Muon Physics Instructions

You are encouraged to read through in detail the manual (in particular - pages 15 - 26) supplied with this experiment: filename: **mu_man_4aug19.pdf** . Note also that the computer that interfaces with the unit is running on Windows XP - don't be thrown off by this - just work with it. You will also need to use some DOS commands to do some of the basic data manipulation mentioned in this document - these are easily found on the internet.

Background Information:

The active volume of the detector is a plastic scintillator in the shape of a right circular cylinder of 15 cm diameter and 12.5 cm height placed at the bottom of the black anodized aluminum alloy tube. Plastic scintillator is transparent organic material made by mixing together one or more fluors with a solid plastic solvent that has an aromatic ring structure. A charged particle passing through the scintillator will lose some of its kinetic energy by ionization and atomic excitation of the solvent molecules. Some of this deposited energy is then transferred to the fluor molecules whose electrons are then promoted to excited states. Upon radiative de-excitation, light in the blue and near-UV portion of the electromagnetic spectrum is emitted with a typical decay time of a few nanoseconds. A typical photon yield for a plastic scintillator is 1 optical photon emitted per 100 eV of deposited energy. The properties of the polyvinyltoluene-based scintillator used in the muon lifetime instrument are summarized in table 1.

To measure the muon's lifetime, we are interested in only those muons that enter, slow, stop and then decay inside the plastic scintillator. Figure 2 summarizes this process. Such muons have a total energy of only about 160 MeV as they enter the tube. As a muon slows to a stop, the excited scintillator emits light that is detected by a photomultiplier tube (PMT), eventually producing a logic signal that triggers a timing clock. See the "Electronics" section below for more details. A stopped muon, after a bit, decays into an electron, a neutrino and an anti-neutrino. (See the next section for an important qualification of this statement.) Since the electron mass is so much smaller than the muon mass, $m_\mu/m_e \sim 210$ (where m_μ is the mass of a muon and m_e is the mass of an electron), the electron tends to be very energetic and produce scintillator light essentially all along its pathlength. The neutrino and anti-neutrino also share some of the muon's total energy but they entirely escape detection. This second burst of scintillator light is also seen by the PMT and used to trigger the timing clock - the time between the first trigger and this second trigger is essentially a measure of the decay time of the muon. The distribution of time intervals between successive clock triggers for a set of muon decays is the physically interesting quantity used to measure the average muon lifetime.

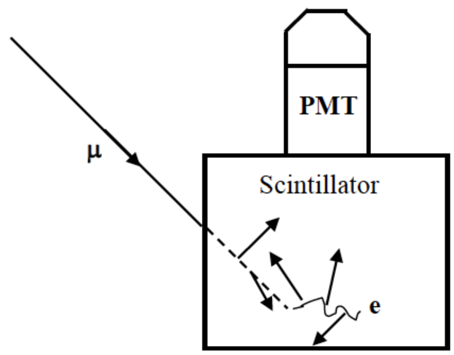

Figure 1. Schematic showing the generation of the two light pulses (short arrows) used in determining the muon lifetime. One light pulse is from the slowing muon (dotted line) and the other is from its decay into an electron or positron (wavy line). The temporal difference in these two events is a measure of the muon decay time.

Mass Density	$1.032 gm/cm^3$
Refractive Index	1.58
Base Material	Polyvinyltoluene
Rise Time	0.9ns
Fall Time	2.4ns
Wavelength of Maximum Emission	423nm

Table 1: General Scintillator Properties

Electronics

A block diagram of the readout electronics is shown in figure 2. The logic of the signal processing is simple. Scintillation light is detected by a photomultiplier tube (PMT) whose output signal feeds a two-stage amplifier. The amplifier output then feeds a voltage comparator ("discriminator") with adjustable threshold. This discriminator produces a TTL (Transistor - Transistor Logic : ~ 1.5V) output pulse for input signals above threshold and this TTL output pulse triggers the timing circuit of the FPGA (**F**ull **P**rogrammable **G**ate **A**rray - designed as an accurate timing circuit) . A second TTL output pulse arriving at the FPGA input within a fixed time interval will then stop and reset the timing circuit. (The reset takes about 1 msec during which the detector is disabled.) The time interval between the start and stop timing pulses is the data sent to the PC via the communications module that is used to determine the muon lifetime.

If a second TTL pulse does not arrive within the fixed time interval (40μs or 40000ns), the timing circuit is reset automatically for the next measurement.

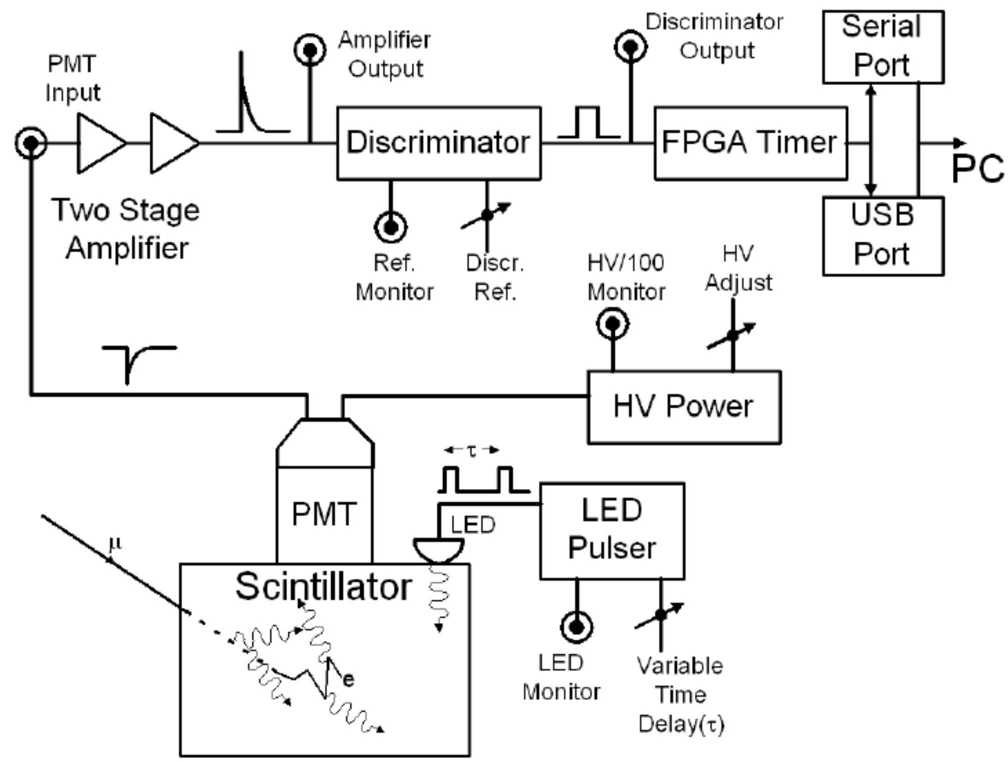

Figure 2. Block diagram of the readout electronics. The amplifier and discriminator outputs are available on the front panel of the electronics box. The HV supply is inside the detector tube. The LED pulser can be controlled separately. Additional details of the components are provided in the Muon Physics Manual : **mu_man_4aug19.pdf**.

Key Points about Readout Electronics:

1. Output (i.e. decay time) from the FPGA Timer is immediately sent to the controlling software on the PC via the USB port (*Note: the Serial Port does not exist in this latest version of the Electronic Box*). This is updated by the software and included in the filename “**muon.data**” - defined with the suffix “**.data**”.
2. The LED pulser is independent of the circuit that counts the scintillations occurring in the PMT and has separate controls for varying the time duration between LED photon output via the Variable Time Delay control seen in the figure. This will be used to verify operation of the FPGA timer.

3. During the regular data collection related to muon decay both the Amplifier Output and Reference Monitor from the discriminator should be connected to CH1 and CH2 of the oscilloscope respectively.

IMPORTANT!!!

Make sure you read and understand the section on Electronics/Software and User Interface (pgs. 15-26) found in the Muon Physics Manual (filename: **mu_man_4aug19.pdf**). These pages supply the details not covered by this brief Instructions Manual.

SECTION I: Measure the gain of the 2-stage amplifier using a sine wave.

Apply a 100kHz 100mV peak-to-peak sine wave using a Function Generator to the input of the electronics box input (i.e. labelled as PMT Input). Measure the Amplifier Output and take the ratio Vout/Vin which is essentially the gain of the amplifier. Due to attenuation resistors inside the electronics box inserted between the amplifier output and the front panel connector, you will need to **multiply this ratio by the factor 1050/50 = 21** (assume a 1% uncertainty in this ratio) to determine the real amplifier gain..
Q: Increase the frequency. How good is the frequency response of the amp? Generate a plot of Gain (= Vout/Vin) vs Frequency (50kHz - 1MHz) - use your judgement on frequency increments to generate the plot.
Q: Estimate the maximum decay rate you could observe with the instrument.

SECTION II: Measure the saturation output voltage of the amplifier.
Increase the magnitude of the input 100kHz sine wave (starting at 100mVpp) and monitor the amplifier output.

Q: Does a saturated amplifier output change the timing of the FPGA? Generate a plot of Vout vs Vin. Range of Vin is from 50mVpp to 300mVpp.
Q: What are the implications for the size of the light signals from the scintillator?

SECTION III: Examine the behavior of the discriminator by feeding a sine wave (set to 100kHz and 100mVpp) to the Electronics Interface box input (labeled **PMT Input**) and adjusting the discriminator threshold. Monitor both the amplifier and the discriminator output. Describe the shape of the discriminator signal as the threshold voltage is varied. Capture a screen shot to show the shapes of both signals. Use a DMM to measure the discriminator setting (probe points just below the “THRESHOLD” label on the box. To get a feel for the required measurements in this section, rotate the potentiometer for the discriminator voltage to the mid-range value (~5). Use the “TIME” cursors (available when you push the CURSOR button) on the oscilloscope and position the cursors on opposite sides of the maximum of the sine wave where the discriminator pulses intersect with the sine wave signal. We choose the maximum of the sine wave because the output of the amplifier when measuring muon decay has a positive going pulse. Measure the difference in time between the cursors. Measure the amplifier voltage where the discriminator pulse intersects the amplifier signal (choose either the rising or falling edge of the discriminator pulse). Once you get the feel for how to do both these measurements, vary the discriminator voltage (measure this value from the front panel) in suitable steps (choose a suitable step-size) of the potentiometer and perform both measurements. Generate two plots: One of discriminator voltage (independent variable) and time difference (dependent variable) and the other of discriminator voltage (independent variable) and amplifier voltage at the discriminator pulse intersection (dependent variable). What does this tell you about the function of the discriminator?

SECTION IV: Measure the timing properties of the FPGA:

a) The LED pulser on the detector is used in this section. Attach a “T” connector to the connector labeled **Pulse Output** on the PMT (see fig. 3). Run a coax cable from one end of the “T” to the PMT input on the electronic interface and another coax cable to CH1 of the scope. Switch on the Pulser and measure the time between successive rising edges on an oscilloscope. You can vary the time difference by changing the position of the potentiometer (labeled “TIME ADJ” - see fig. 3). Do the comparison by using the “TIME” cursors on the oscilloscope. You will need to change the time base of the oscilloscope to see both pulses on the screen. Compare this number with the number from the software display by following these steps:

- Run the program **muon** and choose COM3 in the configuration file. Leave all other parameters as they are. Get out of the configuration setup.
- Once you have the LED pulser operating at your chosen condition (set by the “TIME ADJ” potentiometer), run the **muon** software for about 30 seconds.
- Stop the software. **DON’T HIT THE QUIT BUTTON!!!** Hit the “View Raw Data” button and read in say 10,000 pts. As you scroll through the data, you should be able to see the FPGA timing output in units of nanoseconds. Note down the readings in your lab notebook and look for slight fluctuations. Grab about 20 readings and use those as a measure of the timing accuracy of the FPGA. Compare these averaged readings (with the associated std. dev.) with the readings from the oscilloscope for a particular setting.

b) Measure the linearity of the FPGA:

Alter the time between rising edges and plot scope results v. FPGA results; Use a range of time between 0.5 μs and 20 μs in steps of 2 μs.

Generate plot of time difference between rising edges and FPGA output by doing the following:

- Repeat the process from the previous activity (Section IV part (a)) for each of the time steps you create with the LED pulser. You don't have to hit the "Quit" button after each measurement. Use the "Pause" button and restart the measurement after the LED pulser is set up and running. Scroll through the Raw Data and pick out the relevant data from the most recent dataset.
- Make sure you note down the uncertainties in both measurements (FPGA and Oscilloscope). You will need to use this in your analysis.

Note: You need to set up to do the Muon Lifetime Measurement about 30mins before you leave the class. We recommend running the software for at least 48hrs so you have sufficient data to generate decent statistics in your analysis. Suggested starting settings for PMT and Discriminator Voltages can be found on pg. 29 of the user manual(filename: **mu_man_4aug19.pdf).**

SECTION V: Muon Lifetime Measurement and associated calculations

You need to familiarize yourself with the detailed instructions of running the software and information about the various folders/software

- Run software **muon** with the following parameters in the Configuration setup: COM3 and bin size 10 microseconds
- Make sure the HV and Discriminator settings are set to the following values: HV at 700V and Discriminator at 210mV. Check with the DMM both settings and note them down in your lab notebook. Display both the Amplifier Output and the Discriminator Output on the oscilloscope to make sure they have the right features. Make any necessary changes to the settings if either output does not look proper.
- Before you leave make sure the decay spectrum displayed in the software looks right. **You will need to run for about 30mins to make this judgement.**

Start and observe the decay time spectrum.
Q: The muons whose decays we observe are born outside the detector and therefore spend some (unknown) portion of their lifetime outside the detector. So, we never measure the actual lifetime of any muon. Yet, we claim we are measuring the lifetime of muons. How can this be?

When you come in (after ~ 48hrs), perform a Fit using the capability of the **muon** software. Using your smartphone collect an image of the displayed curve and the associated fit and Reduced Chi-sq. Note down the fit parameters.

Use the following steps to save generated data from your run for further analysis:

- Go to the appropriate folder and make sure the dataset from your run is stored.
- Go to page 26 of the User Manual for this Experiment (filename: **mu_man_4aug19.pdf**) and read up on the various utility software that is available. We will only need one of the them: **sift**
- Run **sift** on the dataset you generated and save the "sifted" data into a file which you will use for analysis. The nice feature of this software is that it ignores all the timeout data.

Required Analysis of collected Decay Spectrum:

Method 1:

Write python code to read in the saved muon decay data. Within the code generate histograms with three different bin sizes: 0.5, 1, and 2 us. Associate a bin size error for each bin size at three levels: 10, 20 and 30% of each bin size. Compute histograms for the various bin sizes. Decide on how you want to remove or account for the background radiation from the initial histograms. Read how it's done in the Muon Physics Manual (filename: **mu_man_4aug19.pdf**) - feel free to use any technique to achieve this result. Discuss with your instructor about your approach before applying it. Compute the decay times using ODR taking into account the three possible bin size errors. You already know how to account for the error due to the accumulated counts in each bin. Create a 2D table of Bin Size, Bin Error and the computed decay time and associated uncertainty. Which approach gives the best fit and how would you define "best" in this context? To make a decision on the "goodness" of the fitting process, plot the histograms for the various bin sizes.

Method 2:

Pick one of the bin sizes. Compute the mean and standard deviation of the data within each bin size. Use these to define your "x-values" and associated uncertainties. Now use ODR to do the same kind of fit as in the previous approach. Compare the results between these two approaches.

- From your measurement of the muon lifetime and a value of the muon mass from some trusted source, calculate the value of Fermi coupling constant G_F (see Muon Physics

Theory document). Compare your value with that from a trusted source. Remember to cite your sources

- Using the approach outlined in the text, measure the charge ratio ρ of positive to negative muons at ground level.

To include in the Report:

SECTION I:
- A plot of Gain vs Frequency (50kHz - 1MHz)
- The maximum decay rate one could observe with the instrument

SECTION II:
- Generate a plot of Vout vs Vin
- Determine the saturation output voltage of the amplifier
- Does a saturated amp output change the timing of the FPGA?

SECTION III:
- Generate a plot of discriminator voltage (independent variable) and time difference (dependent variable)
- Generate a plot of discriminator voltage (independent variable) and amplifier voltage at the discriminator pulse intersection (dependent variable)
- Capture a screenshot or plot the *.csv files from the oscilloscope to show the shapes of both signals i.e. discriminator and amplifier outputs.

SECTION IV:
- Compare LED pulse rising edges averaged readings (with the associated std. dev.) from the software (i.e. from the FPGA) with the readings from the oscilloscope
- Measure the linearity of the FPGA i.e. the time between rising edges from the LED pulses and plot scope results v. FPGA results. Discuss the implications of the curve with respect to the errors generated with the FPGA timer.
- What is the maximum time that the FPGA can detect between signal pulses?
- What is the minimum decay time you can measure with this instrument?

SECTION VI:
- Create a 2D table of Bin Size, Bin Error and the computed decay time and error from the Muon Decay data. Which approach gives the best fit (minimum error)? To make a decision on the “goodness” of the fitting process, plot the histograms for the various bin

sizes to support your choice. Compare the two approaches (Method 1 and Method 2) detailed in this section.

- Calculate the value of Fermi coupling constant G_F (see Muon Physics Manual (red folder from TEACHSPIN)). Express your answer in terms of $\frac{G_F}{(\hbar c)^3}$ which has units of GeV^{-2}. Compare your value with that from literature. Cite your source.
- Using the approach outlined in the Muon Physics Manual (red folder from TEACHSPIN/electronic version is:filename: **mu_man_4aug19.pdf**), measure the charge ratio ρ of positive to negative muons at ground level

APPENDIX:

1. Scintillator Electrical Connections:

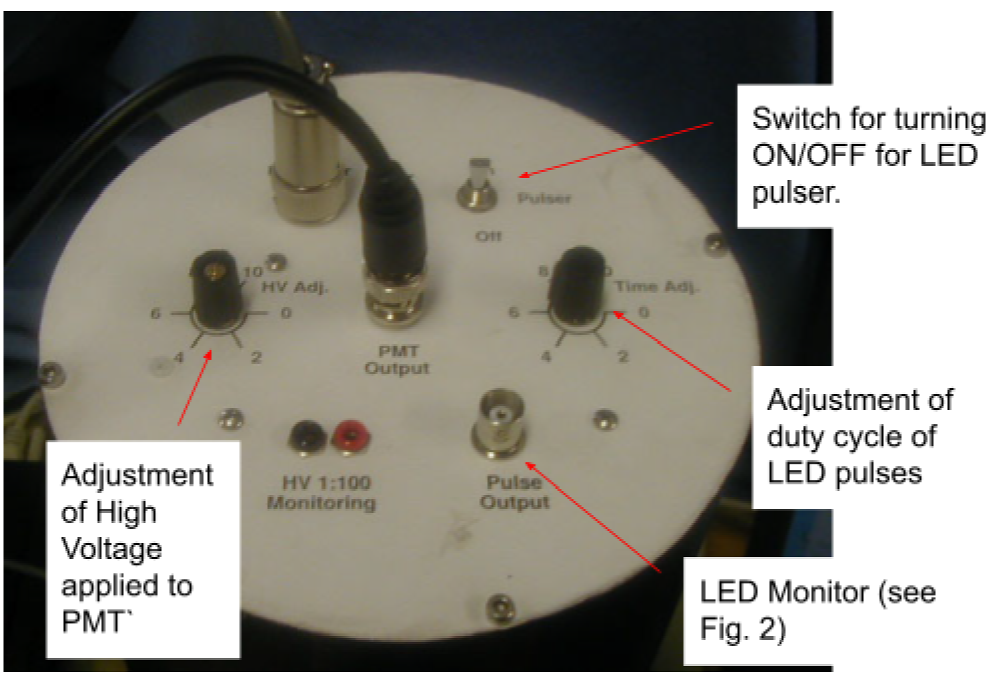

Figure 3: Top view of scintillator inputs showing LED controls and output

Figure 3 is the top view of the scintillator connection and controls. For the PMT (Photomultiplier Tube), the adjustment of the applied High Voltage to the PMT is done with the potentiometer (labelled **HV Adj.**). The actual HV level can be measured at the output connectors labelled **HV 1:100 Monitoring** using a

DMM. The measured voltage needs to be multiplied by 100 to get the true value of the high voltage applied to the PMT. The output connector labelled **PMT Output** is connected to the front connector, labelled **PMT Input**, of the Electronics Interface Box.

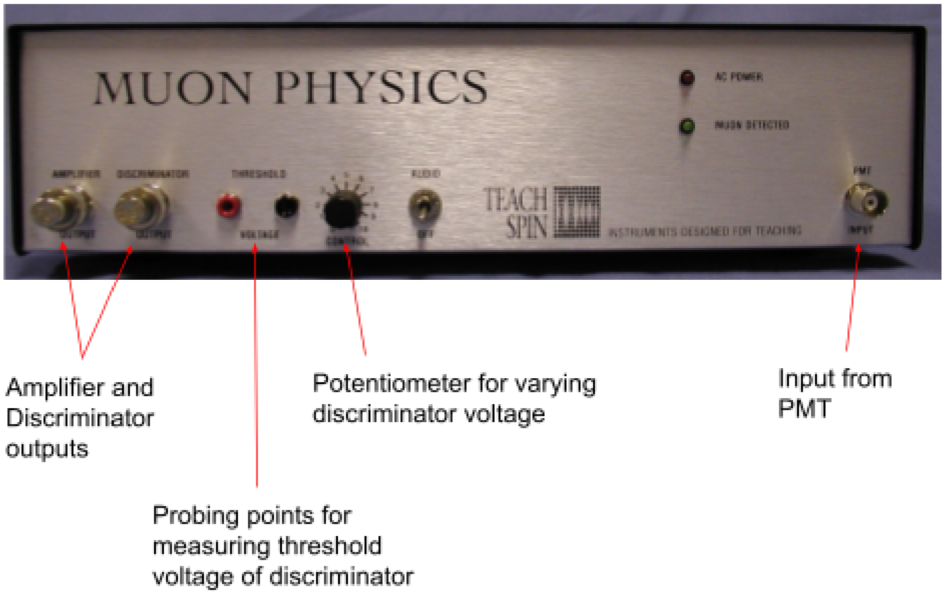

Figure 4: Front panel of Electronics Interface Box showing input/output connections and controls

Figure 4 is an image of the front panel of the Electronics Interface box. The outputs that are continuously monitored by the oscilloscope are the Amplifier and Discriminator Outputs. The Discriminator threshold is set by the potentiometer (labelled in the fig. 4) and measured at the associated probing locations by a DMM. This value should be noted prior to starting a measurement of the average muon decay. The output of the PMT is connected to the labelled input connector.