A Study of the Silicon Photomultipliers used in the ND280 upgrade for T2K

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I. Introduction

1. Neutrino Oscillation

There are three types of neutrinos, which we call neutrino flavors: the electron neutrino (ν_e), the muon neutrino (ν_μ) and the tau neutrino (ν_τ). All three neutrino flavors are fundamental particles that are very hard to detect. Neutrinos oscillate between flavors over time. A given tau neutrino can turn into a muon neutrino after a certain amount of time and so on.

2. The T2K Experiment and The ND280 Detector

T2K is a neutrino experiment designed to investigate said neutrino oscillation. An intense beam of muon neutrinos is generated at the J-PARC nuclear physics site on the East coast of Japan and directed across the country to the Super-Kamiokande neutrino detector in the mountains of western Japan. The beam is measured once before it leaves the J-PARC site, using the near detector ND280 and again at Super-K: the change in the measured intensity and composition of the beam is used to provide information on the properties of neutrinos.

ND280 is scheduled for an upgrade after about a decade of data acquisition. This upgrade includes the installation of three new detectors in the basket of ND280. One of these three new additions is the Time of Flight (ToF) detector, the one that our group is working on.

3. ToF Detector

The ToF detector has a modular structure. Each module represents an array of 20 plastic scintillator bars which are stacked in a plane of 2.4 × 2.2 m2 area. Six modules of similar construction will be assembled in a cube, thus providing an almost 4π enclosure for an active neutrino target and two TPCs.

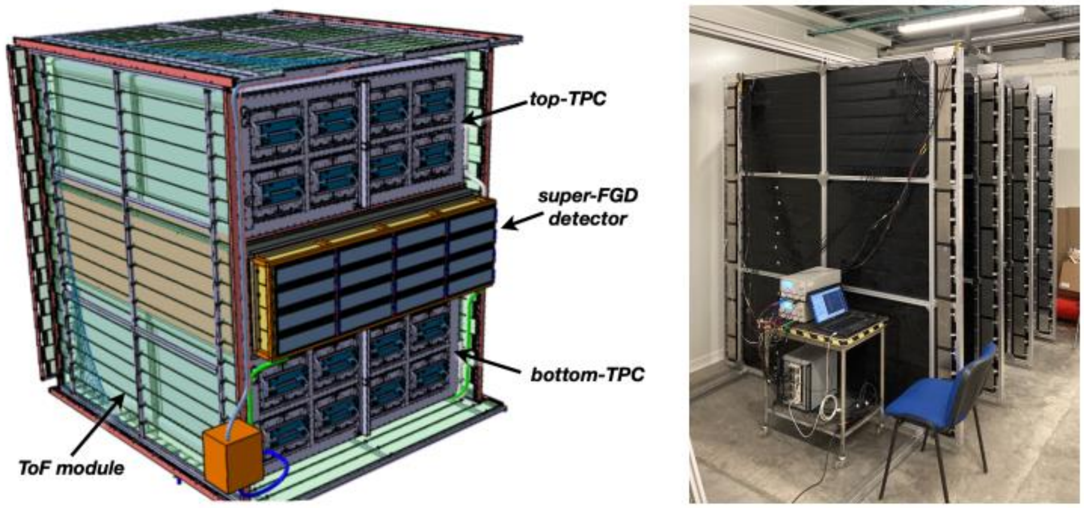

Figure 1. *Left:* six modules of ToF assembled in a cube covering the sFGD and two TPC detectors. The front ToF module is not drawn in order to see the interior. *Right:* photo of four ToF modules during the test with cosmics in the CERN neutrino platform building.

4. Silicon Photomultipliers (SiPM)

The light emitted by scintillator is absorbed by arrays of large-area silicon photomultipliers (SiPMs) which are attached to both ends of every bar. A SiPM consists of a matrix of small-sized sensitive elements called micro-cells (or pixels) all connected in parallel (Figure 1 and 2). Each micro-cell is a Geiger-Mode avalanche photodiode (GM-APD) working beyond the breakdown voltage (Vbd) and it integrates a resistor for passive quenching. Our SiPM arrays contain 8 SiPMs each, grouped into 4 pairs.

Figure 1: SiPM Array

II. Data Acquisition

1. Equipment

Figure 2: Low (4V) and Bias (9V) voltages generator

Figure 3: High Voltage (120V) generator

Figure 4: Oscilloscope

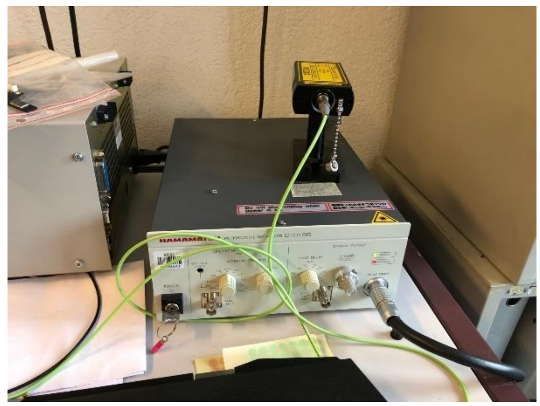

Figure 5: Laser

2. Setup

Figure 6: Full setup

A SiPM array is connected to both generators and to the oscilloscope. It is then placed in a support structure that is connected to the laser.

The low voltage, bias voltage and high voltage are set to 4V, 9V and 120V respectively. The high voltage generator is also set to 50mA.
The laser is set to minimum intensity and to a frequency of 50kHz as it is the highest frequency value the laser can produce at which the signals don't interfere.

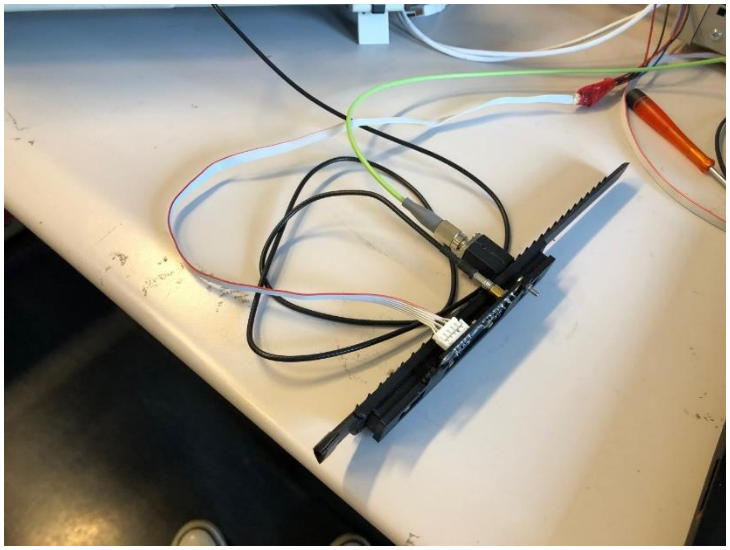

Figure 7: Connections to the SiPM array (Green is connected to the laser, White to the power supplies and Black to the oscilloscope)

3. Methodology

For reference, in the rest of this report I will refer to the SiPMs on a given array by numbers from 0 to 7, 0 being the leftmost SiPM, as specified in fig. 8.

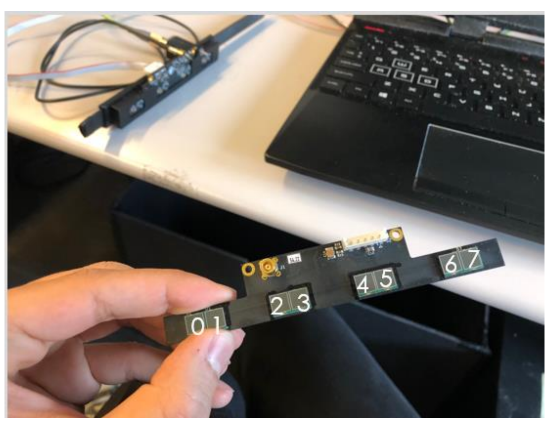

Figure 8: SiPM numbering nomenclature

The laser port on the SiPM support structure allows us to move it laterally thus shooting the laser at a different SiPM from the array or even at the intermediate space, depending on how we position it. It is important to note however that the signal readout from the SiPM array, which we can visualize on the oscilloscope, is the sum of the signals at all SiPMs. In other words, we cannot isolate the signal generated at a specific SiPM at the data acquisition level. Now a possible solution would be to design a mount that has separations between the individual SiPMs that way the photons from the laser only hit one SiPM at a time. This was not available at the time, but it might be a potential upgrade for the testing setup.

With every array, I aim the laser at each SiPM, place it in a dark box and get from the oscilloscope the point-to-point average waveform of 2500 waveforms, which I then save as a CSV (comma separated values) file.

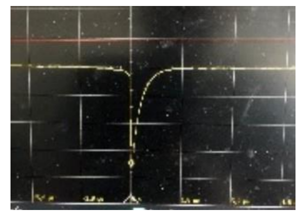

Figure 9: Typical waveform

III. Data Analysis

1. Computations of interest

Using the CSV files produced for each SiPM of each array, I compute the following:

- The signal baseline, by targeting the piece of the waveform preceding the photon excitation of the SiPM and averaging out the voltages. I then subtract this voltage value from the signal to normalize it for further study.
- The signal amplitude, which we define as the absolute value of the difference between the signal peak and its baseline.
- Noise, which I defined in this study as the ratio of the amplitude of the signal at the baseline to the amplitude of the full waveform. Another possible definition, and probably a better one, would have been the standard deviation of the signal at the baseline.
- The Full Width at Half-Maximum, which is the time difference between the two points where the voltage value is half that of the peak voltage.
- The Falling and Rising edges, respectively the time the signal takes to go from 2% to 100% of the peak voltage and then back (the signal is negative which is why the first one is the falling edge and not the rising)
- The integral of the signal, the total light collected

2. Results

The following plots depict the collected signals from all 6 studied SiPM arrays.

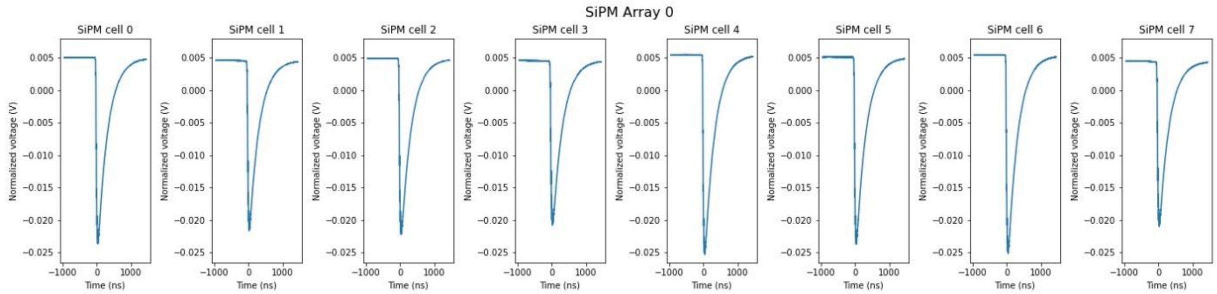

Figure 10: SiPM array 0 output voltages

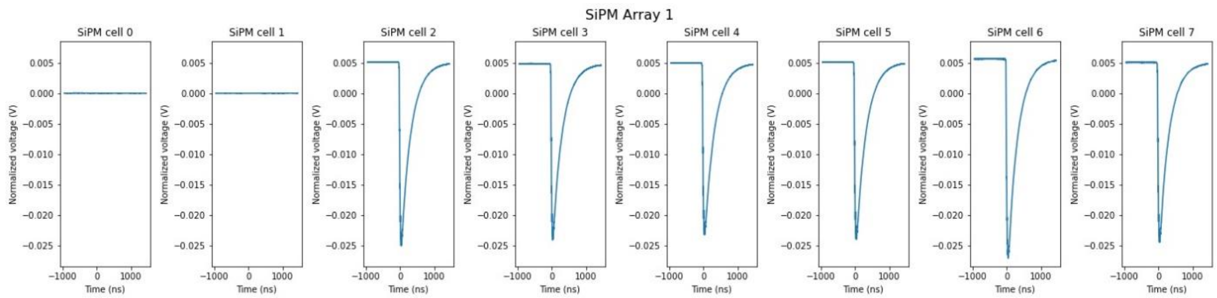

Figure 11: SiPM array 1 output voltages

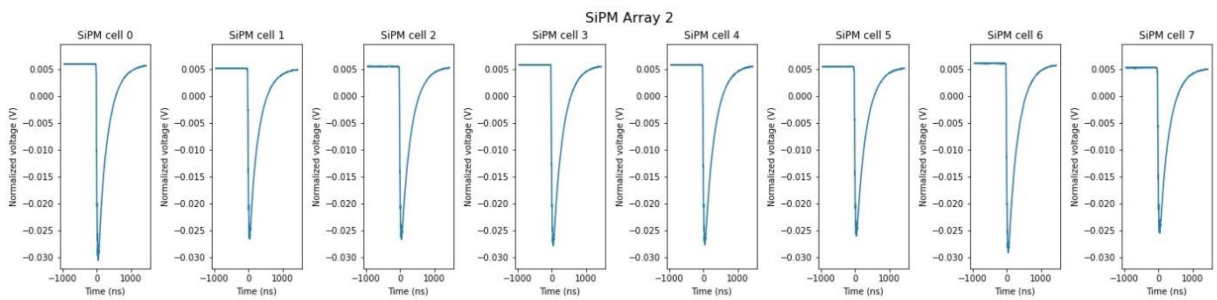

Figure 12: SiPM array 2 output voltages

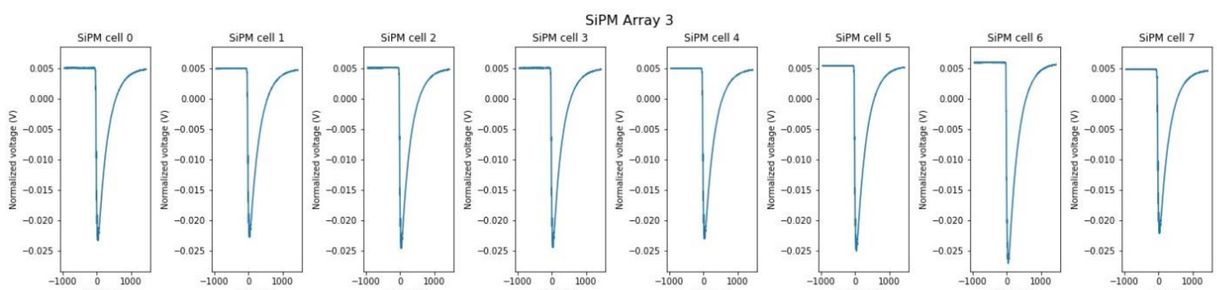

Figure 13: SiPM array 3 output voltages

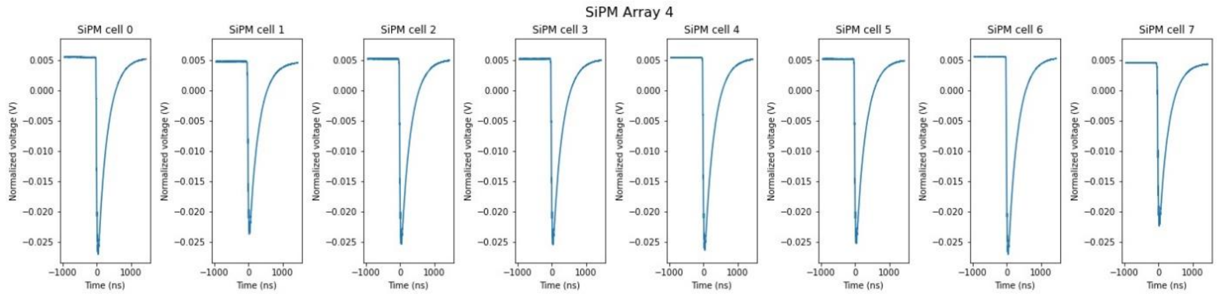

Figure 14: SiPM array 4 output voltages

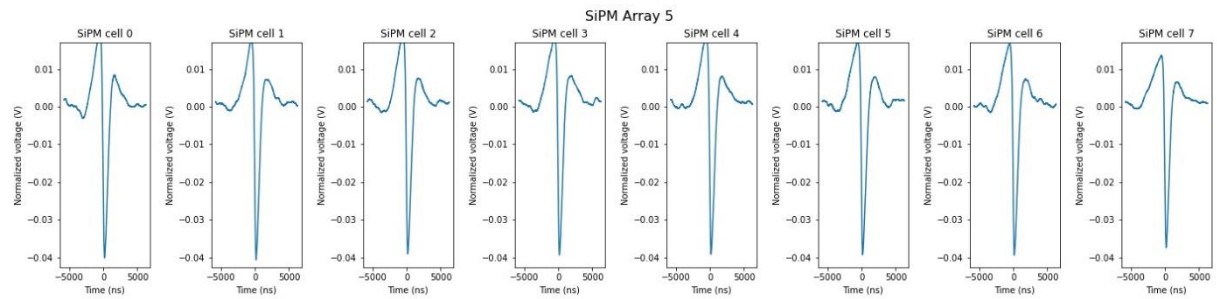

Figure 15: SiPM array 5 output voltages

What we can already see is the two cells of SiPM array 1 are not collecting any signal and that the signals collected from SiPM array 5 are different in shape than the rest. It is still unclear what is causing this odd discrepancy.

Now we look at the results of the data analysis for each SiPM array.

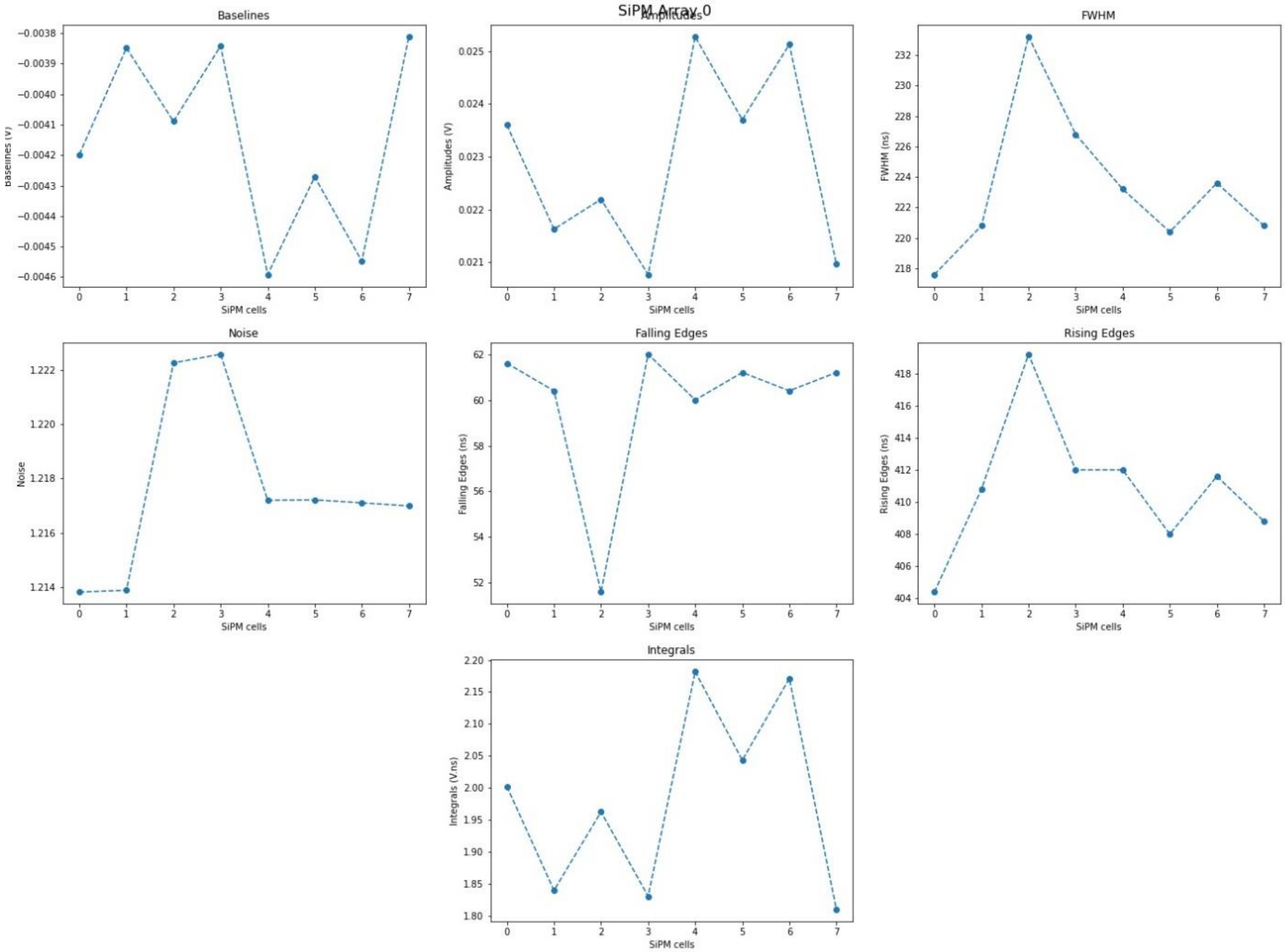

Figure 16: SiPM array 0 data analysis results

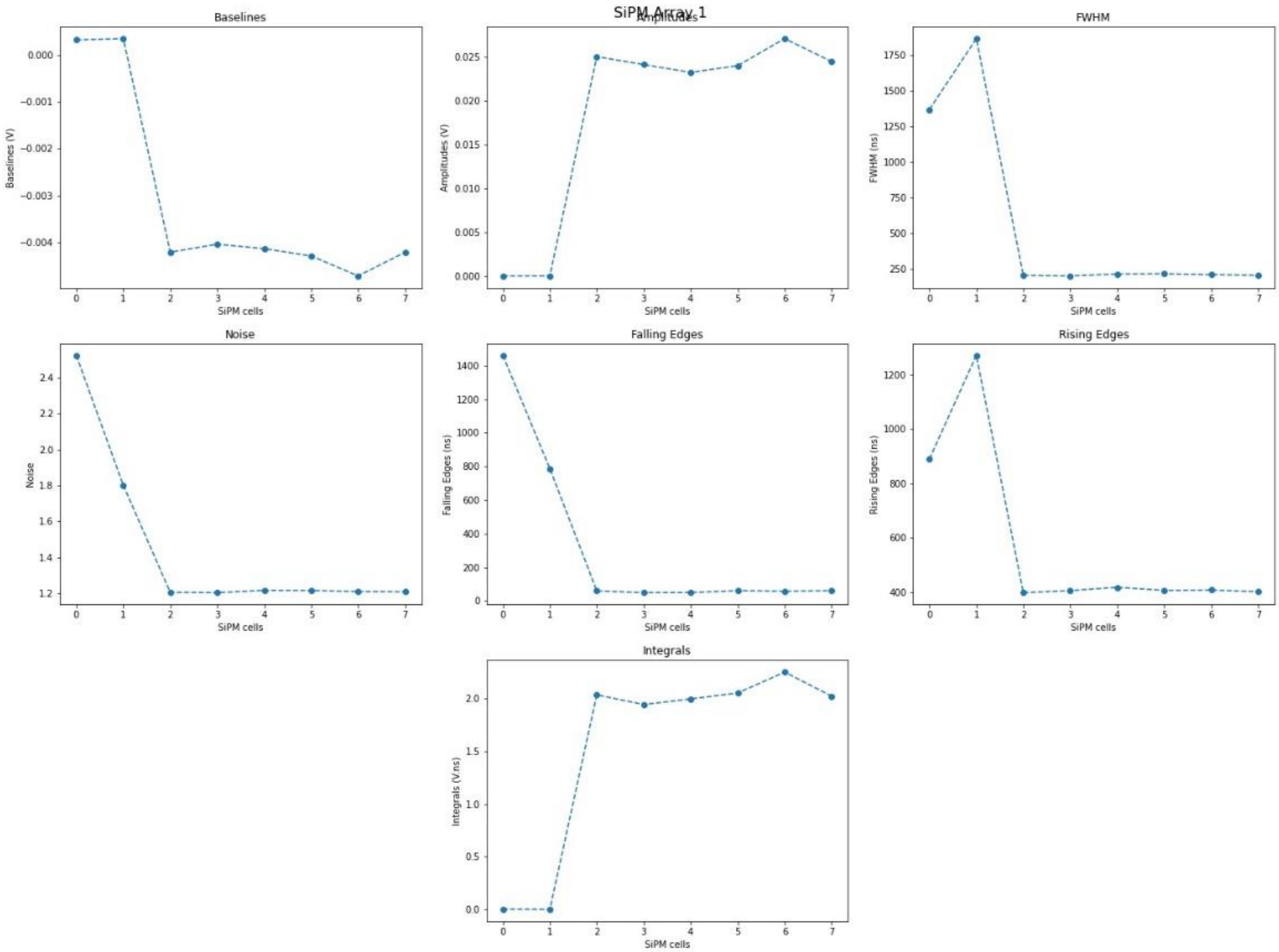

Figure 17: SiPM array 1 data analysis results

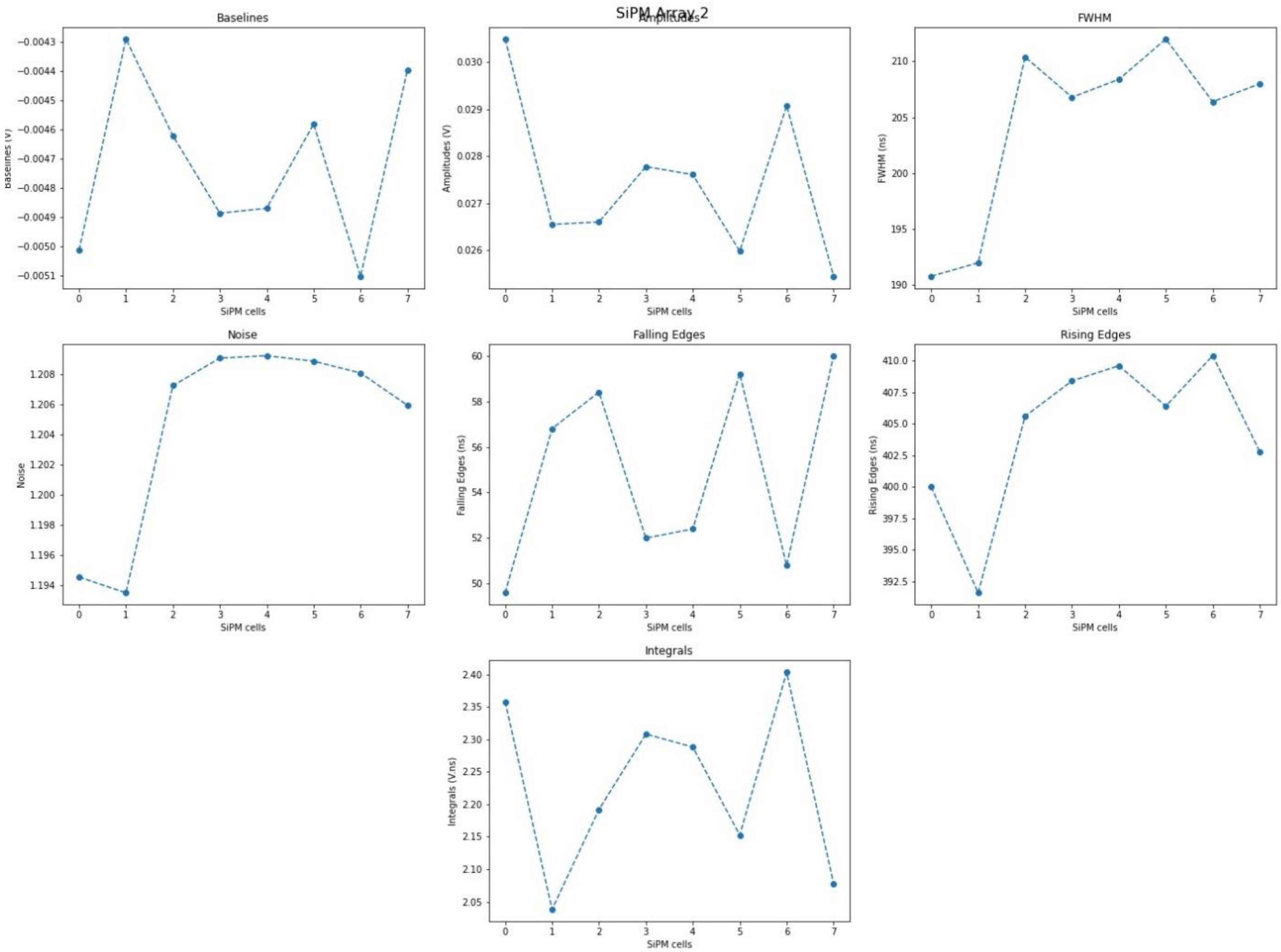

Figure 18: SiPM array 2 data analysis results

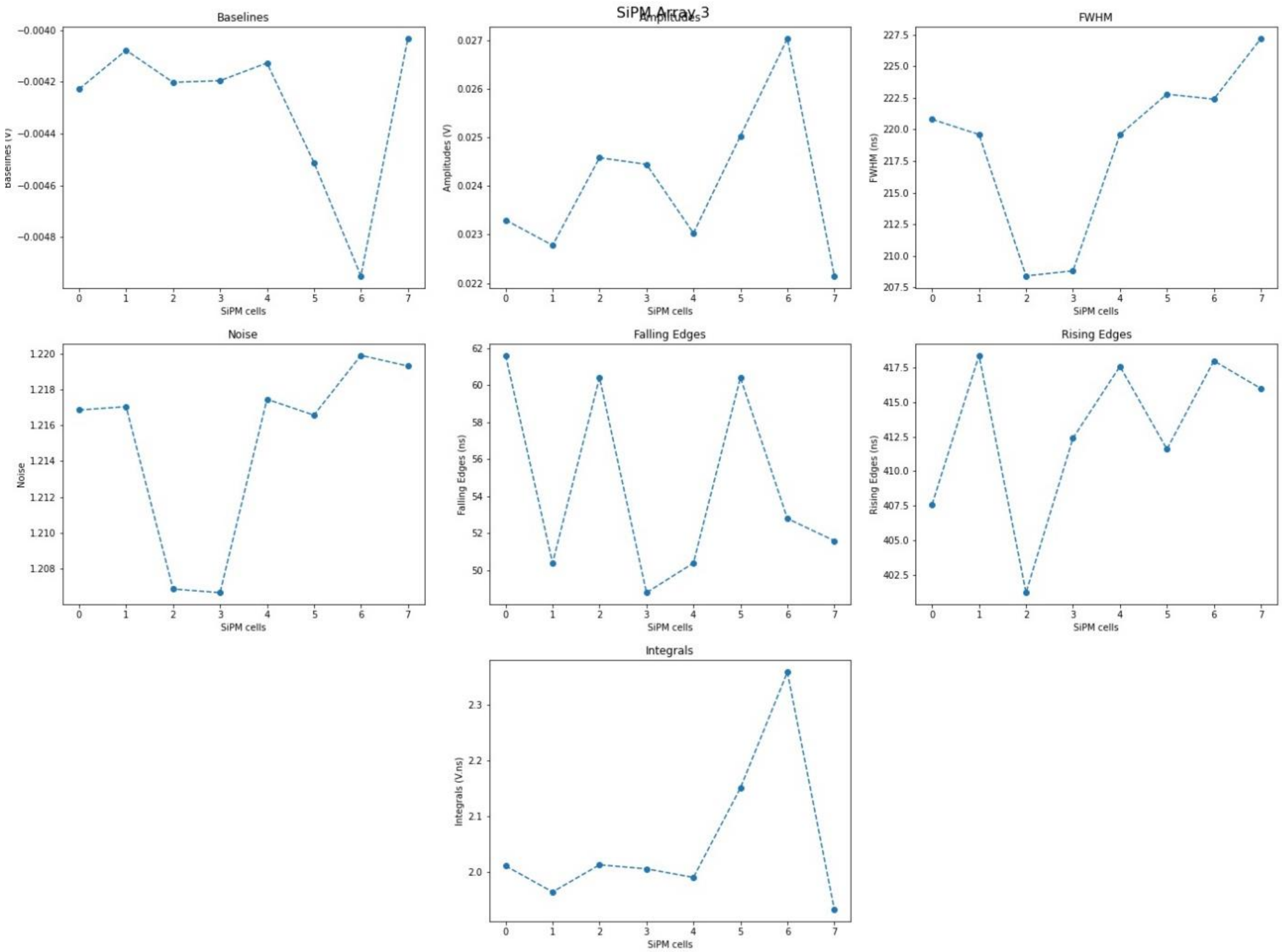

Figure 19: SiPM array 3 data analysis results

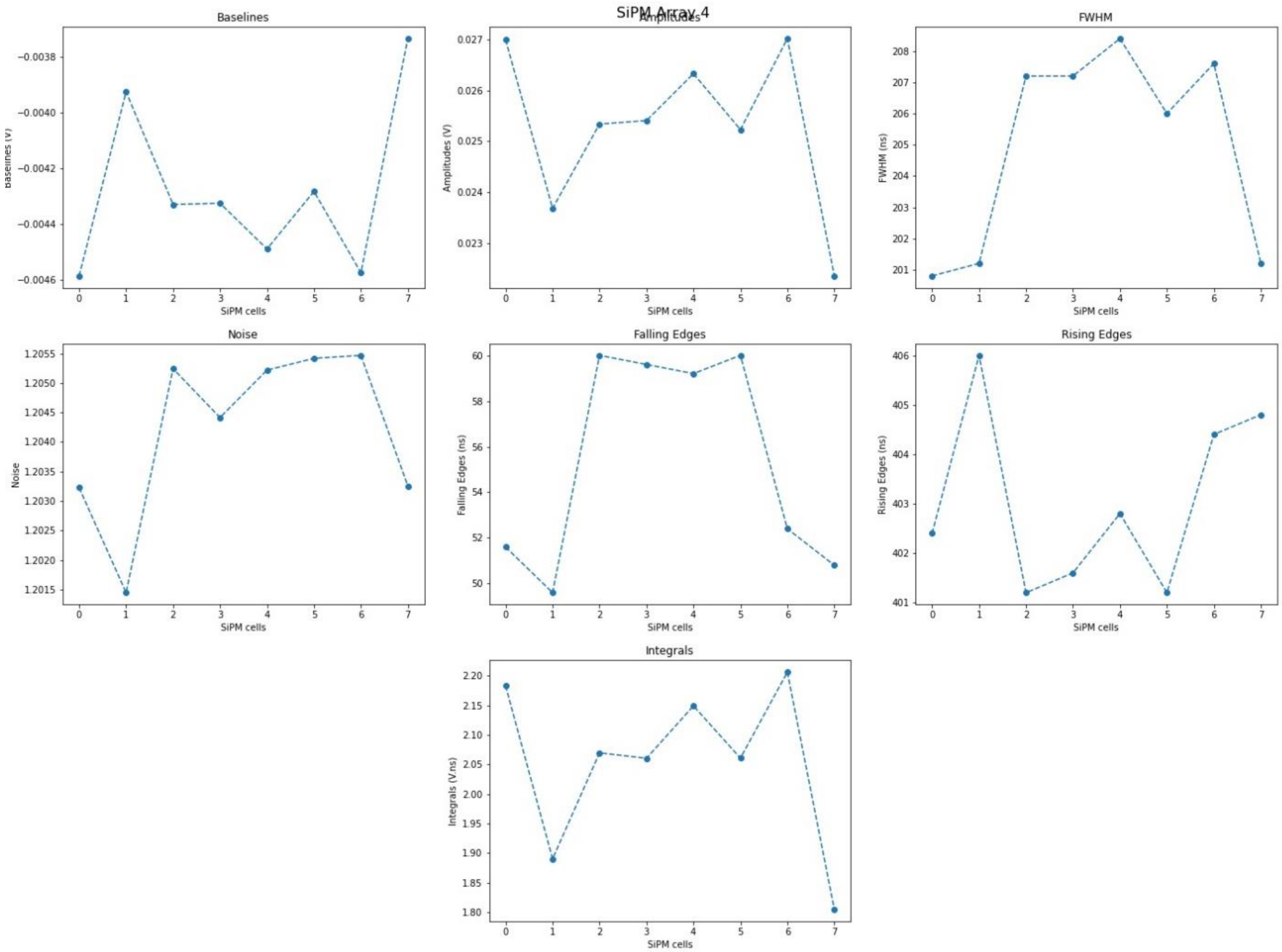

Figure 20: SiPM array 4 data analysis results

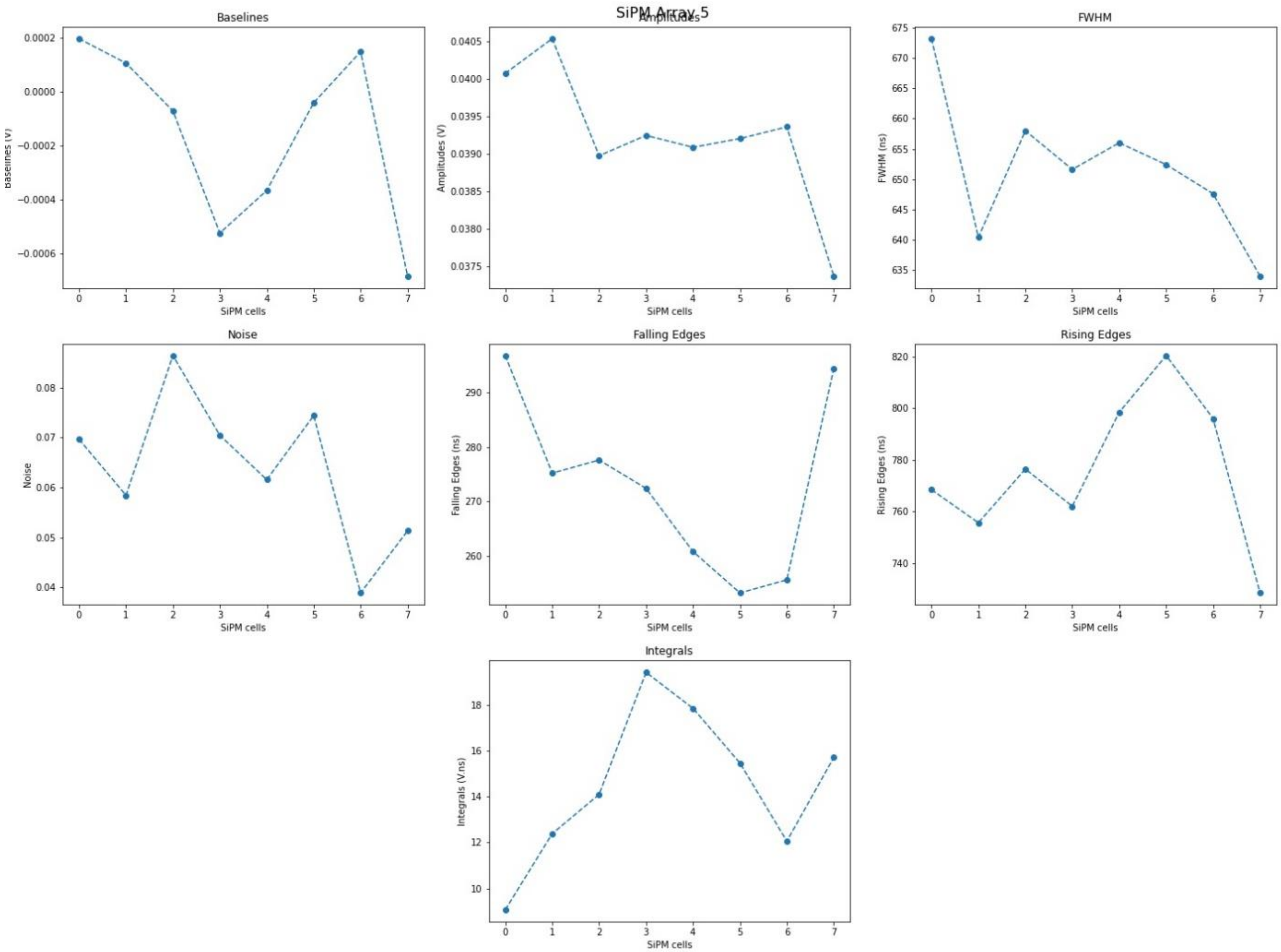

Figure 21: SiPM array 5 data analysis results

IV. General results

The following plots sum up all the results for SiPM arrays 0 through 4. I have decided to exclude array 5 from the plots I show here as it is a big outlier that makes it very hard to visualize the variation in the other data.

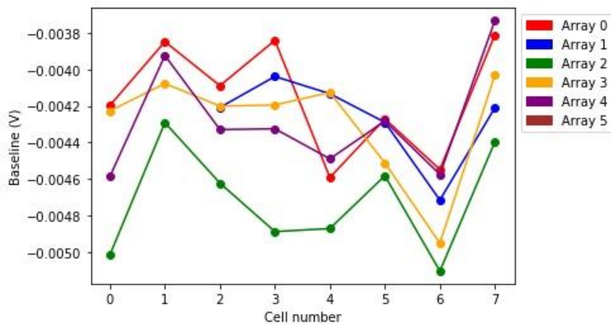

Figure 22: Signal Baselines

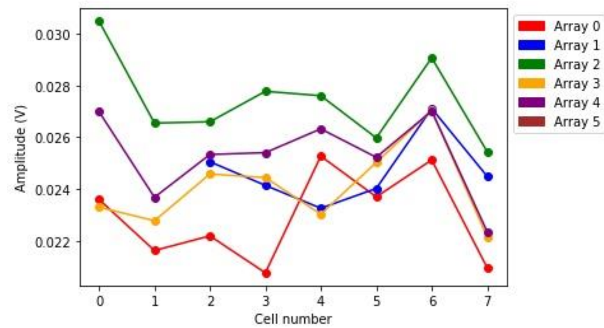

Figure 23: Signal Amplitudes

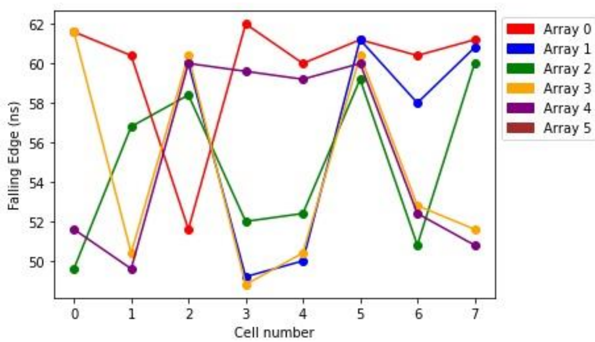

Figure 24: Falling Edges

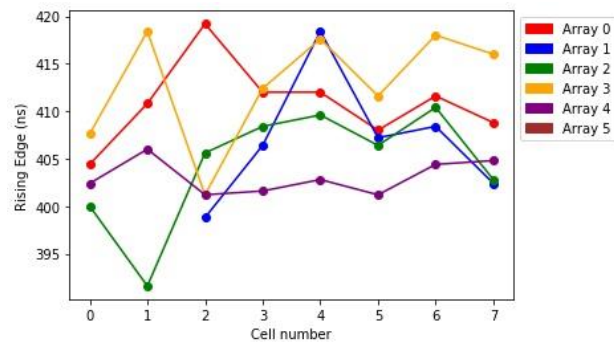

Figure 25: Rising Edges

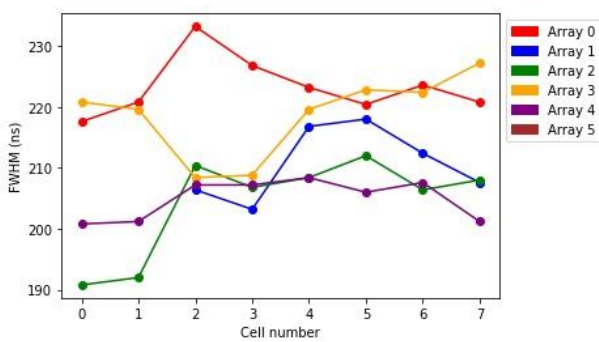

Figure 26: Full Width Half-maxima

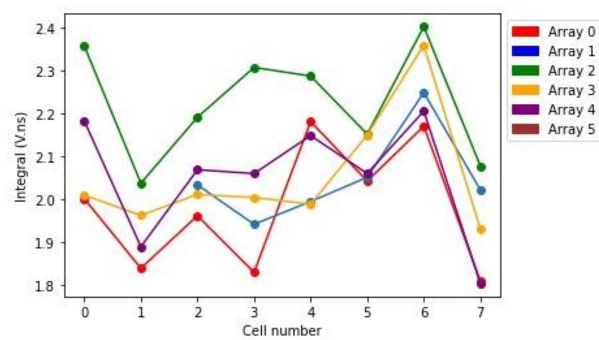

Figure 27: Signal Integral

V. References

- 2109.03078.pdf (arxiv.org) - A 4$\boldsymbol{\pi}$ time-of-flight detector for the ND280/T2K upgrade, A. Korzenev et al.
- T2K experiment - Wikipedia
- AN_SiPM_Introduction_E.pdf (first-sensor.com) - Introduction to silicon photomultipliers (SiPMs), First Sensor

VI. Acknowledgements

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