Using the Hamamatsu S13615-1050N-08 with a Vertilon PhotoniQ DAQ

Application Note

Overview

The Hamamatsu S13615-1050N-08 is an 8 by 8 silicon photomultiplier array that is ideal for particle physics and other applications where a short pulse of light is created in response to randomly arriving particle events. Its compact size, excellent timing properties, and relatively high photon detection efficiency make it well-suited for use in laboratory experiments that demonstrate SiPM devices in combination with scintillators and software signal processing algorithms.

In this application note we describe a simple, plug-and-play, real-world setup that utilizes a Hamamatsu S13615-1050N-08 SiPM array in combination with standard, off-the-shelf equipment from Vertilon. The equipment is configured to continuously capture and measure quasi-randomly arriving, low-level, short duration optical events. The SiPM array is mounted to a Vertilon SIB1064 sensor interface board that is in turn connected to a Vertilon PhotoniQ IQSP582 charge integrating, 64 channel data acquisition system (DAQ). An optical fiber positioned in front of the array is configured to generate very low levels of short duration (<50 nsec) UV light pulses. The light event is sensed by the SIB1064 whose adjustable discriminator generates a trigger to the IQSP582 DAQ whenever the total signal from the SiPM element exceeds a user-defined threshold. For each trigger, real-time data is displayed in the PhotoniQ's graphical user interface and logged to an attached computer.

The challenge in the described application is in how to reliably trigger the DAQ when a short duration optical event occurs. By the time the event has been detected and trigger generated, the signal from the event is gone. While this problem is typically solved by passing the SiPM signal through a delay line or shaping circuit, it can be impractical when working with the 64 individual SiPM signals from an 8 x 8 array. Further complicating the triggering is the fact that an 8 x 8 array would require 64 discriminator circuits to effectively produce the trigger signal to the DAQ. Although this technique is possible, the added complexity may not be necessary in most applications.

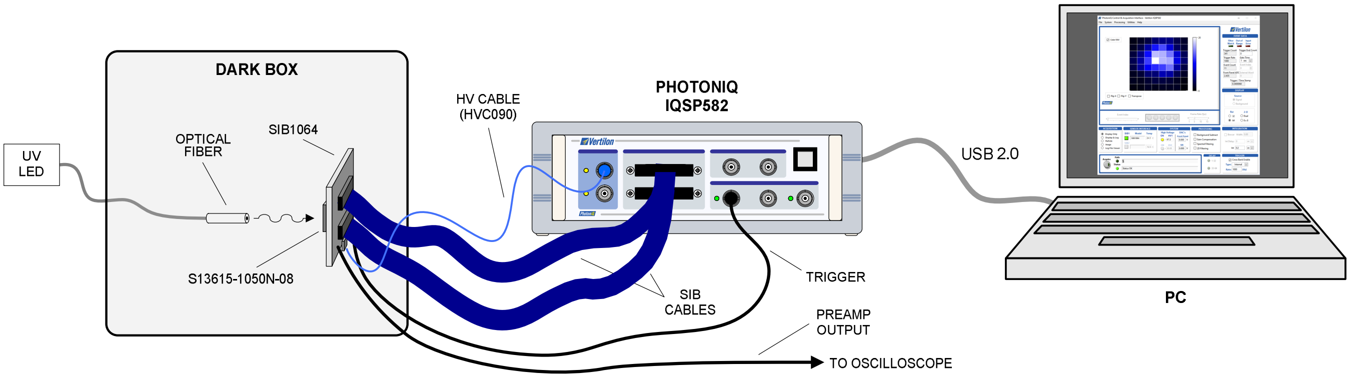
The implementation discussed in this application note balances the tradeoff between circuit / system complexity and system performance. The Vertilon IQSP582 DAQ has a standard trigger mode called *Pre-Trigger*. This mode, which operates in a manner similar to a digital oscilloscope, effectively measures signals that occur prior to the DAQ trigger signal. But unlike a digital oscilloscope, the IQSP582 has 64 parallel channels each performing a continuous integration of the SiPM array's 64 cathode signals. Independently of the trigger signal, the output from each integrator is continuously sampled and stored internally to the IQSP582. The trigger signal is basically used as an index into the stored integrator values so that the desired sample (the sample that includes the short duration light pulse) can be displayed and logged to the computer. Trigger generation is simplified on the SIB1064 by using a signal formed by combining the 64 SiPM anodes to create one input to one discriminator. While this technique results in a higher minimum detectable threshold, it has a much simpler level of complexity than a solution utilizing 64 individual discriminators.

Setup

Data presented in this application note was collected using a setup consisting of a Hamamatsu S13615-1050N-08 8 x 8 SiPM array mounted to a Vertilon SIB1064 sensor interface board, a Vertilon PhotoniQ IQSP582 64 channel charge integrating data acquisition system with standard software, and a custom light-tight enclosure (dark box).

System

The Hamamatsu S13615-1050N-08 silicon photomultiplier array is mounted to the SIB1064 which is positioned inside a light-tight enclosure (dark box) to detect incoming light from an optical fiber driven by an external pulsing 405 nm UV LED source. The 64 cathode outputs from the SIPM array are routed on the SIB1064 to the SIB connectors that connect to the two SBC090 SIB cables that exit the dark box along with the trigger and preamp outputs. The SIB cables carrying the SiPM array signals connect to the PhotoniQ IQSP582's 64 input channels and the SIB1064 trigger output connects to the IQSP582 trigger input. The preamp output is connected to an oscilloscope for monitoring. Additionally, the IQSP582 supplies the user-adjustable SiPM array bias voltage on the HVC090 blue high voltage cable that enters into the dark box. When operating, the discriminator channel on the SIB1064 produces a trigger to the PhotoniQ any time an optical event is detected on one or more of the 64 SIPMs in the Hamamatsu S13615-1050N-08 array. The threshold for the event is adjustable using the SIB1064 popup dialog box accessible through the PhotoniQ graphical user interface. Charge signals from the 64 cathodes of the SiPM array are acquired by the PhotoniQ for each trigger produced by the SIB1064. Digitized output data from the PhotoniQ is sent through a USB 2.0 connection to a PC for display and logging. In the figure below, the PhotoniQ GUI is set to display an 8 x 8 image of the energy levels for each event captured.



Electronics Setup

Software Configuration

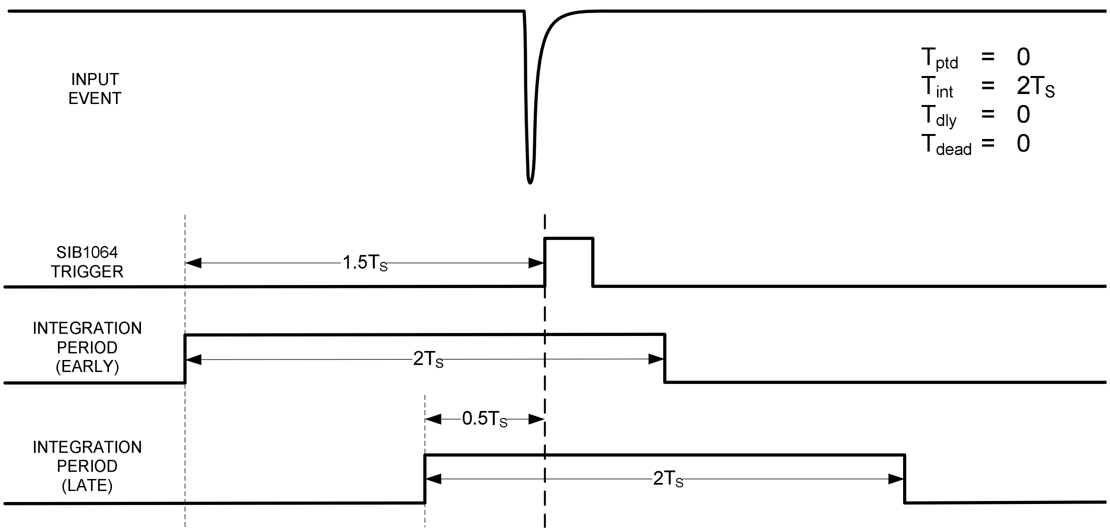
The standard software package included with the PhotoniQ IQSP582 DAQ allows the user to set triggering and acquisition parameters, enable different display modes, control the high voltage bias to the SiPM array, and log data to a file on an attached computer. Additionally, a configuration dialog box specific to the SIB1064 is accessible by pressing the green "SIB1" button on the GUI front panel. Here, several functions on the SIB1064 can also be enabled and adjusted. A complete description of all functionality of the PhotoniQ data acquisition systems and sensor interface boards can be found in the PhotoniQ user manual and SIB1064 user guide. Because some of these functions directly relate to the operation of the system described in this application note, they are described in extra detail below.

Internal Trigger Mode

When set to *Internal* trigger mode, the IQSP582 operates as a free running data acquisition system with the acquisition frequency set by the associated *Rate* parameter. *Internal* trigger mode is most suitable for measuring continuous signals such as electronics leakage current or dark current from the SiPM device. The *Rate* is ideally set to 1000 Hz and the *Integration Period* should be set as long as practical to optimize the accuracy of the measurements.

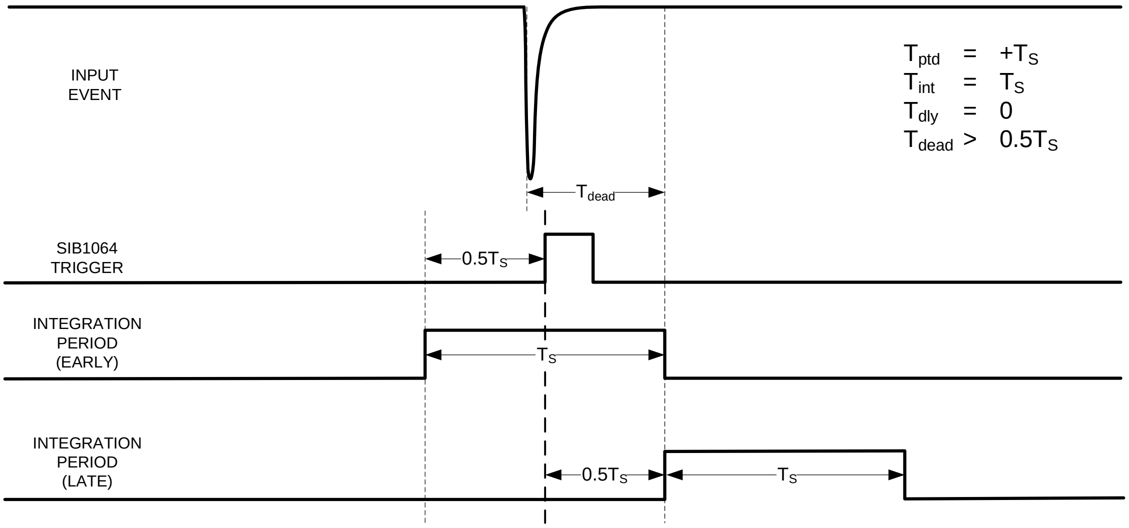
Pre-Trigger Mode

Short-duration, randomly arriving optical events are best captured by using the IQSP582 *Pre-Trigger* mode. The advantage of this mode is that it allows for the integration and capture of narrow light pulses occurring just prior to the arrival of the trigger signal to the DAQ. However, because the IQSP582 is running asynchronously to the trigger from the SIB1064, the integration period can only be positioned relative to the trigger with an accuracy of one sample period (T_S) of the DAQ. Furthermore, the *Integration Period* can only be specified in integer multiples of the sample period. Given these constraints, the *Integration Period* must be set to twice the minimum ($2T_S$) to guarantee that the short duration events are never missed. The disadvantage to this is that noise and dark current are integrated two times longer than necessary. The timing diagram below shows this configuration with the *Pre-Trigger Delay* (T_{ptd}) set to zero. Since *Pre-Trigger* mode has an *Integration Period* uncertainty of one sample period, the two timing extremes are shown in the figure. The *Integration Period* can start as early the "Early" timing signal and as late as the "Late" timing signal. Everything in between is also possible with equal likelihood.



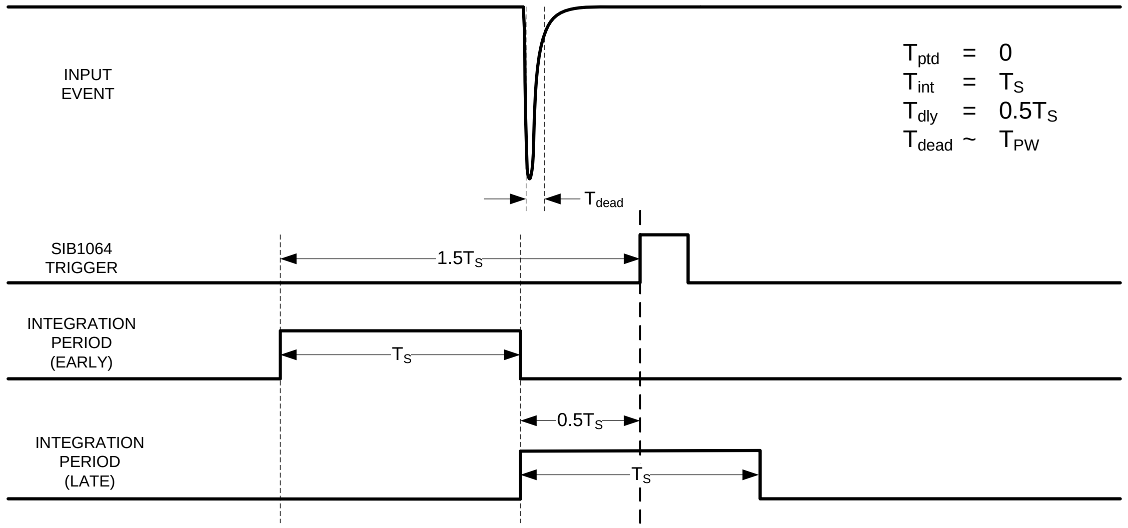
Pre-Trigger Timing ($T_{int} = 2T_S$)

If the noise and dark current are large relative to the event amplitude, the IQSP582 *Pre-Trigger* timing can be configured so that the *Integration Period* is set to the minimum period of T_S. Under these conditions the *Pre-Trigger Delay* is set to one positive sample period ($+T_S$). While this configuration reduces the integrated noise and dark current by a factor of two, a random dead period (T_{dead}) exists whereby the DAQ has the potential to completely miss (or even split) the signal over 50 % of the time. The timing diagram illustrates this case.



Pre-Trigger Timing (T_{int} = T_S)

A tradeoff between the two previously discussed cases utilizes the *Trigger Delay* function that is part of the SIB1064. This function adds an intentional delay (T_{dly}) to the trigger output relative to the optical event. Under ideal conditions this delay is set to one half of the sample period. In the timing diagram below, the *Integration Period* is set to one T_S and the *Pre-Trigger Delay* is set to zero. The likelihood of missing or splitting an event is reduced significantly because the dead time is more or less equivalent to the event pulse width (T_{PW}). A good approximation is that missed / split events occur T_{PW} divided by T_S of the time. For a pulse width of 30 nsec and a sample time of 870 nsec, this equates to about 3.5%.



Pre-Trigger Timing (T_{int} = T_S, Trigger Delay Enabled)

Pre-Trigger Behavior at Low Event Rates

When operating in *Pre-Trigger* mode under low event rate conditions (< 50 Hz), the front end integrators of the IQSP582 may sometimes undergo an automatic reset. This occurs because the integrators (which are always connected to the SiPMs), will approach saturation due to continuous integration of the SiPM dark current. When the event rate is high enough, the integrators will normally be reset immediately after each trigger and thus never have enough time to saturate. However, if the time in between triggers becomes long, the integrators will approach saturation. The IQSP582 will detect this condition and simultaneously reset all 64 integrators back to the baseline. This has the undesirable effect of injecting charge out from the inputs of the IQSP582 and through the SiPMs on the SIB1064. Since the SIB1064 cannot distinguish the charge from the auto-reset from an actual optical event, a trigger to the IQSP582 is inadvertently generated. The result is an event of zero signal on all 64 channels. These events should be flagged in the logged data file and discarded.

The time between auto-resets can be estimated based on the IQSP582's auto-reset threshold and the SiPM's dark current. The auto-reset threshold of the IQSP582 is factory-configured to approximately 850 pC which is near the top of the full scale range. The Hamamatsu S13615-1050N-08 SiPM array has been empirically determined to have a dark current of about 14 nA per element at a bias voltage of 54V. Given these two conditions, the IQSP582 integrators will automatically reset if the time between successive triggers is greater than about 60 msec.

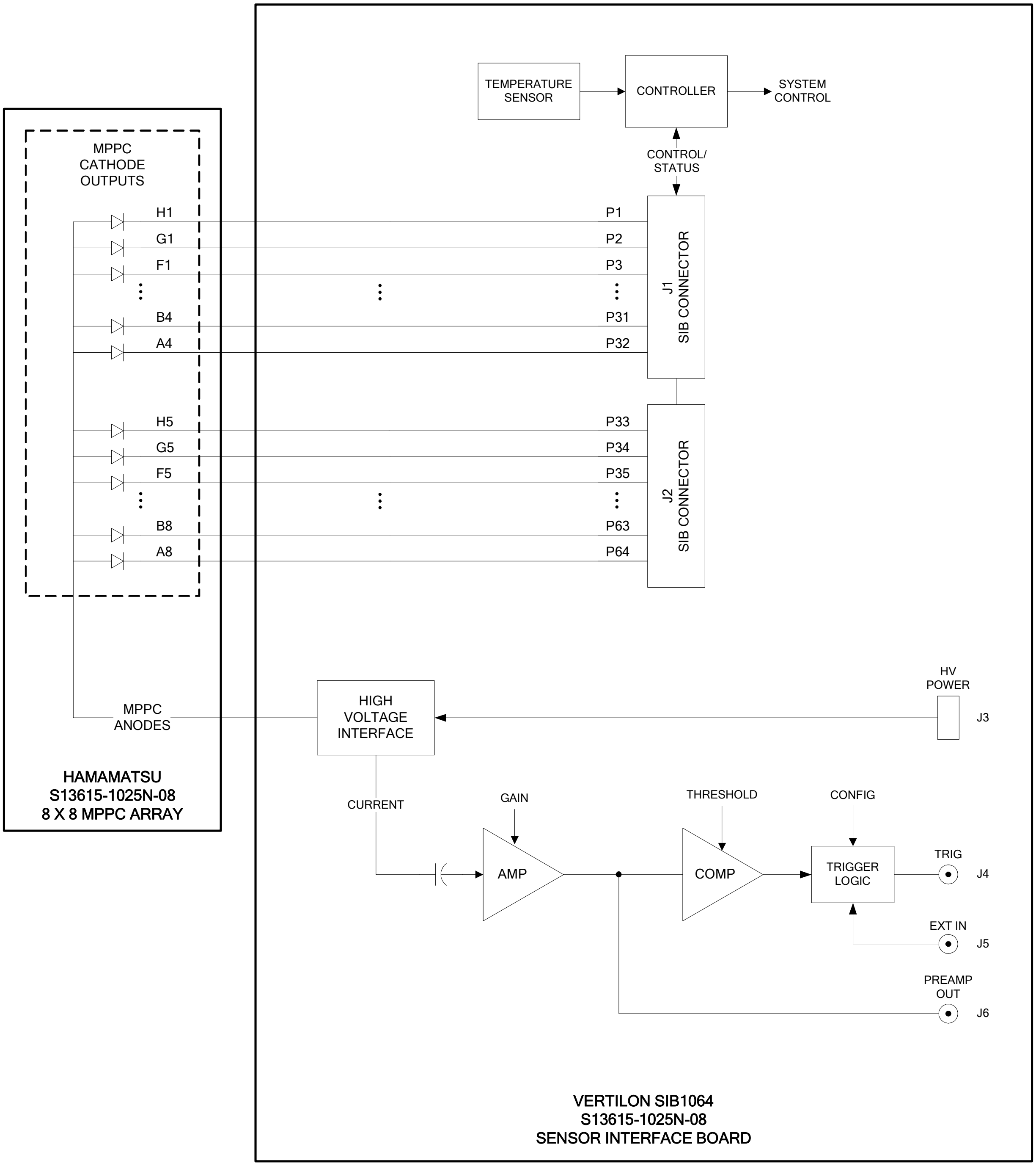
SiPM Array High Voltage Bias

The Hamamatsu S13615-1050N-08 is biased from the IQSP582 internal high voltage bias supply which is connected to the SIB1064 through the HVC090 light blue high voltage cable. This negative voltage is generally set between 51 volts and 63 volts as specified in the Hamamatsu datasheet for the SiPM array. Before the user can access these GUI front panel controls, the supply must first be enabled and configured under the *High Voltage Supplies* item in the *System* dropdown menu. To minimize the potential for damage to the SiPM array, the voltage limit should be set to about 65 volts.

SIB1064 Sensor Interface Board

Block Diagram

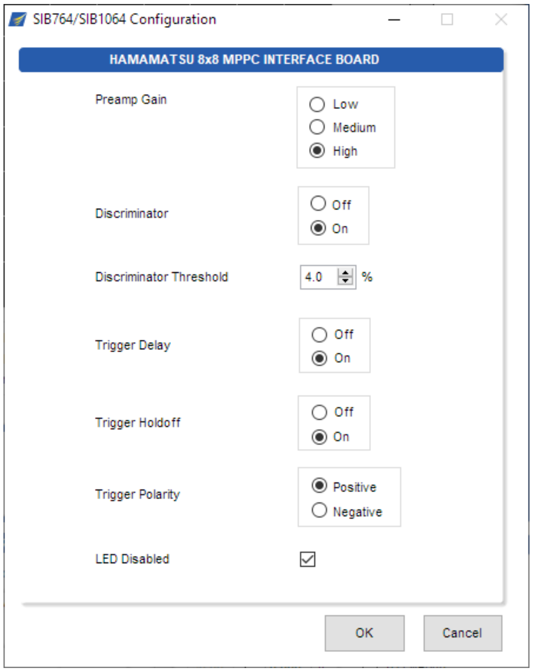
The block diagram for the SIB1064 is shown below. For a detailed description of its operation, refer to the User Guide.



SIB1064 Functional Block Diagram

Discriminator Operating Conditions

The operating parameters for the preamp and discriminator on the SIB1064 sensor interface board are set through the PhotoniQ IQSP582 graphical user interface and are generally determined empirically. The SIB1064 discriminator generates a logic signal when a pulse from the preamplifier exceeds a user-defined threshold. The SIB1064 GUI dialog box allows the user to set this threshold between 0 and 50% where 50% is equal to one half of the maximum possible signal amplitude in the discriminator channel. When a pulse is detected, the trigger output from the board becomes active. For this application the *Trigger Polarity* is set to *Positive*. Additionally, the *Trigger Delay* and *Trigger Holdoff* are both enabled. The IQSP582 GUI dialog box shown below shows the configuration parameters for this setup although the *Discriminator Threshold* was often varied to optimize performance.



SIB764/SIB1064 Configuration

HAMAMATSU 8x8 MPPC INTERFACE BOARD

Preamp Gain: ○ Low ○ Medium ● High

Discriminator: ○ Off ● On

Discriminator Threshold: 4.0 %

Trigger Delay: ○ Off ● On

Trigger Holdoff: ○ Off ● On

Trigger Polarity: ● Positive ○ Negative

LED Disabled: ☑

SIB1064 Dialog Box

Discriminator Threshold Level

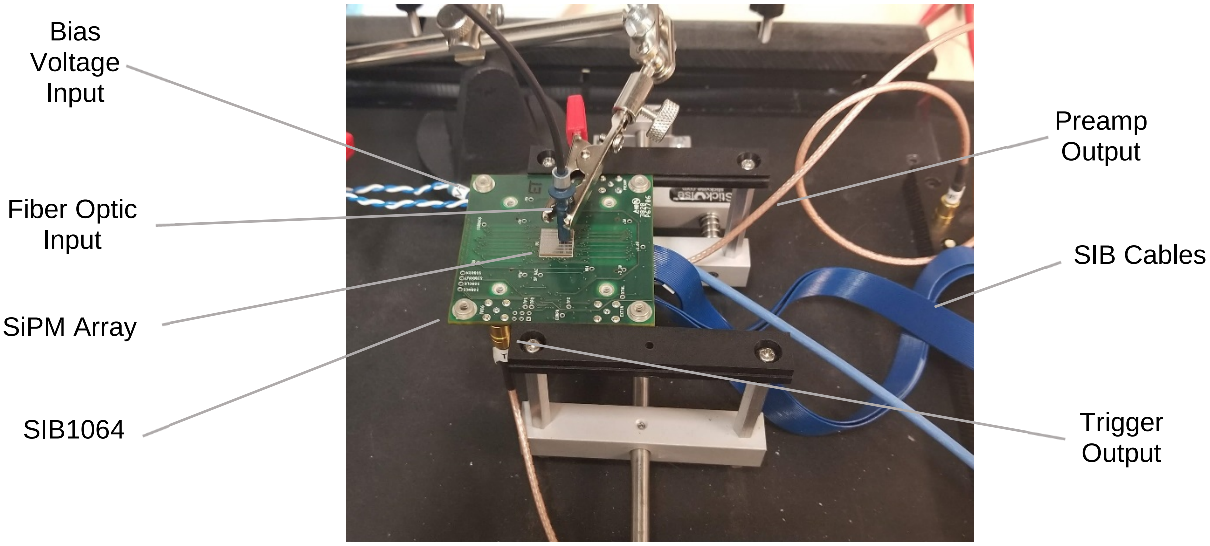
The bias to the SiPM array is set to a level such that the dominant noise source at the discriminator input is due to the device dark counts. Given this, the discriminator threshold is set just above this noise level so as to minimize false triggers to the IQSP582 data acquisition system. The Hamamatsu datasheet specifies the dark count to be between 90 Kcps and 270 Kcps for each SiPM element. Because the anodes from the 64 elements in the SiPM array on the SIB1064 are connected together, the dark count at the discriminator input is much higher than the dark count from a single element in the array. Assuming that the dark count mechanisms for each element are completely independent, the dark count rate at the discriminator input will be 64 times higher (5.8 Mcps to 17.3 Mcps). Piled-up dark counts within the preamp bandwidth directly impact the practical lower limit for the discriminator threshold.

Dark Box

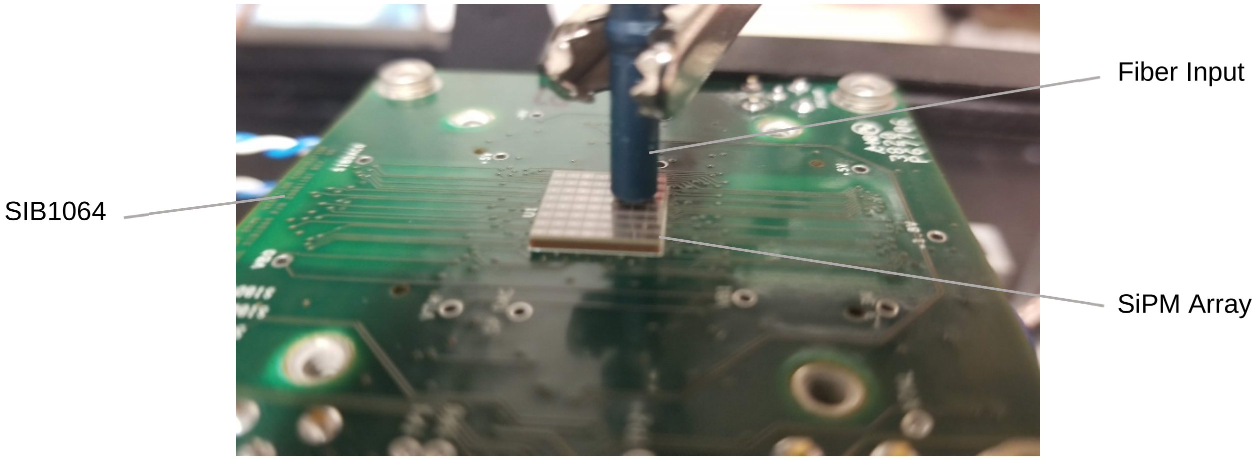
The exterior and interior views of the light-tight enclosure as well as the connections to other electronic equipment are shown in the photos below. The SIB1064 with the S13615-1050N-08 SiPM array attached is situated inside of the enclosure with associated cabling. The exterior electrical connections are located on the right side of the enclosure and consist of the SIB cables that carry the 64 cathode signals from the SiPM array, the trigger and preamp outputs, and the high voltage bias input. The fiber optic input that is located on the left side of the enclosure provides the 405 nm pulsed optical signal to the array. In the photos of the interior view of the dark box, the fiber optic signal is located directly above the SiPM array and positioned so that the incident signal illuminates only one detector in the array. Several other unused cables and connectors can be noticed in these photos. They are built into the dark box and are not used in this application.

Light-Tight Enclosure (Electrical Connections)

Light-Tight Enclosure (Fiber Optic Input)



Light-Tight Enclosure (Interior View)



SiPM Array Fiber Optic Coupling

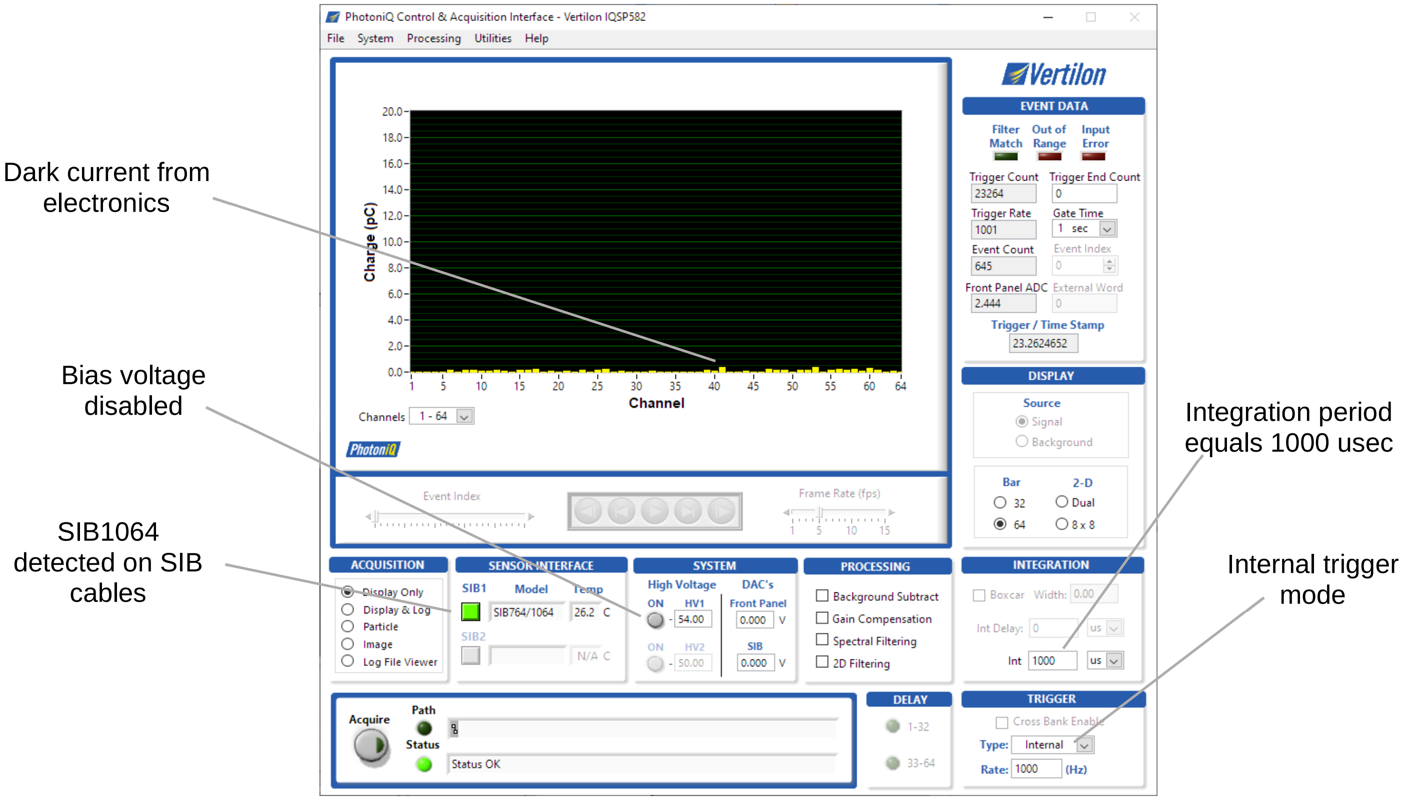
Experimental Data

The oscilloscope traces and GUI screenshots in this application note were taken by connecting all cabling as previously discussed and by operating the IQSP582 GUI in Display mode. The experimental data was collected by following the procedure listed below.

- <u>IQSP582 Electronic Dark Current:</u>	Observe / record in the GUI display
- <u>SiPM Array Bias:</u>	Enable and adjust the high voltage bias
- <u>SiPM Array Dark Current:</u>	Observe / record in the GUI display
- <u>Discriminator Parameters:</u>	Enable the UV LED and setup the discriminator
- <u>Optical Signal Level:</u>	Observe / record in the GUI display

IQSP582 Electronic Dark Current

The electronic dark current of the IQSP582 is best characterized by disabling the SiPM array bias and operating the DAQ in *Internal* trigger mode (free running). The free running mode is necessary because the SIB1064 will not generate triggers when the SiPM array is not biased. Since the optimum *Integration Period* of the unit in *Pre-Trigger* mode is 870 nsec (one sample wide), it normally would be best to also use 870 nsec for this setup. However, because the dark current of the IQSP582 is so low, this relatively short integration time is not long enough to observe any noticeable signal in the GUI display. The figure below shows some perceptible dark current when the *Integration Period* is set to a value that is considerably higher than the one sample time of 870 nsec.



Dark current from electronics

Bias voltage disabled

SIB1064 detected on SIB cables

Integration period equals 1000 usec

Internal trigger mode

Channels: 1 - 64

Trigger Count: 23264
Trigger End Count: 0
Trigger Rate: 1001
Gate Time: 1 sec
Event Count: 645
Event Index: 0
Front Panel ADC: 2.444
External Word: 0
Trigger / Time Stamp: 23.2624652

Source: ● Signal ○ Background
Bar: ○ 32 ● 64
2-D: ○ Dual ○ 8 x 8

Acquisition: ● Display Only ○ Display & Log ○ Particle ○ Image ○ Log File Viewer

Sensor Interface: SIB1 Model SIB764/1064 Temp 26.2 C; SIB2 N/A C

High Voltage ON HV1 - 54.00; ON HV2 - 50.00
DAC's: Front Panel 0.000 V; SIB 0.000 V

Processing: ☐ Background Subtract ☐ Gain Compensation ☐ Spectral Filtering ☐ 2D Filtering

Integration: ☐ Boxcar Width: 0.00
Int Delay: 0 us
Int 1000 us

Trigger: ☐ Cross Bank Enable
Type: Internal
Rate: 1000 (Hz)

Path
Status: Status OK

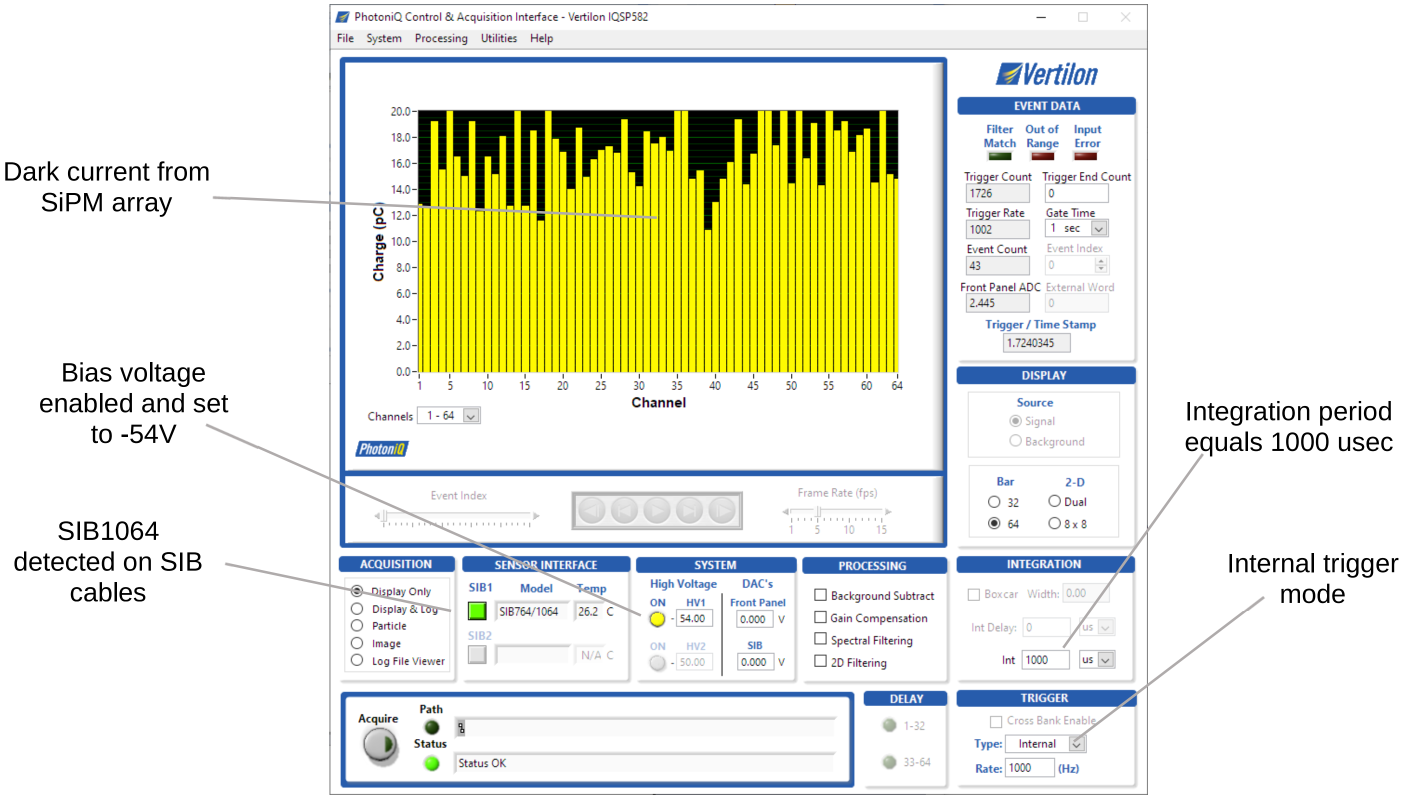
IQSP582 Dark Current

SiPM Array Bias

The recommended operating voltage (V_{OP}) of the SiPM array as specified in the Hamamatsu datasheet varies over a large range. While V_{OP} is specified as the device breakdown voltage (V_{BR}) plus an overvoltage (V_{OV}) of 3 volts, the breakdown voltage itself is specified as 53V ± 5V. Even if V_{BR} could be accurately specified, the recommended overvoltage may not necessarily be optimum for the given application. The device photon detection efficiency (PDE), dark count, crosstalk probability, and gain are all affected by the operating voltage. The data presented in this application note optimizes the SiPM array operating voltage as it relates to the gain of the device and does not consider the other device specific parameters. In particular, the V_{OP} for the SiPM array is set so that the dark noise from the device slightly exceeds the electronics noise at the preamp out (discriminator input) on the SIB1064. The method used to empirically determine the optimum bias voltage is to start with the voltage at a minimum and increase it until the noise on the preamp output begins to increase. The resulting bias voltage is 54V.

Device Dark Current

Like the electronic dark current of the IQSP582, the SiPM array dark current is not easily observable at an *Integration Period* of 870 nsec. The IQSP582 is therefore operated again at an *Integration Period* of 1000 usec. The nominal charge generated in the 1000 usec interval across all 64 SiPM elements is about 14 picocoulombs (pC). This corresponds to a dark current of about 14 nA. The Hamamatsu datasheet specifies a dark count between 90 Kcps and 270 Kcps. Using 1.6 x 10^{-19} coulombs for the electronic charge and 1.7 x 10^6 as the nominal gain of the SiPM array, the expected dark current is between 24 nA and 73 nA. The most likely explanation for the discrepancy between the specified and measured device dark current is the uncertainty in the SiPM gain. At an operating voltage of 54V, the SiPM array is likely operating at a gain below 1.0 x 10^6.



Channels 1 - 64

Trigger Count 1726
Trigger End Count 0
Trigger Rate 1002
Gate Time 1 sec
Event Count 43
Event Index 0
Front Panel ADC 2.445
External Word 0
Trigger / Time Stamp 1.7240345

Source: ● Signal ○ Background
Bar: ○ 32 ● 64
2-D: ○ Dual ○ 8 x 8

● Display Only
○ Display & Log
○ Particle
○ Image
○ Log File Viewer

SIB1 Model SIB764/1064 Temp 26.2 C
SIB2 N/A C

High Voltage: ON HV1 - 54.00
ON HV2 - 50.00
DAC's: Front Panel 0.000 V
SIB 0.000 V

☐ Background Subtract
☐ Gain Compensation
☐ Spectral Filtering
☐ 2D Filtering

☐ Boxcar Width: 0.00
Int Delay: 0 us
Int 1000 us

Path
Status: Status OK

Delay: 1-32, 33-64

☐ Cross Bank Enable
Type: Internal
Rate: 1000 (Hz)

Dark current from SiPM array

Bias voltage enabled and set to -54V

SIB1064 detected on SIB cables

Integration period equals 1000 usec

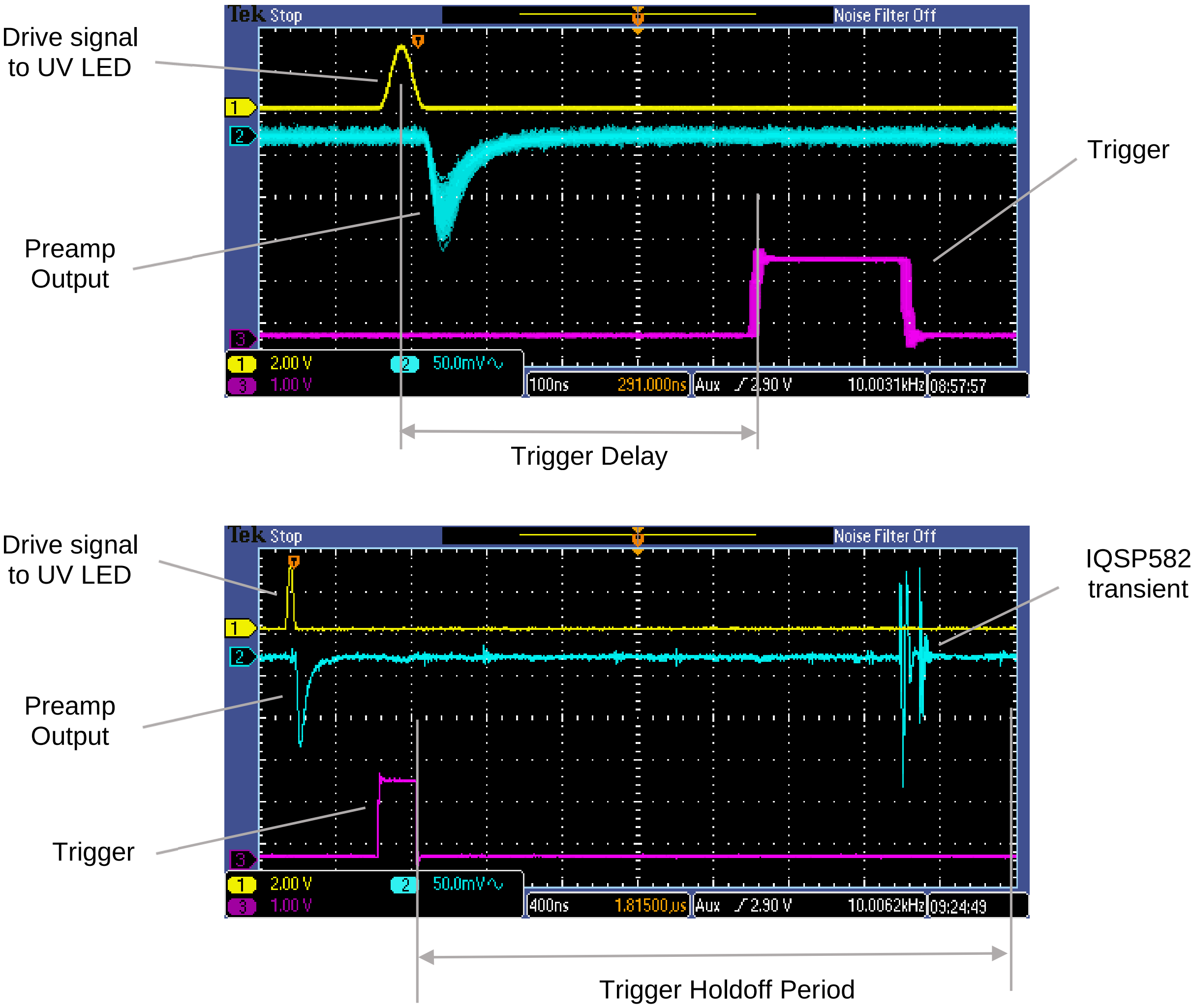
Internal trigger mode

SiPM Array Dark Current

Discriminator Parameters

The bias to the SiPM array is set to a level such that the dominant noise source at the discriminator input is due to the device dark counts. With the UV LED enabled, the discriminator threshold is set just above the noise level such that the light pulse is the only source of the triggers. This setting minimizes false triggers to the IQSP582 data acquisition system. In the figure below, the upper oscilloscope trace shows the LED drive signal, preamp output, and trigger output when the discriminator threshold is set to 4% (~ 40 mV at the discriminator input). The *Trigger Delay* is enabled so that the actual trigger signal to the IQSP582 DAQ is generated approximately 435 nsec after the optical event occurs. As previously discussed, this feature improves the signal quality by minimizing unnecessary signal integration time in the DAQ.

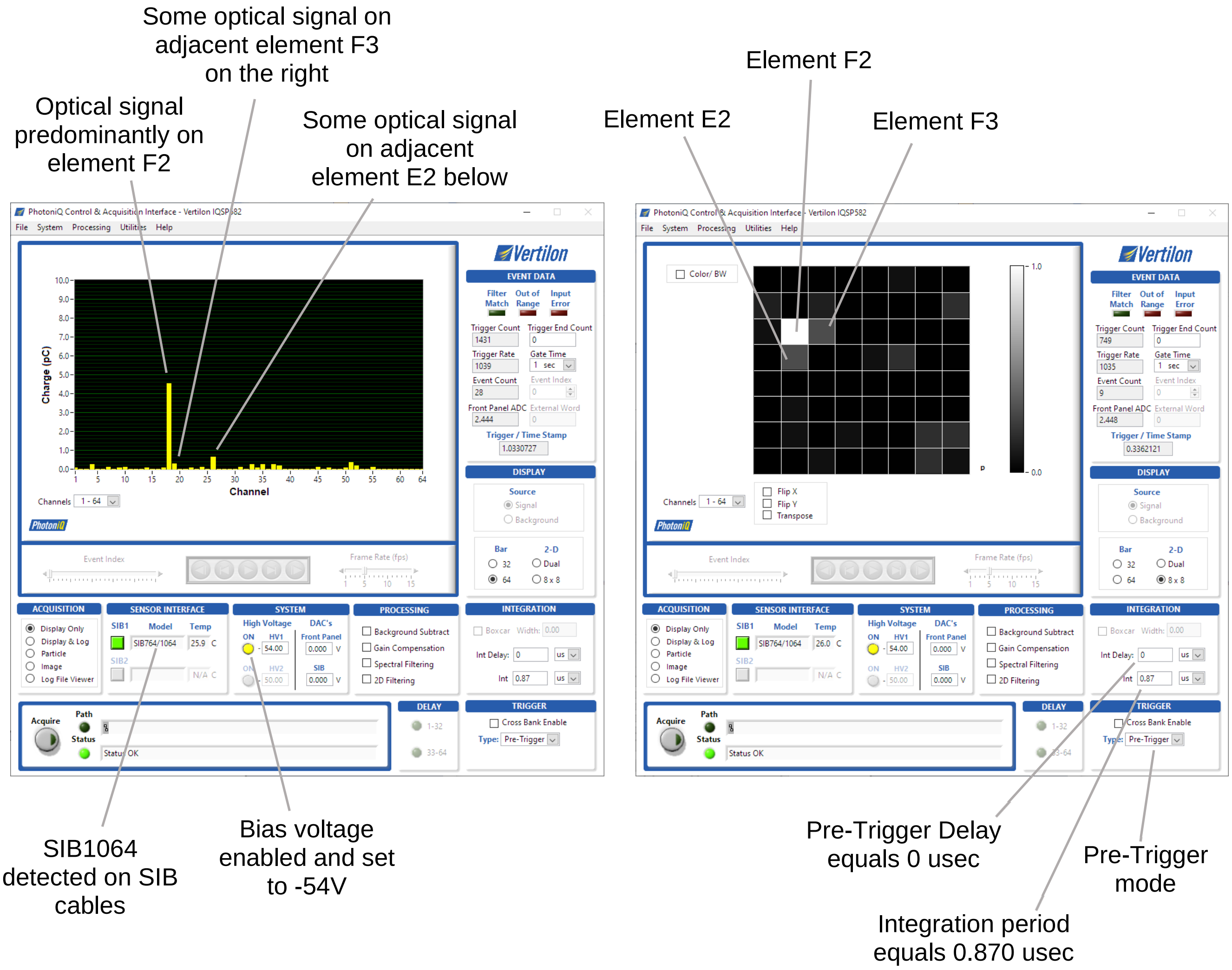
The lower oscilloscope trace shows the same configuration but over a longer time scale. Approximately 3 usec after the trigger signal is generated, a transient created by the IQSP582 appears on the SIB1064 preamp output. The transient results from the resetting of the internal integrators in the DAQ. It is coupled into the 64 cathodes connected to the IQSP582 inputs through each SiPM element's capacitance (~40 pF) and into the SIB1064 preamp input. The transient is large enough that under some conditions it could retrigger the discriminator. By enabling the *Trigger Holdoff* feature on the SIB1064, additional triggers are blocked until the transient has died out. Enabling the *Trigger Holdoff* has little effect on the IQSP582 trigger rate because the unit ordinarily cannot retrigger until well after the transient disappears.



Discriminator Timing

Optical Signal Level

The optical signal is displayed in the PhotoniQ IQSP582 graphical user interface display window. The figure below shows the GUI display side-by-side in 64 channel bar graph mode and 8 x 8 2D mode. Total charge from the optical event (which spans across three elements) is about 5 pC. Using 1.6 x 10^{-19} coulombs for the electronic charge and 0.5 x 10^6 as the gain of the SiPM array, the incident signal is estimated at 62 photons. Channel 19 of the bar graph below clearly shows the DAQ system's ability to resolve signals below 5 photons. These displays were created by setting the discriminator threshold to a level that only occasionally produced triggers from the SiPM dark counts. By setting the threshold even lower (or setting the SiPM array bias even higher), the SIB1064 will generate triggers for smaller optical signals. The drawback to this is the additional data created by the triggers from piled-up dark counts that are unrelated to external optical events. However, although additional unnecessary triggers occur, post processing of the logged data can be performed to selectively sort through actual optical events. This is possible because piled-up dark count triggers will result in charge signals distributed across the 64 elements of the SiPM array while actual optical events would likely only appear on at most, three or four adjacent elements.



Trigger Count 1431; Trigger End Count 0; Trigger Rate 1039; Gate Time 1 sec; Event Count 28; Front Panel ADC 2.444; Trigger / Time Stamp 1.0330727; Channels 1 - 64; SIB1 Model SIB764/1064, Temp 25.9 C; HV1 -54.00; Front Panel 0.000 V; SIB 0.000 V; Int Delay 0 us; Int 0.87 us; Type: Pre-Trigger; Status OK

Trigger Count 749; Trigger End Count 0; Trigger Rate 1035; Gate Time 1 sec; Event Count 9; Front Panel ADC 2.448; Trigger / Time Stamp 0.3362121; Channels 1 - 64; SIB1 Model SIB764/1064, Temp 26.0 C; HV1 -54.00; Front Panel 0.000 V; SIB 0.000 V; Int Delay 0 us; Int 0.87 us; Type: Pre-Trigger; Status OK

Optical Signal Response

Related Documents

SIB1064 Product Sheet:	https://vertilon.com/pdf/PS2748.pdf
SIB1064 User Guide:	https://vertilon.com/pdf/UG2877.pdf
IQSP582 Product Sheet:	https://vertilon.com/pdf/PS2710.pdf
PhotoniQ Data Acquisition Systems User Manual:	https://vertilon.com/pdf/UM6177.pdf
Hamamatsu S13615-1050N-08 Data Sheet:	https://www.hamamatsu.com/resources/pdf/ssd/s13615_series_kapd1062e.pdf

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