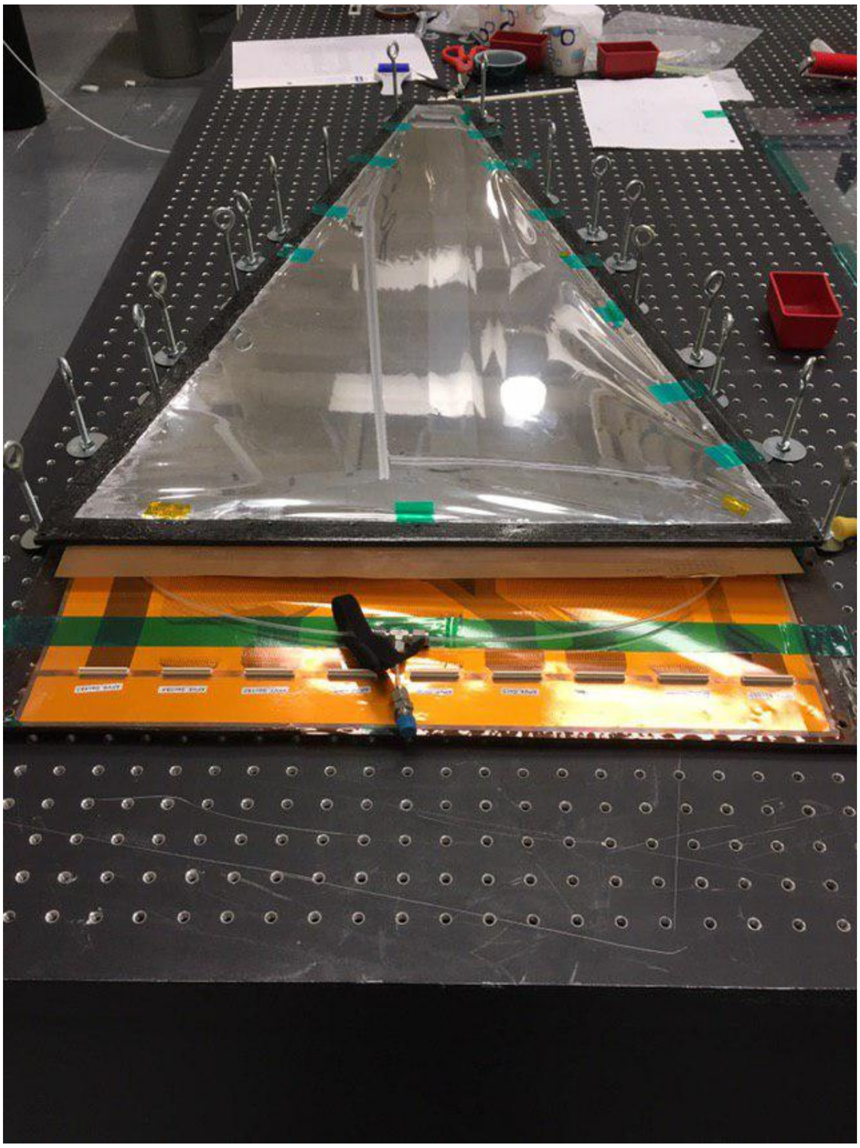
Report on Large-Area Gas Electron Multiplier



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Summary

The aim of this document is to present content that is useful for hardware developers in the EIC (electron-ion collider) group at Florida Tech. Included is an outline of everything to do with constructing the prototype large-area gas electron multiplier (GEM). Since developing a large-area GEM is the focus of the EIC hardware group, it is imperative to understand construction procedures. Afterwards, capacitance measurements between and of the foils are used to estimate what the electric fields will look like in the stack. An extensive appendix is provided that highlights safety information, an overview of useful supplies and materials, and instructions on how to use Autodesk Inventor.

Contents

1 Stretching GEM Foils

1.1 Overview of Method

The most important aspect of constructing a large-area gas electron multiplier (GEM) is in the stretching of the foil assembly making up the detector. One method that has been proven to be useful in sufficiently stretching the GEM foils is to pre-stretch each foil during the stack construction. This can be implemented with thinly cut strips of green tape attached uniformly around the perimeter of each foil.

Figure 1 illustrates how this method is implemented. A small portion of green tape is attached to a GEM foil between adjacent pull-outs, and more pieces of tape are attached in the same way between each pull-out on the long sides and wide end of the stack.

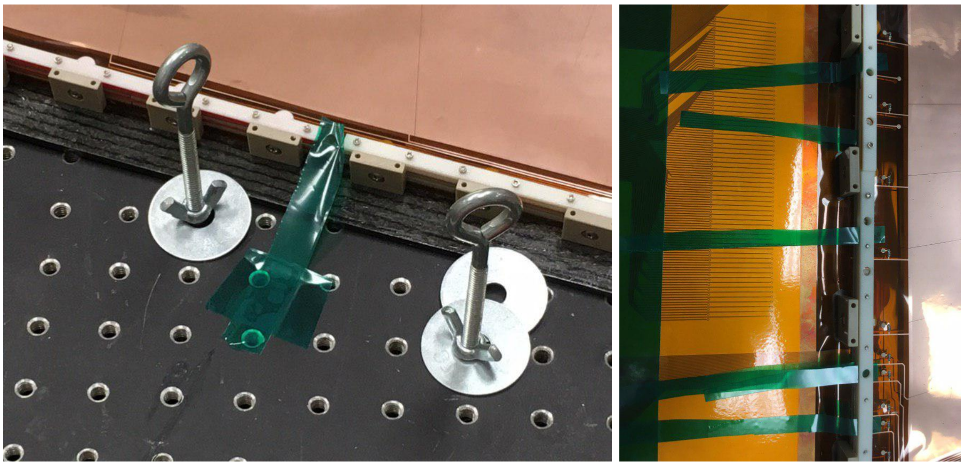

Figure 1: Examples of the pre-stretching method on the long sides and wide end where a portion of green tape is attached to a GEM foil between pull-outs

Various parts of the chamber were replaced with stronger equivalents. In the case of the stack, two layers of 3D printed inner frames were replaced with layers of machined poly-ether-ether-ketone (PEEK) frames. Since PEEK is stronger than ABS, the plastic material extruded in the 3D printing process, and the structural integrity of milled parts is greater than that of printed ones, this enabled the production of a stronger and more evenly spaced stack. With regards to the pull-out parts, the elements of the chamber responsible for stretching the stack, all of the 3D printed pull-outs were replaced with PEEK equivalents. The same logic applies with these parts as with the inner frames, resulting in a better pull on the stack. The fragility of ABS and the sturdiness of PEEK is displayed in Figure 2

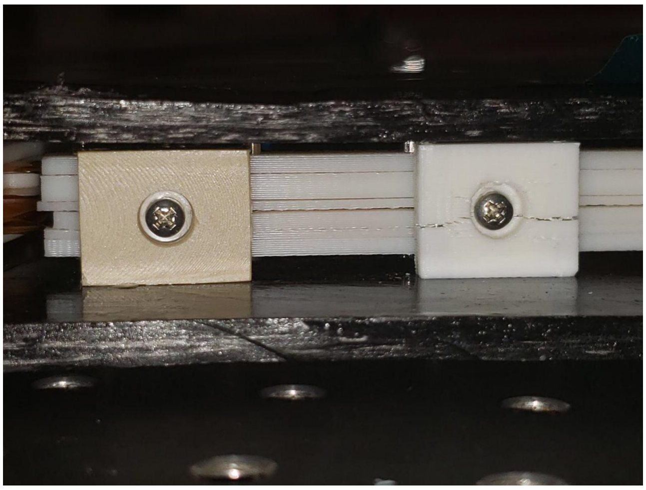

Figure 2: Comparison of PEEK (left) and ABS (right) pull-out parts shows how strong PEEK is in comparison to ABS

1.2 Basic Construction Procedure

The following provides an overview of constructing a large-area low-mass GEM. Note that this is not an extensive tutorial. An assumption is that the only parts attached to the read-out frame (clamped to the optical table) are: the read-out foil, pull-outs, and the bottom layer of inner frames with stack screws inserted. The stack screws act as guides for placing frames and foils.

1. Place layer of 2 mm inner frames on top of read-out foil
2. Place GEM 3 foil on top of inner frames
3. Attach green tape strips around perimeter of foil
4. Stretch foil with attached green tape and attach to optical table (Fig. 3)
5. Repeat previous steps for next two foils
6. Place stretching nuts in corresponding notches in inner frames
7. Place 3 mm inner frames on top of GEM 1 foil
8. Place drift foil on top of inner frames and repeat stretching method
9. Place final layer of inner frames on top of drift foil
10. Place stack nuts on stack screws and tighten nuts
11. Remove pieces of green tape
12. Attach stretching screws to stretching nuts
13. Tighten stretching screws, starting at corners and moving inwards

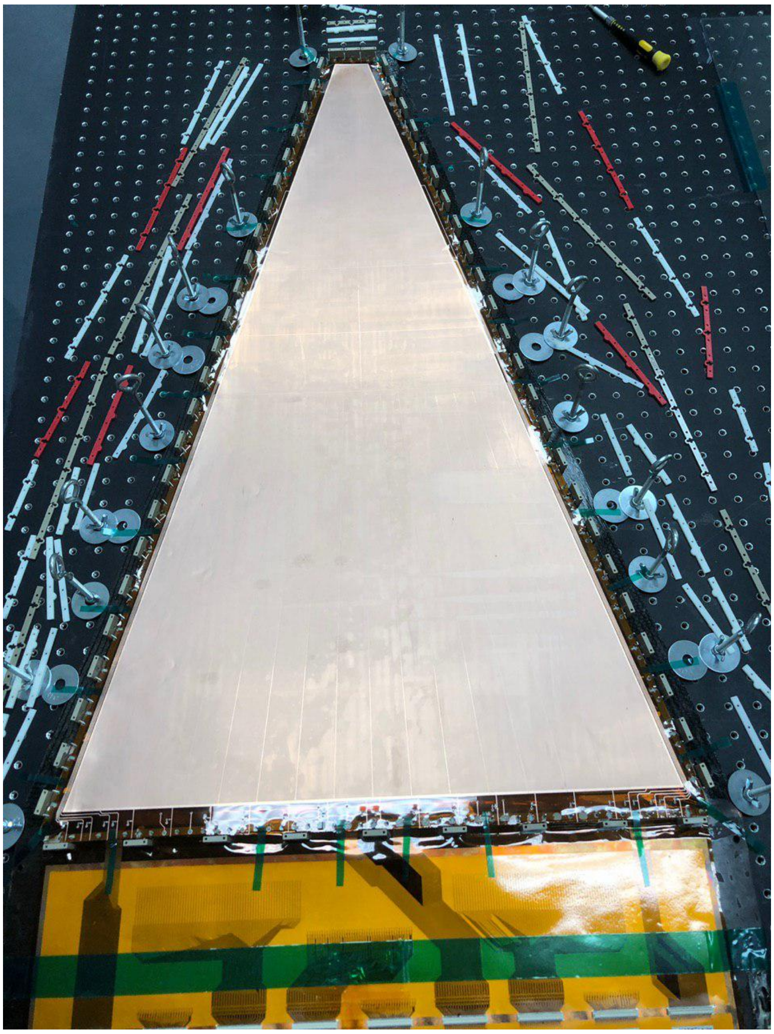

Figure 3: Third GEM foil undergoing pre-stretching via green tape portions

There are different aspects that are critical in putting together or taking apart a large-area low-mass GEM. First and foremost, one should take their time with removing nuts and use appropriately sized screw heads for removing nuts and screws. These screw heads may be found on the corner table of the cleanroom. Whenever a nut accidentally moves onto the active region of GEM foils, DO NOT remove it with gloved hands or tweezers. Instead, roll a small bit of green tape up and use it to carefully pick up stray nuts. Another thing to keep in mind is organizing parts. Whenever taking apart the stack, make sure the parts are organized such that one can easily remake the stack. This is critical since one does not want to lose parts.

1.3 Comparison With and Without Pre-Stretching

Without the pre-stretching implementation, one can easily see how effective this method is. Figure 4 compares the two cases. When constructing a GEM, it is critical to acheive and maintain flat foil surfaces. Through this pre-stretching method, this requirement is met.

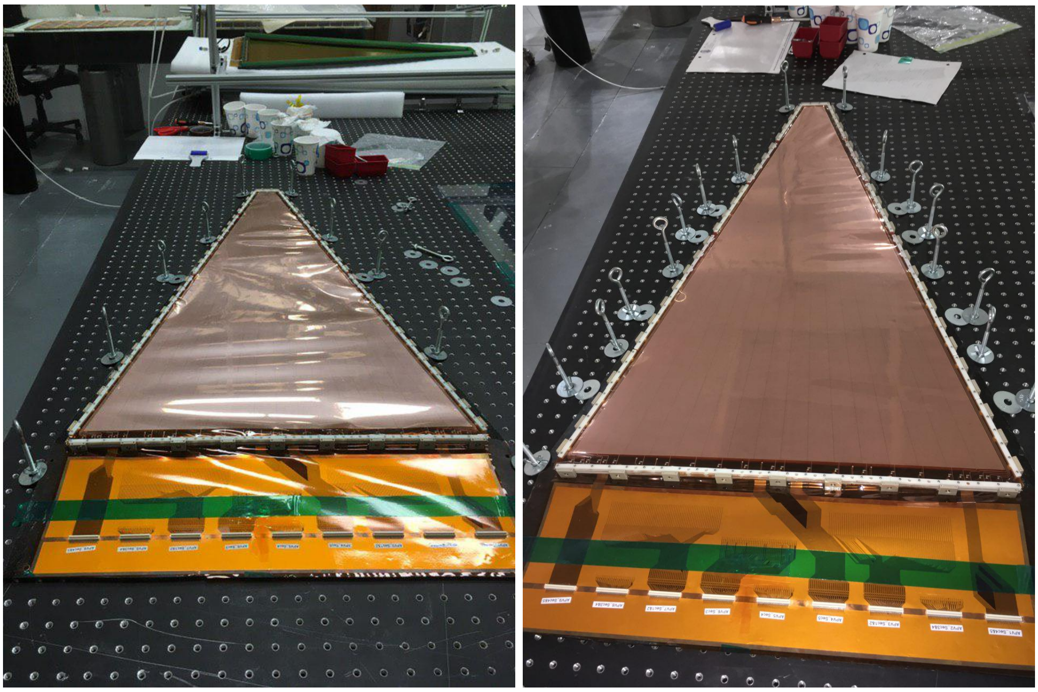

Figure 4: Without (left) and with (right) pre-stretching method, illustrating the effectiveness of this method

2 Projected Electric Field Trend in Stack

2.1 Theoretical Calculations

The geometry of GEM foils indicates that one could consider it as a parallel plate capacitor. A GEM foil consists of two 5 μm thick copper foils sandwiching a 50 μm thick polyimide layer. Figure 5 illustrates the geometry of a GEM foil.

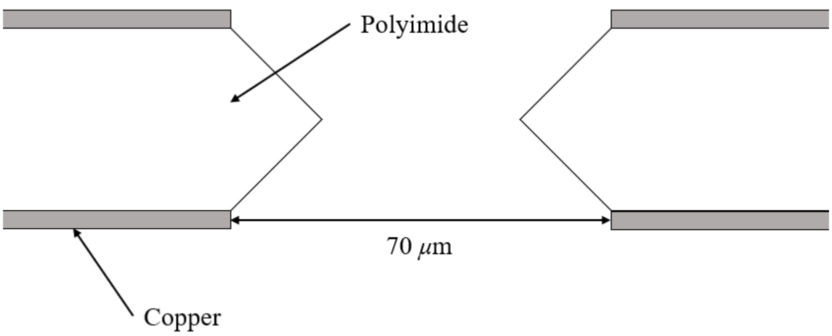

Figure 5: Cross-sectional view of a GEM foil, showing the hole diameter

As is commonly known, the capacitance between two parallel plates separated by an insulator is defined by the following formula.

$$C = \frac{\kappa \epsilon_0 A}{d}$$

In this case, κ is the relative permittivity associated with the insulating material, ϵ_0 is the permittivity of free space, A is the area of one plate, and d is the separation distance of the plates. It is trivial to extrapolate that a simple measurement of the capacitance of and between the GEM foils leads to a calculation of the actual spacing of and between the GEM foils.

According to Sharma's study on charge transfer in a GEM, the relative permittivity of air is 1, copper is 0, and polyimide is 3.4 [1]. Thus, one can calculate the relative permittivity of a GEM foil as follows. Since five-sixths of the foil is polyimide while one-fifth is copper, one can add the two permittivity values with their corresponding weights. This leads to a relative permittivity of 2.83.

The total area of the active region is a trapezoid, with long end of 529.0 $\pm$ 0.5 mm, short end of 43.0 pm 0.5 mm, and height of 904.0 $\pm$ 0.5 mm. Each value was extrapolated from models of the foils and the errors were assumed if one would measure using a meter stick. Using these values, the total area was calculated as 258,544 $\pm$ 3,020 mm^2. Using figure 5, the area of each copper hole was calculated as 70.0 $\pm$ 0.7 μm. This error was assumed for a one percent accuracy. As Sauli mentions in his 2016 paper on GEMs, the hole density on each foil is at most 100 mm^{-2} [2]. Using these values, a total area attributed to the holes was calculated and subtracted from the total area of the foil. This actual area came out to be 159,045 $\pm$ 2,445 mm^2.

With these calculations in hand, the theoretical capacitance of each GEM foil was easily calculated. Simply plugging in the actual area of copper, the relative permittivity of the foils, and 60 μm for the distance separating charges residing on each foil, the capacitance of each foil was calculated as 66.5 $\pm$ 0.7 nF. In a similar fashion, the capacitance in the drift, transfer, and induction gaps were calculated. Table 1 outlines the results from this calculation, the stack being in a 3-2-2-2 mm spacing configuration.

Table 1: Capacitance values for different gaps in the stack, calculated from considerations of optimal configuration of a triple stack

Gap	Capacitance [nF]	Error [nF]
Drift	0.469	0.005
GEM 1	66.499	0.665
Transfer 1	0.704	0.007
GEM 2	66.499	0.665
Transfer 2	0.704	0.007
GEM 3	66.499	0.665
Induction	0.704	0.007

2.2 Experimental Calculations

Using a capacitance meter, the capacitance between and of the foils was measured three times. A mean and standard deviation of the mean (SDOM) were calculated in the usual fashion. The error in measurement, 0.1%, was added in quadrature with the SDOM. These measurements are displayed in Table 2.

Table 2: Measurements of capacitance between and of GEM foils with discrepancies from theory

Gap	Capacitance [nF]	Error [nF]	Discrepancy [σ]
Drift	0.427	0.005	8
GEM 1	41.002	0.410	62
Transfer 1	0.688	0.009	2
GEM 2	41.370	0.414	61
Transfer 2	0.549	0.007	22
GEM 3	41.452	0.415	60
Induction	0.760	0.010	6

Clearly, these measurements deviate dramatically from Table 1, leading one to distrust the performance of the chamber in its current state. However, one must not rush to conclusions so soon, and so a calculation of the electric fields of and between the foils must be performed and compared to theory. The electric field between two parallel plates is inversly proportional to the plate separation. Thus, one simply switches around terms in the equation for a parallel plate capacitor to solve for plate separation. This equation is displayed below.

$$d = \frac{\kappa \epsilon_0 A}{d}$$

Using this formula and the measurements in Table 2, the spacing between and of the GEM foils was calculated. Uncertainties were calculated using the fractional uncertainties in area and capacitance. These results are displayed in Table 3. As with the capacitance measurements, one can note a dramatic deviation from theory. However, this calculation is very close to a 3-2-2-2 mm stack with 60 μm thick foils. The most important aspect of this calculation is that it shows there are no shorts between adjacent foils. This is critical in building a GEM detector since a short can significantly reduce the gain uniformity and potentially burn out electronics.

Table 3: Calculated spacing of and between foils with discrepancies from theory

Gap	Spacing [mm]	Error [mm]	Discrepancy [σ]
Drift	3.298	0.064	5
GEM 1	0.097	0.002	21
Transfer 1	2.047	0.041	1
GEM 2	0.096	0.002	21
Transfer 2	2.565	0.051	11
GEM 3	0.096	0.002	21
Induction	1.853	0.037	4

With this calculation in hand, the intra- and inter-foil fields can easily be calculated using the following equation.

$$|\mathbf{E}| = \frac{V}{d}$$

This was performed in a range of applied potential difference on the foils of 400 to 500 volts in steps of 20 volts. Figure 6 presents these results with corresponding trendlines and compares with theoretical fields, calculated using the optimal spacing values.

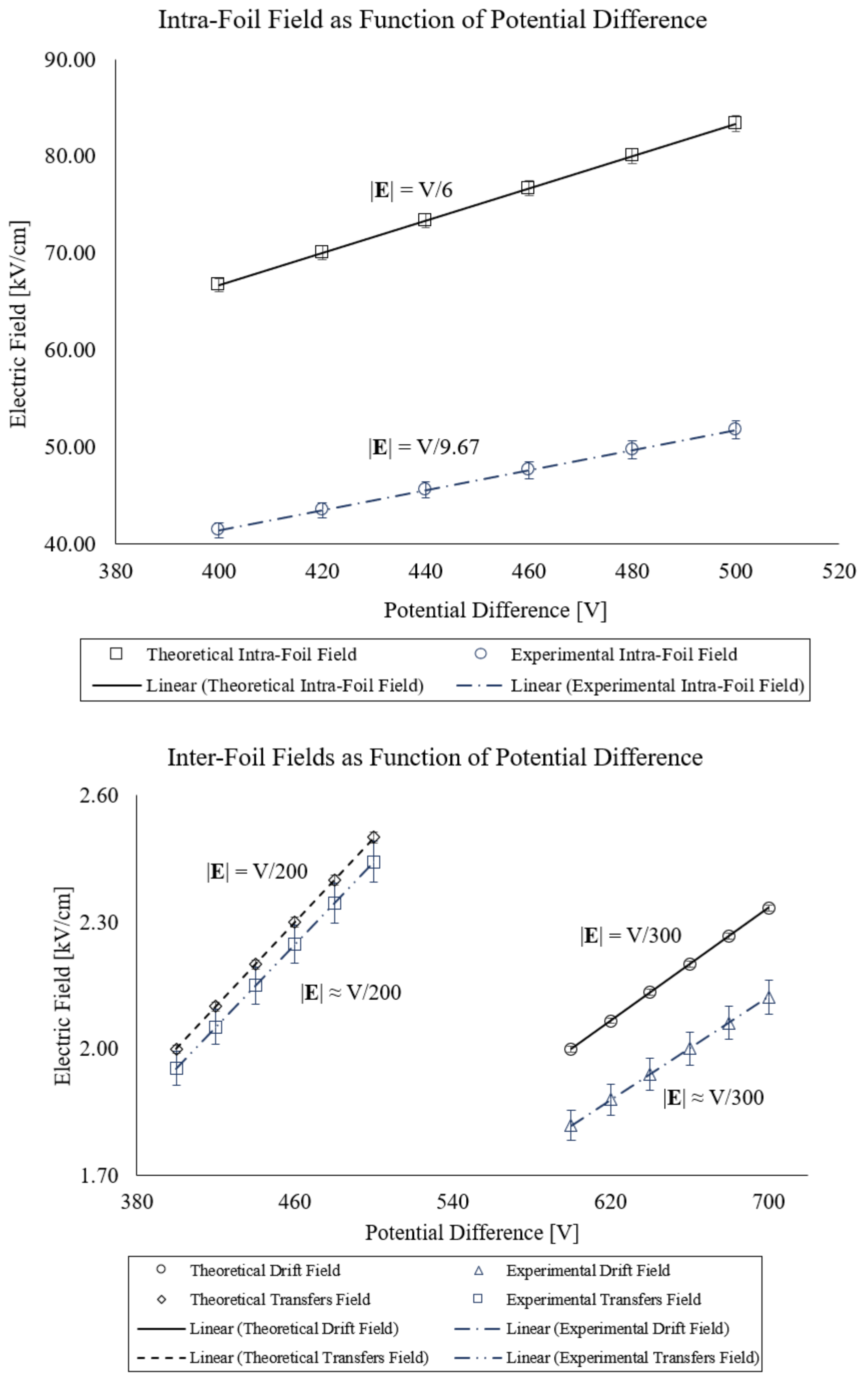

Figure 6: Intra- (top) and inter- (bottom) foil field trends for varying voltage; inter-foil fields follow essentially the same trend as theory, while the intra-foil field trend differs from theoretical considerations

2.3 Analysis

As can be seen in Figure 6, the calculated electric field trends throughout the stack tend to differ from theoretical expectations. However, when it comes to GEM detectors, the inter-foil fields are important for directing electron avalanches towards the readout structure. These also happen to trend in a similar fashion to theory, with slopes exactly that of theory. This indicates that, despite calculations deviating many σ's from theory, the electric fields between the foils would act nominally.

On the other hand, the fields in each GEM foil will not be as strong as what theory would suggest. The experimental slope is approximately 62% of what theory predicts, indicating that one should apply a larger voltage to achieve the optimal intra-foil electric fields for amplification of electron avalanches. As the chamber undergoes high-voltage tests in the future, the full voltage range of the chamber will be studied thoroughly to determine how high applied voltage can be while maintaining stability.

One thing to note is that these calculations were performed without consideration of the high-voltage divider, just similar voltages applied across each foil. A future study using trial divider resistance values and input voltage would shed more light on how the electric field tends to act in the current stack configuration.

A General Safety Guidelines

A.1 Working in the Cleanroom Environment

The cleanroom is an incredible asset in constructing GEM detectors. It reduces the particle count in an enclosed area, allowing one to confidently work on sensitive electronics such as GEM foils. The reason a GEM foil is so sensitive is because of the small hole diameters in the geometry of its active area.

Before entering the cleanroom, one must suit up. The following are critical cleanroom attire:

- Lab coat
- Shoe covers
- Hairnet

These are worn in all situations that one would be in the cleanroom. However, when working with exposed GEM foils, one needs the following elements:

- Face mask or beard cover
- Non-latex gloves

One should not stay in the cleanroom too long, a few hours at a time should be enough. If one stays in too long, perspiration builds up and the risk of ruining electronics increases. Take breaks when needed to avoid exhaustion.

A.2 Working with Epoxy or Varnish

Without the necessary instruction, using epoxy or varnish can result in irritation and skin damage. The chemicals involved are abrasive, so one should always put on gloves before using epoxy or varnish. For epoxy, use a flat surface, such as a metal plate, to mix the resin and hardener extruded from the two-in-one container in the bottom drawer at the gluing/soldering station. In the case of varnish, use the plastic containers in the same drawer to mix varnish and hardener. For both cases, do not throw away liquid waste. Let the left over portions dry and throw out the solid waste.

B Supplies and Materials (S&M)

As a hardware developer, it is important to know where S&M are located. Next to the clean room, a set of bookshelves is located that contain tools in clearly marked containers. This is where one would find screwdrivers and other necessary tools for building a particle detector. Next to the bookshelves are two yellow containers with black lids stacked vertically. In these boxes are screws, high voltage dividers (in a labeled antistatic box), and other various items used by the EIC group. The screws and nuts are discriminated as follows for different parts of the detector:

- M1.6 nuts and screws, stack construction
- M2.5 nuts and short screws, stack stretching

- M2.5 long screws, chamber closing

The distinction between various components is key to understanding the construction of the GEM.

The high voltage dividers, located in a small black box with appropriate labeling, are configured for 3-1-2-1 mm foil spacing in the stack. If one wishes to modify a divider to accomodate for shorts, simply connect the legs that attach to the shorted region with a small piece of metal wire. In the case of modifying a divider for different stack geometries (such as 3-2-2-2 mm foil spacing), simply take total and pair resistance measurements of the divider and modify the pair resistances appropriately with high voltage resistors.

Other materials an EIC hardware developer should be aware of are the raw materials used to make different parts or add to the detector. These include sheets of poly-ether-ether-ketone and the roll of aluminized KAPTON for sealing the chamber. Two thicknesses of KAPTON are available, 2 and 5 mm. The 2 mm thick sheet has been used to machine inner frame pieces, while the 5 mm thick sheet was used for making pull-out parts.

C Autodesk Inventor Professional: A Quick Tutorial

C.1 Motivation

Solids modeling is an important skill to understand when working with hardware. With the widespread availability of 3D printers, one can easily design parts and manufacture them in a short amount of time. Since the large-area GEM for EIC uses parts that are 3D printed and novel, one should understand how to use a solids modeling software package. Inventor is an easy to learn, GUI-based solids modeling software. A powerful student version is available for free through Autodesk. Simply input your "my.fit.edu" email address to make an account and choose the version to download.

C.2 Sketching Shapes

When performing sketches, one should remain in the "Sketch" environment, found on the top menu bar. Click on "Make Sketch." In this environment, one can easily find various shapes to make sketches with. Whenever making a sketch, be sure to start from the simplest shapes to make a design (i.e. circles, rectangles, and lines). After laying down these initial shapes, removing unnecessary lines is easy. Another thing to keep in mind is to always add dimensions to sketches. This makes life easier when changing parameters.

C.3 Extruding Sketches: 2D to 3D

After making a sketch, simply move to the main environment and click on "Extrude." This allows one to select elements of a sketch to extrude in various directions. Select the direction of extrusion (forward, backwards, or both ways) and the desired extension length, and a solid 3D shape will emerge. The amazing thing about solids modeling softwares like Inventor is that once a 3D shape is created, one can sketch on surfaces of the shape and either remove or add material to the shape.

C.4 Afterword

When working with Inventor, try to visualize the object and how it could be made in the simplest fashion. This will reduce headaches and increase the maintainability of a design. Since this overview is not extensive, when encountering a problem look online for forum entries similar to that issue. Most likely, it has already been solved and tips will be outlined.

References

[1] A. Sharma. "A How-to Approach for a 3d Simulation of Charge Transfer Characteristics in a Gas Electron Multiplier (GEM)." CERN, Geneva, Switzerland. GSI Darmstadt, Germany. 2000.

[2] F. Sauli. "The gas electron multiplier (GEM): Operating principles and applications." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. Vol 805, pp 2-24. Jan 2016.