# Tests of Quartz Radiators for Beam Precision Timing Monitor

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**Abstract**

This paper describes the results of a series of tests in which cosmic rays were used to determine the feasibility of charged track detectors based on Cherenkov light from quartz radiators, as detected with photomultiplier tubes (PMTs). During the tests, it was found that using the resin component of optical cement between the quartz and the PMT significantly increased the light yield relative to the previous technique of simply mating the surfaces. We have found that after this improvement, these detectors provide adequate light for at least 90% detection efficiency per radiator, with an acceptably small probability coincident random noise hits.

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## 1 Introduction

A number of intensity frontier experiments depend on a precise knowledge of "longitudinal halo"; that is, beam with is outside of the nominal bucket in time. Such out-of-time beam can result in losses during acceleration or in unwanted backgrounds to rare decay experiments, with the Mu2e Experiment[1] being a specific example of the latter.

Unfortunately, the dymanic range required to measure such out-of-time beam in the presence of the much larger in-time bunch makes this measurement very challenging. A recent LDRD was

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proposed and funded[2] to use a statistical technique to measure out-of-time beam at a fractional level of $10^{-5}$ or better. A scattering foil or collimator will be used to scatter a small fraction of the beam into a hodoscope telescope. The acceptance is tuned such that a small number of scattered particles are detected from the in-time bunch. By integrating over many bunches, a statistical time profile can be built up of the out-of-time beam. The sensitivity will ultimately be limited by fake tracks due to cosmic rays or accidental coincidence of noise or background hits. Similar techniques have been used to measure transverse halo in the past[3].

The configuration proposed for the LDRD is comprised of four arms, each consisting of four detectors, as shown in Figure 1. Each detector element consists of a quartz radiator attached to a photomultiplier tube. We have chosen to rely on the Cherenkov light from quartz rather than scintillators because it is completely insensitive to soft background, such as neutrons, and also because it has no issues with afterglow from large signals. The disadvantage is that the light yield is significantly lower than that scintillator, so we have carried out a test using cosmic rays to insure that it will meet our needs.

## 2 Experimental Setup

We used quartz radiators that were 1"x1"x1/2", attached to the photomultiplier tube as shown in Figure 2, such that a charged particle's path length could be either 1/2" or 1", depending on the orientation. The PMT was a Hammamatsu tube with a UV glass window and a light transmission range of approximately 185 to 650 nm[4].

We went through several configurations of the cosmic ray telescope, which are described elsewhere[5][6]. The final configuration is shown in Figure 3. two scintillators with approximately 1cm x 1cm area were placed above and below the quartz radiator. A third scintillator of approximately 3cm x 3cm was placed below that, separated by a lead brick, oriented so that cosmic rays would pass through 2" of lead to reach it. Since a triple coincidence would be required for a trigger, this insured that triggering muons had at least 100 MeV, so they would be sure to produce Cherenkov light in the quartz.

Data were recorded using a Tektronics 3054B oscilloscope, which was triggered by a triple coincidence of the scintillators. Data from the scope were read out by a laptop computer via the VXI11 interface. Because of the small size and limited solid angle of the scintillators, the trigger rate was only a few per hour. For the final data set, 4096 samples were taken at 1ns per sample for each waveform from approximately 1 $\mu$sec before to 3$\mu$sec after the trigger. Data were analyzed using ROOT[7] macros that implemented a simple threshold algorithm, which they used to determine times and peak pulse heights for each wave form. No further corrections (eg slewing corrections) were done.

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# 3 Analysis and Results

Figure 4 shows the arrival times of the peak with the maximum height in each wave form. The signal from the quartz radiator is in channel 2. These plots were used to set a 10ns wide window to define a "hit" in each counter, to be used in efficiency calculations.

To estimate the single photoelectron signal, a small pinhole was made in the optical tape shielding the quartz radiator, and it was allowed to self-trigger. The resulting spectra are shown in Figure 5 for both all detected peaks and the triggering peak. The scope threshold was set at 40 mV for this run, which has clearly biased the signal, but the mean of the second plot sets an upper limit of .074V for the mean single photoelectron signal.

It was found that the light yield was somewhat lower than expected, so the resin component of Bicron BC-600 optical cement was applied between the quartz crystal and the PMT to act as optical grease. This significantly improved the light yield, as shown in Figure 6. The average signal for the "flat" (short path) orientation increased from .272V to .448V, an increase of 64%. The "skinny" (or long path) orientation has a mean signal of about .770V, or about 72% more than the flat orientation. Based on the single photoelectron spectrum above, this sets lower limits for the photoelectrons from short and long path length runs, with grease, of 6 and 10 photoelectrons, respectively.

Because of the somewhat small signals, accidental noise hits are a concern. Because of the sensitivity goal of the experiment, we require less than a $10^{-5}$ probability of an accidental noise coincidence in period between bunches, which is envisioned to be up to the 11 $\mu$sec period of the Fermilab Recycler.

Efficiency was determined by requiring all three scintillators to have a signal within the specified 10 ns window and then counting the fraction of these event that also had a hit in the quartz radiator during its 10 ns window. Efficiency could then be studied by varying the software threshold for the quartz radiator in the peak-finding algorithm. Because of the low data rate, statistics were limited, with between 150 and 200 events per run. Figure 7 shows the efficiency as a function of software (software) threshold for both the short and long path configurations, as well as the probability of a noise hit in 10 ns. We would expect a higher efficiency for the "skinny" (long path length) orientation; however, geometrical effects likely resulted in some loss of efficiency, in that the trigger scintillators were roughly the same size as the cross-sectional area in this configuration, and alignment was only approximate.

We see that a threshold of around 170 mV gives $> 90\%$ efficiency in both orientations, while having a $< 10^{-4}$ probability of a noise hit in 10ns. If we were to require a quadruple coincidence to define a track, this would give a single track efficiency of at least 65% with a probability of an accidental noise coincidence of $10^{-13}$ in the 11 $\mu$sec Recycler period. Relaxing the requirement to 3 out of 4 hits would raise the single track efficiency to 95% while maintaining a still acceptable $4 \times 10^{-9}$ probability of an accidental coincidence in one Recycler period. The probability of a random coincidence could be made even lower by requiring at least one radiator to have a large signal.

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# 4 Conclusions and Next Steps

These results have shown that this quartz radiator/PMT combination has sufficient sensitivity to provide adequate track detection efficiency while maintaining acceptibly low probability of accidental coincidences caused by noise triggers.

There may, however, be problems associated with the higher rates expected in actual experimental use. We therefore intend to conduct further tests, using both test beams and LED flash systems.

# 5 Acknowledgements

We would like to thank Sasha Dychkant at Northern Illinois University for assembling the radiator/PMT sets and Anatoly Ronzhin at Fermilab for providing the scintillator/PMT trigger paddles and the optical grease.

# References

[1] `http://mu2e.fnal.gov/`

[2] E. Prebys and D. Hedin, "Beam Precision Time Profile Monitor (LDRD Proposal)", FNAL-BEAMS-DOC-5015 (2015)

[3] K. Ehret, *et al.*, "Observation of coasting beam at the HERA Proton-Ring, arXiv:hep-ex/0002002v1 (2002)

[4] S. Dychkant, *private communication.*

[5] L. Rudd, "Characterization of Quartz Radiators for Mu2e Upstream Extinction Monitor", FNAL-BEAMS-DOC-5016 (2015)

[6] M. Jamison-Koenig, "Evaluating Quartz Crystal Radiators for Beam Extinction Monitoring", FNAL-BEAMS-DOC-5017 (2015)

[7] `http://root.cern.ch/`

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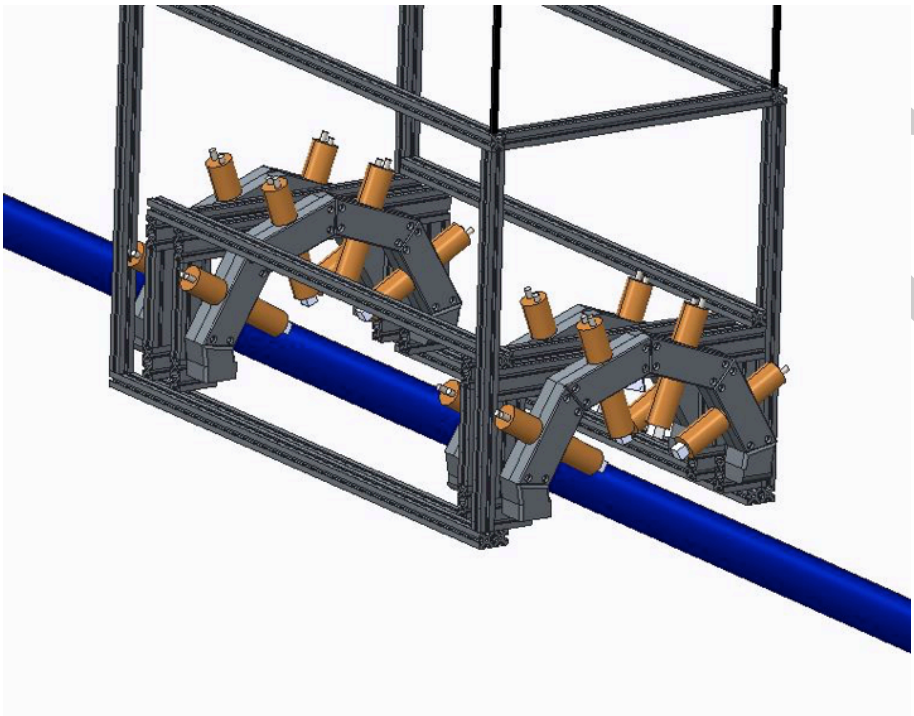

Figure 1: Proposed detector layout for precision timing monitor.

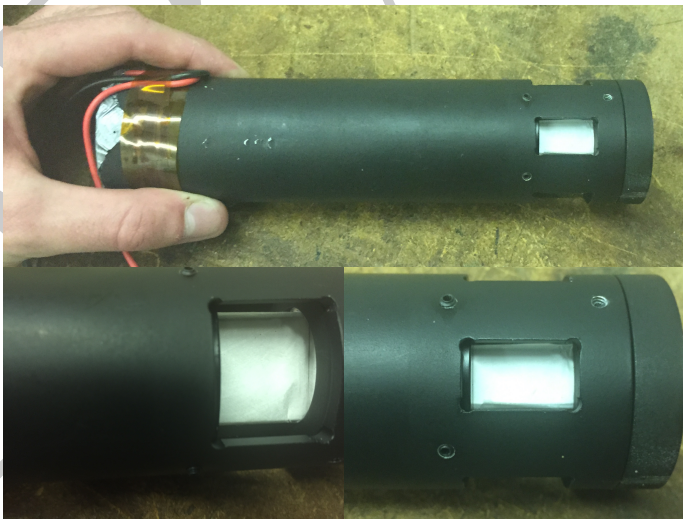

Figure 2: Orientation of quartz radiator and photomultiplier tube, prior to wrapping with light tight tape.

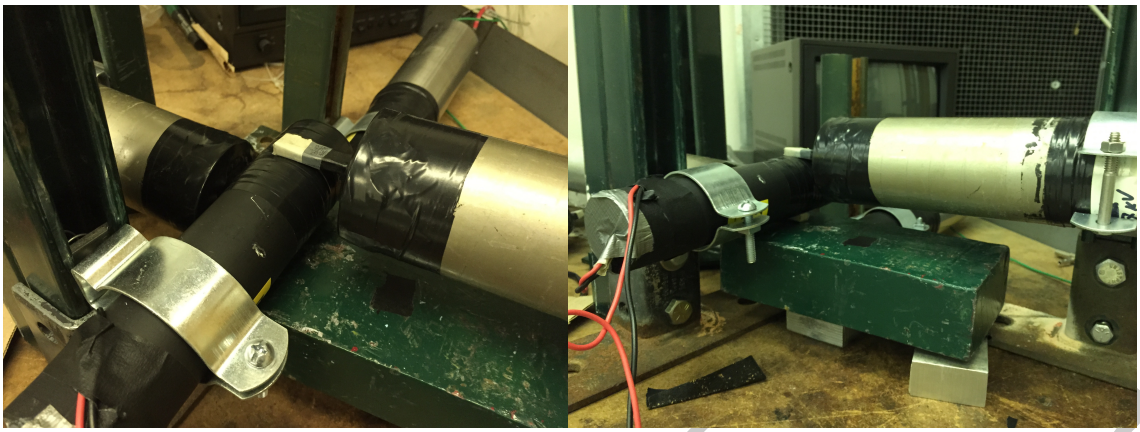

Figure 3: Cosmic ray test setup. Two small scintillators are placed above and below the quartz radiator. A third, larger scintillator is placed beneath a lead brick which was added to filter out muons with kinetic energy below 100 MeV.

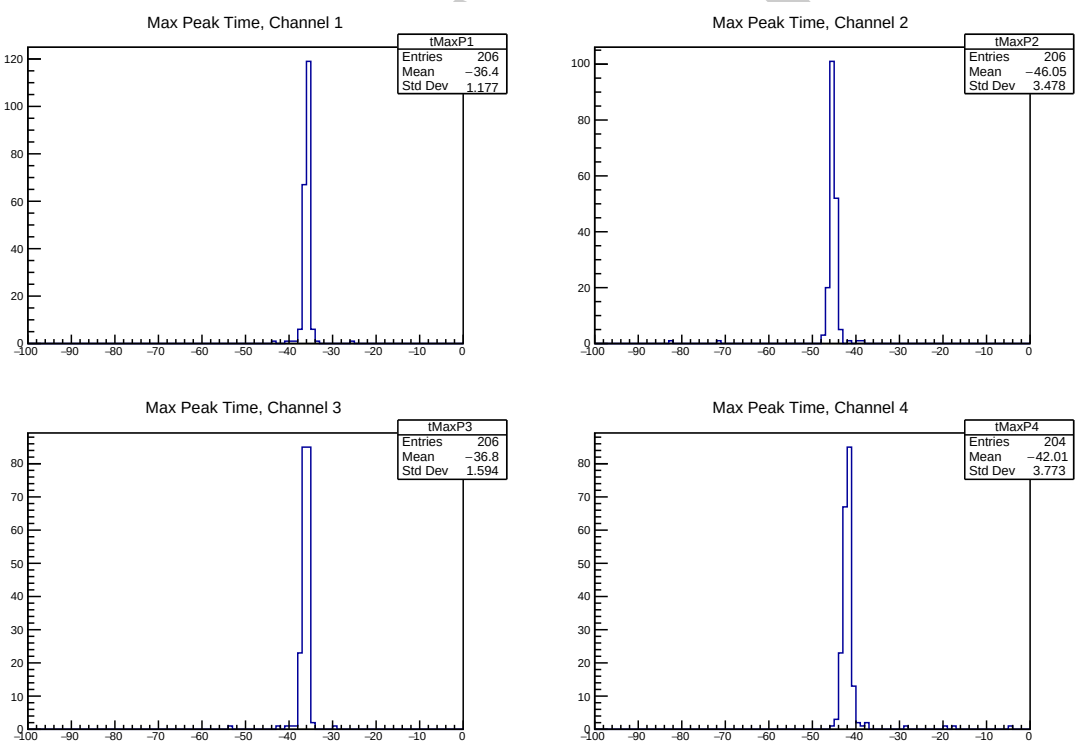


Figure 4: Arrival times of signlas, in ns.

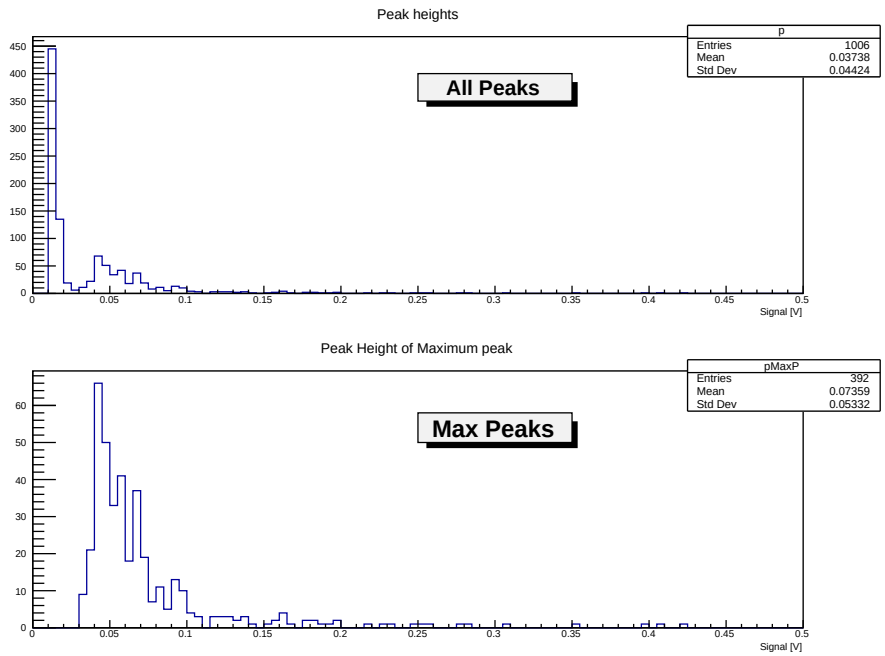


Figure 5: Single photon respose. The top plot shows all peaks found, including noise, while the bottom shows the maximum, triggering peak.

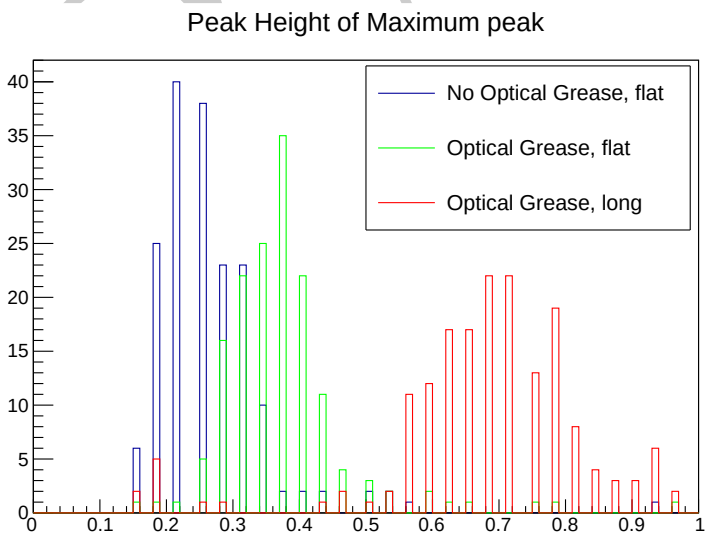


Figure 6: Signal height for the flat (1/2" path length) orientation, with and without optical grease, and the long (1" path length) orientation with grease. Horizontal scale is in volts.

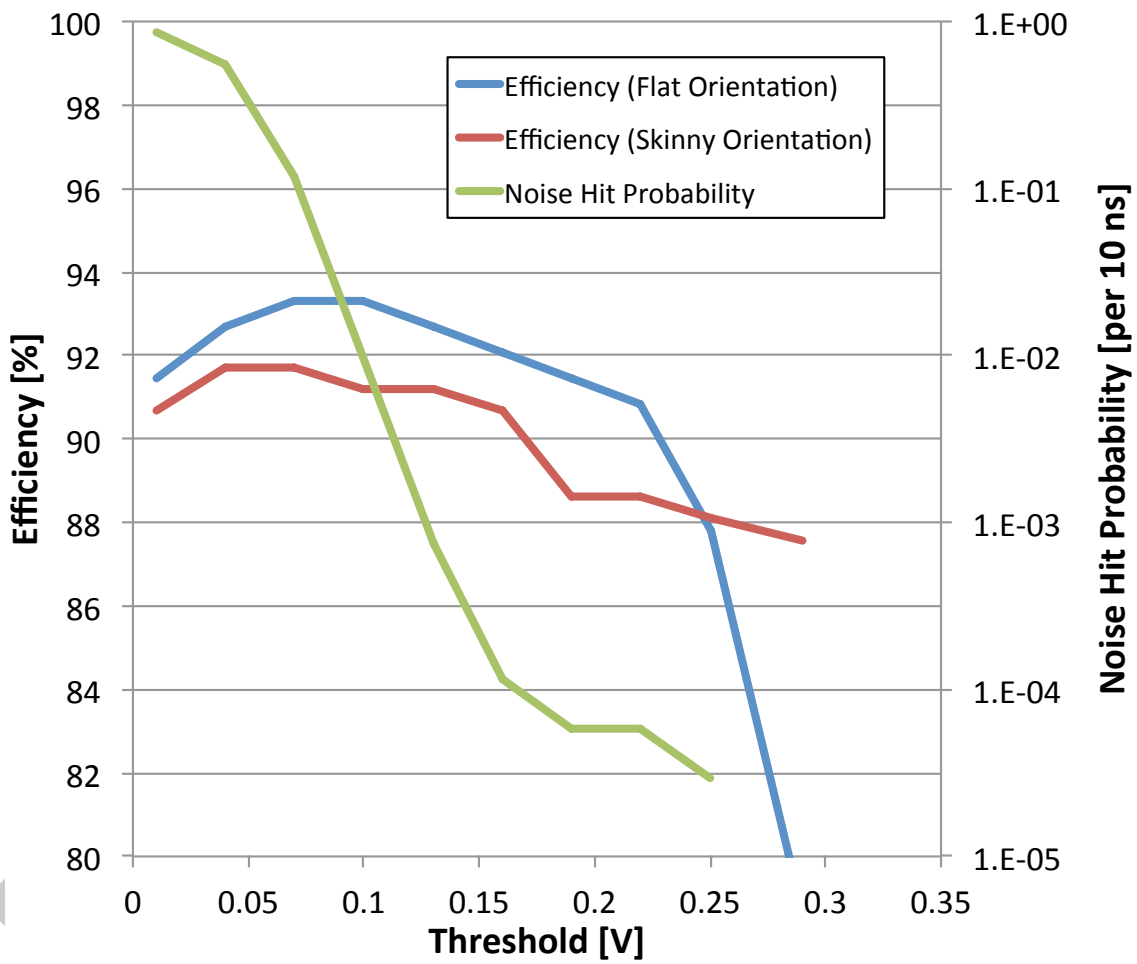


Figure 7: Efficiency and noise hit probability as a function of threshold for both orientations. The low efficiency for the long path length is probably largely due to geometric factors.