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TECHNICAL REPORT

Afterpulse timing and rate investigation of three different Hamamatsu Photomultiplier Tubes

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ABSTRACT: We present the results of the tests performed on 90 photomultiplier tubes (PMT) to characterize their afterpulses. Three different types of Hamamatsu PMTs (R7525, R6427, and R1398) were studied for their afterpulse rates and timings at different incident light intensities and gain values, at the University of Iowa PMT test station. Afterpulse rates show slight increase with the PMT gain, but there is almost no dependence on incident light intensity. Three specific time delays are determined for the afterpulses, and their individual rate contributions are characterized. The results from manufacturer's independent tests on R7525 PMTs are reported, as well. The possible effects of these afterpulses on the future hadron collider experiments are also discussed.

KEYWORDS: Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others); Calorimeters.

2008 JINST 3 T01001

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Contents

2008 JINST 3 T01001

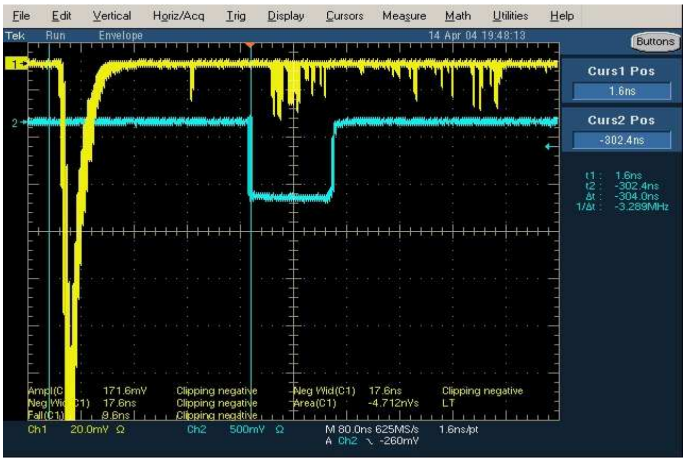
1. Introduction

Afterpulses are small signals, few photoelectron level, that appear after the main pulse of a photomultiplier tube (PMT) [1]. These narrow pulses can easily be observed with an oscilloscope as shown in figure 1. Afterpulses are divided into two categories depending on their delay from the main pulse. The short delay afterpulses appear up to several tens of nanoseconds after the signal. They are caused by the elastic scattering of the electrons from the first dynode. The long delay afterpulses appear from several tens of nanoseconds to several microseconds after the main pulse. The main cause of these afterpulses are the positive ions which are generated by the ionization of residual gases in the PMT [2]. All the afterpulses discussed in this report are long delay afterpulses. The afterpulse effects on counter measurements [3], and different afterpulse reduction techniques [4, 5] have been studied earlier.

This report focuses on the afterpulses from 84 Hamamatsu R7525 PMTs, which is a 8-stage, head on PMT with a bialkali photocathode. Hamamatsu R7525 PMTs are selected to be used on the forward calorimeter of the Compact Muon Solenoid (CMS) experiment. We also report the results from the tests on the similar type of PMTs, five Hamamatsu R1398 and one Hamamatsu R6427, for comparison purposes. Results of the manufacturer's independent tests on R7525 afterpulses are included into the discussion and conclusion section. The possible effects of PMT afterpulses on future collider experiments are also discussed.

2. Test setup

The setup used to measure the timing and charge accumulation of the afterpulses is shown in figure 2. The charge accumulation measurements were done by using LeCroy 2249 ADC, which was monitored online with LabView software. The timing measurements were performed with 5Gs/s Tektronix Digital oscilloscope. Since the afterpulses appear as random fast flashes, we used the envelope function of the digitial scope to see them on the screen (see figure 1). A blue LED, with peak wavelength of 420 nm was used as light source. The initial light intensity is set to 500 photoelectron level. The LED was driven by a dual pulser that provides TTL gate signal, as well. We used LeCroy 222 dual gate generator to create gate signal from trigger (see figure 2).



Tek Run Envelope 14 Apr 04 19:48:13

Curs1 Pos 1.6ns

Curs2 Pos -302.4ns

t1 : 1.6ns
t2 : -302.4ns
Δt : -304.0ns
1/Δt : -3.289MHz

Ampl(C 171.6mV Clipping negative
Neg Wi C1) 17.6ns Clipping negative
Fall(C1) 9.6ns Clipping negative
Neg Wid(C1) 17.6ns Clipping negative
Area(C1) -4.712nVs LT

Ch1 20.0mV Ω Ch2 500mV Ω M 80.0ns 625MS/s 1.6ns/pt
A Ch2 ⤥ -260mV

Figure 1. A sample scope view of the Hamamatsu R7525 PMT afterpulses at a gain of 10^6. The blue line shows the 125 ns gate, the yellow line shows the signal. Both inputs are shown in envelope mode for demonstration purposes.

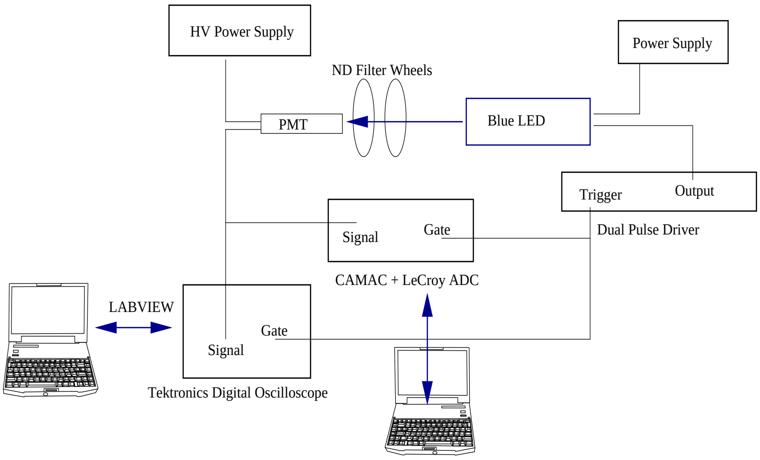


Figure 2. The setup used at the University of Iowa PMT Test Station for the afterpulse measurements.

3. Afterpulse timing

We measured the afterpulse delays of 35 Hamamatsu R7525 PMTs with respect to the main signal. The 2000 scope samples with the resolution of 800 ps were recorded in 4 μs range. The afterpulses have a width around 4 ns. To make sure that each afterpulse is counted once, the afterpulses in 4ns bin are counted as single afterpulse.

The afterpulses appear randomly in a big time range, but there are three specific delay regions where most of the afterpulses are localized (see figure 3). For some PMTs, only one or two of these peaks appear, but the majority of PMTs have afterpulses on all three regions. We specified the locations of these afterpulse timing regions with respect to the mean position of the signal. Then fitted these peaks into gaussian, and recorded the mean and sigma values. The results are

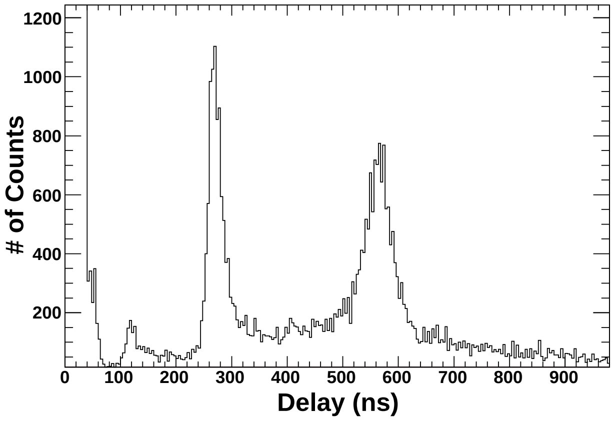


Figure 3. Delays of the Hamamatsu R7525 (Serial Number 1372) afterpulses with respect to the main signal, at a gain of 10^6. Three distinct afterpulse timing regions can easily be identified.

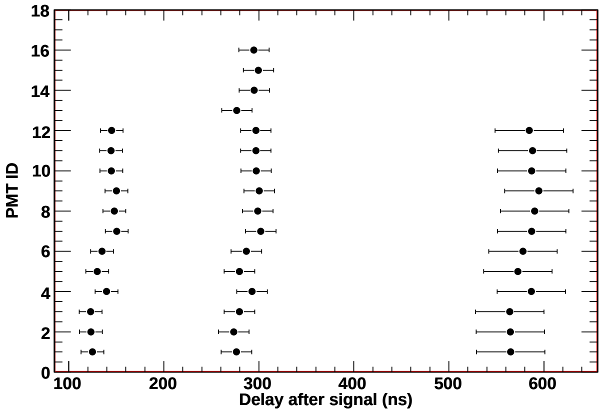


Figure 4. Timing delays of the afterpulse positions with respect to the signal peak position, at a gain of 10^6. Data points show the mean, and the error bars are the σ of the gaussian fits.

summarized in figure 4. The three specific afterpulse delay regions are as follows: 110 ns - 150 ns, 270 ns - 310 ns, and 540 ns - 610 ns with respect to the main signal. These afterpulse timing values were calculated at a gain of 10^6.

We repeated the tests at a gain of 10^5 and 10^4. The afterpulses appear to be delayed up to 10% for lower PMT gains. The timing measurements done on Hamamatsu R6427 and R1398 PMTs yield very similar afterpulse timing distributions.

4. Afterpulse charge accumulation rate

We measured the charge accumulation at the areas where the afterpulses are localized and compared it to the charge accumulation of the main signal. We used fixed ADC gate size (125 ns) and moved it throughout the time scale with a delay unit. We recorded 10,000 events with ADC, and calculated the charge accumulations from the signal and the afterpulse regions. The afterpulse rate is defined as the ratio of the integrated charge of the afterpulses to that of true pulse. This rate can be stated as:

$$RATE = (Q_{\text{Afterpulse}}/Q_{\text{Signal}}) \times 100$$

For each PMT, the afterpulse rate at all three afterpulse timing regions are calculated. We also investigated the variations on the afterpulse rates for different light intensity and PMT gain levels.

The figure 5 shows the afterpulse rates of three different types of PMTs at various light intensities. The afterpulse rate of the R7525 and R6427 PMTs do not vary with incident light intensity, it is almost constant at around 3% to 4%. Whereas R1398 PMTs yield around 30% rate at 100 photoelectron signal level, as the incident light intensity increased the afterpulse rate reduces, and it reaches to %10 at 650 photoelectron level.

The afterpulse rates of three different types of PMTs at various gain levels are shown in the figure 6. The R7525 and R6427 PMTs yield a rate of 2% to 4% at lower gains, and it slightly increses up around 4% to 5% at the gain of 10^6. On the other hand, the R1398 PMTs yield the afterpulse rates changing considerably with the PMT gain from 10% to 25%. The rate is higher at lower gain values.

The variation of the charge carried by afterpulses with different delays is also investigated. Figure 7 shows the afterpulse rates of the 84 R7525 PMTs, from three distinct timing regions separately. The contribution of the individual timing regions to afterpulse rate is almost always less than 2%. The first afterpulse region (between 110 ns and 150 ns) yields less than 0.4% rate. The second afterpulse region (between 270 ns and 310 ns) yields almost always less than 1% rate. The third afterpulse region (between 540 ns and 610 ns) shows as much as 2.5% rate for some R7525 PMTs.

Charge accumulation rates at different repetition rates of the incoming LED pulses was investigated as well. The rate of the PMTs do not show any variation with the frequency of the incoming light.

5. Discussion and conclusion

The manufacturer (Hamamatsu) provided us independent afterpulse measurements on the R7525 [9]. Hamamatsu uses two different techniques: Charge Mode and Counting Mode [10]. The afterpulses were reported to appear in the first 2.5 μsec after the main signal. The test results show afterpulse rate of 3.19 ± 0.45 for charge mode and 4.12 ± 0.36 for counting mode. These rates are measured by integrating the charge of the afterpulses for 10 microsecond region with the gain of 10^6. It is reported that incoming light and pmt gains do not have significant effect on the afterpulse rate. The manufacturer is positive that the afterpulses from R6427 and R1398 are designed to be at the same afterpulse rate level with R7525.

At the University of Iowa, we studied afterpulses on 84 R7525 PMTs and on the samples from other PMT types (R6427, and R1398). There are 3 distinctive timing regions in which afterpulses appear. These timing positions tend to shift with the gain of the PMT. These discrete delays of the afterpulses are in good agreement with H_2^+, He^+, and CH_4^+ gas molecules [2, 11]. The charge

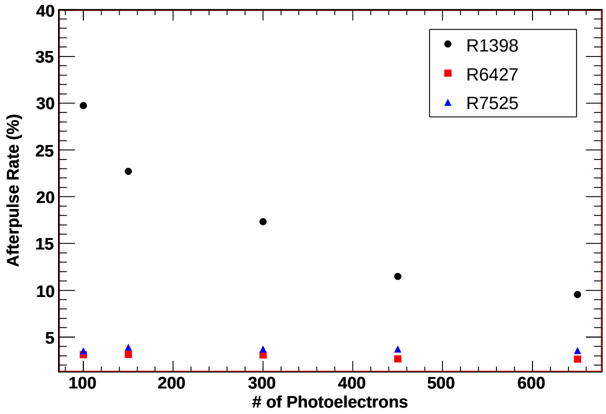


Figure 5. Charge accumulation rates of 3 PMT types for different light intensities. Black circles-R1398, blue triangles-R7525, red squares-R6427.

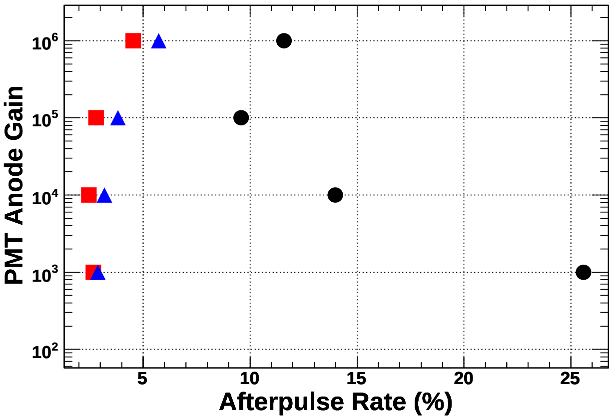


Figure 6. Charge accumulation rates of 3 PMT types, for different PMT gain values. Black circles-R1398, blue triangles-R7525, red squares-R6427.

accumulation rate of the afterpulses from R7525 and R6427 are measured to be around 3% to 4%, and this rate does not vary much with the intensity of the light or with the gain of the PMT. However, R1398 PMTs have substantially higher charge accumulation rates. We discussed our results with the manufacturer, the only possible explanation for the R1398 high afterpulse rate is aging. The R1398 PMTs used for these tests are 8 years old, and the vacuum inside them has been worsened in time. Especially, small gas molecules leak into the PMTs from atmosphere, contribute to the high rate [10]. R7525 and R6427 PMTs are 1 year old, we expect same behavior from R7525 and R6427 PMTs in time.

The PMTs similar to are effectively used in high energy physics experiments, especially in calorimeters for energy measurements [6 – 8]. The high energy physics is entering a new era with the future hadron colliders, which will have unprecedented beam energies and very short bunch-

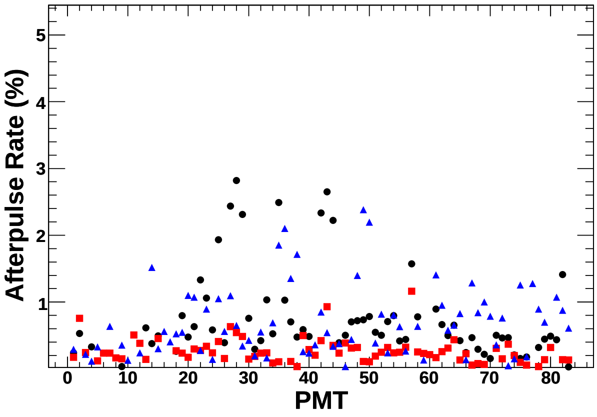


Figure 7. charge accumulation rates of 84 R7525 PMTs at a gain of 10^6, for three distinct timing delay regions: Red 110ns - 135 ns, blue 270 ns - 310 ns, and black 540 ns - 610 ns. The data taken with 650 photoelectron light intensity.

crossing times. The Large Hadron Collider (LHC) is the first of the future hadron colliders. It will run at a high luminosity (10^{34} cm^{-2}s^{-1}) and with 14 TeV of center of mass energy. The designed bunch-crossing time of the LHC is 25 ns, and it is foreseen to be even shorter after a future upgrade (superLHC). With the short bunch crossings, there is a possibility that the afterpulses from previous collisions are recorded as a new signal in the absence of the true signal, or change the strength of another true signal. These effects will create increase in fake rates, and errors on the jet and missing transverse energy (ME$_t$) measurements in the calorimeters.

The future collider experiments will search for the Higgs boson, its properties, and signature of new physics like supersymmetry (SUSY). The precise jet energy measurement, and accurate ME$_t$ measurements will be crucial. For low mass Higgs boson scenerios [12] or low mass SUSY points [13] the average missing (E$_t$) is around 30 GeV.

This report shows that PMT afterpulses have the potential of being a source of error in this energy scale. Since the afterpulses do not change with incoming light intensities, at lower intensities (i.e. few photoelectron level), the amplitude of the afterpulse can be bigger than the signal [2].

This report focused on the Hamamatsu R7525 PMTs which were selected to be used in CMS experiment hadronic forward calorimeter [8]. For the ME$_t$ measurement in the forward region, CMS experiment heavily relies upon the presicion of these PMTs. As time passes the afterpulse rates of PMTs are going to reach to higher levels. This study reveals the specific delay times and the rates of the expected afterpulses with different gain and signal levels for Hamamatsu R7525 PMTs. These effects should be taken into account during offline jet, and ME$_t$ reconstructions. Considering that the projected run time of the LHC is 10 years, the R7525 PMTs should be monitored continuously for the effect of aging on afterpulse rates.

Acknowledgments

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