Characterization of Quartz Radiators for Mu2e Upstream Extinction Monitor

Lee Teng Summer Research Project
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Abstract

A cosmic ray telescope was developed using three scintillators, a quartz radiator, and PMTs for signal readout. The setup was optimized to study the efficiency of a quartz radiators planned to be implemented in the Mu2e Upstream Extinction Monitor. It was found that the quartz radiator in the vertical orientation produced signals with a mean amplitude of 740mV and had an efficiency of about 36%, while the horizontal orientation produced signals with a mean amplitude of 450mV and had an efficiency of approximately 72%.

Introduction

The Standard Model of particle physics requires that leptonic flavor numbers are to be preserved if and only if neutrinos were massless. However, since the discovery of neutrino oscillations, neutrinos do have a small nonzero mass and therefore lepton flavor numbers are only approximate. This implies that the lepton conservation laws must hold for interactions containing charged leptons and therefore it should be possible to observe rare decays such as $\mu N \rightarrow eN$. If a process such as this is observed, this will provide evidence of Charged Lepton Flavor Violation (CLFV), pointing to many new models of physics beyond the Standard Model.

The Muon to Electron (Mu2E) experiment at Fermilab is an experiment designed to measure the ratio of direct conversion of Muons to Electrons in the presence of a nucleus, with respect to the rate of typical muon capture on the nucleus,

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}$$

Currently the most sensitive experiment of this kind is SINDRUM II, with a sensitivity of $R_{\mu e} < 7 \times 10^{-13}$. The Mu2E experiment will measure four orders of magnitude beyond SINDRUM II with $R_{\mu e} \approx 2.87 \times 10^{-17}$.

Extinction Monitoring with Quartz Radiators

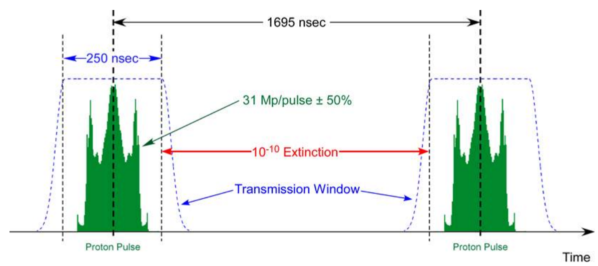

Figure 1: 8 GeV proton beam pulsed at 0.6 MHz

In order to suppress backgrounds low enough to obtain the goal sensitivity of $R_{\mu e}$, the ratio of beam between pulses to the beam contained in the pulses – defined to be extinction of the beam – must be less than 10^{-10}. Extinction of the 8 GeV pulsed proton beam will be measured in two parts: (1)At the Upstream Extinction Monitor (UEM) on the order 10^{-5}, and (2)at the Target Extinction Monitor on the order of 10^{-10}. The UEM (Figure 2) for the Mu2e experiment plans to employ a charge telescope composed of a series of quartz radiators attached to UV sensitive PMTs to statistically monitor beam scattering in the M4 beam line.

This study investigates the method of using quartz radiators in the UEM, in particular characterizing the signals and efficiency of the radiators.

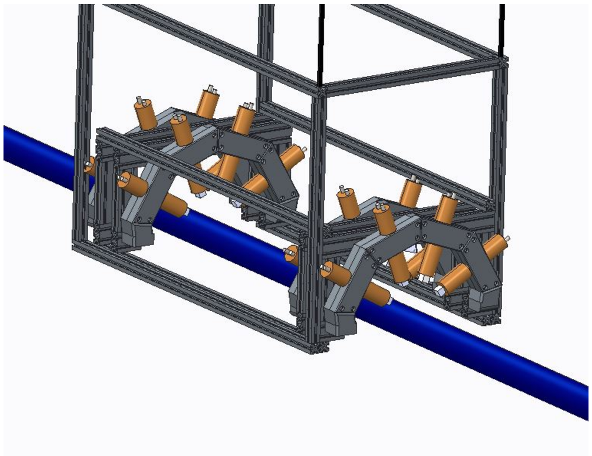

Figure 2: Upstream Extinction Monitor

Other components similar to quartz radiators such as scintillators have previously been used for measuring beam characteristics, however quartz radiators have been chosen for this study over scintillators for three main reasons:

- No intrinsic after pulses.
- Very fast response time.
- Blind to soft particles

This study uses atmospheric cosmic rays as a source to measure for two different orientations of a quartz radiator to determine the optimal orientation of the radiators in the UEM. Because scintillators are well understood, they were aligned with the quartz radiators to detect particles traversing through the quartz from the same direction.

Cosmic Ray Telescope

Two, 1.3cm x 1.5cm x 0.6cm and one 2.1cm x 2.2cm x 0.6cm scintillators, and a 2.4cm x 2.0cm x 1.3cm quartz radiator were connected to PMTs to readout the signals produced by a particle passing through each scintillator/quartz radiator. Stands for the PMTs were constructed using Unistrut metal framing and mounts (Figure 3).

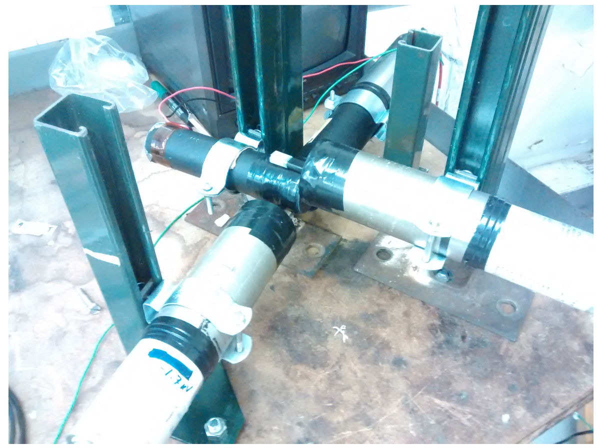

Figure 3: Cosmic ray telescope

A C++ program was improved to configure the Tektronix TDS3054B oscilloscope to trigger on a particle passing through all three scintillators and store the data for each channel from a triggered event. Nuclear Instrumentation Modules (NIMs) were used to count the number of triggered events as well as accidental triggers by delaying the scintillator on ch. 3 by about 50ns into a separate counter.

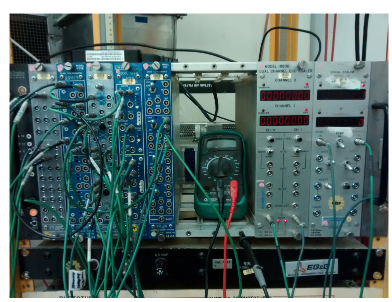

Figure 4: NIM electronics

The NIM electronics (Figure 4) used were manufactured by LeCroy Research Systems and are a standard in many nuclear/particle physics experiments. Our setup consisted of the following components: (1) 623B discriminator, (2) 429 Fan In / Fan Out, (3) 364AL Dual 4-Fold Logic Unit, (4) 622 Quad 2-Fold Logic Unit, and (5) 1880B dual channel BCD scaler. The threshold and width on the discriminator were set to about 30mV and 10ns respectively to prevent noise from triggering the counters on the BCD scaler.

Figure 5: Detector components from top to bottom and their respective channels: scintillator (Ch 1), Quartz (Ch 2), scintillator (Ch 3), and scintillator (Ch 4)

A C++ data analysis program was improved to pick out only the number quadruple coincidences – events where a particle passes through all three scintillators and the quartz radiator (Figure 6). While the scintillators are sensitive to softer particles, only hard particles (eg: muons with $KE > 50 MeV$) will cause a signal to be produced in the quartz radiator.

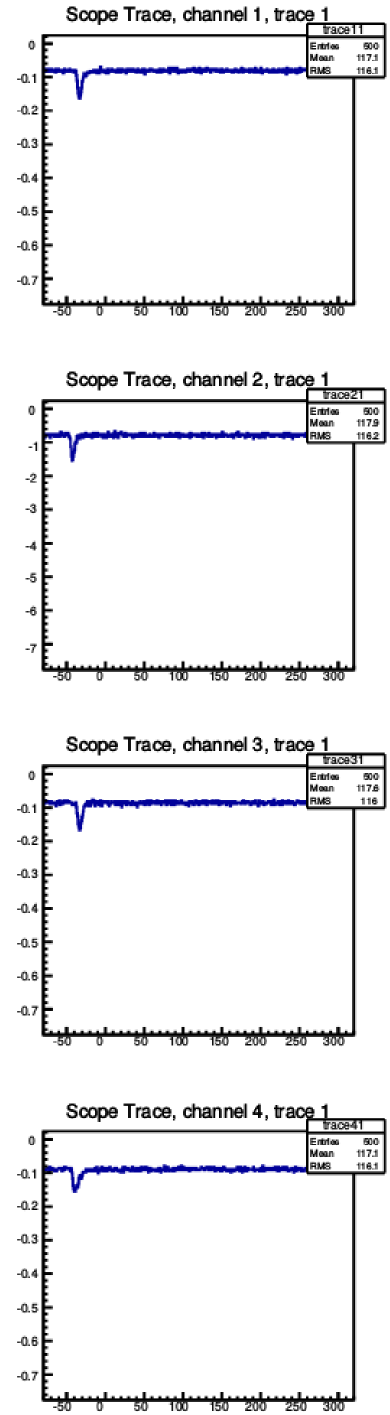

Figure 6: Quadruple coincidence event shown in all four channels

Rate of quadruple coincidences and accidental quadruple coincidences were collected with two different orientations of the quartz radiator (Figure 7).

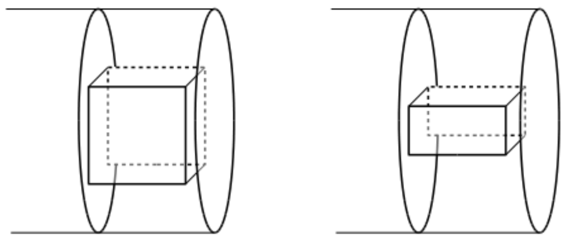

Figure 7: Vertical orientation of Quartz (left) and horizontal orientation (right)

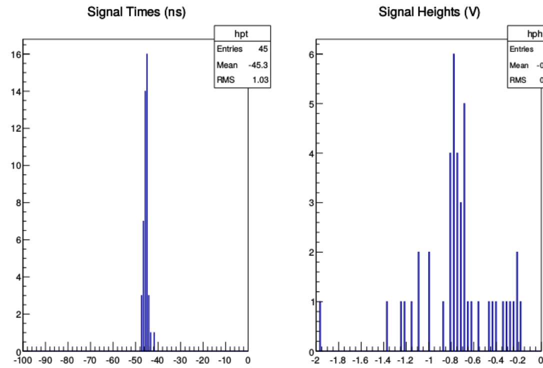

Figure 9: Ch. 2

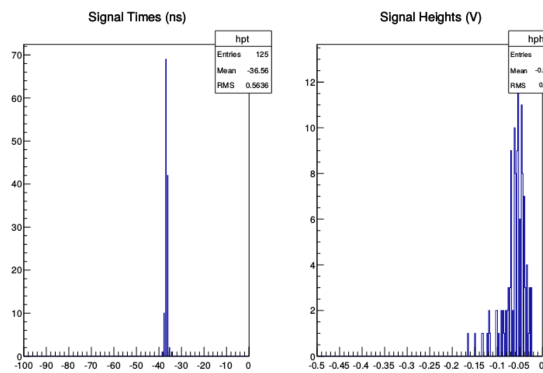

Figure 10: Ch. 3

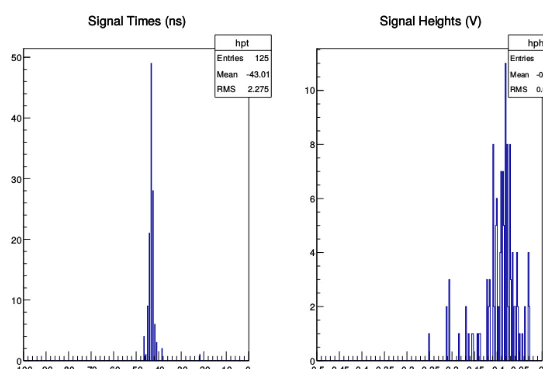

Figure 11: Ch. 4

Results and Conclusion

In the vertical orientation, the NIM counters registered 130 triggered events with 3 accidental over the course of about 40.5 hours. Data analysis program shows that out of 125 records, 45 records (36%) are a quadruple coincidence hits, giving a rate of approximately 1.11 events/hour. The mean amplitude of the signals produced by the quartz in this orientation was approximately $740mV$. Figures 8-11 show the signal times and amplitudes for each channel for the vertical orientation of the quartz.

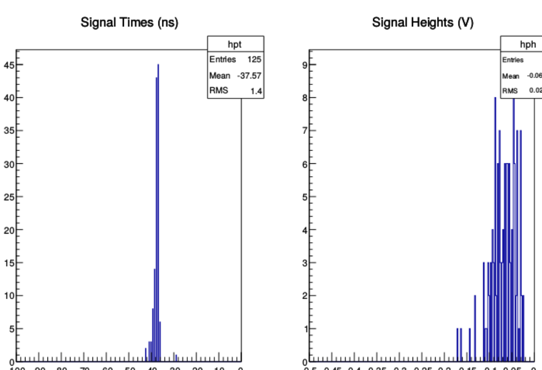

Figure 8: Ch. 1

In the horizontal orientation however, the NIM counters registered 66 triggered events with 8 accidental over the course of about 26.3 hours, and the data analysis program shows that out of 54 records, 39 records (72%) are a quadruple coincidence hits giving a rate of about 1.48 events/hour. The mean amplitude of the signals produced by the quartz in this orientation was approximately $450mV$. Figures 12-15 show the signal times and amplitudes for each channel for the horizontal orientation of the quartz.

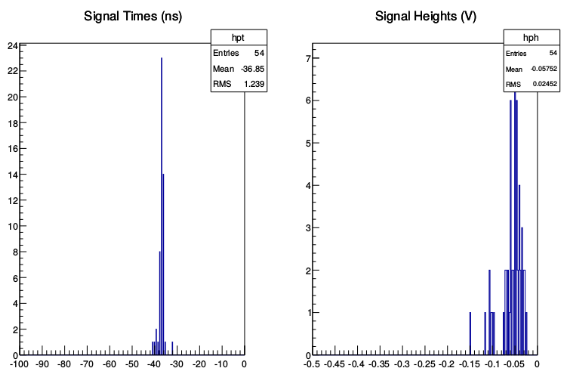

Figure 12: Ch. 1

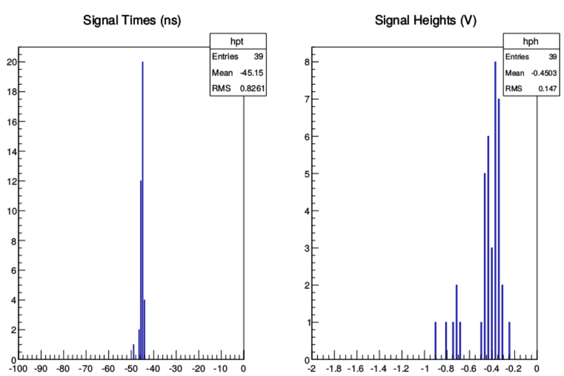

Figure 13: Ch. 2

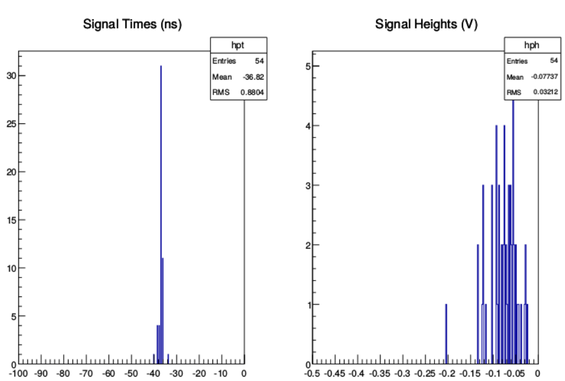

Figure 14: Ch. 3

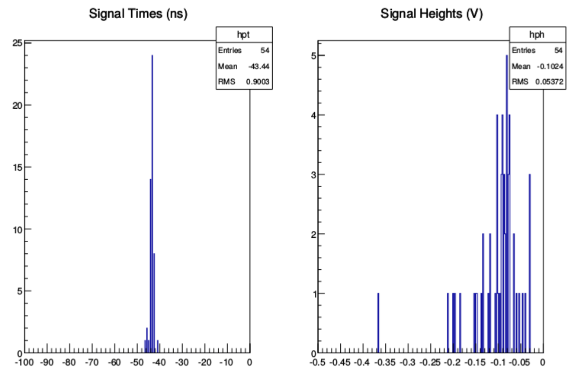

Figure 15: Ch. 4

The time on this project was mostly spent developing and optimizing the telescope, and NIM and DAQ setup, including the C++ programs, so there was little time to collect and analyze data thoroughly. Therefore these preliminary results are very rough figures.

The vertical muon flux in the atmosphere at about 200m above sea level where the tests took place is approximately $100m^{-2}s^{-1}sr^{-1}$ for particles with $E > 1GeV$.[1] Using the solid angle of our experimental setup our expected rate for muons above 1GeV would be approximately 0.16/hour for the vertical orientation, and 0.64/hour for the horizontal orientation. However since the quartz is sensitive to any muons with $KE > 50MeV$ we would expect to see the much higher rate that we do.

Since the numbers from the NIM counters don't agree with the number of records acquired by the program, the accidental coincidence rate cannot be certain. For future work an improved version of the data acquisition program should be developed to account for accidental coincidences as well as real ones. However, the fact that we are getting large distinct signals from the quartz compared to the scintillators (mean signal amplitude of about $77mV$) and are able to extract the quadruple coincidence event information shows that this method is a viable way monitoring beam extinction.

Discussion and Future Plans

Since the number of photons emitted per unit path length of a particle with charge ze and per unit energy interval of the photon is given by,

$$\frac{d^2N}{dEdx} = 370Esin^2\theta_c \; eV^{-1}cm^{-1}$$ [2]

and the PMTs we are using are sensitive to light with $200nm < \lambda < 600nm$, we can show using the cosine of the Cherenkov angle ($cos\theta_c = \frac{1}{\beta}$) that the percent of photons emitted by a track with a particular β relative to the maximum amount of photons are being emitted in the quartz radiators is given by,

$$\frac{n^2 - \frac{1}{\beta^2}}{n^2 - 1}$$

The plot in Figure 13 shows this ratio vs the KE of the particles producing Cherenkov radiation in quartz.

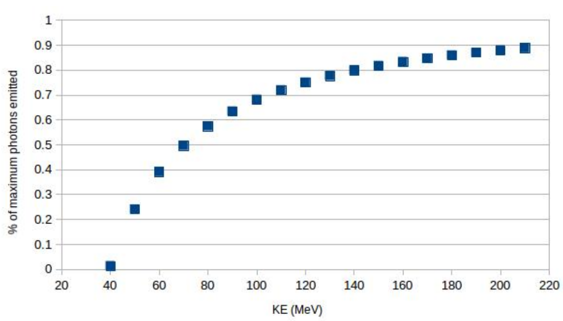

Figure 16: % of max photons emitted from Cherenkov radiation vs KE of particle

Given the stopping depth for lead needed to block out lower energy muons[3], our next plan is to implement a lead brick to block out muons with $KE < 100MeV$. This will insure that all events captured with our setup will be with muons that emit about 70% of the max light yield. In addition one of the scintillators will be replaced with another quartz radiator so that we can capture more events using more of the quartz radiators. Figure 14 show one possible configuration of our improved setup.

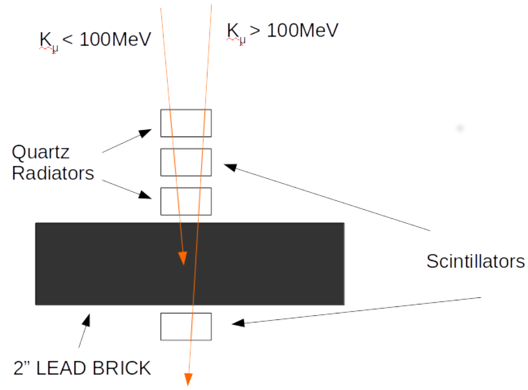

Figure 17: One possible configuration of improved future setup

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References

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[2] Olive, K.A. et al. "*32. Passage of Particles Through Matter*" Particle Data Group. Web 2014. Pgs. 33-34

[3] Darijani, R. et al. "*Formulation of muon range 0-100 TeV and transmission through lead*" Indian Journal of Pure & Applied Physics. Web 2014. Pg. 10