Technote: Characterization of the LED Flasher Calibration System for the μBooNE PMT Array

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August, 2014

1 Introduction

Operating an optical system with high timing and charge resolution requires careful calibration. In the case of MicroBooNE, the detector volume is sealed, and calibrations must be performed with a pre-installed optical fiber flasher system. The structure and installation of this system is described in great detail in [1]. In brief, the system consists of a bundle of optical fibers, each of which faces an individual PMT on one end, and is fed through the cryostat to an LED pulser array on the other.

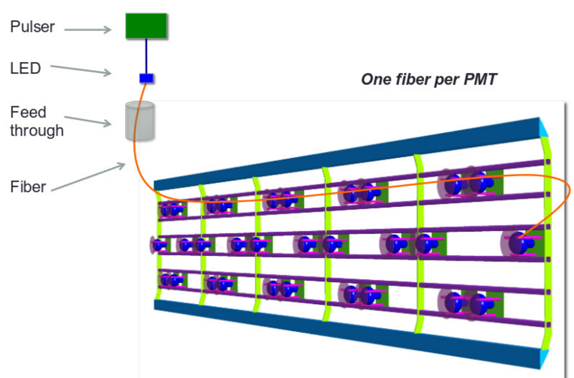

Figure 1: A diagram of the flasher system [1].

Here I present the results of the LED array/LED driver characterization and measured timing parameters. The first section will address the practice of using the flasher, and the subsequent sections will discuss these measurements.

1.1 Circuit Description

The fiber bundle is formed into a square array just outside of the feedthrough. This array is mated to an array of 36 LEDs mounted on the LED flasher board.

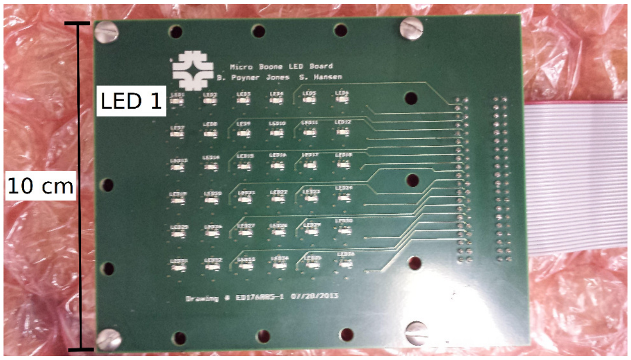

Figure 2: The LED Array Board

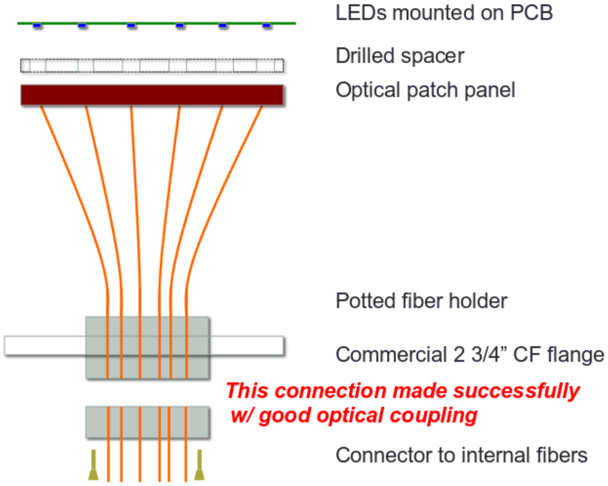

Figure 3: A diagram of the flasher feedthrough: [1]

The LED board is controlled by a driver board using a pulse generator and a serial console. This system is described in detail below.

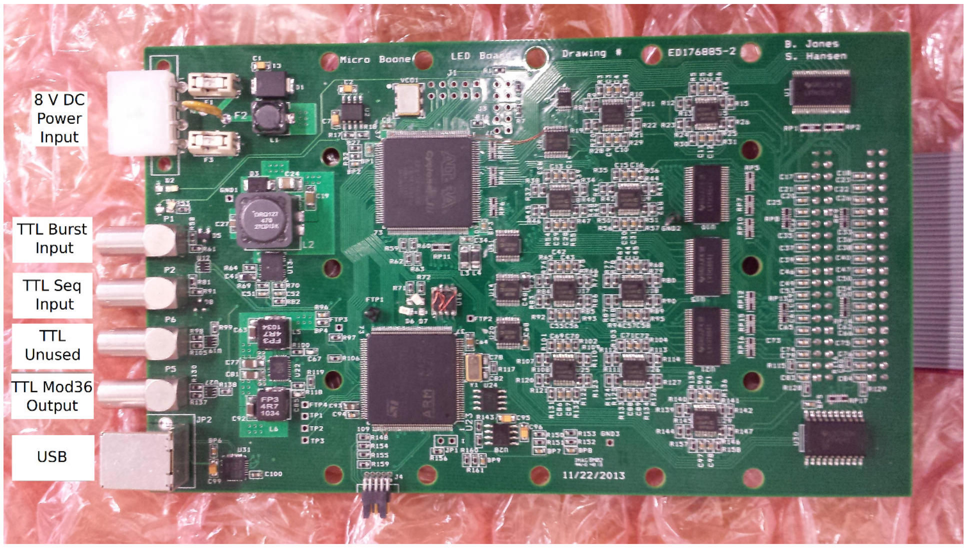

Figure 4: LED Driver Board

The LED driver board receives configuration information over USB, and trigger pulses through a LEMO connector.

When a trigger pulse is received, one or more LEDs receive a TTL signal riding on a DC offset voltage over the ribbon cables from the driver board.

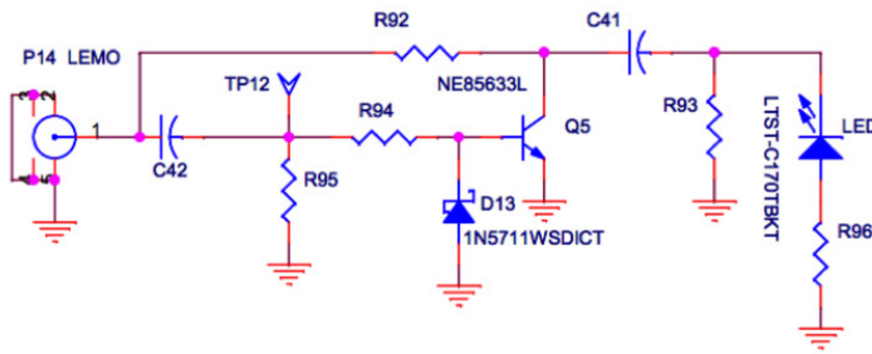

Figure 5: Flasher circuitry for a single LED [2].

The DC offset charges the capacitor (C41) coupled to the LED. A TTL pulse is split off of the DC charging voltage by C42, causing transistor Q5 to conduct, draining C41 charge to ground, driving current through LED5, and causing LED5 to emit a short pulse of light.

This system has the advantage that the transient (trigger) pulse height does not have to be carefully controlled. The only parameters relevant to light output are TTL pulse timing and bias voltage.

The circuit is well conceptualized as a simple RC circuit during charging and discharging cycles. If the trigger pulses are sufficiently spaced, there is virtually no dependence of light output on pulse frequency. However, if pulsed too fast, the triggers will cut significantly into the charging cycle of the capacitor, thereby decreasing light output.

On the other end of the ribbon cables are Digital to Analog Converter (DAC) chips and TTL drivers. The DACs set DC offset, while the TTL drivers provide trigger pulses. Both are controlled by an FPGA. The FPGA is controlled by a microcontroller, which loads configuration files from flash memory and writes them to the FPGA. The microcontroller can communicate with a computer using a serial protocol over USB. The computer can be used to alter configurations and set DAC values. DAC values can be set and saved to a configuration file that will be loaded on boot, in order to perform quick calibrations with amplitudes already dialed in.

The led pulses (whether in sequence or burst mode) are triggered by a user supplied TTL pulse through LEMO P1 (TTL Burst in Fig. 4), or LEMO P2 (TTL Seq in Fig.4). If a pulse is supplied to LEMO P1, the LEDs will all fire simultaneously (burst mode). LEMO P2, by contrast, is not operated by a single pulse, but rather a pulse train. Each pulse in such a train will trigger a successive LED on the flasher board. After 36 pulses, the sequence resets and LED1 will again be triggered. In this way, it is possible to scan rapidly through all channels and examine each PMT individually. It should be noted that LEDs have exponential I-V curves, so small variations in DAC output may cause large variations in LED output. As a result, it will not generally be true that LED A set to DAC voltage X will produce the same output amplitude as LED B set to the same voltage. These voltages can, however, be set individually over a serial interface.

1.2 Serial Interface

The serial communication between control computer and microcontroller occurs over USB with the aid of a serial console (hyperterm, putty, screen, etc.). On a linux machine, the board should register as a ttyACM or ttyUSB device (/dev/ttyACMX or /dev/ttyUSBX where X is 0,1,2,..). The serial console must be operated at 115200 baud. All commands to the board are sent after a carriage return. Backspacing is not supported. To bring up a help menu, enter HE. There is a whole slew of commands listed, but the most important are FF, RD, RDI, and WR.

FF reloads the flash configuration to the FPGA. Ideally, this command isn't necessary, but firmware bugs currently require us to reload configuration on boot up.

RD [address] returns the hex value at output register [address]. There are 36 registers relevant to calibration, each of which holds the DAC value for an LED. These registers are numbered 0x10 through 0x33. These values are all in hexadecimal! Each register stores a value between 0x000 and 0xFFF, (4096 DAC values). This range maps to a voltage range between 0 and ~16 volts.

RDI [address] returns the value at the address in question, as well as a number following. Use this to read large numbers of registers at a time.

WR [address] [value] writes value 0x[value] to register 0x[address]

2 Measurements

The purpose of this work, other than familiarization with the boards and interfaces, was to measure two unknown timing parameters.

The first parameter is the delay between the arrival of the TTL signal at the board (rising edge, in sequence mode) and the rising edge of the signal at a PMT observing the whole array. This parameter is measured for each LED in the sequence, and the variance in this value is calculated and discussed.

The second parameter(s) is(are) the maximum and minimum delays between pulses in the sequential pulse train that will properly trigger the LED board. There is a timeout after which successive members of the pulse train will start a new sequence instead of advancing to the next LED, providing an upper bound for the pulse train delay. On the other hand, if the pulses are too close together, they might not be properly interpreted as individual pulses, causing a failure at very low delay times. We wish to determine these two breaking points to avoid trouble during calibrations.

The first question was addressed by aiming a PMT at the face of the flasher board in a dark box, setting all DACs to zero, and individually upping the DAC voltage in the presence of a trigger pulse (sequence mode) for each LED in the array.

The second question was addressed (again in sequential pulser mode) by constraining one PMT to observe light from LED 1 only, and aiming another PMT at the remaining 35 LEDs. By turning up DAC voltages one by one, it can be verified that each LED is delayed by the expected number of pulses from the LED 1 pulse. Playing with pulse frequency then allows us to search for sequence failure.

3 Setup

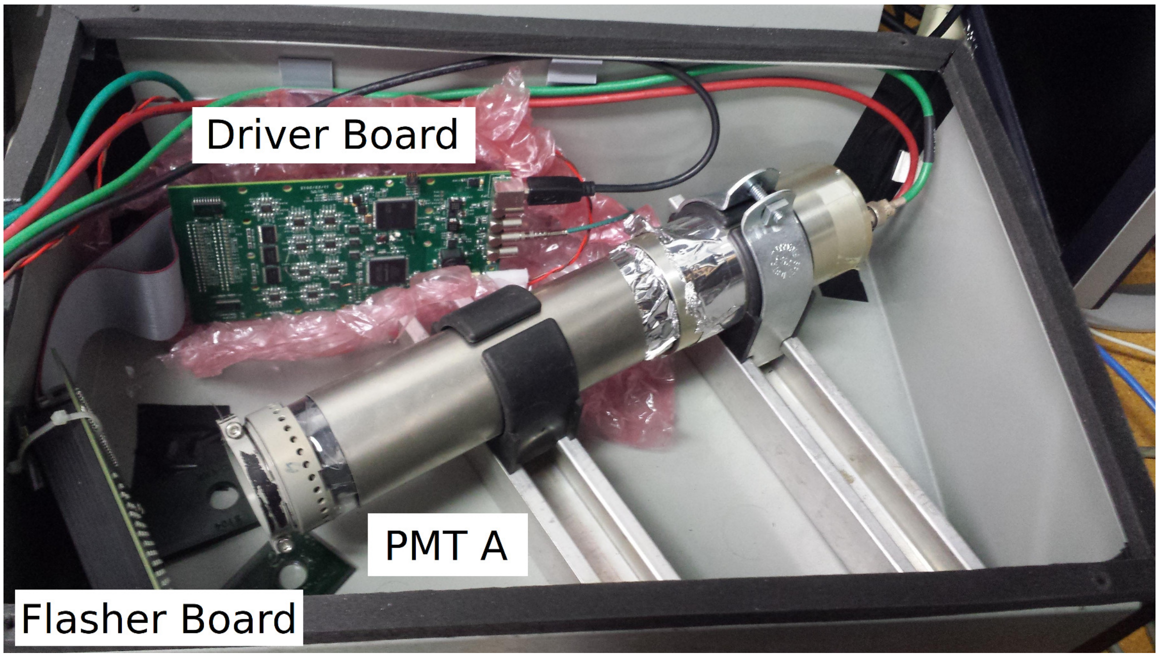

Figure 6: Test setup for LED timing measurements.

All tests were performed in a makeshift dark box, really a glorified conduit box with a foam rubber lip and sealed edges.

Two PMTs were used in the testing. One (PMT A) was kindly lent to us by NMSU, and is a shielded 2“ PMT of unknown make or model. The other PMT (PMT B) is a 2“ cryogenic PMT (Hamamatsu R7725 MOD).

A pulse generator (HP 8082A) provided trigger pulses to the driver board, which sat in the dark box next to the flasher board. NOTE: driver board power and status LEDs were disabled before testing. Dont burn your PMT!

Two HV Power supplies provided bias voltages to the PMTs.

PMT A received 1600 volts from a PDP HV-1547

PMT B received 1900 volts from a Fluke 415B A NIM bin was set up to perform counting measurements which will be discussed in detail later. Finally, an oscilloscope (Tektronix TDS5054B-NV) recorded pulser output and PMT signals.

4 LED Timings

The execution of the first test was simple. With PMT A aligned as shown in the section above, a pulse train of indefinite length was sent to the driver board, and each LED DAC was individually brought high. The DAC value was briefly tuned to bring each LED amplitude close to 80 mV. Although no SPE calibration was conducted, the SPE amplitude was estimated (by eye) at 5-10mV. This estimate puts these tests roughly in the 8-16 photoelectron region. The oscilloscope was then configured to measure and histogram the difference in arrival times of the leading pulser edge and the leading PMT edge. These times were defined as the crossing times for 50% full amplitude as defined by the oscilloscope for both the pulser and the PMT signal.

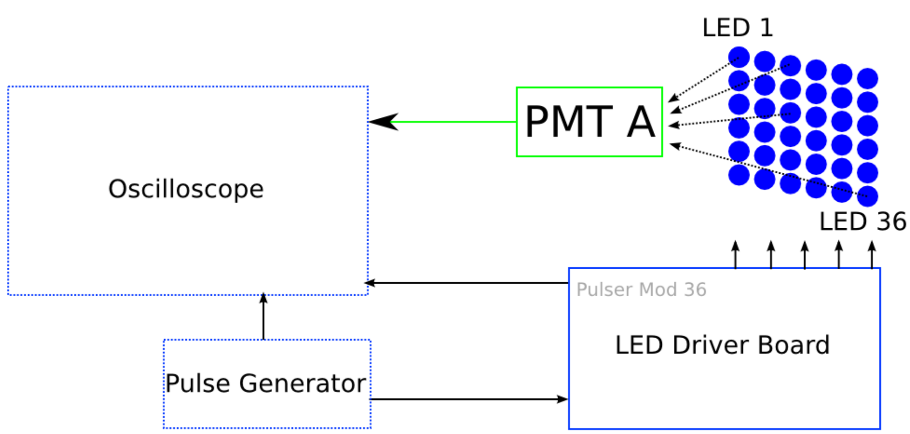

Figure 7: A block diagram of the timing test setup.

μ, σ, and the number of events were recorded for each LED. In each case, between 1000 and 2000 events were recorded.

Additionally, the delays due to differing cable lengths (pulser to board, pulser to oscilloscope, PMT to oscilloscope) were measured and recorded using the same oscilloscope method as above.

After correction for cable delays, the average delay (weighted by the standard error of each delay measurement) ($\langle \mu \rangle$) between trigger pulse arrival and PMT signal output was found to be $125.65 \pm 0.11nS$. The unweighted mean delay is $125.48 \pm 0.11nS$

It is important to remember that the delays measured here incorporate both LED/Driver board related delays and the signal transit time of the PMT.

The maximum σ recorded was $9.75nS$, which, assuming a minimum of samples (1000), gives us a maximum uncertainty on μ of $\sigma/\sqrt{n} = 0.31nS$. The measured standard deviation of delay among LEDs of $0.68nS$ is significantly larger than the statistical uncertainty associated with the mean delay of any individual LED. The mean delay times are plotted below as a function of LED number.

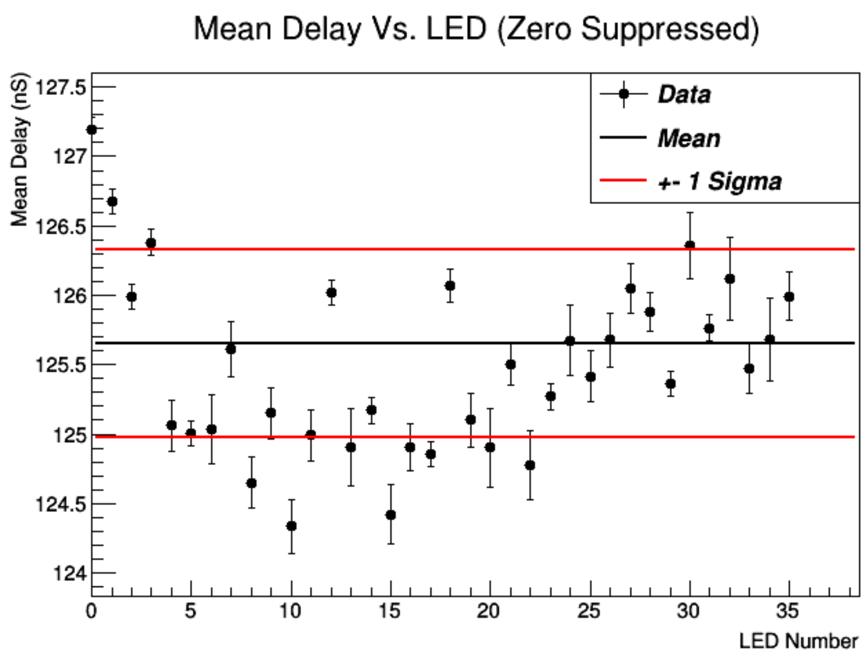

Figure 8: Means of timing measurements by LED. In black is the mean of the data points, weighted by uncertainty in these points. In red is $\pm$ 1 standard deviation of the data points around the mean, weighted in the same way.

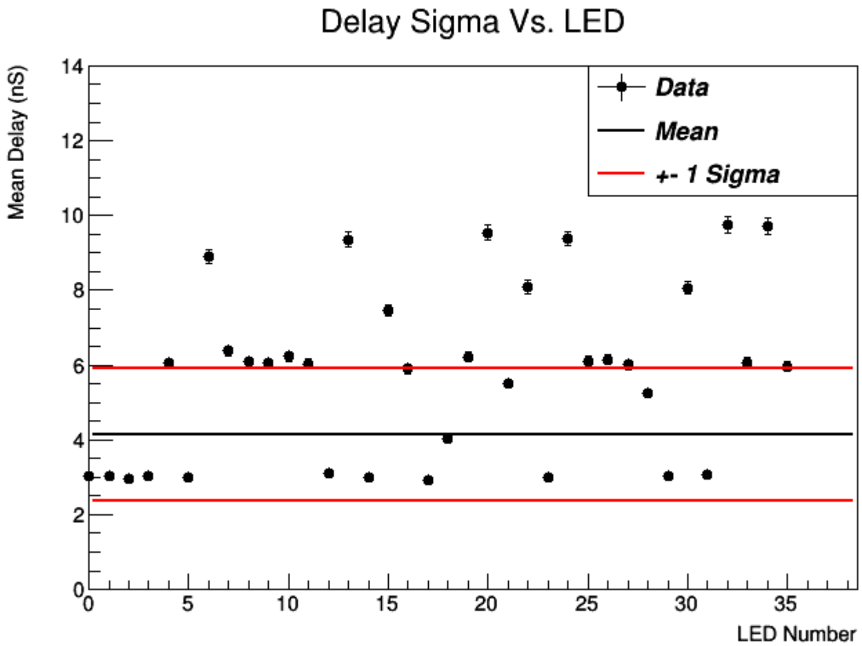

Figure 9: Standard deviations of timing measurements by LED. In black is the mean of the data points, weighted by uncertainty in these points. In red is ± 1 standard deviation of the data points around the mean, weighted in the same way.

The measured mean sigma was $4.15 \pm 0.30nS$ weighted by the errors shown in the plot. The unweighted value was $5.76 \pm 0.38nS$

As the LED array was situated quite close to the PMT (4.6cm on PMT axis), there was a large angular variation in LED-PMT paths. To determine whether there was any obvious correlation between array location and delay mean or delay spread, these values were plotted in a grid corresponding to the physical layout of the LEDs.

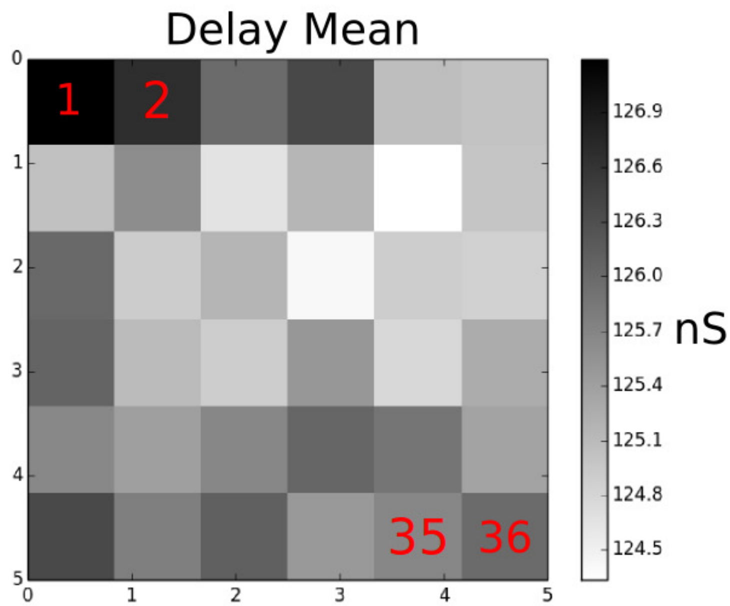

Figure 10: Mean delay for each LED

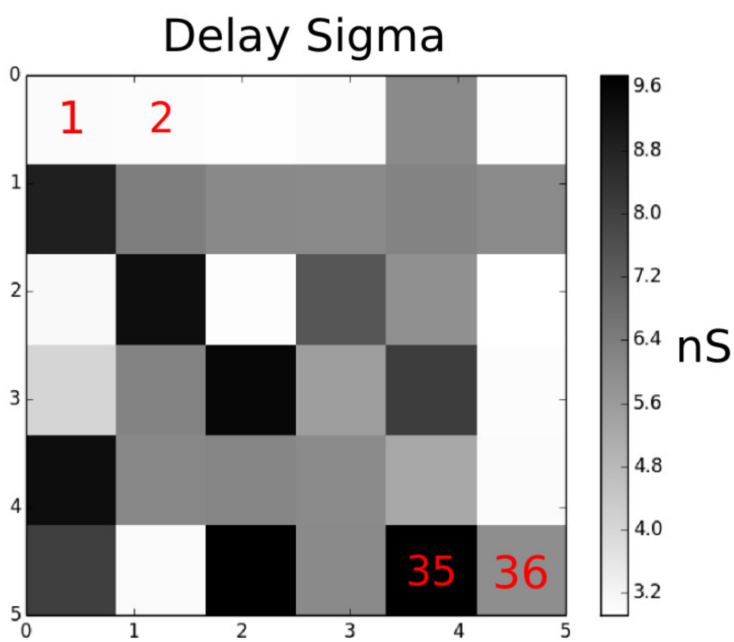

Figure 11: Sigma delay for each LED

If there were a reliance of timing behavior on angular distribution, we would expect the center of the array to behave differently than the edges. There is no such pattern apparent in either plot.

5 Pulse Sequence and Extremal Frequencies

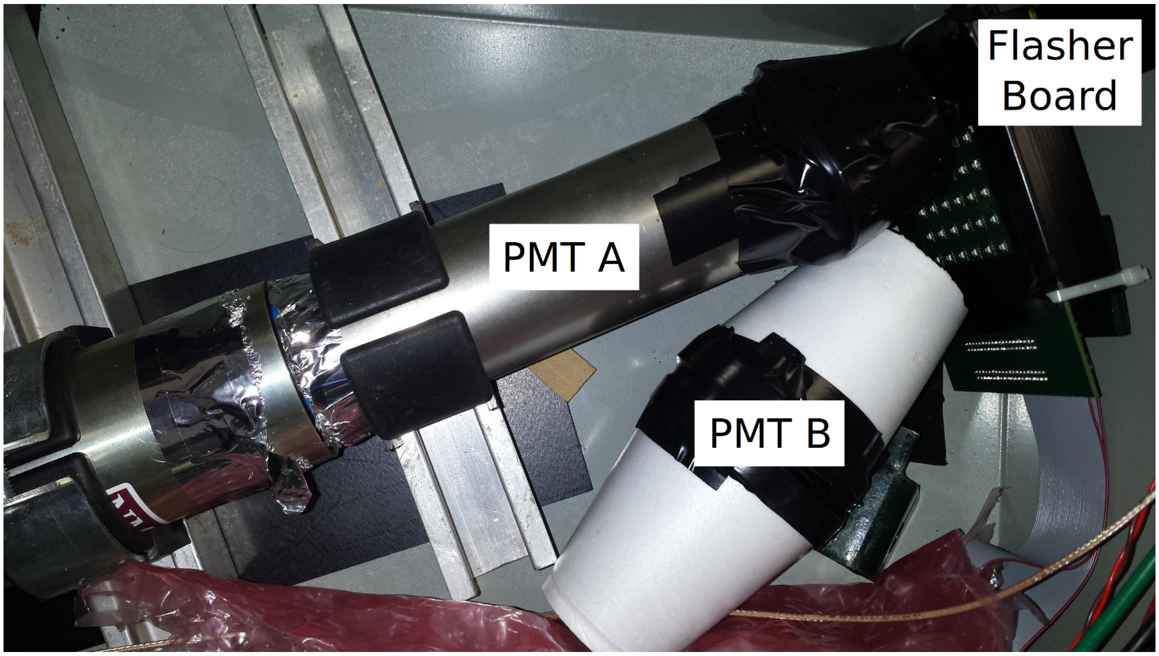

Figure 12: Test setup for pulse sequence measurements.

The second test required the addition of a second PMT and the constraint of the first PMT to LED 1. This was achieved with a black vinyl mask attached to the LED board, an opaque cover attached to PMT A, and an opaque tube connecting the hole in the mask in front of LED 1 to the hole in the PMT A cover. the rest of the board was left uncovered, and PMT B was aligned to observe LEDs 2 through 36.

As before, an indefinite pulse train was sent to sequence input, and all DACs were zeroed except for LED 1 and one other LED. By overlaying pulser input and PMT output on the oscilloscope, the temporal position of the LED illuminating PMT B could be determined relative to the PMT A/LED 1 trigger.

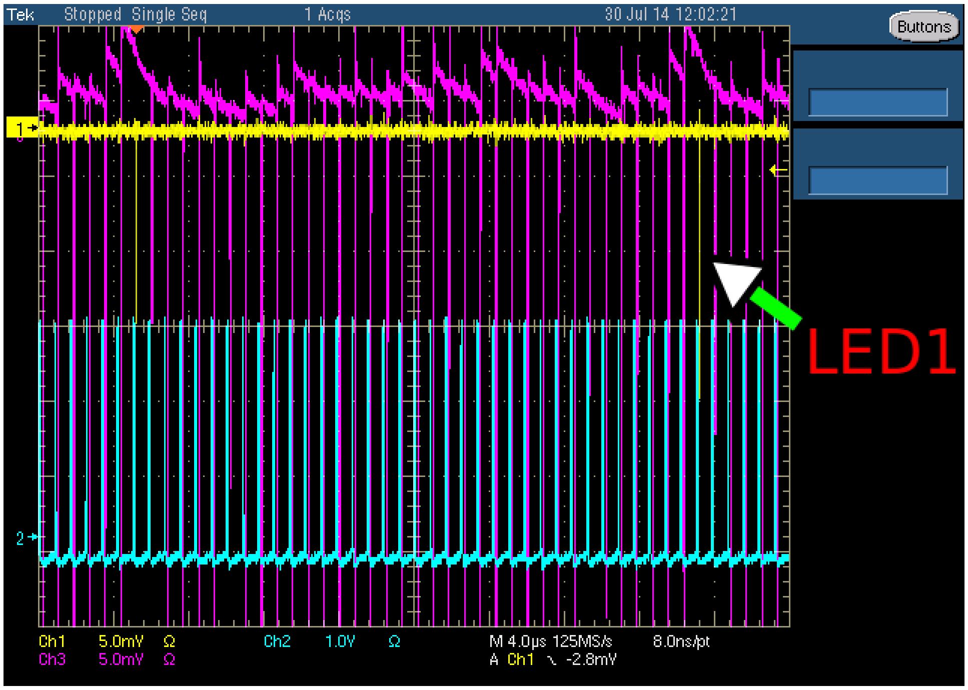

Figure 13: PMT A (yellow) signals when LED 1 triggers. PMT B (purple) signals when it sees light from the other 35 LEDs in sequence.

Initially, the first four LEDs were arriving out of order, with LEDs 4, 3, and 2 flashing before LED 1. The board was taken to Sten Hansen, who discovered a mismatch in the pin-sequence mapping in the FPGA configuration. Correcting the configuration file produced the correct sequence of LEDs firing in the dark box setup.

A NIM bin was then set up to record firing efficiencies at different pulse frequencies:

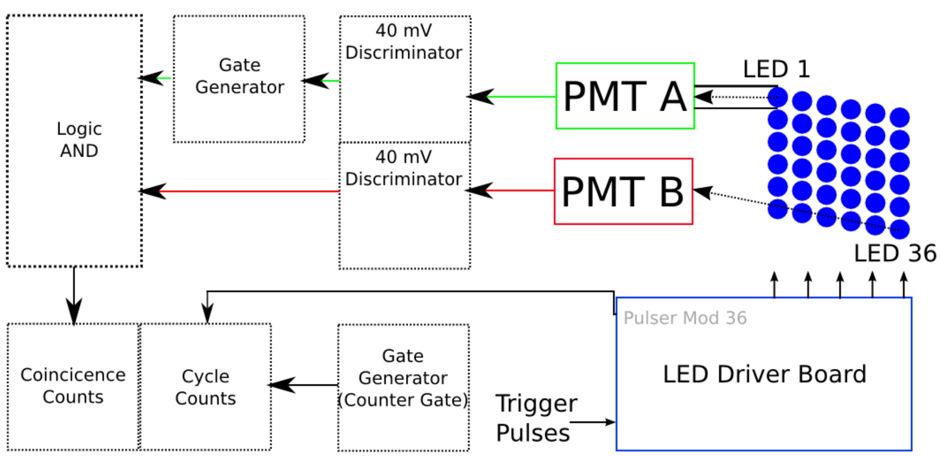

Figure 14: The two PMTs. The top PMT (PMT A) is masked to LED1 with black vinyl.

Pulses from PMT A and PMT B are sent to 40mV discriminators. LED amplitudes are tuned to produce roughly 150mV pulses on each PMT. Given the SPE amplitude estimate mentioned in the previous section, this puts these pulses in the 15-30 pe region. The PMT A logic signal then opens a gate that lasts for 35 trigger pulses. This gate is fed to a logic unit along with the PMT B discriminator signal. If a PMT B signal arrives within one pulse sequence (36 pulses) of the PMT A signal, then a coincidence signal is produced and fed to a scaler. Simultaneously, the mod-36 pulse counter output from the board is fed to a TTL-NIM translator, and then to the scaler. A gate generator tuned for 1.0 or 10.2 seconds then opens a counting gate in which cycles and coincidences are counted simultaneously. The ratio of coincidence triggers to cycle counts is treated as an efficiency. Dark coincidence rates and optical/electrical cross talk rates were measured and determined to have made a negligible contribution to these efficiency measurements.

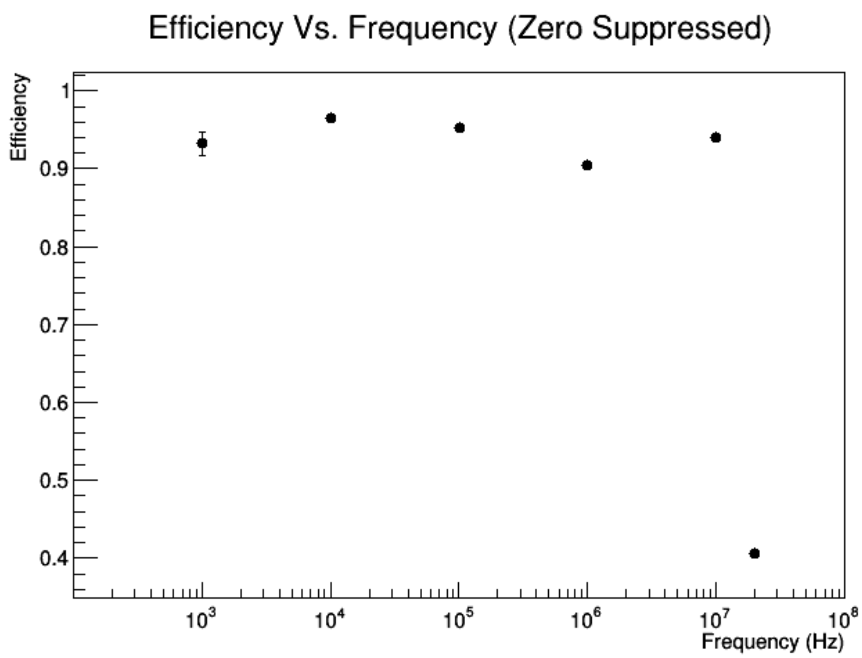

Figure 15: Sequence efficiency as a function of pulse frequency.

Apparently, the behavior of the flasher system in sequential mode is quite stable between 1kHz and 10MHz. The small inefficiencies in this region have not been entirely explained, although we expect the discriminator thresholds to introduce percent level inefficiencies due to variance in PMT pulse height (see Appendix 7.1). The pulse generator was unable to provide frequencies lower than 1kHz, but manually pulsing the sequential trigger input revealed that the expected timeout (after which the sequence resets to fire LED 1) is very large: between 10 and 15 seconds. Above 10MHz, the sequence begins to fail drastically, dropping the percentage of sucessful sequences from some 95% to below 50%. Visual inspection of pulse sequences in this region reveals excessive glitching: timing hiccups that cause pulses to be missed and gates to misalign.

Additionally, very high trigger frequencies prevent the LED driving capacitor from recharging fully, and LED intensity drops rapidly with increasing frequency past about 1MHz. The dependence of amplitude on frequency was measured with PMT B at a DAC value of 345. The results follow:

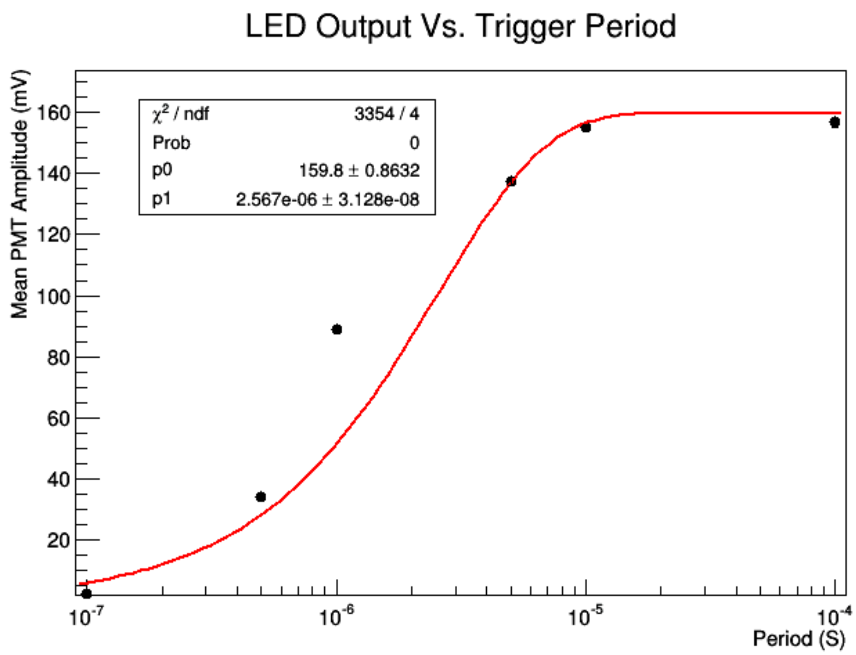

Figure 16: LED amplitude as a function of pulse period.

The function in red is of the form $p_0(1-exp(-\frac{x}{p_1}))$. It describes the voltage as a function of time in an RC circuit during charging. If the trigger cuts into this charging time, then we would expect the effect of trigger period on LED intensity to be well described by this function. The terrifying χ^2 comes primarily from the 1 microsecond point with a curiously large amplitude. The other points fit quite well, however, and give us a sense of stable operating frequencies. Bear in mind, however, that these values represent the behavior of only one LED at one amplitude.

If high frequency operation is desired, the LED amplitudes will have to be adjusted whenever frequency changes. Luckily, these amplitude configurations can be saved and loaded to the flasher board at will.

There was serious instability in LED amplitude over time observed past 10 MHz, but it was seen only in one LED (out of two observed in this range). The instability was not quantified, but this is all to say that fluctuations in pulse height at high trigger frequencies are something to keep an eye out for.

6 Conclusion

The flasher system has been successfully tested in a dark box, and should be ready for installation and in situ testing. Its sequential pulse mode has been tested and verified from 1kHz to 10MHz. Slight inefficienies at these frequencies have been observed, and warrant further study. The burst mode has not been checked at high frequencies, but it is likely to have a lower frequency operating region (each LED pulses 36 times faster in this mode than in sequential pulse mode). The delay between pulse arrival and PMT output has been measured to good precision for each LED. Finally, decreasing LED output amplitude as a result of excessive triggering frequency was observed and measured. The effect is tolerable below 200kHz. Higher frequencies can be used if LED intensities are recalibrated, although it is not entirely clear how stable output will be at extremely high frequencies ($> 1MHz$).

7 Appendix

7.1 Data from Frequency Measurements

Each efficiency value is calculated as $e = k/N$ where k is the number of coincidence counts, and N is the total number of LED board cycles executed.

The error on the efficiency σ_e is calculated as $\sigma_e = \sqrt{\frac{e(1-e)}{N}}$

$50nS$

	DAC	Mean (mV)	Sigma (mV)	Samples
PMT A	42E	148.3	20.0	1049
PMT B	3B0	154.3	56.0	1049

Coincidence	461555
Cycles	1138134
Dark	0

PMT B voltage is unstable.

Added a 64nS delay line from PMT out to scope to allow for gating.

1.0 S count time.

$100nS$

	DAC	Mean (mV)	Sigma (mV)	Samples
PMT A	3D8	148.0	35.5	1146
PMT B	37B	152.5	28.0	1146

Coincidence	267218
Cycles	284072
Dark	0

PMT B voltage is unstable.

Added a 32nS delay line from PMT out to scope to allow for gating.

1.0 S count time.

$1\mu S$

	DAC	Mean (mV)	Sigma (mV)	Samples
PMT A	3A4	149.7	35.0	1041
PMT B	349	149.1	43.1	1136

Coincidence	251275
Cycles	277746
Dark	1

10.2 S count time.

$10\mu S$

	DAC	Mean (mV)	Sigma (mV)	Samples
PMT A	3A0	154.0	36.4	1096
PMT B	343	145.2	44.0	1083

Coincidence	26596
Cycles	27914
Dark	12

PMT B led was accidentally left on during the dark count.

10.2 S count time.

$100\mu S$

	DAC	Mean (mV)	Sigma (mV)	Samples
PMT A	3A2	159.4	38.0	1023
PMT B	346	160.4	42.0	1040

Coincidence	2682
Cycles	2782
Dark	1

10.2 S count time.

$1mS$

	DAC	Mean (mV)	Sigma (mV)	Samples
PMT A	3A2	144.7	36.1	1031
PMT B	345	151.0	43.7	1023

Coincidence	261
Cycles	280
Dark	0

10.2 S count time.

References

[1] B. Jones, *PMT and Flasher System Status*, MicroBooNE Doc-DB 3026.

[2] B. Jones, T. Strauss, *Proposal to Install a PMT Flasher System in MicroBooNE*, MicroBooNE Doc-DB 2672.