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Methods of Testing Gas Electron Multipliers For Use in a Time Projection Chamber

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Dear Sir:

This report entitled "Methods of Testing Gas Electron Multipliers For Use in a Time Projection Chamber", was prepared as my 2A Work Report for the Department of Physics at Carleton University. This is my first work term report.

Studies are underway at Carleton University in the development of particle detectors for use in a future linear collider experiment.

This report will analyze the effectiveness of the methods used in the testing of Gas Electron Multipliers for use in a Time Projection Chamber. The current experimental set-up is also outlined in detail, to be followed by new experimenters working with GEM detectors for the first time.

This report was prepared by me and has not previously been submitted for academic credit at this or any other institution. I would like to thank Madhu Dixit, Jacques Dubeau, Dean Karlen, and Ernie Neuheimer for their assistance with this report.

Sincerely,

M. C. Garrett
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Summary

This report focuses on the methods of testing Gas Electron Multiplier (GEM) particle detectors, to be used in a Time Projection Chamber (TPC) readout in a future linear collider experiment. The detectors are tested by use of an x-ray source, and the signals produced by the detector are collected and analyzed. The scope of this investigation is to provide a description and analysis of these testing methods, with considerations given to the entire experimental set-up and detector theory.

Gas Electron Multiplication is achieved through the application of a strong electric field to a volume of monotomic gas, in the presence of radiation. Charged particles ionize gas atoms through collisions, releasing valence electrons. When the electric field intensity is great enough, the freed electrons gain enough kinetic energy to ionize other gas atoms through collisions, creating an "avalanche" of electrons; a charge cloud. The electric signals produced by these charge clouds can be analyzed, and the position and energy of the charged particle's interactions can be measured.

Accurate testing of these GEM detectors requires the use of modified electronics that do not distort the small signals and consistent and precise methods of data acquisition and analysis. Methods of modifying these electronics, and of properly acquiring data are discussed, and it is also concluded that these methods are entirely practical.

The reduction or removal of all signal distortions, and the use of modified electronics, as well as the use of consistent data acquisition methods are recommended.

1.0 Introduction

Particle detectors have always been an important part of high-energy physics experiments. Whether tracking high-energy charged particles produced in a linear collider, or cosmic rays from elsewhere in the universe, it's important to have a robust, accurate, well-tested detector to record such events.

The first particle detector was the Proportional Counter, developed in 1908 by H. Geiger and E. Rutherford, which could only detect a particle's presence, but not it's position or trajectory. Today, detectors are capable measuring a charged particle's energy, position, and trajectory to a high degree of accuracy.

Studies are currently underway at Carleton University of Gas Electron Multipliers (GEMs) for use in Time Projection Chamber (TPC) readout in a future 500-800 GeV electron-positron collider experiment.

To study these GEMs, the proper experimental set-up is important. The GEM detector must be put together properly, an appropriate radiation source must be used, the electronics must handle the signals with as little distortion as possible, and data must be properly acquired and analyzed. This report explains and suggests the best methods of testing the experimental GEM set-up. The study includes a description of the current set-up and the basic theory behind it, techniques used to modify the electronics, methods of acquiring and analyzing data, and plans for future research and development.

2.0 Current Set-up

2.1 GEM Structure

The double GEM detector consists of four main components: The drift plane on top, the readout plane on the bottom, and two GEM meshes in between (see fig. 1).

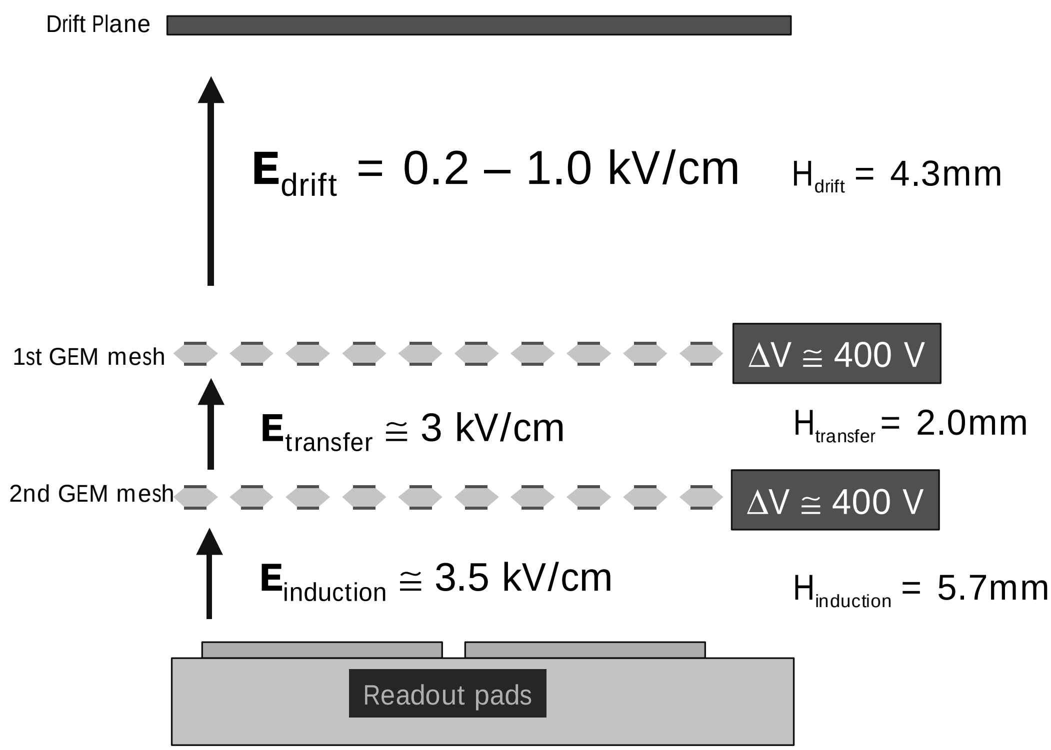

Figure 1. Layout of double GEM detector

The **drift plane** is a conductive layer of metallized mylar. It is connected to a high negative potential (usually 3 – 5kV), thus repelling electrons towards the GEM meshes. The drift plane and the first mesh are separated by a gap of 4.3mm, called the **drift region**. The electric field in the drift region is typically 0.2 - 1.0kV/cm.

Each of the **GEM meshes** is made up of an insulating layer of kapton, about 50 microns thick, with thin conducting layers of copper on either side, each about 5 microns in thickness. The three layers are perforated with a matrix of small circular holes, 50 microns in diameter with a 140 micron pitch, arranged in a hexagonal pattern (see fig. 2). Because of the two-sided chemical etching technique, the holes have a double conical shape. There is a potential difference of about 400V between the top and bottom copper layers, intensifying the electric field within the holes (see fig. 3). The first and second meshes are separated by a gap of 2.0mm, called the **transfer gap**. In this gap, the electric field is about 3kV/cm.

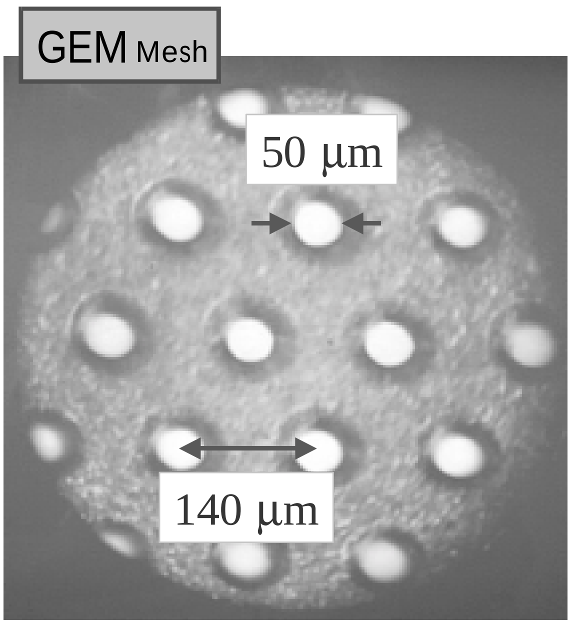

Figure 2. GEM mesh under microscope

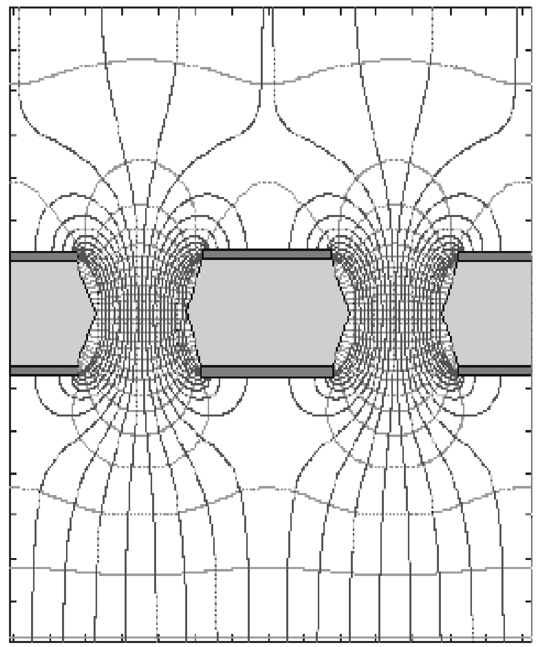

Figure 3. Electric field lines within GEM mesh holes

The **readout plane** is a printed circuit consisting of 32 pads of 2.5mm pitch and 32 strips of various widths on copper clad G10; a common circuit board material (see fig. 4). Each pad or strip is connected to an individual channel in the electronics. The readout plane is at ground potential, thus absorbing electrons. The second mesh and the readout plane are separated by a gap of 5.7mm, with an electric field of about 3.5kV/cm, called the **induction gap**.

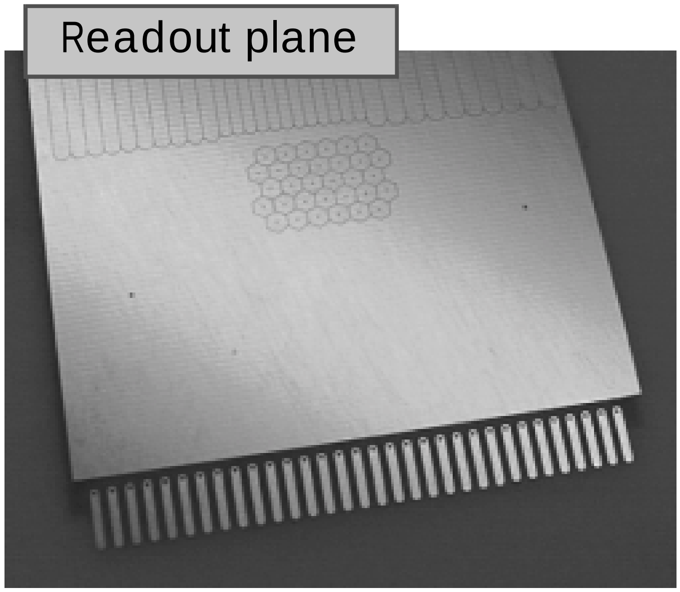

Figure 4. Readout plane

2.2 X-Ray Source

An x-ray tube is used to test point resolution in the GEM detector. This source produces an x-ray beam with a mean energy of 4.5keV, which passes through a pinhole collimator, shaping the beam to a diameter of 50 microns. The beam is pointed at the detector perpendicularly to the drift plane. The horizontal (x-axis) and vertical (y-axis) positions of the x-ray beam can be adjusted using the 2D micrometer stage (see fig. 5).

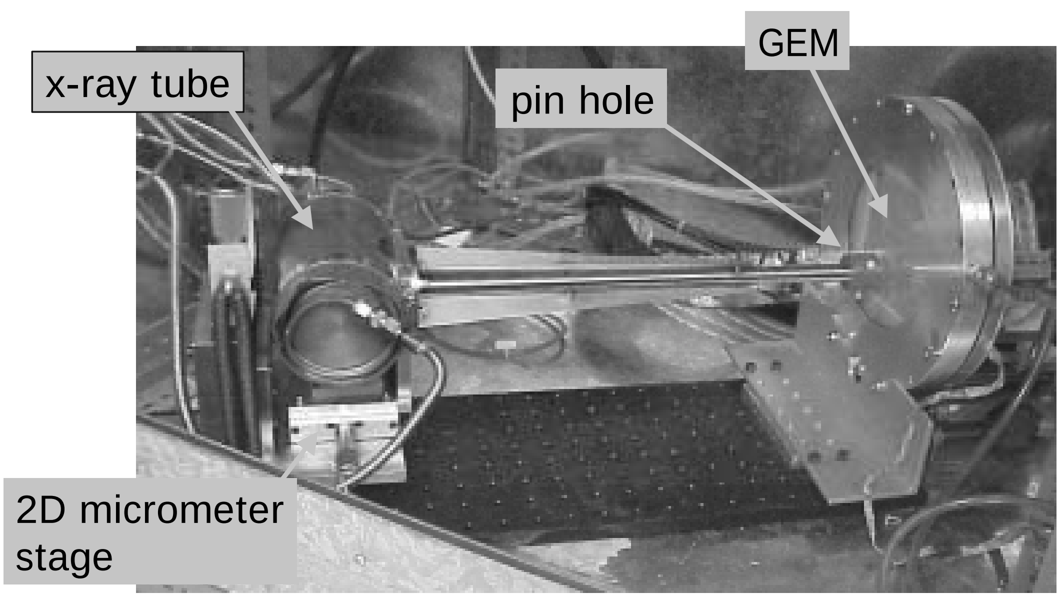

Figure 5. X-Ray and GEM set-up

2.3 Electronics

When pulses are produced in any of the 32 pads or strips on the readout plane, they must pass through a system of electronics so that they may be collected as data. The channels first pass through a pre-amplifier (pre-amp) to immediately increase the signal sizes so that they are not lost amongst the electronic noise. They then pass through the amplifier, where they are enlarged further, and then passed into the digital oscilloscopes. After appropriately adjusting the time and amplitude scales of the ocsilloscopes, the signals can be acquired on computer by using a data acquisition program, which records the waveforms diplayed on the oscilloscopes (see fig. 6).

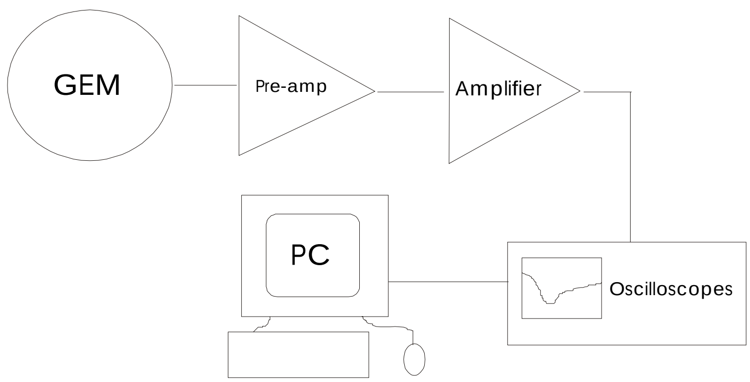

Figure 6. Electronics set-up

2.4 Basic Theory

The process of particle detection begins when a charged particle enters the drift region. As it moves through the gas volume within the drift region, it collides with some of the gas molecules. When a collision occurs with sufficient energy, the gas molecule is ionized, releasing one of its valence electrons. Because of the strong electric field in the drift region, the freed electron, called a **primary electron**, is pulled towards the first GEM mesh, while the positive ion is pulled towards the drift plane.

As a primary electron is accelerated towards the first GEM mesh by the electric field, it is pulled into one of the holes in the mesh, where the electric field is most intense. In this intense field, the electron gains enough kinetic energy to ionize other gas molecules with which it collides, releasing more valence electrons. A chain reaction of ionizations occurs, resulting in the release of between 50 and 100 more electrons for each primary electron. This chain reaction is called a **Townsend avalanche**, as it is analogous to an avalanche, only with charge acted upon by an electric field, as opposed to mass acted upon by a gravitational field (see fig. 7). This cloud of electrons is pulled though the transfer region by the electric field and into the holes of the second mesh, where the same avalanche process occurs a second time. The number of electrons that are released in the avalanche for each primary electron created is called the **gain** of the GEM. In the current detector, the gain in each GEM mesh is about 70, for a total gain of about 5000.

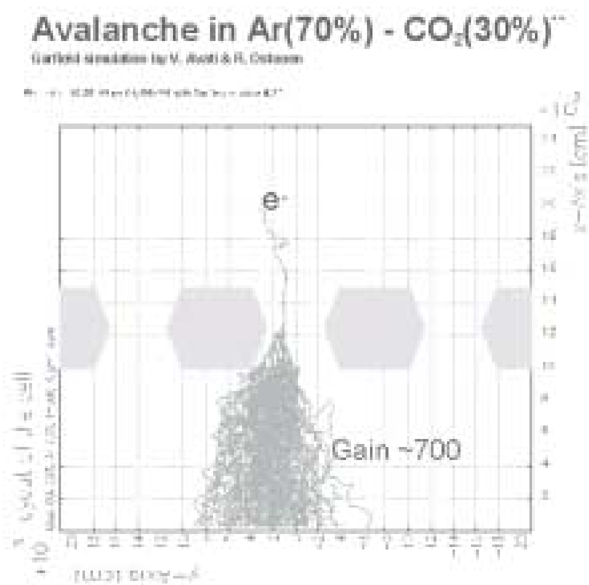

Figure 7. Simulation of Townsend avalanche

After the cloud of electrons passes through the second GEM mesh, it is propelled towards the readout plane by the electric field in the induction gap. As the charge cloud approaches the readout plane, it repels the electrons in the pads or strips, creating an **induced pulse** of amplitude inversely proportional to the proximity of each pad or strip. When the charge cloud finally reaches the pad(s) or strip(s) over which it is centred, the pad(s) or strip(s) absorbs the electrons, creating a large **direct charge pulse**, which slowly rises back to zero voltage over a period of time, as the charge must take time to drain. Those pads or strips that do not absorb any charge and experience only an induced pulse, however, return to zero voltage immediately. Some pads or strips may absorb a small amount of charge, but also have a visible induced pulse component, resulting in a **mixed pulse** (see fig. 8).

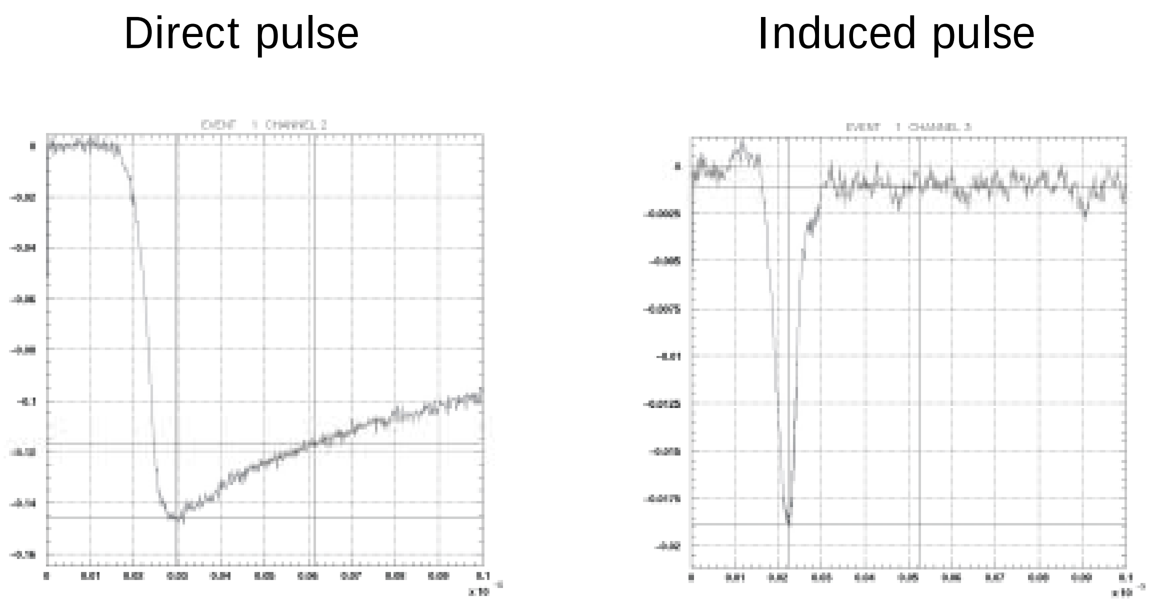

Figure 8. Direct and Induced pulses

The signals then travel through the system of electronics mentioned earlier: pre-amp, amplifier, oscilloscope, and finally acquired by the computer system.

2.5 Fill Gas

The fill gas used in the detector is P10, which is a 90:10 mixture of argon and methane, respectively. Argon is used because it is a monatomic gas, and such gases are much more easily ionized by incident radiation. Pure monatomic gas mixtures realize gains which are too high and unstable, so a small volume of a polyatomic hydrocarbon gas, in this case methane, is added to keep the gain stable. This is called a **quenching gas**, and because of it’s polyatomic structure, absorbs most energy without being ionized, thus limiting and stabilizing the gain.

3.0 Modification of Electronics

3.1 Noise Reduction

In all electronics, analog signals are subjected to noise. **Noise** is a disturbance in the signal, caused by random surrounding electromagnetic radiation. The static signal one might hear or see on an untuned radio or television is an example of noise. Noise is responsible for the fuzzy appearance of a signal viewed on an oscilloscope.

Because the signals from a detector are relatively small (especially the induced pulses), they can be lost in the noise. To avoid this, several techniques can be applied to reduce the amount of noise in the electronics.

The most important technique in the current set-up is to immediately split up the signal after it comes from the detector, before it enters the pre-amp. The signal is split into two identical signals, but one of them is inverted. The twin signals then travel in neighbouring channels through the pre-amp and amplifier, and are subjected to a nearly identical noise pattern, since they are traveling though the same electronics at the same time. The inverted signal is then subtracted from the upright signal, thus cancelling out the noise and doubling the size of the signal.

Another way of reducing noise is to **shield** all electronics with a grounded, conductive metal casing. Exterior noise is then mostly absorbed by the shielding. This technique can also be applied to wires. Shielded or coaxial wires are wrapped with a grounded conductive layer, which surrounds the inner, insulated signal-carrying wire. It is important to ensure that all shielding is well grounded. Conductive copper tape is very useful in securing connections to ground and should be applied liberally where needed.

3.2 Cross-Talk

Side-by-side channels in printed circuits often have capacitive coupling between neighbouring channels. To test this, a pulse generator was used to inject a pulse of known size into one of the channels, while the neighbouring channels were observed.

When the injected pulse passes through one channel in the circuit, miniature signals are induced in neighbouring channels, with amplitudes on the order of 1% of the amplitude of the injected pulse. This is called **neighbour-dependant cross-talk**, because the cross-talk signals are largest in the channels neighbouring the channel through which the injected pulse passes. These cross-talk signals may not seem large, but when one considers that an induced pulse coming from the detector is usually less than 10% of the amplitude of a direct charge signal, an additional 1% is significant. These cross-talk signals are produced in all of the electronics to some extent, but most severely in the readout plane, the pre-amp, and the circuit board connecting the pre-amp to the detector.

The pre-amp itself was originally found to contribute a cross-talk signal equal to 0.7%. To reduce this cross-talk, several modifications have been made. The pre-amps have small, upright circuit boards for each channel, stacked side-by-side like dominos. It was assumed that capacitive coupling between these circuits was the cause of most of the cross-talk in the pre-amp. So grounded copper plates were inserted between each pair of channels, and covered with an insulating layer of kapton tape to prevent shorting the circuits. Filtering capacitors connected to ground were also added to each channel, as well as increasing the +/- voltage input capacitance. This lead to a drop in cross-talk from 0.7% to 0.1%; a negligible value for the pre-amp cross-talk.

Cross-talk in the circuit board connecting the pre-amp to the detector was reduced somewhat by adding small capacitors to each channel, and some other techniques have been attempted, but this circuit board is still the main cause of cross-talk. It is responsible for multiplying the cross-talk signal ten fold. A new connecting circuit board must be used if cross-talk is to be considerably reduced.

The pads and strips in the readout plane are responsible for increasing cross-talk an additional two fold and four fold, respectively. Because the readout plane is a part of the detector itself, this cross-talk cannot be reduced without taking apart the detector and replacing the readout plane with a new pattern of pads and strips.

There is also another type of cross-talk which is not neighbour-dependant. It is a late cross-talk, occurring a reasonable time after the peak of the injected pulse. The origin of this cross-talk is still unknown, although it's speculated that it could be resulting from capacitance between the second GEM mesh and the readout plane.

3.3 Bias-Free Triggering

For the oscilloscope to record a set of signals, or **event**, from the detector, it must use the signal from one of the channels as a **trigger**, so that it knows when a set of signals is coming. When the amplitude of the trigger signal crosses the trigger threshold, set on the oscilloscope, the oscilloscope will receive and display the set of incoming signals. This threshold is typically set to a value slightly larger than the amplitude of the noise, so that noise signals aren't received, but genuine signals from the detector are received.

If the beam is centred over the middle of one of the strips, that strip would be best as the trigger channel, because it will carry the largest signal of all the channels, and therefore, the most easily distinguishable from noise and the closest to the source of the x-rays. The events caused by the x-rays are spread out over a 50 micron diameter, as that is the width of the x-ray beam, so it's best to select the pad or strip over which most of the events will be centred. However, if the beam is centred on the border of two strips, each strip will be receiving a direct charge pulse of equal amplitude. One of the two channels must be used as a trigger, although either one would be an equally correct choice. The problem with choosing one over the other is that events centred over the strip used as the trigger channel will be more frequently selected by the oscilloscope. This creates a **bias** in the events the oscilloscope selects. When the average waveforms of the events are analyzed, it will seem as though the beam is actually not centred over the border of the two strips, but is located on the side of the strip used as the trigger channel. The trigger channel will display an average pulse with a slightly larger amplitude than that of the channel on the other side of the border, while their amplitudes should in fact be identical.

To eliminate this bias, a sum of the signals from each channel must be used as a trigger. A summing board, attached to the amplifier, receives copies of the signals from each channel, before they are passed on to the oscilloscope. The summing board then sums the signals, and outputs the summed signal to the oscilloscope, which uses that signal as the trigger (see fig. 9). This way, all sufficiently large events will be read by the oscilloscope, regardless of the pad or strip over which the event is centred.

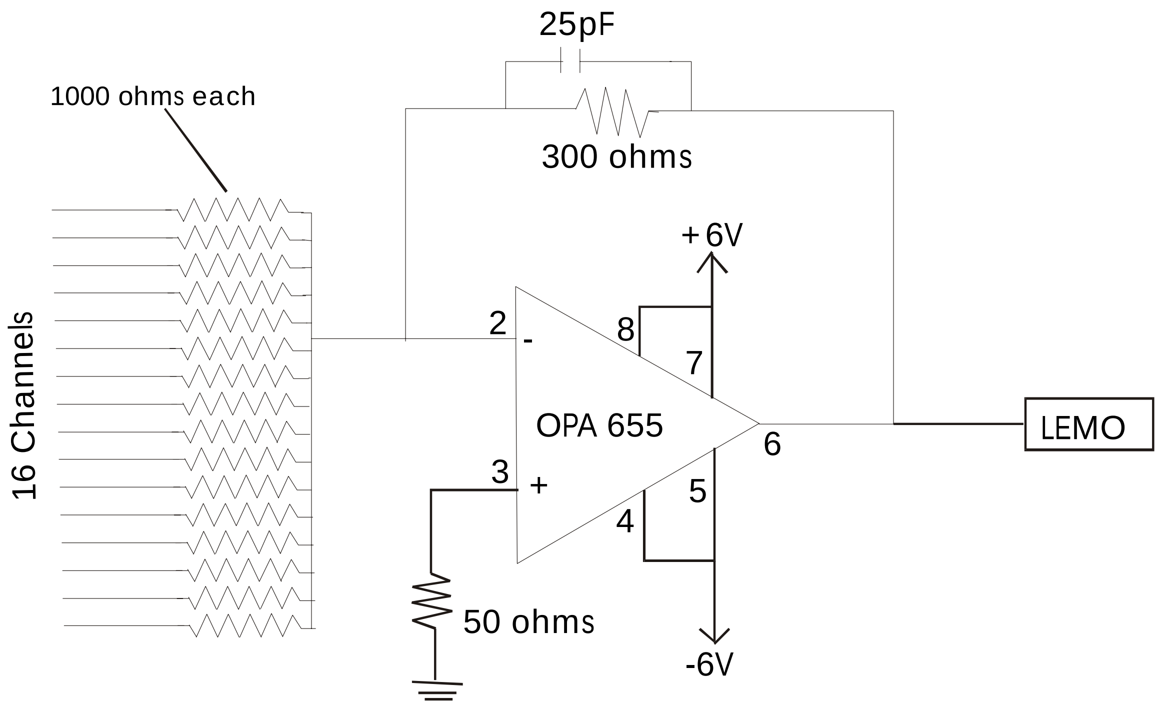

Figure 9. Circuit diagram of summing board

4.0 Data Acquisition

4.1 Equipment Set-up

The first thing that must be done before acquiring a set of data is to set up all of the equipment. Before anything else is done, the P10 gas flow must be started. The gas flow is typically set to 0.1 or 0.2Lpm (litres per minute). It is important to begin gas flow before turning on the voltage in the detector, because if there is regular air inside the detector while the voltage is on, discharges could occur and destroy the detector. After turning on the gas, the detector voltage can be turned on. The amplifier and oscilloscopes can be turned on at any time. Finally, the x-ray must be set up. It is important to ensure that a gentle flow of water is entering the cooling coils of the x-ray tube while it is being operated, so as not to overheat it. The collimator, with the 50 micron pinhole, must be about 1mm away from the mylar window of the detector. The x-ray source control can then be turned on, and voltage and current values should be adjusted to the desired level (usually 6.0kv and maximum current).

When taking measurements where high gain stability is crucial, gas flow and detector voltage should be left on, with a radioactive source present, over night or over the weekend, depending on the circumstances. The main cause of poor gain stability is that charge slowly builds of on the kapton layers in the meshes, increasing the gain over time. The longer this charge has been building up, the more stable the gain, so it’s best to have the detector in operation for a couple days to build up charge and hence, stabilize the gain.

4.2 Adjusting X-Ray Position

Before moving the x-ray position, the x-ray must be placed on standby mode, so that x-rays are no longer being emitted, since the radiation is hazardous to one’s health. Even if this step is forgotten, the x-ray will automatically go into standby mode as soon as the shielding door is opened. Of course, this means that when turning the x-rays back on, the shielding door must be well secured; otherwise, the x-rays cannot be turned back on.

When moving the x-ray beam position, it is important to do so with as much care as possible. Because precision on the order of 10 microns is desired, even a small nudge of the x-ray tube can throw off the beam position considerably. It is also important to consistently move the micrometers in the same direction before stopping at the desired value. For example, if the desired value is arrived at by twisting the micrometer in the clockwise direction, then all values must be arrived at in this way. If necessary, the desired value must be overshot by passing the value, twisting in the counter-clockwise, and then returning to the value by twisting in the clockwise direction.

4.3 Oscilloscopes

The two oscilloscopes currently used are Tektronix 4-channel digital oscilloscopes. They act like FADCs (Flash Analog to Digital Converters), by digitally recording and displaying the analog waveforms. The first step in operating the oscilloscopes is to set the trigger channels. Before doing this, ensure that the scope is acquiring waveforms in sample mode and not average mode. The trigger channel must be selected, the proper trigger slope (positive or negative) must be entered, and finally, the trigger level must be adjusted so that the signals from the detector appear, but noise signals do not. After the signals are appearing properly on the scope, vertical and horizontal positions and scales must be adjusted so that each waveform can be displayed as largely as possible, without being cut off by the edge of the screen.

When using the oscilloscopes to roughly determine the position of the x-ray beam, the average mode should be used for acquiring the waveforms. Using the “peak-to-peak” measurement feature, the exact peak-to-peak amplitude can be read from the display at the right of the screen. If, for example, one is trying to locate the border of two strips, they should continue changing the x-ray position and rechecking the peak-to-peak values of the waveforms from the two strips until they are equal. Keep in mind that because average mode is being used to locate such points, triggering biases may be significant, so the summed signal must be used as the trigger.

For more information on the features of the oscilloscopes, the Tektronix user manual should be consulted

4.4 Recording DAQ Files

DAQ (Data Acquisition) files are the most important files used for analysis. They are a collection of single events, usually 500, that can be analyzed one by one. These events are taken in sample mode, so the oscilloscopes must be set accordingly. The files are recorded by a program written specifically for this experimental set-up.

To begin, run the program, entitled "GEM Data Acquisition.exe". Next, enter the number of events to be recorded, as well as any necessary comments, including absolute and relative x-ray beam positions, gas flow, and other details. A filename and directory must also be selected. The filenames usually consist of the year, month, and day during which they are taken, and a lowercase letter representing the number of files which have already been recorded that day (yymmdd*.dat). For example, the fifth file recorded on April 20th, 2001, would be named 010420e.dat. The channel numbers used must be checked off, and their corresponding pad or strip numbers must be entered in the corresponding boxes. When acquiring data from the pads, a pattern of 7 pads is used, with the central pad used as the trigger channel for both scopes (see fig. 10). Finally, all channels on both scopes must have the same settings, except for vertical postion and scale. For more instructions on using the data acquisition program, the DAQ lab notes should be consulted.

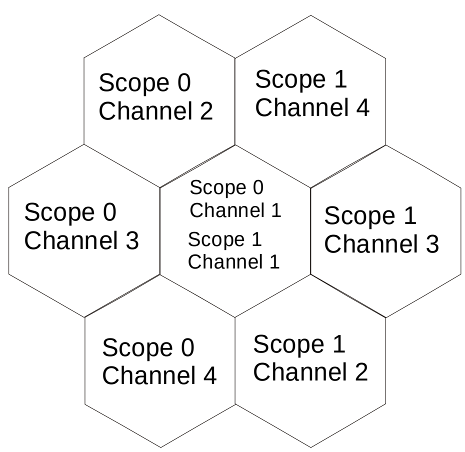

Figure 10. Pad layout and scope/channel numbers

4.5 Recording CSV Files

CSV files record the amplitude versus time points of average waveforms in a tabular format, which can be opened and analyzed in a spreadsheet. To record a CSV file, set the oscilloscopes to acquire waveforms in average mode. After letting the average waveforms settle, press the run/stop button on the oscilloscopes, and run the program "Wavestar for Oscilloscopes". On the left-hand side of the screen, open the branch "Local – Scope0/Scope1 – Data – Waveforms". If the Scope0/Scope1 branch isn't there, then open "Tektronix Instrument Manager", and select "add instrument". Scope0 is connected to GPIBO::1::INSTR, and Scope1 is connected to GPIBO::2::INSTR. After adding the two scopes, exit Instrument Manager and return to Wavestar. After opening the branch mentioned above, open a new YT Sheet. Next, simply click and drag the channels with the desired waveforms over to the YT Sheet. Then go to file – export file as .csv, enter a filename in the same fashion mentioned in section 4.4, and save it to an appropriate directory.

For more information on Tektronix software, the user's guide should be consulted.

5.0 Data Analysis

5.1 Moving and Converting DAQ Files

Before DAQ files are analyzed, they must go through a series of conversions on the bragi and surt servers. The following steps must be followed to prepare the files for analysis with the program, PawX11. The process requires a basic knowledge of Unix commands. When using ftp, make sure to copy all files in binary mode.

1) ftp to bragi, copy .dat files to bragi//files3/gem/RawData/[monthyy]
2) Telnet to surt, go to /data109/gem/akristof/realdata
3) ftp to bragi, copy .dat files to surt
4) run ../akristof/convert and follow instructions to convert .dat files to .out files in the realdata directory
5) logout from surt, go to bragi//files3/gem/Analysis/[monthyy]/hp
6) ftp to surt, retrieve .out files
7) byte-swap .out files by running the uswapgem program. Follow synax instructions and byte-swap each file individually. It's a tedious process, but one can keep bringing back the previous command line, and switch file names to speed up the process.
8) Write a "Do All" .inp file which will use a series of commands from the "gemanal" program to create ntuple files (.rz), which can be analyzed by PawX11.
9) Execute the "Do All" file from within the gemanal program to create the nutple files.
10) Analyze ntuple files using PawX11, located in the directory, //local/cern/pro/bin/pawX11

This is a complicated process, so if in doubt, ask someone who is more familiar with it for assistance. For a guide to using PawX11, check the CERN website, http://vsnhd1.cern.ch/online/lambda/subseciton4.1.html

5.2 Analysis of Files

Several aspects of the detector events can be analyzed with PawX11. Direct charge and induced pulse components can be separated, gain variation can be measured, position resolution can be determined from analyzing both the direct charge and induced pulse components, and many more details can be analyzed. A detailed analysis of all GEM data sets is located on the webpage, http://www.physics.carleton.ca/~karlen/gem/

6.0 TPC and Future Plans

6.1 FADCs

FADCs (Flash Analog to Digital Converters) are currently being developed in Montreal. Once completed, they will be able to convert analog signals from 32 channels to digital signals, at a rate of 200MHz. By using FADCs, the oscilloscopes no longer need to be used, and 32 channels can be analyzed simultaneously, as opposed the current limit of 8 channels (2 4-channel oscilloscopes).

6.2 Charge Barrier

Because some pads or strips absorb charge and some do not, the signals in the various channels do not have the same shapes. As explained earlier, some are direct charge pulses, some are induced pulses, and some are mixed pulses. If all signals had the same shape, position resolution analysis would be much easier, since the induced and direct charge signal components would no longer have to be separated. Only the peak-to-peak amplitudes in each channel would need to be analyzed. One possible way to solve this problem would be to put a sheet of high-resistance material in the induction gap, blocking the charge just before it reaches the readout plane. By doing this, the charge cloud would not be absorbed by the readout plane, but an induced pulse would still occur in the pads or strips, with amplitude inversely proportional to the proximity to the point where the charge cloud was blocked by the sheet. All channels would then have the same shape of an induced pulse, with amplitudes depending on the position of the charge cloud.

6.3 Miniature TPC

The testing of these GEMs is being done with the intention of using GEMs in a Time Projection Chamber (TPC). A TPC consists of a stack of electrodes, making up a very large drift region, sitting on top of a double GEM structure. When a charged particle travels through this large drift region, it will leave behind a trail of primary electrons from the gas molecules it ionized along its path. Each primary electron will be pulled towards the double GEM structure, where gas multiplication will occur. By analyzing the locations and times of the series of events, the trajectory and energy of the particle can be determined.

Assembly of a miniature TPC is currently underway. It will consist of 30 brass electrodes, stacked 5mm apart, for a drift region 15cm tall. The top electrode is connected to a negative potential of 10kV, with each electrode below at successively lower potentials, down to the top GEM mesh, which is at about 3.5kV. The entire structure is enclosed in a cylindrical metal casing. Once assembled, the FADCs will be used with a pad structure, analyzing the signals from a pattern of 32 pads simultaneously. Cosmic rays will be used for testing, as well as a laser source, which can be fired through one of the windows in the TPC outer casing.

7.0 Conclusions

Since the invention of the Gas Electron Multiplier in 1996 by Fabio Sauli, gains have increased from 10 to 1000 and higher today. Position resolution is now to the point of being able to determine the position of an event to within 100 microns. GEMs are constantly realizing higher gains and better position and energy resolutions.

In the testing of the double GEM detector, it is very important, as it is in any experimentation, to ensure the measurements taken are as precise as possible. To achieve this, the proper set-up for testing is crucial. It is necessary to have electronics that function with as little noise as possible, free of cross-talk signals, or triggering biases. All data sets must be acquired and analyzed using consistent methods. Changes in methods can yield significant discrepancies in the data. However, when necessary, it is also important to develop new and more precise methods of testing.

The use of GEMs in a future TPC readout for the TESLA linear collider appears promising. The miniature TPC, incorporating a double GEM, will soon be completed, and new testing methods will need to be developed. Once again, proper electronics and data acquisition methods will be crucial. The completion of FADCs will also allow testing over a much larger area since 32 readout pads can be analyzed simultaneously, as opposed to 8.

8.0 Recommendations

To ensure accurate experimental results, the testing methods outlined in this document should be followed. All methods used, new or old, should be done consistently.

To further improve the electronics, additional shielding should be added wherever possible, and connected to ground as securely as possible. If it's necessary to further reduce crosstalk, a new circuit board connecting the readout plane to the pre-amp should be devised, since this circuit board is currently the source of most of the cross-talk. When recording DAQ files, it is unnecessary to use the summed signal, since only individual events are analyzed. However, when using average measurements to locate the position of the x-ray beam, the summed signal must be used to avoid the effect of the triggering bias.

For the testing of the new miniature TPC, the same techniques should be applied to the modification of any electronics used. The methods of data acquisition, whatever they may entail, must be followed consistently.

9.0 References

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