Stopping Muon Detector (SMD)

Graduate Instrumentation and Detector School (GRIDS)

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Introduction

This setup was originally designed to study the effect of low energy muons which can cause single event upsets in electronic devices such as SRAM memories. The particular muons of interest are below 10 MeV (with a range in silicon of a few mm) and may cause upsets when the muon deposits most of its energy. There are older measurements of the rate of low energy muons at surface level but these measurement differ by up to an order of magnitude and did not positively identify the particles as muons.

This manual discusses the design and operation of a detector capable of identifying low energy stopping muons and their decay products. The detector can be used to measure the energy and rate of the stopping muons. The detector is portable and large in volume in order for measurements to be made under various conditions (i.e. altitude, latitude and location within TRIUMF). Due to the size of the detector it can acquire appropriate statistics for an accurate muon lifetime measurement in under 12 hours. It can also distinguish between muons that stop in the detector and muons that pass through. The detector was built at TRIUMF Canada's National Particle and Nuclear Physics Laboratory. The initial design study for this detector was funded by Cisco Systems in San Jose, CA. For an example of the use of the detector for Soft Error studies see ref[[1]].

For the GRIDS lab, the detector can be configured in various ways to make measurements which relate to the scintillator and PMT properties and performance such as time and energy resolutions as well as properties of muons such as the decay energy spectrum and lifetime. The section below Performing your Own Measurements and Analysis describes some example measurements you can make with this setup.

Please read the entire manual before operation of the detector.

Detector Design

The Stopping Muon Detector (SMD) consists of four 10cm x 10cm x 100cm plastic scintillators shown in Figure 1a. The plastic material is Bicron-400 (BC-400). When a charged particle like a muon interacts with the scintillator visible wavelength photons are emitted. The light output of the scintillator is proportional to the energy lost by the particle that traverses the detector as illustrated in Figure 2.

FIGURE 1a: Shows the detector completely assembled with the control laptop. PMTs 0, 2, 4, and 6 (1,3,5,7) are associated with light guides 1a, 2a, 3a, and 4a (1b, 2b, 3b, and 4b).

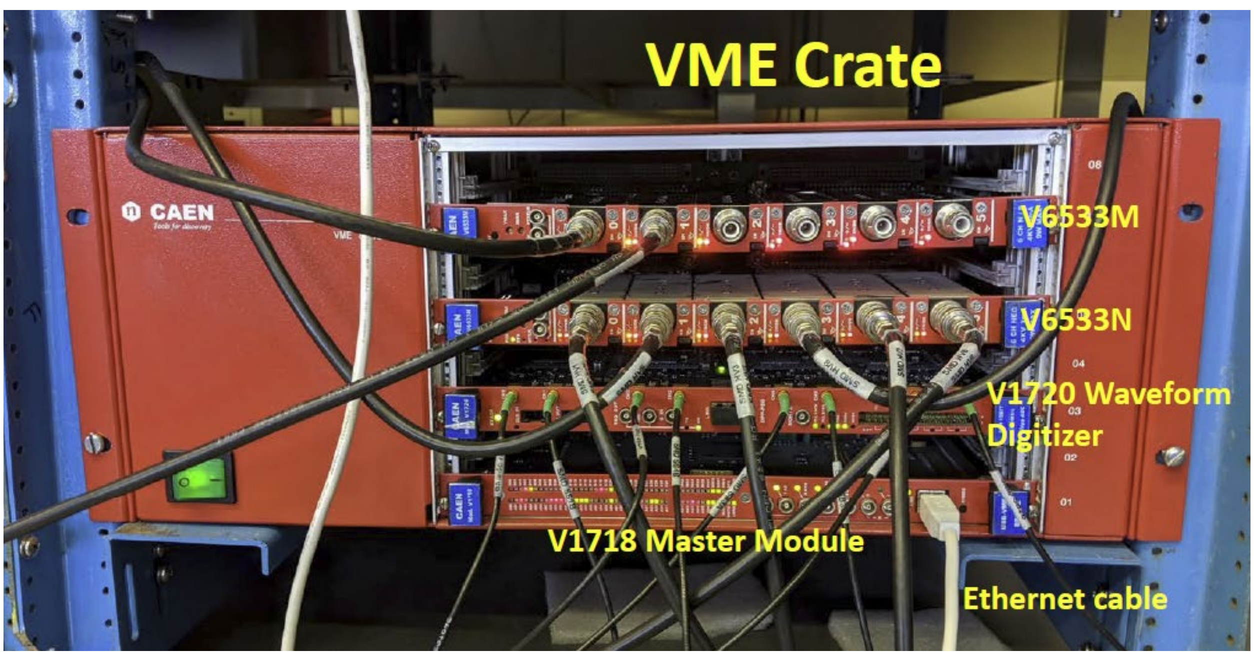


FIGURE 1b: VME Crate and modules.

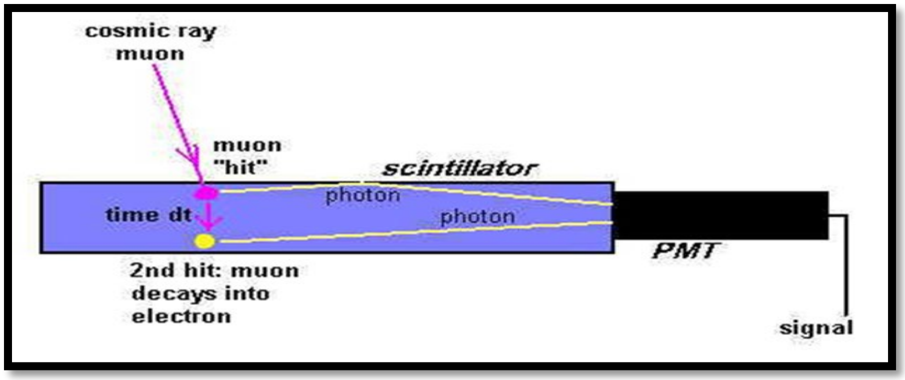


FIGURE 2: Schematic diagram of a muon stopping and decaying in a plastic scintillator.[12] In the lab configuration, the scintillator bars are viewed at both ends by photomultiplier tubes (PMT).

The scintillation photons are transmitted directly and through total internal reflection through a light guide and to a photomultiplier tube (PMT) which converts the signal to a small current, and amplifies the signal producing a measurable current. Each scintillator bar has a Philips XP2262 PMT at each end (making for a total of 8). The PMT's consist of a photocathode and a series of powered dynodes in an evacuated glass structure. When the photons from the scintillator strike the photo-cathode, electrons are emitted with some probability (the quantum efficiency, typically 15-30%). The electrons are accelerated towards a series of additional electrodes called dynodes. This cascading effect creates 10^5 -10^7 electrons for each photo-electron emitted. See Figure 3.[6]

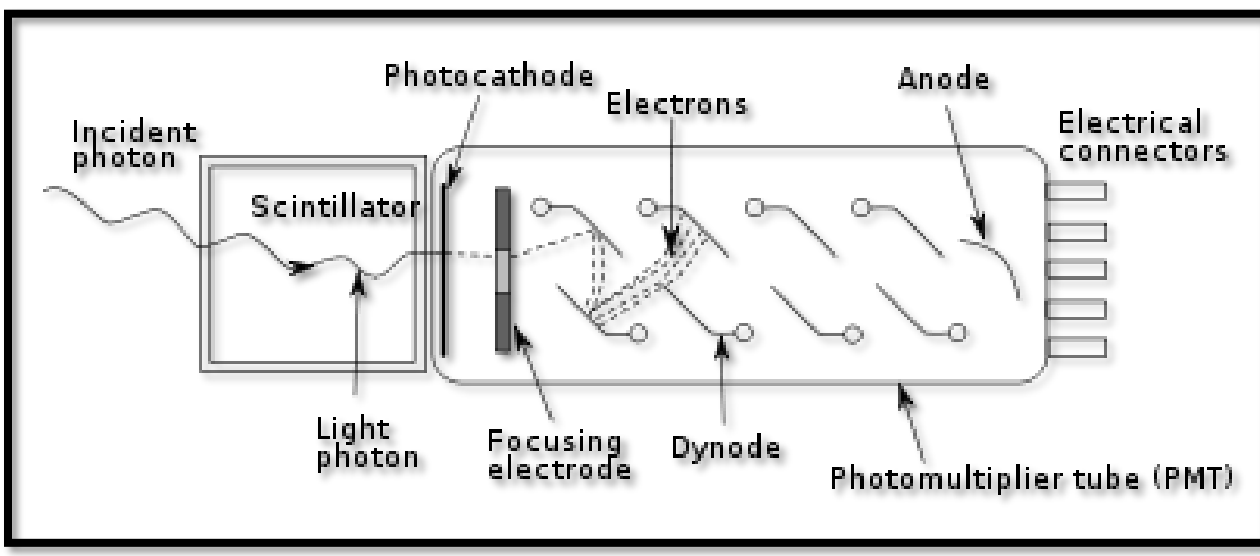


FIGURE 3: Schematic diagram of a gamma ray (e.g. an X-ray) producing light in a scintillator which impinges on the PMT.[2]

The PMT's are powered by CAEN V6533N and V6533M modules which are 6-channel VME [3] Programmable High Voltage Power Supplies shown in Figure 1b. The V6533N provides 6 channels of negative voltage and the V6533M has 3 negative outputs (0-2) and 3 positive outputs (3-5, unused). The HV outputs are delivered on high voltage cables through Safe High Voltage (SHV) connectors; *HV connectors should only be inserted or removed when the HV is off*. Each PMT has been set at a voltage to produce about the same pulse height for passing through muons; these may need some adjustments. The scintillators are labeled 1-4, with light guides labeled a and b on each end. See Table 1 for the voltage settings and Appendix 3 for the channel and cable assignments.

HV Output	Voltage (V)
V6533N 0	1693
V6533N 1	1644
V6533N 2	1680
V6533N 3	1550
V6533N 4	1663
V6533N 5	1584
V6533M 0	1663
V6533 M 1	1650

TABLE 1: Approximate High Voltage Settings.

The PMT's last dynode outputs are connected to CAEN V1720 flash analog to digital converters (ADCs). See Appendices 1 and 3 and Figure 1b. The V1720 [4] houses 8 channels of 12 bit 250 MS/s Flash ADC Waveform Digitizer. In this module the analog to digital conversion occurs as close as possible to the detector. The operation of the digitizer is similar to an oscilloscope; when a trigger occurs, a certain number of samples are saved into one memory buffer. An algorithm (in the V1720) will continuously calculate the baseline of the input signal by averaging the samples over a moving window. The input signal is compared against the value of the trigger threshold and the trigger fires as soon as it is crossed by the signal – thus, the ADC is self-triggered by any observed pulse. The trigger enables the event building, and the event data is saved into a memory buffer. The control software automatically optimizes both the number of events inside the buffer and the number of total buffers in the memory [15]. The integral of the pulse charge corresponds to the energy of the incident particle; calibration is required before actual energy units can be assigned. In addition, a time stamp of the trigger is recorded. Figure 4 illustrates a single pulse and its parameters. (The specific detector parameters can be seen in Table 2.)

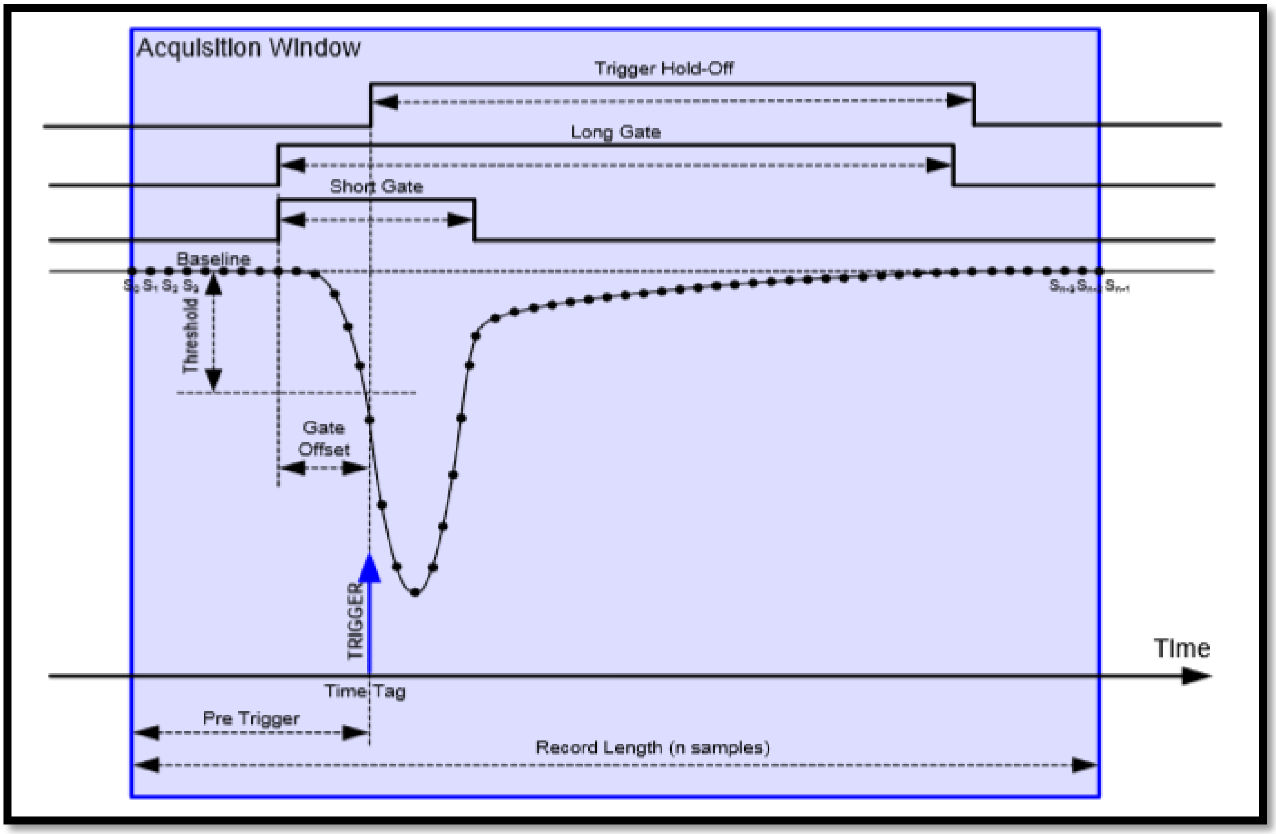


FIGURE 4: Diagram illustrating the pulse parameters. The trigger fires as soon as the signal crosses the threshold. [15]

Parameter	Value
Trigger Hold-Off	80 ns
Long Gate	200 ns
Short Gate	40 ns
Threshold	100
Pre Trigger	12 ns

TABLE 2: Details the parameters of the V1720 digitizer.

Both the V1720 and the V6533 modules are controlled by the master module, CAEN V1718 [5]. The module is operated through a USB port to a laptop computer. The V1718 provides all the addressing and data transfer. The V1720, V6533 modules, and V1718 are all contained in a VME crate. The laptop uses the MIDAS data acquisition system (Maximum Integrated Data Acquisition System) developed at TRIUMF. MIDAS provides the frontend template for acquiring hardware information, data transfer, full run control and web interface for experimental control. A tailored analysis program (using some of the MIDAS framework as a backbone) was developed for demonstration as discussed below. The analysis program uses coincidence gating to detect stopping muons and produce energy spectra. Custom analysis of the data can also be done as described below.

One of the unique things about this detector is its customizable configuration. Examples of setups shown in Figure 5 include A) 4x1 horizontally; B) 2x2; and, C) 4x1.

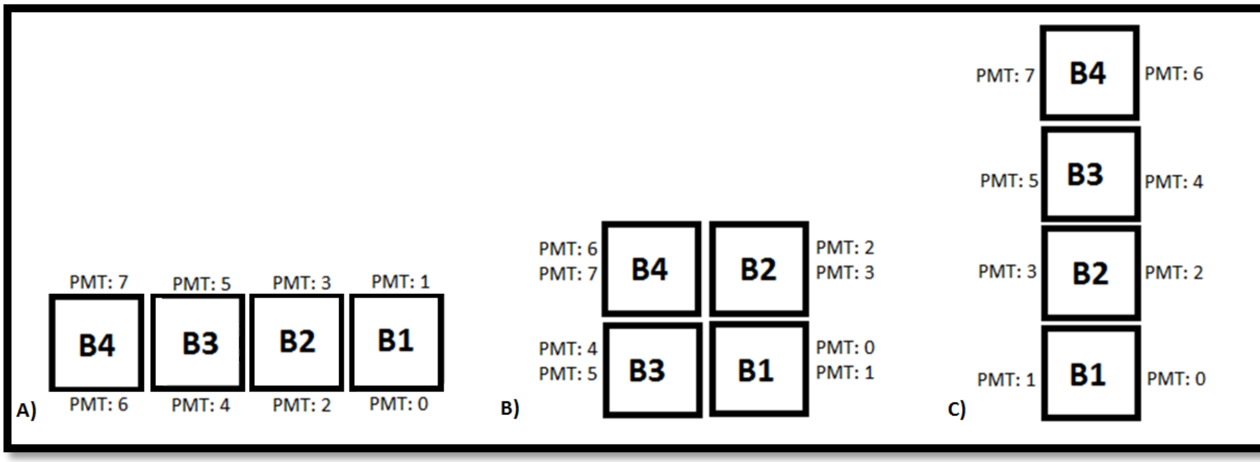


FIGURE 5: Some possible configurations of the SMD; A) 4x1 horizontal; B) 2x2; and C) 4x1 vertical. Before re-confguring the setup, turn high voltages off.

Description of Analysis Program

The SMD detector can be set to take data for a specific amount of time or to be free running. During operation, it will sense all particles (muons being the most abundant) that pass directly through the scintillator as well as the muons that stop and subsequently decay. Muons decay by emitting electrons and neutrinos via the reaction $\mu \rightarrow e\nu\nu$; the kinetic energy of the decay particles runs from 0 to half the muon mass 52.3 MeV. The analysis program is designed to distinguish between pass through and stopping muons. A particle that will pass through will excite the scintillator producing a single pulse. The integrated pulse energy of this particle is put in a histogram called the “Passing Through Event Spectrum”. An example of this spectrum is given in Figure 6.

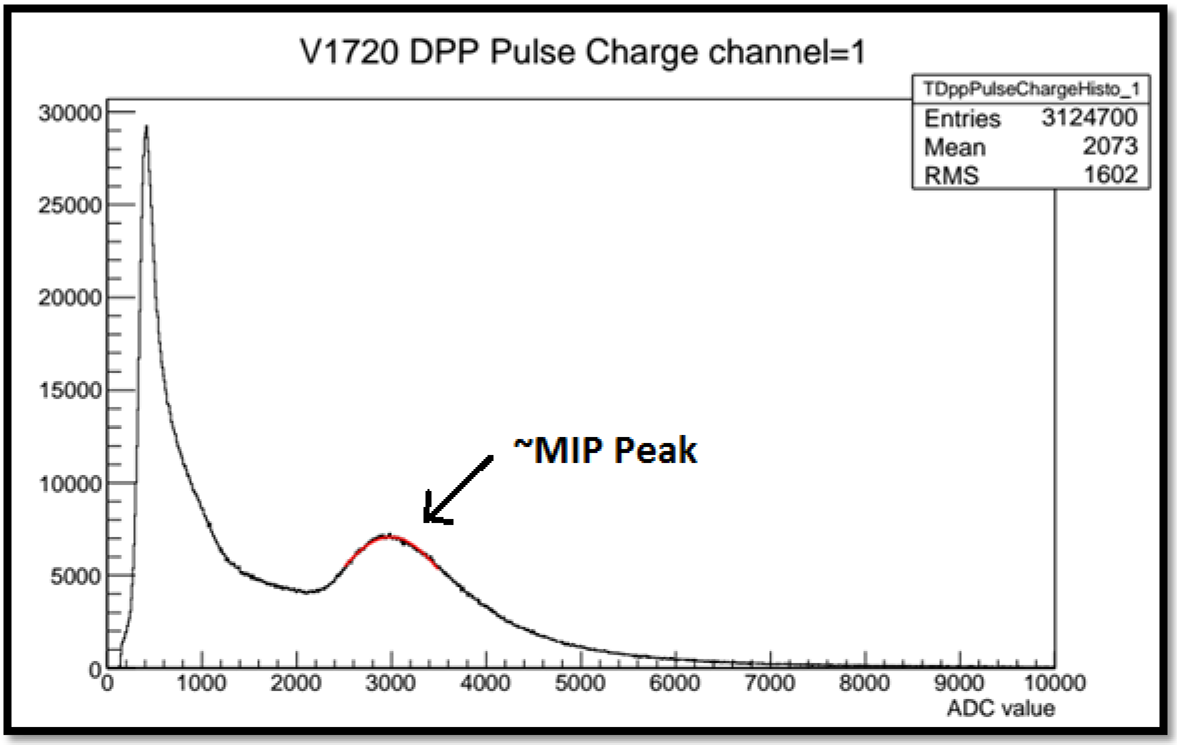


FIGURE 6: A standard "passing through particle event spectrum" of cosmic radiation; the "MIP peak" represents the energy lost by minimum ionizing (high energy) particles traversing the scintillator block.

Note that the ADC value is plotted in Figure 6 because the energy calibration has not yet been completed. The Minimum Ionizing Particles (MIP) peak corresponds to cosmic muons that don't stop. The peak is roughly at 22 MeV. There is also a chance that muons which have low enough energy to stop in a bar will decay into an electron inside the bar. This will produce two pulses in the same bar and maybe also in other bars in coincidence. See Figure 7 for pulse comparisons. The muon lifetime is 2.2 µs.

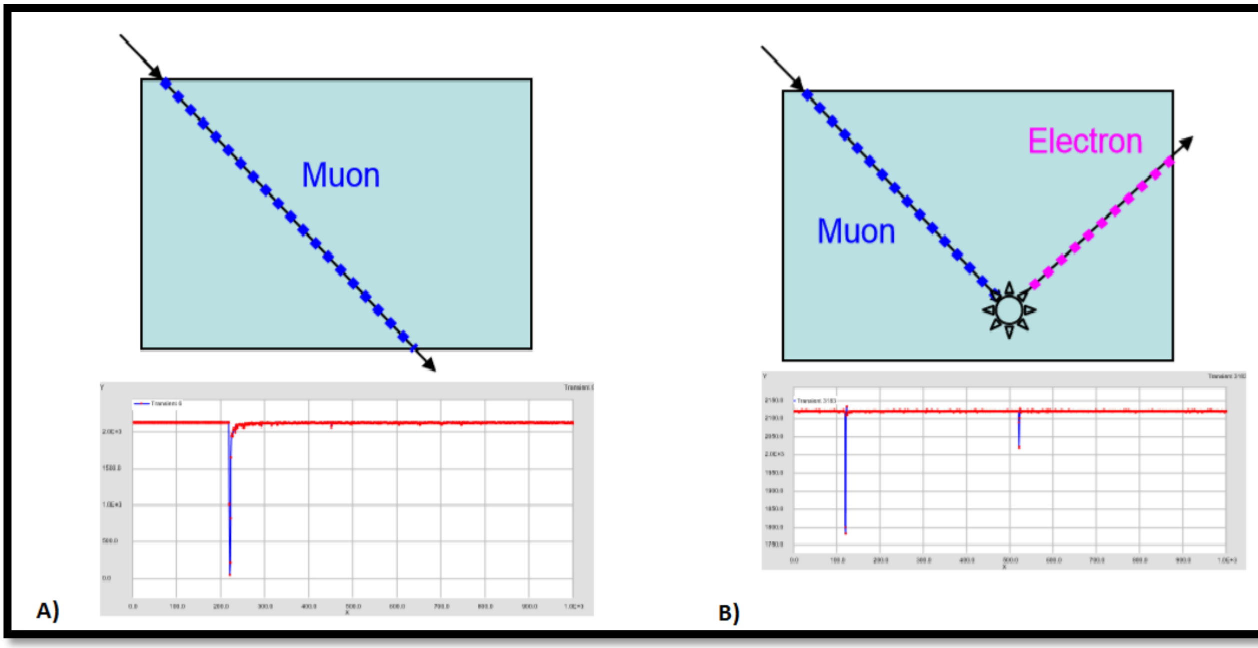


FIGURE 7: A) A muon (or other particle) that passes through the detector without decaying. B) A muon that stops and decays to an electron inside the bar.[17]

If the time difference between the pulses is less than 20 µs the difference is recorded in the “Time Difference Histogram”. See Figure 8 for an example. This histograms corresponds to the decay time distribution (which is used to fit the distribution)

$$D(t) = \lambda \exp(-\lambda t) + B. \qquad (1)$$

If the parameters of the fit indicate a lifetime of ~2.2 µs the particles can be identified as muons. (Cosmic rays may consist of both positive and negative muons which have slightly different lifetimes when stopped in plastic scintillator. Do you know why?)

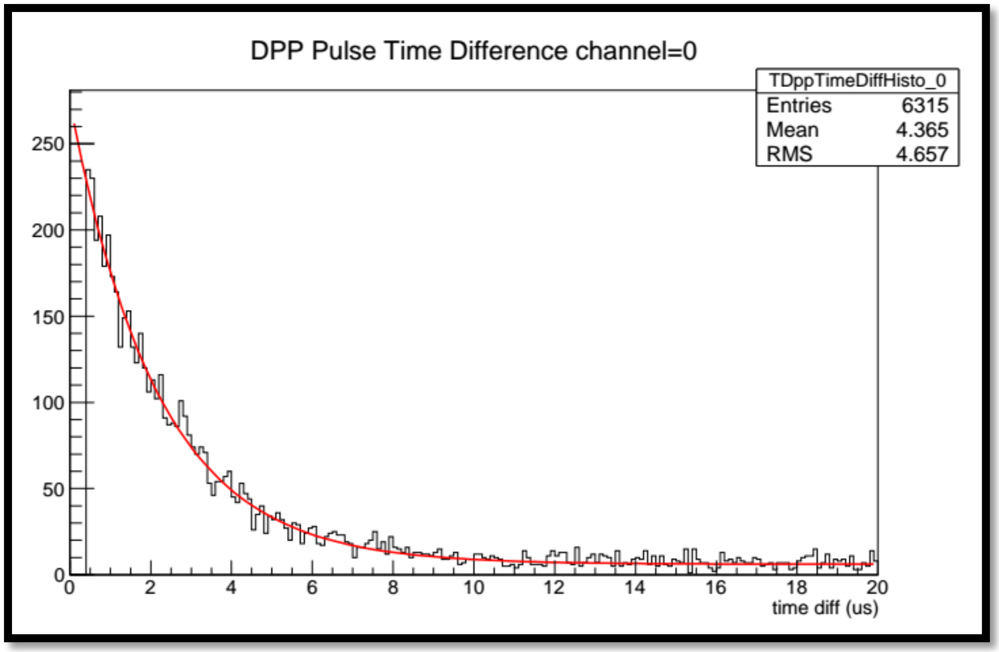


FIGURE 8: Muon decay time distribution.

Once identified as a muon (events with 2 pulses found) the energy of the 2nd pulse (the electron) is recorded. See Figures 9-10 for the incident muon and electron energy spectra.

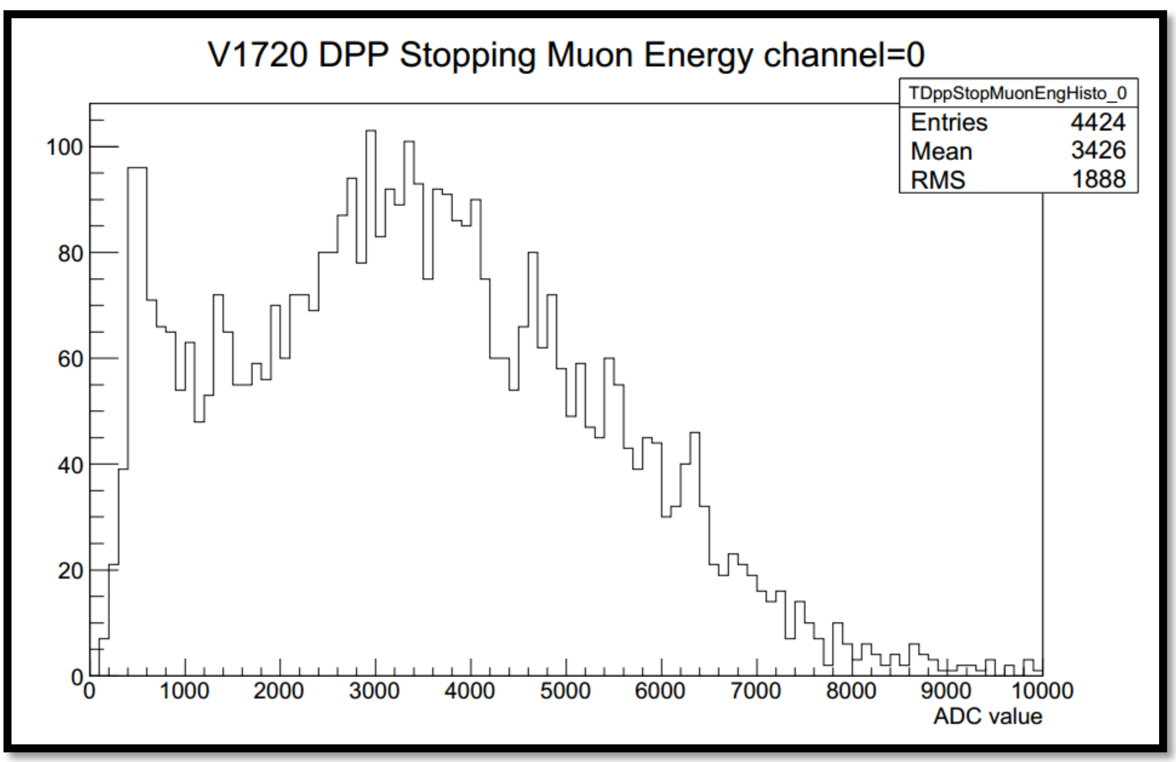


FIGURE 9: Cosmic ray muon stopping energy spectrum.

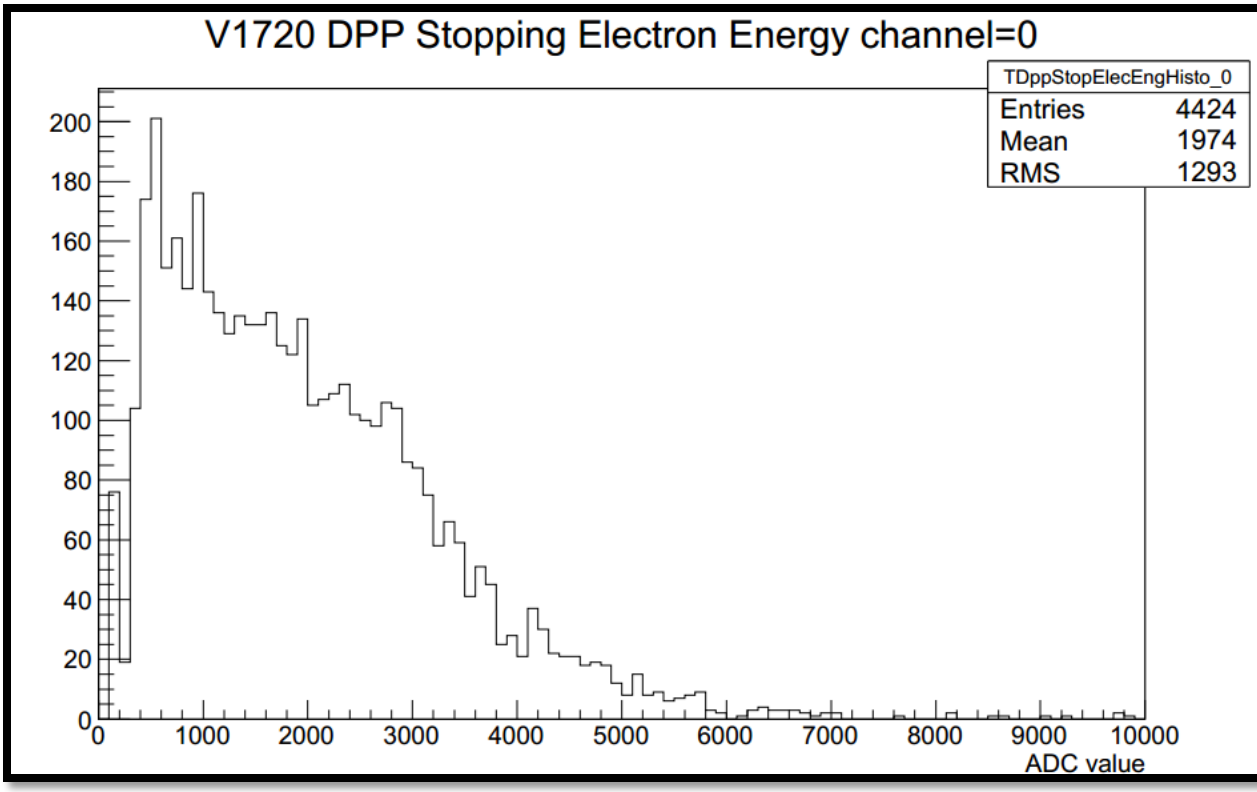


FIGURE 10: Muon decay electron energy spectrum.

The above analysis is performed live, separately on each of the PMT's. In the end, eight histograms are produced for the passing though event spectrum for single hits, and the decay time distribution, the stopping muon energy spectrum and the decay electron energy spectrum for 2-hit events.

From an average cosmic ray spectrum (i.e. no external sources or shielding) there is an average of ~130 muons/sec that pass through while only 16 muons/min stop. The system is able to distinguish between these types of events.

There are many other measurements that can be done with this system using the pulse data from the PMTs as discussed below (see "Performing your own Measurements and Analysis").

Operation

There are two main software components to the Stopping Muon Detector system. The MIDAS front end and the tailored analysis program. The detector is controlled by the laptop through the front end MIDAS system. Here all aspects of the detector can be changed.

The laptop name is daqlap01.triumf.ca. An account has been setup named daquser which requires a pw which will be supplied.

The daq system is controlled via a web interface: http://daqlap01.triumf.ca:8081/ which looks as follows:

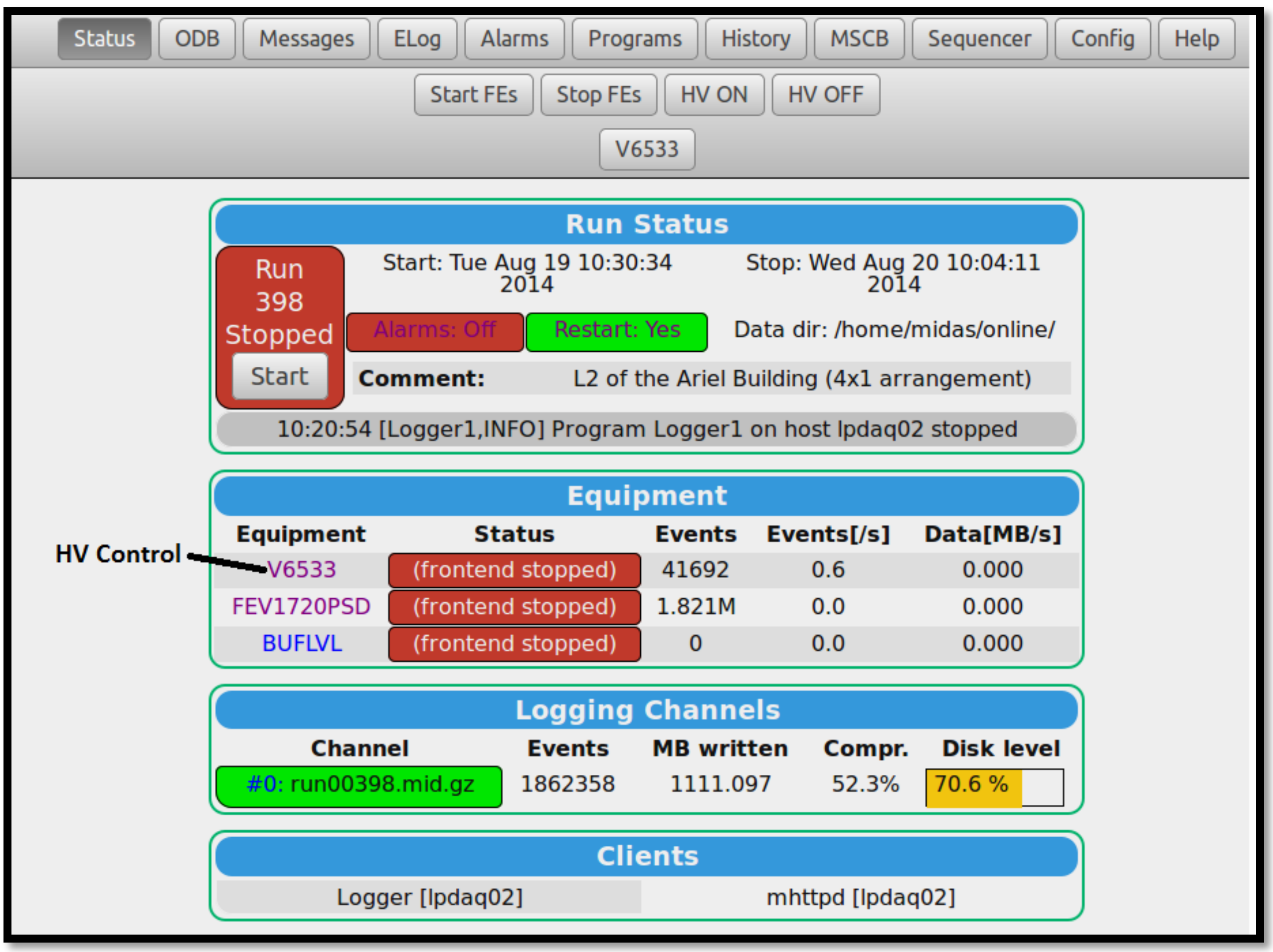


FIGURE 11: MIDAS control system

Before starting a run, make sure that the FEV1720PSD and V6533 frontend programs are running. If they are not, go to the Programs page and start them:

http://daqlap01.triumf.ca:8081/?cmd=Programs. The FEV1720PSD program acquires the data from the digitizer board.

When the frontend programs are running, you can se HV ON from the **Status** page, and start a run. You can decide whether you actually want to write the data for a particular run. The trigger rate for the V1720 is ~18Hz.

The eight PMT high voltage values are set via the **ODB** tab on the main **Status** page. Choose "**Equipment**" and then "V6533", then "**Variables**"; view, set, or change the HV values (which are normally set to nominal values). ***Consult the lab supervisor before changing the HV.*** The nominal HV values are set to put the pass through muon peak at roughly the same adc sum value

Starting A Single Run With No Time Limit

If the detector is completely set up there is an easy way to start a run. This run will only stop when stopped manually.

STEP 1: Open the MIDAS control: This can be done through two links

- ➔ TRIUMF network connected: Type the URL: **daqlap01.triumf.ca:8081.** If the link does not open. See Opening A TRIUMF Network Link in Appendix 1.
- ➔ TRIUMF network not connected: Type the URL: **localhost:8081**

STEP 2: Select the **START** button in the red square of the MIDAS control

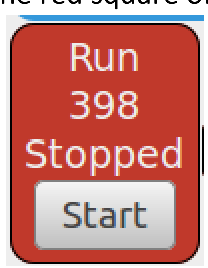


FIGURE 12: Start button of MIDAS control

STEP 3: A screen will appear asking for a comment and a run number (Enter a comment if you need to.)

STEP 4: The run will continue until the user manually presses the **STOP** button

Starting Multiple Run's With Time Limit

There is a way to allow multiple runs of a specific time.

STEP 1: On the MIDAS front end control panel select the **SEQUENCER** tab

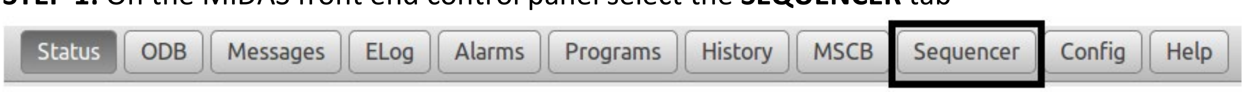


FIGURE 13: Sequencer tab on the MIDAS control.

STEP 2: Select the **Start Sequence** button
STEP 3: The screen will then give you the option of selecting the number of runs and the time of each run (in seconds). Once satisfied with those parameters select okay.
STEP 4: The run will then run for the given amount of time. After the run is finished the next one will start after a given amount of time. This value can be changed by editing the script

Running an analysis live

It is sometime beneficial to analyse the run as it is taking data. In this way any error or loose cables can be noticed before a lot of time is wasted.

STEP 1: From the laptop open a terminal

STEP 2: Enter: **cd online/src/analyzer**

STEP 3: Enter: **./SmdDisplay.exe**

STEP 4: The analyzer program will then appear and data will start to fill the histograms. The analysis program includes the Passing Though Event Spectrum, The Decay Time Distribution, The Stopping Muon Energy Spectrum, The Decaying Electron Energy Spectrum and the Waveform Spectrum.

STEP 5: The analysis window will continue to update until the run is stopped and all data points are entered.

Running an analysis on a previous run

Previous runs are saved on the laptop and backed up occasionally by Pierre Amaudruz. The files can be viewed by opening a terminal and entering **cd online.** In this folder all the runs can be viewed. Each run will have two associated files. The first one is run00###.mid.gz which contains all the run data. The second is run00###.odb which is a text file with the stored parameters of the run.

STEP 1: From the laptop open a terminal

STEP 2: Enter: **cd online/src/analyzer**

STEP 3: Enter: **./SmdDisplay.exe ~/Data/run00###.mid.gz –S3000000**;
Revision (analyzes whole run) : **./SmdDisplay.exe ~/Data/run00###.mid.gz –S**;
This will start the analyzer; it is very similar to the live analysis except we select a specific run and number of events.

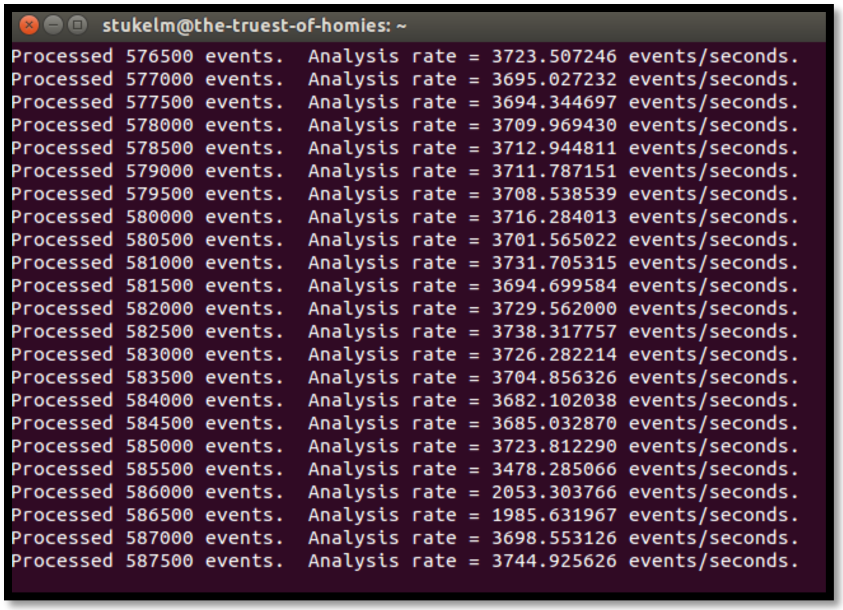


FIGURE 14: Events being processed.

STEP 4: After step 3 is entered, the progress of events analysed will scroll down the terminal. If the number of events chosen is more than the total events of the run the analysis window will not appear. So, the first time you do step 3 you should select an abnormally high number of events. In this way you can determine the actual number of events.

STEP 5: Once the progress stops, the analysis window will appear.

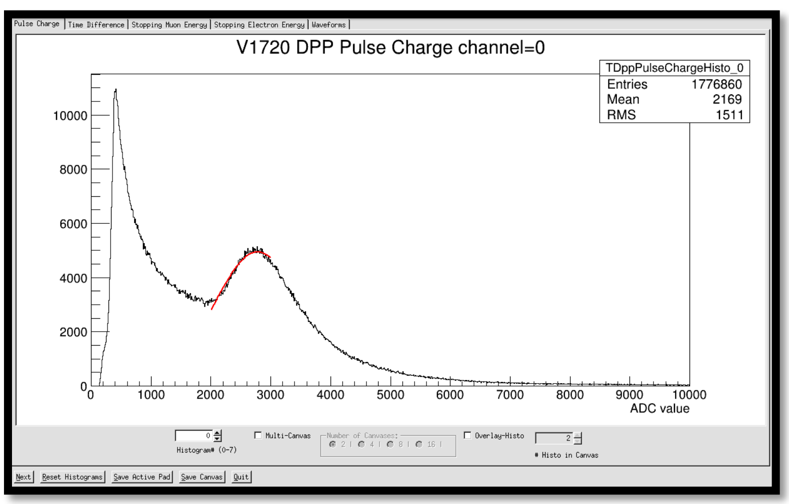
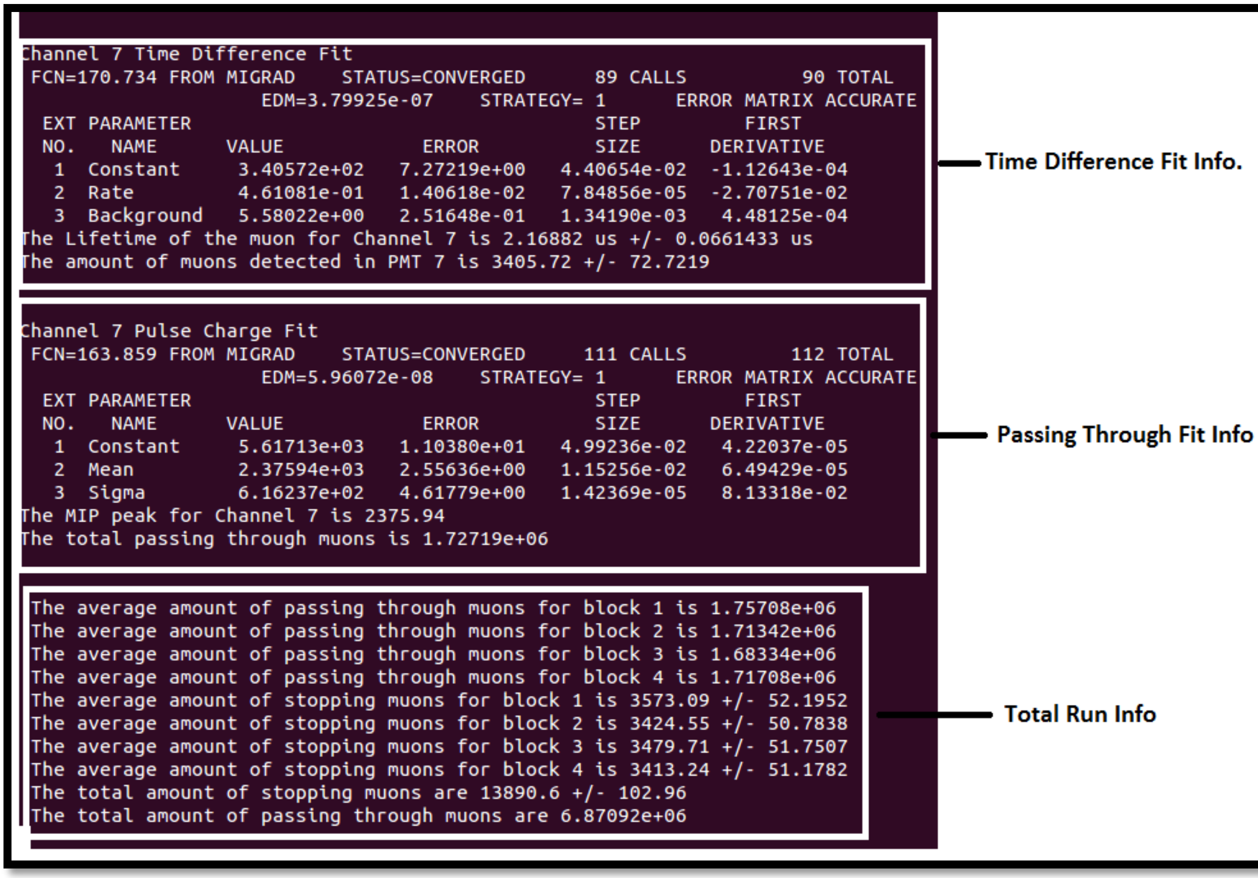


FIGURE 15: General Analysis Window

STEP 7: The analysis window allows you to save the canvases in a selected format like .eps. The results of the run can be found on the terminal screen. This includes the fit for each PMT, the total stopping muon rate, and the total passing muon rate.


```
Channel 7 Time Difference Fit
 FCN=170.734 FROM MIGRAD    STATUS=CONVERGED      89 CALLS          90 TOTAL
                     EDM=3.79925e-07    STRATEGY= 1      ERROR MATRIX ACCURATE
  EXT PARAMETER                                STEP         FIRST
  NO.   NAME      VALUE            ERROR          SIZE      DERIVATIVE
   1  Constant     3.40572e+02   7.27219e+00   4.40654e-02  -1.12643e-04
   2  Rate         4.61081e-01   1.40618e-02   7.84856e-05  -2.70751e-02
   3  Background   5.58022e+00   2.51648e-01   1.34190e-03   4.48125e-04
The Lifetime of the muon for Channel 7 is 2.16882 us +/- 0.0661433 us
The amount of muons detected in PMT 7 is 3405.72 +/- 72.7219

Channel 7 Pulse Charge Fit
 FCN=163.859 FROM MIGRAD    STATUS=CONVERGED     111 CALLS         112 TOTAL
                     EDM=5.96072e-08    STRATEGY= 1      ERROR MATRIX ACCURATE
  EXT PARAMETER                                STEP         FIRST
  NO.   NAME      VALUE            ERROR          SIZE      DERIVATIVE
   1  Constant     5.61713e+03   1.10380e+01   4.99236e-02   4.22037e-05
   2  Mean         2.37594e+03   2.55636e+00   1.15256e-02   6.49429e-05
   3  Sigma        6.16237e+02   4.61779e+00   1.42369e-05   8.13318e-02
The MIP peak for Channel 7 is 2375.94
The total passing through muons is 1.72719e+06

The average amount of passing through muons for block 1 is 1.75708e+06
The average amount of passing through muons for block 2 is 1.71342e+06
The average amount of passing through muons for block 3 is 1.68334e+06
The average amount of passing through muons for block 4 is 1.71708e+06
The average amount of stopping muons for block 1 is 3573.09 +/- 52.1952
The average amount of stopping muons for block 2 is 3424.55 +/- 50.7838
The average amount of stopping muons for block 3 is 3479.71 +/- 51.7507
The average amount of stopping muons for block 4 is 3413.24 +/- 51.1782
The total amount of stopping muons are 13890.6 +/- 102.96
The total amount of passing through muons are 6.87092e+06
```


FIGURE 16: Fit information for PMT

STEP 8: Click the quit button or close the window. (Cntrl c).

STEP 9: Once the analysis window is closed Enter: **emacs previous_run_results.txt**. This will produce a text file with all the results of the previous run. Save this file in Project/smd/analyzer/observations. Using the name convention shown there.

STEP 10: The information can then be entered in the run log found in SMD_run_log.xlsx

Turning off the Detector

Before the detector can be moved it must be properly disassembled.

STEP 1: Turn off the HV by selecting **HV OFF** button on the **Status** page. You can see the voltage decrease by selecting the **V6533** link.

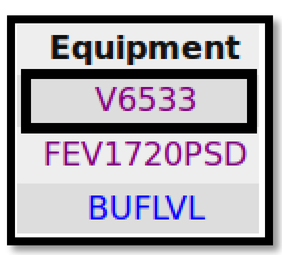


FIGURE 17: V6533 link

STEP 2: Once the voltage is at zero select the programs tab.

FIGURE 18: Programs tab on the MIDAS control

STEP 3: Click **Stop** on the scV6533 and fev17120psd system. They should turn red.

STEP 4: Turn off the power button, and unplug the power cables. The Detector is now ready to be moved. If possible the laptop can remain connected to V1718 Master Module.

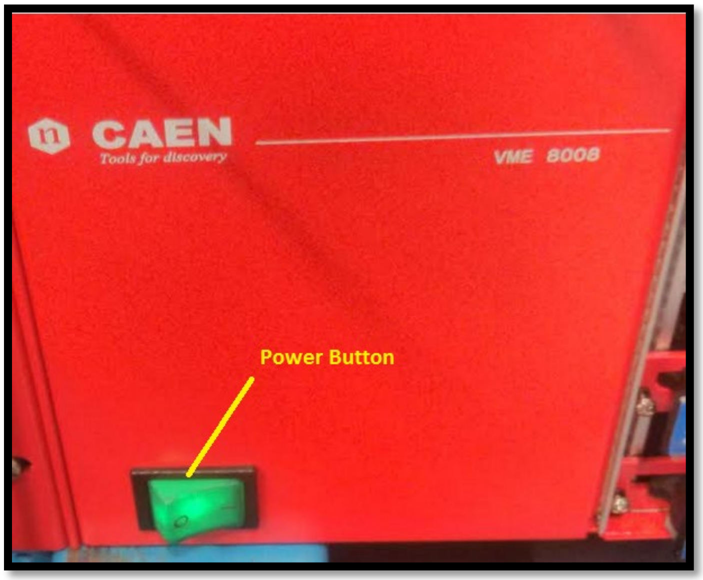


FIGURE 18: Power Button on CAEN crate

Performing your own Measurements and Analysis

On-line Software/Analyzer

As indicated above, pulses from the eight PMTs attached to the bars are digitized by the CAEN V1720 digitizer card. This card has a 250 MSPS (Mega-sample per second) ADC for each channel. The data from this ADC is processed in real time by the Field Programmable Gate Array (FPGA) on the digitizer card to find and process hits. The online pulse processing that is implemented on this card is called PSD (Pulse Shape Discrimination). The basic idea is that you get a charge and a time for each individual hit that the FPGA finds. The online monitoring can be used to display information from the DAQ during a run. To start the online monitor enter

/home/daquser/online/src/analyzer/SmdDisplay.exe

The same program can also be used on a MIDAS file that has already been written. For instance,

/home/daquser/online/src/analyzer/SmdDisplay.exe /home/daquser/Data/run00016.mid.gz

The program shows plots of the charge, time difference between hits and waveforms for each of the digitizer's channels.

Output Data Text Files

Once a run is finished, another program automatically converts the key information in the MIDAS file to a text file. **These text files can be analyzed by you** using whatever program you like e.g. Python, ROOT, Gnuplot, Excel. The text files are in the directory

/home/daquser/Data/text_output/

The output text file consists of lists of the last 10 SMD hits in each channel, with one hit per line. Each line consists of three numbers:

TimeTag, Channel, Charge

where

- TimeTag: the internal clock time for each hit; clock is 250MHz; multiply TimeTag by 4 to get time in nanoseconds. **N.B. the time tag is a 32 bit signed integer that wraps around every 17 s.**
- Channel: 0-7, the channel of the 1720 digitizer

- Charge: the integrated charge for the pulse (in digital counts)

To find coincidences between the two ends of bars or between bars, write a program to sort through the list of times to find matches (or near matches). To find double hits (e.g. indicative of muon stop and decay) find time matches within the 20 µs time memory of the digitizers.

Propose and Perform Measurements

The SMD setup is quite versatile, so many possible measurements can be performed and different configurations of the scintillator bars can be made as indicated in Figure 5. Some measurements might involve the use of additional material in which to stop muons or to ensure that you are dealing with high momentum particles. ***Before reconfiguring the scintillators (see Figure 5) consult the lab supervisor and turn off all PMT high voltages.***

Here are some example measurements you could design and carry out for studying detector performance and/or the properties of muons (**Bold recommended for GRIDS students**):

- **Detection efficiency vs. voltage**
- **Average rate of energy loss (dE/dx) for through-going cosmic ray muons**
- **Average energy loss ΔE for for stopping muons in the scintillation bars**
- Timing resolution of the PMTs and scintillator bars dT(ΔE) e.g. measure the end-end time differences, or resolution of coincidence hits between bars, etc.
- **Spatial resolution using signals from two ends of one bar and/or multiple bars or compare with the locations of µ→e decays; this could be done by correlating the positions of the through-going and stopping muons using the decay electrons or positrons.**
- **Positive Muon lifetime**
- Lifetime of negative muons stopping in materials; stopping negative muons can form muonic atoms which result in reduced lifetimes which vary considerably depending on the material. [6]
- µ→e decay energy measurement (using one or more bars); spatial and timing information is valuable here.
- µ -e decay forward-backward asymmetry to determine polarization of positively charged cosmic ray muons; this requires some more subtle considerations since muons depolarize in some materials like plastic scintillator.

Form a small group of 2-4 students and propose a set of measurements using a particular configuration of the four bars; once begun, measurements can be monitored remotely and data can be taken over a 10-24 hour period. Explain briefly how you will perform the proposed measurements and what your expectations are. Discuss your proposal with the lab supervisor or others.

(**For Phys. 531:** Submit the proposal including some proposed days and times for the measurements (≤ 1 page) to the Phys531 Program Review Committee (DB!).) After taking the data and analyzing it, write up a brief summary of the measurements, results, and comparison with expectations (e.g. simulations, calculations, other known measurements, if any, etc.).

Appendix 1

Moving the detector (unplugged)

The detector rests on top of a pull cart with wheels, this allows it to be moved around. The only requirement of re-positioning the detector is availability of a power outlet. Access to the TRIUMF network is helpful, as it allows you to access the computer from an external location, but this is not compulsory for performing a run.

STEP 1: Move the detector to the desired location.
STEP 2: Connect the plug to an outlet.

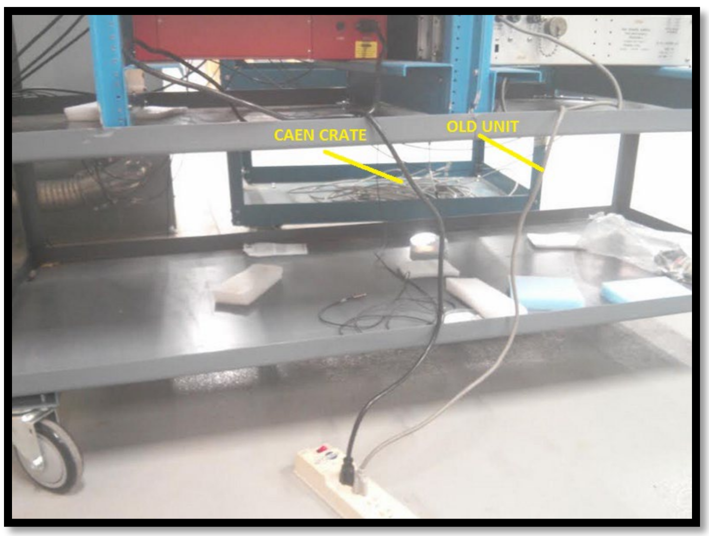


FIGURE 19: Power cord of the CAEN CRATE (black). (The current system has only one power cord.)

STEP 3: Reconnect the USB output from the V1718 Master module to the laptop.

FIGURE 20: V1718 Output USB

STEP 4: Power on the detector by switching the green power button

STEP 5: The detector is turned on by reversing the order of how it was turned off. Make sure the voltages are fully ramped up before starting a run.

Opening A TRIUMF Network Link

On occasions when the detector is moved the connection to the TRIUMF network must be re-established. This also works if the computer is restarted. For this to work the laptop must be connected to a working Ethernet port. The laptop can be run locally through: **localhost:8081** whether or not it is connected to the network.

STEP 1: Make sure the laptop is connected to the internet and open a terminal

STEP 2: Enter: **cd online/src/bin**

STEP 3: Enter: **./start_daq.sh** This will open the connection and if everything is working should produce a MIDAS front end window under the link **daqlap01.triumf.ca:8081**

STEP 4: Once this link is established you will be able to access the laptop from other computer connected to the TRIUMF network.

STEP 5: To do this open a terminal on your own personal computer.

Enter: **ssh daquser@daqlap01.triumf.ca -X**

STEP 6: You will then be asked for a password. This can be obtained from Doug Bryman or the lab supervisor.

Appendix 2

On-line Analysis Program Details

This section contains a brief introduction to the code layout of the built-in analysis program. It also details auxiliary scripts that have been developed and provides instructions on how to run this scripts. Knowledge of C++ and root is required to modify the program.

Introduction to the Analysis Program

The analysis program includes ten files. A brief description is given below. The files must be compiled before the analysis program can be run.

TWaveformHisto.cxx: Creates the class that creates the histogram for the wavefunction of the individual pulses. Relevant header (TWaveformHisto.h) is included.
TV1720DppData.cxx: Create a class to store the V1720 Dpp information. Relevant header (TV1720DppData.h) is included.
TV1720WaveformData.cxx: Creates a class to store the V1720 waveforms from the DPP processing. Relevant header (TV1720WaveformData.h) is included.
SmdDisplay.cxx: This is the main function and create the GUI for the analysis program. Relevant header (SmdDisplay.h) is included.
TSmdAnaManager.cxx: This class fills the different histograms. Also includes the option to output the data to: **Projects/smd/analyzer/compcoinc.** See below for more information. Relevant header (TV1720WaveformData.h) is included.
TDppPulseChargeHisto.h: Creates the histogram for the Passing through muons.
TDppTimeDiffHisto.h: Creates the histogram for the decay time spectrum.
TDppStopMuonEng.h: Creates the histogram for the energy of the stopping muons.
TDppSopElecEng.h: Creates the histogram for the energy of the decay electrons.
Makefile: The make file required for compilation.

Extra Analysis Programs

There are certain results that can only be obtained by running external scripts on the data obtained from a given run. It is not that these scripts couldn’t be contained in the analysis program it’s that the live event processing would be drastically slowed down by these scripts.

The script is designed to check coincidence between different PMT's. It is currently set up to check muons that pass through three PMT's and stop in a fourth. The energy spectrum of these muons at each step of the way is produced. It can be modified for different functions.

Run the Program

STEP 1: Choose the run you would like to check the coincidence of. (ex 356 or something) and open a terminal.

STEP 2: Enter: **cd online/src/analyzer**. When the selected run is analyzed you need the data to be saved in external text files. In this way more complicated analysis can be performed.

STEP 3: The analysis program already contains the code necessary to output the data as external text files it is just commented out. The analysis program runs faster when text output section is commented out. Enter: **emacs TSmdAnaManager.h &**

STEP 4: Un-comment the following section. Then save and close the file.

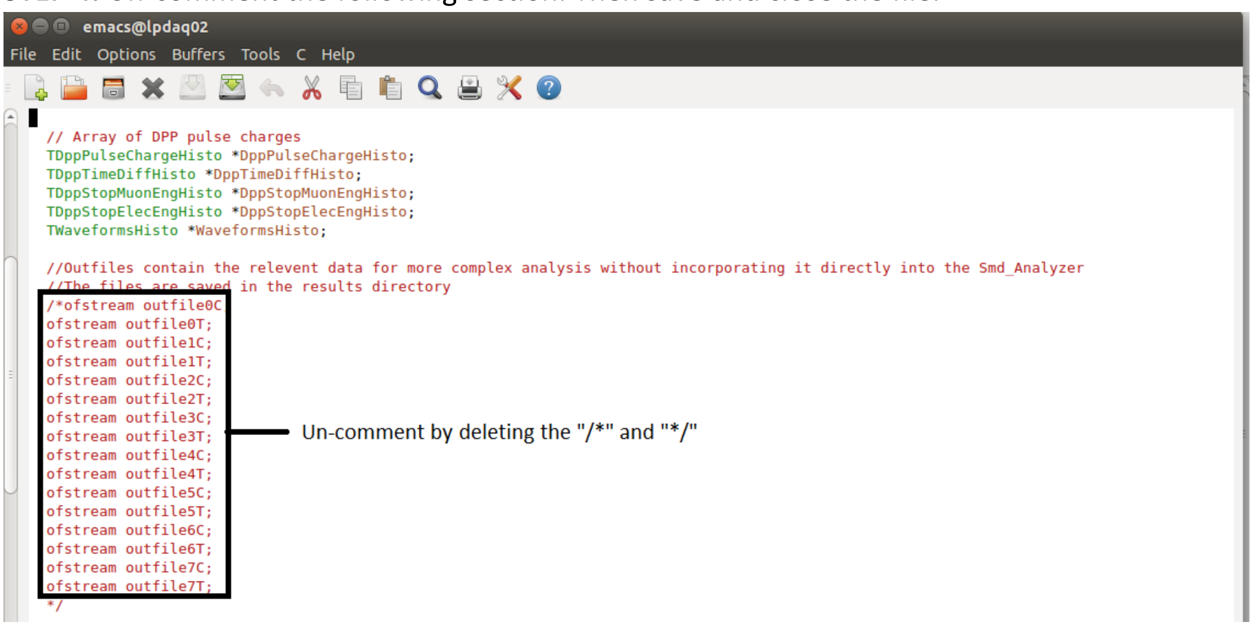


FIGURE 22: Section required to un-comment on the TSmdAnaManager.h file

STEP 5: Enter: **emacs TSmdAnaManager.cxx &**. Un-comment the following two section. Then save and close the file emacs@lpdaq02

File Edit Options Buffers Tools C++ Help

```cpp
DppStopMuonEngHisto = new TDppStopMuonEngHisto();
DppStopMuonEngHisto->DisableAutoUpdate();

DppStopElecEngHisto = new TDppStopElecEngHisto();
DppStopElecEngHisto->DisableAutoUpdate();

WaveformsHisto = new TWaveformsHisto();
WaveformsHisto->DisableAutoUpdate();

/*
outfile0C.open("/home/midas/Projects/smd/analyzer/compcoinc/results0C.txt");
outfile0T.open("/home/midas/Projects/smd/analyzer/compcoinc/results0T.txt");
outfile1C.open("/home/midas/Projects/smd/analyzer/compcoinc/results1C.txt");
outfile1T.open("/home/midas/Projects/smd/analyzer/compcoinc/results1T.txt");
outfile2C.open("/home/midas/Projects/smd/analyzer/compcoinc/results2C.txt");
outfile2T.open("/home/midas/Projects/smd/analyzer/compcoinc/results2T.txt");
outfile3C.open("/home/midas/Projects/smd/analyzer/compcoinc/results3C.txt");
outfile3T.open("/home/midas/Projects/smd/analyzer/compcoinc/results3T.txt");
outfile4C.open("/home/midas/Projects/smd/analyzer/compcoinc/results4C.txt");
outfile4T.open("/home/midas/Projects/smd/analyzer/compcoinc/results4T.txt");
outfile5C.open("/home/midas/Projects/smd/analyzer/compcoinc/results5C.txt");
outfile5T.open("/home/midas/Projects/smd/analyzer/compcoinc/results5T.txt");
outfile6C.open("/home/midas/Projects/smd/analyzer/compcoinc/results6C.txt");
outfile6T.open("/home/midas/Projects/smd/analyzer/compcoinc/results6T.txt");
outfile7C.open("/home/midas/Projects/smd/analyzer/compcoinc/results7C.txt");
outfile7T.open("/home/midas/Projects/smd/analyzer/compcoinc/results7T.txt");
*/
```

Un-comment by deleting the "/*" and "*/"

FIGURE 24: First section required to un-comment on the TSmdAnaManager.cxx file

emacs@lpdaq02

File Edit Options Buffers Tools C++ Help

```cpp
               << pulse->Pur << std::endl;
     DppPulseChargeHisto->GetHistogram(pulse->Channel)->Fill(pulse->ChargeShort);
     //Output file section////////////////////////////
     /*  if(pulse->Channel == 0){
       outfile0C << pulse->ChargeShort<<endl;
       outfile0T << pulse->TimeTag<<endl;
      }

     if(pulse->Channel == 1){
       outfile1C << pulse->ChargeShort<<endl;
       outfile1T << pulse->TimeTag<<endl;
     }
     if (pulse->Channel == 2){
       outfile2C << pulse->ChargeShort<<endl;
       outfile2T << pulse->TimeTag<<endl;
     }
     if (pulse->Channel == 3){
       outfile3C << pulse->ChargeShort<<endl;
       outfile3T << pulse->TimeTag<<endl;
     }
     if (pulse->Channel == 4){
       outfile4C << pulse->ChargeShort<<endl;
       outfile4T << pulse->TimeTag<<endl;
     }
     if (pulse->Channel == 5){
       outfile5C << pulse->ChargeShort<<endl;
       outfile5T << pulse->TimeTag<<endl;
     }
     if (pulse->Channel == 6){
       outfile6C << pulse->ChargeShort<<endl;
       outfile6T << pulse->TimeTag<<endl;
     }
     if (pulse->Channel ==7){
       outfile7C << pulse->ChargeShort<< endl;
       outfile7T << pulse->TimeTag<< endl;
       }*/
     ////////////////////////////////////////////////////
```

Un-comment by deleting the "/*" and "*/"

FIGURE 25: Second section required to un-comment on the TSmdAnaManager.cxx file

STEP 6: Because changes have been made the analyzer needs to be re-compiled. Enter: **make clean.** Then Enter: **make**. This will compile the analyzer

STEP 7: Run the desired run (See Running an analysis on a previous run). The data from the PMT's will be put into external text files. The text files are located in the directory /**home/daquser/Data/compcoinc**. Each PMT has 2 files.

1) results#C.txt: This contains the energy of each pulse from the PMT #
2) results#T.txt: This contains the time tag of each pulse from the PMT #

NOTE: If you run another analysis the text files will get overwritten by the values of that case. So once you're finished you should comment out the output section and recompile.

STEP 8: Close the analysis window and Enter: **cd compcoinc**.

STEP 9: Enter: **emacs fourcoinc.C &.** This file is the script that performs the coincidence analysis. The code is designed to look for muons that stop in PMT 1, it then will determine what other PMT this muon travelled through. Currently it is set up to check PMT 3, 5 and 7 (one from each block). It can be configured to your personnel needs.

STEP 10: Before the script can be started the number of events from the text files must be entered. The number of events can be taken from the event files themselves. Just Enter: **emacs results#C.txt &**. Scroll to the very end and look at the line number. This must be done for all PMT's.

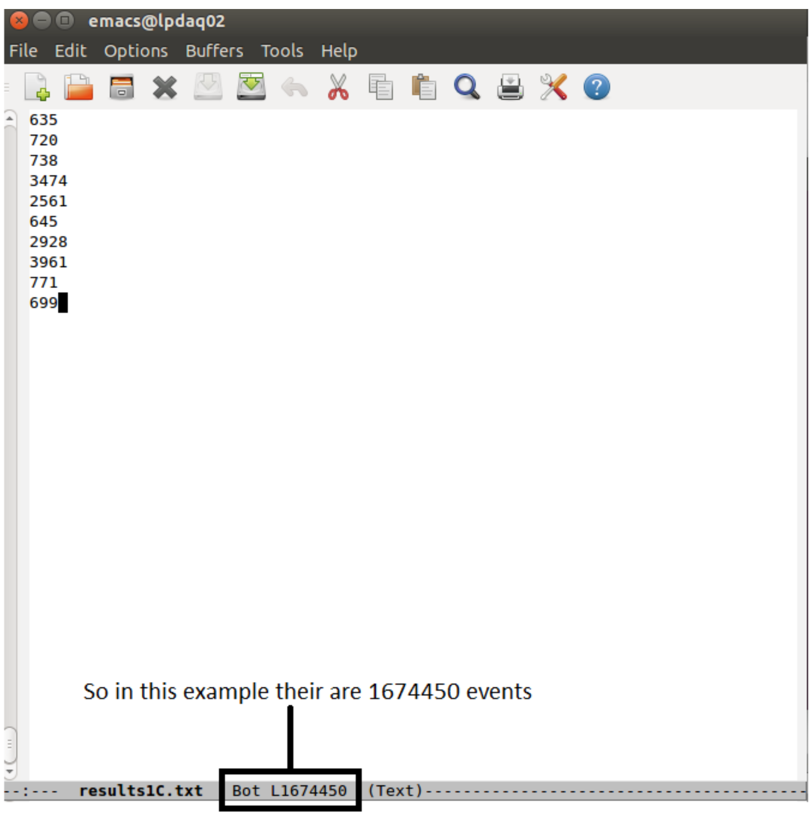


FIGURE 26: Number of event files for PMT 1

STEP 11: The event must be entered for each PMT. The section that they must be entered in is highlighted here.

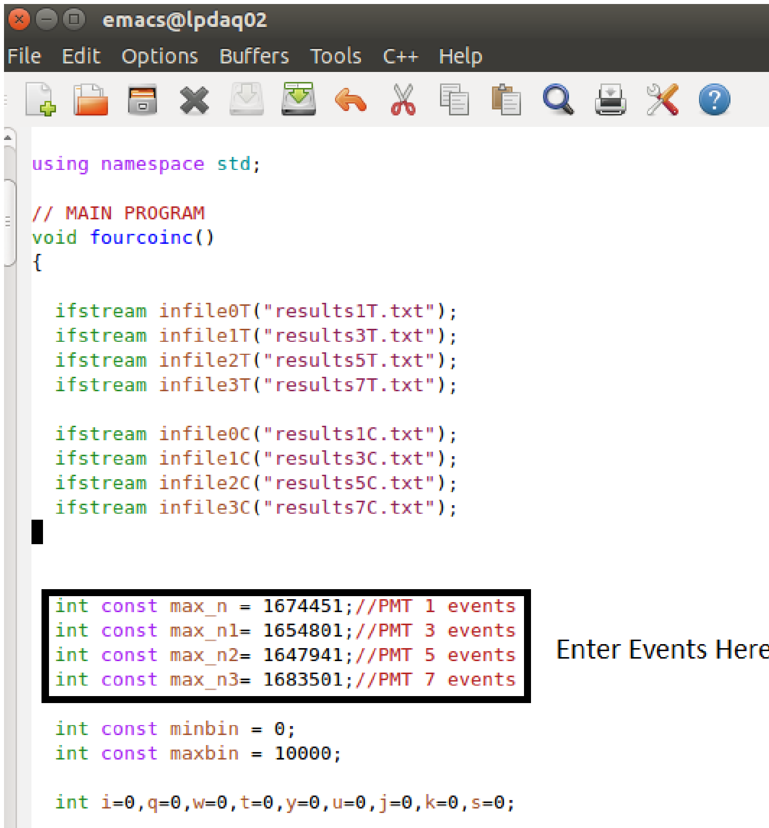


FIGURE 27: Enter the events

STEP 12: Once the events are properly entered save the document then close it.

STEP 13: Enter: **root –l**

STEP 14: Enter: **.x fourcoinc.C.** This will start the run.

STEP 15: The run will go for a while, when it is finished it will produce the following in the terminal. This will show the percent of muons that passed through each PMT.

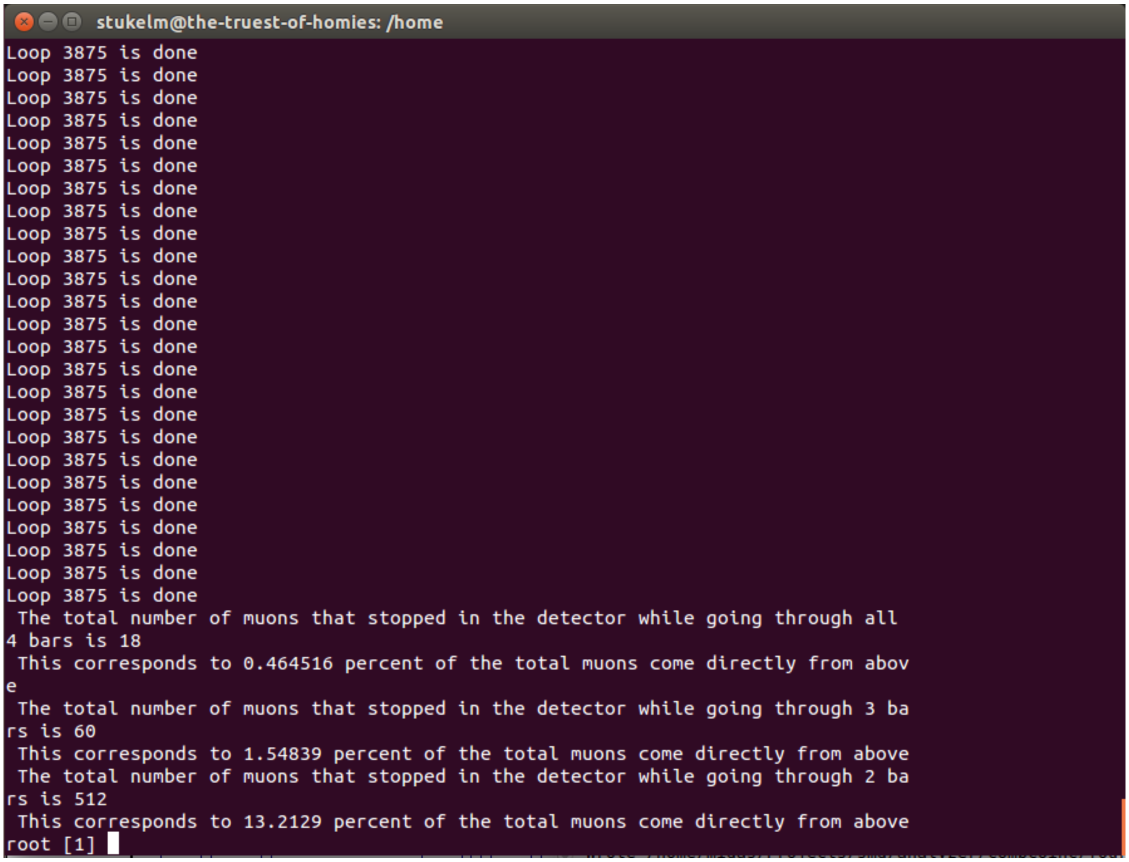


FIGURE 28: Terminal results of a run

STEP 16: Energy spectra are also given.

In the same folder there is a script **twocoinc.C** this will check the coincidence between any two PMT's and produce their energy spectrum. It is used in an identical way.

Appendix 3

Signal and HV Cabling (Revised May 16, 2025)

Light Guide Label	Signal cable	Digitizer Channel Caen 1720	PMT HV Cable	HV Power Supply Channel*	Nominal HV(V)
1a	Spare B	0	SMD HV5	1	1644
1b	200	1	SMD HV8	4	1663
2a	SB2A	2	SMD HV7	6	1663
2b	100	3	SMD HV1	0	1693
3a	SB3A	4	SMD HV6	5	1584
3b	SB3B	5	31	2	1680
4a	SB4A	6	SMD HV4	7	1650
4b	SB4B	7	P	3	1550

*HV channels 0-5 are connected to the CAEN 6533 module, outputs 0-5; HV channels 6 and 7 are connected to outputs 0 and 1 on the 6533M module.

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FIGURE 21: Ewart Blackmore who built the SMD Detector.

References

1) E. Blackmore et al., IEEE Trans. Nuc. Sci. 62,2792 (2015).
2) Matthew Stukel; Carleton University; *PHYS 3007: Laboratory #4: Muon Lifeime.*
3) CAEN; Technical Information Manual; VME Programmable HV Power Supply.
4) CAEN; Technical Information Manual; MOD V1720 Digitizer; CAEN; UM 2580 DPSD User Manual.
5) CAEN; Technical Information Manual; MOD V178 Master Controller.
6) T.Suzuki and D.F. Measday; UBC; Total nuclear capture rates for negative muons.