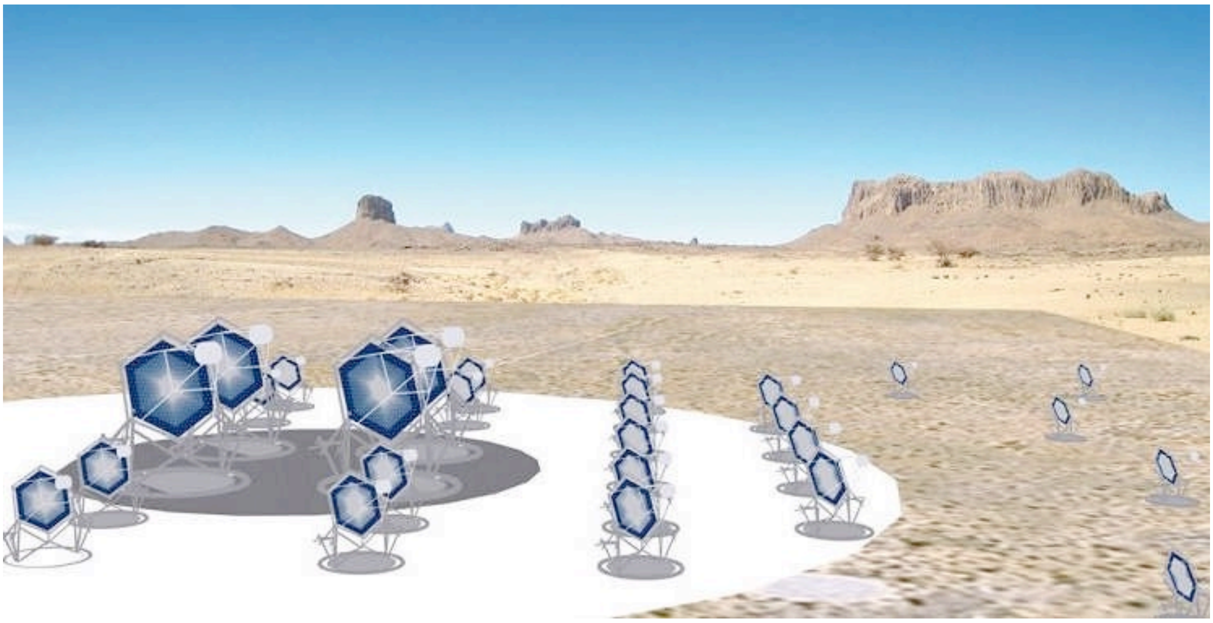
OSSERVATORIO ASTROFISICO DI CATANIA

Electro-Optical Characterization Report

Device: SiPM MPPC HAMAMATSU S/N. A0007 100μm



Osservatorio Astrofisico di Catania

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SiPM CHARACTERIZATION REPORT

OSSERVATORIO ASTROFISICO DI CATANIA
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Misure Eseguite da Giuseppe Romeo

DATE	**July 05, 2013**
SiPM	**HAMAMATSU** **Type No: S12652-100C(X)** **3x3 S/N A0007 100 μm pitch cell** **V_{OP} = 60.33V @T=25°C** **G = 2.51E+06** ***Dark: 246.5 KHz (0.5 pe- Thr)*** **Temperature coefficient of V_{BD}:** **TC=dV/dT=56mV/°C** **(from Hamamatsu data sheet)**
OP. MODE	**Photon Counting with CAEN Power Supply Amplifier Unit (PSAU) and Tektronix counter**
SER. N.	**A0007 100 μm pitch cell**

CONTENTS

INTRODUCTION

Due to the complexity of the device and of the set-up utilized to carry-out the measurements, a brief introduction is mandatory. The steps of the adopted procedure are here briefly listed.
For this device we decided to carry out only the optical characterization.
As Electrical parameters we used those given with the device.

The Optical characterization procedure is:

1. Select the operating temperature *T*;
2. Set the operating voltage V_{OP};
3. Cross-talk and Dark Count Rate (DCR) assessment with temperature compensation;
4. DCR Stairs to establish the optimal threshold signal level;
5. DCR measurements vs. gate time from 20 to 120 ns, to establish the optimal gate time;
6. Linearity measurements vs. photon rate, to avoid saturation, pile-up and consequent PDE degradation;
7. PDE measurements at a given operating voltage, and relevant comparison;
8. PDE measurements at a given temperature, and relevant comparison.

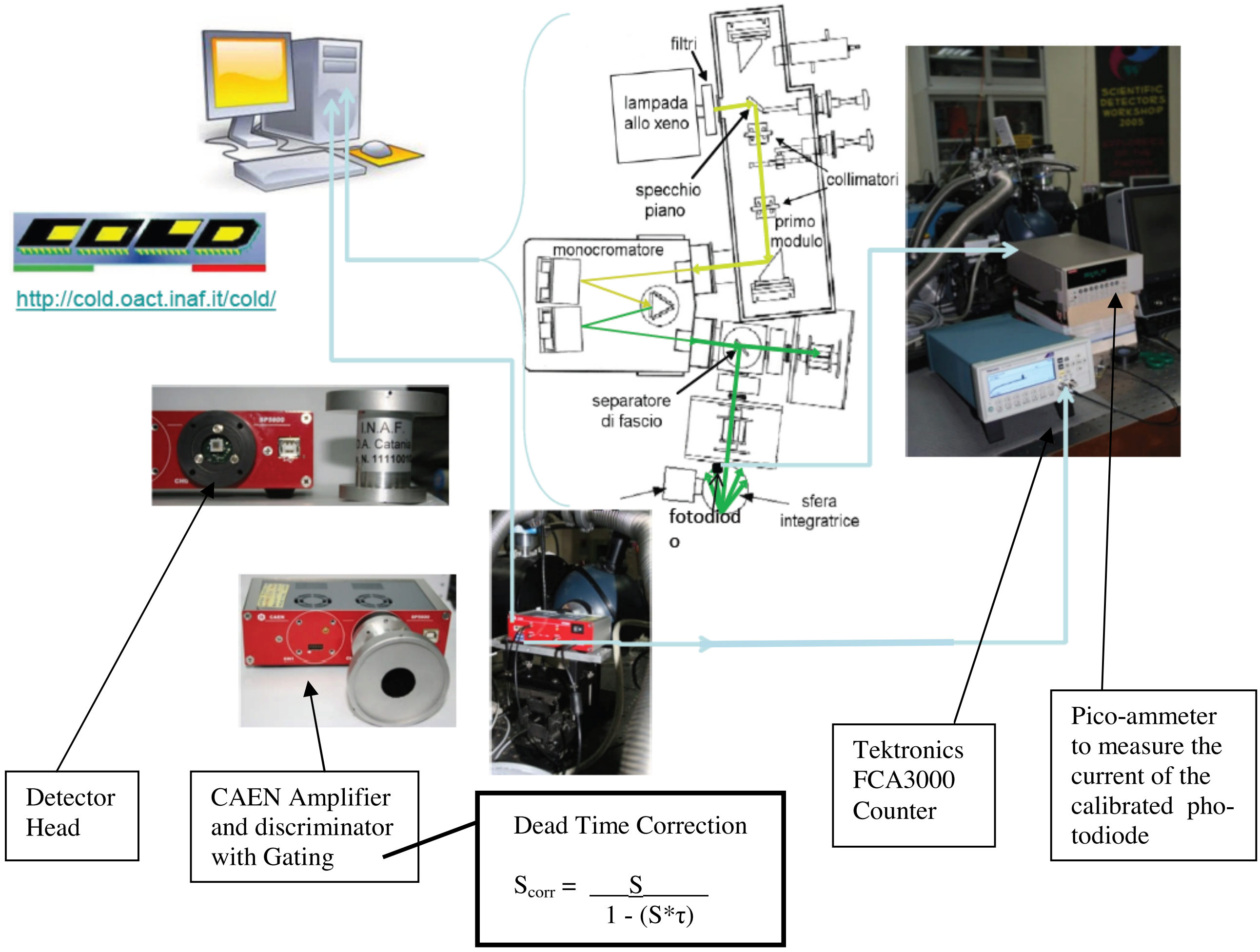
The procedure in a flow chart form is reported on the previous test report:

Type No: 3x3mm 100 μm Sample-DA

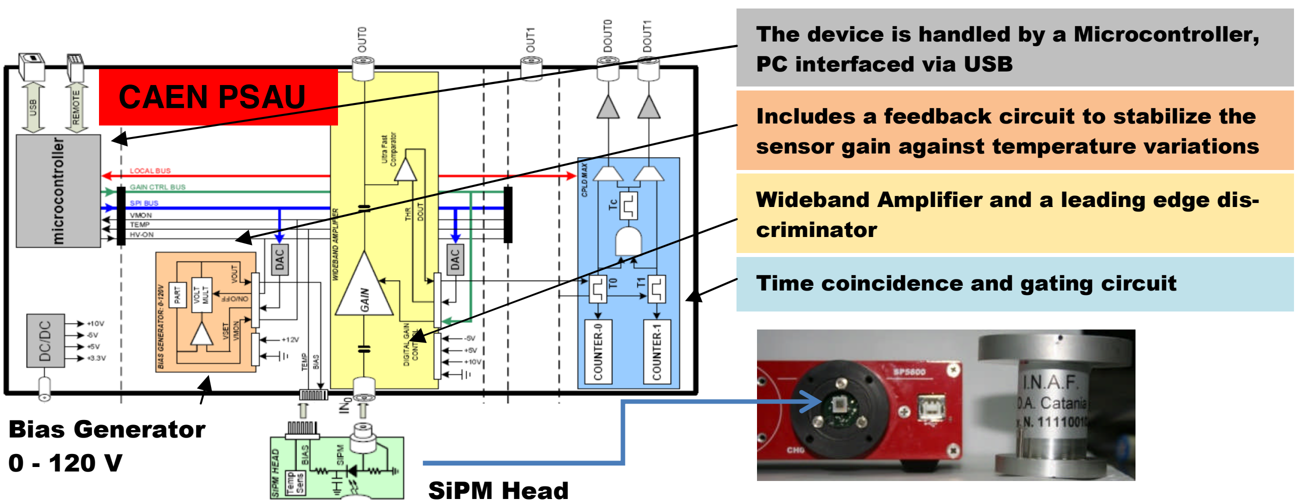
- Pixel pitch: 100 μm
- Effective area: 3x3 mm
- Number of pixel: 900
- Fill Factor: ??
- Terminal capacitance: 320 pF
- **V_{OP}:** **60.33 V to have G=2.51E+06**
- **Dark:** **246.5 KHz (0.5pe thr.) @25 °C**

1.0 Optical characterization: PDE in the 350-950 nm range at V_{OP}=60.33 V and T=25°C

PDE measurements are carried out by using the set-up shown below:



The set-up is constituted by an illuminating section, a monochromator, an integrating sphere where the SiPM is hosted, the front-end electronics and the calibrated photodiode with its output going to the Keithley ammeter. The front-end electronics is currently based on the CAEN Power Supply and Amplification Unit (PSAU), whose the schematic is here shown:



After the selection of the working temperature at which the PDE is carried out, the set-up of some parameters has to be arranged:

- on the SiPM control electronics:
  - the **threshold** to establish the optimal threshold level and account for **cross-talk**;
  - the **hold-off time** to avoid the **after pulsing** effect as much as possible;

- on the optical apparatus:
  - the **illumination level** at the integrating sphere output ports to **prevent** measurements from **pile-up**;
  - the **photocurrent** measured by the calibrated photodiode (sufficiently high) to **avoid low level signal measurements**.

These last two parameters if not selected accurately can severely degrade the PDE.

1.1 Stairs at V_{OP} = 60.33 V with temperature compensation

It is extremely important that the SiPM operating conditions are maintained stable versus the working temperature during measurements. Apart from DCR, other two parameters are affected by temperature variations: the breakdown voltage and the Trigger Probability (TP). By the known dV/dT coefficient (in this case 56 mV/°C) it is possible to compensate the V_{OP} with respect to temperature variations. The PASU CAEN allows to stabilize the operating voltage ensuring Gain and TP stability. This last parameter plays a fundamental role in PDE evaluation. In fact the PDE is given by:

$$QE \times FF \times TP$$

The Quantum Efficiency (QE) depends on the material and on the manufacturing technology (depletion layer etc.), the Fill Factor (FF) depends on the geometry of the single microcell and on the dead area resulting from the total detector layout, the TP depends on the electric field applied to the depletion region responsible for the avalanche and is given from the overvoltage beyond the breakdown; in other words, the TP depends on the V_{OP}. And if TP is unstable an inaccurate PDE measurement will result.

The dark stairs obtained at V_{OP} =60.33 V and T=25°C is shown in Fig. 1.

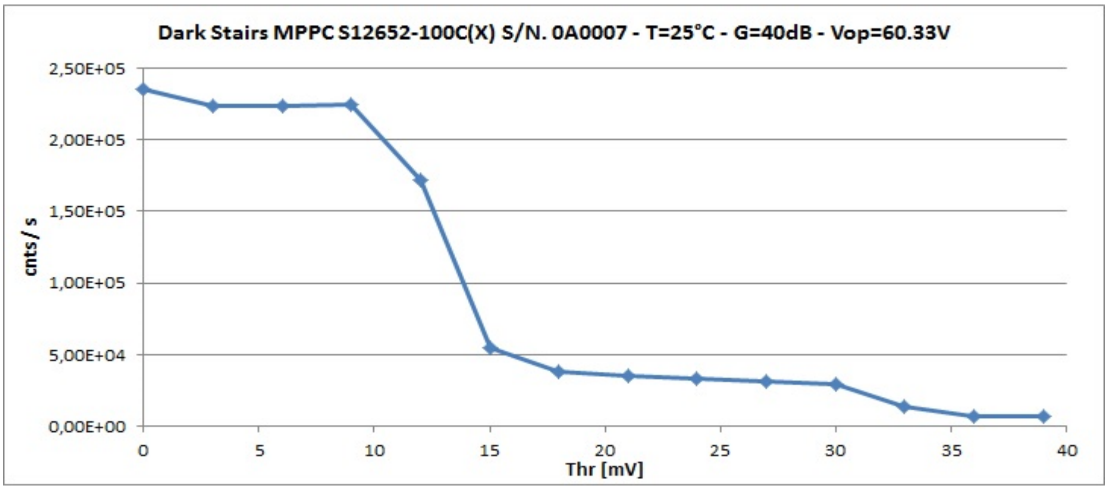


Fig. 1 - DARK Stairs for V_{OP}=60.33V (V_{OPHAM}) at T=25°C

From the stairs plot we derive that the optimal threshold at 0.5 pe- is $\mathbf{V_{Thr}}$**= -6 mV**.
At this threshold we find a **DCR** of **224 KHz**.

1.2 Dark count rates at different hold-off time from 30ns to 120ns

Measurements were performed at T=25°C, V_{OP}=60.33 varying the gate time from 30ns to 120ns. In Fig. 2 data are plotted with and without dead time correction.

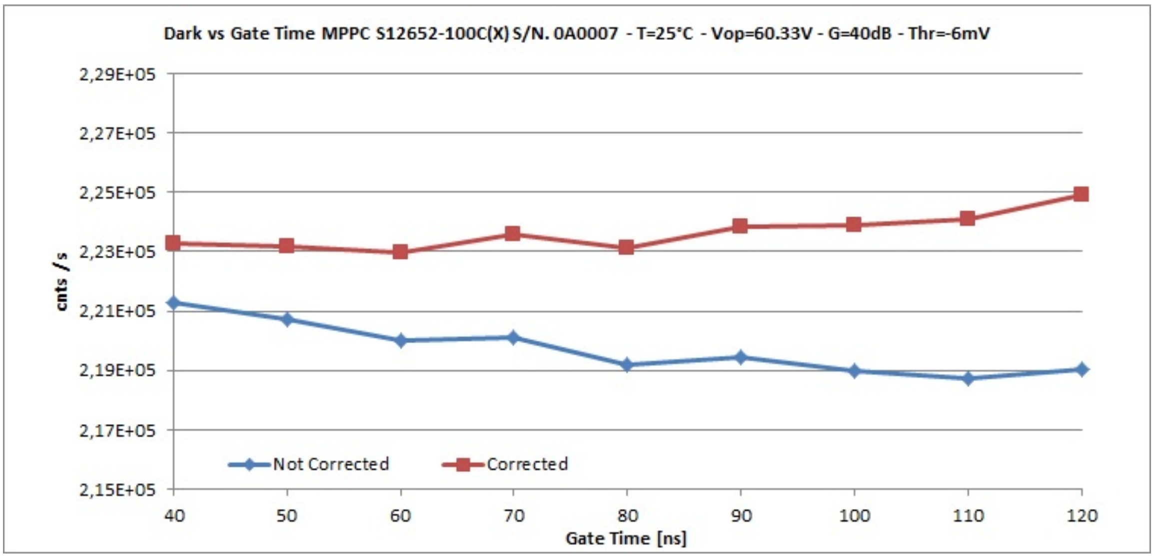


Fig. 2 - DARK vs hold-off time at Vop=60.33 V - Thr=-6 mV T=25.0° the temperature compensation is activated.

From the above plot it is clearly evident that when applying dead time correction, the dark count rate is over-estimated, while it is exactly that obtained from stairs measurements. This behavior tells us that afterpulses are negligible and **hold-off is not necessary**.

Thus, in this case, we have decided not to apply any hold-off.

1.3 Dark count rates versus time at V_{OP} = 60.33 V and *T*=25 °C

To be sure that, during PDE measurements, DCR variations do not affect the photogenerated signal, the DCR stabilty has been evaluated.

Fig. 3 shows the DCR plot in an interval time of 120 seconds.

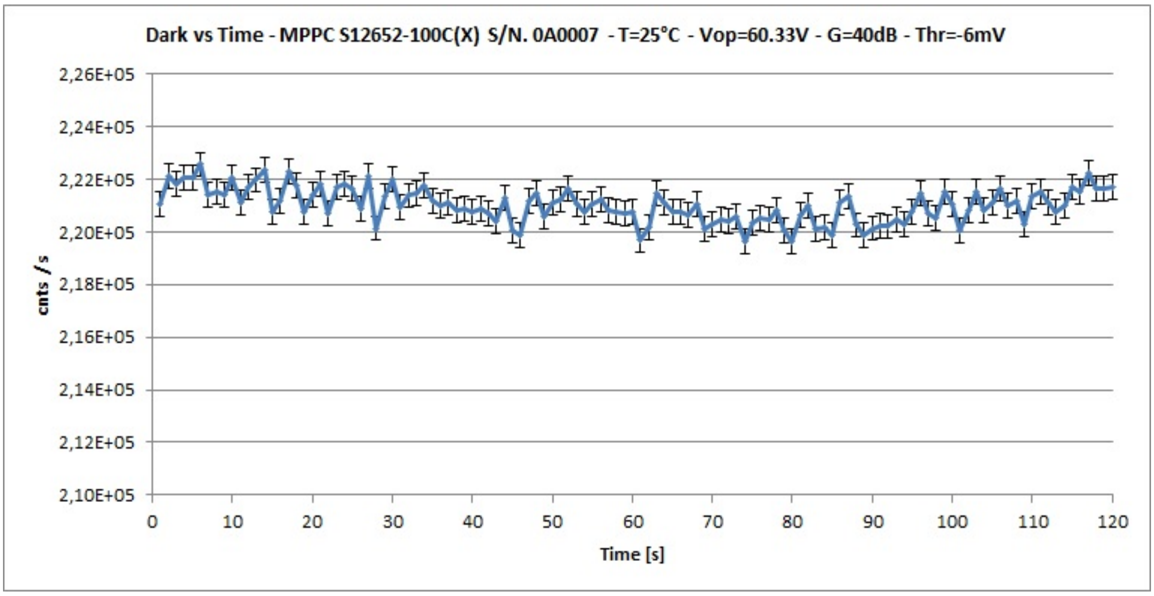


Fig.3 – DCR versus time. Note the value of 221KHz is maintained stable during the elapsed time No dead time correction in this case is applied.

1.4 Linearity measurements and PDE versus photon counting rate

As stated before, to prevent the system from saturation, preliminary illumination, or better photon rate measurements, have to be carried out.

Measurements were performed illuminating the integrating sphere with a monochromatic flux (λ=500nm). The SiPM is operated by selecting T=25°C, V_{OP}=60.33V and without hold-off time.

Fig. 4 shows the photon rate at 500 nm versus the photocurrent measured by the calibrated photodiode. Of course the dark current in the calibrated photodiode and the dark count rate (DCR) in the SiPM are subtracted.

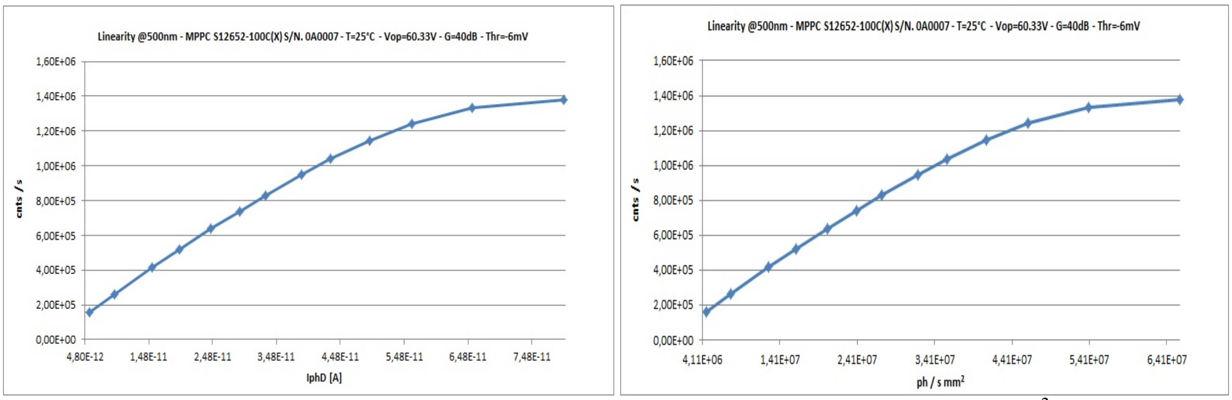


Fig. 4 – Linearity at λ=500 nm. Each rate is plotted with the corresponding photon rate per mm^2. This is obtained by knowing the NIST traced QE at 500 nm of the calibrated photodiode. For example 500KHz on the MPPC means about 2x10^7 photons/s per mm^2.

From both these plots we derive a non-linearity behavior at about 1.2 Mcnts/s, corresponding to a photon rate of about 4.5×10^7 photons/s mm^2.

As reported on the previous test report a more efficient method to evaluate the PDE degradation due to the uncorrected illumination is to directly evaluate the PDE(500nm) versus the photon counting rate, as shown in Fig. 5.

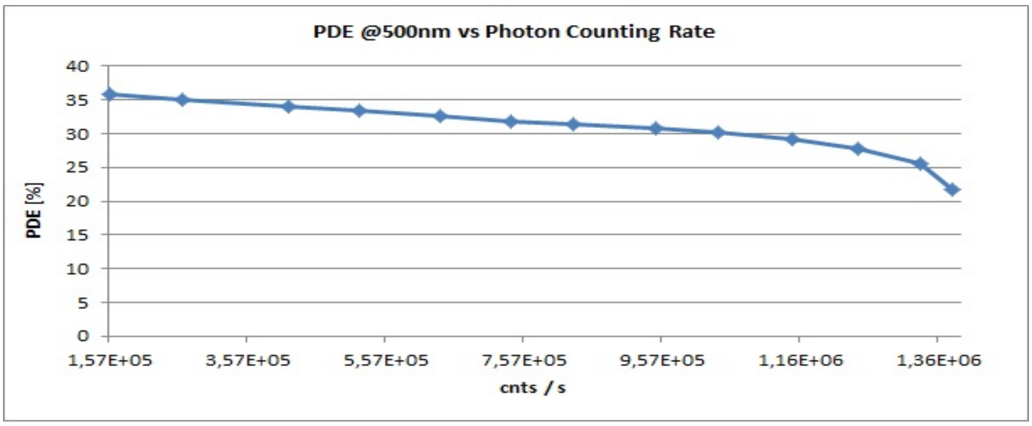


Fig. 5 –PDE versus photon counting rates with dark removed at λ=500 nm.

This plot allows us to better select the appropriate photon rates. In fact the PDE drop off at rates greater than **500 kHz** (corresponding to **2x10^7 ph/s per mm^2** or 1.8x10^8 ph over the MPPC area) is clearly evident, which means about 730 kHz including the DCR contribute. From this plot we also note that a degradation due to a sort of pile-up phenomenon begins at very low signal and becomes unacceptable at count rates higher than 900 KHz, which including the dark means about 1.1 MHz.

1.5 PDE in the 350–950 nm spectral range at V_{OP}= 60.33 V and T=25°C

As stated in the previous paragraph, we worked in such illuminating condition to avoid degradation of the SiPM counting rate. But in this low level signal condition we can experience a not very accurate measurement by the Keithley pico-amperometer. To avoid low photocurrent levels measured by the calibrated photodiode, a neutral density filter (calibrated at our laboratory) has been inserted in front of the SiPM. The introduction of the filter allows us to work with higher signals on the NIST photodiode with a consequent reduction of error bars.

The PDE plot at V_{OP}**= 60.33 V** and T=25°C is shortly reported (section 4.0), where PDE plots obtained at different V_{OP} and at the same temperature are reported.

2.0 PDE in the 350 – 950 nm spectral range at V_{OP}=60.63 V (V_{HAM}+0.3V) and T=25°C

2.1 DCR Stairs and gate time measurements at V_{OP} = 60.63 V (V_{HAM}+0.3V) with temperature compensation

According to the established procedure (see the above reported flow chart), we changed the V_{OP} and repeated the same measurements as the previous chapter.

The dark stairs obtained at V_{OP} =60.63 V and T=25°C are shown in Fig. 6.

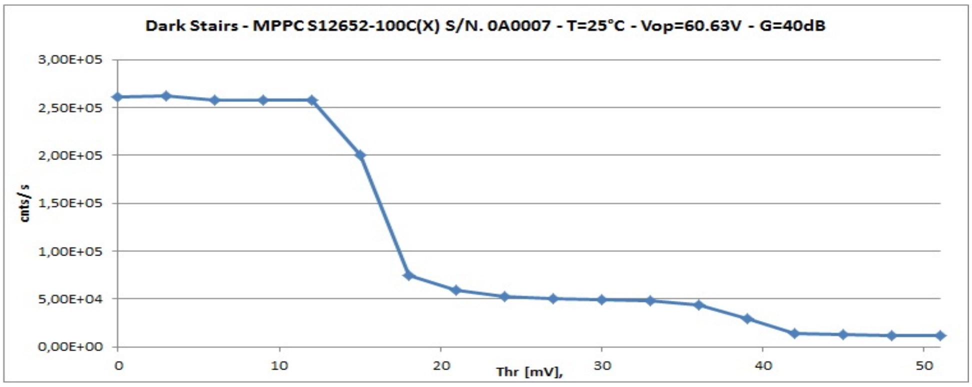


Fig. 6 – DARK Stairs – V_{OP}=60.33V (V_{OPHAM} +300mV) at T=25°C.

From the stair plot we derive that the optimal threshold at 0.5 pe- is $\mathbf{V_{Thr}}$ **= -9 mV**. The **DCR** at the selected threshold is **250 KHz.**

2.2 Dark count rates versus time at V_{OP} = 60.63 V and T=25 °C

Fig. 7 shows the DCR plot in a time interval of 120s at V_{OP}=V_{HAM}+0.3V and T=25°C.

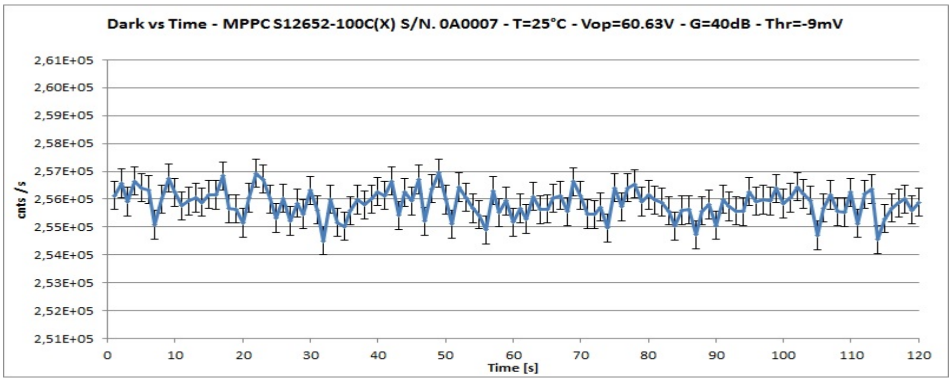


Fig. 7 – DCR versus time. Note that the value of 256KHz is maintained stable during the elapsed time.

2.3 Linearity measurements and PDE versus photon counting rate

Fig. 8 shows the photon rate at 500 nm as a function of the number of photons/mm^2.

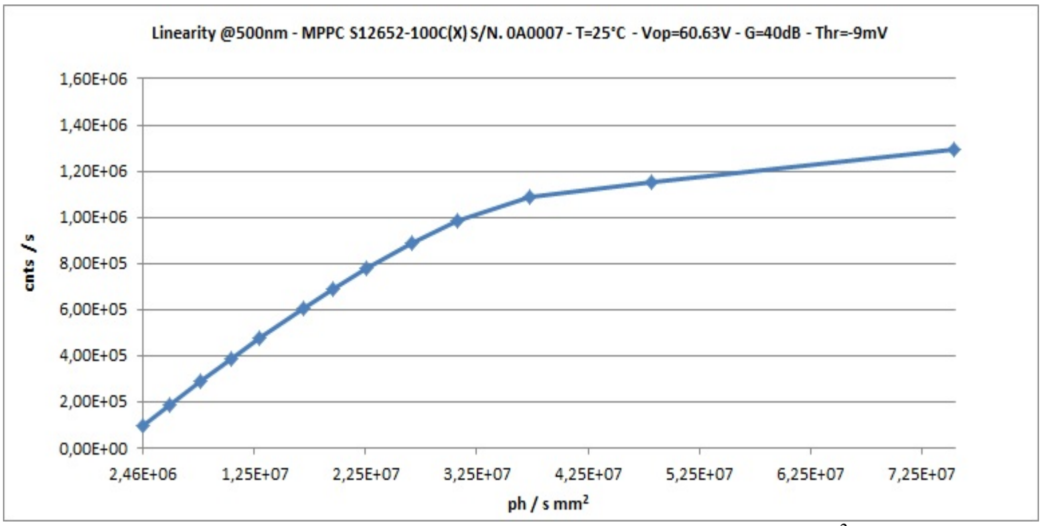


Fig. 8 – Linearity at λ=500 nm. Photon rate as a function of the number of photons/mm^2.

From the above plot we derive a non-linearity behavior of about 1.0 Mcnts/s, corresponding to a photon rate of about 4×10^7 ph/s per mm^2.

Fig. 9 shows the PDE(500nm) degradation versus the photon counting rate.

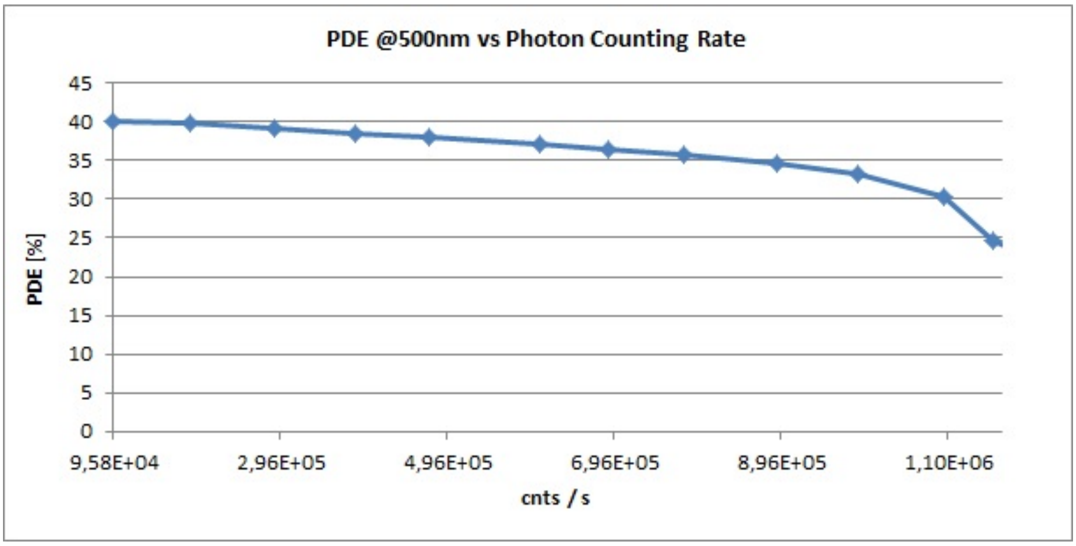


Fig. 9 –PDE versus photon counting rates with dark removed at λ=500 nm.

Also in this case we observe a PDE drop off at rates greater than 450 kHz that means about 700 KHz including the DCR contribute. The PDE degradation becomes unacceptable at count rates higher than 450 KHz that including the dark means about 700 KHz.

2.4 PDE in the 350–950 nm spectral range at V_{OP}= 60.63 V and *T*=25°C

The PDE plot at V_{OP}**= 60.63 V** and *T*=25°C where PDE curves obtained at different V_{OP} and at the same temperature are compared is shortly reported.

3.0 PDE in the 400 – 600 nm spectral range (step 50 nm) at V_{OP}=60.83 V (V_{HAM}+0.5V), V_{OP}=61.03 V (V_{HAM}+0.7V) and V_{OP}=60.13 V (V_{HAM}-0.2V) and T=25°C

3.1 DCR Stairs and gate time measurements at V_{OP} = 60.83 V with temperature compensation

The DCR stairs obtained at V_{OP} =60.83 V (Vop_{Ham}+0.5V) and T=25°C and gate time plot are shown in Fig. 10.

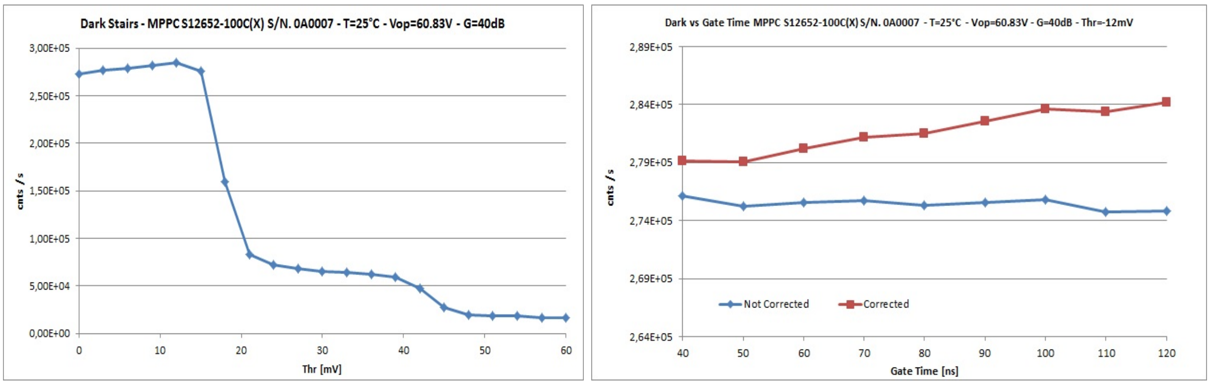


Fig. 10 – DCR Stairs – V_{OP}=60.83V (V_{OPHAM} +500mV) at T=25°C.

From the stair plot we derive that the optimal threshold at 0.5pe- is **V_{Thr} = -12 mV**.
The **DCR** at the selected threshold is **280 KHz.**
While from the gate time plot we derived that the hold-off time is unapplied.

3.2 Dark count rates versus time at V_{OP} = 60.83 V and T=25 °C

Fig. 11 shows the DCR plot in an interval time of 120s at V_{OP}=V_{HAM}+0.5V and T=25°C.

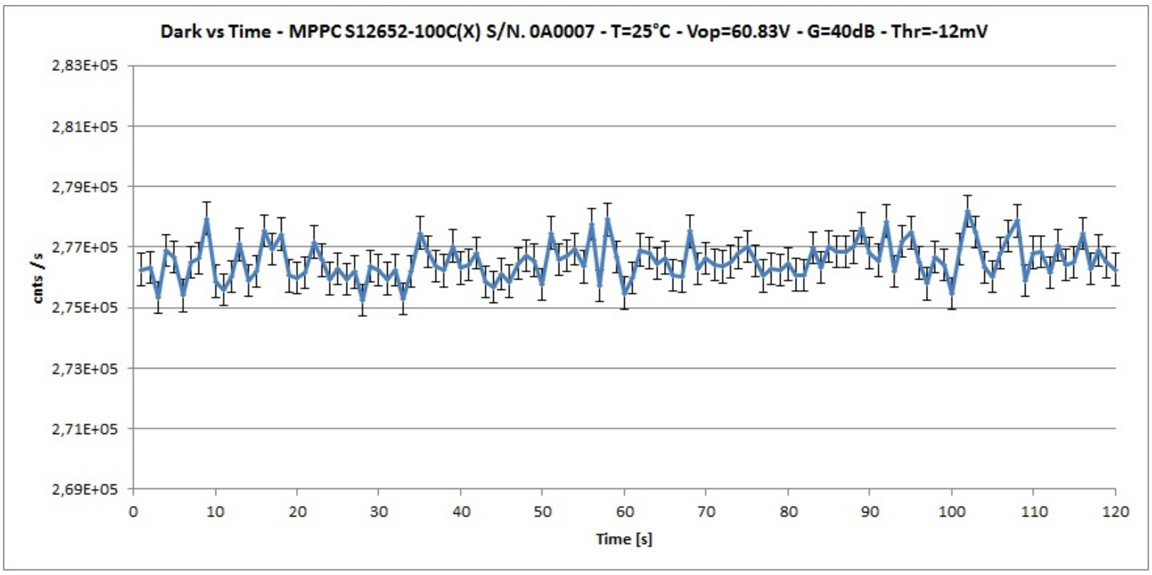


Fig. 11 – DCR versus time. Note that the value of 277 KHz is maintained stable during the elapsed time.

3.3 DCR Stairs measurements at V_{OP} = 61.03 V and V_{OP} = 60.13 V with temperature compensation

The DCR stairs obtained at V_{OP} **=61.03 V** (V_{OPHAM}+0.7V) and *T*=25°C is shown in Fig. 12.

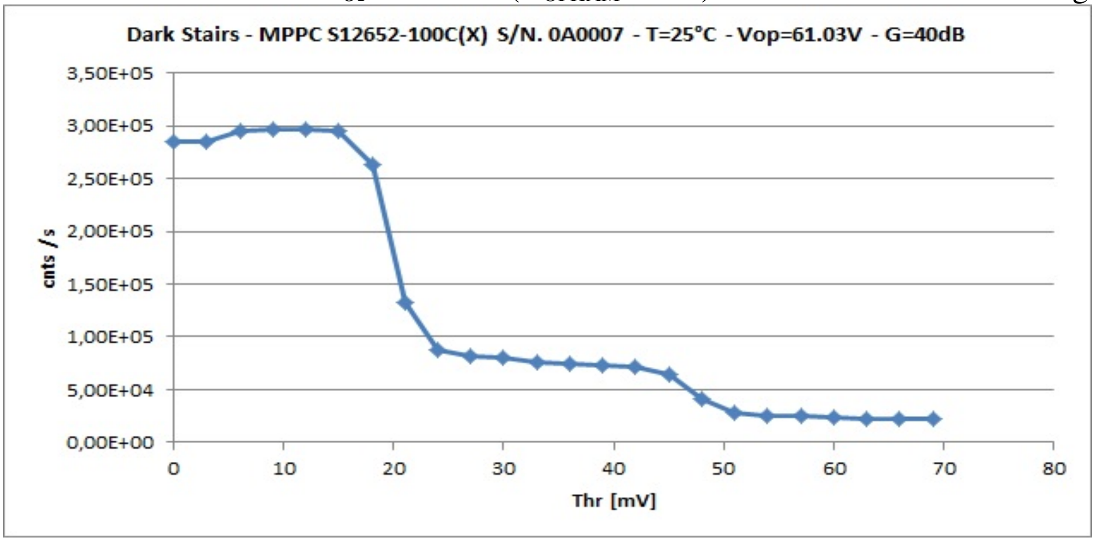


Fig. 12 – DCR Stairs – V_{OP}=61.03V (V_{OPHAM} +700mV) at T=25°C.

From the stair plot we derive that the optimal threshold at 0.5pe- is $\mathbf{V_{Thr}}$ **= -12 mV**.
The **DCR** at the selected threshold is **300 KHz.**

The DCR stairs obtained at V_{OP} **=60.13 V** (Vop_{Ham}-0.2V) and *T*=25°C is shown in Fig. 13.

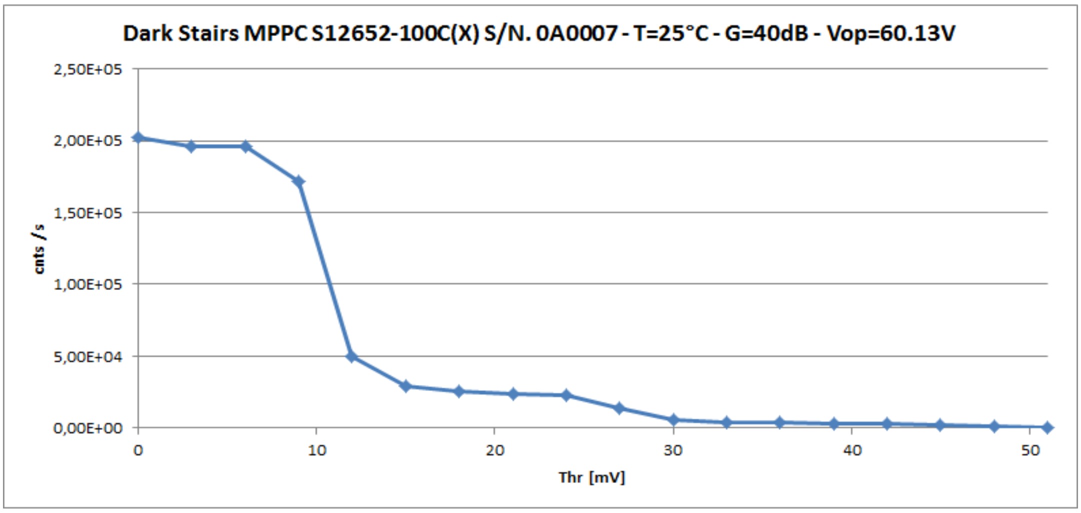


Fig. 13 – DCR Stairs – V_{OP}=60.13V (V_{OPHAM} -200mV) at T=25°C.

From the stair plot we derive that the optimal threshold at 0.5pe- is $\mathbf{V_{Thr}}$ **= -3 mV**.
The **DCR** at the selected threshold is **200 KHz.**

3.4 PDE in the 400 – 600 nm spectral range (step 50 nm) at V_{OP}= 60.83 V, V_{OP}= 61.03 V, V_{OP}= 60.13 V and T=25°C

The PDE plot at **V_{OP}= 60.83 V, V_{OP}= 61.03 V, V_{OP}= 60.13 V** and T=25°C where PDE curves obtained at different V_{OP} and at the same temperature are compared is reported in next section.

4.0 PDE in the 350 – 950 nm range at $V_{OP}=V_{OPHAM}$, $V_{OP}=V_{OPHAM}+0.3V$, and in the 400 – 600 nm range at $V_{OP}=V_{OPHAM}-0.2V$, $V_{OP}=V_{OPHAM}+0.5V$, $V_{OP}=V_{OPHAM}+0.7V$

Finally, PDE measurements at 25°C and for five different operating voltages, i.e. 60.13 V, 60.33 V, 60.63 V, 60.83 V and 61.13 V, are compared in Fig.14.

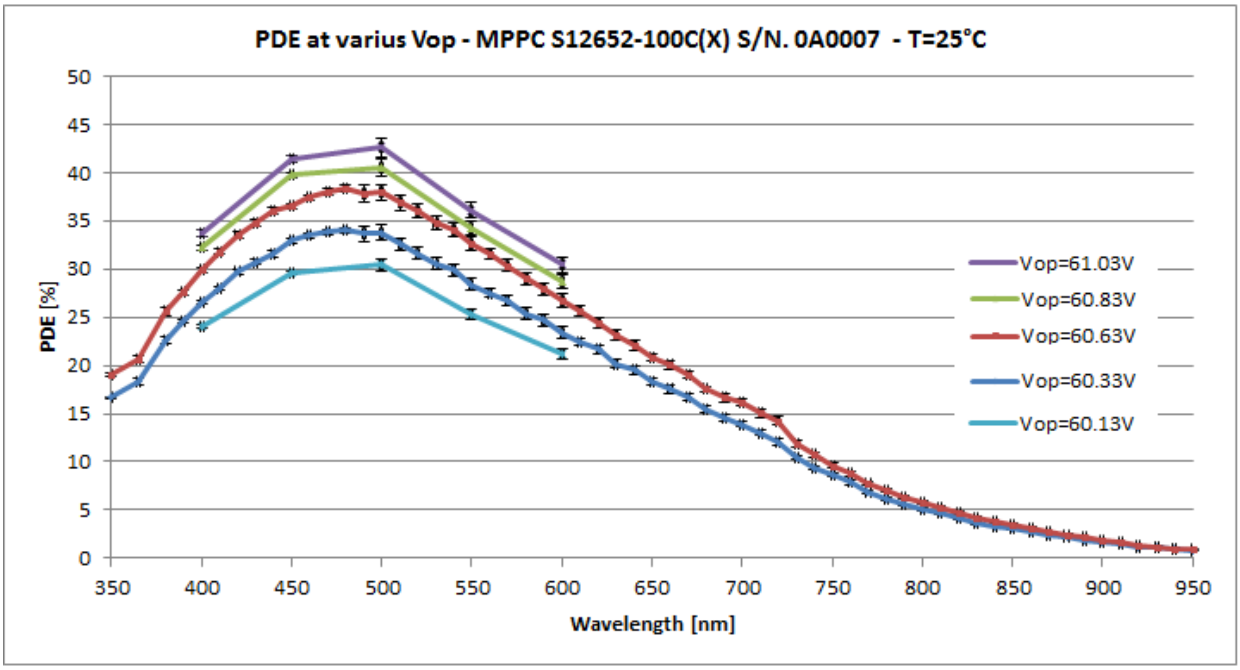


Fig. 14 – PDE measurements comparison for the SiPM operated at V_{OP}=60.13V (in the 400-600 nm), V_{OP}=60.33V (in the 350-950 nm), V_{OP}=60.63V (in the 350-950 nm), V_{OP}=60.83V (in the 400-600 nm) and V_{OP}=61.03V (in the 400-600 nm). All PDE measurements were performed at T=25°C. The error bars are also reported.

At the operating voltage V_{OP}= 60.33 V, suggested by Hamamatsu, a PDE that peaks at a value of 34 % in the 470 -490 nm spectral range has been found. The MPPC also shows an acceptable 26.5 % of PDE at 400 nm.

As expect and discussed in chapter 1.0 the PDE depends essentially on the Trigger Probability that in turn means on the overvoltage beyond breakdown.

By operating the device at VOP greater than that so called V_{OPHAM} we observe an increase of PDE, but this happens at expenses of cross-talk (see next chapter).

For instance, from the plots at higher V_{OP} as 60.83 ($V_{OP}=V_{OPHAM}$+0.5V) a PDE of 40% is achieved but a crosstalk of 22.5 % has been also measured.

5.0 Optical characterization: Cross-talk and DCR versus V_{OP} at T=25°C

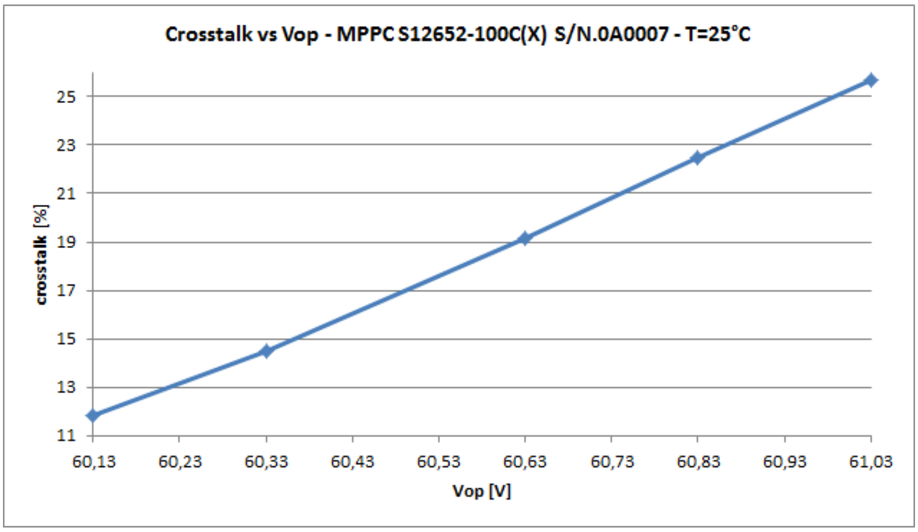
Following the flow chart discussed in the previous section, we have investigated the crosstalk showed by the MPPC. The crosstalk is estimated as the ratio between the primary event count rate and the second event count rate, that means acquiring DCR stairs at various operating voltages. From the previous section we have the stairs at V_{OP}= 60.13V, V_{OP}= 60.33V, V_{OP}= 60.63V V_{OP}= 60.83V, V_{OP}= 61.03V, and from them we can derive the cross-talk and the DCR.

The crosstalk and DCR at the various operating voltages are listed in Table 1, and plotted in Fig. 15.

TABLE 1

Crosstalk and DCR at various V_{OP} and T=25°C

V_{OP}	V_{OPHAM}	DCR [kHz]	Xtalk [%]
60.13	- 0.2 V	200	11.8
60.33	**+ 0.0 V**	**240**	**14.5**
60.63	+ 0.3 V	270	19.1
60.83	+ 0.5 V	290	22.5
61.03	+ 0.7 V	300	25.7



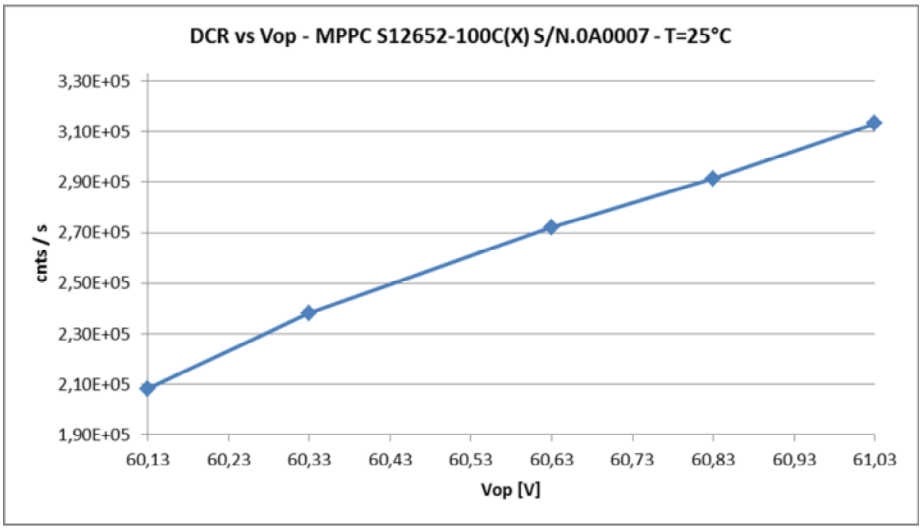


Fig. 15 – Upper panel: crosstalk vs. V_{OP} – Lower panel: dark count rate vs. V_{OP}. Both measures were performed at T=25°C.