Hamamatsu PMT R7056 Study for the Extinction Monitoring System of the Mu2e Experiment at Fermilab

S. Boi, A. Dyshkant, D. Hedin, E. Johnson, C. Mott, E. Prebys, P. Rubinov

Abstract–**The Mu2e experiment at Fermilab proposes to search for the coherent neutrino-less conversion of muons to electrons in the presence of a nucleus. The experimental signature for an aluminum target is an isolated 105 MeV electron exiting the stopping target no earlier than ~700 ns after the pulse of proton beam hits the production target. Any protons that hit the production target in between the pulses can lead to fake conversion electrons during the measurement period. We define the beam extinction as the ratio of the number of protons striking the production target between pulses to the number striking the target during the pulses. It has been established that an extinction of about 10^{-10} is required to reduce the backgrounds to an acceptable level. It would be desirable to measure the extinction of the beam coming out of the accelerator in a minute or less. Studies for the fast extinction monitor based on Hamamatsu PMT R7056 is the subject of this publication.**

Keywords: photomultiplier tube, after pulsing, Mu2e experiment, extinction monitoring, divider current, anode load.

INTRODUCTION

A muon typically decays into an electron and neutrinos via a weak interaction. But if there is only electron then the muon has changed flavor. Extended versions of the Standard Model (SM) predict a small rate of neutrino-less muon to electron conversion. Searching the muon to electron conversion in a field of atomic nucleus is a very sensitive method for a new physics in charged lepton flavor violation (CLFV) processes. If verified, it would point to a new physics beyond the SM. With a sensitivity of four orders of magnitude better than previous experiment, the Mu2e experiment at Fermilab [1] will search for the coherent neutrino-less conversion of muon to electron CLFV processes in a field of nucleus by stopping low energy muons on an aluminum target, forming muonic atoms and then register isolated mono-energetic about 105 MeV electrons. The Mu2e experiment consists of three consecutive large superconductive solenoids:

1) The production solenoid with the inside production target and an incident primary proton beam, where secondary particles are produced and graded field pushes back pions and muons;

2) The S-shaped transport solenoid transfers the beam of low energy muons through the volume with rotatable collimators, selects momentum of positive or negative muons and removes neutrals;

3) The detector solenoid enclosed a muon stopping target foils, a particle tracker for the momentum measurements, an electromagnetic calorimeter for the identification of electrons from muons, and a fast triggering.

In the stopping target stopped muons fall into 1*s* orbit around Al nucleus with about 864 ns lifetime and can undergo a decay in orbit (39%), or a nuclear capture (61%), or a direct conversion into mono-energetic electron of 105 MeV. Mu2e also has a 99.99% efficient cosmic ray veto system, a Germanium stopping target monitor, and a proton beam extinction monitoring system which measures the fraction of out-of-pulse protons.

II. PULSED BEAM AND BACKGROUND SUPRESSION

For the Mu2e experiment it is crucial to minimize the beam-induced backgrounds. Suppression of prompt backgrounds requires a pulsed proton beam, in which the ratio of the amount of protons between pulses to the amount of protons contained in a pulse is less than 10^{-10}. This ratio is defined as the beam extinction.

The 8 GeV primary beam will have about 38 million protons per pulse, a 250 ns pulse length, and a period of about 1695 ns. It is incident on the production target and produces bunches of muons that are transported to and stopped in the aluminum stopping target.

The measurement period of ~700 - 1700 ns after injection matches the life time of muonic aluminum. Backgrounds can be produced by protons hitting the production target during or slightly before the search window. The Mu2e proton beam cycle and the delayed search window allows for the effective

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elimination of prompt backgrounds when the number of protons between pulses is suppressed to the required level. Because extinction of the proton beam in the search window is crucial, the Mu2e has a special design of beam line and an extinction monitoring system.

The required beam extinction will be achieved in two steps. First, the technique for generating the required proton bunch structure will naturally lead to an extinction of ~10^{-5}. Second, the beam line to the production target has a set of oscillating (AC) dipoles that sweep out-of-time protons into a system of collimators with additional extinction of about 10^{-7} or better.

The level of beam extinction needs to be under control during all the time when Mu2e experiment collects data. This is the main purpose of the extinction monitoring system.

A. Extinction Measurements

Direct extinction measurement is difficult due to the high rate. Instead scattered particles from the target will be measured using a detector with good time resolution and a small effective acceptance. Then a statistical picture of the out-of-time population can be built over many bunches.

There are two time scales in terms of an extinction measurements. For measurements with precision of 10^{-10} on a time scale of about an hour (the high precision measurement) the experiment has a dedicated production target extinction monitor. It detects particles with a time resolution of 25 ns and an average momentum of 4.2 GeV/c. It consist of a permanent magnet in conjunction with input and output collimators. Eight planes of 4 cm x 4 cm pixel detectors will be used for track reconstructions and ten scintillation counters to trigger the system and identify muons.

For potential failures of the beam delivery system with precision of 10^{-5} in about a minute or less, a second monitor can be placed upstream of the AC dipole to detect particles scattered from a small obstruction in the beam path [2]. Similar techniques have been used to measure a beam halo [3]. The requirements to such a detector are a time resolution that is short compared to the nominal proton pulse length and a low fake rate. The fake rate can be generated, for example, by after pulses in the photomultiplier tubes if that is not less than 1% compare to the true pulses rate. The rate of chance coincidence of uncorrelated and partially correlated signals in different counters is a fast growing number at high rate. Such "upstream" monitor is not included in the Mu2e project baseline.

B. Upstream Extinction Monitor

Our technique is based on a telescope of four Cherenkov counters to register beam particles scattered off of a thin foil (5 μm Ti) installed in the beam line. The telescope located outside of the beam line at about 2 m downstream of the foil and positioned in a straight line to its beam point intersection. It has a limited acceptance tuned in such a way that scattering from the in-time protons will not cause saturation. That means about one count of true coincidence in the telescope per bunch of the primary proton beam, or about 0.6 million counts per second. Particle detection will be accomplished by four such telescopes.

The Cherenkov light is registered by a photomultiplier tube (PMT). The PMTs outputs will be connected to waveform digitizers that will allow the time structure of the Cherenkov light to be analyzed in detail. Data acquisition will be synchronized to the 2.5 MHz RF clock. The general issues of such measurements are the need for a wide dynamic range, the ability of the photo detector to withstand high rates, a good time resolution, and no or low fake responses generated, for example, by after pulses time-correlated with the true pulses [4], [5] in a triple coincidence system.

The main telescope unit is a Cherenkov counter. It consists of a radiator and a photodetector. The following Cherenkov radiators have been tested with cosmic rays: a fused quartz [6] GE type 021, a UV transparent PMMA [7], and a Cherenkov plastic EJ-299-15 [7]. As photodetectors, that we tested for after pulsing and ability to withstand high rate, were mainly the Hamamatsu PMT R7056 [8] and FEU-115M. Both PMTs have about 28.5 mm outer diameter with about 25 mm diameter of an active area of photo cathode. Because both PMTs have similar dimensions, the FEU-115M housing [9] was also employed for R7056. The R7056 has a potential advantage in being able to detect more Cherenkov light because of its UV glass window and for this reason it was used in the most following tests.

With the same PMT used the fused quartz and Cherenkov plastic provided similar response. The UV transparent PMMA had a lower response.

III. Test Measurements

A. PMT after Pulse Observation

To verify that PMTs have sufficiently low (about 1% or less [5]) rate of after pulses within about 1.8 μs time window after the true pulses the following tests were performed. The 1.8 μs time window was chosen as an interval close to the Mu2e proton pulse beam time structure on the production target that had an interval of 1695 ns.

The R7056 with the Hamamatsu (A) socket assembly E2624-14 [10] were tested with cosmic rays at a high voltage about 1.45 kV. The setup consisted of three Cherenkov counters. The Cherenkov radiators had a rectangular shape with dimensions about 100 mm length, 27 mm width, and up to 12.7 mm thickness. Each radiator had orientation of the largest surface in a horizontal plane and assembled vertically on the top of each other and tune like a projection tower with PMTs on the sides. The distance between top and bottom counters was about 10 cm.

The coincidence between top and bottom counters was used as the trigger to an oscilloscope. The average trigger rate was about 3 counts per minute. The data acquisition system was oscilloscope based using LabVIEW. The PMT outputs were digitized by the oscilloscope. The true and after pulses were recognized first as a minimal response in the region of appropriate time of 2 μs long digitized wave form. The first 200 ns was a true pulse region followed by 1.8 μs of an after pulse region. Then the pulse height distributions for minimal responses were checked for the true pulse present in the first 200 ns and then checked the second part of wave form for an after pulse(s) with an amplitude not in a region from 0 to -30 mV that consist of mostly the oscilloscope base line points. Because minimal value always exist it does not mean that is a real true or an after pulse peak point. The -30 mV level of discrimination was used as a common discriminator minimal threshold value. The after pulses produced by the PMT were observed at about 20% relative frequency within the time window of 1.8 μs after the true pulse. This observation enforced then to look for a possible way to suppress the rate of after pulses. One of the possibilities is to reduce the applied voltage [4, 5] and when the output pulse becomes small a high gain amplifier can be used. There were no attempts to clarify reason(s) for such level of the after pulse rate at the company recommended supply voltage.

In conjunction with the x10 PM amplifier LeCroy model 612A the supply voltage to PMT was reduced to about 1 kV and the test was performed using a Hamamatsu (B) socket assembly E2624-04. The after pulse rate dropped to about few per cent relative frequency compare to the true pulses due to both the lower supply voltage applied to the PMT and also the lower voltage between the photocathode and the first dynode [4]. To reduce voltage at the first stage of PMT even more a custom made tapered voltage dividers were used.

B. PMT High Rate Performance Observation

As it was already estimated, the Mu2e fast/upstream extinction monitoring system should provide an adequate response to up to at least a million counts per second. A PMT response at high frequencies was studied using an LED (LED5-UV-400-30) and, by modification of the LED pulse height, observed at a large (about 500 mV) and a small (about 10 mV) PMT output pulses in the frequency range from about 0.07 to 20 MHz A restriction of the PMT output pulse height was observed due to a low value of the divider current (about 0.2 mA at 1 kV). At low illumination the amplitude of the output pulses was very sensitive to frequency and to the average value of the anode current. At about 2 μA average value of the anode current (at low illumination) the PMT responded up to a frequency of 20 MHz The observations in a pulse mode point to the importance of the average anode current level and a ratio of the average anode current to the voltage divider current as well [8,10].

To mimic high rate the study was performed at some level of permanent light from the LED and the voltage drop on the anode load and the last dynode were measured. The level of light from the LED was modified in a wide region by a small variation of the DCV applied to the LED. A set of custom made voltage dividers with a larger value of the divider current (up to 10 mA) was developed and tested.

C. Custom Made Voltage Dividers

Let's assume, for example, that the output pulses we expected to observe from the Cherenkov counter have a peak anode height of about 50 mV and a full width at half of maximum of 2 ns. The 2 ns is a full width at half of maximum of the Hamamatsu PMT R7056 anode output waveform. Because Cherenkov light flux is short, let's also assume then it will not elongate the anode output waveform, so the width of the output pulse will be about 2 ns. Let's also assume that pulse observed on the oscilloscope with 50 Ω input impedance. Then the peak anode current height will be about I=1 mA and the pulse charge q=Ixt= 1mA x 2 ns = 2 x 10^{-12} coulomb. At a number of pulses per second of about million counts per second, the current will reach 2 μA. Because PMT voltage divider current needs to be about 100 times larger, it means that the current value through the voltage divider needs to be about 200 μA. That is about what a divider from a market shelf usually provides. This is the minimal value of a voltage divider current that will not distort the PMT output pulse.

The PMT factory anode load also needs to be modified and a lower value is preferable [8] [10], because at a high rate the anode current will be large. If the anode load is low (about 50 Ω) then at a large anode current this will cause a few millivolts voltage reduction at the last PMT stage and a minimal corruption of the voltage distribution. In addition, the 50 Ω anode load will remove possible output pulse reflections.

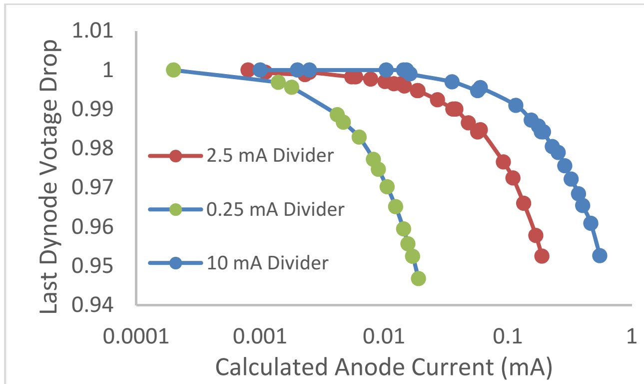

Fig. 1. Divider current effects on relative last dynode voltage drops at different anode currents.

Custom made tapered voltage dividers with the divider current about 0.25 mA, 2.5 mA, and 10 mA at 1kV were tested (Fig. 1). In addition to the modified divider current and anode load the resistor between photo cathode and first dynode had been also reduced.

As it illustrated in Fig. 1 the absolute maximum value of the average anode current of 0.1 mA may be achieved if the voltage divider current is about 2.5 mA or larger.

D. Test Setup for After Pulsing Study

A cosmic ray test setup to study after pulses was made from a vertical assembly of three Cherenkov counters. The top (channel four input to the oscilloscope or CH4) and bottom (CH2) counters are in coincidence. The distance between the top and bottom radiators was about 10 cm (see schematic in Fig. 2). The coincidence output was used as the trigger to the oscilloscope Agilent Technologies InfiniiVision MSO7054A (CH3 with vertical sensitivity 200 mV per division and horizontal sensitivity 200 ns per division) with the pulse wave form digitized every 2 ns. The trigger pulse was positioned at the first division or at about 200 ns.

The counter under test was located between the top and bottom counters. The counter used a Hamamatsu PMT R7056 [8, 10] with the custom made voltage divider (see table 1 for details) connected to the 12.7 mm thick UV PMMA radiator [7]. At a negative supply voltage of 1 kV the divider current was about 2.5 mA.

The bottom counter used a Hamamatsu PMT R6427 with the Hamamatsu factory voltage divider with the distribution ratio A and a 12.7 mm thick quartz radiator. At 1 kV positive supply voltage the divider current was about 0.21 mA.

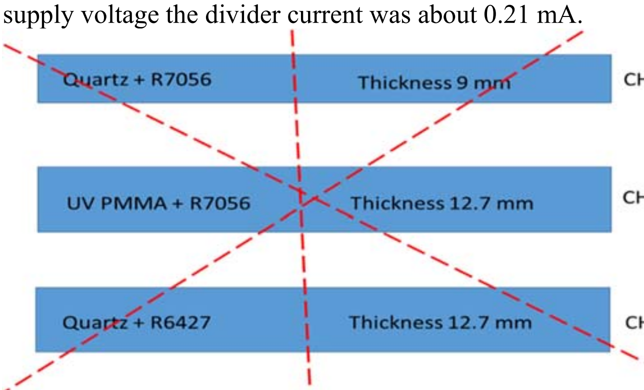

Fig. 2. Cherenkov radiators setup schematic (not to scale). All radiators are about 100 mm long and about 27- 28 mm wide. The red chain lines mimics possible directions of cosmic rays.

The top counter used a Hamamatsu PMT R7056 with the Hamamatsu factory voltage divider with the distribution ratio B (tapered) and a 9 mm thick quartz radiator. At 1 kV negative supply voltage the divider current was about 0.25 mA.

Table 1. Divider's voltage distribution ratios (Hamamatsu A and B, and Custom).

Electrodes	Cathode →	Dy1 →	Dy2 →	Dy3 →	Dy4 →	Dy5 →	Dy6 →	Dy7 →	Dy8 →	Dy9 →	Dy10 →	Anode
Ratio A	4	1	1.5	1	1	1	1	1	1	1	1	
Ratio B	4	1	1.5	1	1	1	1.2	1.5	2	3.3	3	
Custom	2	1	1.5	1	1	1	1.2	1.5	2	3.3	3	

All PMT outputs were connected to the PM Amplifiers LeCroy Model 612A. One output of each amplifier was connected to the oscilloscope inputs, like the CH1 with 50 mV per division, the CH2 with 200 mV per division, and the CH4 with 100 mV per division. The choice of sensitivity depends of the peak pulse height from a particular counter. The second amplifier output of the top and the bottom counters were also connected to the discriminators type LRS Model 621L and then to the coincidence type LRS Model 622. The thresholds of the discriminators inputs were at about -30 mV. The output pulses of the discriminators and the coincidence had a 20 ns width.

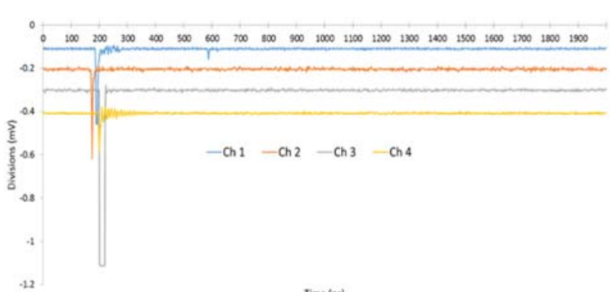

Fig. 3. Cosmic ray event restored from the file. Scope screen event had an after pulse (at about 580 ns) in Ch1.

The Hamamatsu PMT R6427 [8, 10] has a borosilicate glass window with a spectral response from about 300 to 650 nm. The wavelength of maximum response is at about 420 nm. The Hamamatsu PMT R7056 [8, 10] has a UV glass window with a spectral response from about 185 to 650 nm. The wavelength of maximum response is at about 420 nm.
For the optical coupling of the radiators to the PMT windows the optical grade silicone EJ-550 and the EJ-560 [7] optical interface pad 28 mm diameter and 1.5 mm thick were tested as well as with a minimal achievable air gap. Each quartz radiator was flame finished, wrapped in one layer of Tyvek, and then a layer of Tedlar. Each counter had an individual high voltage power supply.

For each trigger to the oscilloscope the true pulses were observed for each counter traces as the lowest voltage in the time window of about 200 ns. The after pulse(s) was observed as the lowest voltage in the time window from 0.2 to 2.0 µs. Because such minima always exist, it does not mean that the minima is a real true or an after pulse as seen in Fig. 3.

Table 2. Supression of the after pulse ratio by reducing the suply voltage and the voltage division. The true and after pulse data collected at 40 and 80 kΩ resistor between the photo cathode and the first dynode as described in Table 1. Voltage dividers with the Hamamatsu ratio B as the reference and a custom ratio at different suply voltages.

Voltage at 40 kΩ (kV)	1.0	1.1	1.2
True pulses	1531	5138	4115
After pulses	0	4	47
Ratio A/T (%)	-	0.08	1.14
Voltage at 80 kΩ (kV)	1.1	1.2	1.3
True pulses	3325	3536	3927
After pulses	5	27	131
Ratio A/T (%)	0.15	0.76	3.34

The main goal of this study was to estimate and attempt to reduce the after pulse rate. Those were studied using the custom made voltage divider at a different value of the supply voltages in the region from 1.1 to 1.3 kV and at both "high" or 4R and "low" or 2R voltage /resistor (see Table 1) between the photocathode and the first dynode in the counter being tested. The counter under the test had a custom made voltage divider with 50 **Ω** anode load. The low value of anode load is preferable at high rate [11]. In this case we are looking for the voltage divider optimized for both a low after pulse rate and ability to work at high intensity beam (more than a million counts per second).

E. After Pulsing Study

Residual gases in the PMT can cause a detectable current if their atoms can be ionized by the electrons. The ions will be accelerated towards the cathode or dynodes and can knockout new electrons. Such processes result in after pulses [5, 11-13] occurring in a time needed for the ions to transit the tube. It can be from a few hundred nanoseconds to microseconds. At a high tube current, after pulses may also be caused by the glow of the last dynodes. Because these are usually one-electron events, their amplitudes are generally small.

It is important to prevent the occurrence of large variations of a potential between the dynodes due to the changing currents in the tube. Such variations would cause changes in the overall gain and linearity of the PMT. For this reason, it is important that the current in the resistance chain be large compared to the tube current [5, 11-13].

Table 2 illustrates the amount of true and after pulse events observed at different supply voltage conditions been tested. The amount of after pulses is sensitive to the applied voltage. Higher voltage gives higher after pulse rates [5, 11-13]. In addition, reduction of voltage at the first stage of PMT [4] (for example, as in the custom voltage divider in Table 1) also suppresses the amount of after pulsing. Table 2 gives the results of testing custom divider, represented with 40 kΩ resistor, compared to ratio B divider with 80 kΩ resistor in the first PMT stage at different values of the applied voltages. At the same divider current the PMT with B ratio demonstrates more after pulses than the custom divider.

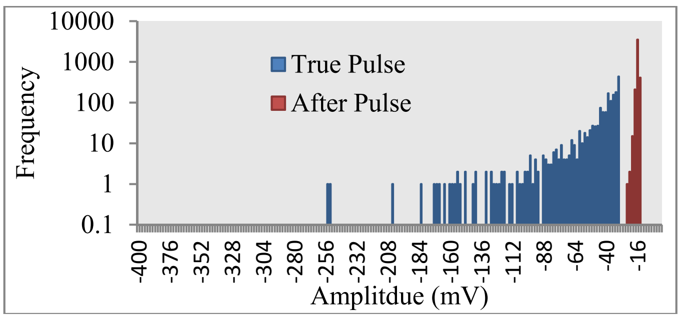

Fig. 4. Amplitude distribution of minimal responses in the true and after pulse regions at supply voltage of 1.0 kV, and the resistor of 40 kΩ at the first stage of custom divider.

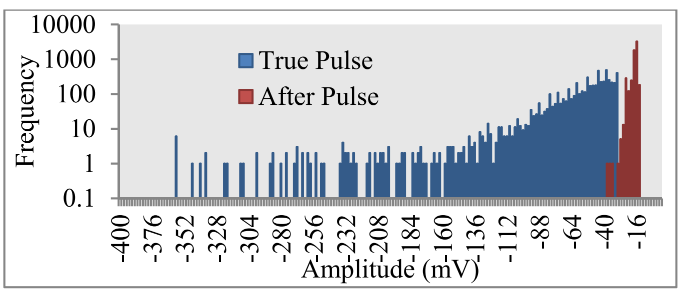

Fig. 5. Amplitude distribution of minimal responses in the true and after pulse regions at supply voltage of 1.1 kV, and the resistor of 40 kΩ at the first stage of custom divider.

Fig. 4-9 show distributions for minimal responses in the true and after pulse time regions. Those distributions do not provide any indication of a large after pulse amplitude presents. It means that after pulses were not generated in the photocathode – first dynode stage. If after pulsing is a result of "ion" bombarding the photocathode from the inside of the tube that will knock out many photo electrons giving an after pulse with a large amplitude [5]. Because we do not observe after pulses with a large amplitude, it means that those processes are rare.

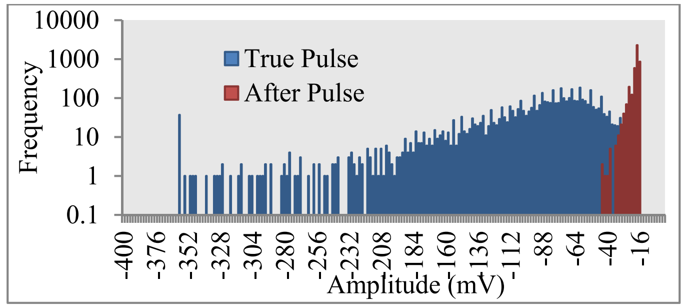

Fig. 6. Amplitude distribution of minimal responses in the true and after pulse regions at supply voltage of 1.2 kV, and the resistor of 40 kΩ at the first stage of custom divider.

Figures 4-9 consist of some true pulse events with large amplitudes that saturate the oscilloscope screen input range. Those amplitudes can be due to multi-particle events [14] or cases with a better light collection.

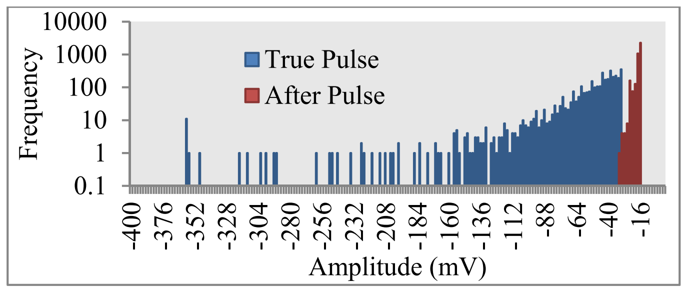

Fig. 7. Amplitude distribution of minimal responses in the true and after pulse regions at supply voltage of 1.1 kV, and the resistor of 80 kΩ at the first stage of custom divider.

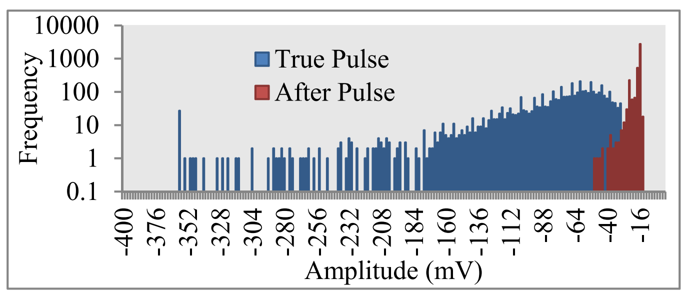

Fig. 8. Amplitude distribution of minimal responses in the true and after pulse regions at supply voltage of 1.2 kV, and the resistor of 80 kΩ at the first stage of custom divider.

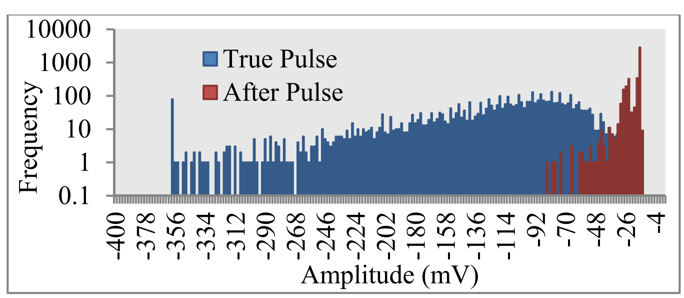

Fig. 9. Amplitude distribution of minimal responses in the true and after pulse regions at supply voltage of 1.3 kV, and the resistor of 80 kΩ at the first stage of custom divider.

IV. OBSERVATIONS WITH TRIGGER COUNTERS

A silicon optical grease EJ-550 and a silicon soft pad EJ-560 can improve the optical coupling between Cherenkov radiator and PMT input window (Fig. 10-12). But those silicon materials have absorption at shorter wavelengths. Their UV-absorption edge is at about 300 nm and is also sensitive to the thickness of material used [7]. For those reasons (increase from reduced reflections but decrease from absorption) the silicon rubber optical interface between the radiator and the PMT input window was tested with and without a 1.5 mm thick soft silicon pad EJ-560 (Fig. 12). A thin layer of optical grade silicone grease between the photocathode and the radiator increased about 1.6 times the average amplitude of true pulses.

The frequency of the true pulse and after pulse amplitude (29,130 events) from the Hamamatsu PMT R6427 is shown in Fig. 13 while Fig. 14 gives the frequency of the after pulse time. The time histogram has maximum at about 500 ns. This time-correlated after pulses may indicate on the possible presence of helium ions inside the tube [4].

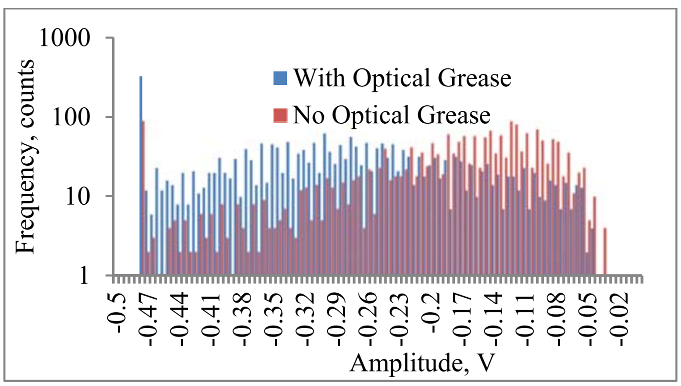

Fig. 10. Frequency of the output pulse amplitudes from the Hamamatsu PMT R6427 connected to the quartz radiator made of GE021 with and without silicon grease.

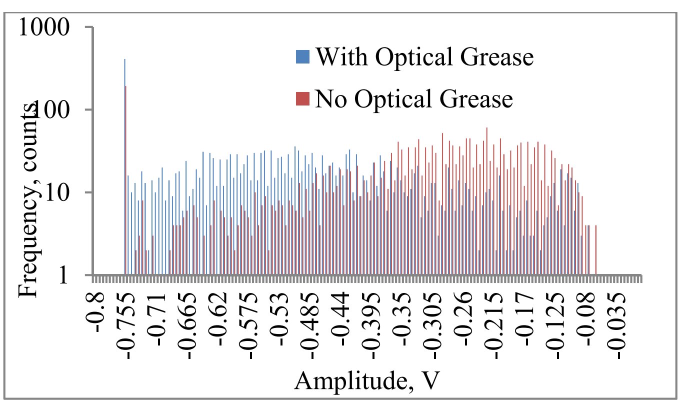

Fig. 11. Frequency of the output pulse amplitudes from the Hamamatsu PMT R7056 connected to the quartz radiator made of GE021 with and without silicon grease.

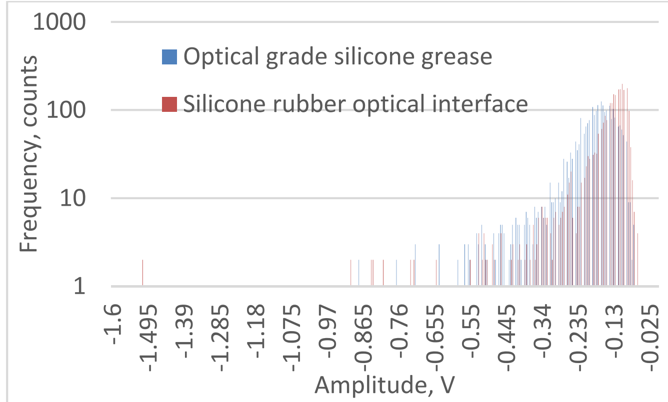

Fig. 12. Frequency of the output pulse amplitudes for soft silicon pad or optical grease between quartz radiator and PMT R7056.

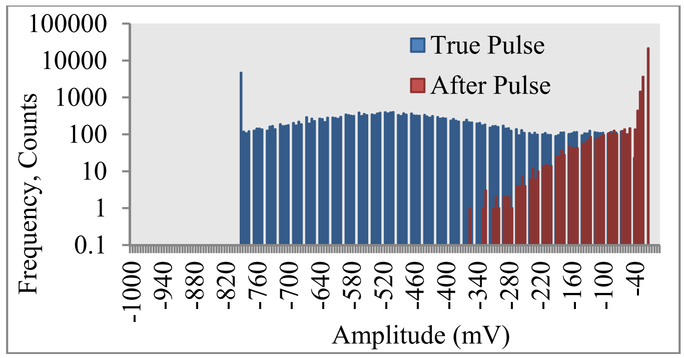

Fig. 13. . Amplitude distribution of minimal responses in the true and after pulse regions from the PMT 6247.

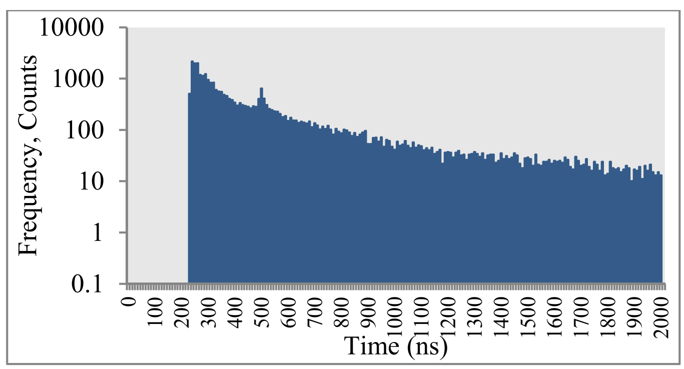

Fig. 14. Time distribution of minimal responses in the after pulse region for PMT R6247.

V. SUMMARY

For the Hamamatsu PMT used with a voltage divider available from a market shelf an after pulsing occurrence at about 20% level compare to the true pulses rate was observed during 1.8 μs time window after true pulse. Why did this PMT after pulsing rate so high was not a subject of this research.

Using a cosmic rays a PMT after pulse rate was studied as a function of HV and voltage division for different tubes. In general, a lower applied high voltage produced a lower after pulse rate (in order of up to one of magnitude).

To use the Hamamatsu PMT R7056 as a photo detector in the mu2e extinction monitoring system, its high after pulsing rate needs to be suppress. For this reason, PMT was used at a high voltage of about 1 kV in conjunction with amplification about x10 or more. To further reduce occurrence of after pulses we used a custom made tapered voltage divider with the relative voltage between the photocathode and the first dynode decreased by a factor of two.

The after pulse rate for a Hamamatsu PMT R7056 with the custom made voltage divider was reduced to about 0.1% level or more than two order of magnitude lower.

At high rate a PMT anode load of 50 Ω is to be preferred.

Application of a thin layer of optical grade silicone grease between the photocathode and the quartz Cherenkov radiator increased the average amplitude value for true pulses about 1.6 times.

There is an indication that PMT R6427 and R7056 have similar responses to the quartz Cherenkov radiators for the cosmic rays events.

The 1.5 mm thick soft silicon pad applied between a quartz Cherenkov radiator and a PMT input window does absorb some input light compare to the thin layer of the optical grade silicone grease.

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