Timing Resolution Studies of Hamamatsu Silicon Photomultipliers

Eric Liu

Mentors: Maria Spiropulu, Si Xie, Artur Apresyan, Anatoly Ronzhin, Cristian Peña

Abstract

Photodetection technology has wide application in modern scientific and commercial fields, from spectrometry to subatomic particle detection. Timing precision of detectors is critical in the performance of modern particle detectors, which calculate particle masses using strong magnetic fields and precise time-of-flight measurements. Silicon-based photodetectors are currently in use in the Large Hadron Collider (LHC), since silicon's performance and timing precision are largely unaffected by strong magnetic fields. The current detectors have a time resolution of 200-300 ps, which is an order of magnitude too large to handle the increased collision rate of the next LHC upgrade. Sample detectors from the next generation of silicon photodetectors were tested using picosecond-duration laser pulses.

Introduction

Photomultipliers are highly light-sensitive devices that rapidly convert an incident photon's energy into an output voltage pulse. Measuring the time resolution of the output pulse (the variation in the timing of the pulse relative to the incident photon's arrival) is important because some applications of photomultipliers rely on the output pulse time of arrival, such as for spatial reconstruction. Previous work [1] has established the typical time resolution of these devices to be on the order of 100 ps. The goal of this project is to characterize the timing properties of the newest generation of silicon photomultipliers (SiPMs) made by Hamamatsu Photonics. We are investigating how SiPMs' time resolution depends on bias voltage, light intensity, as well as the type of output circuit and preamplifier.

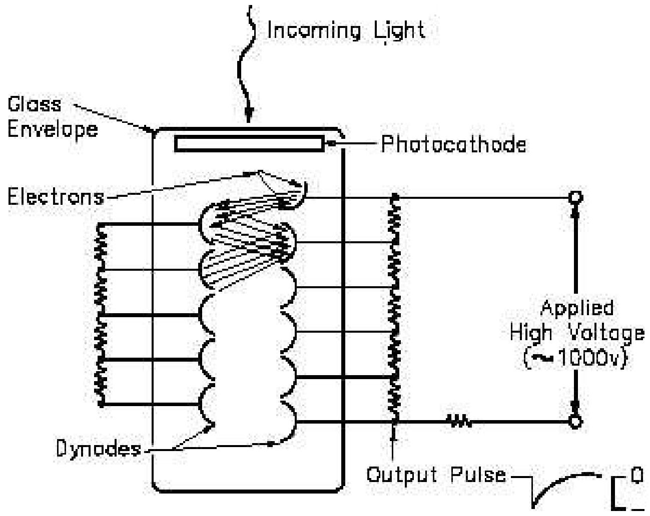

Fig. 1. Photomultiplier diagram. When a photon enters the photomultiplier, its energy triggers a cascade of lower energy photons, which are then integrated into a voltage pulse at output.

Experiment

The main SiPM we have worked with thus far is a Hamamatsu 1x1 mm^2 sensitive area, 100x100 um^2 pixel size. Other SiPMs tested include Hamamatsu 1x1 mm^2 sensitive area, 15x15 um^2 pixel size and 3x3 mm^2 sensitive area, 50x50 um^2 pixel size. Timing tests were performed in a darkened chamber with picosecond-length laser pulses. (Fig. 2) The trigger signal for the laser comes from a picosecond-level pulse generator, and is split between the laser and the domino ring sampler (DRS) system. The DRS triggers on each trigger pulse and records 1024 voltage values, 2 ps apart, for both the trigger and signal pulses, shown below (Fig. 3).

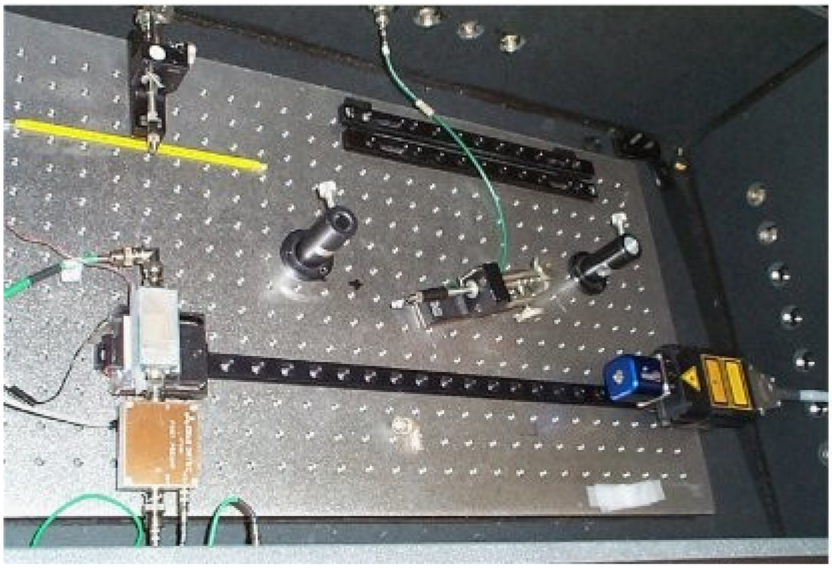

Fig. 2. Experimental setup: laser at right, SiPM is housed inside output circuit box (white) at left, which is connected to a preamplifier (brown).

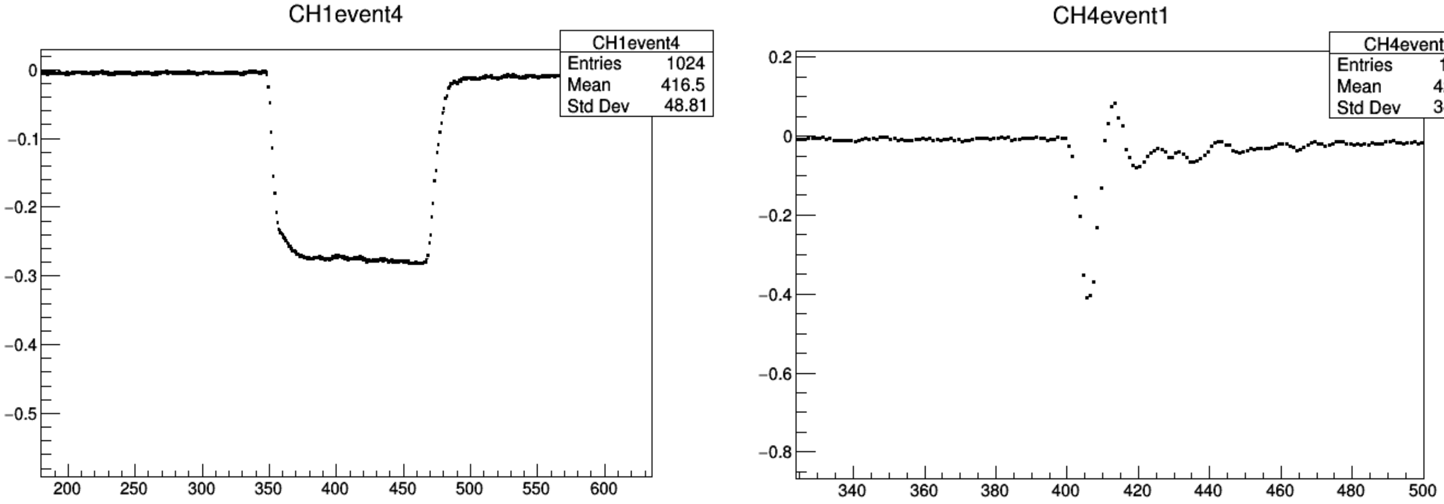

Fig. 3. Trigger pulse shown at left, SiPM signal pulse shown at right.

Methods

For each set of conditions (bias voltage, preamplifier type, laser intensity), we recorded 10,000 events. For each event, the time difference between the trigger and signal pulses is calculated. The trigger pulse is assigned a time-stamp equal to the time at which the initial edge reaches 60% of its maximum value.

The signal pulse's time-stamp is found by a Gaussian fit around the main peak of the pulse. The time difference is thus the difference in these two time-stamp values. The events are then sorted according to the number of incident photons in the event (Fig. 4) Once the events have been sorted into single-photon events, double-photon, etc. the single-photon time resolution (SPTR) can be plotted against the bias voltage placed across the SiPM. A typical STPR vs. voltage plot is shown below (Fig. 5).

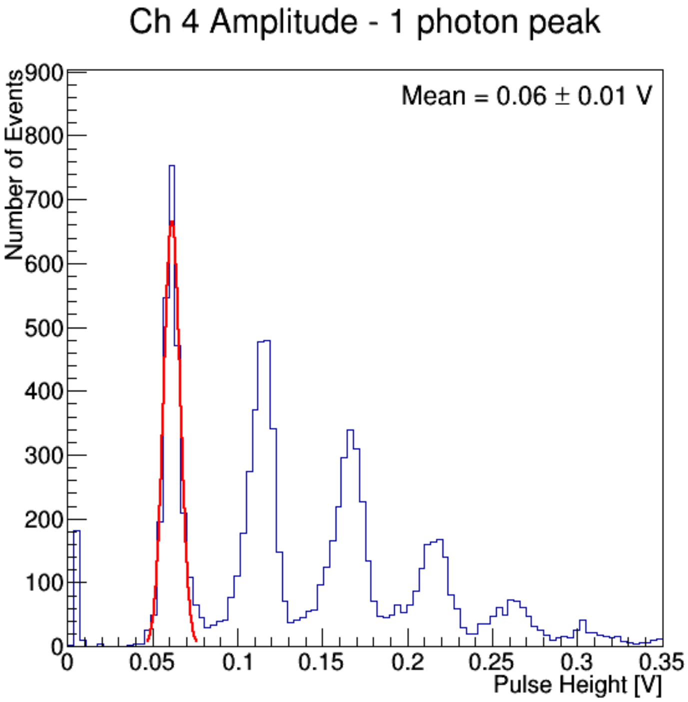

Fig. 4. Histogram of signal pulse amplitudes for all events for a typical run. The peaks correspond to events in which 1, 2, etc. photons entered the sensitive area of the photodetector. The red Gaussian shown determines the bounds on the signal amplitude for single-photon events.

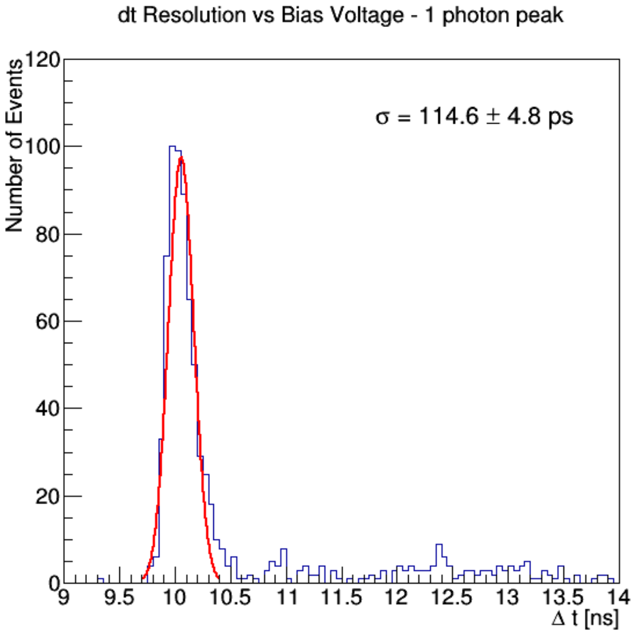

Fig. 5. Plot of time difference (trigger timestamp – signal timestamp) for single-photon events. The standard deviation of the Gaussian fit about the peak is taken as the single-photon time resolution.

Results

The time resolutions of the newest generation of Hamamatsu SiPMs were found in the range 60-150 ps.

For any particular SiPM, output circuit, and preamplifier configuration, 6-8 bias voltage values were swept and 10,000 events were recorded for each. ROOT, a C++ library, is used to perform the data analysis and generate relevant plots. The analysis ROOT script calculates all time-difference values, performs rudimentary Gaussian fits to determine the bounds on signal amplitude (to determine which events counted as single-photon, etc.), sorts the events accordingly, then creats the time-difference plots for each type of event and performs Gaussian fits again to determine the SPTR, DPTR, etc. Lastly, for the list of data files supplied, the SPTRs are aggregated and plotted against bias voltage.

We determined which preamplifier (Fig. 6) would display the best timing resolution and lowest noise level. The two output circuits tested were made by Anatoly Ronzhin and Sergey Los from Fermilab; the preamplifier configurations tested were: MITEQ AU-1054, ORTEC VT-120, Hamamatsu 36 dB, and 2 ORTEC amplifiers in series. A 10 dB attenuator was placed on the signal channel when necessary, to prevent the DRS readout from saturating (above 500 mV). The preamplifier with the best performance was the Hamamatsu 36 dB preamplifier, with a nominal noise level of 5 mV. Shown below is a plot of SPTR vs. bias voltage for this configuration and a noisier configuration (Fig. 7).

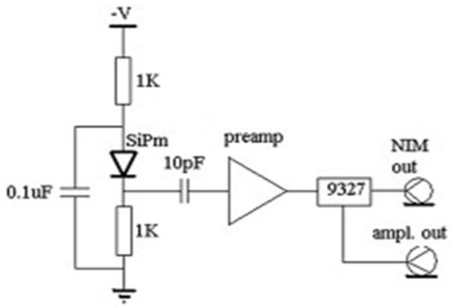

Fig. 6. SiPM output circuit designed by Anatoly Ronzhin.

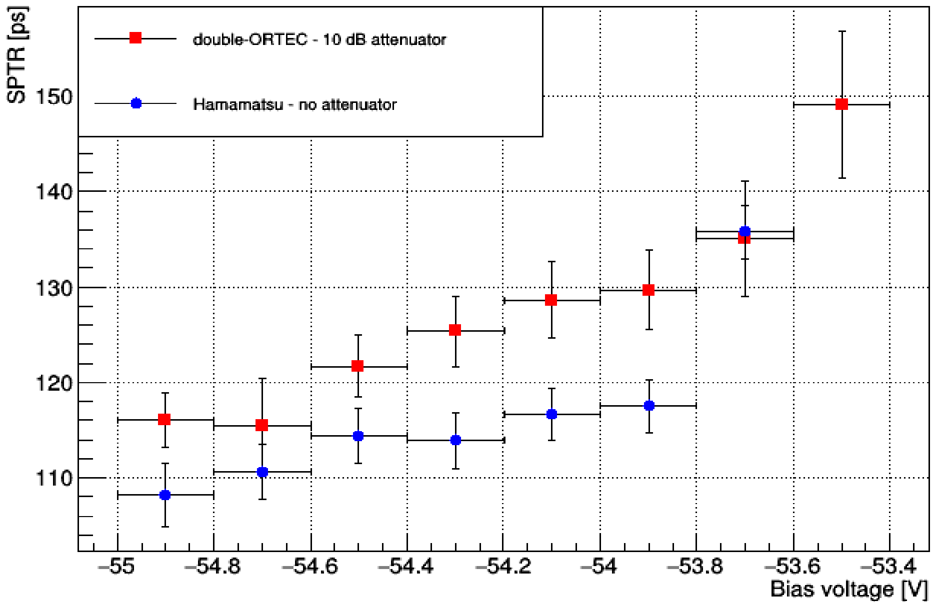

Fig. 7. SPTR vs. bias voltage for two preamplifier/attenuator configurations.

In addition, we performed a study to isolate the cause of the time resolution's improvement for events with more photons. In particular, we wanted to see if the time resolution improves due to improved photostatistics or due to increased signal amplitude. For the set of bias voltages, we performed runs with and without a 10 dB attenuator on the signal. Since 10 dB corresponds to a signal amplitude decrease by approximately a factor of 3, we expected (and saw) that the single-photon peak in an unattenuated run and the triple-photon peak in the corresponding attenuated run would have the same amplitude (Fig. 8). Thus we could compare the time resolutions without the effect of increased signal amplitude. We observed that the time resolutions were mostly within each other's error bounds, and thus concluded that the improvement of time resolution as the number of incident photons increases is due to the increase in signal amplitude.

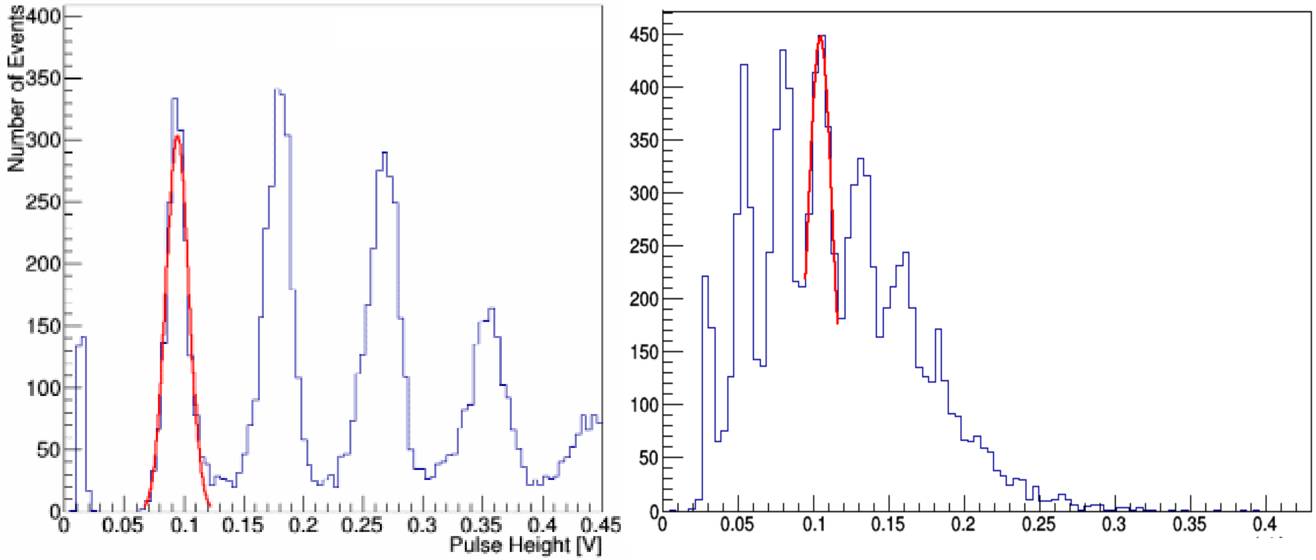

Fig. 8. Signal amplitude histograms for a pair of runs at a bias voltage of -53.5 V. Left plot is unattenuated, right plot is with a 10 dB attenuator on the signal. The amplitudes of the unattenuated single-photon peak and the attenuated triple-photon peak are both 100 mV, to within the error bounds.

During SiPM tests, neutral density (ND) optical filters were used to reduce the laser intensity to acceptable levels, when clear separation of individual peaks was observed in the amplitude distribution (seen above in Fig. 8). As seen above, this occurred when the most common events involved few photons, so photon-sized fluctuations are still significant relative to the total signal amplitude. The different ND filters were compared to determine their effect on the laser. The expected effect of a filter with ND rating d is to reduce the intensity by a factor of 10^-d. Shown below in Fig. 9 are two otherwise identical runs, taken with no filter and with a ND=0.3 filter. If the ND filters behave as expected with regards to reducing the laser intensity, we should observe the most common photon count per event decrease by a factor of 10^-0.3 = 0.5 when the ND=0.3 filter is added.

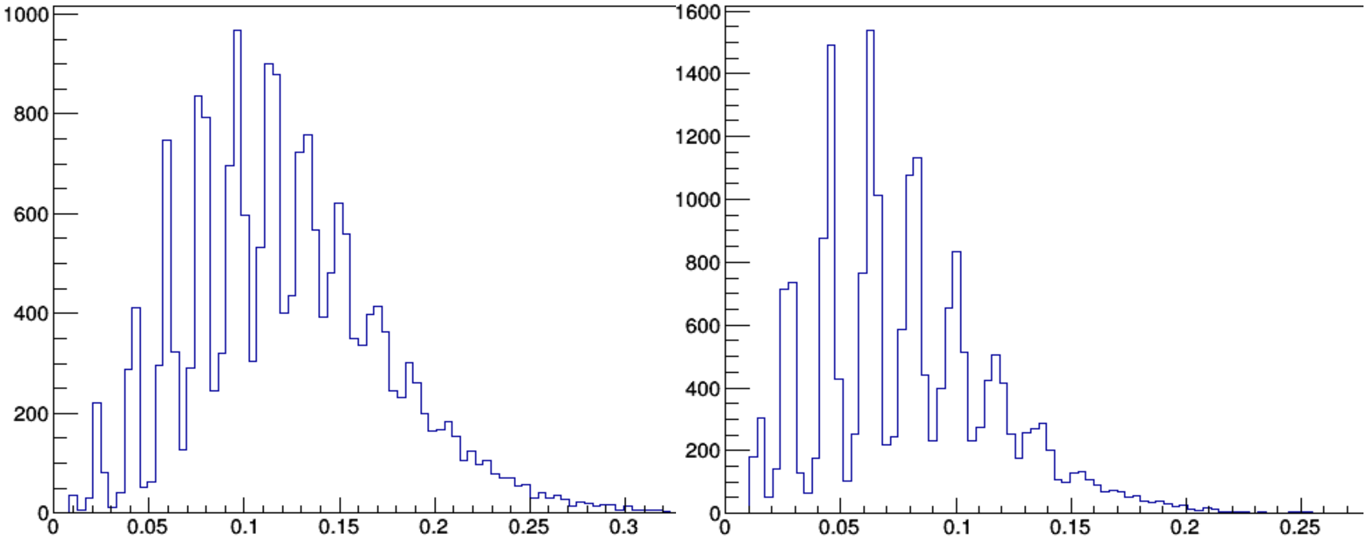

Fig. 9. Signal amplitude distributions for runs without ND filter (left) and with an ND=0.3 filter (right). Both runs were performed on a Hamamatsu SiPM (serial no. S12571-010C), with bias voltage -70.0V. The most common photon counts per event are 5 for no ND filter and ~2.5 for ND=0.3, which is lower by a factor of 2 as predicted.

Future Goals

Similar timing tests should be performed on other Hamamatsu SiPMs: 3x3 mm^2 sensitive area, 25x25, 15x15, and 10x10 um^2 pixel sizes, to obtain the time resolution as a function of number of photoelectrons, and to check the dependence of single-photon time resolution on pixel size. Also, the tails of the time-difference distributions were determined to be due to flaws in the fitting algorithm: events occasionally have secondary pulses that peak at a greater absolute voltage than the main pulse, and as a result these pulses are occasionally selected as the the target for the Gaussian fit by the algorithm. The algorithm will need to be altered such that the main pulse is not the pulse reaching the greatest voltage, but is always the first pulse exceeding a particular threshold amplitude. The time resolutions obtained show promise, but further improvement is required if sillicon-based photodetector technology is still to be used in higher-luminosity particle detection.

Acknowledgments

I acknowledge and am grateful for my mentors while at FNAL, Artur Apresyan, Si Xie, and Anatoly Ronzhin, for their guidance and technical expertise. I would like to acknowledge faculty mentor Prof. Maria Spiropulu for providing experimental material as well as laboratory facilities. Lastly, I would like to acknowledge Caltech SFP for their funding and continued support of this projects and others like it.

References

[1] – A. Ronzhin, M. Albrow, K. Byrum, M. Demarteau, S. Los, E. May, E. Ramberg, J. Va'vra, A. Zatserklyaniy, Tests of Timing Properties of Silicon Photomultipliers. Nucl. Instr. Methods Phys. Res. Sect A 616 (2010) 38-44