Electron Transit Time Measurements of 5-inch Photomultiplier Tubes

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Abstract

We investigated the uniformity of electron transit times for two 5-inch photomultiplier tubes: the Hamamatsu R1250 and the Adit B133D01S. We focused a highly attenuated short-pulse laser on the tubes while they were mounted on a programmable stage. The stage translated the tubes relative to the incident beam so that measurements could be made with light focused at points along a grid covering the entire photocathodes. A portion of the incident light was split from the incident beam and measured and recorded by a fast photodiode. Electron transit times were measured by computing the time delay between the recorded photodiode signal and photomultiplier signal using software constant-fraction discrimination. The Hamamatsu tube exhibited a uniform timing response that varied by no more than 1.7 ns. The Adit tube was much less uniform, with transit times that varied by as much as 57 ns. The Adit response also exhibited a spatially varying double-peak structure in its response. The technique described in this paper could be usefully employed by photomultiplier tube manufacturers to characterize the performance of their products.

Keywords: Photomultiplier tubes, Detector calibration methods

1. Introduction

Photomultiplier tubes (PMT) are often used with scintillation detectors in applications where timing is important, such as in coincidence or time-of-flight

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10 experiments, or in positron emission tomography (PET) [1]. In these appli-
 11 cations, the electron transit time in the PMT usually contributes the largest
 12 temporal variation to the overall system. Photons arriving at different locations
 13 on the photocathode produce photoelectrons with varying trajectories through
 14 the tube, which results in timing variations in the output signal. This timing
 15 variation becomes more pronounced as the size of the PMTs increases. In ex-
 16 periments where the light signals illuminate the photocathode uniformly, the
 17 timing and shape of the electronic output pulse tends to be fairly uniform be-
 18 tween events. However, localized illumination of the photocathode results in
 19 variations in shape and timing of the response pulses with the location of the
 20 input light. In experiments with localized illumination, such as in low-photon
 21 counting or when the PMT is coupled to optically isolated detector segments,
 22 it is important to understand the relationship between PMT timing and the
 23 location of the incident light on the photocathode.

24 Our interest in the spatial variation of the time response came from doing
 25 energy-dependent efficiency calibrations of neutron detectors using time-of-flight
 26 techniques. The detectors involved were capture-gated detectors that were con-
 27 structed with optically isolated sections of scintillator surrounded by cadmium
 28 foil. We originally used Adit B133D01S PMTs, but found the time-of-flight data
 29 to be minimally useful because of the timing spread of the detectors.

30 Researchers at UCLA investigated the timing characteristics of a 3-inch
 31 Hamamatsu R11410-10 tube used in a vacuum cryostat for Dark Matter de-
 32 tection experiments. They found that the transit time was highly position
 33 dependent, with deviations of about 5 ns near the edges of the PMT [2]. They
 34 also found symmetry along the axes corresponding to the location and design
 35 of the first dynode. In an unpublished study, Xu Wang and Ye Tian at Shan-
 36 dong University investigated several 1-inch and 2-inch PMTs for applications in
 37 cosmic ray astronomy. Their initial results confirm those of the UCLA study.
 38 In addition, they found that locations with a slower relative transit time, such
 39 as the edges, also have greater transit time spread among the samples taken
 40 at that location. Xia *et al.* have studied the spatial uniformity of the sensi-

Figure 1: Schematic of the measurement setup. An 800 nm laser pulse is frequency-doubled in a BBO crystal to produce 400 nm light pulses. The 800 nm laser pulse is removed using a BG-39 spectral filter, and the 400 nm pulses are attenuated and focused onto a PMT. A photodiode triggers the oscilloscope, and a computer records each PMT output pulse.

41 tivity 1-inch and 2-inch PMTs, and separately looked at their timing response
 42 (although they did not study the spatially resolved timing response) [3].

43 These prior results were each obtained for tubes 2-inches or less. In this
 44 paper, we present results for the timing behavior of 5-inch diameter PMTs.
 45 These larger tubes have the potential for larger timing variations due to the
 46 larger geometry, and timing studies have not yet been reported.

47 2. Experimental Procedures

48 A schematic of our experiment is shown in Fig. 1. A Ti-Sapphire laser
 49 produces 100 ps pulses at 800 nm, which are frequency doubled in a Beta Barium
 50 Borate (BBO) crystal to produce 400 nm pulses. These 400 nm pulses are a good
 51 match for the PMTs used in this measurement, which have a peak sensitivity
 52 wavelength about 420-460 nm. The laser pulses then pass through a Schott BG-
 53 39 filter to remove the 800 nm light, and a beamsplitter diverts a portion of the
 54 beam to a fast photodiode (ThorLabs DET210) used to trigger the oscilloscope.

Figure 2: The dots represent the PMT positions at which data were recorded. The circled dots are locations where PMT signal were detected.

55 The remainder of the light is attenuated with neutral density filters and focused
 56 using a lens onto the surface of the PMT at normal incidence, with a spot less
 57 than 2 mm in diameter. An oscilloscope digitizes both the PMT output pulse
 58 and the trigger pulse from the fast photodiode, and both traces are then saved
 59 to a computer for later data analysis.

60 A pair of computer-controlled linear stages translate the PMT in the plane
 61 parallel to the photocathode to vary the spatial location where the optical pulse
 62 strikes the PMT. The PMT is oriented such that features of the interior geom-
 63 etry are aligned to the axes of the stages. Data are taken on a rectangular grid
 64 over the entire face of each photocathode with 5 mm spacing in both dimen-
 65 sions. The positioning uncertainty of the stage is about 10 μm . We verified
 66 the location of the PMT by spatially scanning over our square grid. When the
 67 laser pulse position was outside the active area of the PMT, no PMT pulse was
 68 produced. This allowed us to verify the location of the tube within the scanned
 69 grid. The dots in Fig. 2 show the locations where data were taken, and the
 70 circled dots are positions where signal was observed.

71 We used this system to measure the timing characteristics of two 5-inch
 72 PMTs: an Adit B133D01S and a Hamamatsu R1250. The Hamamatsu tube is
 73 designed to optimize timing response, while the Adit tube is engineered to op-

74 timize detection efficiency. Both tubes are head-on type PMTs that use bialkali
 75 photocathodes with a minimum useful diameter of 120 mm. The Hamamatsu
 76 employs a 14-stage linear focused dynode structure with a maximum operat-
 77 ing voltage of 2000 V. The Adit has a 10-stage box-and-grid dynode structure
 78 with a maximum operating voltage of 1500 V. In these measurements, the PMT
 79 voltages were set near their maximum voltages. To prevent saturation, we at-
 80 tenuate the incoming laser pulses by inserting sufficient neutral density filters
 81 in the beam to just eliminate the PMT signal, and then remove a filter with
 82 optical density one to restore the signal. The Hamamatsu PMT has a larger
 83 gain, so the Hamamatsu PMT requires more attenuation than the Adit.

84 **3. Analysis**

85 The primary goal in this study is to characterize the relative timing between
 86 the fast photodiode trigger pulse and the photomultiplier tube response. The
 87 intensity of the Ti-Sapphire laser pulses varies shot-to-shot by 20%, and the
 88 efficiency of the frequency doubling process is quadratic with intensity. This
 89 results in fluctuations in peak height for both the fast photodiode and the PMT
 90 response. These fluctuations can affect the relative timing between the two
 91 signals when a simple voltage threshold method is used to identify pulse arrival
 92 times for the two pulses. To remove this effect, we employed a software constant
 93 fraction discrimination (CFD) algorithm to the recorded trigger pulse to adjust
 94 the relative timing. This process adds an inverted, attenuated pulse to the
 95 original trigger pulse and adjusts the time axis so that the zero-crossing of the
 96 summed pulse gives the arrival time of the pulse, as illustrated in Fig. 3. The
 97 CFD algorithm reduces jitter that arises from variation in pulse size.

98 The formula for the summed pulse in the CFD algorithm can be written as

$$S(t) = P(t - t_d) - \alpha P(t) \quad (1)$$

99 where $S(t)$ is the summed pulse, $P(t)$ is the original pulse, α is the attenuation
 100 factor, and t_d is the delay time. We found that for single-peak pulse shapes in

Figure 3: A schematic representation of the process used to determine timing with a CFD algorithm.

our experiment there was very little sensitivity to the choice of α or t_d within the reasonable choices for these parameters. However, the Adit tube exhibited a distinctive double-peak structure in its response. For this type of double-peak structure, the α parameter can be varied to distinguish the arrival of the two peaks.

Typical response curves for our setup shown in Fig. 4 for the Hamamatsu and Fig. 5 for the Adit. Note the small peak preceding the main response in the Adit response curve. This double-peak behavior occurred when testing certain regions of the PMT and not in others. This suggests a bifurcation of the transit paths of electrons through the PMT amplification chain, but it is unclear whether or not single photons would produce a double-peaked pulse. For double-peaked pulses, small values of α pick the timing from the first peak and larger values from the second peak. We analyze the data using both $\alpha = 0.1$ and $\alpha = 0.9$ for the Adit tube to separately study the timing of the two types of electron trajectories. With the Hamamatsu tube, we only display the analysis done with $\alpha = 0.1$.

Figure 4: Typical response for the Hamamatsu PMT. The triggering fast photodiode is also shown for comparison. The peak voltage of the fast photodiode signal has a significantly smaller amplitude than the PMT, so for plotting purposes we have multiplied the fast photodiode voltage by ten to aid visual comparison of the two peaks.

Figure 5: Typical pulse for the Adit PMT. The triggering fast photodiode is also shown for comparison. The peak voltage of the fast photodiode signal has a significantly smaller amplitude than the PMT, so for plotting purposes we have multiplied the fast photodiode voltage by ten to aid visual comparison of the two peaks.

117 4. Results

118 Although the light incident on the photocathode is localized, the photoelec-
119 trons ejected from the photocathode still exit with a range of angles and energies.
120 These variations result in shot-to-shot fluctuations in timing at a given position.
121 To average out this effect, we measure ten pulses at each location on the grid.
122 Then we calculate the difference in time between the PMT pulse and the fast
123 photodiode pulse, Δt , for each laser pulse and average the values of Δt for each
124 spatial point.

125 The calculated values of the time delay Δt between the photodiode trigger
126 and the PMT response include an arbitrary constant that depends on cable and
127 electronic delays. To remove this constant, we subtract the average value of all
128 valid measurements, $\langle \Delta t \rangle$ from all the individual measurements of Δt in our
129 results. The average values $\langle \Delta t \rangle$ are of some interest as a comparison between
130 the different measurements, however. For the Adit tube with $\alpha = 0.1$, the CFD
131 algorithm gives the arrival time of the first peak. The average arrival time Δt
132 of this first peak is 83.5 ns with a standard deviation of 11.7 ns. When we use
133 $\alpha = 0.9$, the CFD algorithm gives the arrival time of the second peak. The
134 average arrival time of the second peak is 111.7 ns with a standard deviation of
135 14.5 ns. Biasing the data toward the later peak increases the measured value of
136 the transit time, as expected, but it also increases the transit time spread.

137 To spatially resolve the transit times, the procedure described above is ap-
138 plied to the data at each location. Figure 6(a) shows a map of the delay time
139 as a function of position for the Adit tube with $\alpha = 0.1$, which selects for the
140 early peak. Figure 6(b) plots a histogram of transit times at all positions. The
141 largest peak in the histogram occurs at about 8 ns, which correspond to the
142 large outer portion of the PMT as seen in Fig. 6(a). The inner portion of the
143 PMT has much shorter delay times, corresponding to the lower portion of the
144 histogram. Note the annular region about 15 mm from the center where there
145 is an early double peak leading to shorter transit times.

146 When we switch to $\alpha = 0.9$ for the Adit tube, we consistently take our timing

Figure 6: (a) Difference of transit time and mean transit time as a function of the position of optical stimulation for the Adit tube with $\alpha = 0.1$. (b) Histogram of the transit time minus the mean transit time for the Adit tube with $\alpha = 0.1$.

Figure 7: (a) Difference of transit time and mean transit time as a function of the position of optical stimulation for the Adit tube with $\alpha = 0.9$. (b) Histogram of the transit time minus the mean transit time for the Adit tube with $\alpha = 0.9$.

147 information from the later peak. Figure 7(a) plots a map of the delay time as
 148 a function of position for $\alpha = 0.9$, and Fig. 7(b) plots a histogram of transit
 149 times. The histogram shows a wide distribution in transit times. If plotted as
 150 a surface, the data in Fig. 7(a) resembles a paraboloid with a large variation in
 151 transit times from the center to the edge. The shortest transit times are near
 152 the middle, with the delay time increasing by over 50 ns as the laser position is
 153 shifted to the edge of the PMT.

154 We expected that the timing characteristics of the Hamamatsu tube would
 155 be much better than the Adit tube, and this is borne out in the data. A spatial
 156 map of the delay times for the Hamamatsu tube is plotted in Fig. 8(a) for
 157 $\alpha = 0.1$, and a histogram of the delay times is plotted in Fig. 8(b). The spatial

Figure 8: (a) Difference of transit time and mean transit time as a function of the position of optical stimulation for the Hamamatsu tube. Note that the color scale for this plot represents a very small range of transit times (only about 1 ns of variation), so the structure visible in the plot is mostly noise. In contrast, the variation for the Adit tube was several tens of nanoseconds, as seen in the level scales for Figs. 6 and 7. (b) Histogram of the transit time minus the mean transit time for the Hamamatsu tube.

map shows that the timing response is very spatially uniform with a few noise-level artifacts. There is a slightly longer delay time just at the edge of the PMT, but this effect is very minor compared to the Adit tube. The average delay $\langle \Delta t \rangle$ was 63.6 ns. The standard deviation for the distribution shown in the histogram is 0.2 ns, and the distribution has a FWHM of 0.4 ns. Thus, the Hamamatsu tube has a shorter transit time than the Adit, and minimal spread in transit times.

165 5. Conclusions

166 We have investigated the transit time variations for electrons produced by
167 photons originating at different locations on the photocathodes of two commer-
168 cial 5-inch PMTs: the Hamamatsu R1250 and the Adit B133D01. The Adit
169 tube exhibited significant spatial variations in transit time, while the Hama-
170 matsu was relatively uniform. The Hamamatsu tube, which is engineered for
171 excellent timing properties, performed much better than the Adit tube. The
172 distributions of transit times for the Hamamatsu tube varied with a FWHM
173 of only 0.4 ns. Within the minimum useful diameter, transit times in the Adit
174 tube varied by as much as 57 ns from one location to another. Furthermore the
175 double peaking of the Adit tube requires care when analyzing timing pulses,
176 especially when localized optical signals are detected on various portions of the
177 detector. It would be helpful for users if manufacturers provided this type of
178 timing analysis.

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