

# TACTIC Prototype GEM TPC Detector

*Student Manual for UBC Physics 531 and GRIDS-TSI*

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## Introduction

The TRIUMF Annular Chamber for the Tracking and Identification of Charged Particles (TACTIC) (see Figure 1) is a combined cylindrical ionization/time projection chamber detector used for very low energy nuclear reactions. The energies of the beam and products are so low that they would lose too much energy, or possibly stop, in even the thinnest metal foils. Consequently the amount of material traversed by both the incoming beam and the scattered reaction products must be very low to allow particle tracking and energy measurements. In TACTIC, the gas target along the central axis can be “windowless” to reaction products (ejectiles) (i.e. the target and detector gases are the same), so that these ejectiles lose little energy as they pass into the (so called “drift”) region where they will be tracked.

TACTIC is unique not only because its windowless target allows reactions to be measured at very low energies, but also because it acts as both as a gas ionization chamber (IC) and a time-projection chamber (TPC) simultaneously, using gas electron multiplier (GEM) grids for signal amplification. An IC measures the total energy of an ejectile by measuring the total accumulated charge of electrons released by the product ionizing the detector gas. A TPC tracks the path of these products by measuring the arrival time of the ionization electrons to the segmented outer anodes after the ejectile traverses the drift volume (see Figure 2). Due to the low density of the gas, the particles do not produce many ionization electrons per unit track length, so the signals induced on the anodes would be too small to detect above the usual electronic noise. So, a GEM is placed just before the anodes to multiply the number of ionization electrons onto a given strip, creating a signal large enough to be detected. TACTIC TPC operation will be detailed below.

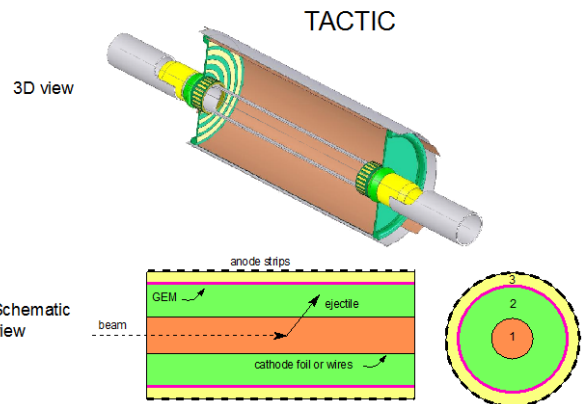


Figure 1 Schematic 3D and side 2D views of the cylindrical TACTIC detector.

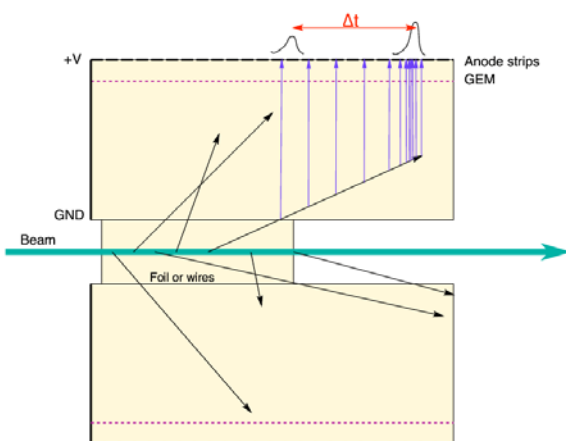


Figure 2 Schematic representation of TACTIC operating as a time-projection chamber. The arrival time of the ionization electrons on the anode strips is a measure of how far they had to drift.



These are called *field-shaping* strips and are used to improve field uniformity throughout the drift volume (see Figure 5).

The drift region terminates at the grounded entrance side of the gas electron multiplier, GEM amplifying region. The GEM has a voltage of 450 to 500 V across its 50  $\mu\text{m}$  thickness. The GEM anode plane, separated by about 5 mm from the GEM, is segmented into strips oriented perpendicular to the nominal alpha particle trajectory. The GEM anode strips are held at about 1500 V to collect the amplified electron signal. Each GEM anode strip, coupled to a pre-amplifier channel through a capacitor (see  $C_s$  in figure 4), corresponds to one position in the longitudinal direction.

Electrons ionized from the gas feel a force from the drift field and move towards the anode. Collisions with the gas atoms will quickly bring electrons to a constant terminal velocity, called the *drift velocity*. A constant drift velocity is essential to determine the relative distance travelled by the ionization electrons to a given anode strip from the relative time difference between the arrival time of a signal on a strip and some reference time (see Figure 6). In our case, the reference time will be the first or second GEM anode strip that receives a signal. This information provides the vertical position of the alpha particle trajectory below a particular anode strip. If the strip farthest from the source gets a signal first, that means the trajectory is upwards, and, conversely, if the nearest strip fires first the track trajectory will be downwards. So, anode strips and the drift time to each strip together give two dimensions of the alpha particle trajectory. This is the basis of TPC operation. (In many TPC detectors, a second set of anodes oriented at an angle to the first, or pixelated anode “pads” would be used to get the transverse trajectory position in order achieve full 3D track reconstruction.)

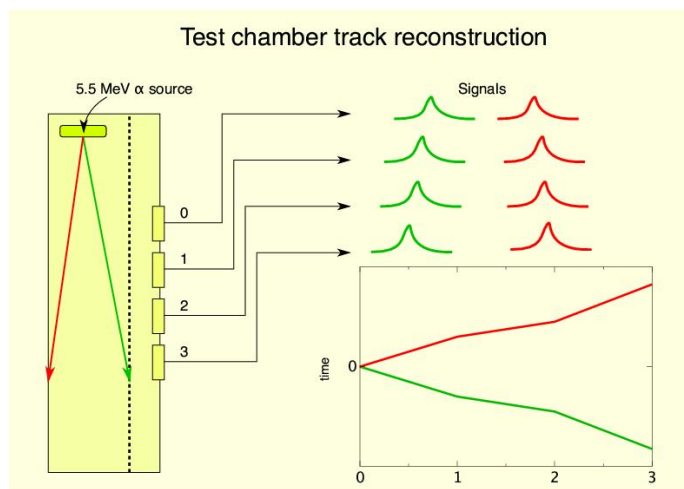


Figure 6. Schematic representation of how the alpha particle trajectory affects the signal timing at GEM anode strips.

The relatively small number of ionization electrons created by the alpha along each section of its track are not enough to create a large enough signal on the anodes to be detected above electronic noise. This is where the GEMs come in. A GEM is a (typically) 50 micron thick double-sided copper sheet sandwiching an insulating layer which is perforated with (typically) 50 micron diameter holes spaced (typically) 150 microns apart. The two sides of the GEM are kept at (again typically) a 450 V potential difference. This voltage creates a very powerful electric field in the region immediately outside and inside the GEM holes (see Figure 7). An ionization electron entering this region will quickly accelerate to an energy sufficient to ionize gas molecules in the hole. The

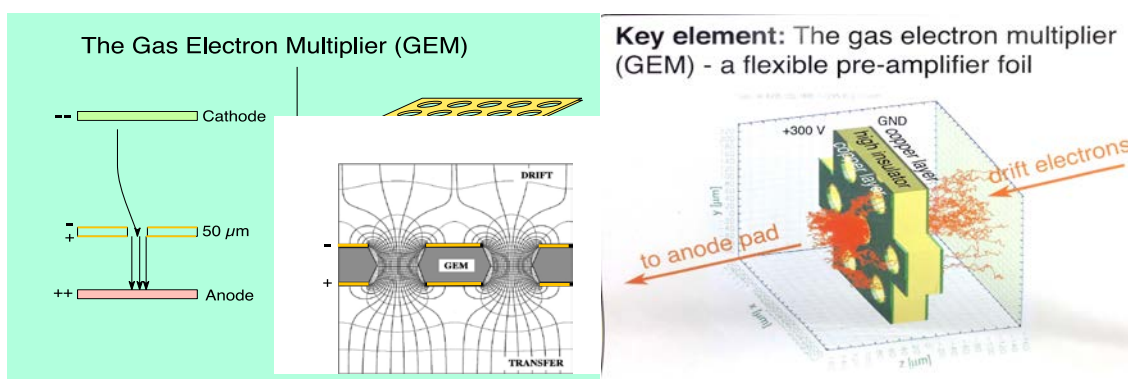
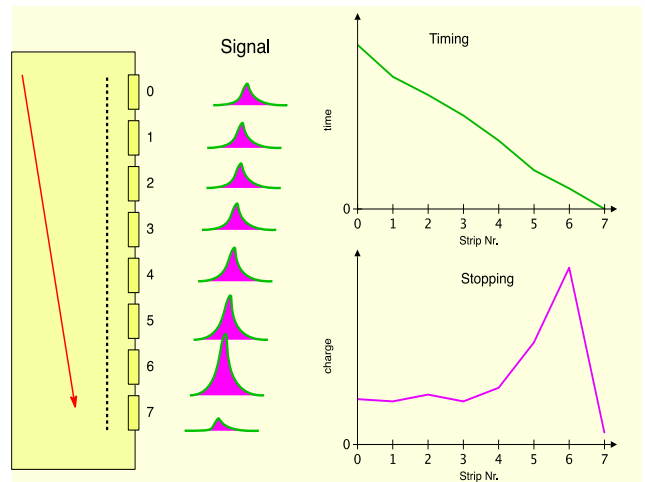


Figure 7 Schematic close up view of GEM electric field lines (left) and avalanche multiplication of drift electrons (right).

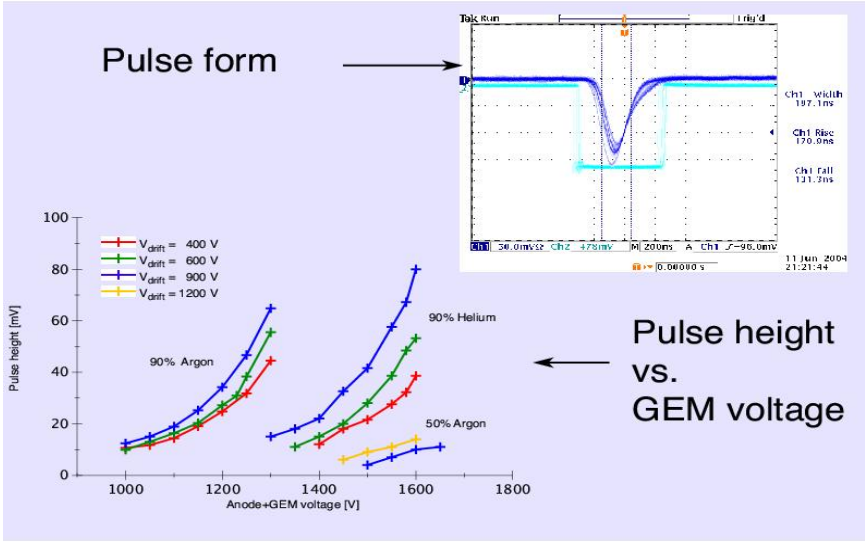
resulting *secondary* ionization electrons in turn quickly accelerate to ionize gas molecules, and so on, resulting in an *avalanche* of secondary (tertiary...) electrons emerging on the anode side of the GEM (see Figure 7). The electron avalanche with gain  $\sim 1000$  is big enough to create a detectable signal on the closest anode strip, and moreover, the size of the resulting electronic pulse is proportional to the number of ionization electrons created by the alpha particle in that segment of its trajectory below the anode strip. This is crucial if the detector is to act also as an ionization chamber.

Some ionization chambers are designed to have the reaction products of interest stop within the detector volume. The total charge accumulated on the anode plane is then a measure of the kinetic energy of the ejectile. The ejectile's range can be determined from the characteristic Bragg peak formed by plotting the charge accumulated on each GEM anode strip (see Figure 8). Both these measures aid in particle identification.



**Figure 8 Schematic representation of timing and pulse size on anode strips for a typical stopping track.**

The choice of drift gas depends on a number of factors. The mass density of the drift gas (molecular weight and pressure) may be chosen to stop the ejectiles of interest (like highly ionizing alphas). The gas molecules must have a low enough ionization energy so that ejectiles of interest can create enough ionization electrons, but not so low so too many are created, destroying the proportionality of the resulting signal amplitude to the particle energy loss. Usually the drift gas is a mixture of molecules, one to create the ionization electrons, and one to “soak up” secondary UV photon emissions (“quencher gas”) to keep the ionization process in check. In addition, choices of drift field voltage, and in our case, the GEM voltage, are crucial to obtaining suitable signal strengths at the GEM anode strips while keeping the signal vs. energy loss proportionality and avoiding electrical breakdown (sparks) (see Figure 9 for results using typical Argon/CO<sub>2</sub> and Helium/CO<sub>2</sub> mixtures). And in the case of the TACTIC TPC, the drift gas could also be the target gas, adding another layer of complexity. All in all, arriving at the best choice of gas mixture and pressure and chamber voltages is an important part of the design optimization process, which in most cases can only be deduced empirically.



**Figure 9** Pulse-height dependence of GEM anode strip signal on the test chamber gas composition and high voltage.

## Operation

This section will outline the setup used for the Tactic TPC test chamber lab measurements. Figure 10 shows a photo of the chamber with some key aspects noted. ***It is important that you read through the entire manual before beginning to operate the chamber.***

***N.B.*** Since this was a prototype-test chamber, temporary solutions were found for its construction to make it safe to operate; take note of the regions of high voltage connections some of which are insulated by Kapton tape and be careful not to touch the chamber (other than the preamplifier connections) while high voltage is applied. See Figure 10.

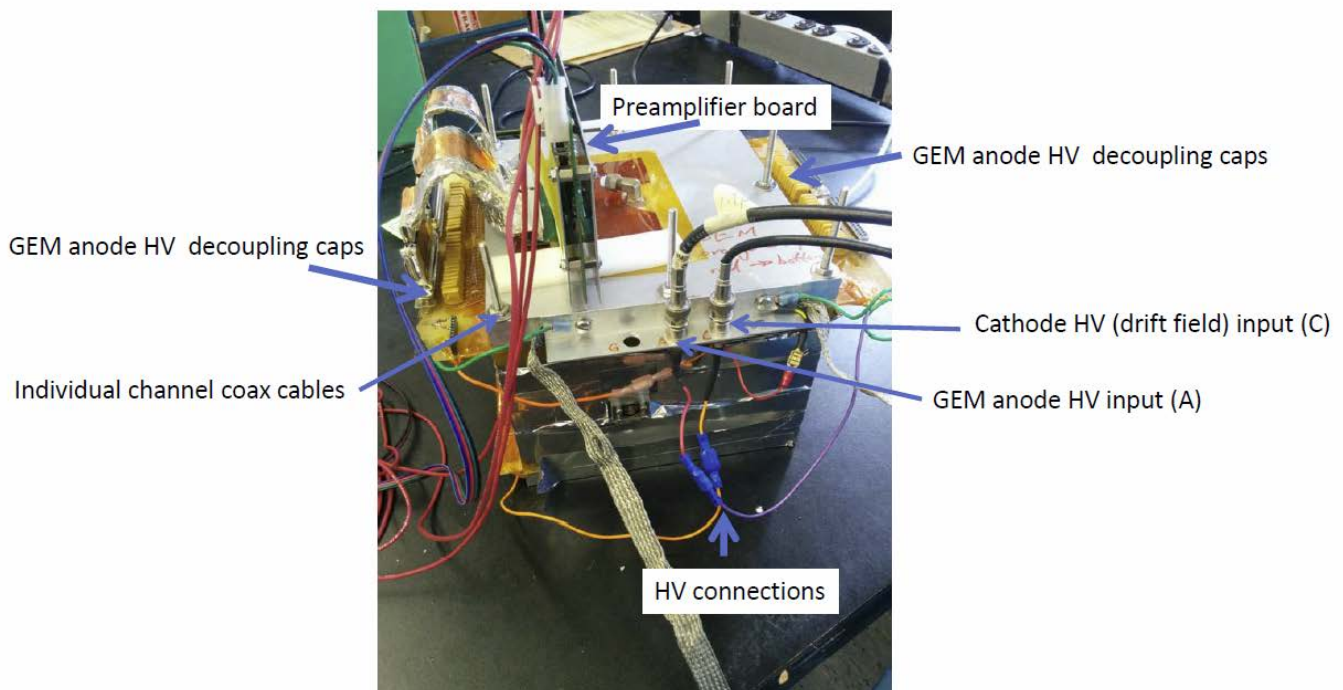


Figure 10. Tactic TPC HV connections.

## Chamber Geometry

The test chamber is constructed from stainless steel plates with outer dimensions 226mm (L) x 207mm (W) x 144mm (H). Each plate is 16mm thick, and the side walls are 21mm thick. The resulting inner dimensions are 184mm (longitudinal to nominal alpha particle beam), 165mm (horizontal transverse) and 112mm from the cathode plane to the grounded side of the GEM.

The source is mounted on a movable arm, 58.5mm from the GEM and 53mm to the cathode plane, set to one side 59mm to the closest wall (to the right facing downstream with the alpha particle beam). Refer to Figure 4.

The anode strips are 3mm wide and oriented transverse to the nominal  $\alpha$  particle beam direction. The distance between the center of adjacent strips is 3.125mm. See Figure 11.

### Radioactive Source

Americium-241 is used as the radioactive source to provide ionizing alpha particle for the test chambers. Am-241 emits predominantly alpha particles with energy  $\sim 5.4$  MeV (see above) with a half-life of about 432 years. This isotope is commonly used in smoke detectors.



Figure 11 View of anode strips showing the pitch dimension.

The Am-241 is deposited on a flat disk, so the alphas are emitted roughly uniformly into the forward hemisphere. A collimator can be employed in order to restrict the alpha particles to a tight beam in the forward direction.

### Gas Handling System

The test chamber is configured to allow input from gas sources via flexible plastic tubes (see Figure 1). The test chamber setup utilizes a two-gas mixture, Helium/ $\text{CO}_2$ , nominally (70%/30%). The test chamber is not sealed very well, so the chamber runs at slightly above atmospheric pressure to prevent air from entering. As such, the system does not allow pressures less than atmospheric. However the mass density of the drift gas can be varied by adjusting the ratio He(or Ar): $\text{CO}_2$  by adjusting the flow rates from the compressed gas cylinders. This is achieved by setting the flow rate of each individual component manually, using a visual flow meter. The default mixture for this lab system is 70:30 He/ $\text{CO}_2$ , which is sufficient to stop the alpha particles within the chamber volume. A flow meter (not calibrated) in the gas line system shows that gas is flowing to the chamber.

The gas mixture can be changed by adjusting the flow rates of the components, or by connecting different gas cylinders to the gas-flow system. Any change in the gas mixture should be allowed to flow through the chamber for 1.5 to 2 hours to flush the old mixture and establish a new equilibrium. See the lab instructor if you wish to try another gas mixture.

### High Voltage

The chamber must be supplied with separate high voltages for the drift region (cathode to GEM ground) and the amplification/collection region (bottom of GEM to top of the GEM, and top of the GEM to the GEM anode strips, using two power supplies (see Figure 12). The bottom of the GEM is kept at ground potential, and the drift voltage of the TPC cathode is typically -1500V applied between cathode and ground. The second voltage is applied to the GEM anode strips and gets distributed with a 2:1 voltage divider (R1 and R2 in Fig. 5) to power the GEM and the GEM anode strip



Figure 12 High voltage power supplies for the cathode- and GEM-to-anode planes.

fields. So, if +1500V is applied to the GEM anode strips, there will be +1000V between GEM anode strips and the GEM upper side, and the voltage across the thin GEM will be 500V.

If the voltages are set too high the electronics could be damaged. The GEMS have been tested to operate at 500V (meaning 1500V GEM anode strip voltage), but they may start to spark at around 600V across the GEM, although this value is dependent on the gas mixture and can be significantly lower. At too low a voltage the signals on the anode strips become too small to distinguish from the electronic noise.

### Signal Amplification and Display

The signals from the anode go through a preamplifier before being passed along for further processing. See Appendix 2 Figure A2.1 for the preamplifier power supply settings. The output of the preamplifier can be taken on a coaxial cable for observations or digitization. We can first use a simple setup where a multi-channel digital oscilloscope is used initially to display the analog signals from individual anode strips on a separate channels. The scope can be operated in single-shot mode, where one of the first anode strip signals triggers the scope and captures all the signals on the input channels within an adjustable time window. Figure 13 shows an example where 16 channels of GEM anode strips are simultaneously displayed on 3 scopes for one event. Our initial setup will have a single 4-channel scope.

The pulse height with respect to the baseline gives a measure of the ionization deposited on a given anode strip, while the time position of the peaks gives the relative time difference with respect to the triggered anode (see Figures 6 and 8). Since the drift velocities of the ionization electrons in the drift gas is constant for a fixed drift field, the time differences are a proxy for the differences in position of the primary ionizations under the anode strips.

**Figure 13 View of a single-shot capture of GEM anode strip pulses in the test chamber.**

## Lab Measurements

This section will outline some lab measurements that can be performed using the test chamber setup. Some initial measurement and observations can be made using the oscilloscope display. More detailed measurements can then be made by digitizing the output of 32 GEM anode strips for each event and analyzing the data off-line.

### Measurements and observations using the 4-channel oscilloscope.

Some basic observations of the TPC operation can be made by connecting four coaxial cables from the preamplifier output to the scope. See Appendix 2, Figure A2.2. Choose different GEM anode for the outputs to view; see if you can figure out how to make some basic observations like those mentioned below.



**N.B.** The MAXIMUM applied voltage on the GEM anode strips (HV input A) is 1500V, which corresponds to 500V on the GEM and 1000V between the GEM upper surface and the anode collection strips. All voltages lower than the maximum are safe; at very low voltages, the pulse height becomes comparable to the noise. Two Bertan high voltage power supplies (Figure 12) are present in the setup:

- “Cathode” – this is the drift field supply nominally at -1500V.
- “Anode” – this is the GEM anode strip supply, nominally at +1500V.

The voltages are set with thumb-wheel adjustments **using the digital volt meter attached to the “voltage monitor” output of the supply**; note also, the “current monitor” output and determine if the current and voltage readouts are reasonable. (The thumb-wheel readings can not be used to determine the voltage settings.)

### Measure the rates of hits on various strips

Connect the output of a preamplifiers to a NIM discriminator located in the same NIM crate as the HV modules. Use the scaler module to determine the rate of hits. What can you infer from this information?

### Investigate the relationship between applied voltages and the pulse height and time differences.

This is a measurement to investigate how the ionization drift speed, pulse heights, and time differences change with respect to the applied voltages. Of particular interest is to note the sensitivity of these variations.

### Determination of alpha particle range

This measurement makes use of the pulse heights recorded on each of the anode strips for horizontal trajectories (determine how you can identify such trajectories).

### Estimation of ionization electron drift velocity

This measurement requires an open source (as in our initial setup), and involves identifying those tracks that stop when hitting the GEM, as opposed to those that stop in the gas volume. (How can you know if a track hits the GEM?)

### Plotting individual track trajectories

Using information of the relative timing of the anode strips, the longitudinal and vertical transverse trajectory of the alpha particle can be plotted. The drift velocity can be used to convert the vertical time measurement into a distance.

### Investigating the relationship between gas mixture and alpha particle range and anode signal size

Measurements can be repeated for different drift gas mixtures (e.g. Ar/CO<sub>2</sub> vs He/CO<sub>2</sub>), or compositions for the same mixture (e.g. 80:20 vs. 60:40 He/CO<sub>2</sub>). However, it takes several hours for the gas mixture to stabilize so such changes should be done in conjunction with the digital measurements described below.

## Measurements and observations by digitization of the 32 GEM anode strips for each event

After making some initial analog measurements with the scope, remove the coaxial cables and connect the GEM anode preamplifier to the CAEN 5740 62.5 MHz 12 bit digitizer to record data from complete alpha particle trajectories in the chamber. See Appendix 2, Figures A2.3 and A2.4. More information can be found at [CAEN5740](#). The data for each anode strip hit will be written to a text file which can be analyzed off-line using any available program e.g. ROOT, Gnuplot, Excel, .... The measurements described above and others can now be done in considerable detail by analyzing the data.

The digitizer is connected by a USB cable to a laptop running Linux:

Laptop name: grids01.triumf.ca;

Account login: grids

    Password: triumph2018

The working directory is: /home/grids/wavedump-3.8.2/Setup/

### Operating the CAEN TD5740 digitizer:

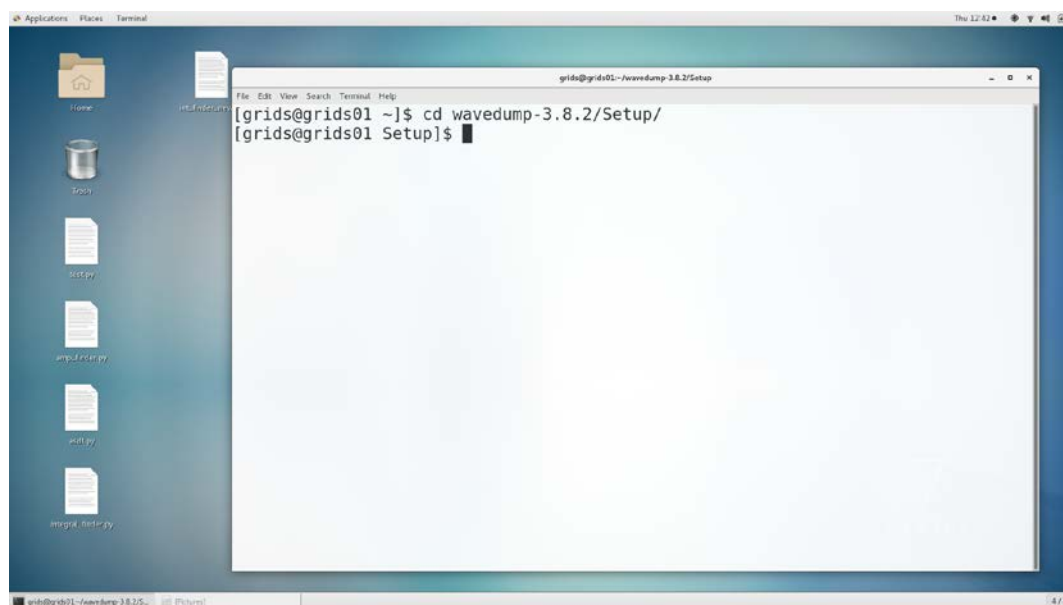
First connect the cables with the assistance of the lab supervisor (See Appendix 2, Figure A2.4):

- connect the power cable for the digitizer
- connect ribbon cables connecting the preamp to the digitizer (2 ribbon cables into an adapter)
- connect the USB cable from the digitizer to the laptop

Turn on the digitizer (wait for it to initialize, takes about 4 seconds).

Open a terminal on linux, and change to the work directory:

```
[grids@grids01 ~]$ cd wavedump-3.8.2/Setup/
```



Using the  
SOFTWARE:

Start the CAEN software for the examination/recording of the waveforms:  
[grids@grids01 Setup]\$ **wavedump test.txt**

You are now ready to start the program. However, before doing that, please turn off the power on the power supply for the preamplifier, so that there are no signals on the input of the digitizer.

Press “s” to start the data examination. First you will notice that the program will report that calibration is done for four groups of channels (0-3). There are 8 channels in each group, totaling 32 channels. Once the calibration is done you will start noticing that program will report that no data is coming in. The digitizer is now set up to trigger on one of the channels (channel 0 of the digitizer).

Now, turn on the power on the preamplifier power supply and you should notice that the data is starting to come in.

The commands available are as follows:

p – plot a waveform (only from one group of channels)  
g – change the group of channels  
P – enable/disable continuous plotting of waveforms  
w – write one event out  
W – enable/disable continuous writing of events  
[SPACE] – for help

Waveforms will be written out into files: wave0.txt wave1.txt.... wave31.txt. Hit W to begin writing data and press W again to stop writing.

**N.B:** Each time the program runs, these files will be overwritten. Take data for only a couple of minutes to collect several thousand events.

Once you have taken data it will be time to process it, by running the script process:

```
[grids@grids01 Setup]$ ./process
```

This will run a program to analyze the recorded waveforms and produce an ASCII file with the amplitudes and times in all the instrumented channels for each event.

The output file will be stored in /home/grids/wavedump-3.8.2/Setup/analysis/output.txt.

The data format is 32 space-separated pairs of time and amplitude data in one line for each event:

```
time0 amplitude 0 time1 amplitude1 time2 amplitude2 ..... time31 amplitude31
```

```
...
```

```
...
```

where timeX and amplitudeX denote the time and amplitude of the channel X. For the cases where there was no pulse value of 0 0 will be present for time and amplitude.

**After each run, copy the file output.txt to a file name of your choice which will be used for further analysis.** Copy your file to a memory stick and use any available software to analyze the data.

```
..
```

## Appendix 1

### Monte Carlo Simulation of Test Chamber

A simple GEANT4-based Monte Carlo simulation was developed that will help students visualize and interpret measurements taken with the test chamber. Data from the simulation can be plotted to see the expected range,  $dE/dx$  vs strip number, etc. to compare with lab observations. Contact the lab supervisor to obtain the MC data.

The simulation data file name is `edep.csv`, containing the result of the simulation of 1,000 alpha particles. Note that the results are averages of many events. The chamber is divided into a mesh of cells ( $x, y, z$ ).

The file reads

```
# mesh name: boxMesh_1
# primitive scorer name: edep
# iX, iY, iZ, total(value) [MeV], total(val^2), entry 0,0,0,0,0,0
0,0,1,0,0,0
0,0,2,0,0,0
0,0,3,0,0,0
0,0,4,0,0,0
0,0,5,0,0,0
0,0,6,0,0,0
...
```

The three first columns are the bin indexes. In the example, we have one bin along the  $X$  and  $Y$  axis and 1,000 bins along the  $Z$  axis. There is one line per cell. The next three columns are the sum of the energy deposits, the sum of the energy deposits squared and the number of energy deposits in a particular cell. That is, to get the average energy deposit in a cell one has to divide the total energy column by the number of hits in the entries column. The alpha source was placed at  $z=1$  cm. The figure below shows the average energy deposited vs the  $z$  position. Can you explain the shape of this curve?

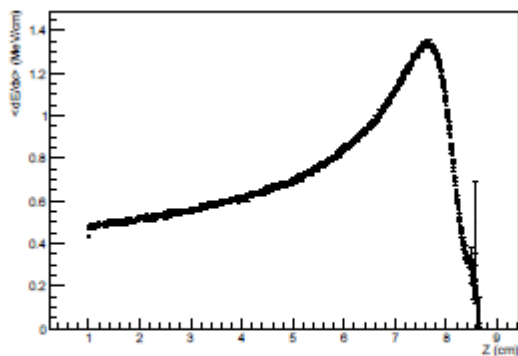


Figure 1: Typical energy spectrum for 5.49 MeV alphas in a  $\text{HeCO}_2$  mixture. The collimated source is placed at  $Z = 1$  cm.

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## Appendix 2

Tactic TPC instrumentation photos.

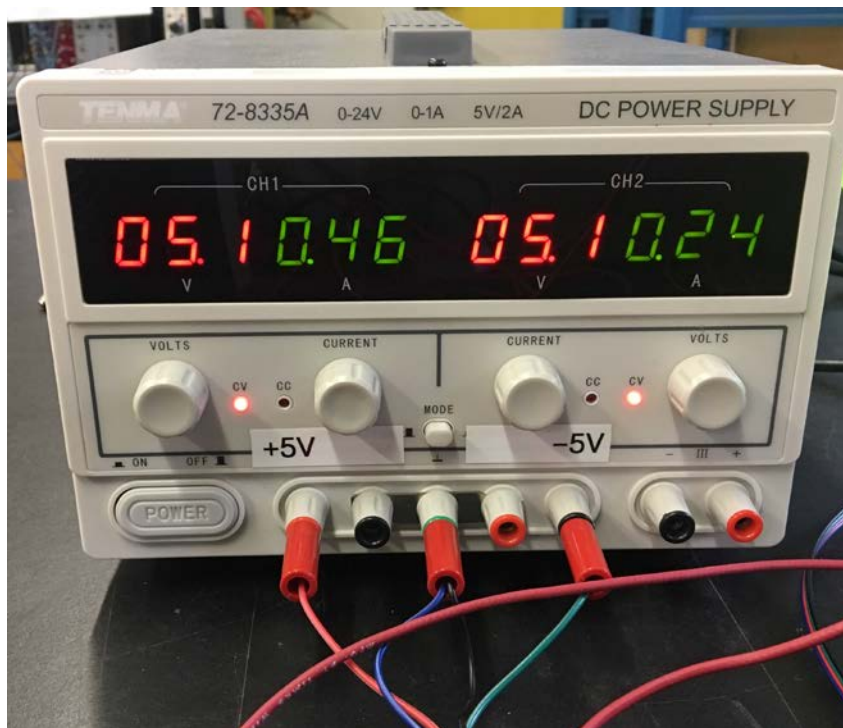


Figure A2.1 Preamplifier power supply.

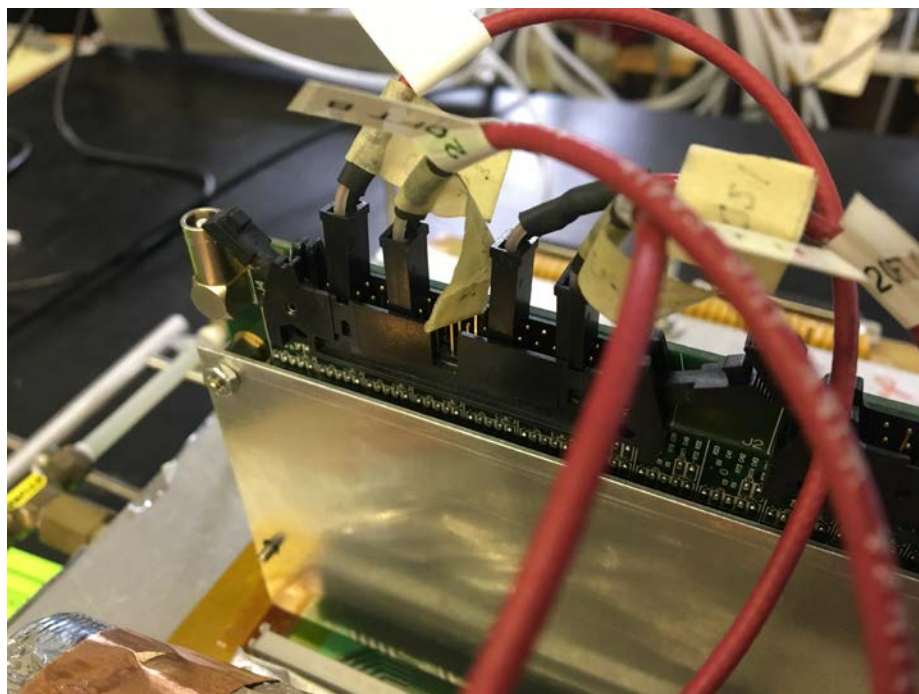


Figure A2.2. Coax cable connections to preamplifier. Note cable polarity.



Figure A2.3 CAEN 5740 32 channel 12 bit 62.5 MHz digitizer module.

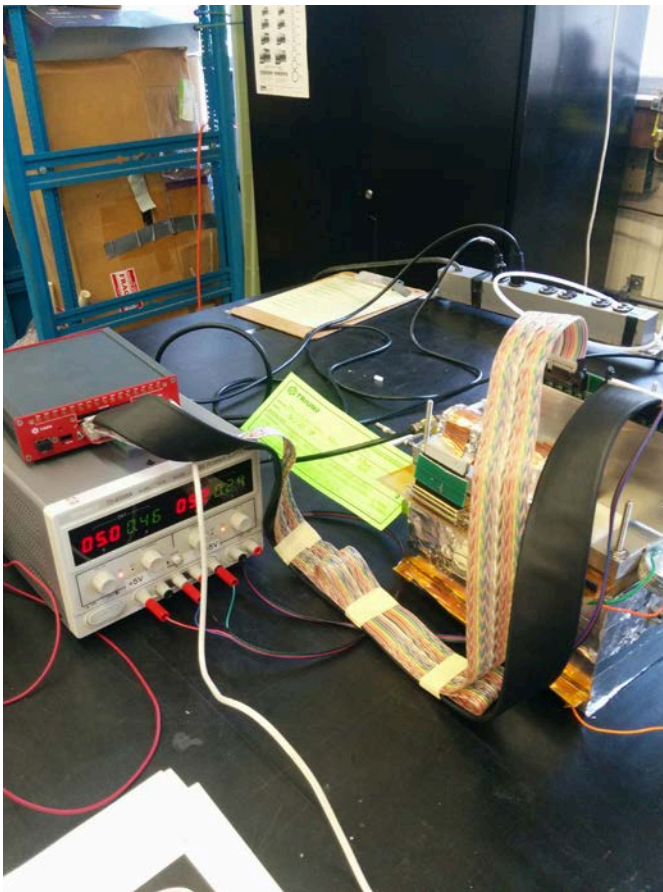


Figure A2.4 CAEN 5740 cabled up. See Appendix 3 for more details.

### APPENDIX 3 Digitizer cabling

Indexing on the channels of the digitizer and channels on the amplifier corresponding to the strips is a bit convoluted. Below is a table to explain it:

Digitizer channel	Strip Number	Digitizer channel	Strip Number
Not connected	1	Not connected	17
0	2	1	18
2	3	3	19
4	4	5	20
6	5	7	21
8	6	9	22
10	7	11	23
12	8	13	24
14	9	15	25
16	10	17	26
18	11	19	27
20	12	21	28
22	13	23	29
24	14	25	30
26	15	27	31
28	16	29	32