Discharge Investigation in GEM Detectors in the CMS Experiment

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Abstract

The Endcap Muon detectors in the CMS experiment are GEM detectors which are known to have occasional discharges between layers of the detector. A less known phenomenon is a double discharge which is a second discharge initiated by the primary discharge in the following transfer gap. The probability of the double discharge was measured as a function of the electric field of the following transfer gap and found that the probability transitions from 0-100% when the field strength is between 7-10 kV/cm. An experimental setup is ready to be used to understand the physics and cause behind double discharges, and as a means to test electronics for their resistance to discharges.

1 Introduction

1.1 CERN and the LHC

Conseil Européen pour la Recherche Nucléaire (CERN) is a large physics laboratory located in Geneva, Switzerland. It aims to provide service and research space to experiments many of which are devoted to expanding the knowledge of the Standard Model of physics.

The largest draw CERN has to offer to particle physics experiments is the Large Hadron Collider (LHC) which is a 27 km circumference particle accelerator. The LHC is capable of accelerating particles close to the speed of light and crashing them together at dedicated collision locations in a hope to observe rare phenomenon, informing scientists about the Standard Model. The acceleration happens as a series of stages with the penultimate stage splitting the beam of particles into two bunches which travel around the LHC in opposite directions. In the case of proton-proton collisions (p-p) these bunches can contain up to 10^{11} particles [1].

The two main variables used to describe the condition under which the LHC operates at are the Luminosity, $\mathcal{L}$, and center-of-mass energy, $\sqrt{s}$.

The luminosity, in simple terms, is a measure of the scale of physics which you are able to observe after a period of time. When the luminosity accounts for the period of time, it is called integrated luminosity. Luminosity is dependent on the number of particles in each bunch, n_1 and n_2, the frequency of bunch crossings, f, and the transverse beam profiles σ_x and σ_y:

$$\mathcal{L} = f\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

Integrated luminosity is often expressed in units of inverse cross-section at a very small scale, fb^{-1}. When is multiplied by an interaction cross-section this gives you an expected number of events which will have occurred.

The center-of-mass energy is quite simply the energy of the p-p collision which is only dependent on the mean energy of the particles in each bunch, E_1 and E_2:

$$\sqrt{s} = \sqrt{E_1^2 + E_2^2}$$

Currently the LHC is in the middle of run 2 which will provide CMS and Atlas with an expected integrated luminosity of around 100 fb^{-1} at a center-of-mass energy of 13 TeV [2]. The LHC will undergo a shut down in the coming years to increase the capabilities of the accelerator leading to higher collision energies, and greater luminosity. The result of this is the ability to probe rarer physics processes, however care must be taken to ensure detectors are capable to cope with the more energetic and frequent collisions.

1.2 CMS

One of the experiments at CERN is the Compact Muon Solenoid (CMS). Think of it as an inward facing camera which is focused on one of the collision points of the LHC. This "camera" is watching the products of the p-p collisions, and reconstructing the events in the hope to observe rare interactions. The reconstruction is done by using a layered series of detectors as shown in Figure 1

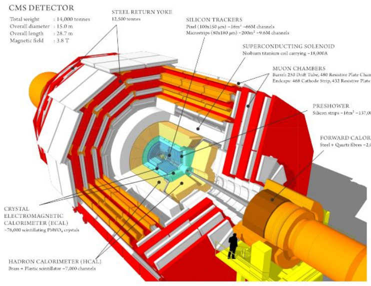

Figure 1: Diagram of the CMS Detector with the main areas labeled. Figure from [1]

The focus of this project is on the Endcap Muon Chambers which are responsible for detecting, characterizing the energy, and tracking the trajectories of muons released as a product of the p-p collision. Already there has been an observation of electric discharges in the muon detectors currently installed which have a risk for damaging the VFAT readout electronics. As mentioned, the LHC is undergoing an upgrade to increase the luminosity, meaning that all detectors will be exposed to higher levels of radiation and high energy particles. The issue of the observed discharges damaging the long term operation of the detector will only become more serious with this upgrade.

1.3 GEM Technology

CMS Endcap Muon detectors are Gas Electron Multipliers (GEMs) which work as proportional counters, meaning the final output signal is a multiple of the initial deposited energy. The working principle is that a particle entering the detector will ionize the gas, creating free electrons. These electrons are then exposed to an electric field with varying intensities causing them to collide with other gas atoms, ionizing those atoms, which in turn will repeat the ionization, resulting in an avalanche effect. The large number of electrons reach the bottom readout plate and are measured as a signal. A schematic of this detector is shown in Figure 2.

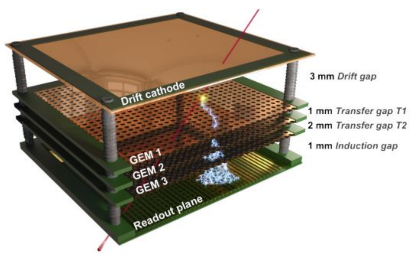

Figure 2: Schematic of the GEM detector showing a mock avalanche effect from an ionizing muon. Figure from [1]

The GEM detectors are triple GEMs which means that they have 8 nodes; drift, the top and bottom nodes of each of the three GEMs, and the readout plane. A high negative voltage will be applied to the drift plate after which a voltage divider circuit is constructed to apply varying voltages to each node. The voltage gradient in the detector causes negative charges to accelerate towards the readout plane. The GEM plates themselves resemble Swiss cheese with patterned holes through a very thin (50 μm) plate. The small distance between the top and bottom of the GEM foils result in a very high electric field, of order 80kV/cm, which is where most of the electron multiplication occurs. Figure 3 shows the spacing and electronic connections in the GEM detector.

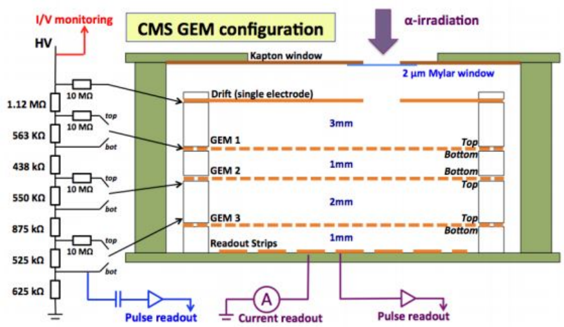

Figure 3: Diagram of the GEM detector showing the spacing and voltage divider circuit to cause the strong electric field. Figure from [1]

The multiplication factor is called the gain, G, of the detector:

$$G = \frac{I_{out}}{I_{in}}$$

Where I_{out} is the current leaving the detector from the readout plate and I_{in} is the initial current deposited in the GEM. I_{in} can be thought of as the number of initial free electrons as a result of the ionizing energy coming from the incoming particle (to detect). This effective current is how much charge is moving into the detector per second:

$$I_{in} = \frac{R * E * q_e}{W_i}$$

Where R is the rate of the incoming particles, E is the mean energy deposited by each particle, q_e is the charge of an electron, and W_i is the average ionization energy of the gas in the chamber.

Electronically, there were two ways to detect particles in the system. The Pulse Readout system was configured to the GEM 3 Bottom plate.

As a cascade of electrons passes through the detector, the sudden increase in negative charge in close proximity to the foil causes electrons to be repelled which is measured as a negative pulsed peak. The signal is sent through an ORTEC preamplifier before being sent to a discriminator and counting electronic system. Counting the number of peaks gives the number of cascades, and therefore the rate of the incoming particles R. The second way to measure particles in the system is to measure the current coming out of the readout board which was done simply with a Keithley pico-ammeter.

2 Project Goals

This project focuses on properties and conditions of discharges in GEM detectors, and will hope to provide a set up for potential solutions to the discharge problem to be tested. Discharges are a release of electrical potential that occurs between the two sides of a GEM foil through one of the holes, which can be thought of simply as a spark. These discharges have the potential to cause damage to the readout electronics of the detector, as well as providing a source of noise resulting in lost data.

3 Calibration

To accomplish the understanding of the discharges in GEM detectors, a small 10cm x 10cm prototype detector was chosen for its ease of use, and relatively low cost. The structure of the detector inside is equivalent to those used in the GEM detectors in CMS, however for this test detector windows were cut in the shielding to allow for alpha particles to penetrate into the detector when a source is placed on top. A picture of the detector is shown in Figure 4.

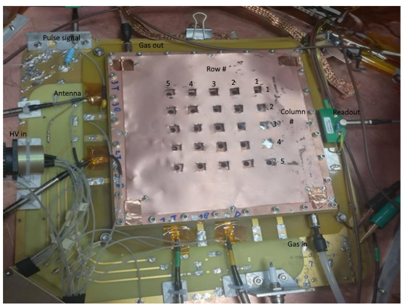

Figure 4: Picture of the 10x10 Prototype detector in the Faraday cage box. Source location numbering convention is labeled. Also pictured at the gas input and output, 4 antennas, readout, and high voltage input. Shown here is the multi-channel high voltage power supply set up

The first step in using any detector is to understand its behaviour and ensure that it is properly calibrated. With GEMs in the CMS group this is done procedurally by having detectors undergo Quality Control tests (QCs).

For this detector, there were many issues with QC4, which is the high voltage test. During this test, the detector is filled with safety gas (CO_2), to prevent the cascade discharges, and high voltage is applied to check for spurious discharges in the detector which might indicate a physical problem (such as a poor connection between a plate and the electronic circuit). This gives a controlled environment to burn off any contaminants, such as dust, which may have entered the detector area during construction. The issue for this detector was that the detector would consistently discharge at currents lower than the maximum QC4 currents, specifically around 600-700 μA which corresponded to 3-3.5 kV. Two tests were designed and executed in a hope to uncover which node was problematic.

The first test was to short half the circuit above a given resistor to the same high voltage, and all of the circuit below the node to ground, in order to isolate the potential difference to be only between two nodes. The circuit used is shown in Figure 5 (Left) with the shorting connections moving between tests. We were able to operate the detector at high current, up to 900 μA, while still staying at relatively low voltage. This test gave the relative operating voltages across resistors to see if discharges were occurring between adjacent nodes. All resistors passed this test which meant that the issue we were having before was between a node and ground, or between a node and a non-adjacent node.

The second test was to again systematically short half the circuit above a given resistor, as shown in Figure 5 (Right). This left the rest of the nodes below the short to achieve their operating voltages when appropriate current is applied, while leaving the circuit above at lower than operating voltages. The results from this test were that all nodes up to G1Top were able to make it to their operating current (and therefore voltage) of 900 μA while G1Top only achieved 830 μA before discharging, which corresponded with around 3.4 kV potential for it, and the drift board.

The conclusion drawn from this was that the issue must be with the drift board since all other foils were able to achieve voltages higher than that at which they were when the detector would discharge in the original QC4 test. The Drift was subsequently substituted for a new drift board and the detector passed QC4.

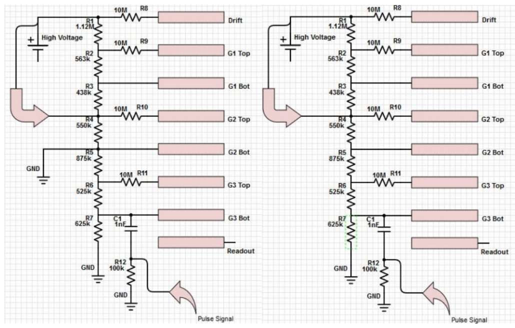

Figure 5: Circuit diagram of the two tests implemented to discover the problematic node. The first test (left) to see whether the issue was caused due to discharging between adjacent nodes or between GEM gaps, the second test (right) to determine if the issue was between a node and ground.

To determine the threshold for counting particles with the pulse readout system, a Multi Channel Analyzer (MCA) was attached to the pulse readout and the detector was irradiated with an ^{55}Fe source. The MCA produces a histogram binning events into channels corresponding to voltage values, which in turn correspond to an energy value from the source. Since the gamma energy from ^{55}Fe is well known, we were able to calibrate our threshold on the discriminator to only count events above background.

We were curious about the gain of each hole in the screen to be able to make informed decisions about source placement for future tests. We used the MCA with the ^{55}Fe source to measure the relative gain of each source position by finding the mean channel of main peak. This was done by finding the bin number of the maximum value of the gaussian fit applied to the MCA data as shown in Figure14. Due to low counts resulting in high error on some data points, it was decided to retake data for some of the positions. An apparent increase in gain was noticed as shown in Figure 6 which was inconsistent with the previous measurement for the retaken positions.

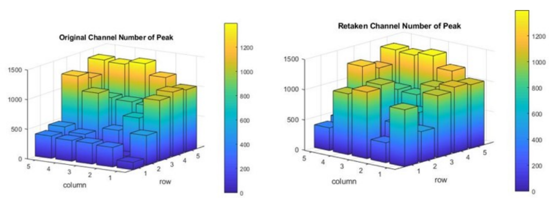

Figure 6: Mean MCA peak number originally and with retaken data points. All data points have been offset by 3000 channels to highlight the differences between positions

A series of tests were conducted to highlight a number of potential factors which may have changed between the first and second measurements. The first variable tested was the orientation of the source sitting on the detector window. The effect this may have had was increasing the pressure of the gas inside the detector which in turn affects the gain [1]. The second variable was the frequency of the source irradiating the detector which was controlled by the slight variance in position of the source over a hole. The length of time which a hole had been irradiated by the source was the final parameter to be tested. The conclusion of the tests was that the responsible factor was a charging up effect which happens when the ions in the gas drift towards the surface of the kapton in the GEM holes [1]. This conclusion was drawn from the results of the time test which is shown in Figure 7.

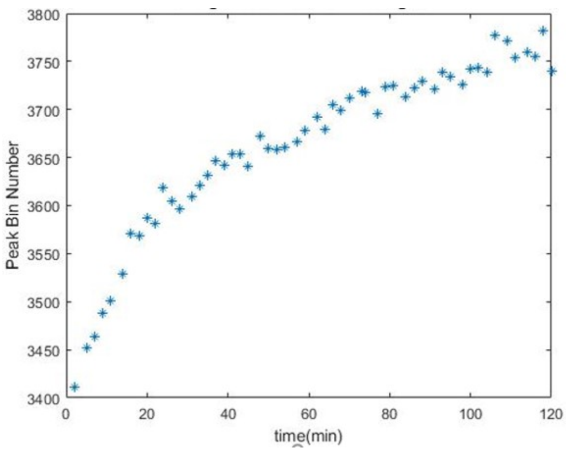

Figure 7: Mean MCA peak number as a function of time the detector has been exposed to the source. The cause for the increase in gain is known to be charge buildup as discussed in [1]

4 Findings

Once the behaviour of the detector was well understood, work began to understand discharges. The discharge probability of the detector with the standard voltage divider was measured at varying gains and is summarized in Figure 8. The detection of a discharge was accomplished by attaching antennas to the leads attached to the Drift and three GEM top nodes. The antennas pick up on a sudden change of magnetic field which is caused by the high current, such as that present in a discharge.

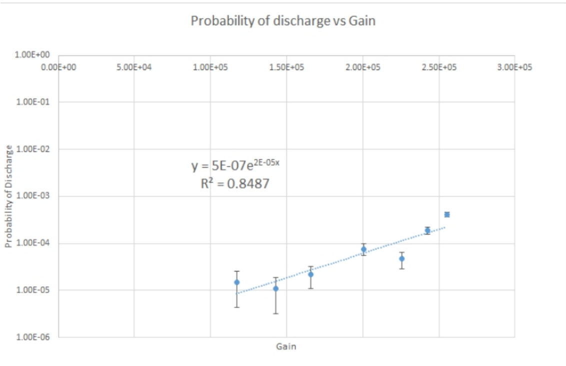

Figure 8: Probability of a Discharge as a function of the gain of the detector

In order to have a controlled discharge in a GEM foil of our choosing as will be required for the future tests, the gain across one GEM foil (we selected GEM3) was to be doubled. This was accomplished by building a voltage divider circuit with the same resistances as the compact voltage divider, with the flexibility to change resistance values. The resistance value added was determined by using a study of of gain vs. applied voltage across a single GEM foil performed by another group in the lab with their results shown in Figure 15.

An observation of occasional double discharges is cause for concern since the second discharge is between the bottom foil of the first discharge across the gap to the top of the next foil. The concern comes when the second discharge is to the readout board since this node is connected to the data collection electronics. A sketch of the double discharge phenomenon is shown in Figure 9. To better understand discharge propagation and to be able to test potential mitigation strategies, the primary discharge is designed to occur in GEM3 with the propagated discharge in the induction gap.

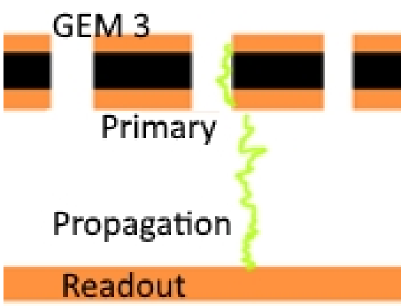

Figure 9: Sketch of a double discharge occurring in the detector showing the first discharge from GEM3 Top to GEM3 Bottom followed by a propagated discharge from GEM3 Bottom to the Readout

To be able to measure and count double discharges, additional electronics were required in the NIM system. The raw signal from the antenna is connected to a discriminator which outputs a logic pulse indicating a discharge. The settings on the discriminator were set such that the integration time setting and threshold value were to be at such a value so that a single pulse from an antenna could not double trigger the discriminator. A capture of the raw data signals on the 4 antennae is shown in Figure 10. The logic signal was split into two paths, with one path connected directly to a counter which serves a purpose as an "all discharge" count, A, while the other path begins a 100 μs timer on a dual timer module. When the timer finishes, the end marker signal is sent to a second channel on the counting module with this channel's purpose being the "initial discharge" count, I. The number of double discharges, D was simply the difference between A and I and the number of single counts was the difference between D and I. The double discharge probability is the ratio of D/I.

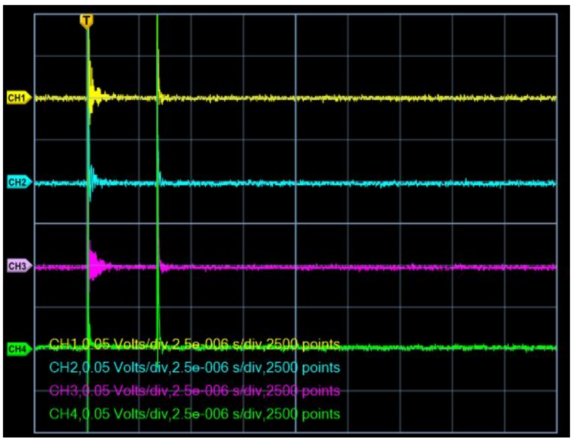

Figure 10: Screen capture of a double discharge viewed on a Tektronic 2024C oscilloscope showing all antenna channels

As previously determined by other experiments, one of the most important variables which result in a double discharge is the electric field strength of the gap immediately after the GEM where the primary discharge occurred [3]. For this reason the electric field strength in the induction gap was varied and the double discharge probability was measured with results of two different source locations shown in Figures 11 and 12.

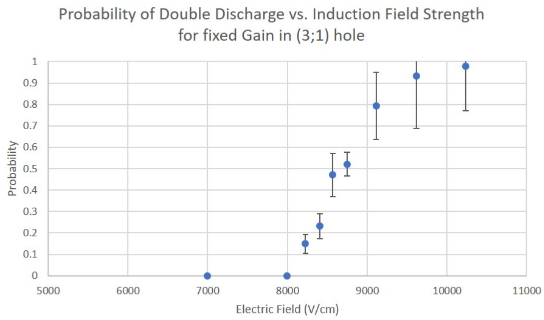

Figure 11: Double discharge propagation probability as a function of electric field strength at source location 3;1 along the edge of the detector

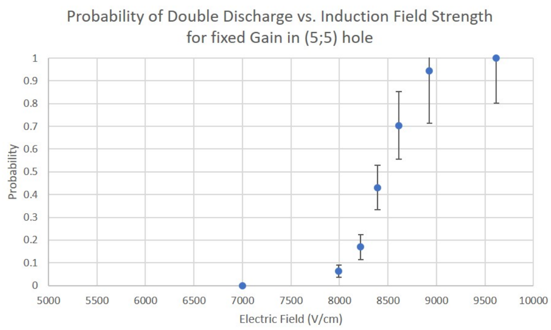

Figure 12: Double discharge propagation probability as a function of electric field strength at source location 5;5 at a corner of the detector

It was noticed that between the two source locations the behaviour of the probability curve is different. The reason for this is not well known, however it is speculated that this may be due to separation variations between GEM3 and the readout node which can cause large electric field differences.

5 Conclusion

A prototype GEM detector setup was created to induce discharges in a controlled manner. The phenomenon of double discharge, a single discharge between layers of a GEM foil propagating to the subsequent layer, was observed and the probability was measured as a function of electric field strength. This setup is ready to be used as a means to test potential VFAT electronic readout boards and their response to discharges in the GEM detector. Additionally, the setup will be used to test under which specific conditions double discharges occur, and if there is a way to potentially reduce their likelihood further mitigating the potential for damage in the CMS muon detectors.

6 Acknowledgements

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References

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[2] CERN, "Lhc 10 year schedule," Available at http://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-schedule-update.pdf.

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Appendix: Supplemental Tables and Figures

Orientation	Mean Bin
North	3802
East	3740
South	3504
West	3582

Table 1: Results of the orientation of source on the mean bin number measured by MCA

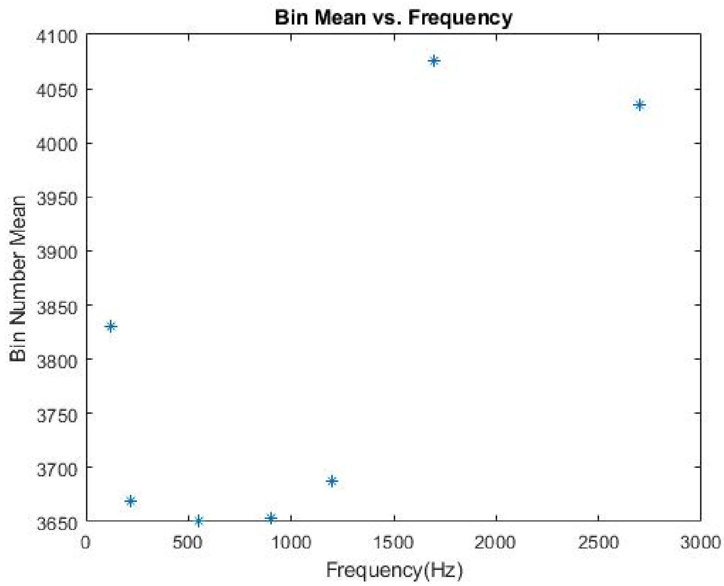

Figure 13: Results of the effect of frequency of the source on the mean bin number measured by MCA

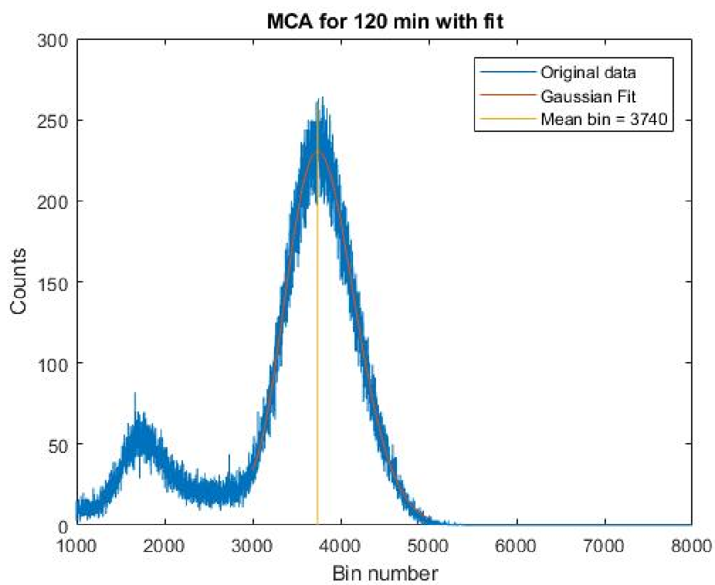

Figure 14: Example of an MCA plot with Gaussian fit applied to the main peak. This plot was taken from the analysis of the effect of charging up time vs. mean bin value. The two peaks correspond to the 5.9 keV ^{55}Fe X-ray and the Ar escape peak

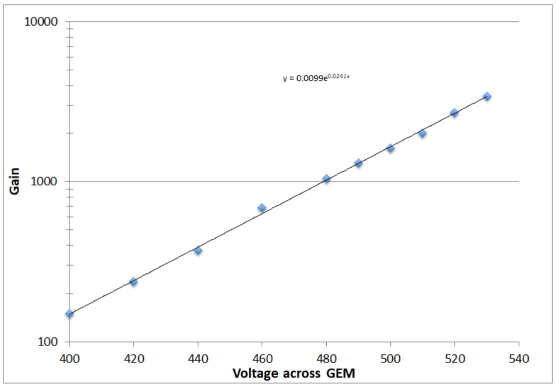

Figure 15: Gain as a function of voltage applied across a single GEM foil