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March 28, 2011

Introduction: what is the SiPM?

The Silicon PhotoMultiplier (SiPM) consists of a high-density (up to ~10^3 /mm^2) matrix of diodes connected in parallel on a common Si substrate. Each diode is an Avalanche Photo Diode (APD) operated in a limited Geiger-Müller regime connected in series with a quenching resistance, in order to achieve gain at level of 10^5 - 10^6. Fig. 1 shows the equivalent circuit of a SiPM. As a consequence, these detectors are sensitive to single photons (even at room temperature) feature a dynamic range well above 100 photons/burst and have a reasonable Photon Detection Efficiency (PDE). Moreover the SiPM measures the light intensity simply by the number of fired cells.

The CAEN **SP5600B Evaluation Kit** provides two different 1x1 mm^2 SiPM from Hamamatsu, the MPPC[(1)] S10362-11-25C and the MPPC S10362-11-100C in order to study the behaviour of the two extreme side sensors. The 25C with its 1600 cells has a wide dynamic range but a low fill factor and, as a consequence, a low PDE; on the other hand, the 100C, due to its 100 cells, has a narrow dynamic range but a high fill factor.

[(1)] *MPPC® (Multi-Pixel Photon Counter) is a trademark of Hamamatsu Photonics.*

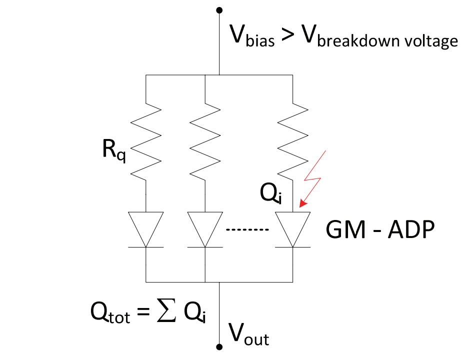
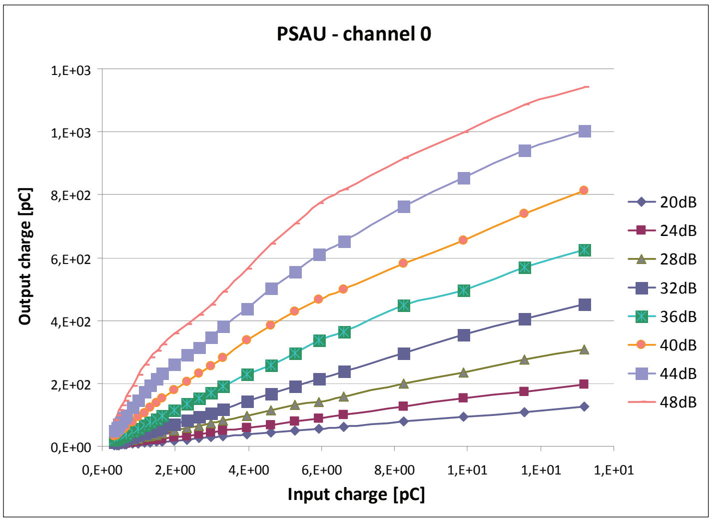


Fig. 1: Equivalent circuit of a SiPM: each pixel provides information on whether or not it is fired.

Before the SiPM measurement: the linearity of the PSAU



Before starting the measurement with the SP5600 - 2 Channels Power Supply and Aplification Unit (PSAU) and the Digitizer, it's necessary define the linearity of the amplification of the PSAU. The Fig. 2 shows the output charge versus the input charge for one PSAU channel at different amplification gain. At high amplification gain values (G > 40dB) the amplifier of the PSAU shows the saturation effects.

Fig. 2: PSAU Linearity

The first measurement: the Gain of the SiPM and the resolution power

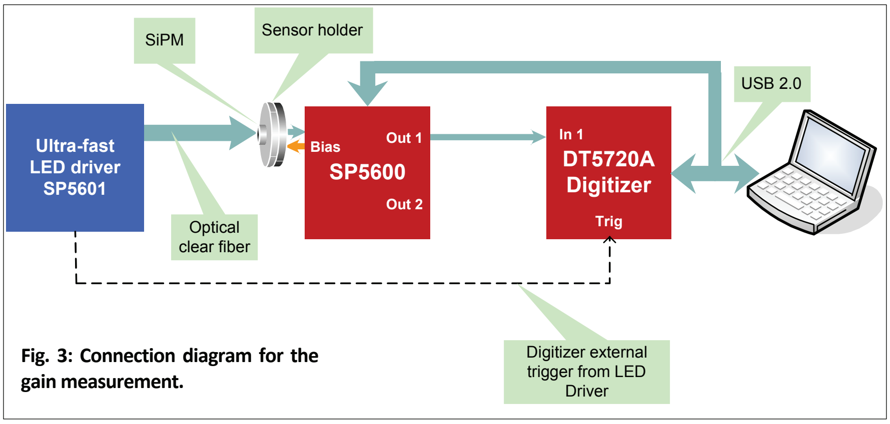


Fig. 3: Connection diagram for the gain measurement.

The gain of the SiPM can be evaluated from the output charge of the sensor. Fig. 3 shows the CAEN set-up diagram: the light pulse from the SP5601 ultra-fast LED-Driver is driven through an optical clear fiber into the SP5650X SiPM holder housing the sensor under test and connected to the PSAU. The output signal (from the PSAU) is connected to the input channel of the DT5720A Desktop Digitizer equipped with the charge integration firmware, and triggered by the LED-driver.

The PSAU and the Digitizer are connected to the PC through the USB.

The LabView graphical user interface (GUI) supports the user into setting the devices parameters and performing the measurement.

Fig. 4 shows the GUI main panel: the left-upper side refers to the PSAU, the left-bottom side refers to the Digitizer, the right side refers to the visualization of the measurements and of the data storage

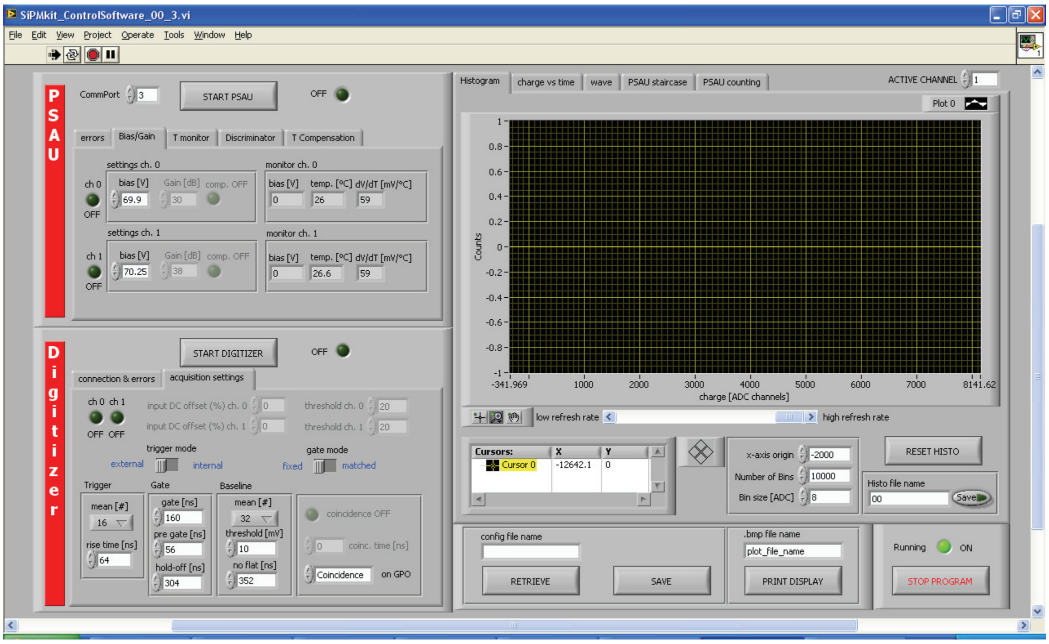


Fig. 4: The LabView GUI main panel.

Let's start with the devices

After checking the communication port of the PSAU, start the PSAU itself clicking on "START PSAU" (the green light 'ON' switches on). Switch on the channel where the SiPM is mounted, set the SiPM nominal operation voltage (in this example a bias of 69.9 V is set) and set the gain of the amplifier of the PSAU (in this example a gain of 30dB is set).

Start the Digitizer clicking on "START DIGITIZER" (the related green light 'ON' switches on), set trigger mode as "external trigger" (the Led-Driver is triggering the acquisition) and set the level of the trigger as 'NIM level' in the PSAU discriminator tab.

Now the system is up and ready to run.

Choosing the right Digitizer parameters for the acquisition

The Digitizer has a special firmware dedicated to SiPM. In the external triggering mode, the only parameters the user has to set are the "Gate parameters" in order to allow the firmware to integrate all the digitized signal. Fig. 5 shows the signal, the gate and the baseline traces related to a gate of 160 ns and a pre-gate of 56 ns for a Hamamatsu MPPC S10362-11-100C.

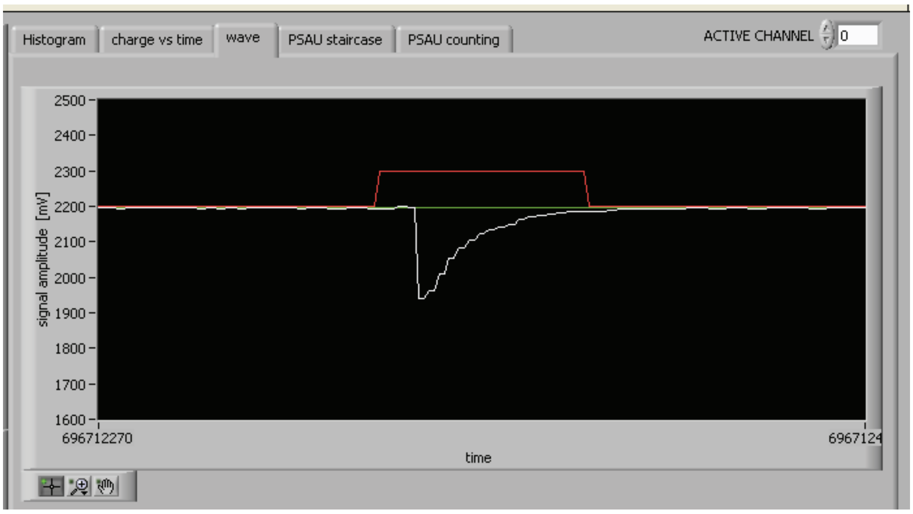


Fig. 5: The trace of a SiPM; the white line is the input signal, the red line is the gate and the green line represents the calculated baseline.

Calculating the Gain

Fig. 6 and Fig. 7 show the spectra for Hamamatsu S10362-11-100C and S10362-11-25C, obtained for the same illumination. The horizontal axis is the ADC channels. The **ADC channel conversion factor** can be calculated according to the following equation:

$$\frac{ADC\ channel}{Coulomb} = \frac{V_{pp}}{R_{IN}} \cdot \frac{1}{2^{Nbit}} \cdot \Delta t \cdot \frac{1}{G_{PSAU}} \qquad [1]$$

V_{pp} = 2V, Digitizer dynamic range
R_{IN} = 50Ω Digitizer Input impedance
Nbit = 12 bit Digitizer resolution
Δt = 4 ns, Digitizer sampling period
G_{PSAU} = 38 for 25*C*, 30 for 100*C*, PSAU gain

The calculated ADC channel conversion factor is 1.235 f*C*/ADC for 100C and 0.492 f*C*/ADC for 25C.

Referring to the Fig. 6 and Fig. 7, the distance between adjacent peaks is the output charge of one detected photon. According to the following equation, the Gain of the two sensors is estimated:

$$Gain = \frac{2\ peaks\ distance\,[ADC\ channel] \cdot ADC\ conversion\ rate}{charge\ of\ electron}$$

Obtaining:

$$Gain_{100C} = \frac{292 \cdot 1.235 \cdot 10^{-15}}{1.6 \cdot 10^{-19}} = 2.25 \cdot 10^{6} \qquad Gain_{25C} = \frac{93 \cdot 0.492 \cdot 10^{-15}}{1.6 \cdot 10^{-19}} = 2.86 \cdot 10^{5}$$

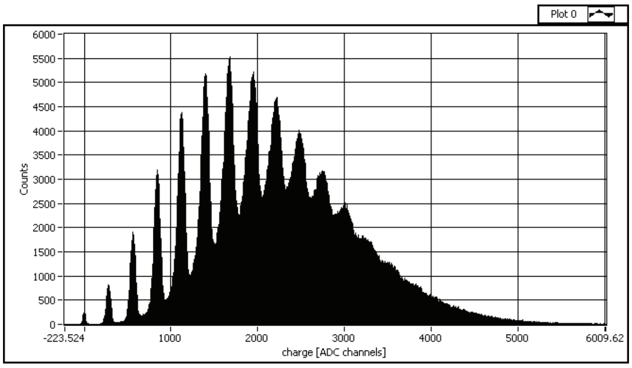


Fig. 6: Spectrum of Hamamatsu S10362-11-100C; Digitizer parameters: gate = 160ns, pre-gate = 56 ns; PSAU parameters: bias = 69.90 V, gain = 30 dB.

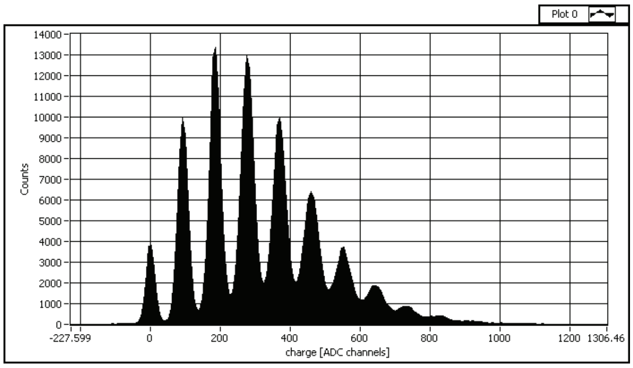


Fig. 7: Spectrum of Hamamatsu S10362-11-25C; Digitizer parameters: gate = 88 ns, pre-gate = 56 ns; PSAU parameters: bias = 70.40 V, gain = 38 dB.

The gain of the sensor varies with the applied reverse voltage. Fig. 8 and Fig. 9 show the Gain of the 100C and 25C for different bias. These results show the linear behaviour of the Gain versus the bias voltage.

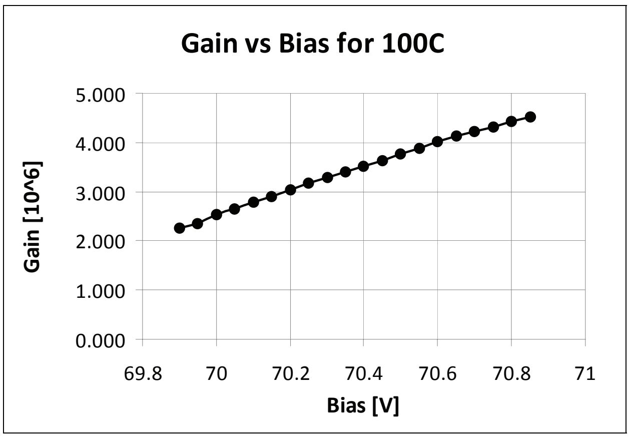


Fig. 8: Gain versus bias for Hamamatsu S10362-11-100C.

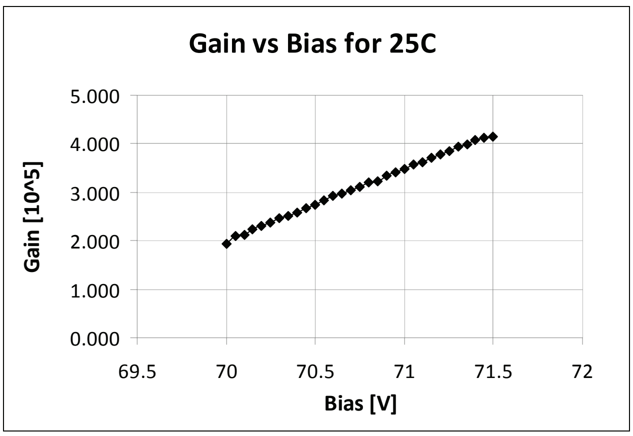


Fig. 9: Gain versus bias for Hamamatsu S10362-11-25C

Defining the resolution power

Fixed the gain of the PSAU amplifier and the bias, and, as a consequence, the gain of the SiPM, the resolution power of the system can be evaluated plotting the σ of each peaks versus the number of peaks. Fig. 10 and Fig. 11 show the resolution power for 100C and 25C, for a fixed light intensity.

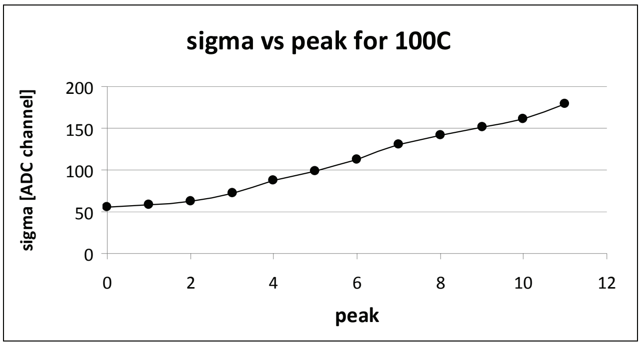


Fig. 10: Peak σ versus peak number for Hamamatsu S10362-11-100C.

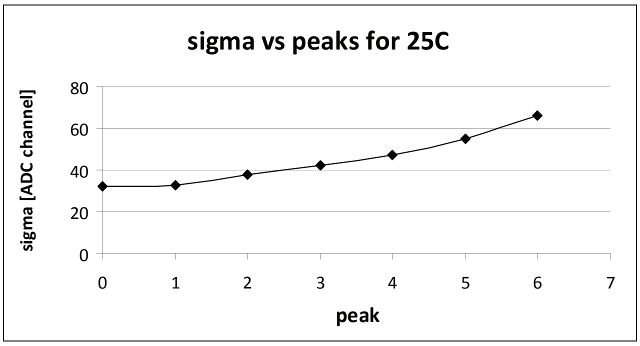


Fig. 11: Peak σ versus peak number for Hamamatsu S10362-11-25C..

The DCR

The noise of the SiPM is represented by the registered number of counts in *absence of light.* This device, being a solid state device, generates noise due to thermal excitation, limiting its single photon detection capability. This noise occurs randomly, and its frequency, called Dark Count Rate (DCR) is essential in estimating the SiPM characteristics.

The Fig. 12 shows a typical scope trace of a SiPM: the signal of different number of cells is well defined. Since the pulse output from a pixel is independent respect to the number of incoming photons, the different traces, even in the absence of light, can be referred to the different photo-electron level.

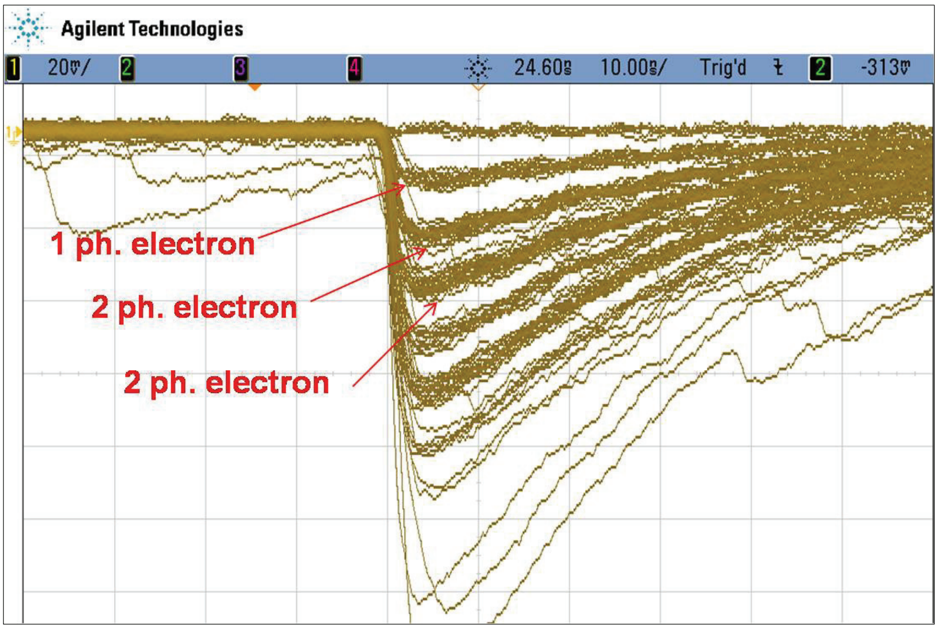


Fig. 12: typical scope trace of a SiPM: the signal corresponding to different number of cells is well defined.

The DCR of a SiPM is the frequency of the pulse of the one photo-electron level; this frequency makes difficult to distinguish a spurious hit generated from the intrinsic noise of the sensor from the signal obtained when a pixel is fired. However the dark count at 2 photo-electron, 3 photo-electron or 4 photo-electron level is unlikely: when a large amount of photons impinges the sensor, the effect of DCR can 'virtually' removed by setting a proper threshold level. On the other hand, when a small amount of photons are detected, the DCR blinds the sensor; this effect is removed setting an appropriate gate time during the measurement if the arrival time of the light is known. As a consequence, the use of the Led-Driver SP5601 to illuminate the SiPM with a small intensity of light suggests the external trigger mode of the digitizer DT5720A.

Measuring the DCR

The PSAU allows the user to measure the DCR of the sensor under test. The 'PSAU staircase' tab (Fig. 13) gives the possibility to scan the rate of the SiPM signals that are over a certain threshold.

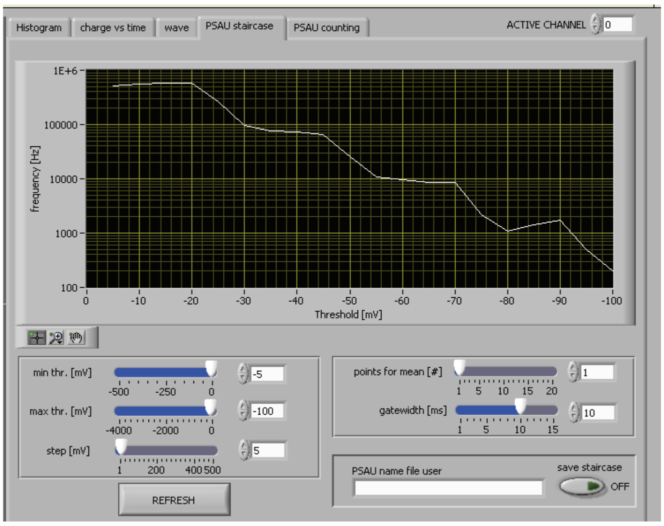


Fig. 13: The "PSAU staircase" tab.

Setting the threshold at 0.5 photo-electron and counting the number of pulses that exceed this value gives the number of times that one or more photons are detected. Setting the threshold at 1.5 photo-electron and counting the number of pulses that exceed this value gives the number of times that two or more photons are detected. Counting the number of pulses that exceed the threshold at N-0.5 photo-electron gives the number of times that N or more photons are detected.

The described procedure can be done automatically, setting the starting and final value for the threshold [mV], the step [mV], the number of acquired points for each threshold value, and the gate time [ns] for the counting. Fig. 14 and Fig. 15 show the acquired threshold scans for the 100C and 25C at different bias.

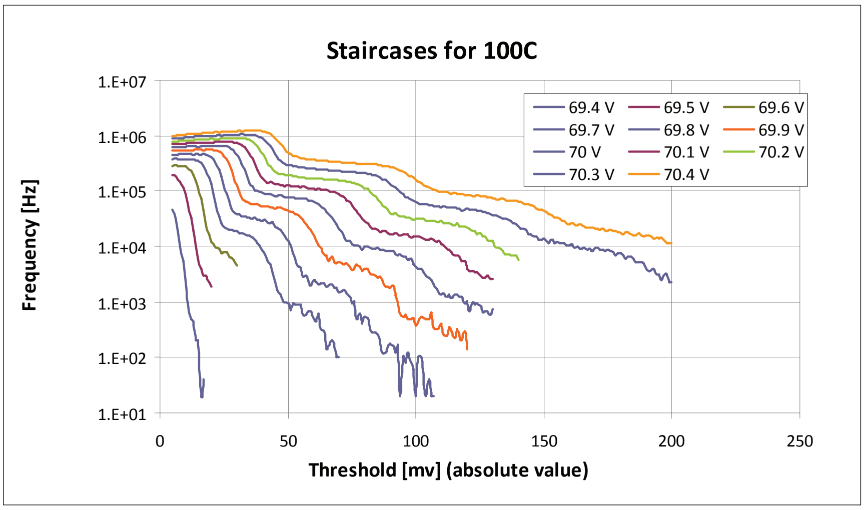


Fig. 14: Staircases for the Hamamatsu S10362-11-100C at different bias.

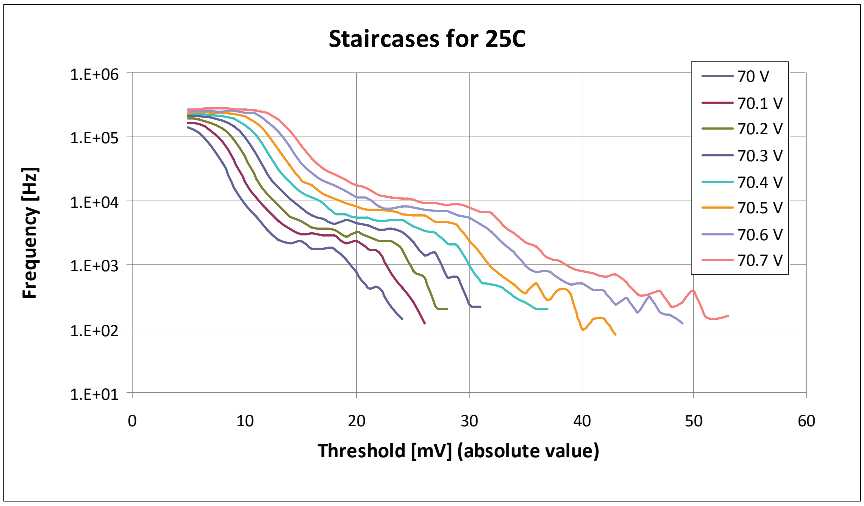


Fig. 15: Staircases for the Hamamatsu S10362-11-25C at different bias.

Looking at the data plotted in Fig. 16 and Fig. 17, is possible to show some example measurements of dark count rate for 0.5 photo-electron and 1.5 photo-electron threshold. Fig. 16 and Fig. 17 show the dark count versus bias for the two SiPM.

The ratio between the dark count at 0.5 p.e. threshold ($DCR_{0.5}$) and the value at 1.5 p.e. threshold ($DCR_{1.5}$) is the definition of crosstalk.

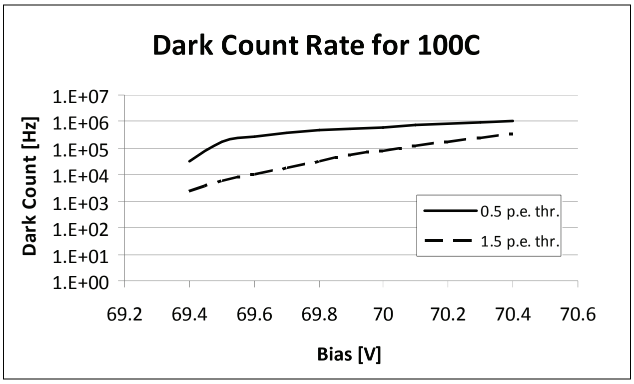


Fig. 16: Dark count versus bias voltage for Hamamatsu S10362-11-100C.

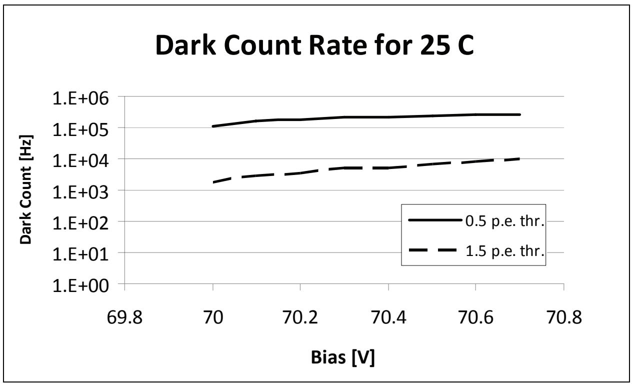


Fig. 17: Dark count versus bias voltage for Hamamatsu S10362-11-25C .

Trade-off of SiPM main characteristics

The optimal working point of a SiPM depends on the application. For example, the gain can be improved by increasing the bias voltage improves, but the dark count and the crosstalk also increase.

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