Test and characterization of a new Triple-GEM detector

by

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Abstract

In my thesis project, I provide a description of the entire process of materials preparation, assembly, testing, and characterization of several triple-GEM (Gas-Electron Multiplier) prototype detectors. GEM detectors represent one of the latest developments in a new style of gaseous particle detectors. They have become well-known and widely used. Improvements in foil production are important for future applications of the detectors to large scale tracking devices. One function of this thesis project is to compare the performances of GEM foils produced by different sources when installed in identical prototype triple-GEM detectors.

Thesis Supervisor: Bernd Surrow
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Chapter 1

Introduction

In studying and researching nuclear and particle physics, we aim to learn more about the fundamental particles (protons and neutrons) and the interactions they experience, but also to learn more about how matter is composed. The idea that matter is composed of elementary particles surfaced first during the 6th century BC, when the joint teacher-student pair of Leucippus and Democritus voiced their belief that matter is made up of indivisible units known as “atomos” [1]. Centuries later, in the late 1700s and 1800s, the emergence of Sir Isaac Newton’s Laws of Mechanics, Michael Faraday and James Maxwell’s work in electromagnetic theory, and Wilhelm Roentgen’s discovery of x-rays were only the beginning of a stream of exciting discoveries of new theories in classical mechanics, electromagnetism, particle physics, and quantum theory. In 1913 Niels Bohr’s model of atomic structure, the theory that electrons travel in orbits around the nucleus of the atom, later won him a Nobel Prize in 1922 [2]. A timeline of particle discoveries between 1898 and 1968 is given in Figure 1-1.

One way to learn about the composition of matter is to investigate what types of particles are produced through different interactions between particles. Often, the desired particles of study are not naturally occurring in nature and are instead created through high-energy collisions between other particles. Identifying which types and amounts of particles are produced and how much energy they have from different varieties of high-energy collisions is a favorite means of research for particle physicists, which requires the use of both particle accelerators and particle detectors.
After colliding high-energy particles, we want to measure the tracks of the particles which emerge from the collision. The best detectors will have fast tracking systems with minimal dead material, and a fast time response since bunch-crossing times can be much lower than 100 ns.

Particle physicists are constantly looking to develop new types of detectors, especially cost-efficient models, and one large area of research and development is in gaseous detectors. Charged particles lose energy while travelling through matter, which is a key property exploited by gaseous detectors. For this thesis, we focus on one specific type of gaseous particle, the GEM detector. This chapter focuses on the studies and developments leading up to the introduction of the GEM detector in 1997 by Fabio Sauli at CERN laboratory [3] and describes the developmental stages of the GEM detector and the motivation and applications for this type of detector.

1.1 Predecessors of GEM detectors

Historically, a novel version of particle detectors using gaseous detection was the single-wire proportional chamber created by Thomas, Rutherford, and Geiger in the early 1900s. Several decades later, a new modified gaseous detector which was based upon that theme was proposed by Georges Charpak in 1968 during his work at CERN [4]. The detector is known as the multi-wire proportional chamber (MWPC). In a
MWPC, ionization of charged particles causes liberation of electrons. These electrons, which are within a region of electric field created by a multi-wire arrangement, are accelerated and then cause a charge avalanche. Tracks of particles passing through a MWPC are created by observing the spatial locations of the detectable signals caused by the charge avalanches. The MWPC detectors, however, had limitations caused by granularity and rate capability, and scientists sought to improve upon the design to eliminate these drawbacks. Inspired by the MWPC concept, other types of gaseous detectors soon developed, such as drift chambers and time expansion chambers. Charpak was recognized for his revolutionary detector development with a Nobel Prize in Physics in 1992 [5].

The next version of position-sensitive gaseous detectors were designed using a pattern of tiny metal strips laid upon a thin support and are generally classified as micro-pattern detectors. A review of various types of micro-pattern detectors is given in [6]. The first type is known as micro-strip gas chambers (MSGCs) and was proposed by Anton Oed in 1988 [7]. The spacing between the strips is approximately an order of magnitude smaller than that achieved between the wires of the MWPC detectors, thus permitting the detector to better handle multiple hits by particles. Other types include the Compteur à Trous (CAT), which contain many narrow holes where the avalanche multiplication of charge occurs, the MicroMeGas design, which utilizes narrowly spaced parallel plates for high gain results, and the Gas-Electron Multiplier (GEM), which is a micro-pattern device and the focus of this proposed project.

The GEM detector was developed by Fabio Sauli at CERN in 1996, and his first paper was published in 1997 [3]. A GEM detector utilizes a GEM foil, which is a thin sheet of polymer material metal-clad on both sides and then chemically perforated by a high-density hole pattern. When voltages are applied to the upper and lower metal layers, the resulting electric fields within the holes draw in electrons above the foil and cause charge multiplication within the holes. The resultant produced electrons are transferred to the region below the foil. One of the important features of a GEM detector is that multiple foils may be stacked for increased gain. Successful
detectors have been made using two and three GEM foils, employing one GEM foil as a pre-amplifier for the next foil.

1.2 Motivation for GEM detector work

Figure 1-2: Cutout view from the side of the STAR experiment proposed detector upgrade. The green areas in the center cylindrical section represent the GEM detectors. Figure provided by B. Surrow.

Many physicists have now taken up research in the field of GEM detector development. Various papers, including the ones cited in this thesis, have been published documenting progress in these efforts. At MIT, the triple-GEM research group has several reasons which motivate our research in triple-GEM particle detectors. We are developing GEM detectors for a direct application to the STAR experiment at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Lab (BNL) [8], and they have already been implemented at COMPASS as well [9].
1.2.1 Applications as tracking detectors for large-scale experiments

The main focus of the STAR experiment is the study of the state of the matter produced from Au-Au collisions. At STAR, triple-GEM detectors are forecast for use as tracking detectors in the endcap calorimeter. A cutout view of the planned detector upgrade apparatus is given in Figure 1-2, and an overall schematic for the detector is given in Figure 1-3.

GEM detectors in various forms have already been implemented as tracking detectors in several large particle physics experiments, including COMPASS, and there are plans to implement such detectors in future experiments at the Large Hadron Collider (LHC). At COMPASS, 20 large triple-GEM detectors of size 31 cm x 31 cm are successfully used as tracking detectors for charged particles [9]. A picture of a COMPASS triple-GEM detector is given in Figure 1-4 [9].

1.2.2 CERN and Tech-Etch foil comparison basis

At the moment, the bulk of GEM foil manufacturing is done by the photolithographic workshop at CERN [11]. Despite the quality of these foils, the role of CERN
is not to be a production facility for these foils. Consequently, researchers asked themselves where there were other manufacturers who could handle the potential of large-scale production of GEM foils for future large detectors. Tech-Etch Inc., based in Plymouth, MA, surfaced as one possibility for industrial production of GEM foils. Tech-Etch Inc. commenced research and trials into producing GEM foils in 2003.

In the MIT Triple-GEM research group, one of our goals is to assess the current differences between the performance of CERN GEM foils and Tech-Etch GEM foils when installed in GEM detectors. Such work will allow for improvements in the Tech-Etch foil-production technology and provide additional, new characterization data on the detectors for reference by other researchers. Already known is that CERN GEM foils are more stable than their initial Tech-Etch counterparts. Tech-Etch has been granted Phase I of a DOE-funded SBIR (Small Business Innovation Research) program proposal. This program fosters collaboration in research development between small businesses and academic institutions such as Tech-Etch Inc. and MIT. The goal of the phase I stage of the program is to explore various GEM foil production techniques which differ from those used at the CERN photolithography lab. Tech-Etch
Inc., with its previous experience in Kapton etched products and good connections to a number of research institutions, is in a good position for self-evaluation and improvement of its GEM foil production processes from working with direct feedback from researchers at these institutions.
Chapter 2

The physics of GEM detectors

In this chapter, I will examine the theory on which GEM detectors are based and explain how the photons produced by sources used in this thesis research are recognized and amplified into a suitable readout signal. I will begin with a discussion on the energy loss of charged particles in an electric field.

2.1 Basic concepts for charge multiplication in a gaseous detector

This section investigates several concepts needed to understand the charge amplification processes which occur inside a gaseous detector. We begin with a brief discussion of the Bethe-Bloch formula, which applies to the majority of applications for GEM detectors, and then focus upon the interactions of photons with the detector gas.

2.1.1 Bethe-Bloch formula for energy loss

For relativistic charged particles, the method of energy in matter loss is highly dependent on the energy of the particle. Ionization and atomic excitation are the two main methods of energy loss for charged particles of a moderately relativistic nature. The expression for the differential energy loss per distance travelled, \(-\frac{dE}{dz}\), is given by the Bethe-Bloch equation:
\[-\frac{dE}{dx} = K \frac{Z}{A} 1 - \frac{1}{2} \ln \left( \frac{2m_e c^2 \gamma^2 T_{\text{max}}}{E} \right) - \beta^2 - \delta \]  \tag{2.1}

where \( A \) is the atomic mass of the medium, \( K = 0.307 \text{ MeV g}^{-1} \text{ cm}^2 \) for \( A = 1 \text{ g mol}^{-1} \), \( Z \) is the atomic number of the medium, \( \beta = \frac{v}{c} \), \( m_e \) is the electron mass, \( \gamma \) is the relativistic \( \gamma \)-factor, \( \delta \) is a density effect correction to ionization, and \( T_{\text{max}} \) is the maximum kinetic energy that a free electron can absorb through a single collision with the particle. \( T_{\text{max}} \) is approximately \( 2m_e c^2 \beta^2 \gamma^2 \) if the particle mass \( M \) is much greater than \( 2m_e \) \cite{12}. A plot giving the Bethe-Bloch calculated energy loss is given here as Figure 2-1.

Beyond the Bethe-Bloch distribution, the energy is further distributed according to Landau statistics for the energy loss within a specific distance \( \delta x \) of the material. The relativistic charged particles moving through the gas will lose energy as suggested by equation 2.1, through ionization of the gaseous atoms.

In addition to functioning as detectors for charged relativistic particles, GEM detectors are also used to detect photons. For the current testing and characterization of our triple-GEM prototypes, we exploited this avenue of GEM detector theory. The next section will describe the physics of using GEM detectors to detect photons.

### 2.1.2 Ionization energy loss of a moving electron in a gas

A radioactive photon source emits photons at a certain energy, \( E_{\text{a}} \). When these photons enter a volume of gas, the photons will interact with the atoms in the gas and experience energy loss. A plot showing the photon total cross section as a function of energy in carbon and lead is given in Figure 2-2, taken from \cite{12}. We will be concerned with photons on the lower-energy portion of the scale, where the total cross-section contribution from the photoelectric effect dominates over others by several orders of magnitude.

For the photoelectric effect, a gas atom absorbs the photon and then ejects a K-shell electron with a nonzero kinetic energy. Since the mass of the atoms in the gas is much greater than the photon energy \( E_{\text{a}} \), there is essentially no recoil energy for...
Figure 2-1: Energy loss rate for particles in a variety of materials. Figure taken from Particle Data Group (PDG) review 2004 [12]
Figure 2-2: Photon cross-section as a function of energy in carbon and lead. Figure taken from PDG Review 2004 [12]. $\sigma_{p.e.}$ is atomic photoelectric effect cross-section contribution.
the atom. Therefore, the kinetic energy of the ejected electron, $E_e$, is approximately $E_s - E_K$, where $E_K$ is the binding energy of the K-shell. An ion-electron pair has now been created within the gas of neutral atoms. The liberated electron is now able to travel about in the gas.

Collisions with other gas atoms causes the ionization of more electrons. The average energy required to produce an electron-ion pair in Argon gas is 26 eV [13]. These electrons are produced almost at rest, in contrast to the initial electron from the photoelectric effect. The original travelling electron (product of the photoelectric effect interaction) continues to liberate electrons through collisions with gas atoms and the creation of more ion-electron pairs. This original electron continues until it has depleted its kinetic energy $E_s$. While colliding with gas atoms, the electron follows a random trajectory, and thus the final resulting cluster of ion-electron pairs is not centered about the initial photoelectric-effect atom. Additionally, it is not obvious where the initial photon-Argon gas atom interaction occurred. For triple-GEM prototypes, the typical distance between ionization collisions is the given by the mean free path of the electron in the detector gas. A typical electron will have a range of a few hundred microns in the gas.

The newly-produced ions in the gas will deal with the hole in the electron K-shell in one of two ways:

1. Fill the hole with a new electron and simultaneously release an electron with the ionization energy of the K-shell (the Auger effect); or

2. Fill the hole with a new electron which falls from the outer electron shells and simultaneously release a photon with energy $E_{Ar}$.

In the first case, there is now a total ionizing electron energy that is detected which is approximately equal to the initial photon energy. In the second case, the total ionizing electron energy is $E_s - E_{Ar}$. Since the probability of detecting the emitted photon is so small, the relative probability of the two cases is dependant on the type of gas. Experimentally, it will be possible to detect the difference between the outcomes of these two cases. We will revisit this point later in the chapter.
2.1.3 Drift of electrons

Under the influence of an electric field, the electrons within the cluster of ion-electron pairs created by the moving electron are accelerated from rest to a drift velocity towards the region of higher potential. In the GEM configuration, the electric field is caused by essentially two parallel plates. Therefore, the electrons are only accelerated in a direction normal to the GEM foils. The electrons may undergo collisions with the gas atoms, as dictated by the mean free path of the electrons, but these collisions will not create any new ion-electron pairs nor destroy the original electron.

In addition, there are effects due to diffusion of the electrons in the gas. The diffusion effects cause a spreading expansion of the electron charge cloud laterally and horizontally.

The drift and diffusion effects both contribute towards the movement of the charge cloud from the top of the gas volume towards the top side of the first GEM foil, which is at a higher potential than the HV foil that closes the top of the detector gas volume. A 1989 study at CERN investigated the drift velocities of electrons in ArCO₂ (70:30) gas such as was used in this experiment, and from this we take the velocity of the drift electrons to be approximately 6 cm/μs in drift electric fields between 2 and 3 kV/cm [14].

2.1.4 Amplification in high electric field regions

Even using fast electronics that are available on the equipment market, single electrons cannot be reliably detected. In fact, the faster the electronics, the more charge is needed for detection. Thus, some amount of charge amplification is needed. While the initial photon causes a charge cloud of electrons to accumulate, the accuracy of detection will be improved if the amount of charge could be amplified. If these electrons are placed within a high enough electric field, between the collisions dictated by their mean free path length, the electrons can gain enough energy from the electric field acceleration to ionize and excite the atoms in the gas. Thus, one of the electrons from the first drift gas volume can create new ion-electron pairs as it travels through
the gas volume with the higher electric field. For argon atoms, the first ionization energy is about 15.6 eV per atom [15].

The number of ionizations per unit length is given by the first Townsend coefficient, \( \alpha \), and is a function of pressure \( P \) and electric field \( \epsilon \), given in simplified form as:

\[
\alpha = A P e^{-\beta P}
\]  

(2.2)

yielding the relation between the number of electrons \( dn \) and the distance travelled \( dx \) as:

\[
dn = \alpha ndx
\]  

(2.3)

Thus, the gain \( G \) as a ratio of the number of electrons in the charge cloud before and after passing through the volume of increased electric field is given by:

\[
G = \frac{n}{n_o}
\]  

(2.4)

\[
G = e^{\alpha x}
\]  

(2.5)

where \( n_o \) is the initial number of electrons in the charge cloud and \( x \) is the total path length travelled. In our GEM detectors, the electron avalanche multiplication occurs within the holes of the GEM foils, the electrons pass through a distance \( x = 60\mu m \). Typical gains for triple-GEM detectors can be of the order \( 10^4 - 10^5 \).

## 2.2 How a Triple-GEM detector works

In a triple-GEM detector, the initial drift gas volume is followed by a sequence of three GEM foils for charge avalanche multiplication and drift volume to the following foil or charge collection plane. A schematic diagram is provided in Figure 2-3. This section will describe the various components of a GEM detector, beginning with the GEM foils.
2.2.1 The GEM foils

Our GEM foils have a micro-hole pattern created by photolithographic etching processes. A close view of a GEM foil is provided in Figure 2-4.

The two copper sides of the foil are put at a high potential difference, and due to a separation of about 50 μm, strong electric fields are created within the hole spaces. As discussed earlier, the GEM foil hole electric fields cause a significant charge gain for the electron charge cloud. This effect cascades through the three GEM foils, and the end result is a greatly magnified detectable charge at the bottom of the detector gas volume. Nearly all of the electrons in the charge clouds pass through these amplification regions since they are guided by the electric field lines of Figure 2-6. The electric transparency is thus close to unity, and the optical transparency $\tau$ of the GEM foils is given by the ratio of the open hole area to the total area of the foil:

$$\tau = \frac{\pi D^2}{2\sqrt{3} P}$$

where $D$ is the copper hole diameter and $P$ is the hole pitch. Approximating $D =$
Figure 2-4: Electron microscope image of a CERN GEM foil hole pattern. The outer copper diameter is about 70 µm and the inner kapton diameter is about 50 µm. Picture taken from [16]. A side cutout view of the holes is given in Figure 2-5.

![Electron microscope image of a CERN GEM foil hole pattern](image)

**Figure 2-5:** Diagrammatic representation of side view of GEM foil holes. Top and bottom outer copper diameters are larger than inner insulator diameter due to the photo-lithographic processes of GEM foil manufacturing.

![Diagrammatic representation of side view of GEM foil holes](image)

70µm and \( P = 140\mu m \), then \( \tau \approx 0.23 \).

In a triple-GEM detector, the first foil acts as a pre-amplifier for the second foil, and the second as a pre-amplifier for the third. In this way, the electric fields can be kept to lower values for each individual foil, since the overall gain in charge will be a product of the three individual GEM foil gains. A representative diagram of the electric field lines within and neighboring the GEM foils is given in Figure 2-6.
2.2.2 Charge collection on readout board

For our experiment, we use a 2D strip readout board for charge collection and detection. After three stages of GEM foil charge multiplication, the electron charge cloud reaches the ground plane readout board. On the readout board, two planes of copper strips provide a means for charge collection and transmission of this information to laboratory electronics systems. The collected charge is proportional to the amount of electrons present in the charge cloud, which is in turn proportional to the initial energy of the incident photon. In this way, measuring the charge via the readout board is a means of indicating the relative energies of incident photons from a radioactive source. The stack of three GEM foils plus the readout board, with the relevant resistor voltage dividing chain included, is schematically represented in Figure 2-3.

2.2.3 Presence of Argon escape peak

As mentioned in the previous section, there are two possibilities to fill the K-shell vacancy in the gas ion. The scenario in which an electron is ejected through auto-ionization is referred to as the Auger effect. The essential difference between the two
possibilities is that they differ in the amount of energy (i.e. charge) that will cause ionizations and generate electrons for the charge cloud. The difference in energy between the two cases is the ionization energy of the K-shell. The case in which a photon is released that is not absorbed into the detector, not an electron, will later be referred to as the argon escape peak energy.

2.2.4 Variation in hole electric field strength

While the majority of electrons in the charge cloud will pass through the holes in the GEM foils, some electrons may enter the middle insulating material of the foil and become stuck to the walls of the foil holes. This activity is commonly referred to as "charging up" of the detector. As electrons accumulate on the walls of the holes, the electric field inside the holes increases in magnitude. The strengthening of the field results in an increased gain of the detector.
Chapter 3

Triple-GEM prototype detector setup and apparatus

This chapter describes the preparation procedures leading up to the detector assembly and the setup of the detector and electronics.

3.1 Detector design

The triple-GEM prototype detectors built for this thesis work were designed by Jim Kelsey (Bates Lab project engineer), Doug Hasell (Bates Lab research scientist), and Professor Bernd Surrow in 2005. The design was based on the GEM detectors used at the COMPASS experiment [9, 17].

The electron amplification occurs within the triple stack of GEM foils, as previously diagrammed in Figure 2-3. There are three framed GEM foils and one framed high-voltage foil (HV foil) that compose the stack. Each framed foil carries a voltage difference of about -380 to -400 volts and is separated from the next foil by a drift gap voltage, $V_D$ about -760 to -800 volts. The voltage divisions are created by a resistive chain which is soldered to the readout board externally to the detector gas chamber volume.

The triple-GEM foil stack and readout board unit is sealed in the gas-tight chamber volume by aluminum casing on the top and bottom, a plastic middle section, and
a combination of plastic and metal screws. The gas-tight seal is created by use of o-rings at the interface of aluminum and/or plastic parts.

3.2 GEM foil preparation

Before installation into the triple-GEM prototypes, the integrity and quality of the GEM foils must first be confirmed. Optical scanning of the GEM foils provides a method to check that there are most importantly no foil defects which could lead to discharges within the gas, and additionally to look for any major obstructions blocking the tiny holes from their purpose of electron multiplication. The high-voltage testing is to insure the foils will not experience shorts across the copper sides when a large potential is placed across them.

3.2.1 Optical scanning

The optical scanning of the GEM foils is done in accordance with the thesis work of Brian Tamm '05 [18]. Tamm’s thesis work was the design and implementation of a GEM foil scanning software interface, named GEMScan, which is run through MATLAB 7.0.1. The scanning apparatus is a stand-alone platform, where the framed or unframed GEM foil is secured between two plates of glass. There are two servo motors which stage the GEM foil through a specified scanning area, and a stationary camera takes images of the foil at each position. The camera images and their respective staging coordinates are sent to the computer via cables. A picture of the scanner is given in Figure 3-1.

The GEMScan program, written by Tamm, then analyzes these camera images and compiles the data. The GUI interface of GEMScan provides a way for the user to step through the analysis of the GEM foil scan. Images of the identified trouble spots on the GEM foil are presented, including locations where there may be blocked holes, missing holes, under/oversized holes, or debris on the foil surface. The GEMScan program produces several MATLAB figures which summarize the scanning results.

An optical scan of a GEM foil takes approximately 30 minutes per side per lighting
choice. Due to the double-conical shape of the holes in a GEM foil, as seen in Figure 2-5, there are two separate scanning programs using front and back lighting. Front lighting, originating from the camera position, provides information about the diameters of holes etched into the copper area of the GEM foil, referred to as “outer holes”. Back lighting, originating from below the glass plates, provides information about the diameters of holes in the middle insulating material region of the GEM foil, referred to as the “inner holes”. Due to the chemical etching process of the holes in the GEM foils, the outer holes have a 10-20 µm larger diameter than the inner holes. For CERN foils, the hole diameter ratio is approximately 70:50, and for Tech-Etch foils, the ratio is approximately 80:55. Calibration procedures detailed in Tamm’s thesis [18] allow for the optimal choice of camera and light settings for each type of foil (CERN, Tech-Etch) and scan (outer, inner hole diameter).

3.2.2 High-voltage testing

After insuring that the GEM foil micro-hole pattern does not have any serious obstructions and that the outer and inner hole diameter measurements have reasonable homogeneity, the GEM foils are promoted to the high-voltage stability testing stage.
In preparation for the high-voltage testing, one GEM foil is placed into a vacuum chamber and vacuumed to remove residual moisture from inside the foil. Two connectors are attached to the upper and lower copper layers of the foil. After the foil is vacuumed for a short period of time, the chamber volume is filled to slight under-pressure with nitrogen gas. Nitrogen is chosen because it does not have avalanche amplification at voltages used in testing, and there is a chance of sparking in the holes if debris present.

The high-voltage stability of the GEM foil is measured by monitoring the voltage and current using a digital dual voltage-current source. The foils are tested for stability to hold currents below a certain threshold for potentials up to -550 V. Ideally, this threshold is 0 A, but in here we hold it to below a few nA, which translates to a GEM foil resistance on the order of a few GΩ.

### 3.3 Geometry of triple-GEM prototype

As mentioned at the beginning of this chapter, our triple-GEM prototype chambers contain several major components: the three framed stacked GEM foils with the HV foil, the detector casing, and the readout board. Here I will describe each of these prototype elements in detail.

#### 3.3.1 GEM foil stacking and voltage divisions

The three GEM foils contained in the detector are referred to as the top, middle, and bottom foil for convenience. The middle and bottom foils are framed using 2 mm square plastic frames with a window of 10 cm x 10 cm. A photo of a framed foil is given in Figure 3-2. The glue used in the framing was 10 parts Epon Resin 828, a Bisphenol A epoxy resin, + 4.5 parts Vesamid 140 curing agent, a Polyamide resin, (parts by weight), which are both products of Miller-Stephenson Chemical Co. The excess insulating foil material (Kapton or Epicor) is cut away from the frames before installation into the detector. The top foil is glued to a different, 3 mm thick, square plastic frame with a 10 cm x 10 cm window, which contains two cut-in outlets to
facilitate gas exit flow. The HV foil, which lies above the top GEM foil, is also glued to a 2mm square plastic frame. The HV foil is one layer of 5 µm-thick copper (without an etched micro-hole pattern) and one layer of 50 µm-thick insulating material. The four framed foils are stacked together and secured to the readout board above the crossed strips detection area.

GEM foils have two copper tabs that correspond to either the upper or lower copper layer of the foil. Ideally, there is no voltage-carrying connection between the two copper sides. Inside the prototype chamber, wires are soldered between these tabs and the readout board on separate pads which are connected to a resistor chain. The chain contains seven resistors: one each for the three stacked GEM foils, and four for the gaps between the foils and their neighbors. The resistors have values of 1.2 MΩ and 2.0 MΩ, providing different voltage drop over the GEM foils $V_D$, and the drift gaps $V_f$, respectively. A resistor chain schematic is provided in Figure 3-3. The total voltage drop, the high voltage $V_{HV}$, is the sum of the four drift gap voltages and the three GEM foil voltages. Each foil has a voltage drop of $\frac{12}{11.6} V_{HV} \approx -380$ to $-400$ V at operating high voltage.

Figure 3-2: A framed CERN top foil before installation into the detector. The frame shown is a 3 mm frame and includes the gas outtake outlet.
Figure 3-3: Triple-GEM prototype resistor chain which provides high-voltage division for the GEM foils and electron drift gaps. Diagram not to scale.
3.3.2 Detector casing and external connections

The detector casing is composed of three elements: a top and bottom aluminum piece, and a middle plastic piece. Pictures of the prototype casing are given in Figures 3-5 and 3-6. The bottom aluminum piece is solid, with some thickness etched out in two of the detector models. The top aluminum piece has a 10 cm x 10 cm window to the HV foil. The middle plastic piece has a central rectangular hole which covers the exposed area of the foil stack and the internal resistor chain area. Plastic is chosen as the middle casing material in order to avoid discharges from the foils to the casing. The readout plane board is secured between the bottom aluminum piece and the middle plastic piece. The casing is held together by four large metal screws and nuts; the internal foil stack is secured to the readout board by four smaller plastic screws.

3.3.3 Charge readout board

The triple-GEM prototype readout boards were designed by Miro Plesko of Bates Laboratory of MIT. A picture of the readout board is given in Figure 3-4. The center of the board is a square area, the size of the 10 cm x 10 cm area of the GEM foils, where there are two planes of 10 cm long, narrow, insulated copper strips, referred to as the upper and lower planes. The two planes of strips are oriented perpendicular to each other, yielding a two-coordinate grid structure. Each plane has 160 parallel copper strips, insulated with Kapton. There are two types of boards which are used in the triple-GEM prototypes: 1-Mil and 2-Mil boards. The difference is in the vertical separation between the upper and lower planes of perpendicular strips, where 1 mil = \frac{1}{1000} \text{ inch} (25.4 \mu\text{m}).

On the 1-Mil readout board, the upper strips are 9 mil (228.6 \mu\text{m}) wide while the lower strips are 20 mil (508 \mu\text{m}) wide. On the 2-Mil readout boards, the upper strips are 5 mil wide while the lower strips are 20 mil (508 \mu\text{m}) wide. The pitch between strips on all planes is 25 mil (635 \mu\text{m}) for the readout boards. The relative width of the strips is chosen to achieve equal charge sharing between the two coordinates.

When charge is detected by a strip on the readout board, the signal is read out
through pins arranged in a double row on the underside of the board. For the testing experiments of this project, a small connector attachment for the double-pin row was created to read the combined signal from a row of 26 parallel strips. The cluster of strips is chosen here because the charge cloud from a photon source such as $^{55}$Fe spans a large number of strips. In the connector, the neighboring 6 strips to either side of the 26 are grounded out to improve the signal stability. When taking one-dimensional measurements, the row of strips for the other readout plane is grounded to prevent voltage floating-up for that plane of strips. In a full experimental application setting, each strip signal would be read out independently and simultaneously.

### 3.4 Supply of materials and assembly of chamber

The machining of the detector chamber casings and the preparation of the gas intake/ouuttake valves are done at Bates Laboratory. The GEM foils and the HV foils are stretched and glued in a clean area at Bates Laboratory as well. These materials are transported to MIT, where the prototype assembly takes place in the triple-GEM clean room. Gas supply tubing installation for the prototypes and the vacuum cham-
ber are done by MIT technicians.

The assembly of the triple-GEM prototypes takes several hours and can be decomposed into the following steps:

1. The high-voltage divider resistive chain is arranged and soldered to the underside of the readout board. The resistors alternate values of 1.2 M\(\Omega\) and 2.0 M\(\Omega\) for the voltage drops across the GEM foils and the drift gaps, respectively.

2. Seven 10 M\(\Omega\) resistors are soldered on the topside of the readout board, inside the chamber volume. These resistors provide a minimum resistance for one foil if there is a short within that foil, to protect the foil from catastrophic damage.

3. The framed GEM foils (set of 3 CERN or Tech-Etch foils plus the HV foil) are installed into the detector. The excess middle insulating foil material is cut closely away from the copper foil-frame borders, and the copper tabs are trimmed back. Each copper tab is soldered to its appropriate voltage pad on the readout board so as to establish the voltage ladder outlined by the resistive chain as outlined in Figure 3-3. Thin wires are soldered between the copper tabs and voltage pads on the readout board to provide the connections. Care is taken to insure that no extra solder material falls upon the exposed GEM foil surfaces, which could cause a problematic short and a defective detector.

4. The stack of four framed foils are secured to the readout board by four plastic screws. The foil-to-readout board connections of higher potential differences are then painted with a light coating of Glyptal paint to reduce the effect of Corona discharges and other potential problematic discharges. The detector is left open for 6 hours to allow the red paint to dry before closing. A picture of the open detector is shown in Figure 3-5.

5. The outer areas of the readout board are wiped with ethanol to clean out any dust and unwanted particles and the detector casings are put into place. The four metal screws are tightly secured in order to insure the gastight seal of the detector chamber volume. The gas intake and outtake tubing are connected to
the detector casings using special gastight connectors. The gas intake occurs on
the readout board plane level, and the gas outtake is located on the opposite
side of the detector, above the foil stack.

6. After closing the detector, the external high-voltage supply connector is at-
tached and its two connections soldered to the ends of the high-voltage resistive
ladder on the underside of the board. The detector is connected to the ArCO₂
gas lines and is left to flush for a day before testing and experimentation begin.
A picture of the closed detector is shown in Figure 3-6.

This assembly process is repeated for all triple-GEM prototypes used for the pur-
poses of this thesis.

3.5 Signal transmission from readout board to com-
puter

In this section I will describe the path of the signal from its detection by the readout
board strips to its input into the data acquisition computer.
3.5.1 **Electronic readout system: Amplification of signal and trigger generation**

As mentioned in section 3.3.3, we read out 26 strips at once to increase the signal strength. This number is chosen to provide a good balance between the height of the signal and the width of the signal. Increasing the amount of strips would yield a wider, lower signal due to the increased capacitance of the signal strip area.

A block diagram of the following signal circuit path is given in Figure 3-7. The signal from the strips is first put through a CREMAT preamplifier which consists of a CR-110 single-channel charge sensitive preamplifier and a CR-150-DC-C evaluation board [19]. The preamplifier has an area less than 1 in\(^2\) (645 cm\(^2\)) and the evaluation board dimensions are 2.0 in x 1.5 in x 0.063 in (50.8 mm x 38.1 mm x 1.60 mm). The preamplifier takes a ±10 V DC supply input from a Tektronix PS280 DC power supply and amplifies signal currents by 1.4 V per pC. It also integrates the signal current pulse over time due to a small capacitance in the feedback loop. The signal current from the detector must be less than 10 nA for DC coupling as used in our testing experiments.
After pre-amplification, the signal is sent to an Ortec amplifier (model 571 or 575A) which integrates the signal over a specified time interval and provides a small amount of additional amplification. Here, we choose 5 ms for the integration time. It is critical to suppress high-frequency noise, for example, radio signal pickup in the 100 MHz range.

The amplified signal is then input to a Phillips Scientific quad linear Fan In/Out device (model 740). One output from the Fan In/Out is sent to the oscilloscope where the signal trace can be observed. A second output is sent to a LeCroy 2249W 12-channel charge ADC CAMAC module. The CAMAC crate, manufactured by Kinetic Systems, is a 3922 parallel bus crate controller which interfaces to a CAMAC driver installed in the data acquisition computer. A third output from the Fan In/Out device is sent through a trigger circuit for the oscilloscope trace and the CAMAC ADC gate. The trigger circuit is composed of a LeCroy Research Systems (LRS) quad discriminator (model 621AL), a LRS logic unit (model 35AL), and a LRS Gate and Delay generator. The trigger circuit generates two outputs: a trigger NIM signal used for the oscilloscope trace, and a gated NIM pulse of duration 2 µs used for the CAMAC ADC gate input.
3.5.2 Data acquisition electronics: CAMAC crate and Root interface

The information about the amount of charge collected by the readout strips is sent through the electronics as described in the previous section and then collected, after 37 dB attenuation by a Telonic 0 to 50 dB attenuator, by the CAMAC 2249W ADC module. The ADC is gated by a signal from the Gate and Delay generator (the trigger) and digitizes its input from the detector electronics circuit during the time of the open gate. The ADC then sends a flag to the CAMAC crate controller [20]. The crate controller talks to the PC through a PCI interface. When the PCI interface notes the flag from the crate controller, it reads out the ADC’s data from a specified channel or channels into the computer and then resets the crate controller to await the next trigger signal.

3.6 Radioactive sources for detector experiments

The main source used for the testing of prototypes in these experiments is a $^{55}$Fe photon source, which produces 5.9 keV photons. The strength of the source was 1 mCi at time of manufacturing, and the source was kept in a safe room adjacent to the main lab rooms. This source was chosen because for its relatively harmless effect on the experimenter during handling and because it produces very suitable spectra for the experiments. The source was manufactured by Isotope Products Laboratories of Burbank, CA.
Chapter 4

Measurements and Analysis

A series of characterization and testing experiments were carried out on the two CERN prototype detectors and the Tech-Etch prototype detector. The testing includes one-coordinate gain mapping, experimentation with two-coordinate gain mapping, and the time-evolution of signal gain. This chapter presents the results of these experiments as well as the results of the prototype assembly preparation testings of Chapter 3, namely optical scanning and high voltage stability testing of the GEM foils.

4.1 Optical scanning of GEM foils

Before installation into the detectors, the GEM foils need to be checked for any serious flaws in the micro-hole pattern and for an acceptable hole diameter homogeneity. The measurements of the copper and insulator hole diameters and pitches, as well as the presentation of the results, were made possible due to the optical scanner apparatus and GEMScan program developed by Brian Tamm '05 [18]. This section describes typical scanning results for CERN and Tech-Etch GEM foils.

4.1.1 CERN foil data

The CERN foils used for the triple-GEM detectors had a fairly narrow range of hole diameters, 65-75 µm for the copper diameters and 45-55 µm for the inner Kapton
diameters. The pitch between the holes in the hexagonal pattern was constant at about 140 \(\mu\text{m} \). A full summary of all the measurements for one foil are presented in Figures 4-1 and 4-2.

There are two functional CERN triple-GEM detectors, CERN-1 and CERN-2. Full optical scanning data on the foils included in these two detectors is found in Appendix A. A summary figure presenting values and errors for measurements of copper and Kapton diameters for the full set of 15 CERN GEM foils is provided in Appendix A.

### 4.1.2 Tech-Etch foil data

In contrast to the CERN GEM foils, the ones produced by Tech-Etch had less severe fluctuations in the hole diameter homogeneity. Comparison plots for the copper and Kapton/Epicor hole diameter homogeneity of CERN and Tech-Etch GEM foils are presented in Figure 4-3. In this figure, we note that the Tech-Etch GEMs have better overall uniformity in their hole diameters than the CERN foils. This result is likely a product of the industrial-style production which occurs at Tech-Etch, with better control of the processes that affect uniformity.

The average pitch remained the same at about 140 \(\mu\text{m} \). For undeterminable reasons, it was much more difficult to get complete foil scan sets for the Tech-Etch foils. While there are not complete scans for the foils in the Tech-Etch detector, sample Tech-Etch GEM foil optical scanning results are found in Appendix B.

### 4.2 High voltage testing of GEM foils

The CERN and Tech-Etch GEM foils were tested to withstand voltage differences of up to -500 V between the upper and lower copper layers without generating large currents. This is meant to insure that the foils maintain a resistance on the order of several G\(\Omega\). In practice, many of the foils used in the triple-GEM prototypes for these tests had currents below 5 nA at -500 V, and at operation conditions for the prototypes, each foil carried a voltage drop of approximately -380 to -400 V. In the
CERN Group A, 2 of 5 – Diameter Histograms

- **Side 1 Copper Hole Diameter [μm]**
  - Mean = 71.45 μm
  - StDev = 1.15 μm

- **Side 1 Inner Hole Diameter [μm]**
  - Mean = 53.34 μm
  - StDev = 1.40 μm

- **Side 2 Copper Hole Diameter [μm]**
  - Mean = 69.30 μm
  - StDev = 1.53 μm

- **Side 2 Inner Hole Diameter [μm]**
  - Mean = 53.18 μm
  - StDev = 1.41 μm

- **Hole Pitch [μm]**
  - Mean = 140.12 μm
  - StDev = 1.17 μm

Figure 4-1: Multi-plot review figure 1 of 2 for CERN foil A-2.
Figure 4-2: Multi-plot review figure 2 of 2 for CERN foil A-2.
Figure 4-3: Comparison plots for GEM foil hole diameter homogeneity of CERN A-4 and Tech-Etch 292138-5 GEM foils. Deviations from the mean are plotted using a color-bar scheme, with all measurements (diameters and coordinates) given in microns.
case of sparking while approaching this voltage during the vacuum chamber testing, a procedure of foil training up to the desired voltage by stepping slowly up through the sparking region until no further sparks occurred was applied as a first method to save the GEM foils for detector use. This procedure is usually referred to as “training the foil”.

4.3 CERN prototype results

After the chamber volume has been flushed with the ArCO₂ (70%:30%) for 24 hours, testing begins using the radioactive sources. This section describes the characterization results of the two CERN prototype detectors, CERN-1 and CERN-2.

4.3.1 One-coordinate readout measurements

This subsection describes the process of one-coordinate readout measurements: the recording of histograms, the fitting to determine peak locations, and the extension to measurements of gain as a function of time.

Energy distribution histograms

The information on the amount of charge detected by the readout strips is passed to the computer for analysis as described in Section 3.5.2. In this manner, data accumulates to generate histograms of the charge detected by the signal strips. Each ADC readout is compiled together by a ROOT data accumulation macro until a specified number of triggered counts have been reached. The macro then produces a histogram of the results and saves the data as a root data file.

The first step for analysis after taking a spectrum histogram is to fit the spectrum to extract information about the peaks.

Fitting using ROOT software

The spectra read into the computer by ROOT from the CAMAC electronics crate were fit to a sum of two Gaussian peaks and an exponentially decaying noise function
in order to extract the peak centroid channels. In the spectra, the largest, rightmost peak represents the amplified energy of the incident photon emitted by the $^{55}$Fe source. As noted in Section 2.2.3, we should also observe the Argon escape peak at a lower amplified energy than the main photon energy peak. In the spectra, this peak has a lower amplitude than the photon peak, and is located several hundred channels to the left of the main photon peak. An example of a fit spectrum for the $^{55}$Fe source with the CERN-2 detector is given in Figure 4-4. For this work, we did not need to calibrate the energy scale of the histograms since our interest lay in the relative position of the two peaks and the relative gain across the area of the prototypes, but this does not bar calibration efforts for further work.
Gain of prototype as a function of time

As mentioned in Section 2.2.4, there is a period of charging-up due to the time-dependent increase in the electric field strength within the GEM foil holes where the charge cascading takes place.

The CERN prototype detectors did not exhibit a drastic charging-up effect after being turned on. The results can be shown in a graph of peak energy channel versus time, where many individual spectra were collected in sequence over a period of several hours. Each point represents a 5000-count measurement histogram peak height analysis, and the time for each measurement was about 3 minutes.

![Graph showing change in gain over time for CERN-1 prototype](image)

Figure 4-5: Change in gain over time for CERN-1 prototype. Prototype high voltage was -3.804 kV. Data collected using $^{55}$Fe photon source.

A figure showing the change of gain over time, or charging-up, of the CERN-1 detector is given in Figure 4-5. This figure illustrates the relatively quick charging-up period characteristic of our CERN prototype detectors. The first histogram's peak channel for the photon peak is normalized to 1, and subsequent measurements are compared to this renormalized value to get the relative change in the photon peak
channel position. We see the smooth increase of about 10% in gain over the first 2.5 hours, and then a leveling off as the detector reaches it's charged-up state. Similar results were obtained from the CERN-2 detector, with a charging-up period of a 2-3 hours. The timescale of charging up depends on the radiation intensity on the detector, which will be revisited later in this chapter.

4.3.2 Two-coordinate readout measurements

After taking successful data using the planes of readout strips separately, we turn to look at a 2-dimensional readout of the source. The trigger signal is taken from one plane, and both signals are read out through the CAMAC crate and are recorded in ROOT.

Energy distribution histograms

From looking at 2-dimensional readout data, we can learn about charge-sharing between the two planes of strips. We also expect to see a linear correlation between the amplitudes of the two planes for each detection over the length of the trial. Unfortunately, early success with these measurements is not replicable. A sample correlation plot for the CERN-2 detector is given in Figure 4-6.

Comparison between upper and lower strips

The comparison between the upper and lower strip charge detections can be approached in a few ways. Figures 4-7 and 4-8 show the gain of the CERN-2 detector as recorded by the top strips and the bottom strips, one coordinate at a time.

From these two figures, we see that the gain has similar behavior when recorded over both coordinates. The areas of lowest gain overlap, likely indicating that this is a consequence of GEM foil conditions and not faulty readout strips.
Figure 4-6: 2D correlation plot for GEM CERN-2 prototype. Data collected using $^{55}$Fe source and prototype high voltage was -3.875 kV.
Figure 4-7: 1D mapping data for upper strips of CERN-2 prototype. Prototype high voltage was -3.803 kV.

4.3.3 Effect of varying readout board model

In our testing, we made the two CERN triple-GEM prototypes with two different versions of readout boards. The boards differ in the vertical spacing between the upper and lower strip planes. For the 1-MIL readout board (CERN-2 prototype), this distance is 1 mil = \( \frac{1}{1000} \) inch; for the 2-MIL readout board (CERN-1 prototype), it is 2 mil. We ran tests at the same voltage (-3.803 kV) on both prototypes for gain mapping and for gain as a function of time to look for any differences caused by the difference in readout board.

Interesting measurements yielding information on the effect of variation in the separation of the charge planes would probably emerge in two-dimensional simultaneous charge readout. However, since there were some complications to getting successful data for such measurements, no results are ready at the present time on this data. We hypothesize that the difference in vertical separation may influence the charge-sharing between the strips; future testing may verify this hypothesis.
Figure 4-8: 1D mapping data for bottom strips of CERN-2 prototype. Prototype high voltage was -3.803 kV.

4.4 Tech-Etch foil detector measurements

The Tech-Etch detector was the third detector assembled, following the same preparation procedure as for the CERN detectors. The readout board installed in the detector is a 2-MIL board, the same as in the CERN-1 prototype.

4.4.1 One-coordinate readout measurements

This section describes the one-coordinate readout measurements taken using the Tech-Etch prototype detector and the \(^{55}\text{Fe}\) source.

Energy distribution histograms

The energy distribution histograms obtained using the Tech-Etch prototype detector have the same characteristic spectrum as those obtained using the CERN prototypes. We again see the main photon peak and then the smaller Argon escape peak, where
Figure 4-9: Comparison figure of pulse height gain for CERN-1 (2-Mil) and CERN-2 (1-Mil) prototypes. Z-axis measures pulse height, adjusted down by 800.
the ratio of the peak locations is about 0.55 (Argon:photon).

**Fitting using ROOT software**

The same macro for histogram fitting was used for the Tech-Etch prototype spectra and the CERN spectra; details are previously given in Section 4.3.1.

**Gain of prototype as a function of time**

In contrast to the CERN detectors, which charged up fairly rapidly and did not produce a large gain increase due to charging up effects, the Tech-Etch detector exhibits a gain increase of about 40%. A plot of one set of measurement results is given in Figure 4-10.

![Figure 4-10: Change in pulse height gain over time for Tech-Etch prototype. Prototype high voltage was -3.950 kV and the $^{55}$Fe source was used for the measurements.](image)

To examine the charging up effect more actively, we took a sequence of 12 measurements on the detector, grouped into three sets recorded under different conditions.
The first three were taken after turning on the fully discharged detector and irradiating a spot with the $^{55}$Fe source. A gain increase of 5% was observed during this initial turn-on period. Next, we irradiated the entire detector with a $^{90}$Sr source, which is a $\beta^-$-emitter. The emitted electrons have two distinguishable endpoint energies of 0.55 MeV and 2.283 MeV from the $^{90}$Sr and subsequent $^{90}$Y decay. The $^{90}$Sr source is much stronger than the $^{55}$Fe source, and should cause the prototype GEM foils to charge up at a much faster rate. In addition, the energy loss probability is higher for electrons compared to photons in a gas. Thus, we expected a sudden significant increase in gain due to the new presence of many more electrons on the insulator walls of the GEM holes. After 4 more measurements, we irradiated again with the $^{90}$Sr source, then took 4 more measurements. Data histograms from the first and second set of measurements are given in Figure 4-11 and the full set of peak data is given in Table 4.1.

From the fitting the histograms as described earlier, we obtained the peak positions, their ratio, and the energy resolution of the photon peak. Here, we define the energy resolution to be the full width of the photon peak at half maximum divided by the peak position.

The results compared in Figure 4-11 illustrate the interesting result that charging-up decreases the energy resolution for the Tech-Etch GEM foils prototype. This result indicates that the holes of the Tech-Etch GEMs do no all charge up in the same way, i.e. that there are different time-scales and gain shifts for each hole. The energy resolution deterioration is not found to be characteristic of CERN GEMs.

### 4.5 Error analysis and possible future modifications

There are several potential sources of error for the GEM prototype detector experiments. This section presents several sources and discusses their effects on the detector’s functionality.
Figure 4-11: Comparison figure for pulse height energy before and after $^{90}$Sr source exposure on Tech-Etch prototype. After irradiation by source, the energy resolution of the spectrum has decreased.
4.5.1 Voltage fluctuations

Any fluctuations in the high voltage supply would be passed on to all of the GEM foils, causing fluctuations in the drift field voltages and on the magnitude of the electric fields within the holes of the foil. These effects would cause shifts in the detector gain. No noticeable voltage fluctuations from the Bertan high voltage supply for the prototypes were observed during experimentations, but overnight trials were not supervised, and there is the possibility of fluctuations during this time could provide a partial explanation for various features in the overnight pulse height spectra results.

4.5.2 Airtight chamber

If the detector gas volume chambers are not airtight, there is potential for entry of external gases into the detector. ArCO₂ (70%:30%) was chosen for the prototype because of good performance in previous detector experiments and for its attractive properties. It is non-flammable, so if there are discharges, there is a very low chance for combustion. If external air enters the detector, however, any discharges and sparking may become amplified and cause harmful effects on the GEM foils and the functioning of the detector.

4.5.3 Resistive chain

During the course of the prototype testing, there were a few instances of problems with the resistors of the voltage divider chain. The problems were alleviated by replacing the resistors with high-voltage rated resistors, but there is always the possibility of identical resistors having slightly different values. This could cause variations in the gain between different prototypes.

One possible modification for the resistor chain involves the use of variable resistors for closer control of GEM foil voltage drops. For the triple-GEM prototypes used in this project, the resistors of the chain are of fixed values. Other experiments utilizing triple-GEM detectors have implemented variable resistor chains.
4.5.4 **Alignment of radioactive source**

In order for a clean signal, the optimal positioning of the radioactive source is directly centered above the strips which are connected to the electronics circuit. There is not, however, an easy method of insuring this positioning. Here it was done visually, by looking at the trace of the amplified and triggered signal on an oscilloscope, and adjusting the positioning to find the cleanest trace. Errors in positioning could result in signal histograms which have an increased signal-to-noise ratio, yielding offsets in the fitting results. The development of an improved method of mapping readout sensor location to positioning from the edges of the GEM prototype window would decrease this experimental error potential.

4.5.5 **Precision and accuracy of mapping**

Due to charging up and gain variation over time, a series of measurements at the same position may yield different results. Likewise, a mapping process of gain across the detector area may be influenced by a variation in the gain due to this charging up effect. One way to avoid this source of error is to insure that a sequence of measurements meant not to measure the time-dependence of gain are done when the detector is fully charged up. The Tech-Etch prototype measurements are more likely influenced by this error due to the 40% charging-up gain increase over several hours which we observed for the prototype, compared to the gain increase of about 10% over 2-3 hours for the CERN prototypes, as reported earlier in this chapter.

4.5.6 **GEM foil defects**

Optical scanning reveals several categories of GEM foil defects which may affect the performance of the foils in the detectors in various ways. The defects include:

- **Undersize/oversize holes**: could cause variation in the gain between sections of the foil if the sections are composed primarily by holes of one type or the other. This defect could be caused by errors in the hole etching process or could be the result of mis-calibration of the optical scanning software/lighting.
• **Debris in the holes**: could cause current between the upper and lower copper layers in the GEM foil, possibly leading to spark discharges or reducing the value of the electric fields within the foil holes. Debris could be the result of incomplete removal of etching chemicals, contamination by particles in the air during prototype assembly, or contamination by particles in the chamber gas supply.

• **Misplacement of holes**: not a very serious foil defect, but could also cause gain variation across the foil area. Misplacement is the result of an error during the hole pattern etching process or the chemical treatment.

• **Missing holes**: could cause notable gain variation if a large cluster of missing holes is present in one section of the foil. This defect is also caused during the etching process or the chemical treatment of the foils.

In general, the foils from Tech-Etch had a greater problem with missing holes and holes that were only partially formed. Since Tech-Etch has not been manufacturing GEM foils for as long as the photolithographic workshop at CERN, it is understandable that there are still ways to optimize and better their manufacturing processes for the GEM foils.

Additionally, the Tech-Etch GEM foils characteristically do not cooperate well with the optical scanning software. For reasons which are not well understood, the GEMScan program frequently crashes while analyzing the image data from the Tech-Etch foils, thus producing no result plots such as those taken for the CERN foils in Appendix A. The scanning results presented in Appendix B are meant to show a range of results from various batches of Tech-Etch foils. Hopefully future production batches of Tech-Etch foils will be amenable to a same development of optical scanning software as the CERN foils currently are.
<table>
<thead>
<tr>
<th>Trial</th>
<th>Photon peak pulse height (channel)</th>
<th>Ar escape pulse height (channel)</th>
<th>Ratio (Ar escape to Photon)</th>
<th>Energy resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>772.6</td>
<td>438.1</td>
<td>0.567</td>
<td>0.23</td>
</tr>
<tr>
<td>1-2</td>
<td>777.2</td>
<td>441.9</td>
<td>0.569</td>
<td>0.23</td>
</tr>
<tr>
<td>1-3</td>
<td>804.8</td>
<td>457.4</td>
<td>0.568</td>
<td>0.24</td>
</tr>
<tr>
<td>2-1</td>
<td>1014.5</td>
<td>559.3</td>
<td>0.551</td>
<td>0.33</td>
</tr>
<tr>
<td>2-2</td>
<td>1046.1</td>
<td>585.3</td>
<td>0.559</td>
<td>0.32</td>
</tr>
<tr>
<td>2-3</td>
<td>1041.8</td>
<td>560.7</td>
<td>0.538</td>
<td>0.33</td>
</tr>
<tr>
<td>2-4</td>
<td>1066.9</td>
<td>587.4</td>
<td>0.550</td>
<td>0.33</td>
</tr>
<tr>
<td>3-1</td>
<td>1058.0</td>
<td>576.1</td>
<td>0.545</td>
<td>0.30</td>
</tr>
<tr>
<td>3-2</td>
<td>1070.5</td>
<td>565.6</td>
<td>0.528</td>
<td>0.34</td>
</tr>
<tr>
<td>3-3</td>
<td>1064.6</td>
<td>579.4</td>
<td>0.544</td>
<td>0.33</td>
</tr>
<tr>
<td>3-4</td>
<td>1057.3</td>
<td>529.5</td>
<td>0.500</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 4.1: Tech-Etch prototype charging data taken using $^{90}\text{Sr}$ source to charge up detector ($\approx 15$ s irradiation duration) after first and second set of measurements. Detector voltage $-3.951$ kV.
Chapter 5

Discussion

In this chapter, I present a discussion summary of the differences between the two versions of prototypes and mention possible future directions for the applications of and uses for GEM detectors.

5.1 Differences between CERN and Tech-Etch prototypes

One of the first differences between the two types of detectors is evident in their gain. In order to get similar histograms from both detectors, with the peaks at similar locations, the Tech-Etch detector was operated at about 150 V higher than the CERN detectors, i.e. Tech-Etch at about -3.950 kV and CERN at about -3.800 kV.

A second important difference between the two prototypes, as mentioned during the Tech-Etch gain results, is the deterioration of the energy resolution as the foils charge up. One possible cause of this effect is the cleaning processes for the foils after the hole-etching process. Further comparative analysis of the two photo-lithographic workshops’ procedures for etching the GEM foils (CERN’s workshop and Tech-Etch’s manufacturing) may lead to the elimination of this energy resolution disparity. Ideally, the energy resolution can be in the 10% area for good pulse height spectra.
One promising feature of the Tech-Etch foils, in comparison to the CERN foils, is that their homogeneity appears more uniform. Hopefully, this may yield more homogeneity in the gain across the triple-GEM detector area.

5.2 Preferences

With the desire to build and implement large-scale GEM detectors as tracking detectors in current and future experiments, the need for large-scale production of the GEM foils is an important consideration that receives some priority. Comparison experiments such as the ones described in this thesis bring forth the differences between the performance of CERN and Tech-Etch GEM foils. Once the set of preferred performance results are selected, a manufacturer will have a clear set of goals to produce towards. Improvements and documentation of the foil production process will yield uniformity and homogeneity between separate batches of foils as well as during testing. The Tech-Etch company is better suited for production of large GEM foils than CERN, which is a research-oriented laboratory. The SBIR proposal of Tech-Etch insures that they will continue to produce GEM foils for testing and improvements, and the company is looking to expand its grant even further from the current Phase I stage.

5.3 Future testing and other applications for GEM detectors

GEM detectors are appealing for several reasons, one of which being their cost-effectiveness. The operation of GEM detectors is less than other silicon-based counterparts, thus making them an attractive alternative. Additionally, GEM detectors have promising futures as fast-tracking devices.

The development of GEM detectors for the STAR upgrade experiment is progressing well, as described in [8]. This upgrade will allow for many exciting discoveries, and the GEM detectors are an integral part of the plan. Research and development of
triple-GEM detector improvements will greatly support successful experiments using the upgraded STAR apparatus.

One possible new application of GEM detectors is in medicine, as imagers. There have already been examples using GEM detectors in this fashion; a sample figure showing an x-ray absorption radiography image of a small bat, recorded using two-dimensional readout from a GEM detector [21] is given in figure 5-1. The pixel size is 100 μm x 100 μm, and there are 36.5 million photo counts which comprise the image. The spine, vertebrae, and several small ribs are all distinguishable within the image.

![Figure 5-1: X-ray absorption image of small bat, using gray-scale to represent the photon count of the pixels.](image)

Other uses for GEM detectors are as two-dimensional trackers within larger experimental setups, and this is already in place in several experiments (COMPASS, HERA-B). GEM tracking detectors may give better position resolution than other tracking detectors, and would be able to distinguish between identical-mass, different-charge particles, such as electrons and positrons, passing through a magnetic field.

An extension of GEM detectors from charged particle detection to neutron detection has also been investigated by various researchers [22, 23].
Appendix A

CERN prototype optical scan results

![Diagram](image)

Figure A-1: CERN foil Group A-1; top foil of CERN-1 detector.
Figure A-2: CERN foil Group A-4; middle foil of CERN-1 detector.

Table A.1: CERN-1 prototype’s GEM foil diameter data.

<table>
<thead>
<tr>
<th>Foil ID</th>
<th>Inner diameter (µm)</th>
<th>Side 1 outer diameter (µm)</th>
<th>Side 2 outer diameter (µm)</th>
<th>Pitch (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>44.14 ± 2.36</td>
<td>69.58 ± 1.26</td>
<td>68.81 ± 1.29</td>
<td>140.10 ± 1.13</td>
</tr>
<tr>
<td>A-4</td>
<td>50.80 ± 2.65</td>
<td>70.58 ± 1.06</td>
<td>73.14 ± 1.00</td>
<td>140.15 ± 1.45</td>
</tr>
<tr>
<td>A-5</td>
<td>45.43 ± 2.89</td>
<td>70.40 ± 0.88</td>
<td>70.67 ± 1.10</td>
<td>140.05 ± 1.32</td>
</tr>
</tbody>
</table>

Table A.2: CERN-2 prototype’s GEM foil diameter data.

<table>
<thead>
<tr>
<th>Foil ID</th>
<th>Inner diameter (µm)</th>
<th>Side 1 outer diameter (µm)</th>
<th>Side 2 outer diameter (µm)</th>
<th>Pitch (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-6</td>
<td>50.08 ± 1.59</td>
<td>70.86 ± 1.25</td>
<td>69.93 ± 1.36</td>
<td>140.01 ± 1.18</td>
</tr>
<tr>
<td>B-3</td>
<td>48.16 ± 1.40</td>
<td>71.12 ± 1.25</td>
<td>69.05 ± 1.41</td>
<td>139.97 ± 1.19</td>
</tr>
<tr>
<td>B-5</td>
<td>47.50 ± 1.39</td>
<td>70.68 ± 1.16</td>
<td>67.96 ± 1.13</td>
<td>140.02 ± 0.94</td>
</tr>
</tbody>
</table>
Figure A-3: CERN foil Group A-5; bottom foil of CERN-1 detector.

Figure A-4: CERN foil Group B-6; top foil of CERN-2 detector.
Figure A-5: CERN foil Group B-3; middle foil of CERN-2 detector.

Figure A-6: CERN foil Group B-5; bottom foil of CERN-2 detector.
Figure A-7: Summary of optical scan results for all 15 CERN GEM foils.
Appendix B

TechEtch prototype optical scan results

Figure B-1: TechEtch foil Lot 292138-1.
Figure B-2: TechEtch foil Lot 292138-2.

<table>
<thead>
<tr>
<th>Foil ID</th>
<th>Inner diameter ((\mu m))</th>
<th>Side 1 outer diameter ((\mu m))</th>
<th>Side 2 outer diameter ((\mu m))</th>
<th>Pitch ((\mu m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>292138-1</td>
<td>53.68 ± 2.42</td>
<td>79.22 ± 2.67</td>
<td>74.76 ± 2.31</td>
<td>139.43 ± 0.73</td>
</tr>
<tr>
<td>292138-2</td>
<td>45.68 ± 1.80</td>
<td>73.91 ± 2.10</td>
<td>69.55 ± 1.96</td>
<td>139.49 ± 0.66</td>
</tr>
<tr>
<td>292138-4</td>
<td>48.24 ± 2.25</td>
<td>75.13 ± 2.14</td>
<td>69.01 ± 2.45</td>
<td>139.49 ± 0.65</td>
</tr>
<tr>
<td>292138-5</td>
<td>56.71 ± 2.07</td>
<td>82.03 ± 2.19</td>
<td>78.41 ± 1.66</td>
<td>139.48 ± 0.65</td>
</tr>
</tbody>
</table>

Table B.1: TechEtch prototype's GEM foil diameter data.
Figure B-3: TechEtch foil Lot 292138-4.

Figure B-4: TechEtch foil Lot 292138-5.
Figure B-5: Summary of optical scan results for 10 selected TechEtch GEM foils.
Bibliography


[23] T. van Vuure et al. High pressure GEM operation aiming at thermal neutron detection.
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