INTRODUCTORY PHYSICS LABORATORY - academic year 2017-2018

Understanding Silicon Photomultipliers (SiPM)

Prof. Dr. Massimo Caccia & dr.Samuela Lomazzi, dr. Luca Malinverno

Como (Italy), Spring term 2018

---

1. **Sensor characterization at the oscilloscope**

   The use of the scope allows to measure a significant number of sensor parameters and get acquainted with the SiPM. The proposed measurements presume to connect to a scope channel the amplified output of the sensor and on a second channel the LED driver output pulse. The proposed measurements can be split in two classes:

   (a) **Dark pulses.** For this set of measurements, NO light shall be conveyed on the sensor, protected by the ambient light by its own cap. Initially, The waveform digitization shall be triggered by the LED pulse. After having chosen a suitable time scale, a reasonable number of screen shots shall be recorded. For every screen shot, measure the number of pulses and, using the vertical cursors, the time interval between pairs of neighbouring pulses; setting the horizontal cursor at the single cell peak amplitude, measure the number of pulses exceeding this value, namely how many dark counts suffered from an optical cross-talk. Analyze the data as follows:

      (a) measure the mean number of pulses in the scope window and estimate the Dark Count Rate (DCR);

      (b) verify whether the distribution in the number of pulses follows a Poisson process;

      (c) calculate the expected mean time of arrival by the DCR; compare it to the measured value;

      (d) estimate the cross talk probability by the ratio between the number of pulses exceeding 1 fired cell to the total number of spurious pulses.

      Moreover, triggering the waveform digitization on the SiPM output channel with a threshold at $\approx 0.5\times$ (Peak amplitude of the single cell signal) [also known as 0.5 p.e., for Photoelectrons] and using the cursors, describe the signal time development in terms of rise time (time interval between the onset of the signal and the peak) and fall time (time interval to reduce the peak value by a factor 'e', a reasonable estimate of the decay time for a simple exponential signal). Measure as well the full development of the signal in time.

   (e) **Light Pulses.** For this set of measurements, light shall be conveyed on the sensor by the optical fibre. The waveform digitization shall be triggered by the LED pulse. Light intensity shall be conveniently chosen to clearly identify signals corresponding to a plurality of fired cells. Using the cursors, the peak-to-peak distance shall be measured and recorded. The measurement shall be repeated changing the biasing voltage with respect to the nominal value in steps of 0.5V and the breakdown voltage shall be estimated.

2. **Staircase Analysis**

The CAEN SiPM kit offers the possibility to perform in a simple and effective way the measurement of the DCR and the Optical Cross-talk. In absence of light illuminating the sensor, the threshold of the comparator embedded in the SP5600 module is changed in a user's defined interval and with the specified granularity. For every threshold value, the frequency of events exceeding it is measured. By the end of the threshold scan, the result is represented, showing the typical 'stair case' trend: in fact, whenever the value corresponding to the exclusion of pulses of amplitude $< n$ cells is exceeded, the rate will drop by a factor corresponding to the inverse of the optical cross talk probability (in the hypothesis of a linear chain of cross-talks, leading to a geometrical distribution). The exercise can be performed as follows:

(i) record a 'staircase' plot;

(ii) identifiy the threshold values corresponding to the middle of the first and second step of the plot, corresponding to the frequency for having pulses exceeding the electronics noise level and exceeding the value for a single fired cell;

(iii) set each of the two values at the discriminator;

(iv) use the 'PSAU counting' tab (actually recording the pulse frequency vs. time) for a more precise measurement of the frequency for each of the two threshold values

(v) estimate the DCR and the Optical cross talk

The measurement can be repeated changing the biasing voltage with respect to the nominal value, as for the gain variation.

3. **Multi-peak histogram analysis**

After having conveniently chosen the settings of the signal integration (gate length and pre-gate, taking into account the previously measured development time of the signal), record a histogram synchronizing the acquisition to the LED pulsing frequency. As above, histogram shall be recorded without light and illuminating the sensor. The analysis shall proceed as follows:

(a) Histogram in the absence of light. Even if no light is illuminating the sensor, the gate may overlap in time with spurious pulses. As a consequence, the histogram is expected to feature a multi-peak structure. This offers the possibility to estimate the Dark Count Rate (DCR). In fact, the dark counts may be presumed to follow a Poisson distribution with mean μ and number of Geiger discharges k:

$$P_k(\mu) = \frac{\mu^k}{k!}e^{-\mu}. \tag{1}$$

In the absence of light, the expected number of Geiger discharges is $\mu = \mathrm{DCR} \cdot \tau_{\mathrm{gate}}$. The probability to measure no Geiger discharge is $P_{k=0}(\mu) = e^{-\mu}$ where $P_{k=0}$ is given by the number of events in the peak centered on 0 (N_0), normalised to the total number of events N_{tot}, i.e. $P_{k=0} = N_0/N_{\mathrm{tot}} \equiv f_{<0.5}$. The DCR can therefore be estimated as

$$\mathrm{DCR} = \frac{-\ln(f_{<0.5})}{\tau_{\mathrm{gate}}}. \tag{2}$$

[**hint**: this measurement requires the estimate of the area under the '0 pulse' peak. In order to do so, zoom in and position the cursors on every bin, but it may be very time consuming. Or think of an estimate assuming the peak to be a gaussian and requiring only the measurement of the number of events in the central bin and the value of the FWHM. Or, if you wish, save the file and look at it with Excel..]

(b) **Histogram for an illuminated sensor.** The analysis of the multi-peak spectrum for an illuminated sensor offers the possibility to gain insight in some of the SiPM and the light source characteristics. The methods can be extremely sophisticated but an interesting analysis can also be performed in a reasonably simple way:

(a) optimal setting of the integration gate. Looking at the peak-to-peak distance vs. gate length, determine its optimal value, namely the minimum duration allowing you to integrate the full charge. Retain this value for this series of measurements. It may be interesting to see how the spectrum quality changes when you go beyond the optimal setting.

(b) measurement of the breakdown voltage. The biasing voltage affects the sensor gain. As a consequence, the distance between neighbouring peaks in the spectrum changes accordingly. Measuring the peak-to-peak distance against the voltage, the value of the breakdown voltage can be estimated as the value corresponding to '0 gain'. The obtained value shall be compared to what was obtained by using the scope and measuring the variation of the peak amplitude rather than the variation of the total charge in the integrated pulse, done here.

(c) statistics of the photons emitted by the LED source. For every pulse, the LED is emitting a number of photons expected to follow a Poissonian distribution. Selecting a light intensity such that peaks corresponding to a different number of fired cells have a small overlap and the peak corresponding to NO fired cell has a reasonable statistics, this hypothesis can be verified as follows:

- estimate the mean number of detected photons by the fraction of events on the '0 photon' peak, following the prescription outlined in the DCR measurement;
- assuming a Poisson distribution, estimate the expected number of events for a given number of fired cells;
- compare it to the experimental results and draw your own conclusions.

4. **Identification of an optimal biasing voltage [OPTIONAL]**

   Is there an optimal biasing value? In principle, the higher the biasing voltage the better it is, since peaks corresponding to a different number of detected photons are more distant apart. However, as the bias increases so do the noise, the optical cross talk and the afterpulses. The gain increases linearly with the excess voltage, the stochastic terms may be super-linear. What is the optimal combination? Think of a relevant figure of merit, define a qualification procedure and perform the measurements.

5. **Prepare a summary table of the sensor characteristics**

   The data set collected so far allows to prepare a summary table of the sensor characteristics. Report the measurements of the breakdown voltage, the gain (in ADC value), the DCR and the optical cross talk. In case you had the possibility to characterise the sensor behaviour at different biasing conditions, report the trend of the basic figures for every biasing voltage.