SIMULATION OF CHARGED PARTICLE DETECTORS FOR FUTURE UPGRADES OF THE CMS EXPERIMENT AT THE LARGE HADRON COLLIDER

An Undergraduate Research Scholars Thesis

by

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TABLE OF CONTENTS

ABSTRACT

Simulation of Charged Particle Detectors for Future Upgrades of the
CMS Experiment at the Large Hadron Collider

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The Gas Electron Multiplier (GEM) is a gas based detector used to detect charged particles in high-energy physics applications. It amplifies signals related to particle interaction within a detector and provides high gas gain, detection efficiency and time resolution. Layers of GEM are expected to be installed in the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) at CERN. This research aims to optimize GEM operation and efficiency by comparing the effect of two different etching techniques-- double mask and single mask—on the detector gain. In the double mask technique, a standard GEM foil is manufactured with photoresist laminations on the upper and lower copper layers. A new manufacturing process called the single mask was developed to improve detector gain. Better structural uniformity is attained in this case as only one of the copper layers are chemically etched. On the other hand, this results in an asymmetrical double-conical hole shape instead of the symmetrical one resulting from the double mask manufacturing process. In this project, we will explore the impact of different hole diameters on the GEM efficiency and gain by simulating detector conditions using a combination of three software tools HEED, ANSYS, and Garfield++.

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NOMENCLATURE

CERN	European Organization for Nuclear Research
LHC	Large Hadron Collider
HEP	High energy physics
CMS	Compact Muon Solenoid
GEM	Gas Electron Multiplier
MPGD	Micro-Pattern Gas Detector

CHAPTER I

INTRODUCTION

The work performed by this team contributes to the studies by the European Organization for Nuclear Research (CERN) to better understand the fundamental particles that make up our universe. The team in Qatar is part of the CMS team, an international scientific collaboration bringing more than 2000 scientists to work together.

CERN

CERN is a French abbreviation which stands for the European Organization for Nuclear Research. It was founded in 1954 and it is located near Geneva in the Swiss-France border. CERN is known to be the largest particle physics laboratory, where it has 22 member states and over 11,000 scientists from all over the world working together [1]. Due to the amount of data that needed to be transferred and shared between scientists, in 1989 the World Wide Web was invented in CERN. It was created solely as a server to share files for scientists in CERN but the impact of that creation is global. Furthermore, Scientists in CERN get to access and work on the accelerator machinery such as the LHC and particle detectors on it.

Large Hadron Collider

The Large Hadron Collider is the biggest particle accelerator with a circumference of 27km. In the LHC the particles are accelerated with an energy up to 7 TeV in two opposite directions, in order to produce proton-proton or heavy ion collisions. The acceleration of particles happens in a clockwise and an anticlockwise direction, where the particles collide at four different locations in the LHC. The collision points are CMS, ATLAS, ALICE, and LHC-B. Each collision point is an experiment on its own with different detector technology used. The purpose of the experiments is to discover new particles and shed light on unexplained physics phenomena. In 2012, CERN made history, where both CMS and ATLAS announced to the world about observing a new particle that resembled the Higgs Boson, which was predicted by the standard model theory [2]. This discovery provided more proof to the incomplete standard model theory.

CMS Experiment

The Compact Muon Solenoid is one of the largest experiments at CERN. CMS is about 100m underground and it is located in the French side of the LHC. The detector is called "Compact" since it is very dense with detector material, as it weighs 14,000Ton – which is double the weight of the Eiffel tower— with a diameter of 15 meters and a length of 21 meters [3]. Moreover, the reason for the second word "Muon" is because CMS is designed to accurately detect muon particles, which are known to be very hard to detect. The third word "solenoid" is because CMS has the strongest solenoid magnet in the world, where it provides a uniform magnetic field of 3T [3]. The magnet is located in the barrel region which is in the middle of the detector. The detector technology in CMS is consisted of calorimeters, the tracking system, and muon chambers

Muon Chambers

Muons are charged particles that resemble the electrons but with a much greater mass. The Muon chambers are located at the outermost part of the detector, outside of the magnet, since muons surpass the inner layers without stopping or deviating. Muon detection is crucial since they appear in the final state of most of the interesting rare events we are looking for.

Gas Electron Multiplier

The Gas Electron Multiplier (GEM) is a gas-based detector, which means that it relies on the ionization of gas particles in the detector as a result of collisions with an external charged particle that enters the detector to detect that particle. Their utility lies in their ability to amplify the signal produced due to particle interaction with the gas inside the detector. As a result, the GEM detector is a strong candidate to be installed in the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) at CERN in the next Long Shutdown. The manufacturing process of the GEM has been the focus of this study due to the effect that geometry alterations might have on the detector's operation.

The GEM consists of a thin Kapton foil (about 50 μm), cladded on both sides with copper layers (of about 5 μm) and a high density of hexagonal holes (of about 70 μm diameter). Resistive ceramic divider, with a single source of voltage, is used to provide this voltage across the drift and the GEM foils. Single electron entering the hole will gain sufficient kinetic energy and produce an avalanche. For further amplification, for example, in the triple GEM, three GEM foils are stacked at relatively small distances to provide additional stages of amplification. Gas gap in the triple GEM detector used is 3/1/2/1 mm for the drift, transfer 1, transfer 2 and the induction gaps respectively, as demonstrated in Figure 1. The gas mixture used is Ar/CO_2 70/30% or $Ar/CO_2/CF_4$ 45/15/40% [4].

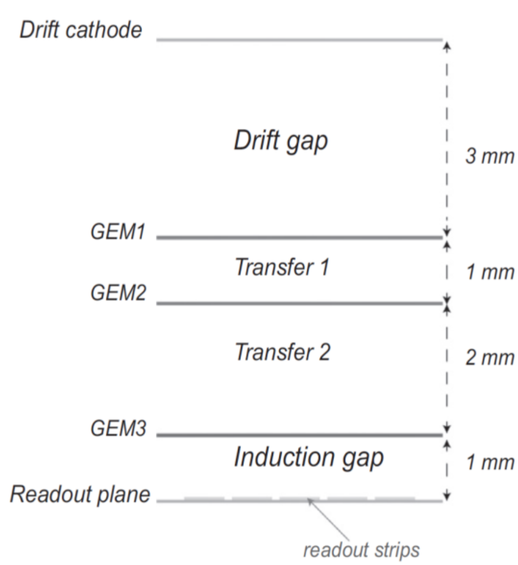

Figure 1. Geometry of detector based on three layers of Gas Electron Multiplier.

Single Mask and Double Mask

The standard manufacturing process for the GEM has been the double mask technique, which involves applying photoresist laminations to both the upper and lower copper layers. UV exposure is then used to transfer the GEM hole pattern. The outer holes in the copper are then used as a mask for the chemical etching of the inner kapton layer. This results in a symmetric double-conical shape of the holes. The single mask technique was developed as a result of this need. One mask is applied in this case, and both the kapton and other copper layer are chemically etched according to the initial hole pattern due to the single mask [5]. The effect of using the single mask is different hole diameters on the upper and lower sides of the GEM. Two configurations of the GEM were identified, where configuration A exhibited a larger upper hole diameter than B.

The effect of using these two configurations is different effective gain. Gain is defined as the number of electrons produced through primary and secondary ionizations due to the detection of a single muon divided by the number of primary ionizations. Higher gain ensures that the signal will be amplified, as shown in Figure 2, and consequently, easily detected at reading strips. As a result, studying different combinations of configurations A and B for the triple GEM setup will support the decision to be made at the installation.

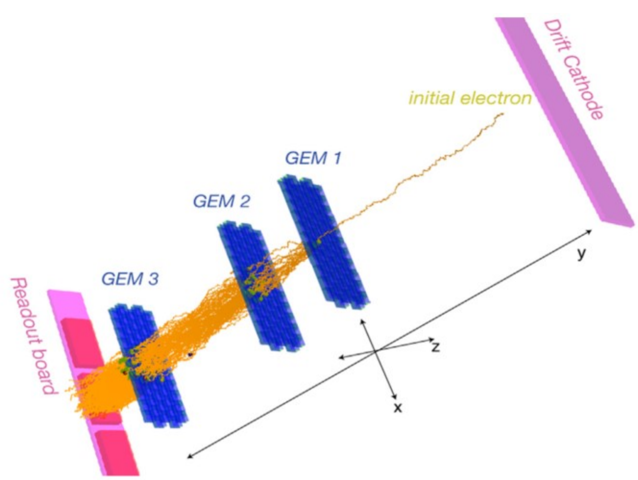

Figure 2. Electron avalanche showed in triple GEM.

CHAPTER II

METHODS

To complete these important studies, three main software were used: HEED, ANSYS, and Garfield++. ANSYS was used to define the detector geometry and compute the electromagnetic field map throughout the detector. That map was then used along with the output from HEED, as an input to Garfield++. The ultimate output of this simulation process is the gain, or the average number of electrons produced due to ionizations per primary ionization. In order to compare the different manufacturing processes of the GEM, three main configurations were defined for every simulation: double mask, single mask orientation A with the wider hole on the top, and single orientation B with the wider hole on the bottom.

ANSYS

ANSYS is a computational fluid dynamics package based on Finite Element Method [6]. The detector geometry is first built using basic volumes, including blocks, cones, and cylinders. ANSYS also allows the user to define the materials and set their attribute. The voltages are then applied to the surfaces of the GEM according to the high voltage divider. The high voltage divider is the method used to provide the correct voltage to the drift cathode and upper and lower copper layers of every layer of GEM. Accordingly, ANSYS proceeds to compute the electromagnetic field at different points of the detector, knowing the voltage boundaries and the gas composition (Ar: CO_2 / 70%: 30%).

To obtain an electromagnetic field map, ANSYS divides the entire detector into a mesh, whose elements are 10-node tetrahedral, defined in ANSYS as SOLID123 [7]. The electromagnetic field is then found at each node of each of these element, and the fineness of the mesh can be set by the user. Finally, ANSYS displays the solution in the form of four lists of the elements, materials used by the program, nodes and their positions, and the potentials calculated at every node.

Garfield++

The list files, obtained from ANSYS, are then used in Garfield++, which employs Monte-Carlo simulation methods to simulate the interactions of the electrons as they are produced and flow through the detector, ionizing more gas particles on the way. Garfield++ uses Magboltz to calculate the electron properties as they interact with the gas in the detector [8,9]. It can then conclude how many secondary ionizations may result from each primary ionization, the average of which is what we consider the gain of the detector. In general, the aim is to maximize this gain to minimize the chances of confusing the detection of a particle like the muon with background noise.

The way the primary ionizations were simulated in Garfield++ is by using a random function to generate the initial position of the primary electron in the drift gap, which is where the muon is expected to have its first interaction with the gas inside the detector. The randomization happens in all dimensions x, y and z. To minimize the margin of error and ensure that the simulation is more representative, several thousand electrons were randomly generated for each simulation. For a single layer of GEM, referred to as single GEM, the regular number of events, or electrons, simulated was 10,000. For three layers of GEM, referred to as triple GEM, the number of events simulated was usually 1,000 to 5,000 because these simulations usually lasted from four days up to a week. For every study of both single and triple GEM, the simulations were repeated systematically for double mask and single mask, orientation A and orientation B. The gain obtained from Garfield++ was then graphed as a function of the studied parameter to compare these different configurations.

HEED

HEED is a software tool that can simulate charged particles passing through a medium, and compute the energy loss by taking into account the collisions between the atoms [10]. This program is perfect for simulating a real charged particle passing through the GEM detector. It shows how many primary electrons would be produced and the number of clusters per cm. The geometry of the GEM from ANSYS is used as an input to HEED. Then, the output of HEED, the number and position of primary electrons is the input of Garfield++. Thus, instead of using the random function to generate random electrons, HEED simulates the actual primary electrons, which makes the simulations more realistic. This is further explained through the results comparing the outputs of HEED and Garfield++ in the Results section.

RAAD2

In order to obtain reliable results from all of the programs used, the simulation needs to be reiterated several thousands of times. This would require a huge amount of computing power and memory to store the data, and thus a supercomputer is used to speed up the process. The supercomputer used is RAAD2, the supercomputer of Texas A&M University at Qatar. RAAD2 consists of 4128 Intel Xeon CPU's. RAAD2 has 4,000 of these CPUs making RAAD2 much stronger than any consumer computer. With that great computation power, there must be a huge storage capability. The sum of the hard disks attached to RAAD2 is equal to 1PB disk storage, 1024 Terabytes of storage to clarify. With these in conjunction with each other, it allows for 172 computer nodes, making 172 jobs in parallel. SuSE Linux is used to navigate the supercomputer and submit jobs through slurm workload manager [11].

GEM Studies

Two studies were performed for single GEM using the aforementioned simulation tools and one study was performed for the triple GEM. Previous studies have revealed that the factors affecting the GEM performance the most are the size and shape of the GEM holes, the electric field in the gas gaps, and the potential difference applied across the GEM layers. Since the variation in hole size is already represented in this study by considering double mask and two orientations of single mask, the two main studies performed for single GEM are the study of gain against electric field in the drift gap and against the potential difference across that GEM layer, called V_{GEM}.

In triple GEM simulations, the study was performed by varying the high voltage, which is the voltage applied to the drift cathode as shown in Figure 3. The voltage divider, which is based on resistive ceramic, is the method employed to apply the required voltages to each layer in the GEM detector as required. The variation of the high voltage leads to a variation in all the subsequent voltages according to this set up. Therefore, voltage sets were used for each simulation.

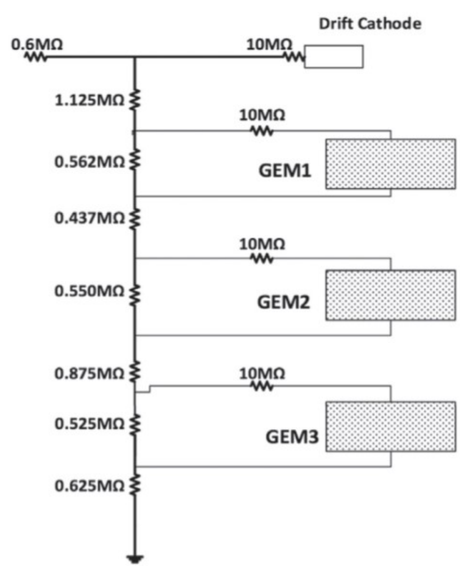

Figure 3. Triple GEM high voltage divider setup.

CHAPTER III

RESULTS

The gain obtained from each simulation was recorded, and graphs were produced to compare the effect of each configuration on the performance of the GEM detector.

Single GEM

When studying the effect of the electric field in the drift gap, the electric field (in kV/cm) was varied while keeping a constant V_{GEM} of 350 V. Similarly, while studying the effect of V_{GEM}, E_{drift} was held constant at 1.3 kV/cm. Figures 4 and 5 show the gain in single GEM plotted as a function of the electric field in the drift gap (E_{drift}) and the potential difference applied across the GEM (V_{GEM}), respectively.

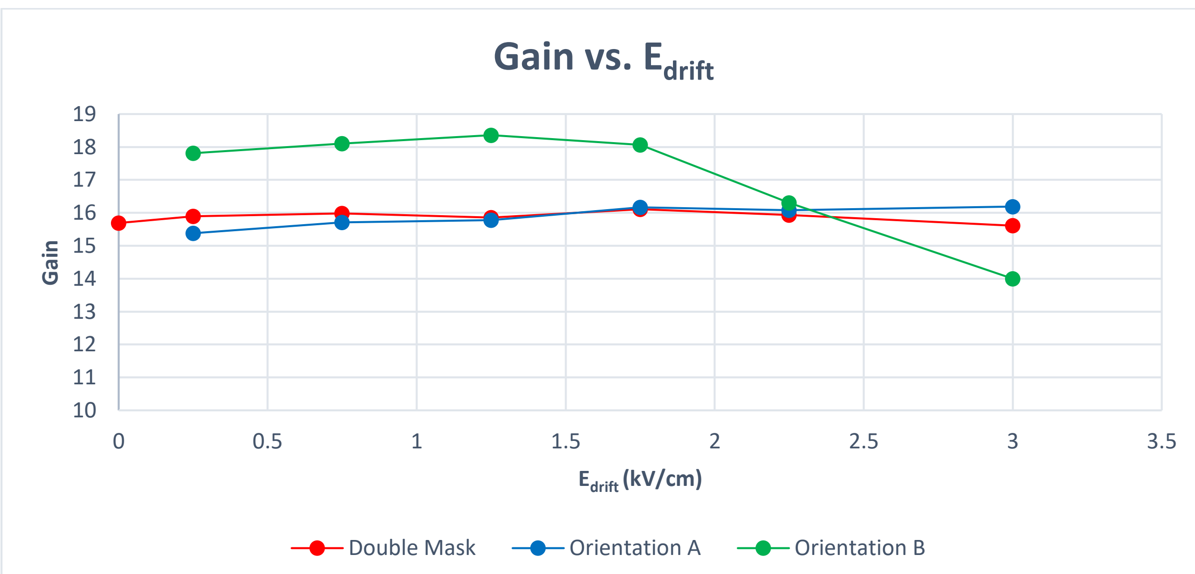

Figure 4. Single GEM: gain as a function of E_{drift}

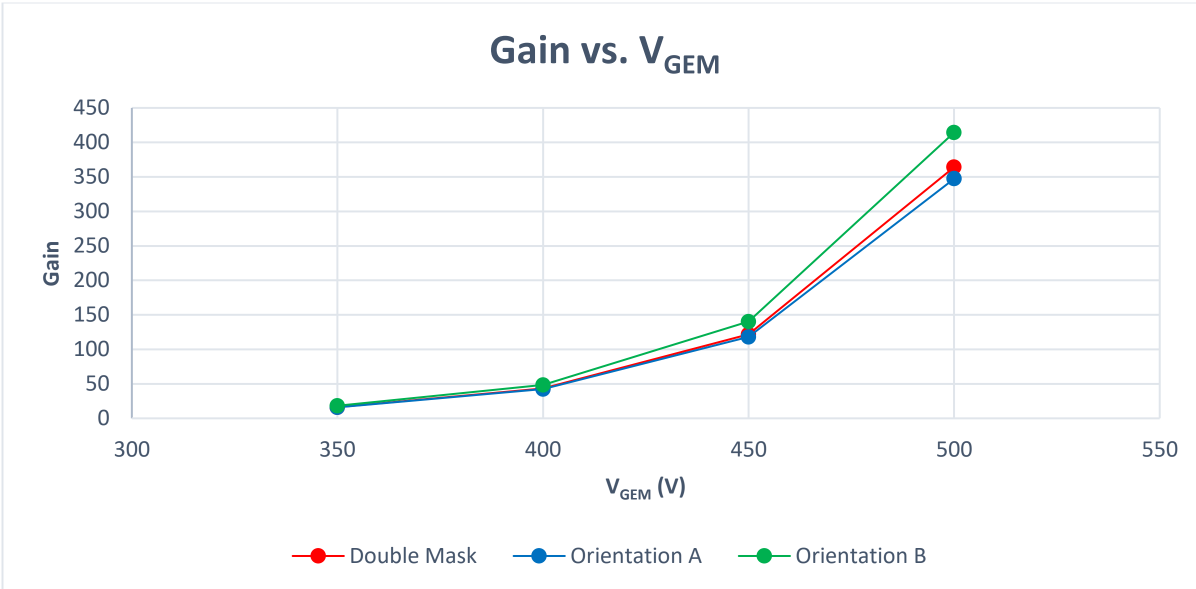

Figure 5. Single GEM: gain as a function of V_{GEM}

In both studies, orientation B of the single mask configuration exhibits a higher gain. The behavior of orientation B in the E_{drift} study exceeding 1.5 kV/cm can be explained as the loss of transparency. Transparency describes the loss of electrons due to higher electric fields as they do not cross past the GEM foils. Transparency is calculated as the fraction of electrons that are transferred through the GEM holes to the other side of the GEM foil [12]. This behavior was expected as it confirms that there is an optimum electric field of operation in the range of 1 to 1.5 kV/cm. Accordingly, 1.3 kV/cm was set as the constant electric field in the drift gap throughout the V_{GEM} study.

Single GEM: Garfield++ vs. HEED

The study of E_{drift} was repeated for single GEM using HEED in order to verify results as well as compare both methods. Figure 6 shows the results of this study. HEED's simulation of a negative muon shows a significant shift in the gain to lower gains. This can be explained by the fundamental difference in the two simulations, which is that HEED simulates a muon passing through the detector while Garfield++ simulates electrons that are randomly generated in the drift gap. Since muons might pass without causing any primary ionizations, the gain is significantly pulled down by some simulations that produced zero gain. This confirms the importance of integrating the simulations of HEED and Garfield++ in order to conduct more comprehensive simulations.

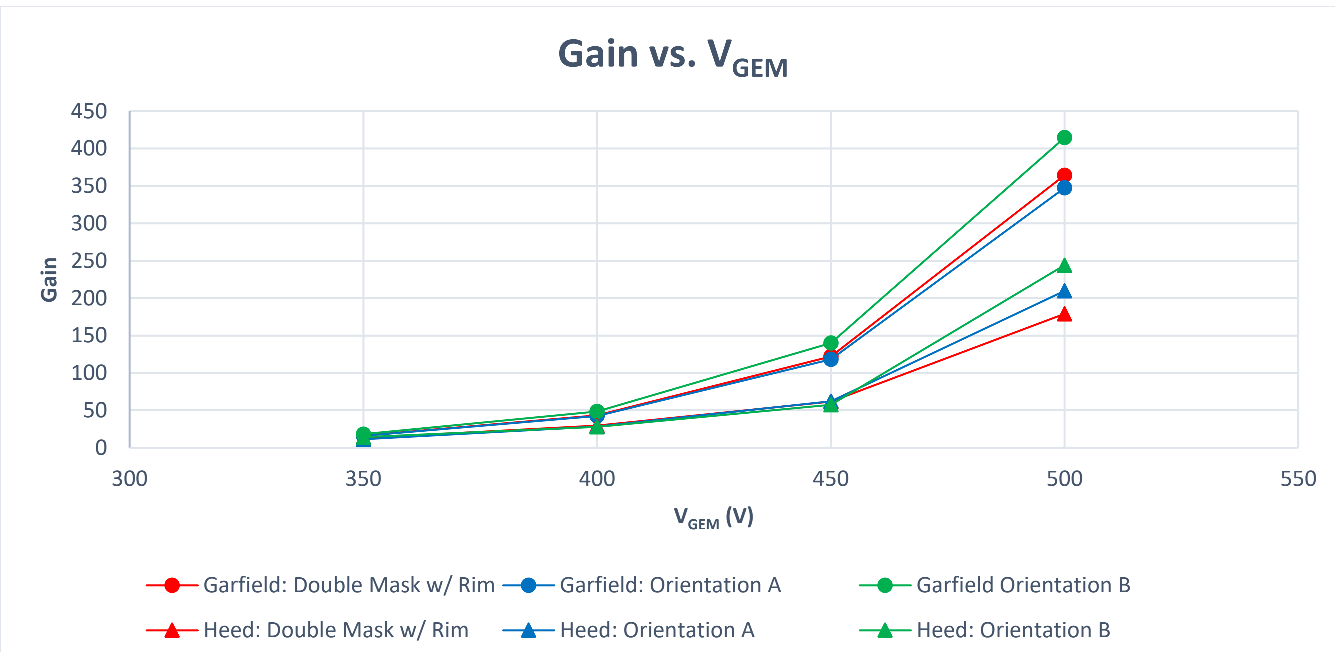

Figure 6. Single GEM: Garfield++ vs. HEED

Triple GEM

The studies performed for a single GEM layer were used as a reference when studying the triple GEM detector of interest. The same tools and simulation methods were used to repeat the study of gain vs. electric field in the drift gap for a triple GEM detector. The results of this study are displayed in Figure 7. The next step was to study the detector's performance compared to the high voltage applied to the voltage divider as described in GEM Studies (Figure 3). The results of this study are displayed in Figure 8.

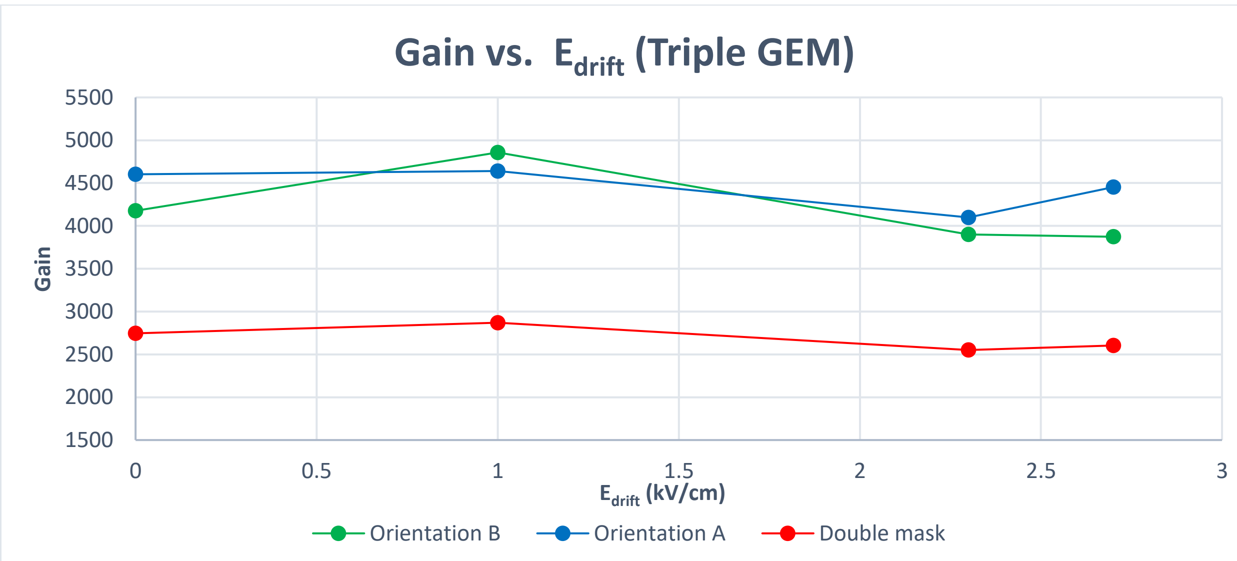

Figure 7. Triple GEM: gain as a function of E_{drift}

When compared to the results of single GEM gain as a function of E_{drift} (Figure 4), the double mask configuration seems to maintain its almost constant behavior. However, orientation A closely matches orientation B in this scenario, and a region of optimum performance is obviously seen in the range of 0.5 to 1.5 kV/cm for E_{drift}. The relationship between E_{drift} and gain obtained from single GEM cannot simply be used to represent triple GEM. As a result, the individual GEM layers in triple GEM must be studied more thoroughly so that the configuration of each can be optimized according to the conditions it is subjected to. Ultimately, this will lead to the most optimum configuration of the triple GEM detector.

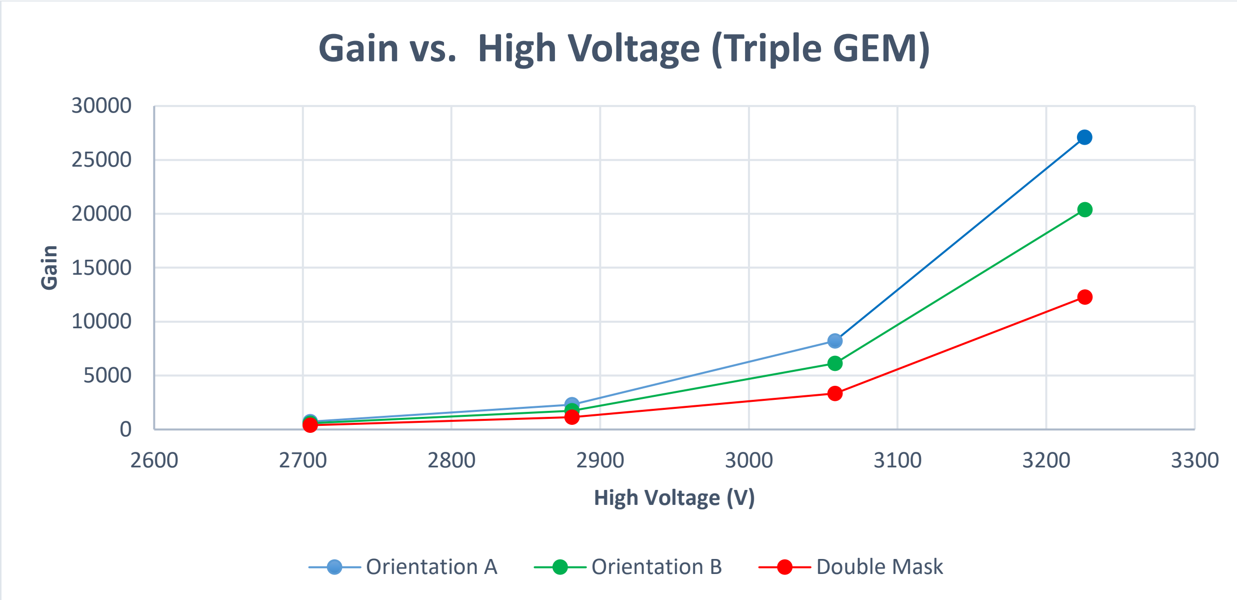

Figure 8. Triple GEM: gain as a function of high voltage

As previously mentioned, the high voltage is the voltage applied at the Drift Cathode as in Figure 3, and it determines the voltages at every level of the triple GEM detector. The values of VGEM at each layer are not constant due to this set up. Therefore, the study was conducted for the high voltage instead of VGEM. The results shown in Figure 8 show a behavior in triple GEM similar to that of single GEM as the gain increases exponentially with high voltage increase. However, it is notable that the gain of orientation A exceeds that of orientation B. The opposite was observed for single GEM. This also proves the need for further investigation of the individual GEM layers of triple GEM.

CHAPTER IV

CONCLUSION

This is a long-term project that is expected to go until 2037. Currently, we are preparing for the future upgrade of the LHC in 2019. This research is an ongoing work and it would be guiding the assembly side of the upgrade. More studies on the GEM would be done, such as testing different concentrations of the gas. Currently, the gas used is 70% Ar and 30% CO_2. The gas would be varied to different concentrations and the effect of it on the gain of the GEM would be tested. In addition, the induction and drift gaps would be varied from 1mm to 3mm, and several simulations would be done in order to optimize the gap size.

Future plans for this project are to collaborate with international teams to reproduce preliminary experimental results for triple GEM. Additionally, the individual GEM layers will be thoroughly investigated to understand the differences observed between the single GEM and the triple GEM detectors as revealed by the results. The ultimate goal of the research is to guide the assembly of the GEM in CMS in 2019.

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APPENDIX

All images currently included have been taken from a paper published by one of the authors (Taif Mohamed). Ref: Akl, M. A., Bouhali, O., Castaneda, A., Maghrbi, Y., & Mohamed, T. (2016). Uniformity studies in large area triple-GEM based detectors. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 832*, 1-7.