltage, therefore much less prone to discharges.

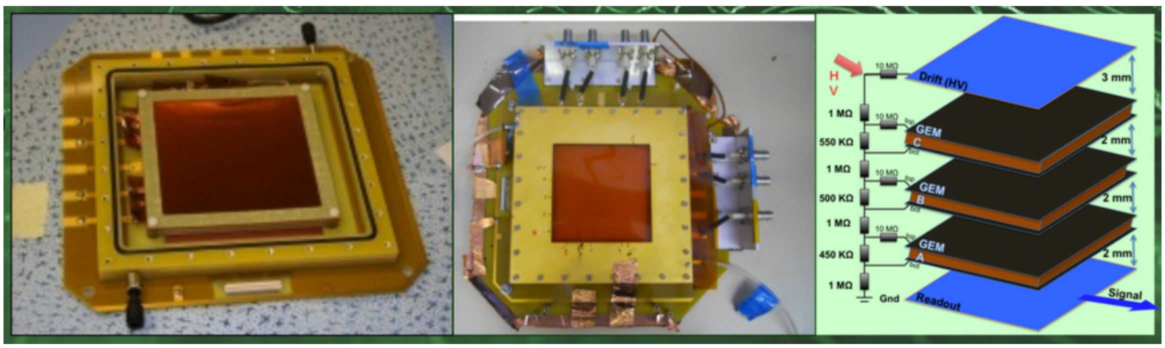

Figure 2. Schematics of a triple-GEM prototype. [1]

A Triple-GEM detector is shown schematically in Figure 2. The result of thorough optimization studies aimed at realizing detectors with high-rate capability and reliability, the device has three identical GEM electrodes and an anode separated by equally long gaps; the drift gap is 3 mm thick, 1 mm for the first transfer gap, 2 mm for the second transfer gap, and 1 mm for the induction, to ensure efficient detection of minimum ionizing tracks.

2.- Methods: My work as a Summer Student

The activities carried out within the context of the proposed objectives comprised a wide and diverse range of approaches (experimental, computational, data analysis) through which specific tasks were completed. Over the course of 2 months, I worked as a Non-Member State Summer Student at the Gas Detectors Development Group (GDD), in conjunction with my supervisor Anna Stamerra and in collaboration with the rest of the lab members, in the characterization of a triple-GEM detector. Created in the late sixties by Georges Charpak, inventor of the Multiwire Proportional Chamber and 1992 Nobel Laureate for Physics, the group has been active in the development and applications of advanced detectors for particle physics. Today, the group is led by Eraldo Oliveri.

2.a. Test on HV stability of each triple-GEM

During this stage, I was tasked with verifying the response of the triple-GEM detectors to high voltages (HV). The stability of the HV must be verified as the equipment has not been used for a long time. Moreover, its operational stability will guarantee a stable effective gas gain and prevent undesirable discharges from ocurring within the GEM.

Before proceeding, the detectors were flushed with a mixture of $ArCO_2$ $(70:30)$ gas with a flow rate of $2L/h$ to remove any presence of dirt or dust inside. Then, I proceeded to verify the integrity of the power circuit (shown in Figure 3) and the values of each resistor using a multimeter.

This circuit is composed of a low-pass filter and a simple ceramic voltage divider used to power the triple-GEMs simultaneously instead of using 7 independent HV channels. This ceramic divider comprises 7 of ohmic resistors with resistances R_i. This HV divider has an equivalent resistance of $R_{div} = 4.7M\Omega$. The current I_d through this network produces voltage drops

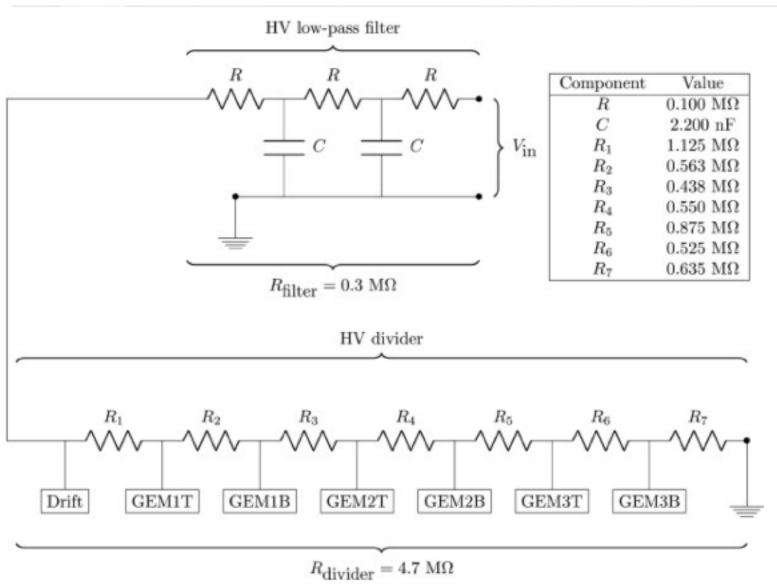

Figure 3. Schematics of Triple-GEM power circuit.

$V_i = R_i \times I_d$ across the various resistors that are used to create the appropriate electric potentials needed to power the different electrodes i of the detector. A custom low-pass protection filter (with equivalent resistance $R_{filter} = 0.3M\Omega$) connects the detector to the power supply to eliminate the high frequency noise. The total equivalent resistance of the ceramic divider and low-pass filter is $5.0M\Omega$.

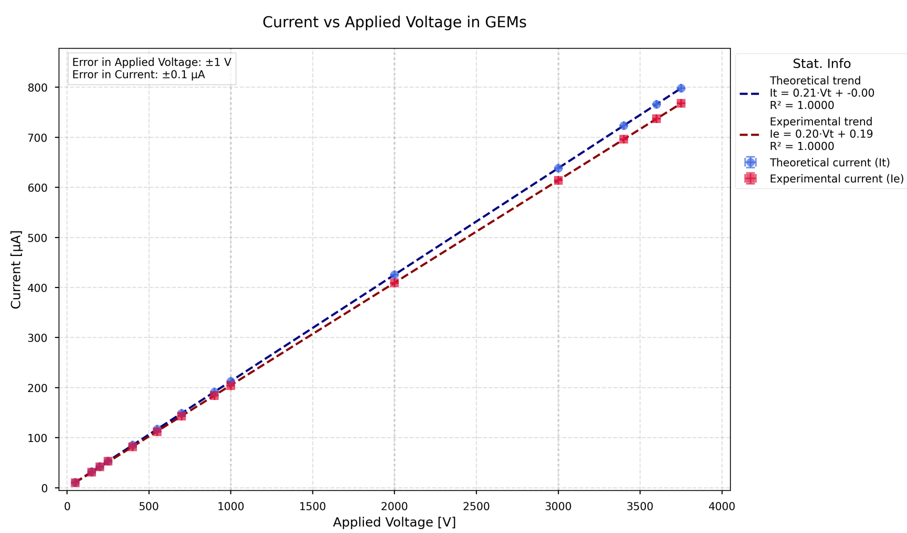

Figure 4. Divider current vs. high voltage curve for one of the triple-GEM detectors under study (red: experimental values, blue: expected values). A linear fit of the measured data points is shown.

After verifying that the experimental values of the circuit resistances corresponded to the expected values reported in previous references, a plot of the divider current as a function of the high-voltage applied was made as shown in Figure 4. The software used to monitor, configure and measure the current and voltage of the set up was *LabView*. The results of the plot indicate a clear linear dependency between the HV and the divider current, which was the expected outcome.

2.b. Measure the gain of the triple-GEMs

The effective gas gain is a crucial parameter for operating a gaseous detector in proportional mode. It is a combination of two main components: the amplification factor given by each GEM foil and the transparency factor, which depends on the fraction of the electrons that get lost because they recombine with the gas ions, attach to gas molecules or get absorbed by one of the GEM electrodes. It governs detection performance such as efficiency and time resolution, which are key parameters for successfully reconstructing detector hits associated with charged particles that traverse the active detector volume.[2]

The effective gas gain is determined experimentally by comparing the primary current induced in the drift gap by an incident, ionizing radiation after the amplification stage, with the signal induced on the readout electrode. The effective gas gain primarily depends on the operating gas and the electric field configuration inside the detector. For a triple-GEM detector, the effective gas gain is also a function of the electron multiplication factor in the GEM holes and the electron transparency of the GEM foils.[2]

The effective $ArCO_2(70:30)$ gain of the triple-GEM is measured in the central readout sector as a function of the divider current. To obtain the gain of the detectors and perform the experiment, I placed a $Fe-55$ source on top of the triple-GEM. This isotope primarily emits low-energy X-rays as a result of electron capture decay. Specifically, it decays into $Mn-55$, and the resulting $Mn-55$ nucleus is in an excited state that quickly transitions to its ground state, releasing energy as X-rays. The main characteristic emission is a pair of closely spaced K_α X-rays with energies around $5.9keV$, which will be our reference for calibrating the DAQ chain.

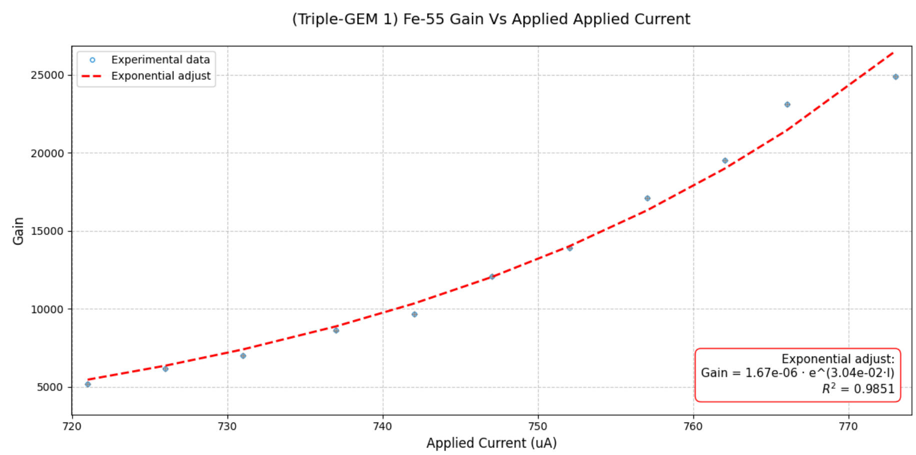

Figure 5. The effective $ArCO_2(70:30)$ gain of the triple-GEM detector as a function of HV divider current.

The high voltage values were modified within the range of 3520V to 3770V. Then, the corresponding divider currents I_d were shown again in LabView's interface. The effective gas gain G is given by the following expression:

$$G = \frac{Q_d}{Q_p}$$

where Q_d represents the deposited charge and the primary charge Q_p produced, given the source and the gas mixture, is approximately $Q_p \approx 196 \times 1.6 \times 10^{-19}C = 3.1 \times 10^{-17}C$ [3]. The detector was read only from the *OR* of the strips of one of the six connectors to minimize the noise; then the signal was amplified and digitized by a Multi Channel Analyzer Amptek's MCA-8000D shown in Figure 6.

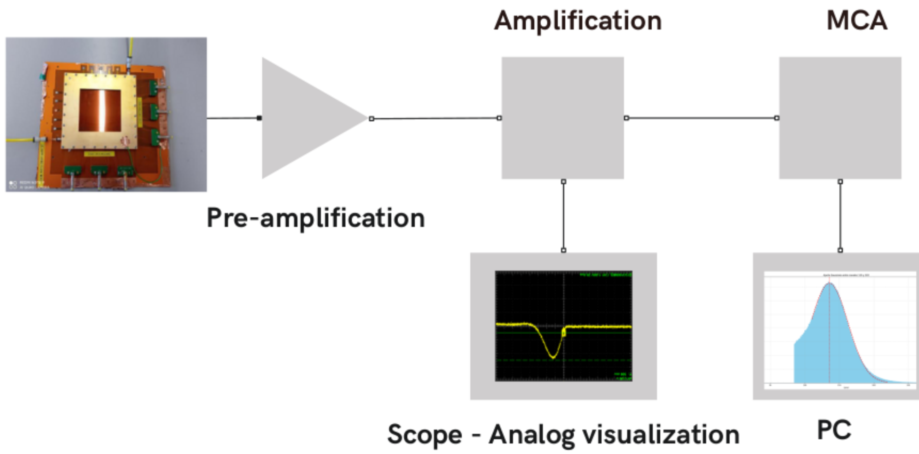

Figure 6. Schematic of the adquisition setup.

To calibrate the ADC channels, we inserted a pulse of $200mV$, found the channel at which the pulse reaches its maximum value and then calculated the deposited charge given a reference capacitance of $C = 1.2pF$. Once this is done, I created a Python script to perform a Gaussian fit to 11 histograms corresponding to the charge deposited by the Fe-55 K_α peak in the ADC channels and 11 different values of the divider currents respectivetily (Figure 5). In the plot, an exponential dependency between the divider current I_d and the gain is shown with a correlation of $R^2 = 0.9851$.

2.c. Test the detector using a muon beam from the H4 beam line of the Super Proton Synchrotron

For two weeks, we worked at the SPS H4 facility, assembling our telescope for the experiment. The H4 beam line of EHN1 is a high-energy, high-resolution secondary beam line. The maximum momentum that can be transported in the experiments is 400 GeV/c protons (primary SPS beam) or secondary mixed hadron beams within the range 10-400 GeV/c, in a variety of production angles. In our case, $150GeV/c$ muons were delivered at that time.

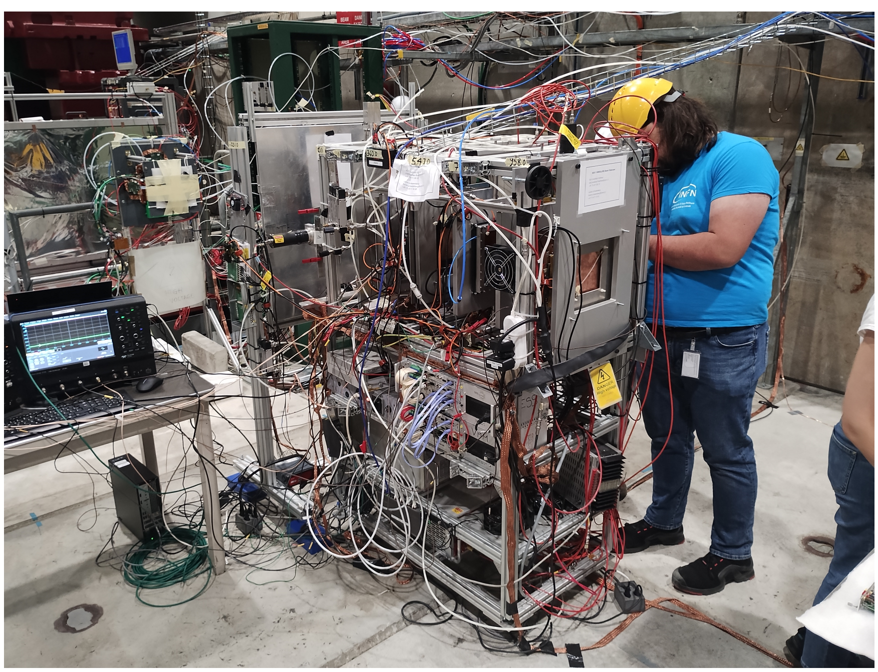

Figure 7. Setup of the DRD1 telescope at the H4 beam line facilities.

We successfully integrated one of our triple-GEM detectors within the DRD1 telescope and performed beam tests over the course of a week. Our setup consisted of four detectors: three triple-GEMs with the role of trackers T_1, T_2, and T_3, and our triple-GEM study detector between the trackers. All are filled with the same concentration of $ArCO_2(70:30)$ gas. Having completed the installation of the telescope, we proceeded to modify the HV of the triple-GEM under study in a range of $3000V$ to $3600V$ and acquire data on the spatial beam distribution in the format *.root* and *.pdf*.

2.d. Analyze the data from the test beam

During this stage, we analyze the data coming from the test beam to start the calibration of our setup. We created the mapping and clusterization algorithm using the software *vmm-sdat* and then started the pre-alignment/alignment of the trackers using the software *corryvreckan*.

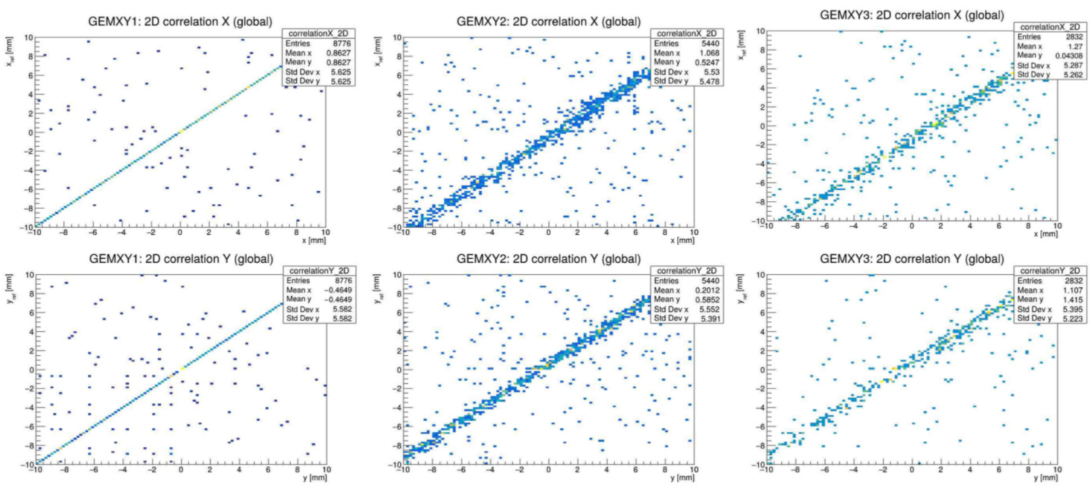

Figure 8. Pre-alignment plots for the Tracker 1 (reference - GEMXY1), Tracker 2 (GEMXY2) and Tracker 3 (GEMXY3) with respect to the Tracker 1.

Our setup consisted of four triple-GEM detectors separated by a fixed distance. The GEMXY1 is used as a reference and is placed at the coordinates $(0,0,0)$. Our detector under study was named GEMXY5 and is located between GEMXY2 and GEMXY3.

In Figure 8, I plotted the coordinates of each of the GEMXY2 and GEMXY3 trackers in relation to the position of the GEMXY1 reference tracker, showing a very good correlation on both the X and Y axes. The alignment with respect to the beam trajectory, the inclusion of the triple-GEM under study (GEMXY5) in the alignment process, and the characterization of its spatial resolution remained to be done.

2.e. Evaluate the performance of the cosmic stand in the GDD lab to integrate the triple-GEMs

As part of the experimental setup outlined in the objectives, work had to be carried out on a cosmic stand located in the GDD laboratory. Our setup consists mainly of six scintillator slabs: three upper slabs and three lower slabs. Each slab has an effective area of $(45 \times 60) cm^2$, which produces a total effective area of $(45 \times 60) cm^2 = 8100 cm^2$ in the upper and lower plates.

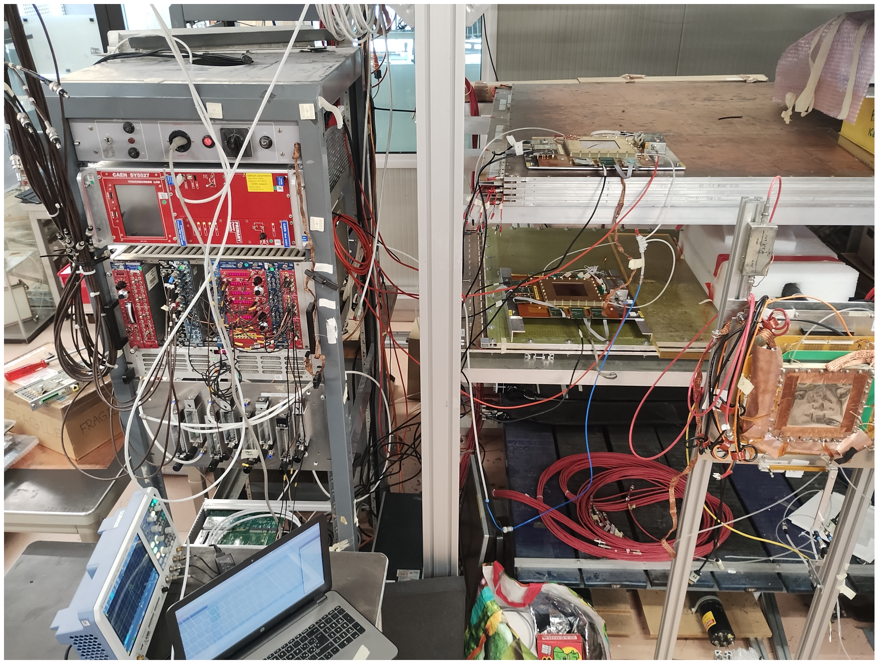

Figure 9. Cosmic stand located in the GDD Lab.

Coupled with the scintillators are PMTs, CAEN readout electronics, a digital signal display (digital oscilloscope), and a computer used to modify the voltages that power the PMTs with *GECCO2020*.

The task was to evaluate the performance of the cosmic stand prior to the integration of the triple-GEM detectors into it. Also, the setup of the cosmic stand using triple-GEM detectors with high spatial resolution will serve as a tracking system for the characterization of MPGD prototypes. To achieve this goal, we had three reference values to work with: Muon counts in the upper detector, Muon counts in the bottom detector and the counts triggered by the coincidence between the upper and bottom detectors.

The first step was to evaluate whether the acquisition electronics were working properly and turning on without problems, since this cosmic stand had not been used in a while. Once its operation was verified, we set an acquisition time of $t = 300 s$ to obtain the characteristic upper counts, bottom counts, and coincidence counts for different HV configurations in each of the six photomultipliers. For simplicity and experimental consistency, it was decided to start with a set of HV values and then decrease them proportionally by a fixed amount until a minimum working value.

Set of HV	Upper1 (V)	Upper2 (V)	Upper3 (V)	Bottom1 (V)	Bottom2 (V)	Bottom3 (V)
1	1650	2250	1850	1800	2050	1775
2	1625	2225	1825	1775	2025	1750
3	1600	2200	1800	1750	2000	1725
4	1575	2175	1775	1725	1975	1700
5	1550	2150	1750	1700	1950	1700

Table 1. PMT High-Voltages configurations for the cosmic stand evaluation.

Once the experimental data were obtained, the computational tools contained in Geant4 were used to simulate the assembly in terms of its dimensions (effective area of the scintillators, separation between the slabs, simulation of the ceiling with a phantom volume, densities of the scintillator slabs) and the properties of the injected muon shower. For simplicity, a simplified version of the Gaisser model for cosmic muons is simulated. In this simplified version, the energy distribution is proportional to:

$$\frac{dN}{dEd\Omega} = A \times E^{-\gamma}\left(\frac{1}{1+\frac{E}{\varepsilon(\theta)}}\right)$$

where a dependency on the spectral index γ and a θ (zenit angle with respect to the vertical) function are shown. Furthermore, the simulated angular distribution is proportional to $\cos^2(\theta)$ considering the altitude values at which the cosmic stand is located.[4]

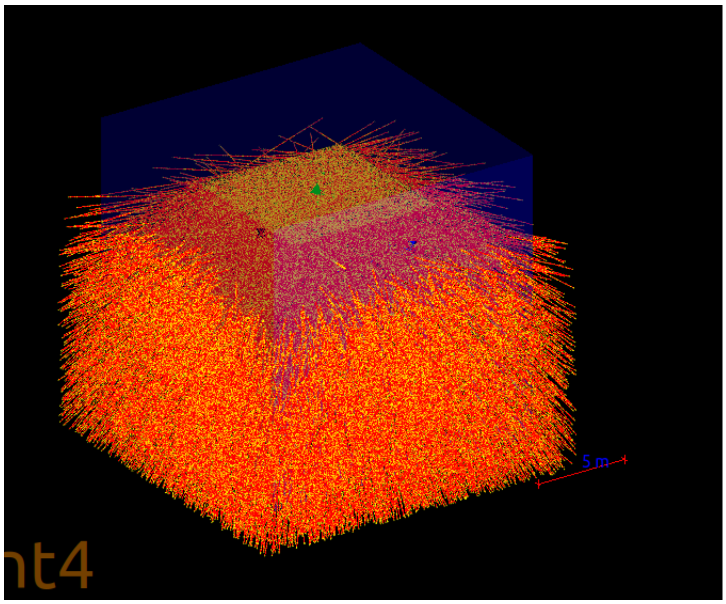

Figure 10. Simulation of the cosmic stand located in GDD lab. Shower of 150000 muons with energy distribution following a simplified version of the Gaisser's Model on cosmic muons, and an angular distribution proportional to $cos^2(\theta)$

After simulating the same rate of upper/bottom counts as the experiment shows, we obtained the number of simulated coincidence counts and plotted the results as shown in Figure 11. The most notable observation from the graph is that there is a decrease in counts (both experimentally and in the simulation) as the HV of the PMTs decreases, which is an expected result. Furthermore, it was found that "HV Set 3" yields a number of muon counts similar to what would be expected at this altitude according to the Gaisser model. However, there is a large discrepancy (more than one order of magnitude) between the simulated and experimental coincidence counts. This may be due to various reasons, such as the simulation not establishing any type of trigger to discard muons that do not meet certain energy criteria, the experiment overcounting coincidence events due to electronic noise, or simply the simulated computational model not being accurate enough to match reality in the laboratory.

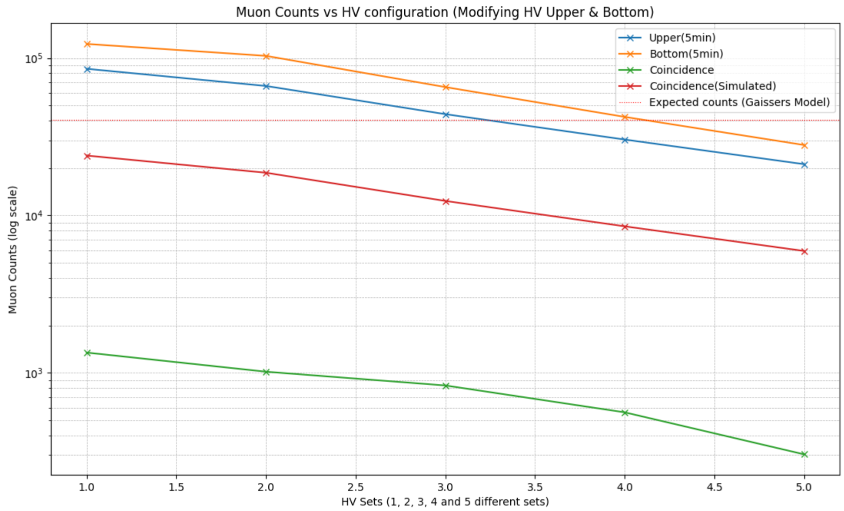

Figure 11. (b) Upper, (o) Bottom, (r) Simulated coincidence and (g) experimental coincidence counts vs. HV sets. The dotted red line represented the expected cosmic muon flux given the efective surface area ($8100cm^2$) and the exposure time ($t = 300s$).

Acknowledgements

Being accepted as a student at the CERN Summer School Program after my second attempt at applying has become one of the most important experiences I have ever had, not only from an academic and professional point of view, but also from a cultural exchange perspective. The amount of things I learned about gas detectors and nuclear physics in a short period of two months is priceless and will be part of me from now on.

One of the aspects I liked the most about my particular project was that I had to challenge myself on a daily basis to overcome the tasks presented to me. Although my training is more focused on experimentation, I am glad that I had the opportunity to step out of my comfort zone and approach the experiment from a more open and unrestricted point of view, as a physicist must do to solve problems.

I would like to thank all the members of the GDD Lab. Thanks to all the summer students who, from time to time, made me feel not that terrible when something was not working very well. In particular, I would like to thank my supervisor during my activities, Anna Stamerra, who was always there for me when I needed help in that chaotic and complex place called CERN.

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