Thermal Stretching of GEM Foils and Characterization of Triple-GEM Detectors for Uses in Astronomy

> BRYANT BENSON ADVISOR: DR. MARCUS HOHLMANN APRIL 25, 2011

#### **Charged Particle Interaction With a Gas**

Average energy lost per unit distance traveled by a fast moving charged particle is given by the Bethe-Bloch function

$$-\frac{\mathrm{dE}}{\mathrm{dx}} = K \frac{z^2}{\beta^2} \frac{Z}{A} \left[ \frac{1}{2} Ln \left( \frac{2m_e c^2 \beta^2 \gamma^2 T_{\mathrm{max}}}{I^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$
$$K = \frac{N_A e^4}{4\pi \varepsilon_0^2 m_e c^2} \qquad T_{\mathrm{max}} = \frac{2mc^2 \beta^2}{1 - \beta^2}$$

This energy loss distribution is fit with an asymmetric exponential function referred to as a Landau curve

$$f(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\lambda + e^{-\lambda})}$$
$$\lambda = \frac{\Delta - \Delta_m}{\xi} \quad \xi = \frac{K}{2} \frac{Z}{A} \frac{1}{\beta^2}$$

Plot of Energy loss vs. the Kinetic Energy of a charged particle moving through air [1]



### Photon Absorption in a Medium

Detection of high energy photons is important for GEM detector development both because radioactive X-ray sources of known energy are used to test the uniformity of the detectors as well as the desire to use GEM detectors for X-ray Astronomy

$$I = I_0 e^{-\sigma NX} = I_0 e^{-\mu x} = I_0 e^{-X/\lambda}$$



Plot of Absorption Coefficient vs. Photon Energy (left) and Mean Free Path vs. Photon Energy (right) for photons in multiple gas mediums [2]



## **Photoluminescence of Metals**

Photoluminescence occurs through the absorption and re-emission of photons with sufficient energy to cause excitation or ionization in the metal

Resonant radiation: Incident photons match the energy of an excitation or ionization level and an electron or new photon of equal energy is quickly reemitted





Simulated plot of Intensity vs. the Wavelength and Energy of photons emitted through photoluminescence of Copper due to field emission [3]

# **GEM Foil Configuration**

GEM foils have holes that are chemically etched through the Copper and Kapton to have a conical shape, which leaves an extra quantity of Kapton as insulation to prevent sparking as well as reduce the hole diameter to concentrate the electric field



Magnified view of a GEM foil showing the hole pattern with 70 µm outer diameter, 50 µm inner diameter, and 140 µm pitch [4]



Cross sectional view of two holes in a GEM foil showing electric field lines (red) and electric equipotential lines (green) [4]

# **Gas Electron Multiplication**

Gas Electron Multiplication starts with an initial electron being liberated in the drift region of the detector, which is then accelerated in the electric fields to cause multiple ionizations along its path



Detector uses an Ar:CO<sub>2</sub> 70:30 mix

Ionizations occur in the Ar, while CO<sub>2</sub> is used to mitigate secondary ionizations

Use of multiple GEM foils, as shown in the diagram, allows for higher gain at lower operating voltages [4]

Gain (G<sub>i</sub>) is the ratio between the number of initial electrons (N<sub>0,i</sub>) and the number of electrons after multiplication (N<sub>f,i</sub>)

$$G = \frac{N_{f,i}}{N_{o,i}}$$
  $G_{tot} = G_1 G_2 G_3$ 

#### **Advantages To Using GEM Detectors**

- Time and Cost of Production
- Active Area of Detector
- Position Resolution
- Time Resolution
- Radiation Hardness and Resistance to Aging Effects
- Specific Energy Sensitivity Range

# **Stretching of GEM Foils**

Stretching of GEM foils is required to ensure a uniformly smooth surface with no sagging, which in turn gives a uniform Electric Field around the GEM foil inside the detector after high voltage is applied



A tension of 1 kg/cm is required to keep the GEM foil from sagging more than 20  $\mu m$ 

### **Conventional Stretching of GEM Foils**

Original stretching of GEM foils has been done in a clean room oven, but a mechanical stretching procedure has been developed with the advent of larger GEM foils



Advantages to using an oven are uniform temperature and multiple stretching [5]



Advantage to using mechanical stretcher is precise tension control [6]

# **IR Stretching of GEM Foils**

Our new method minimizes cost, reduces space required, and provides enough space to work without removing the frame from heat

Direct heat from IR bulbs on a 48cm x 48cm acrylic stretching frame causes expansion, which in turn stretches the GEM foil



Acrylic has coefficient of thermal expansion of 0.0075 mm/m/K, which allows it to expand enough under direct heat to stretch the GEM foil

At 45 degrees Celsius our stretching rack expands almost .09 mm in each direction

#### **Temperature Uniformity Measurements**

A uniform temperature output is required from the IR stretching rack in order to ensure the uniform stretching of the GEM foils



Temperature vs. Location at 95 minutes



Temperature warm up profile for one side of the acrylic stretching frame Temperature uniformity plot every 3 cm after the acrylic stopped expanding

## **Larger IR Stretching Rack**

One of the major reasons behind the development of new IR stretching method was scalability for stretching larger GEM foils

Temperature uniformity mapped for the entire 115 cm x 66 cm acrylic stretching frame along with a histogram of measured temperatures after the temperature has stabilized [7]



Frame stretched 0.20 mm x 0.11 mm

Large CMS test foil uniformly stretched under our larger IR stretching rack



## **Characterizing GEM Detector**

Our GEM detectors were tested with a Cd-109 source both for Gain and rate uniformity. Test points were chosen where our readout capabilities for the X and Y readout planes overlapped. With six channels in each plane, this gave us 36 test locations (72 total tests performed on each GEM detector).

A large paper was marked with similar lines to the figure shown and taped to the GEM detector surface to ensure data was collected at the same location for each trial.



# **Charge Sharing**

X-plane strips (top) have a smaller width than Y-plane strips (bottom) to allow electrons to induce signal on both layers, yielding 2-D readout capability



Both layers have a pitch of 400  $\mu$ m and the top and bottom strips 80  $\mu$ m and 340  $\mu$ m thick respectively [4]

We expect an average energy peak to be approximately 20% higher on the X strips than the Y strips

## **Signal Analysis**

All of our data was collected with a LeCroy oscilloscope, utilizing triggering settings to minimize noise in the data and integrating the area of the signal pulse to read the full charge detected

Trigger settings dictate which pulses are saved in a data set based on a minimum negative threshold



Pulse Area is a better measure of charge detected because of full signal integration

# **Noise Hunting**

Noise was a very serious issue in our detectors until the major sources were identified and eliminated





Symptoms of Noise include:

- RF Pickup
- Periodic signals
- Positive peak signals
- Bipolar peak signals

Major sources of noise include:

- Other electronic equipment
- Power strips
- Electrical cords
- Grounding wire on readout connector

## **Pedestal Measurements**

Pedestal measurements are taken at a non-operational voltage as a baseline noise due to external sources

Pedestal measurements are an average baseline measurement of noise in the detector taken for subtraction from any signal detected

Our pedestal data was taken with 1000 V applied to the detector using an external trigger from a Na-22 source

An external trigger was used to prevent a single burst of noise from dominating the measurement

GEM 9 Pedestal			GEM 10 Pedestal		
Connector	Mean (V*μs)	Rate (Hz)	Connector	Mean (V*µs)	Rate (Hz)
Con1	0.010	37.22	Con1	-0.047	46.80
Con2	0.010	36.85	Con2	-0.047	49.92
Con3	0.009	36.99	Con3	-0.047	50.00
Con4	0.009	36.67	Con4	-0.047	50.25
Con5	0.012	36.54	Con5	-0.047	49.67
Con6	0.013	37.13	Con6	-0.046	50.17
Con7	0.013	36.76	Con7	-0.047	50.00
Con8	0.015	36.63	Con8	-0.049	51.28
Con9	0.014	36.76	Con9	-0.049	50.76
Con10	0.014	36.45	Con10	-0.049	50.59
Con11	0.015	36.58	Con11	-0.049	50.93
Con12	0.014	36.76	Con12	-0.049	51.28
Average	0.012	36.78	Average	-0.048	50.14

#### Cd-109 and Fe-55 Measurements

Energy peaks for the two different sources taken at the same location to calibrate the mean energy value

Each histogram has less than 1% error in photopeak location and rate



High-statistics measurement with Cd-109 source (left) turned out to yield Copper photoluminescent peak when compared to Fe-55 peak

Medium-statistics measurement with Fe-55 source (right) taken over night, requiring the subtraction of cosmic events



#### **GEM 9 X-Uniformity Measurements**

Photopeak energy has σ of 7.1% Trigger rate has σ of 10.8%





### **GEM 9 Y-Uniformity Measurements**

Photopeak energy has σ of 12.69% Trigger rate has σ of 14.76%





### **GEM 10 X-Uniformity Measurements**

Photopeak energy has σ of 7.82% Trigger rate has σ of 11.46%





### **GEM 10 Y-Uniformity Measurements**

Photopeak energy has  $\sigma$  of 9.09% Trigger rate has an  $\sigma$  14.92%





## **GEM 9 and 10 Uniformity Results**

	GEI	M 9	GEM 10	
	Mean (V*µs)	Rate (Hz)	Mean (V*µs)	Rate (Hz)
X Strips	3.6	23.4	2.9	24.4
Y Strips	3.3	30.1	2.3	28.1
Percent Difference	10%	21%	24%	14%

	GEM 9 vs. GEM 10				
	Mean (V*µs)	Rate (Hz)			
X Strips	21.5%	4.2%			
Y Strips	35.7%	6.9%			

## **Cosmic Ray Muon Measurements**

Detection of muons were done on whole clusters of 8 strips, having an active area of 9.8 cm<sup>2</sup>

These plots are very indicative of all the cosmic data taken, having a well defined peak with a good fit to the landau curve





Average peak energy for GEM 9 and 10 are 0.464 and 0.235 V\*us respectively

Both detectors have an average collection rate around 31 Hz

#### **Plateauing GEM Detectors With Muons**

Plateuing is done to determine the ideal operating voltage for the GEM detector

Plateuing is performed with two small scintillator paddles placed above and below the detector for external coincidence triggers



Number of Muons vs. Voltage

## **Coded Aperture Mask**

The coded aperture mask technique used for high resolution imaging of X-ray sources originated with the pinhole camera

Pinhole camera uses a single small aperture in an otherwise opaque mask to focus an inverted image of an object onto a detector



Smaller hole diameter increases the resolution of the image, but decreases the light flux

Optimum aperture size is approximately d/100

Extended exposure time is required for better imaging

## **Coded Aperture Mask Concept**

A coded aperture mask is an instrument with opaque and transparent cells that casts a shadow pattern onto a position sensitive detector in order to obtain a higher quality image than would otherwise be obtained

![](_page_30_Figure_2.jpeg)

Diagram of a coded aperture mask and position sensitive detector showing a projected shadowgram [8] (left), flux from two point sources projecting a shadowgram onto the detector through a mask [9] (middle) and the extent of the Fully Coded Field of View and Partially Coded Field of View for a mask/detector instrument [9] (right)

#### **Angular Resolution From Coded Aperture Mask**

Angular resolution using a coded aperture mask is dependent upon the mask hole width (m), the position resolution of the detector (d) and the distance between the mask and detector (l)

$$\partial \theta = \sqrt{(m/l)^2 + (d/l)^2}$$

Decreasing the mask hole size improves the angular resolution but decreases the SNR and detector sensativity

Increasing the distance between the mask and detector improves angular resolution but decreases the FCFV and the SNR [10]

![](_page_31_Figure_5.jpeg)

## **Coded Aperture Mask Designs**

Coded aperture masks find their origins in the single pinhole camera but have evolved to be much more effective over the last 50 years

#### **Random Mask:**

utilizes a (semi) random assortment of opaque and transparent cells. These masks were the first step in coded aperture mask designs and can have any size dimensions [9].

![](_page_32_Picture_4.jpeg)

#### **Uniformly Redundant**

Array (URA): open cells are placed in a regular rectangular or hexagonal pattern according to an algorithm. The redundant image provides a very high SNR [9].

![](_page_32_Picture_7.jpeg)

Gaussian Random Field (GRF): the spread function for image reconstruction is determined first based on desired imaging characteristics. Hole pattern is then generated based on the desired GRF [11].

![](_page_32_Picture_9.jpeg)

Initial models used an Argon volume as the position sensitive detector, but the program only allowed a 10% efficiency in this detector To solve this problem the Argon volume was replaced with a Nal detector with over 80% efficiency using the same position and energy sensitivities

![](_page_33_Picture_2.jpeg)

Single point source 10 m away imaged with the 400 µm pixel Argon detector with 100 photons

![](_page_33_Figure_4.jpeg)

Vertical and horizontal slice plots of the point spread functions for the reconstruction from which the SNR of 1.8 is found

Each of the extended source models used the 5cm x 5cm Nal detector with 130  $\mu$ m pixels and a 15cm x 15 cm coded aperture mask with 50% opaque cells of dimension 2cm x 2cm

![](_page_34_Picture_2.jpeg)

Single line source 1 m long and 10 m away imaged with 1100 photons

![](_page_34_Figure_4.jpeg)

Vertical and horizontal slice plots of the point spread functions for the reconstruction from which the SNR of 1.1 is found

More complex models using multiple line sources were not as successful in their image reconstructions

![](_page_35_Picture_2.jpeg)

Two line sources each 1 m long and 10 m away in a cross pattern imaged with 3300 photons

![](_page_35_Figure_4.jpeg)

Vertical and horizontal slice plots of the point spread functions for the reconstruction from which the SNR of 1.1 is found

Smaller boxes used as an extended source were successfully imaged, although angular resolution gives the wrong length for the box sides

![](_page_36_Picture_2.jpeg)

Moderately successful reconstruction of a box with 0.5 m sides placed 10 m away imaged with 1200 photons

![](_page_36_Figure_4.jpeg)

Vertical and horizontal slice plots of the point spread functions for the reconstruction from which the SNR of 1.2 is found

Attempts to model more diffuse sources such as spheres, cylinders, large boxes, longer lines, or complex arrangements of lines failed to produce a reconstructed image

![](_page_37_Picture_2.jpeg)

Failed reconstruction of a cylinder with 0.5 m radius placed 10 m away imaged with 1100 photons

![](_page_37_Figure_4.jpeg)

Vertical and horizontal slice plots of the point spread function for the reconstruction from which the SNR barely above 1 is found

## Conclusions

- Designed, developed, and implemented the prototype IR stretching rack
- Constructed two 30cm x 30cm triple-GEM detectors
- Characterized two 30cm x 30cm triple-GEM detectors
- Modeled GEM-like detector with a coded aperture mask
  - Two dimensional readout GEM detectors are an improvement over conventional detectors in use for integrated runs
  - Fast sources, like lightning, may be better served with pixel readout due to limitations in charge sharing

## References

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## **Escape Peak**

An escape peak is formed by a number of photon interactions in the gas resulting in one primary ionization electron and a re-emitted X-ray with a long mean free path

Escape peak for argon is known to be 3.2 keV less than the primary peak

![](_page_40_Figure_3.jpeg)

linear