An LED pulser for measuring photomultiplier linearity

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Abstract

A light-emitting diode (LED) pulser for testing the low-rate response of a photomultiplier tube (PMT) to scintillator-like pulses has been designed, developed, and implemented. This pulser is intended to simulate 80 ns full width at half maximum photon pulses over the dynamic range of the PMT, in order to precisely determine PMT linearity. This particular design has the advantage that, unlike many LED test rigs, it does not require the use of multiple calibrated LEDs, making it insensitive to LED gain drifts. Instead, a finite-difference measurement is made using two LEDs which need not be calibrated with respect to one another. These measurements give a better than 1% mapping of the response function, allowing for the testing and development of particularly linear PMT bases.

Keywords: LED pulser; Photomultiplier response; Calibration

1. Introduction

An LED pulser has been designed to accurately map out the response of a PMT (in this case, an RCA 8575) to pulses with a full width at half maximum (FWHM) of 80 ns. For this application, the output pulse height of interest was up to about 2.5 V. The pulse range used was meant to simulate the response of a Ce-doped Gd\textsubscript{2}SiO\textsubscript{5} (GSO) crystal to photons ranging from 1 to 600 MeV, although pulses of different widths and heights may also be generated using this device. The particular application of interest, a Compton backscattering polarimeter read out by charge integration [1], required excellent and well-understood linearity in PMT response.

The response function of a PMT is defined as the signal output of the PMT given some light input. If the integrated response, \( f(x) \), to a light flash of integrated brightness \( x \) were perfectly linear, then the increase in response resulting from an additional simultaneous flash, \( \delta \), would be constant; i.e.

\[
y(x) \equiv f(x + \delta) - f(x),
\]

the finite difference function of the response, would be independent of \( x \). Saturation of the PMT response would manifest itself by a smaller increment in response due to the fixed signal \( \delta \) as it is added onto progressively larger signals \( x \) (i.e. \( y(x) \) would decrease with increasing \( x \)). Conversely, a PMT base design which over-compensates for saturation would give progressively larger responses to a fixed signal added onto progressively larger signals (i.e. \( y(x) \) would increase with increasing \( x \)). Any variation of \( y(x) \) as \( x \) is varied is thus a sensitive measure of non-linearity.

This measurement is achieved by flashing two LEDs, one of constant low brightness, called here the “delta” LED, which contributes a flash of integrated brightness \( \delta \), and another of variable brightness, called the “variable” LED, which contributes a flash of integrated brightness \( x \). A finite difference measurement is then made by flashing both LEDs concurrently, to measure \( f(x + \delta) \), and then subtracting \( f(x) \), found by flashing just the variable LED. Because this setup measures the response of a PMT to the difference between a changing LED and a constant one, it is insensitive to calibration between the LEDs (unlike, e.g., Ref. [2]). It is, however, critically important that the two LEDs be independent – there cannot be cross-talk between the LEDs. Also, one LED should have a low constant amplitude and the other must be varied over the dynamic range of interest.
2. Pulser Setup

Two LEDs are positioned within a light-tight PMT enclosure such that they shine diffusely on the PMT face by reflection.

The LED pulser runs with a timing sequence of: (1) both LEDs flash, (2) variable LED flashes, (3) delta LED flashes, (4) both LEDs off (shown in Fig. 1). The PMT signal is read out by an Analog to Digital Converter (ADC) at each step of the sequence. The sequence is repeated multiple times, then a new pulse amplitude, set by a computer controlled Digital to Analog Converter (DAC), is chosen for the variable LED. The variable LED setting is repeatedly cycled through the desired range of pulse amplitudes until the desired statistical accuracy for each pulse amplitude data point is obtained. The both-LEDs-off step can be used for pedestal monitoring. The delta-only step is used only as a cross-check and is not required. The both-LEDs-flash and variable-LED-flashes steps are the two used for the actual response-function measurement. Therefore, although four steps were used for this measurement, the sequence could be shortened.

For readout in this particular application, the PMT pulse shape was continuously sampled at 200 MHz by a Struck SIS3320 Flash ADC (FADC), and the clock times of the kHz LED trigger pulses were recorded in a CAEN V830 latching scaler. A 1000 ns sampling period was read out from the FADC memory for each clock time stored, including any portion of the pulse stored from before the trigger. The pulse was then integrated numerically.

3. Pulser Design

The LEDs used in this pulser setup are Nichia blue, 470 nm, NSPB500S LEDs, as recommended by Vičič et. al. These LEDs have the advantage that they will emit a smooth and fast scintillator-like pulse when one side is biased with a fast pulse. The positive leg of the LED is fed this fast TTL pulse from a specially designed LED drive circuit, described below, while the negative leg is given a variable DC voltage between 0 and +5 V (set under computer-control through a DAC implemented on a VME Timing Board), which determines the brightness of the resulting flash.

The LED pulser is based on the 74AC00 NAND gate. The fast and stable pulses used to achieve an 80 ns FWHM LED pulse take advantage of the high current Advanced CMOS Logic (AC) electronics, as recommended by O’Hagan et. al.

Controlling cross-talk requires the division of functionality into three separate circuits: two “driver-boards,” one to flash each of the two LEDs, and one “control-board,” which controls the driver-boards by sending enable bits and a signal which sets the pulse timing. As shown in Fig. 1, this control circuit, which is driven by an external clock, steps the enable bits through a binary sequence and sends a timing-pulse signal to both driver-boards after allowing a settle-time for the enable bits. The control board also produces a sync pulse at the beginning of each binary sequence, to synchronize the DAQ system.

The circuit diagrams for the control-board and driver-board are shown in Figs. 2 and 3. The AND gates shown are implemented as two 74AC00 NAND gates in succession. The one-shot used is a DM74LS221 monostable multivibrator with a Schmitt-trigger input. This can be used to delay the pulse sent to each of the driver-boards, each of which also has a one-shot with a timing width controlled by a variable resistor. This variable resistor allows the user to change the pulse width as needed.

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desired, but since it is important to ensure that
the flashes from both LEDs are of equal width,
the pulse widths for the two driver-boards need to
be matched. It is also important to ensure that
the pulses coming from the driver-boards are
synchronous, which is easily done by looking at the
PMT pulse signal relative to the 1 kHz clock on
an oscilloscope and aligning the responses to the
delta-only and variable-only pulses.

Each driver-board reshapes the timing pulse and,
if the enable bit is set, sends the TTL pulse to
the positive leg of the corresponding LED. The
DC voltage sent to the negative leg determines the
brightness of the flash in response to this pulse.

3.1. Cross-Talk

The major design issue for this pulser setup is
generating two uncorrelated LED signals, since any
cross-talk between the two LEDs destroys the fi-
tinite difference linearity measurement. Cross-talk
can be easily and precisely measured by driving
both LEDs to flash, but with one LED physically
removed from the light-tight PMT enclosure or ob-
scured by opaque tape. Two types of cross-talk are
then measured, as either a variation in the delta
LED signal as a function of the variable LED DAC
setting when the variable LED is obscured, or as a
depletion from zero in $f(x + \delta) - f(x)$ as a
function of $f(x)$ when the delta LED is obscured; the
former type of cross-talk was not as problematic as
the latter. A deviation of $0.02f(x)$ in $g(x)$ (from the
expected $g(x) = 0$ with the delta LED obscured)
over the full range of $f(x)$ was typical of problem-
atic cross-talk. The elimination of this cross-talk
effect is achieved through several important design
features.

One requirement for eliminating cross-talk is
putting the driver-board for each LED into a sep-
ate shielded box. Each box includes low-pass
filters to reduce noise transmission. It is critical
that each driver-board's behavior be independent
of whether the other LED fires. To ensure this,
the control-board sends the same timing pulse to
both driver-boards regardless of whether they are
enabled or not. It was found to be useful to add a
low pass filter to prevent noise returning along the
enable-bit line, which was telegraphing whether the
driver-board had fired its LED. The boxes are also
physically separated from the control-board, which
is in another shielded box.

The fast pulse to turn on the LED needs to be de-
layed until well after the enable bits have switched.
A settling time of 50 µs was used. The pulses are
also re-generated using a one-shot for each of the
two LEDs, so that variation in pulse width cannot
telegraph the enable bit of one LED to the other
LED.
Separate 5 V power supplies are also used for each of the two LED driving circuits, as well as for the main controller circuit.

The LEDs, which connect to each driving circuit via a DE-9 connector, must have cables leading to the PMT enclosure which are short and well shielded. Twinaxial cables were used in this application.

It was also determined that the two LEDs cannot be placed closer together than about 8 cm, or there is cross-talk, as previously seen [5]. Since this effect is seen even when the LEDs are optically isolated from one another, the cross-talk is apparently electro-magnetic. After eliminating all other forms of cross-talk, placing the two LEDs 6 cm apart, instead of 8 cm, contributed a clear deviation of $0.0013f(x)$ in $y(x)$, with the delta LED obscured.

4. PMT Response Function

Two typical PMT finite-difference response curves are shown in Figs. 4 and 5. In each plot, the vertical axis shows the difference between the total integrated signal from the PMT for a pulse with both LEDs flashed and the signal from a pulse with just the variable LED flashed, $f(x + \delta) - f(x)$ from Eq. (1). The horizontal axis shows the calculated light output from just the variable LED, $x$, as described below. This response curve is scaled by a single factor vertically and horizontally to give a maximum of ~1 on the horizontal axis, to simplify fitting of high-order polynomials. The error on each response measurement is taken as the RMS width of the observed distribution scaled down by the square root of the number of events for each value of $x$.

The curve in Fig. 4, corresponding to a PMT base design which has not been optimized for linearity, has a 16% variation, while Fig. 5 shows data taken on a PMT base which has been fine-tuned to minimize non-linearity, and has only a 1% variation in finite difference over the range of interest. The response function extracted from Fig. 5 plotted against an ideal response is nearly indistinguishable from a 45-degree line.

To extract a response function, the PMT response curve $f(x + \delta) - f(x)$ must be fit. The PMT response for an input of size $x$, $f(x)$, is approximated by an $n^{th}$ order polynomial, $F_n(x)$, with $n$ chosen arbitrarily to give an adequate parametrization of the data. For fitting, the initial values of $x$ are approximated as $x \approx f(x)$ and the initial value of $\delta$ is approximated as $\delta \approx y(x=0)$, an initial
$F_n(x)$ is extracted from the fit to $y(x)$, and then the values of $x$ and $\delta$ are recalculated (numerically for large values of $n$) by inverting $F_n$. The process is iterated until the values of $x$ and $\delta$ converge. The first order coefficient of $F_n(x)$ must be picked arbitrarily and, in this case, was set to unity in order to equate the units of $x$ and $f(x)$; the zeroth order coefficient was set to zero.

Given the small residuals of the fit, which has a $\chi^2$ per degree of freedom of $\sim 1$, this setup yields a better than 1% measurement of the PMT response.

5. Conclusion

An LED pulser has been designed to precisely determine the linearity of PMTs using a finite-difference measurement. The main design issue of LED cross-talk can be eliminated with the careful design of the LED drive circuit.

Acknowledgments

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