HEPCAT Annual Report

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Abstract

This report summarizes the progress achieved in the first year of the HEPCAT fellowship. The goals set forth at the beginning of the fellowship were to test the performance of Silicon Photomultipliers (SiPMs) under various electric field configurations to conclude if charge up and relatively high noise would prevent these photo-detectors from being competitive with the more established photomulitplier tubes in upcoming next-gen rare event searches such as nEXO, XLZD, and others. In the first year of the fellowship, I tested the performance of more than 100 SiPMs that will be used in a local research and development experiment at UCSD. Despite challenges with the preamplifier boards, I was able to read clear signals from these SiPMs through our data acquisition system. Further, even though I only used dark counts and read out SiPMs in groups of four, decreasing the signal to noise ratio, I was able to produce a characteristic finger plot, showing clear differences between signals containing different numbers of dark counts. In the following year, I will use our completed local setup to test the performance of the SiPMs in different electric fields and charge up scenarios, and spend a month at SLAC working on a similar detector with their SiPMs.

1 Introduction

This summary will provide an overview of my first year of research for the HEPCAT fellowship on Silicon Photomultiplier (SiPM) development, as well as briefly highlight some goals and plans for the final year of the fellowship.

The tests outlined here were done using 120 SiPMs purchased for the Neutrino Detection with Xenon (NUXE) project at UCSD, a proportional scintillation counter (PSC) that aims to detect coherent elastic neutrino-nucleus scattering (CEvNS) from reactor neutrinos. While constructing NUXE is not the ultimate goal of this fellowship, the goals of the two projects broadly overlap. Further, once NUXE is operational, the setup will allow for testing SiPMs in different electric field configurations, one of the main goals of the fellowship. Starting with single SiPMs, over the course of 2023 we have been able to read out more and more SiPMs simultaneously, approaching the final NUXE detector configuration. The following section will detail successes and challenges overcome in this process.

2 Silicon Photomulitplier Development

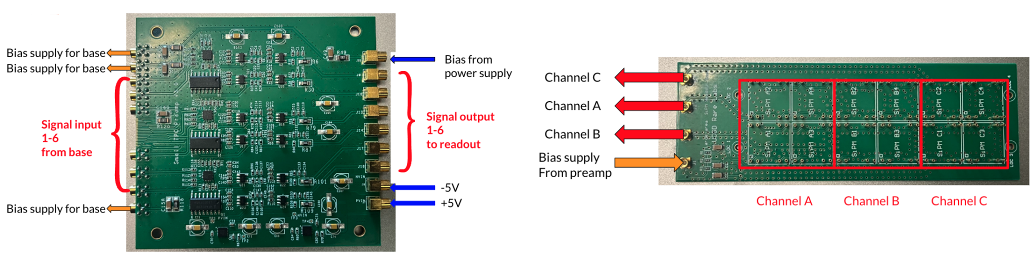

Figure 2.1: Left: Preamplifier schematic, design from the nEXO collaboration. Each board requires ±5 V, a channel for power to the PCB baseboards (right), and reads out six channels independently. Right: PCB Baseboard schematic, designed by Yue Ma. Each board accommodates twelve SiPMs, read out in groups of four.

All of the SiPMs used in this project are Hamamatsu VUV4 S13371 MPPCs, which consist of four independent SiPMs grouped together with preinstalled readout-pins. To decrease the total number of channels and simplify cabling, these SiPMs were readout together. The SiPMs were read out using a preamplifier board based on designs from the nEXO experiment and a custom PCB baseboard designed by one of our graduate students, Yue Ma. These baseboards can accommodate twelve individual SiPMs, read-out in groups of four for a total of three channels per board. Preliminary tests using oscilloscope for readout indicated that a clear dark-count signal could be detected from a single SiPM at room temperature connected to a preamplifier. Therefore, the first test I conducted used six SiPMs (i.e. one SiPM per channel on two baseboards since the preamplifier boards each have six channels). These tests were also conducted in an EC0X Temperature Chamber produced by Sun Electronic Systems Inc, which allowed us to operate at -98° C, closer to liquid Xenon temperature where the inherent noise of SiPMs is significantly reduced. For these first tests, signals were observed using a oscilloscope for ease of testing.

Figure 2.2: Left: First SiPM test configuration. Two baseboard containing three SiPMs were readout individually through a single preamplifier board. All PCB boards were placed inside a cryogenic chamber in order to reduce noise. Right: One baseboard with all 12 SiPMs installed.

While conducting this test, two issues with the performance of the preamplifier board were discovered. First, two of the boards had sets of channels that appeared to return no signals from the SiPMs, regardless of the SiPM and baseboard combination. Second, the same channel on each preamplifier went through a sharp transition where it produced excessive noise that made the channel unusable when brought to temperatures near that of liquid Xenon. This channel was referred to as channel 6 and was located on the same position in each board, nearest to the dual "bias supplies for base" channels in Fig. 2.1. Despite testing with multiple combinations of SiPMs, baseboards, and preamplifiers, this issue appeared on each preamplifier. Since these tests were conducted in the cooling chamber, the change of performance as a function of temperature was clearly visible. Performance at room temperature was comparable to other channels, but near $\sim -90°$C, increasing amounts of noise completely overshadowed any signals, rendering channel 6 unusable (see Fig. 2.3). Other channels seemed to be unaffected by this temperature dependent change. Due to these two issues, the NUXE design was reinterpreted to include five preamplifier boards instead of four to account for the missing channel on each board.

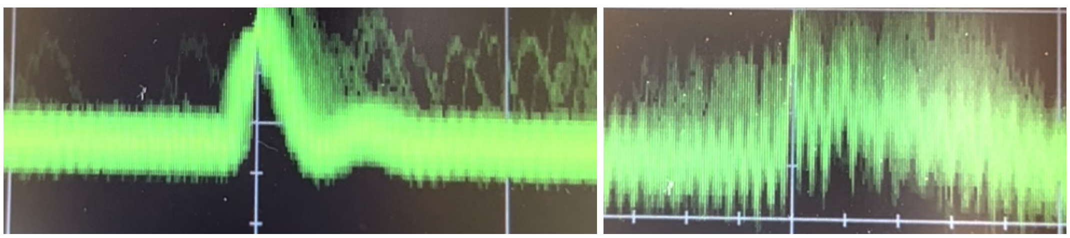

Figure 2.3: Left: The signal on one channel of each preamplifier board consistently performed well at room temperature. Right: This signal then become overwhelmed with noise below $\sim -90°$ C (right).

Despite these challenges, the tests using a single SiPM per channel were largely successful. In order to get a more quantitative picture of the performance, the setup was moved to a small cylindrical vacuum chamber where the readouts could be connected to our DAQ system. The vacuum chamber was placed inside of a Dewar, which was filled with a combination of Ethanol and liquid nitrogen to reach near liquid Xenon temperatures ($\sim -100°$C). The chamber was evacuated to $\sim 10^{-6}$ Torr, then filled with Argon in order to actually transmit the temperature changes. Since Argon has an even lower boiling point than Xenon, the Argon in the chamber was in its gaseous state, making signal detection from Argon scintillation unlikely without a radioactive source. This setup resulted in clean waveforms with less noise than in the cooling chamber (Fig. 2.4).

Following the success of the single channel tests, we proceeded to connect the maximum number of SiPMs (12) to each baseboard. The greatest challenge with this step is that when SiPMs are read out in parallel through a single channel, while the probability of observing a signal increases, so does the noise. A single dark count "signal" that only takes place on one of the four SiPMs is much more difficult to observe, since it has to compete the baseline noise of the other three. For this reason, the large amounts of signals that we used to verify that the SiPMs were functional could only be seen when operating at

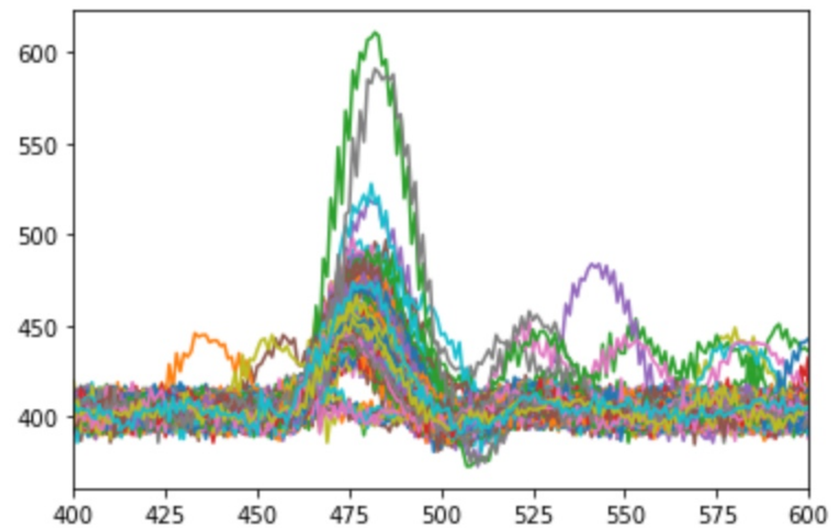

Figure 2.4: Sample dark count waveforms read from SiPMs into the digitizer. Each recorded waveform has a different color, the x-axis is in samples, and the y axis is in ADC counts.

higher bias voltages. During these tests, out of all the SiPMs tested, only one set of four was found to not perform as expected. This was likely due to an overdraw of current during an earlier test. After concluding our preliminary work, we confirmed that 96 SiPMs, 8 base boards, and 6 preamplifier boards were found to be working well.

Some preliminary analyses were performed by combining the outputs of several channels (i.e. SiPMs). Data were taken at different ADC count trigger thresholds in order to observe the effect of noise on signal collection. The areas of the waveforms were estimated by taking the integral and subtracting off the average of the signal baseline before the waveform started. Results of these preliminary analyses are shown in Fig. 2.5.

Populations near zero area are attributed to noise since low area with non zero height indicates that the signal was oscillating around the baseline, and are therefore not shown. The other populations with high density are likely due to integer numbers of dark counts, since there was no light source in the vacuum chamber, and the Argon pressure was near atmospheric pressure. Collapsing the two dimensional histogram in Fig. 2.5 to the area axis allows us to produce a “finger” plot, a standard benchmark for SiPM performance that shows individual photons can be resolved with only dark counts. This

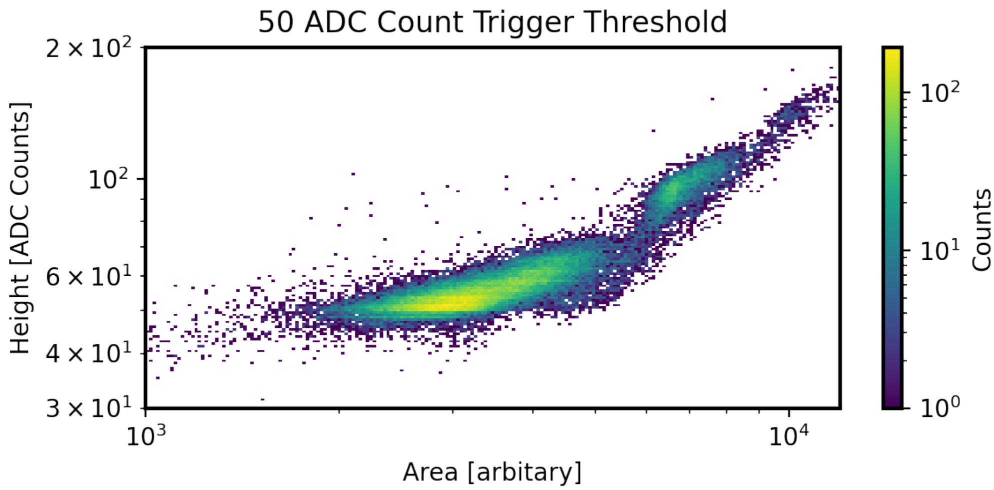

Figure 2.5: Two dimensional histogram showing the calculated area vs. height of the dark count signals collected from the SiPMs through a digitizer. The digitizer was set at a threshold of 50 ADC counts.

result is shown in Fig. 2.6.

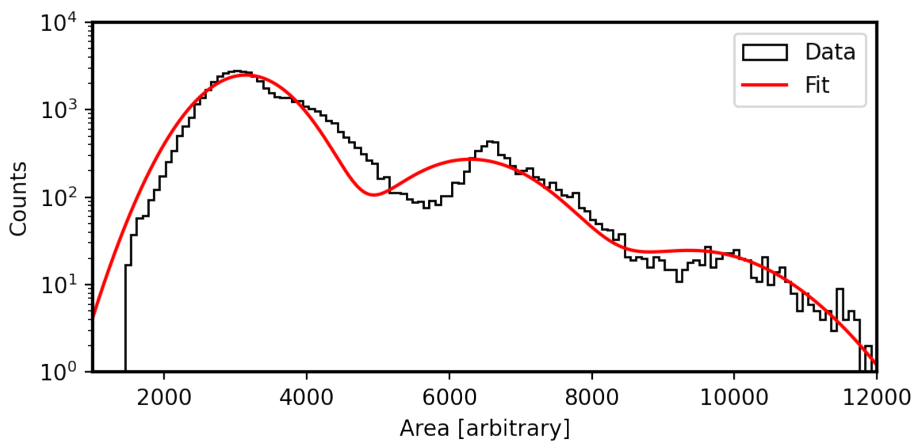

Figure 2.6: "Finger" plot, shows different number of photons from dark counts are clearly separated, a Gaussian distribution with peaks at 1, 2, and 3 photons is fit on top of data.

The combined ADC thresholds 'finger' plot shows three peaks with decreasing amplitude, representing measurements of different integer numbers of dark counts. The clear differentiation between the peaks is a demonstration of the high resolution of SiPM based detectors.

3 Summary

In the first year of the HEPCAT Fellowship I have tested and implemented a setup for over 100 SiPMs. Despite challenges with one channel of the preamplifier boards, I was able to successfully read out groups of four SiPMs in tandem and produce the characteristic finger plot of SiPMs using only dark counts. In the next year of the fellowship, I will work with collaborators at SLAC to design baseboards and install SiPMs in their local setup, as well as continue testing SiPMs at UCSD in different electric field and charge up scenarios.