# Studies of Silicon Photomultiplier Detector Performance

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As part of prototype testing for the Mu2e cosmic ray veto shield, the impact of silicon photomultiplier (SiPM) performance is studied over a range of experimental conditions. SiPMs are exposed to blue LED light pulses to determine response linearity as a function of exposed light intensity. The motivation behind this study is addressed, along with the formalism and methods behind the experimental setup. Detection performance between SiPMs with and without an attached scintillator is compared, and the results are discussed. Other phenomena, including the contribution of double peaks to readout resolution, are simulated using a controlled, generated light pulse. A study characterizing the optimal operating bias voltage is also discussed. The results of these studies are addressed, along with a discussion of planned future experiments. A description of the lab setup and a brief introduction to silicon photomultiplier technology are also discussed.

## I. Introduction and Background

One of the central goals of the Mu2e experiment is to observe charged lepton conversion, which has been rarely observed in an experimental setting. The successful observation of such a process will grant greater understanding of aspects of particle physics, including the relationship between muons and electrons, the validity of many modern unification theories, and will also help to evolve the current Standard Model.

One challenge in observing muon conversion is distinguishing such ultra rare events from background noise. A main contributor of noise is cosmic radiation originating from proton interactions in the Earth's atmosphere. Keeping outside interactions infrequent and well regulated is vital to the success of the Mu2e experiment. This is the role of the Cosmic Ray Veto, a precisely engineered system of scintillators that will function as a shield against these atmospheric particles. This will house a portion of the beam line responsible for detecting and measuring particle momentum and energy. The veto shield will consist of three layers of aluminum absorbers between four layers of plastic scintillators, placed offset to prevent micro gaps.

CRV fabrication efforts at UVa focus on the components of these scintillators, including the fiber optic cables that run through them, and the SiPM detectors that attach to them to collect light transmission data.

## II. Methods

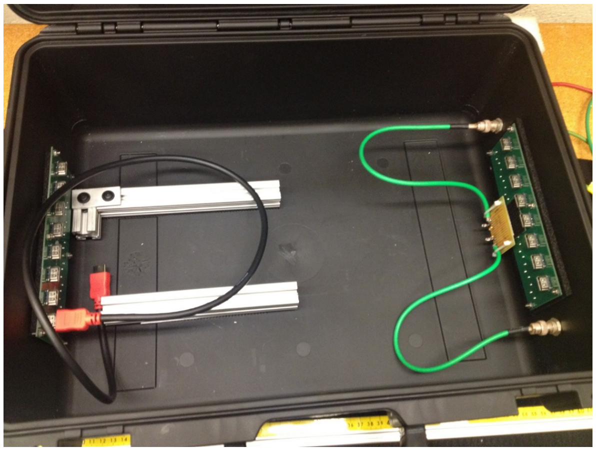


Figure 1: Light-tight box containing LED

Figure 2: Dicounter with fiber optic cables

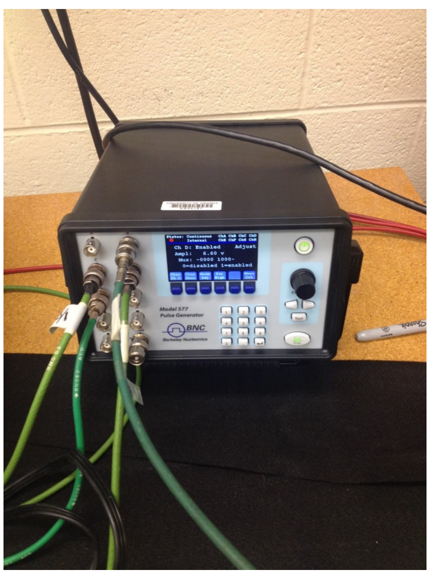


Figure 3: Pulse Generator

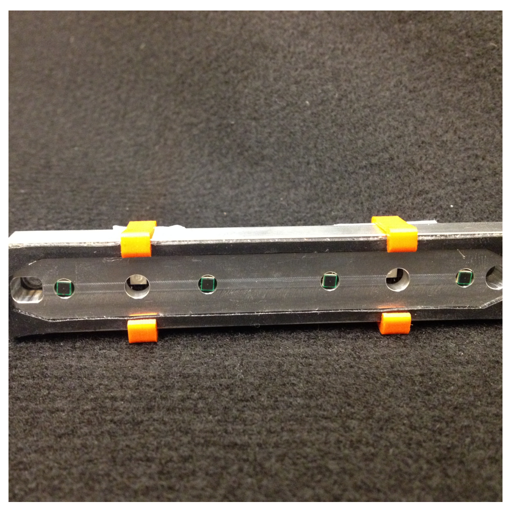
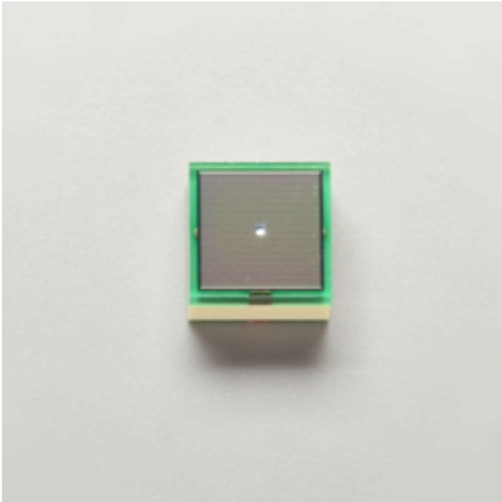


Figure 4: Counter motherboard and four SiPMs, with clamps



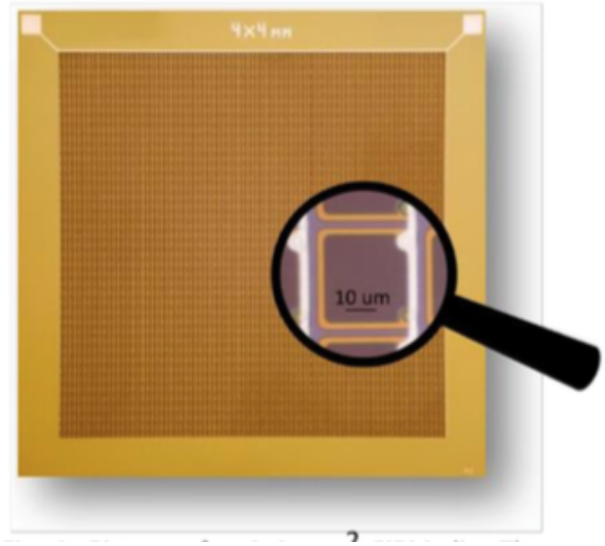



Figure 5: Hamamatsu SiPM [1] at left and
demonstration of a close-up of a micro-pixel array at right [5]

i. Experimental Setup

1. Light-tight box

The light-tight box (shown in figure 1) is where the majority of the SiPM tests are conducted. It serves to block out ambient light and thus reduce dark noise during testing. The light-tight box is fitted with an electrical breadboard, which powers two blue light LEDs, as well as an 80-20 guide bar, which was designed to guide the test dicounter into place. This insures that a standard distance between source and detector is maintained throughout the testing process. The breadboard is affixed to the box using velcro, thus allowing for an adjustable source height.

2. Pulse Generator

The LED cables in the light-tight box are attached to an HDMI output cable, which feeds to the pulse generator (Fig. 3). The pulse generator is implemented in place of the previously used high voltage power supply gate and voltage divider as it can be adjusted to provide a higher frequency of pulses, therefore greatly reducing the time needed to conduct an experimental run. It functions similarly to the high voltage power supply, sending a trigger signal to the Front End Board electronics and triggering a data package to be sent to the computer for analysis. The pulse generator used in this experimental setup is a Berkeley Nucleonics Model 577, and has an output voltage range of 5 to 20V, with an average of 12-15V being suitable for the blue light LEDs used. Using higher voltages for prolonged periods of time have been known to overpower the LEDs, causing permanent damage.

3. Dicounter

'Dicounters' are a technical term used to describe the major component used in the Cosmic Ray Veto Shield. Pictured in Fig. 2, they are composed of two polystyrene scintillators glued together. Two optical fibers are threaded lengthwise through each scintillator, giving a total of four fibers in each dicounter. A completed dicounter includes a fiber guide bar (not pictured), which is situated at the end of the dicounter; the fiber cables are fed through this bar and then cut and polished to create a smooth surface for light transmission. This acts as light transmission interface to the SiPMs.

4. Counter Motherboard (CMB) and SiPMs

The metal manifold casing pictured in Fig. 4 houses the CMB and four 2 x 2 $mm^2$ Hamamatsu silicon photomultiplier detectors (SiPMs). SiPMs are photon counting devices, and are comprised of single-photon avalanche diodes [4]. Fig. 5 shows a macroscopic image of the array, which is composed of 1560 light-detecting pixels. These pixels produce a data signal proportional to a light event from the scintillator, and this data is sent to the Front End Board (FEB) for further analysis.

ii. Software

SiPMs operate at a base bias voltage, which can be adjusted through a GUI program on the designated CRV Test Stand computer desktop, located in the lab. In addition to communicating settings information to the counter motherboard, the software's other main function is to collect trigger event data from the FEB and translate that to graphical information. The FEB serves as a analogue-to-digital converter (ADC) for raw trigger signals coming from the SiPMs, and this ADC data is then sent to the computer. Thus, photon count data is interpreted to be proportional to the reported ADC value.

III. Studies and Analysis

i. Saturation Effects in SiPMs

A known performance issue with pixel arrays is the saturation of signal at high light intensities. Because the number of pixels on each SiPM is finite, there exists a light intensity level at which point pixel performance degrades, as pixels hit by two photons simultaneously cannot fire twice; this is known as the dynamic range [2]. This has implications for the Cosmic Ray Veto Shield, as the detectors might be overwhelmed with high intensity scintillation events during the course of the experiment. Thus, it is important to simulate these conditions in prototype dicounter models.

The effects of saturation were mimicked in the lab by exposing one side of a fully assembled dicounter (scintillator with CMB manifold attached) to incrementally increasing amounts of blue LED light intensity, over a range of 5.7 to 6.7 V, in .1 V increments. Three different data runs were taken; first, one LED was turned on while the

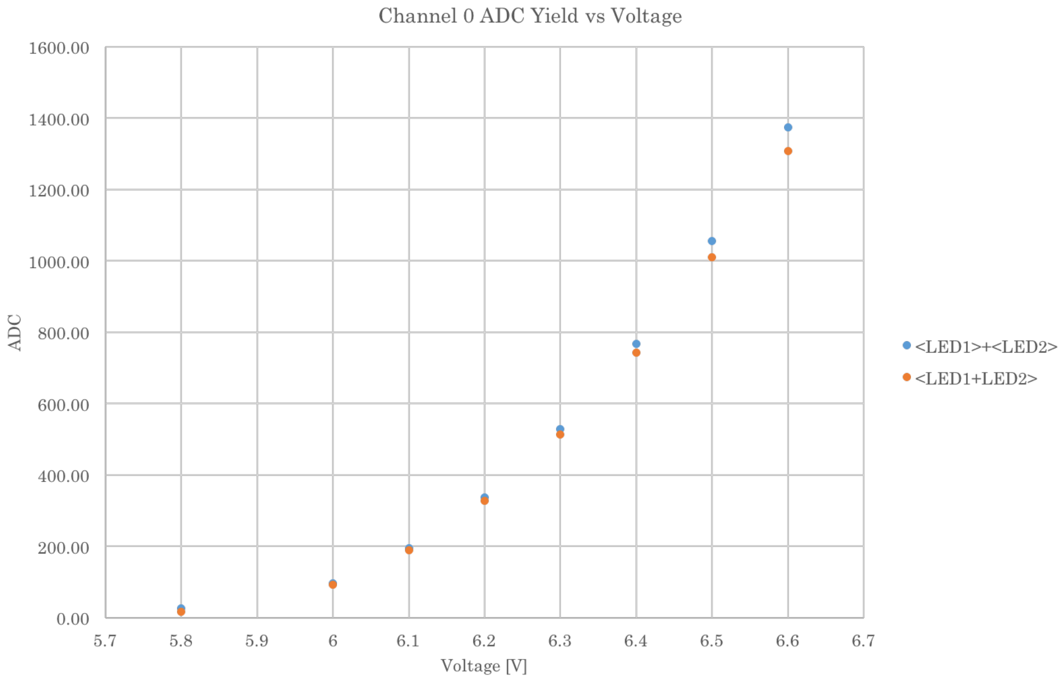



Figure 6: Voltage vs ADC value for SiPM

other was kept off, and the voltage was increased in the manner previously described. Then, the other LED was turned on and the first was shut off, and the steps were repeated. Finally, both LEDs were run at the same time, and the voltage to each was halved so that the total voltage being supplied to both LEDs at once summed to the appropriate voltage range. The ADC value of <LED1+LED2> and <LED1> +<LED2> was compared graphically (Fig. 6).

In theory, the SiPM photon count resulting from exposure to each LED separately should equal the photon count resulting from exposure to both LEDs simultaneously. In other words, ADC values (proportional to incident photon count) should sum linearly. However, Fig. 6 shows a clear saturation effect at higher voltage points (6.3 volts and above), where the two sums deviate.

ii. The Effect of the Scintillator on SiPM Saturation

There are other possible reasons for decreased detector efficiency at high light intensities; the area of the optical fiber might not fully align with the area of the SiPM, thus causing detection discrepancies that are magnified at high incident photon rates. Another reason is that the optical fiber might have preferred angles at which to emit light, meaning that the discrepancy issue is the result of the scintillator rather than the SiPM itself.

In order to determine these effects, runs are taken with and without the CMB attached to a scintillator; in one trial, bare SiPM channels (like the configuration in Fig. 4) are exposed to LED light, and in another, the CMB is attached to a scintillator in the usual setup and the process is repeated.

Using a known relation (Fig. 7) between the number of total fired pixels, the resulting ADC values are converted to photon count.

$$N_f = N\left(1 - e^{\frac{N_{Seed}}{N}}\right)$$

$N_f$ = Number of fired pixels in SiPM  $N$ = Total number of pixels

$N_\gamma$ = Total number of photons  $PDE$ = Photon Detection Efficiency

$N_{seed} = N_\gamma * PDE$

$$N = \frac{\mathrm{N_f^1} * \mathrm{N_f^2}}{\mathrm{N_f^1} + \mathrm{N_f^2} - \mathrm{N_f^{12}}}$$

$N_f^1$ = Pixels fired from LED 1  $N_f^2$ = Pixels fired from LED 2

$N_f^{12}$ = Pixels fired from both LED 1 and LED 2

Figure 7: Equations for calculating the number of fired pixels and total number of pixels

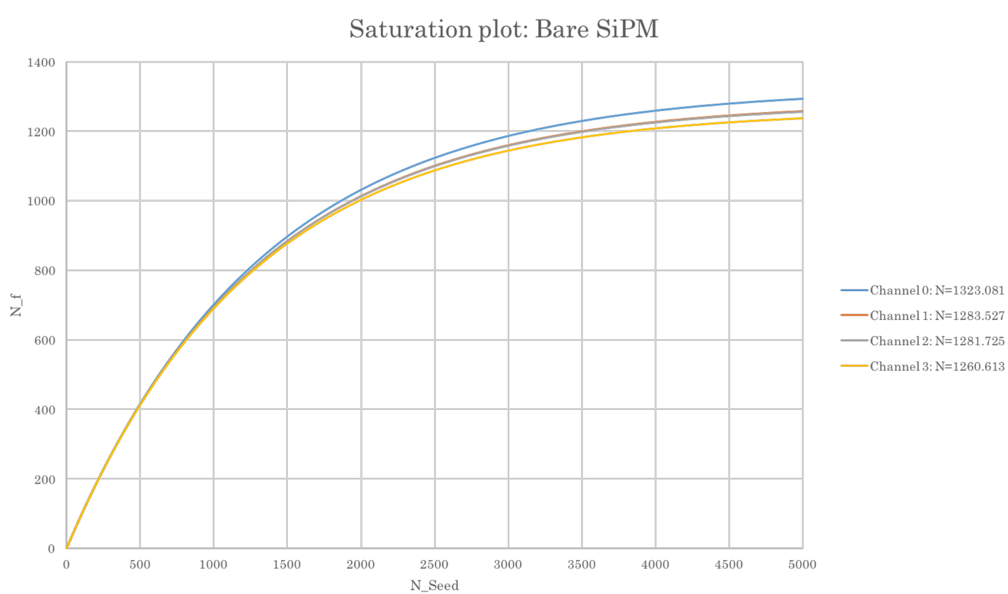



Figure 8: Results of a run without scintillator attached. Channel-by-channel comparison of number of fired pixels as a function of total photon count times photon detection efficiency

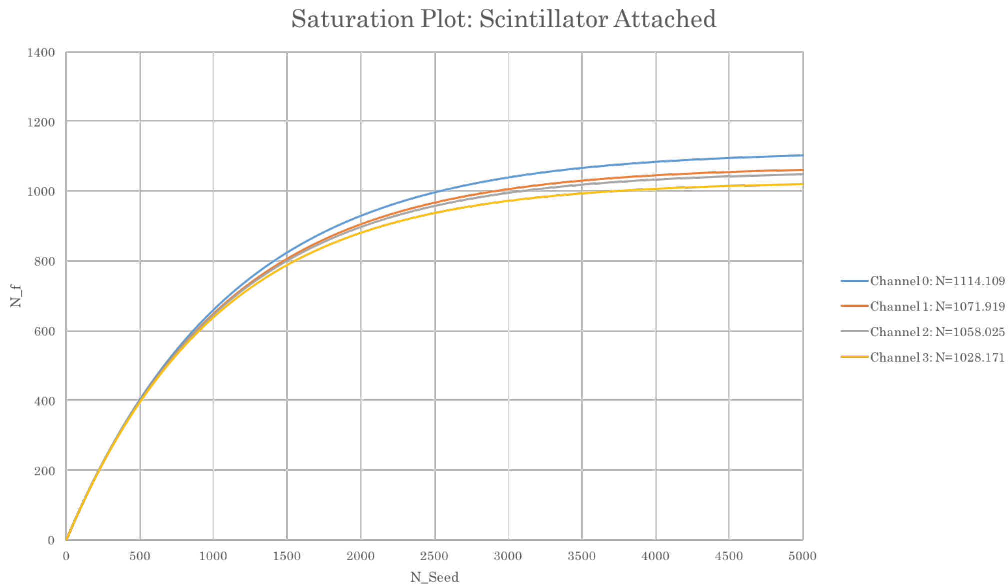



Figure 8: Results of a run with scintillator attached. Channel-by-channel comparison of number of fired pixels as a function of total photon count times photon detection efficiency

Comparison between the graphs indicates that there is a clear difference between SiPM performance with and without the scintillator attached. The maximum number of fired photons is visibly lower in the second case (Fig. 8), which supports the hypothesis that optical fiber geometry has adverse effects on pixel efficiency.

iii. Double Peak Resolution

Double peaks refer to the two peaks in ADC values resulting from separate photon events, the effects of which may alter the timing resolution of the SiPMs. Double peaks are observed experimentally when two pixels fire at a rate that exceeds the recovery time of the pixel. Instead of observing two clear photon events, only one event is recorded by the peak in ADC value (see Fig. 9 below for reference).

These peaks are reproduced experimentally in the lab by altering the time delay settings on the pulse generator. As explained in section II, subsection i (Experimental Setup), the FEB records trigger data when a pulse is sent from the pulse generator. Normally, the pulse generator settings are set to a 0.0 nsec delay, so that there is a simultaneous coincidence between the FEB trigger and the LED pulse; in this study, the delay is set to various time increments between 25.0 and 150.0 nsec, and the time resolution data (ADC value as a function of time) is recorded.

The time resolution graphs demonstrate that the model of SiPMs used in the prototype testing experiences reduced timing resolution at delay levels below 100 nsec.

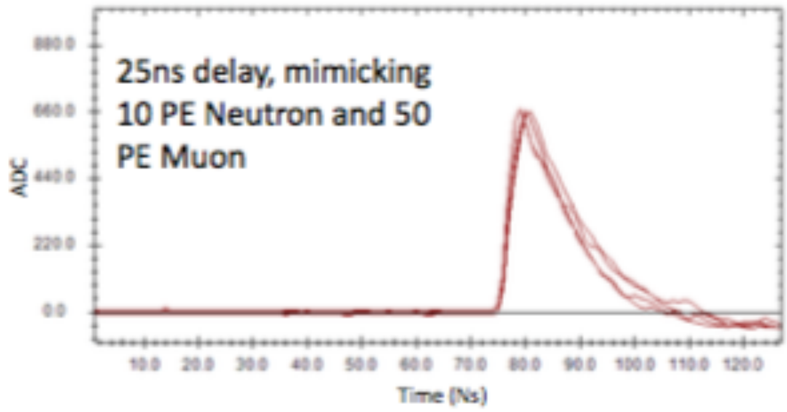



Figure 9: Time Resolution for 25 ns Delay

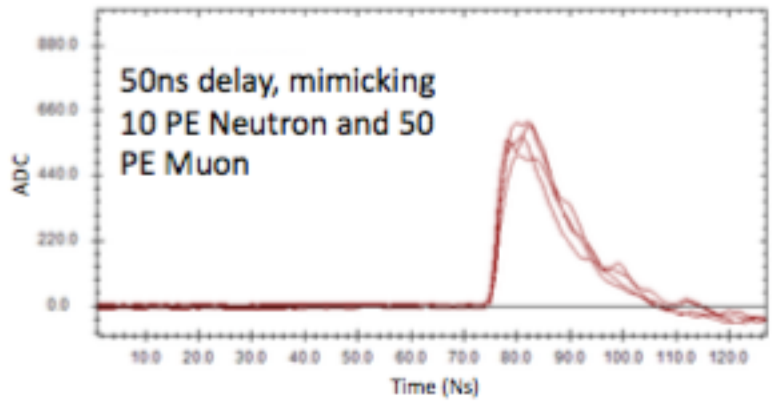



Figure 10: Time Resolution for 50 ns Delay

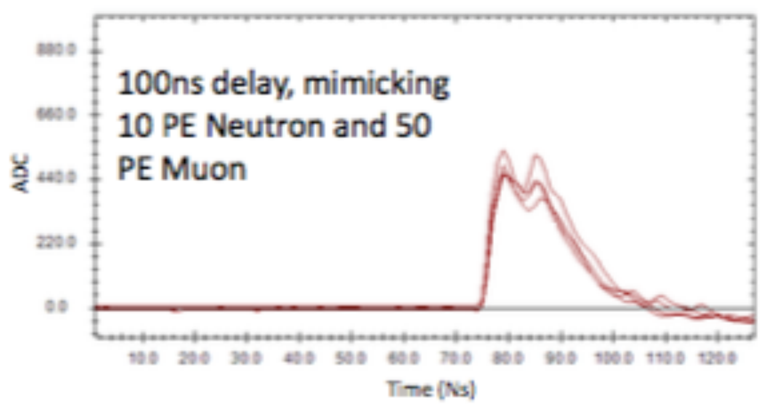



Figure 11: Time Resolution for 100 ns Delay

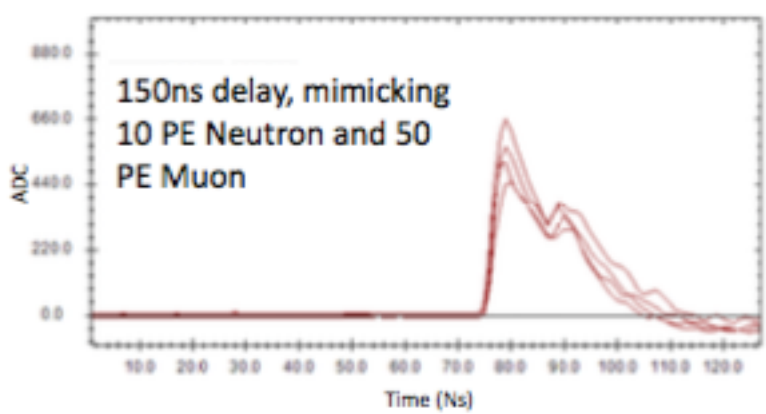



Figure 12: Time Resolution for 150 ns Delay

### iv. Optimal Bias Voltage

Attempts were made to characterize the optimal operating bias voltage. For avalanche diodes like the ones used in this experiment, the bias voltage is a characteristic of the electronics and pertains to the minimum supply voltage needed to sustain a photoelectron avalanche [5]. Increasing the bias voltage improves the sensitivity of the pixels in response to indecent photons, however it also increases the level of crosstalk between pixels. Crosstalk signal contributes to baseline noise and therefore puts constraints on pixel resolution. As such, there exists an voltage where the improved pixel sensitivity outweighs the negative effects of crosstalk and photon resolution is at an optimum. It is important to thoroughly gauge this voltage so that the SiPMs can be appropriately operated in future studies.

In this study, the bias voltage supplied to the SiPMs is manipulated over an incremented range below the breakdown voltage (the breakdown voltage is identified from the IV curve produced by the analysis software). The resulting data distributions are then compared to quantitatively determine which bias voltage yields the most statistically sound data. To ensure quality of results, the tests are repeated for different combinations of SiPMs.

Due to software issues effecting the functionality of the FEB at this point in the study, no conclusive results about the operating bias voltage were collected. Further studies should be conducted to determine whether the current standard for bias voltage (55.4 V as of January, 2017) needs to be adjusted.

## IV. Conclusion

Studies confirm that SiPMs experience saturation effects at high light intensities. They also show that light transmission through the scintillator effects the resolution capabilities of the SiPMs, meaning that issues relating to the geometry of the optic fibers are likely contributing to reduced resolution at high light intensities. However, it is unclear to what extent electronic noise and dark current are being double counted when adding ADC yield from LEDs (see section III.i). This contribution needs to be considered in considering the results of this section.

The results from section III.iii suggests that the model of SiPM used also experiences significant timing resolution issues when two photons bombard a single pixel during time intervals smaller than 100 ns.

All of these discoveries shed light on the overall capabilities of the SiPMs, and give greater understanding about the technical limitations that need to be addressed as fabrication continues. The studies that were conducted could be built upon in the future by altering the current experimental setup; for example, a high frequency pulsar and laser diode could be implemented to gather more information about double peak resolution. It would also be useful to investigate the phenomenon of after pulsing, the effects of which, like double peaking, may alter the timing properties of the SiPMs and have implications on the overall resolution of the detector.

## V. Acknowledgements

Thank you to Professor Craig Group, Dr. Yuri Oksuzian, Professor E. Craig Dukes, and Tyler Lam of the University of Virginia, as well as Paul Rubinov of Fermilab.

## VI. References

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