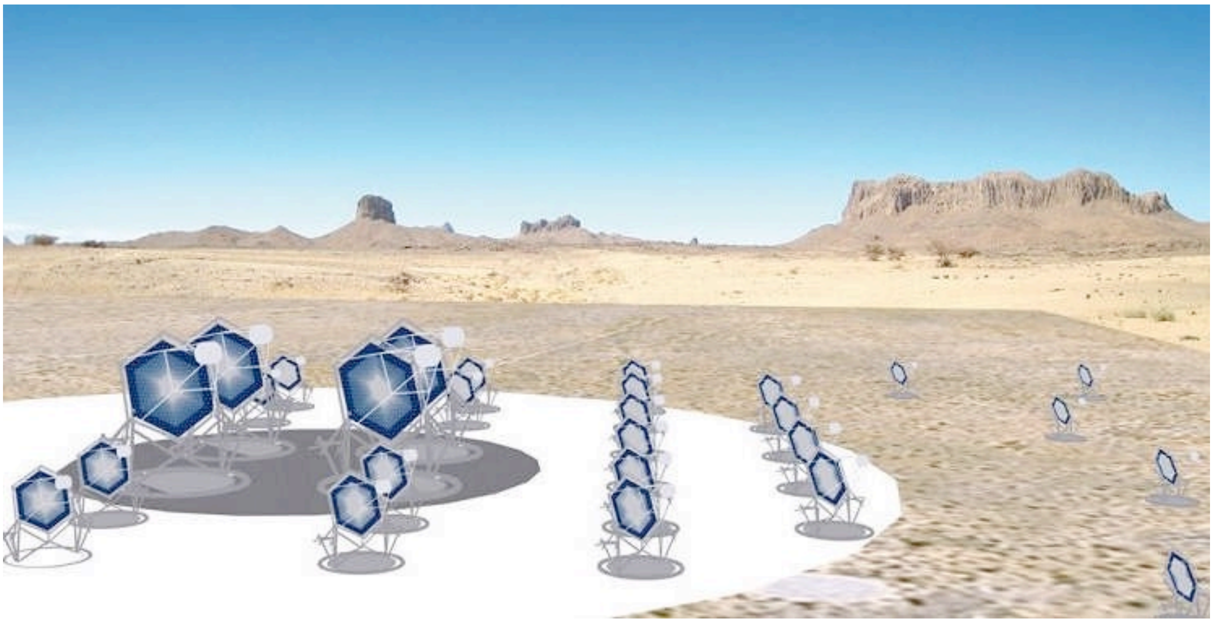
*OSSERVATORIO ASTROFISICO DI CATANIA*

# Electro-Optical Characterization Report

Device: SiPM MPPC HAMAMATSU S/N. 1 50µm



## Osservatorio Astrofisico di Catania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Rapporti interni e tecnici
N.17/2013



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# SiPM CHARACTERIZATION REPORT

OSSERVATORIO ASTROFISICO DI CATANIA
**LABORATORIO RIVELATORI**

Catania Astrophysical Observatory, Laboratory for Detectors

**Misure eseguite da Giuseppe Romeo**

| | |
|---|---|
| **DATE** | **June 07, 2013** |
| **SiPM** | **HAMAMATSU**<br>**3x3  50µm S/N 1**<br>**Vop = 67.02V @T=25°C**<br>**Vov = 0.88 V**<br>**G = 7.5E+05**<br>**Vov** is not exactly the Over Voltage but is assumed as the Voltage at which the **G** is that specified by Hamamatsu that is 7.5E+05<br>**Temperature coefficient of Vbr:**<br>**Tc=dV/dT=56mV/°C**<br>**(from Hamamatsu datasheet)** |
| **OP. MODE** | **Photon Counting with CAEN Ampli/Comparator and Tektronix counter** |
| **SER. N.** | **1** |

# CONTENTS

# INTRODUCTION

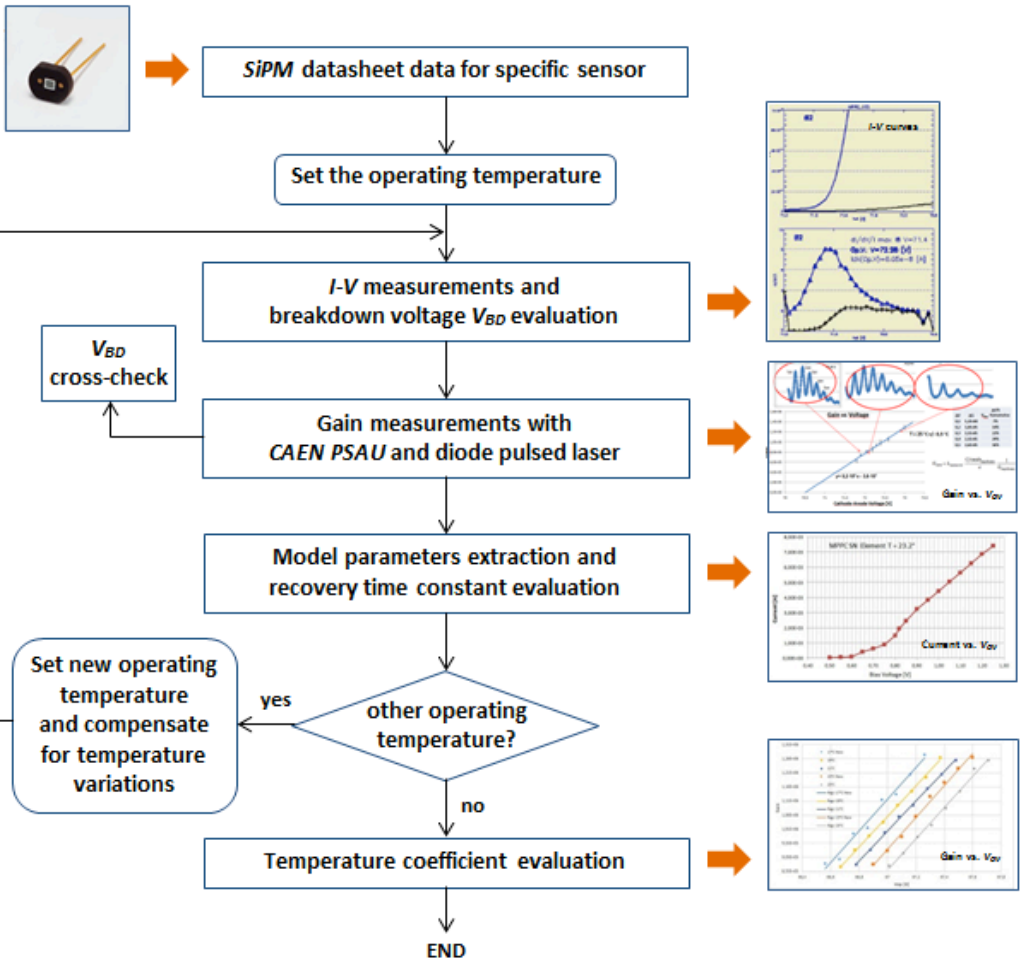
Due to the complexity of the device and of the set-up utilized to carry-out the measurements, a brief introduction is mandatory. Briefly here are listed the steps of the procedure we have used. We decide to divide the entire characterization procedure in two parts: the electrical and the optical. The envisaged steps to obtain a quite accurate electrical and optical characterization are the following:

Electrical

1. Select the operating temperature
2. Reverse I-V measurements and breakdown voltage evaluation
3. Gain measurements
4. Direct I-V measurements and model parameters extraction and recovery time evaluation

Iterating the procedure at different temperatures we can obtain the Gain versus Vop plots as function of T, and an estimation of the thermal coefficient TC=dV/dT is also achieved.

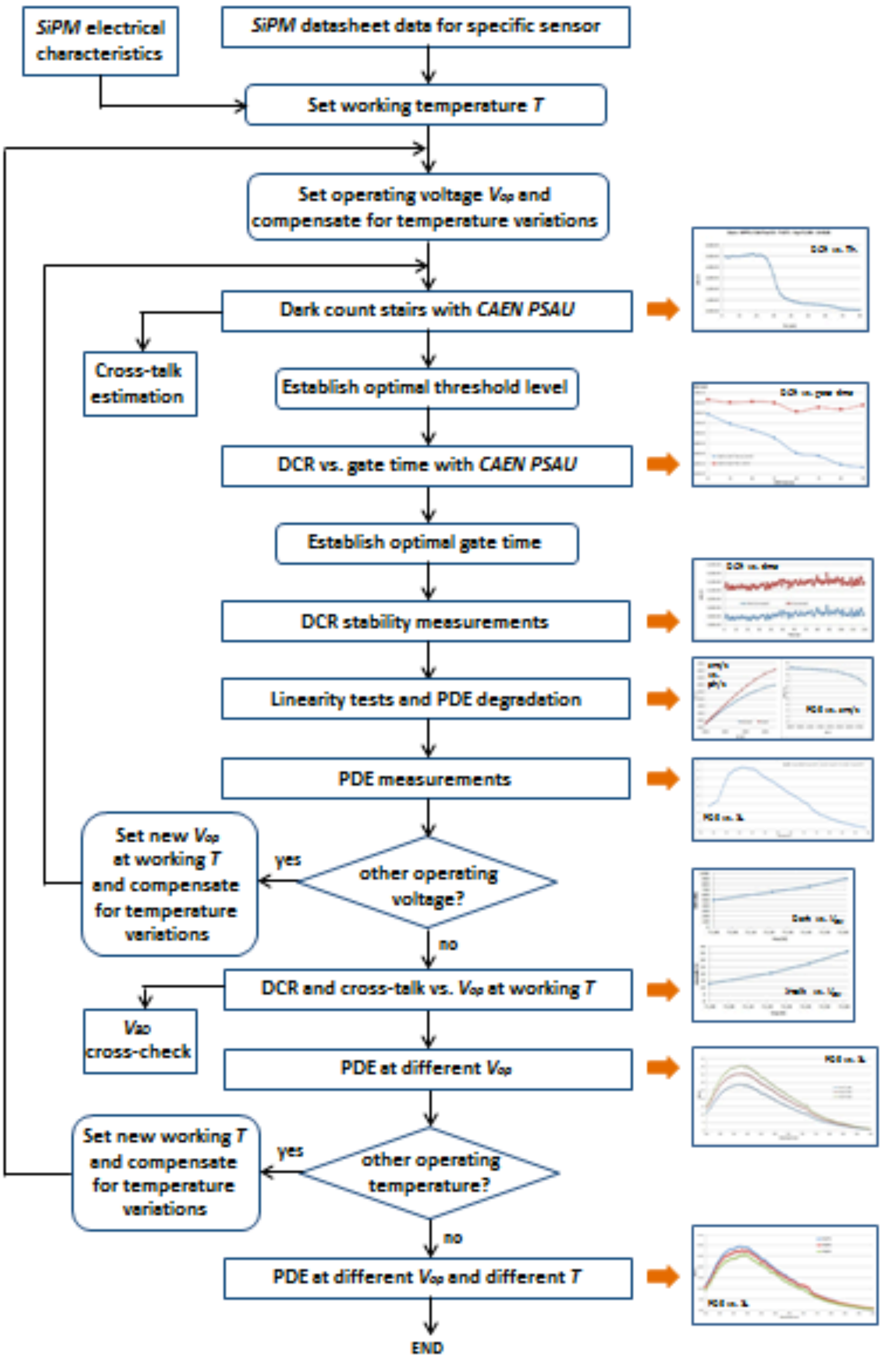
The procedure in a flow chart form is here reported:



<u>Optical</u>

1. Select the operating temperature
2. Set the operating voltage
3. Cross-talk and Dark Count Rate (DCR) characterization with temperature compensation
4. Dark count rate Stairs to establish the optimal threshold signal level
5. DCR versus gate time from 20 to 120 ns measurements to establish the optimal gate time
6. Linearity measurements versus photon rate to avoid the saturation and 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 here reported:



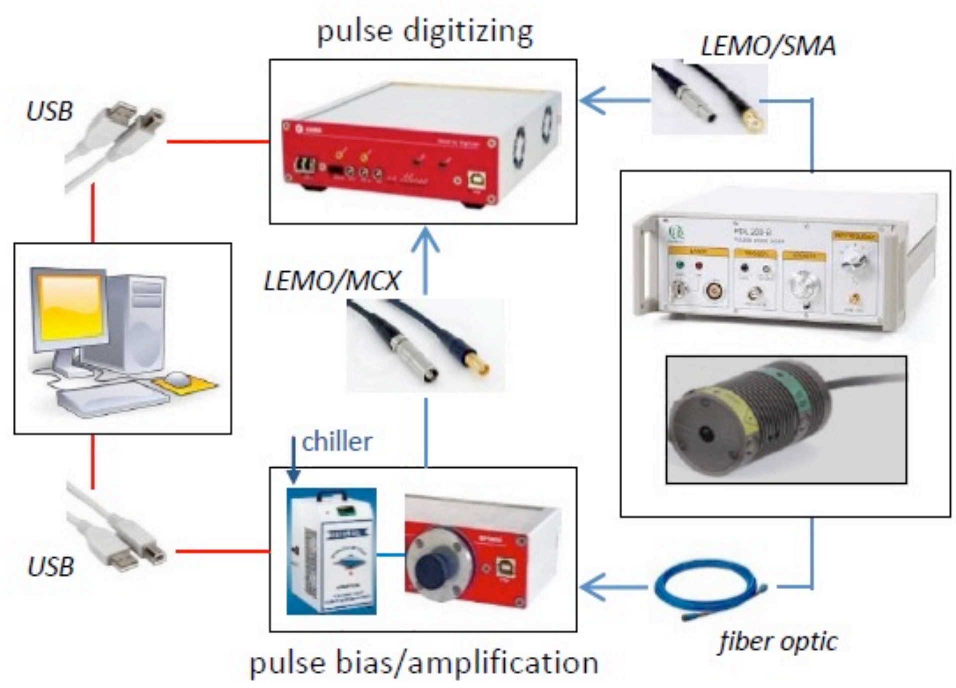
# 1.0 Electrical Characteristics and Physical Dimensions from Data sheet

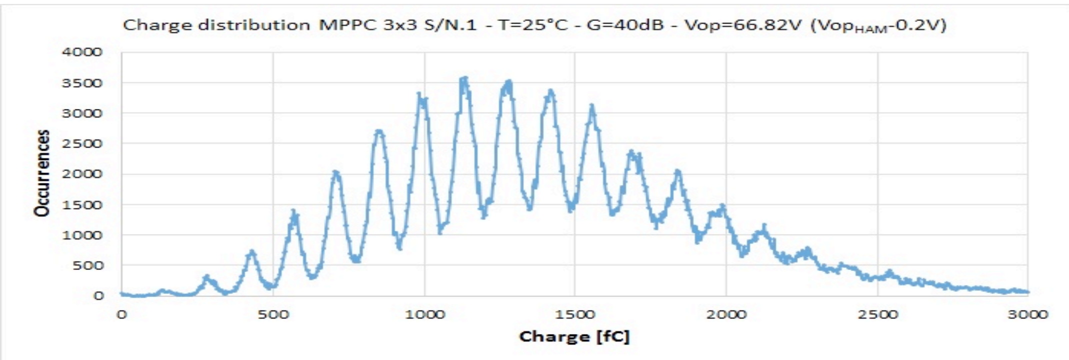
## Type No: 3x3mm 50um Sample-DA

- Pixel pitch: 50 µm
- Effective area: 3 x 3 mm
- Number of pixel: 3600
- Fill Factor: 61.5 %
- Terminal Capacitance: 320 pF
- Vop: 67.02V to have G=7.5 E+05
- Dark: 377 KHz (0.5 pe thr) @25 °C

## 2.0 Electrical characterization: Gain measurements

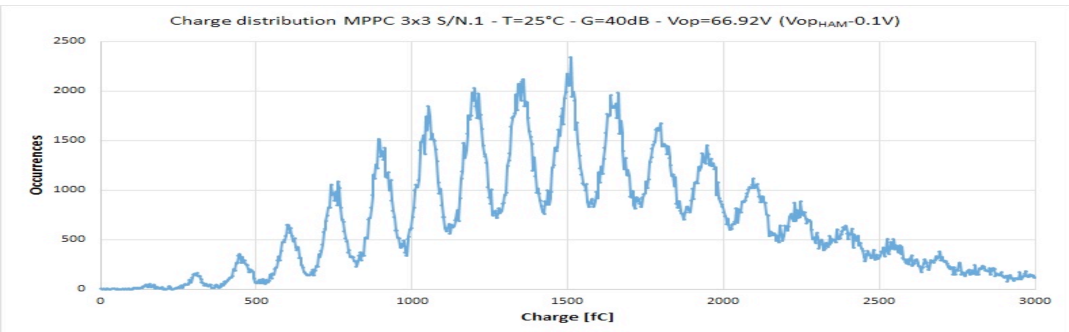
The Operating Voltage for this SiPM given by Hamamatsu is **67.02 Volts** at this voltage Hamamatsu specify a gain **G** of **7.5E+05**.
We set the operating **temperature 25°C** and carried out the measurement by using the set-up shown here:



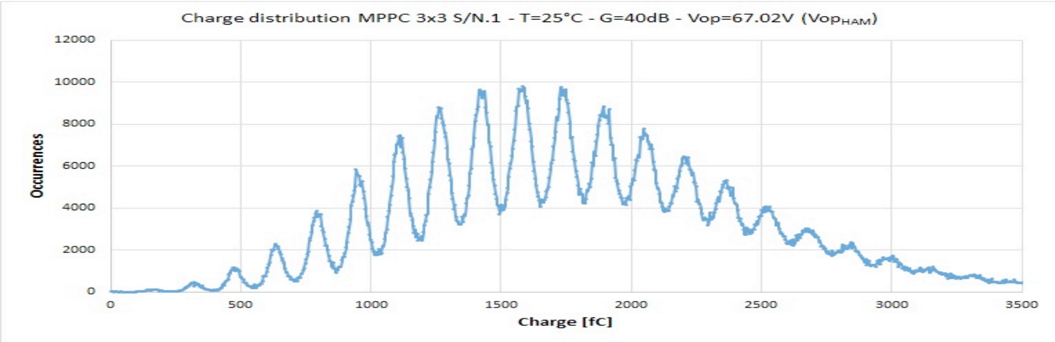

G=8.75E+05

*Fig. 1 - Charge distribution Vop=66.82V ($Vop_{HAM}$- 0.2 V )*



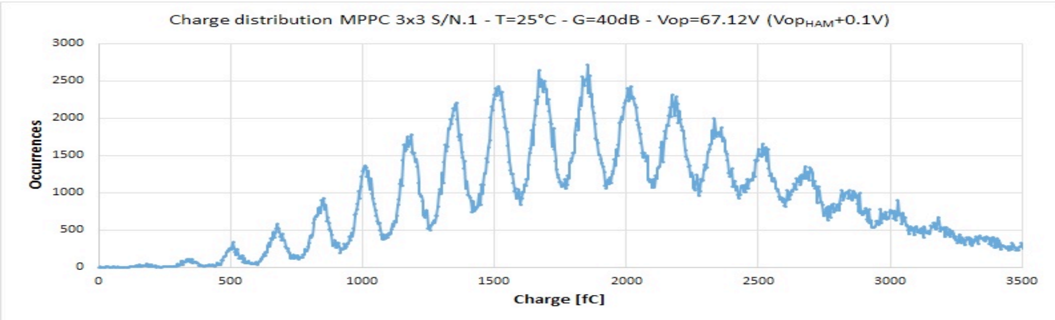

G=9.20E+05

*Fig. 2 - Charge distribution Vop=66.92V (VopHAM- 0.1 V )*



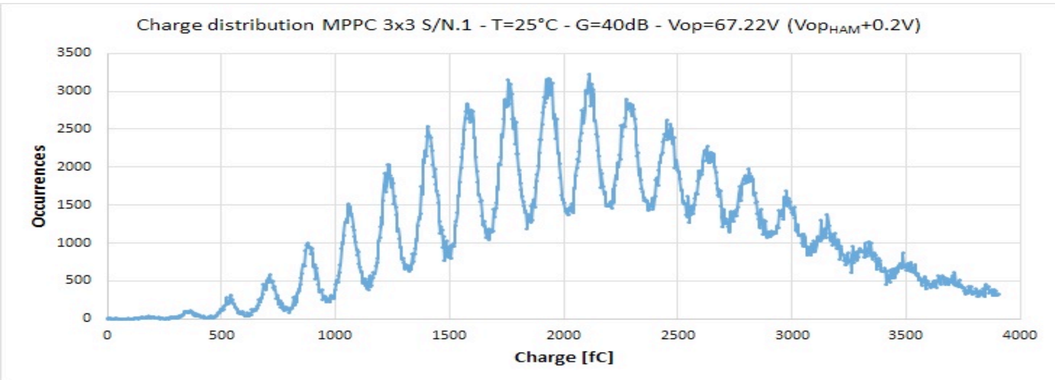

G=9.77E+05

*Fig. 3 - Charge distribution Vop=67.02V (VopHAM )*



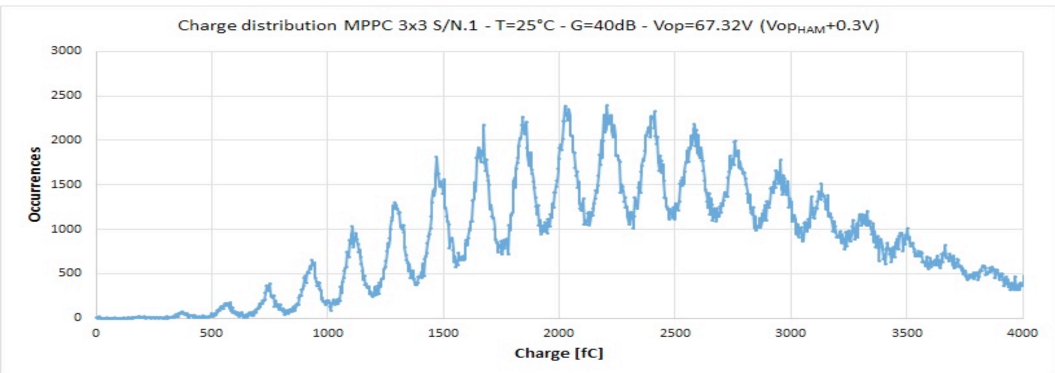

G=1.02E+06

*Fig. 4 - Charge distribution Vop=67.12V (VopHAM+ 0.1 V )*



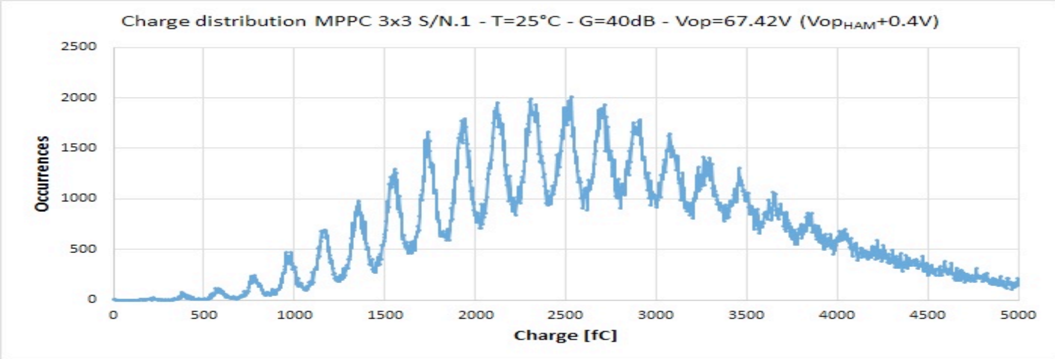

G=1.08E+06

*Fig. 5 - Charge distribution Vop=67.22V (VopHAM+ 0.2 V )*



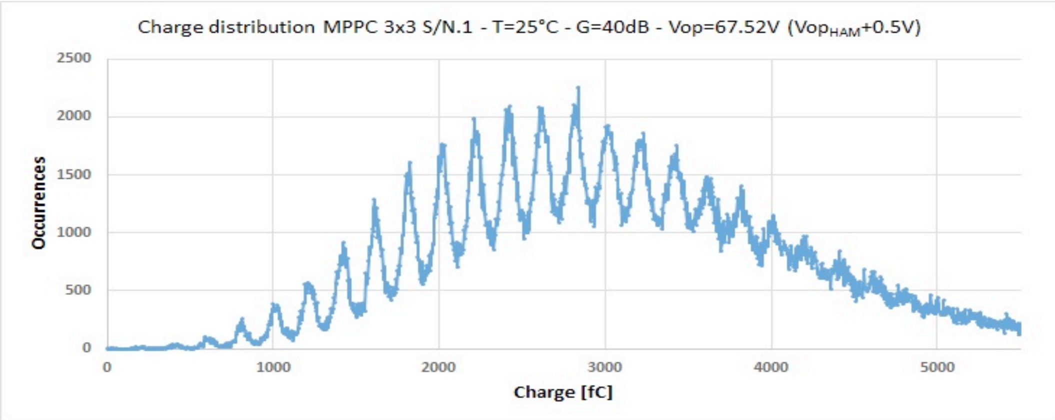

G=1.14E+06

*Fig. 6 - Charge distribution Vop=67.32V (VopHAM+ 0.3 V )*




G=1.22E+06

*Fig. 7 - Charge distribution Vop=67.42V (VopHAM+ 0.4 V )*




G=1.25E+06

*Fig. 8 - Charge distribution Vop=67.52V (VopHAM+ 0.5 V )*

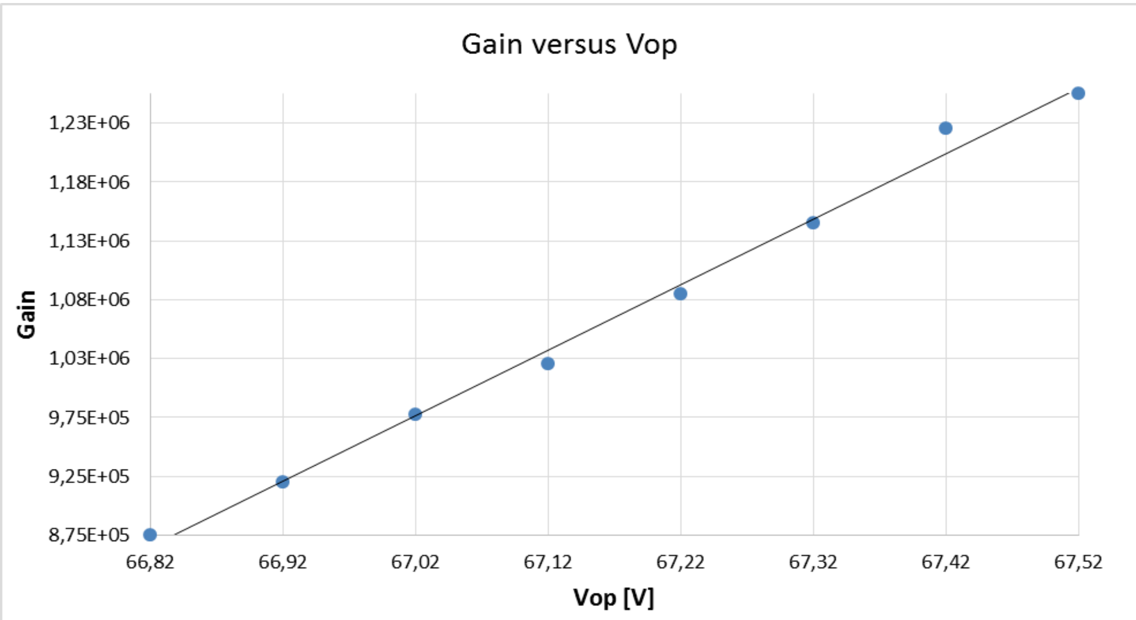
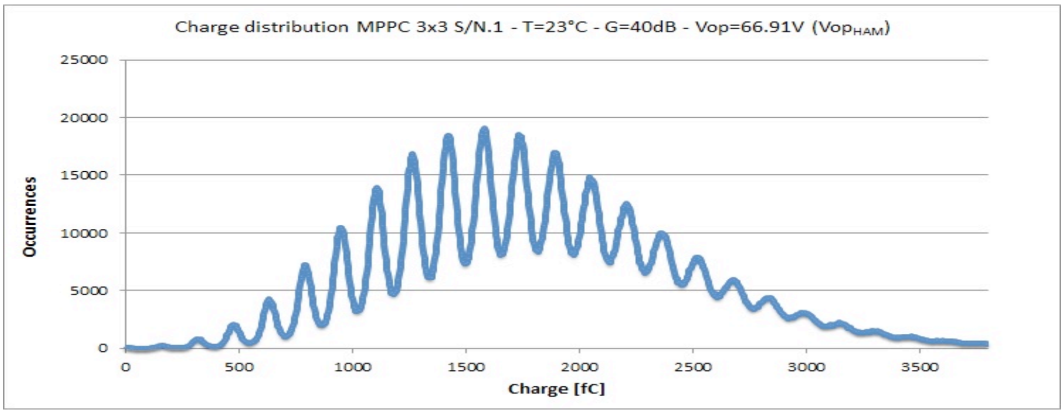



*Fig.9 - Gain versus Vop at T=25°C*

We selcted other working temperatures.
Here, in the following graphs, we report the charge ditribution measurements at Vop =67.02 by selcting **tempeartures: 23°C, 21 °C, 19°C and 17°C**.

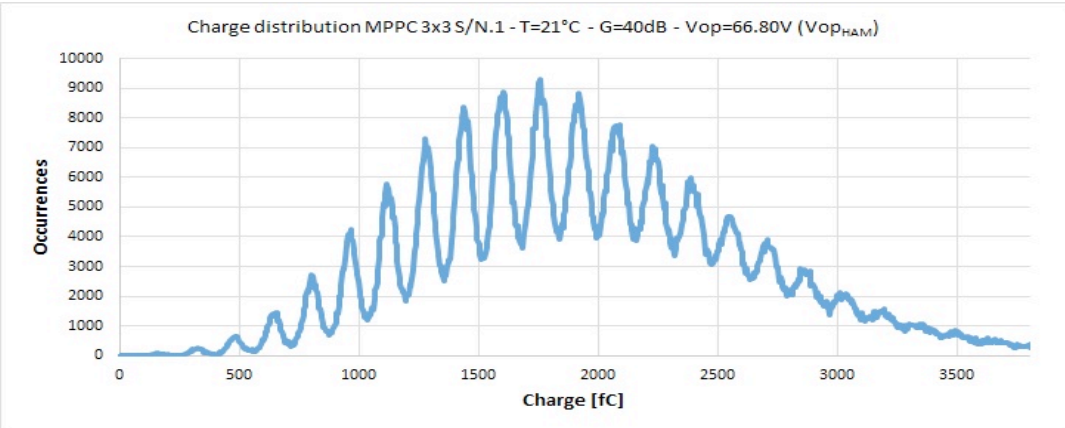
**T= 23°C**




**G=9.77E+05**

*Fig. 10 - Charge distribution Vop=66.92V @ 23°C corresponding to* $Vop_{HAM}$ *=67.02 @ 25°C. As expected the G is the same as that at 25°C.*

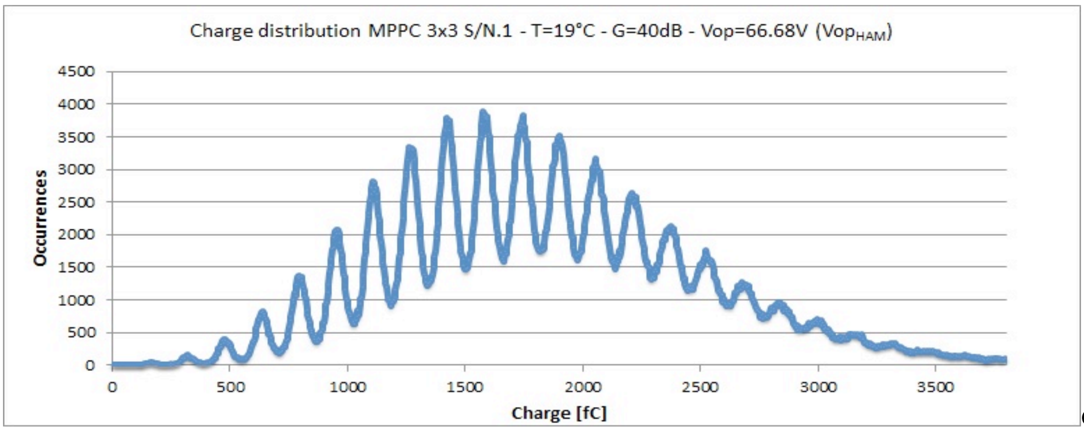
**T= 21°C**




**G=9.93E+05**

*Fig. 11 - Charge distribution Vop=66.80V @ 21°C corresponding to VopHAM @ 25°C.*

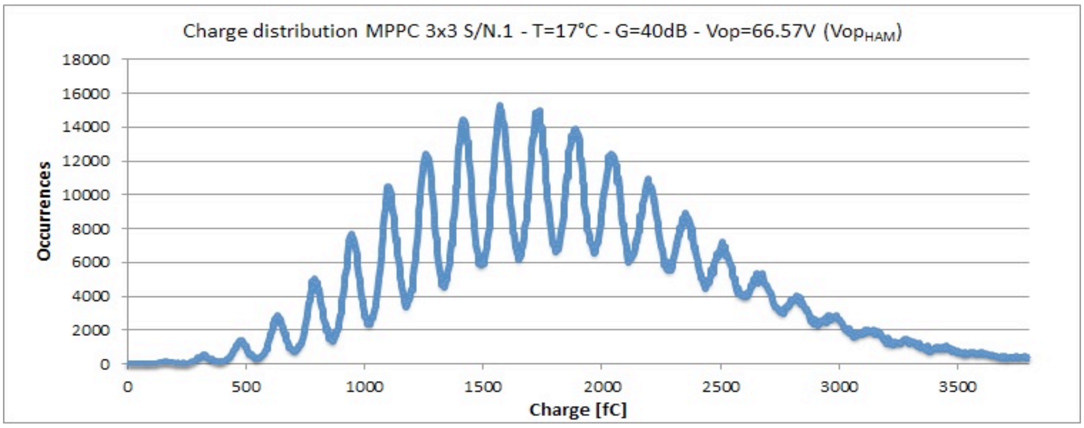
**T= 19°C**




**G=9.81E+05**

*Fig. 12 - Charge distribution Vop=66.68V @ 19°C corresponding to* $Vop_{HAM}$ *@ 25°C*

**T= 17°C**




**G=9.89E+05**

*Fig. 13 - Charge distribution Vop=66.57V (VopHAM ) @ 17°C corresponding to $Vop_{HAM}$ @ 25°C*

As can be noted the gain G doen’t change with the temperature because the applied overvoltage take intoaacount of the working temperature.
In figure 14 the Gain versus the operating voltage Vop at various temperatures is shown.

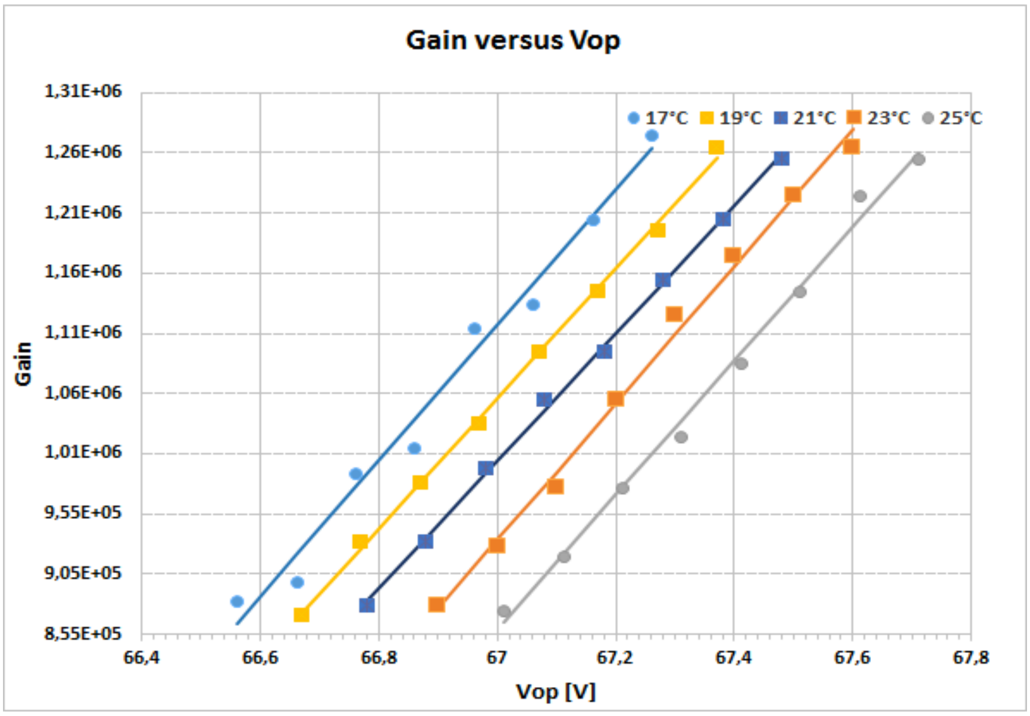
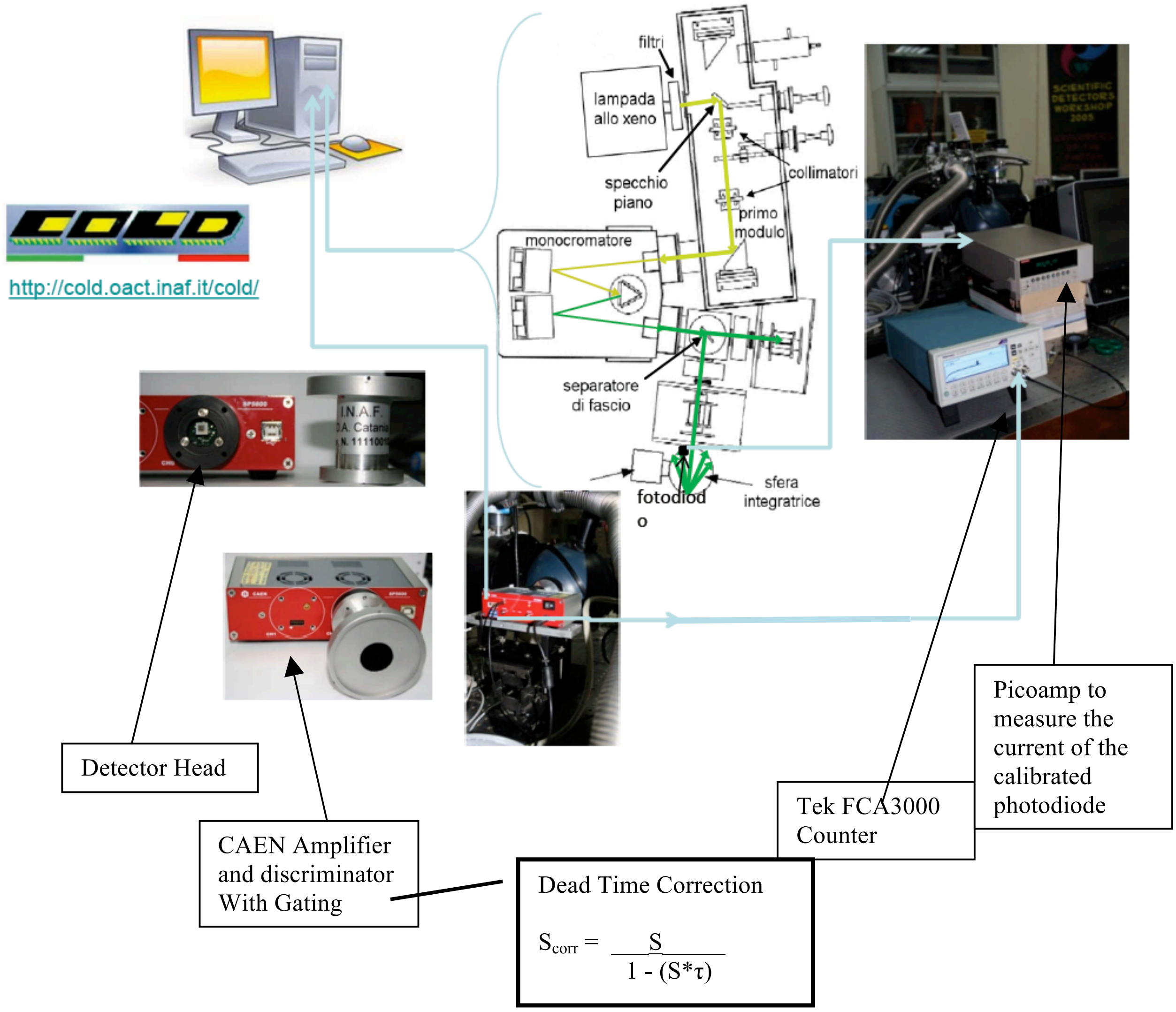


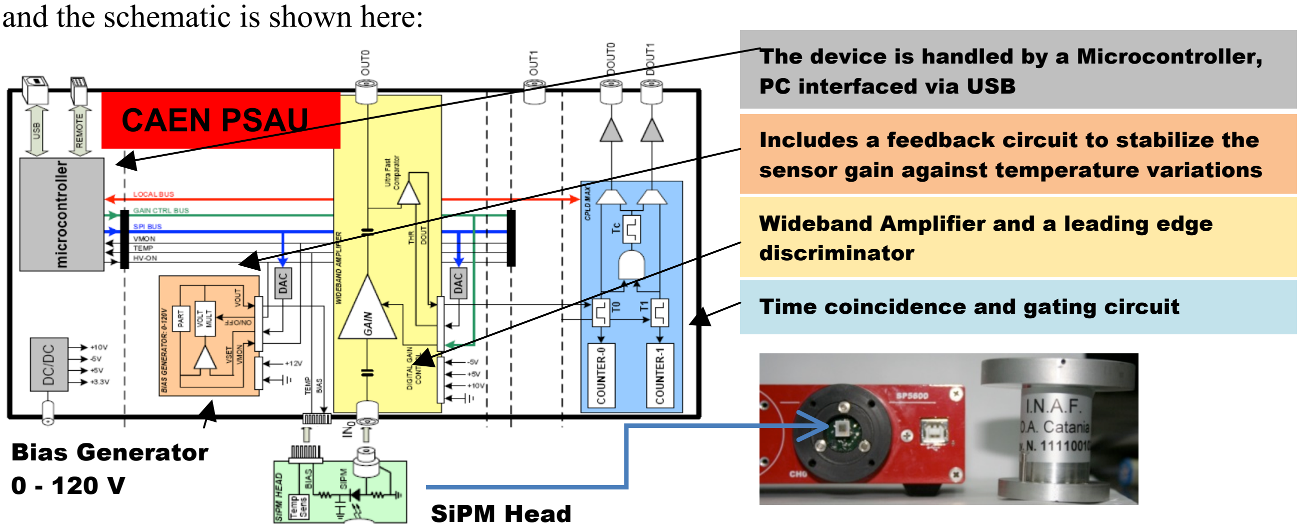

*Fig. 14 – Gain vs Vop at various temperatures*

## 3.0 Optical characterization: PDE in the 350 – 950 nm spectral range at Vop=67.02 V and T=25°C

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




The apparatus is constituted by an illuminating section a monochromator and an integrating sphere where, at the output ports, take place the SiPM included the front-end electronics and calibrated photodiode with the output going to the Keitley picoamperometer. The front-end electronics at the moment is based on the CAEN Power Supply and Amplifier Unit (PSAU) and the schematic is shown here:



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

- on SiPM control electronics
  - the **threshold** to establish the optimal threshold level and accounting for **cross-talk**
  - the **hold-off time** to avoid as much as possible the **after pulsing** effect
- on the optical apparatus:
  - the **illumination level** at the integrating sphere output ports to **prevent** the 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.

### 3.1 Stairs at the operating Voltage 67.02 V with temperature compensation

It is extremely important that the SiPM operating conditions are maintained stable versus the working temperature during the measurements. Apart the DCR other two parameters are affected by temperature variation: the Gain and the Trigger Probability (TP). By knowing the dV/dT coefficient (in this case 56 mV/°C) it is possible to compensate the Vop respect to the temperature variation. 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 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 respect to the breakdown, in other words the TP depends on the Vop. And if TP is unstable an inaccurate PDE measurement will result.

The Dark stairs obtained at Vop =67.0 V and T=25 °C is shown in Fig. 15

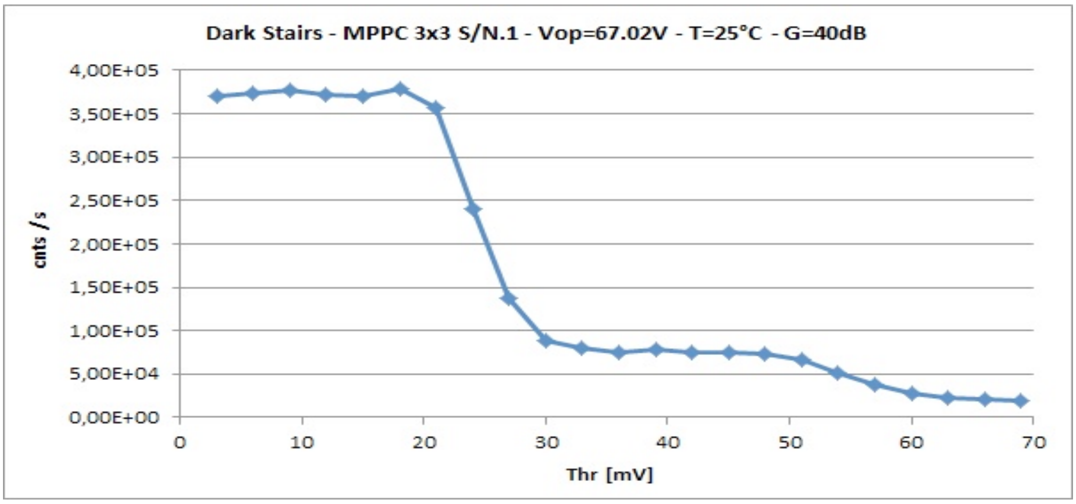



*Fig. 15 - DARK Stairs – Vop=67.02V ($Vop_{HAM}$)– T=25°C*

From the stairs plot we derive that the optimal threshold at 0.5 pe- is $\mathbf{V_{Thr} = -12}$ **mV**.
At this threshold we find a **DCR** of **377KHz** (exactly the same specified by Hamamatsu in the data sheet).

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

Measurements were performed at T=25°C, Vop= 67.02 varying the gate time from 30ns to 120ns.
In Fig. 16 data are plotted with and without dead time correction.

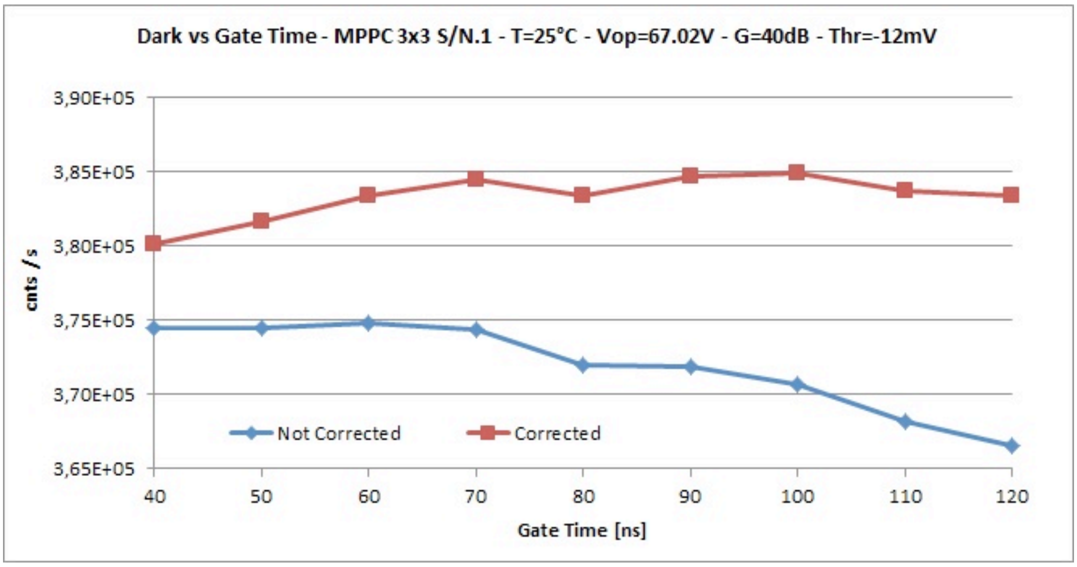



*Fig. 16 - DARK vs hold-off time at Vop=67.02 V - Thr=-12 mV T=25.0° the temperature compensation is activated. Note that the signal loss starts at about 75 ns and the dead time leads to an overestimation of the DCR.*

From the plot of Fig.16 it is clearly evident that aapplying the dead time correction, the dark count rate is over-estimated while the DCR is exactly that obtained from stairs measurements. This behavior tells us that the afterpulse is negligible and **hold-off is not necessary**.
Thus in this case we decide to not apply any hold-off.

### 3.3 Dark count rates versus time at T=25 °C

To be sure that during the PDE measurements the DCR variation doesn't affect the photogenerated signal, the DCR stabilty has been evaluated.
Fig. 17 shows the DCR plot in an interval time of 120 seconds.

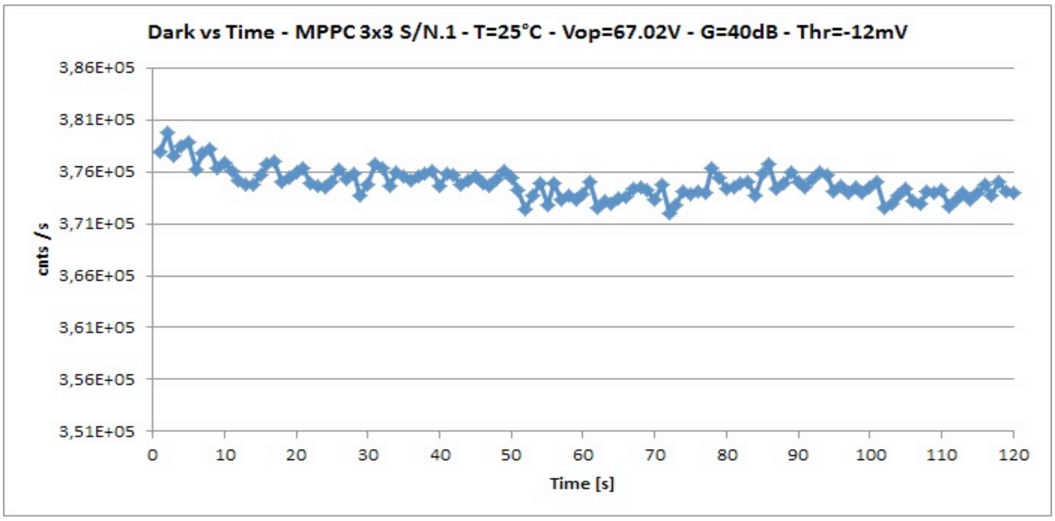



*Fig. 17 – DCR versus time. Note the value of 376KHz is maintained stable during the elapsed time No dead time correction in this case is applied.*

### 3.4 Linearity measurements and PDE versus photon 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 ($\lambda$=500 nm). The SiPM is operated by selecting T=25°C, $V_{OP}$ = 67.02V and without hold-off time.
Fig. 18 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.

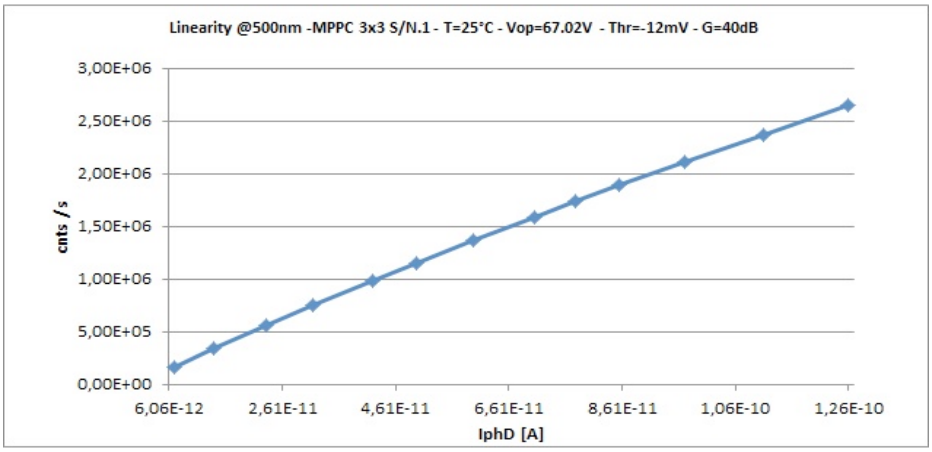



*Fig. 18 – Linearity at $\lambda$=500 nm. Each rate is plotted with the corresponding photon rate per mm$^2$.Values corrected for dead time are also reported. This is obtained by knowing the NIST traced QE at 500 nm of the calibrated photodiode.*

To have an idea of the involved photon flux in terms of number of photons per square mm, anoter representation of the above plot can be given. Simply by knowing the photodiode sensitive area and QE(500nm) by using the following formula:

$$(I_{Sphd} - I_{Dphd})/e-) \times 1/QE_{phd} \times 1/A_{phd}$$

Fig. 19 shows the photon rate at 500 nm as a function of the number of photons/mm$^2$.

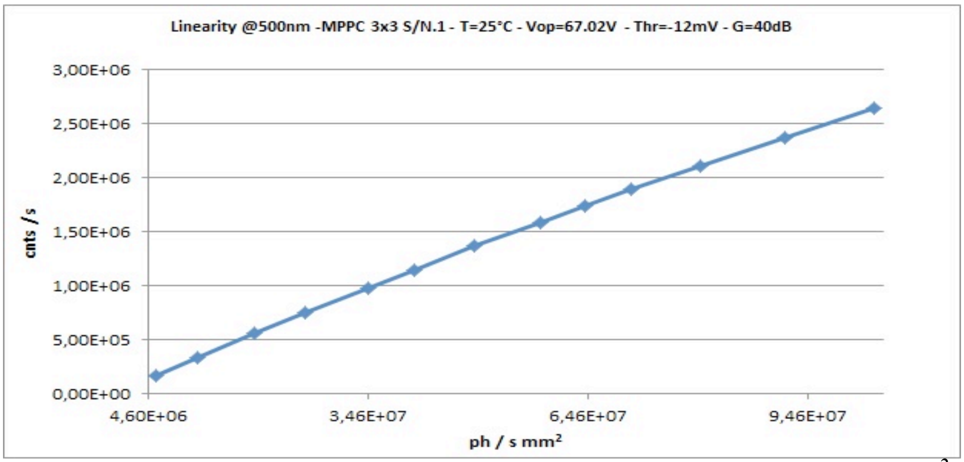



*Fig. 19 – Linearity at $\lambda$=500 nm. Photon rate as a function of the number of photons/mm$^2$.*

From both these plots we derive a non-linearity behavior at about 1.6 Mcnts/s corresponding to a photon rate of about 6.5 × $10^7$ photons/mm$^2$.

A more efficient method to evaluate the PDE degradation due to the uncorrected illumination can be that to directly evaluate the PDE(500nm) versus the photon counting rate as shown in figure 20.

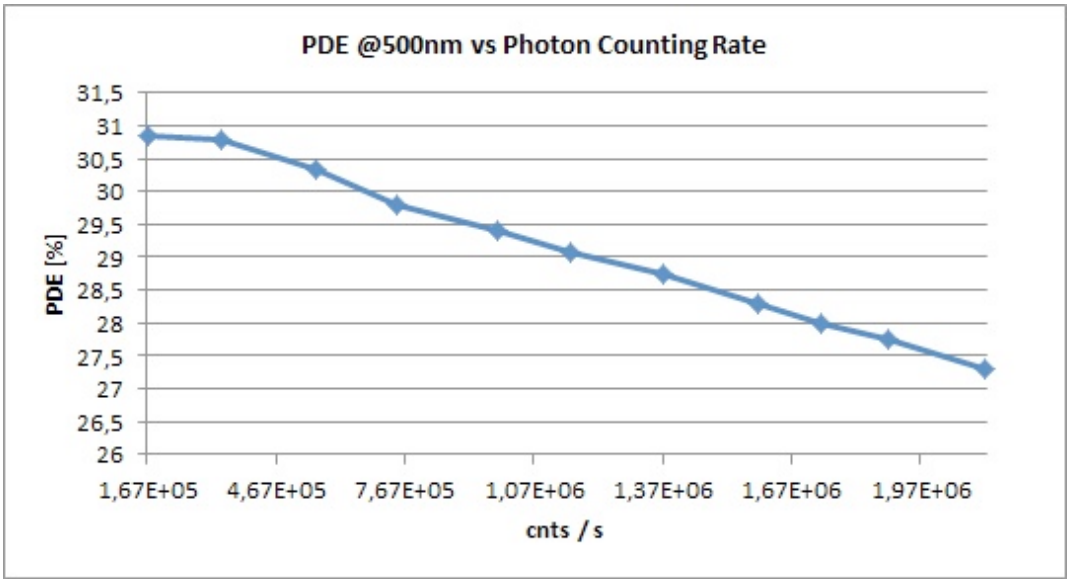



*Fig. 20 –PDE versus photon counting rates with dark removed at λ=500 nm.*

This plot allows us to better select the appropriate photon rates. In fact it is clearly evident the PDE drop off at rates greater than 500 KHz that means about 900 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 1 MHz that including the dark means about 1.4 MHz.

**3.5 PDE in the 350 – 950 nm spectral range at T=25°C and Vop= 62.02 V**

As stated in the previous paragraph, we worked in such illuminating condition to don't degrade the SiPM counting rate. But in this low level signal condition we can experiment a not very accurate measurement by the Keitley 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 is reported in figure --- where is compared with PDE plots obtained at different Vop and at the same temperature.

# 4.0 PDE in the 350 – 950 nm spectral range at Vop=67.32 V ($V_{HAM}$+300mV) and T=25°C

## 4.1 DCR Stairs and gate time measurements at Vop = 67.32 V with temperature compensation

According to the established procedure (see the flow chart above reported), we changed the Vop and repeated the same measurements as the previous chapter.
The Dark stairs obtained at Vop =67.32 V and T=25 °C is shown in Fig. 21

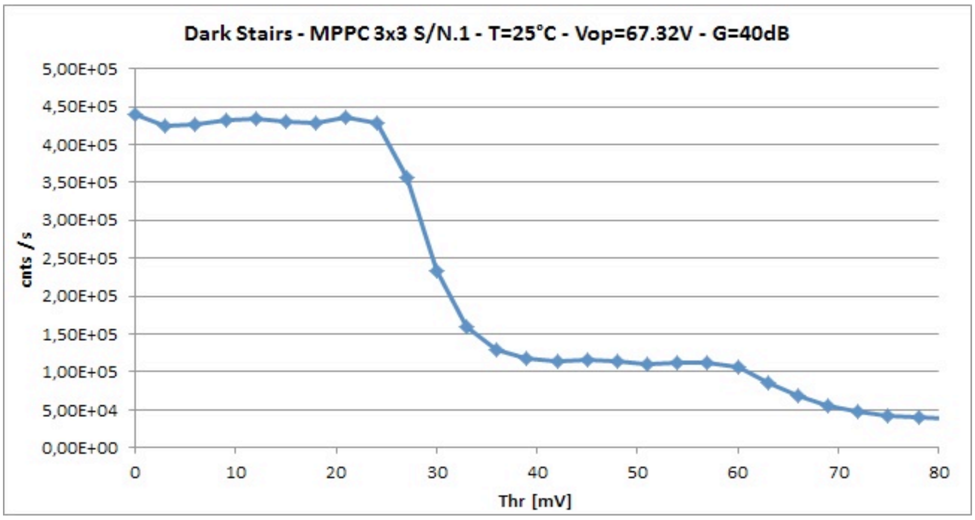



*Fig. 21– DARK Stairs – Vop=67.32V ($Vop_{HAM}$ + 300mV) – T=25°C*

From the stair plot we derive that the optimal threshold at 0.5 pe- is **$V_{Thr}$ = -18 mV**.
**The DCR** at the selected threshold **is 437 KHz.**

## 4.2 Dark count rates versus time at T=25 °C

Fig. 22 shows the DCR plot in an interval time of 120 seconds at Vop=VHAM + 300mV and T=25°C.

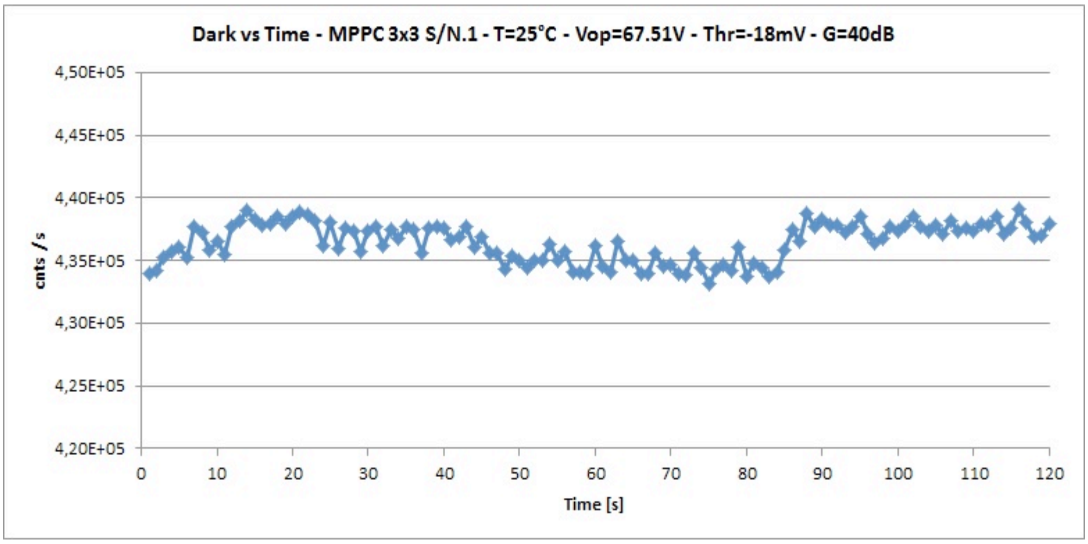



*Fig. 22 – DCR versus time. Note the value of 437KHz is maintained stable during the elapsed time*

### 4.3 Linearity measurements and PDE versus photon counting rate

Fig. 23 shows the photon rate at 500 nm as a function of the number of photons/mm$^2$.

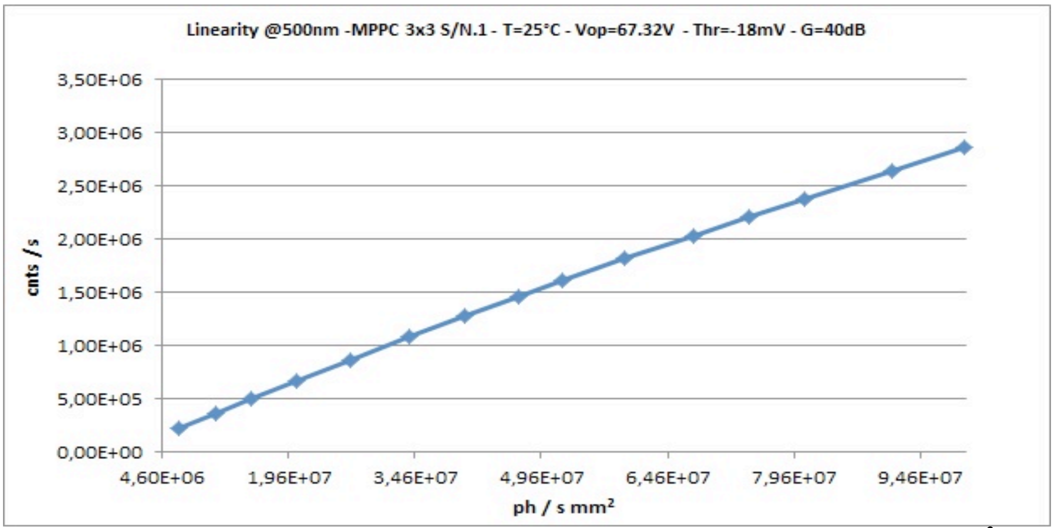



*Fig. 23 – Linearity at λ=500 nm. Photon rate as a function of the number of photons/mm$^2$.*

From the plot we derive a non-linearity behavior of about 1.5 Mcnts/s corresponding to a photon rate of about $5 \times 10^7$ photons/mm$^2$.

Fig. 24 shows the PDE(500nm) degradation versus the photon counting rate.

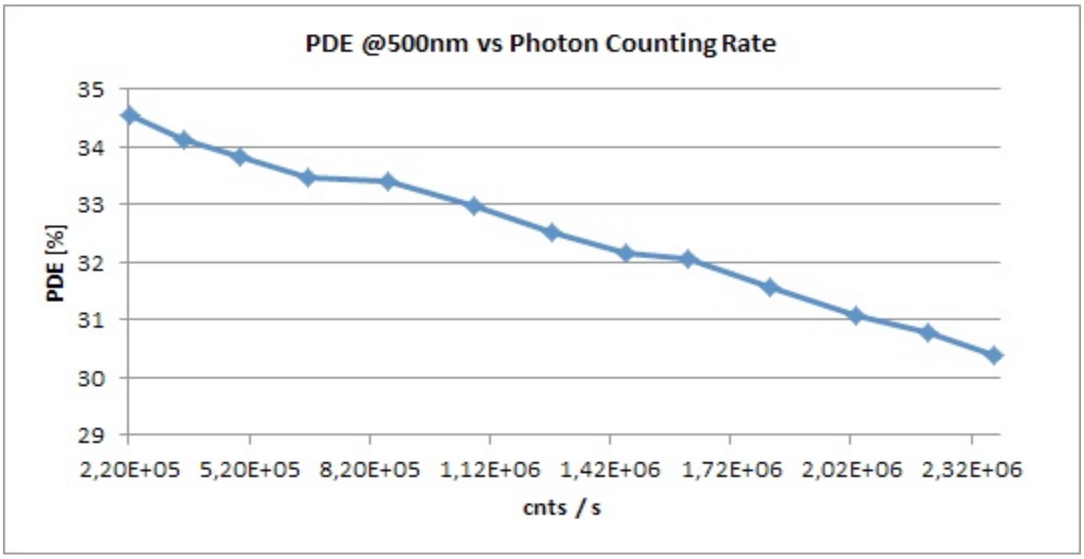



*Fig. 24 –PDE versus photon counting rates with dark removed at λ=500 nm.*

Also in this case we observe a PDE drop off at rates greater than 600 KHz that means about 1 MHz including the DCR contribute. The PDE degradation becomes unacceptable at count rates higher than 1 MHz that including the dark means about 1.4 MHz.

### 4.4 PDE in the 350 – 950 nm spectral range at T=25°C and Vop= 62.32 V

The PDE plot is reported in figure --- where is compared with PDE plots obtained at different Vop and at the same temperature.

# 5.0 PDE in the 350 – 950 nm spectral range at Vop=67.52 V ($V_{HAM}$+500mV) and T=25°C

## 5.1 DCR Stairs and gate time measurements at Vop = 67.52 V with temperature compensation

The DCR stairs obtained at Vop =67.52 V and T=25 °C is shown in Fig. 25.

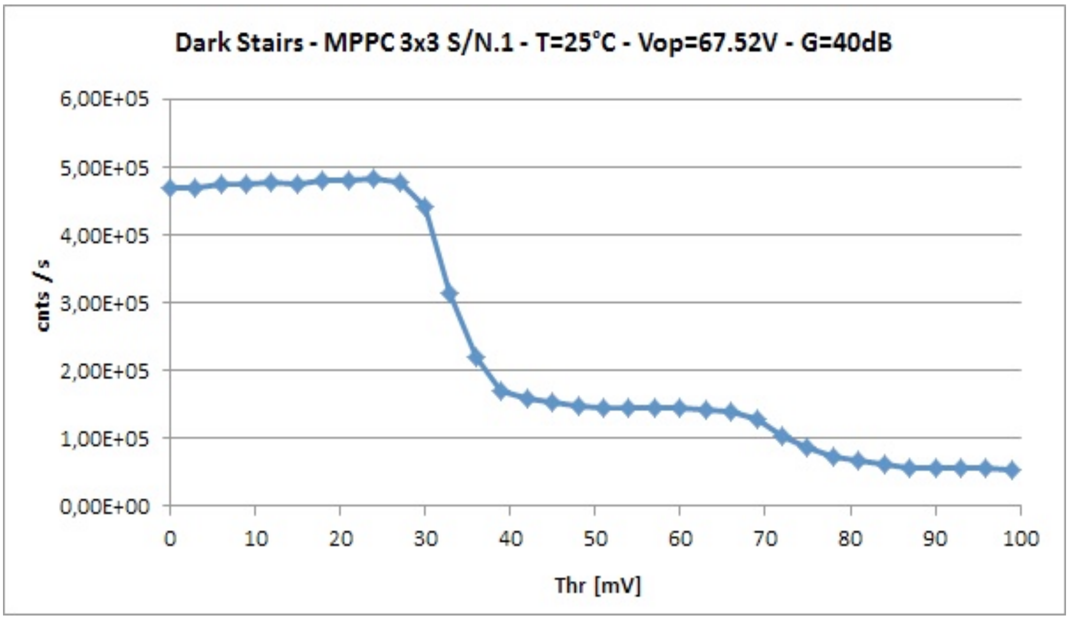



*Fig. 25 – DCR Stairs – Vop=67.52V ($Vop_{HAM}$ + 500mV) – T=25°C*

From the stair plot we derive that the optimal threshold at 0.5 pe- is **$V_{Thr}$ = -21 mV**.
**The DCR** at the selected threshold **is 475 KHz.**

## 5.2 Dark count rates versus time at T=25 °C

Fig. 26 shows the DCR plot in an interval time of 120 seconds at Vop=VHAM + 300mV and T=25°C.

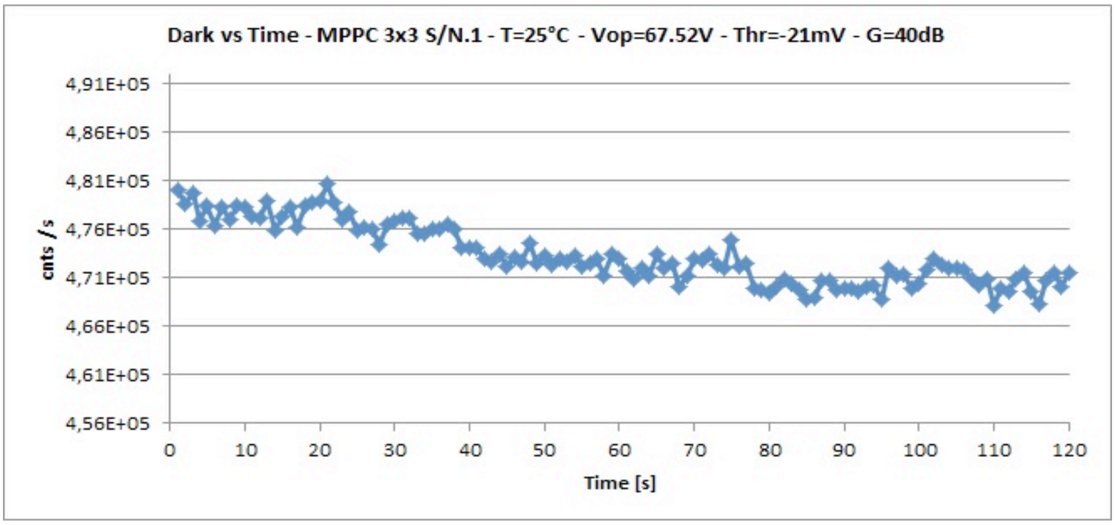



*Fig. 26 – DCR versus time. Note the value of 475 KHz is maintained stable during the elapsed time*

### 5.3 Linearity measurements and PDE versus photon counting rate

Fig. 27 shows the photon rate at 500 nm as a function of the number of photons/mm$^2$.

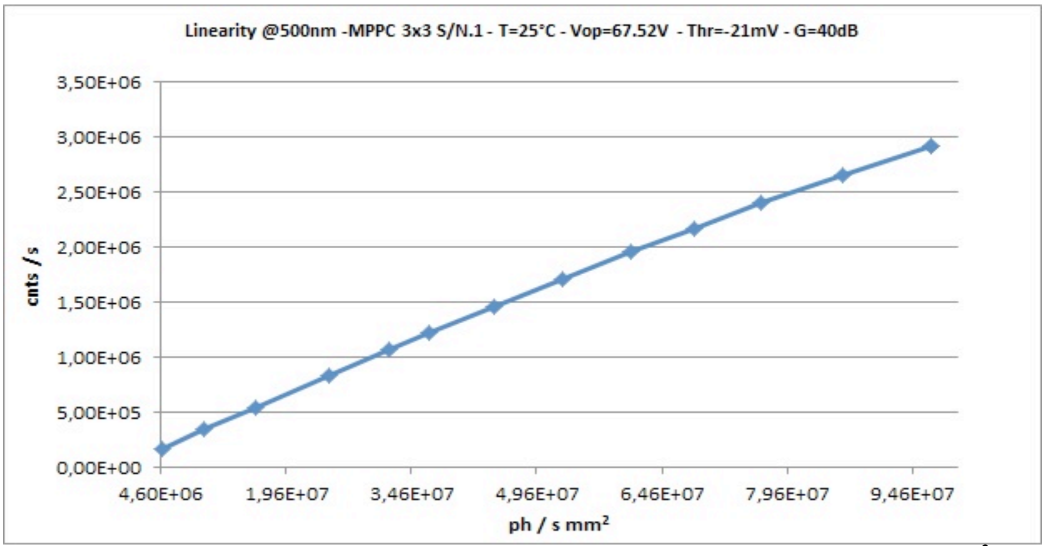



*Fig. 27 – Linearity at λ=500 nm. Photon rate as a function of the number of photons/mm$^2$.*

From the plot we derive a non-linearity behavior of about 1.4 Mcnts/s corresponding to a photon rate of about $4.5 \times 10^7$ photons/mm$^2$.

Fig. 28 shows the PDE(500nm) degradation versus the photon counting rate.

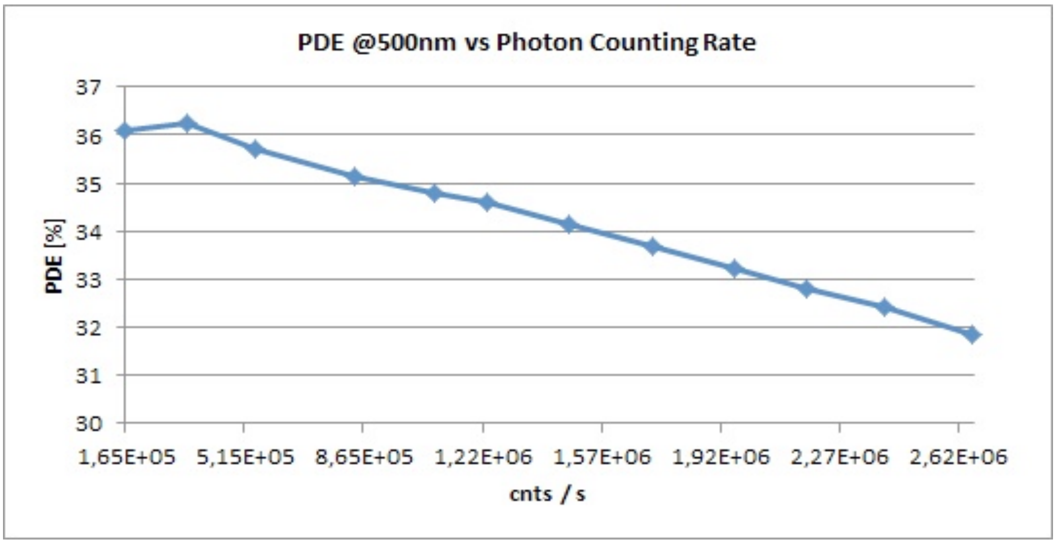



*Fig. 28 –PDE versus photon counting rates with dark removed at λ=500 nm.*

Also in this case we observe a PDE drop off at rates greater than 800 KHz that means about 1.2 MHz including the DCR contribute. The PDE degradation becomes unacceptable at count rates higher than 1.4 MHz that including the dark means about 1.8 MHz.

### 5.4 PDE in the 350 – 950 nm spectral range at T=25°C and Vop= 62.52 V

The PDE plot is reported in figure --- where is compared with PDE plots obtained at different Vop and at the same temperature.

## 6.0 PDE in the 350 – 950 nm spectral range at Vop = $Vop_{HAM}$, $Vop_{HAM}$ +0.3V $Vop_{HAM}$ +0.5V

Finally the PDE measurements at 25°C and the three different operating voltages 67.02 V, 67.32 V and 67.52 V are compared in Fig.29.

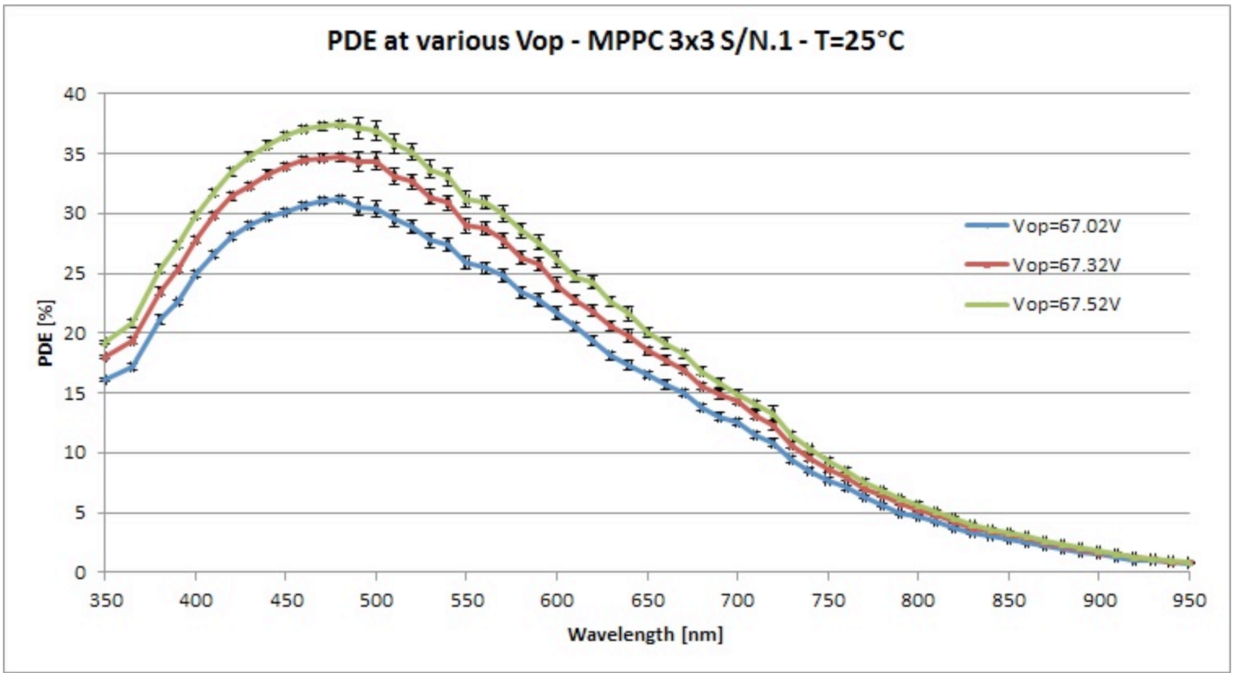



*Fig. 29 – PDE measurements comparison for the SiPM operated at Vop=67.02V, Vop=67.32V, Vop=67.52V @ T=25°C. The error bars are also reported.*

At the suggest by Hamamatsu operating voltage Vop= 67.02 V a PDE that peaks at a value of 31 % in the 470 -490 nm spectral range has been found. The MPPC shows also at 400 nm an acceptable 25% of PDE.

As expect and discussed in chapter 3.0 the PDE depends essentially on the Trigger Probability that in turn means on the overvoltage respect to breakdown.

By operating the device at Vop= 67.52 (500 mV more than that specified by Hamamatsu), in the 470 -490 nm spectral range is clearly evident an increase of PDE of more than7% reaching about 38% and also a satisfactory PDEof 30% at 400 nm has been measured.

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

Following the flow chart discussed in previous sections, we have investigated the crosstalk showed by the SiPM. The crosstalk is estimated by the ratio between the primary event count rate and the second event count rate, that translated means acquire DCR stairs at various operating voltages. Form the previous section we have the stairs at Vop= 67.02V, 67.32V and 67.52V and from them we can derive the cross-talk and the DCR. To have a good representation of the crosstalk and the DCR respect to the operating voltage, other two DCR stairs have been acquired, one at Vop=66.82V ($Vop_{HAM}$ - 0.2V) and one at Vop=67.72V ($Vop_{HAM}$ + 0.7V) A **working temperature of 25°C** has been selected.
Stairs of DCR at Vop=66.82 is shown in fig. 30 while that at Vop=67.72 is reported in fig. 31.

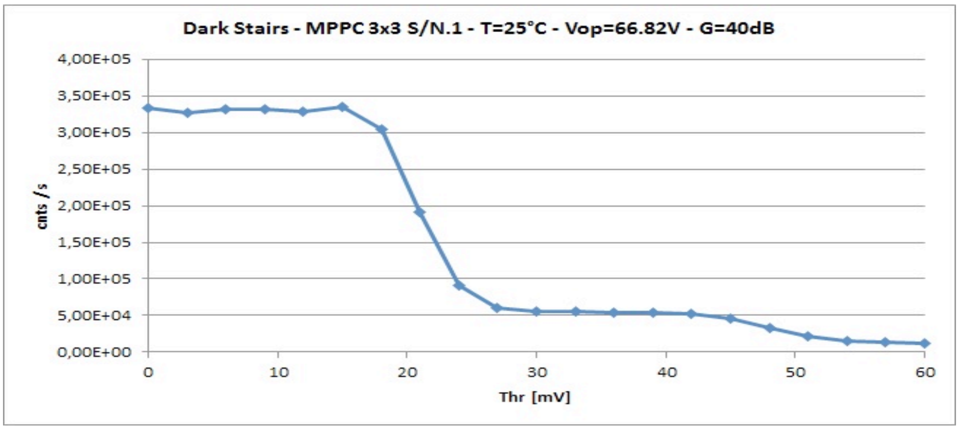



*Fig. 30 - DARK Stairs – Vop=66.82V ($Vop_{HAM}$ – 0.2 V)– T=25°C. The crosstalk in this case results 16.46%*

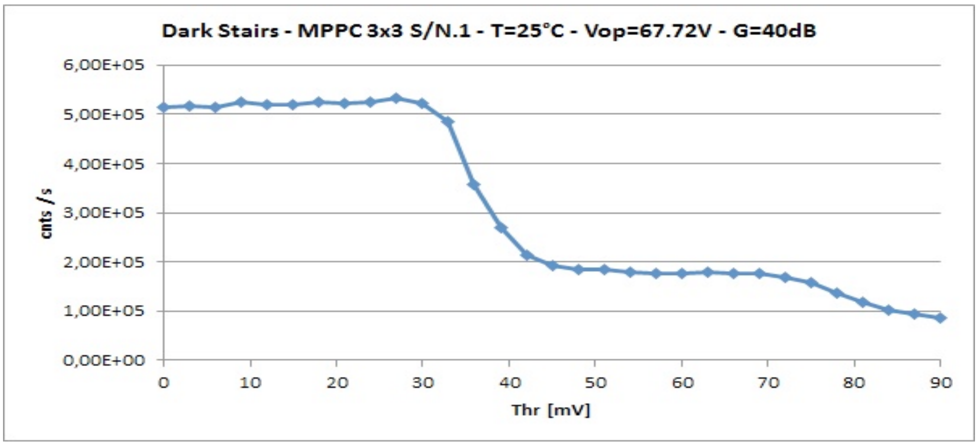



*Fig. 31 - DARK Stairs – Vop=67.72V ($Vop_{HAM}$ + 0.7 V)– T=25°C. The crosstalk in this case results 33.78%*

The crosstalk and DCR at the various operating voltages are listed in the In table 1, and plotted in figure 32.

TABLE 1
Crosstalk and DCR at various Vop at T=25°C

| Vop | $Vop_{HAM}$ | DCR [KHz] | Xtalk [%] |
|---|---|---|---|
| 66.82 | - 0.2 V | 331 | 16.46 |
| 67.02 | + 0 V | 373 | 20.02 |
| 67.32 | + 0.3 V | 430 | 26.11 |
| 67.52 | + 0.5 V | 476 | 30.59 |
| 67.72 | + 0.7 V | 521 | 33.78 |

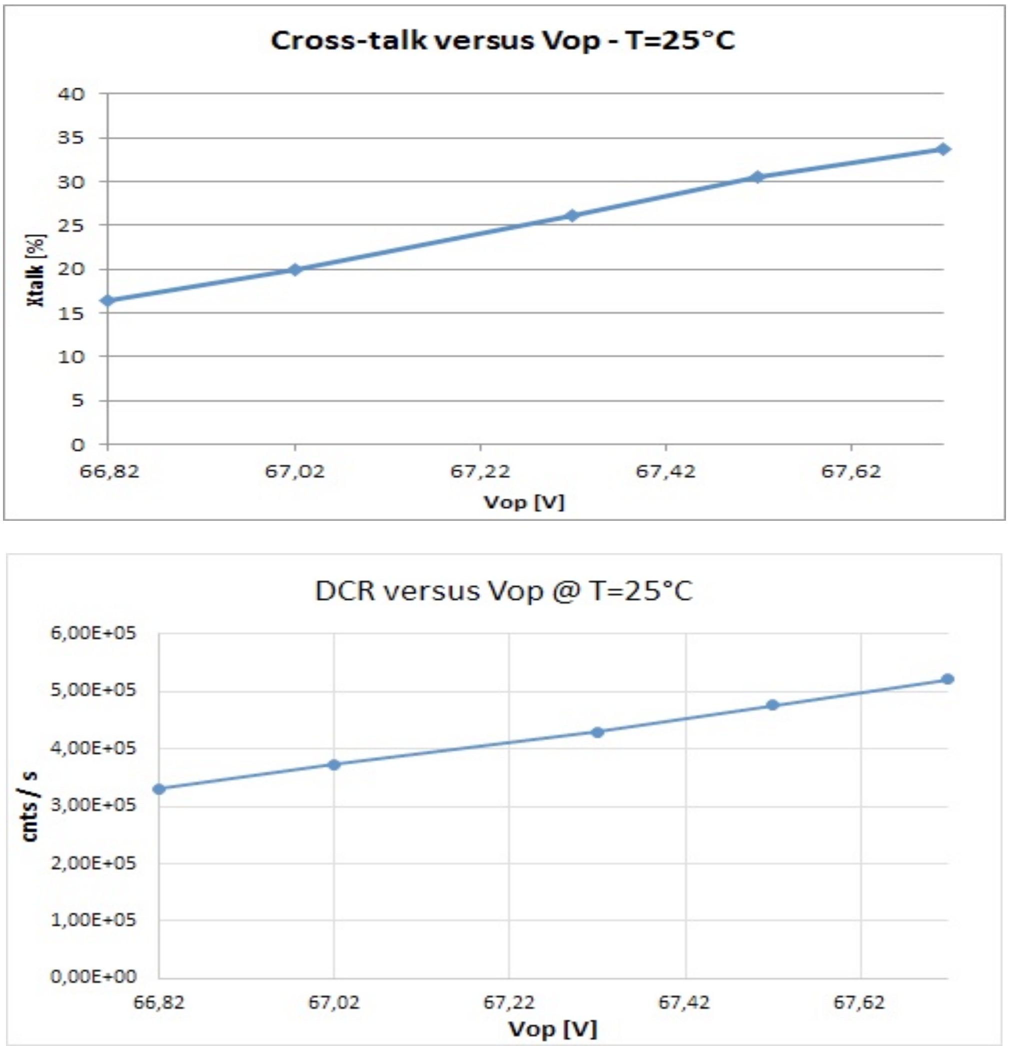



*Fig. 32 – Upper Panel :Crosstalk versus Vop – Lower Panel: Dark Count Rate versus Vop. Both at T=25°C.*

The increasing PDE with the Vop has been evaluated for all the above reported Vop values and this has been carried out in the spectral range from 400 to 600 nm (in steps of 50 nm). In fig. 33 the PDE plots at the various Vop in the 400-600 nm range are presented.

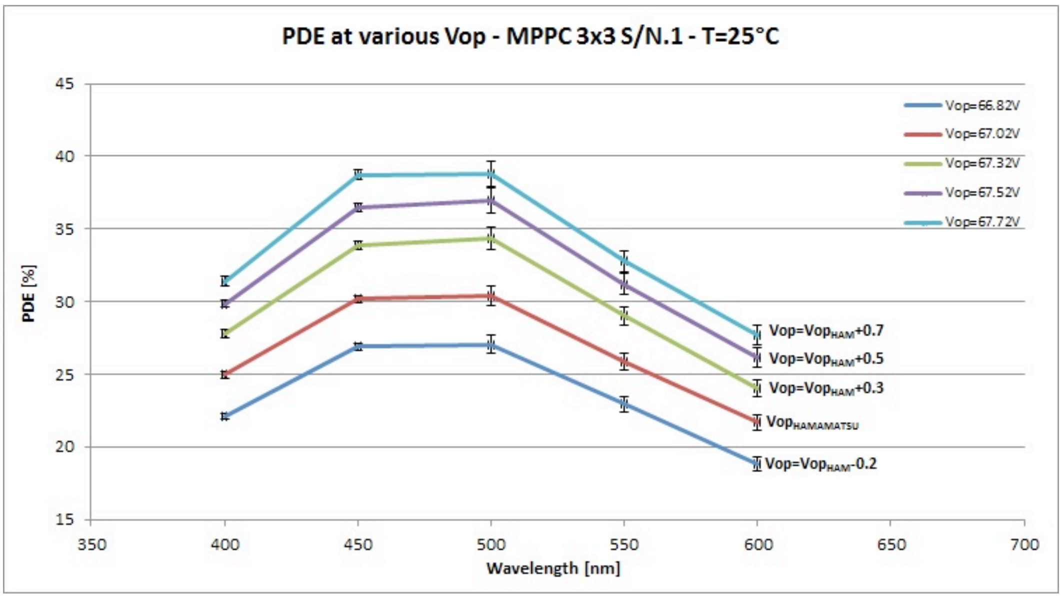



*Fig. 33 – PDE plots at various Vop in the 400-600 nm range*

## 8.0 Cross-talk, PDE and DCR at different temperatures

Finally, according to the flow chart, we changed the working temperature and realized the same tests of crosstalk, PDE and DCR.
The selected **working temperatures ranging from 15°C to 25°Cin steps of 2°C**

### 8.1 DCR Stairs measurements at Vop = 67.02 V and temperatures ranging from 15°C to 25°C in steps of 2°C applying the compensation temperature coefficient dV/dT

After the working temperature was selected and the PSAU temperature compensation activated, the first thing to perform was a DCR stairs. Fig. 34 shows all together the acquired stairs obtained by selecting the Hamamatsu suggested operating voltage Vop=67.02 and at the above mentioned working temperatures.

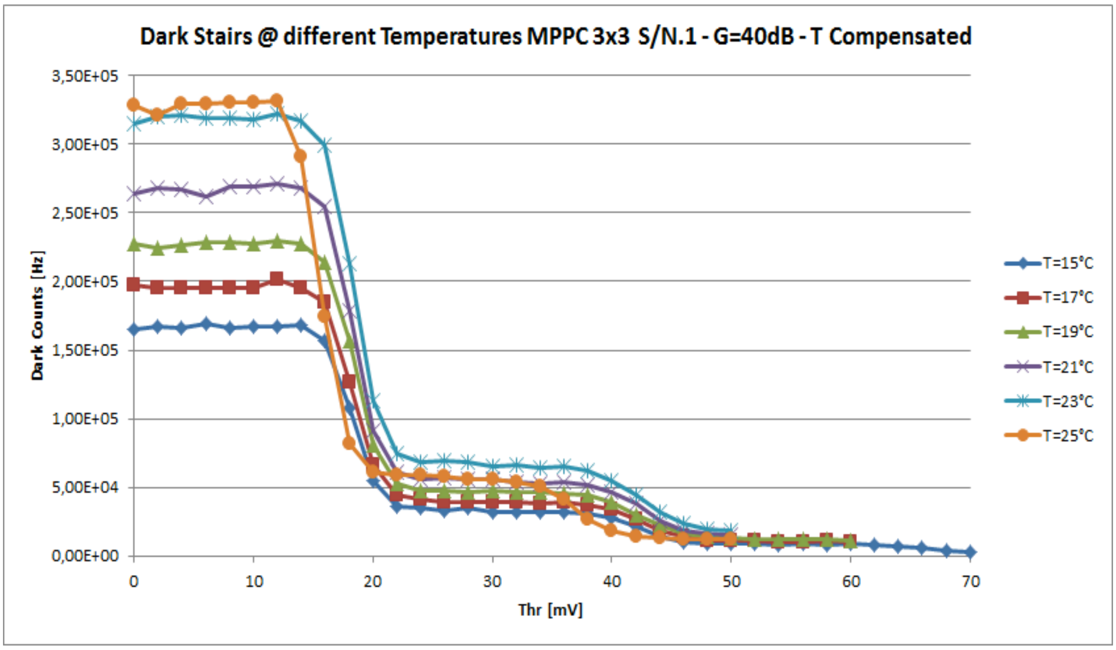



*Fig. 34 - Cross talk at working temperatures ranging from 15°C to 25°Cin steps of 2°C.*

### 8.2 Crosstalk and PDE at temperatures ranging from 15°C to 25°Cin steps of 2°C applying the compensation temperature coefficient dV/dT

From the stairs plots of figure 34 the cross-talk and the DCR can be easily derived.
The measurements report the same values for all the working temperatures meaning that the **crosstalk doesn't depend on working temperature.**
PDE at some wavelengths was also tested at the above cited temperatures by applying the correspondent Vop (using the dV/dT compensation). We found the same PDE at all the selected temperatures, and thus, as expected, the PDE does not vary with temperature.

## 8.3 DCR at Vop=67.02 V and temperatures ranging from 15°C to 25°Cin steps of 2°C applying the compensation temperature coefficient dV/dT

As stated before, from the stairs plots of figure 34 the DCR can be easily evaluated. The DCR is the only parameter that really change when the temperature coefficient dV/dT is used.
From the measurements we can reconstruct the plot showed in fig. 35 that reports the DCR as function of temperature.

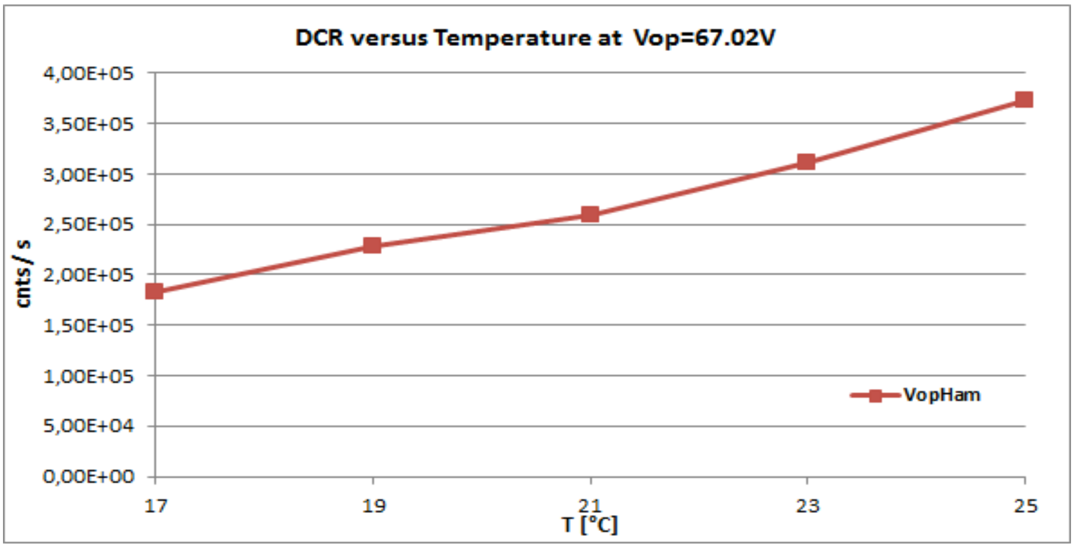



*Fig. 35 - DCR at working temperatures ranging from 15°C to 25°Cin steps of 2°C.*

From the DCR versus temperature measurements we also found, that the DCR halves every about 7 °C, as expected in Silicon devices.

## 8.4 DCR at various Vop and at temperatures ranging from 15°C to 25°Cin steps of 2°C applying the compensation temperature coefficient dV/dT

By repeating the procedure described in section 8.3 at the various Vop above reported we can obtain a comprehensive graph as that showed in fig. 36.

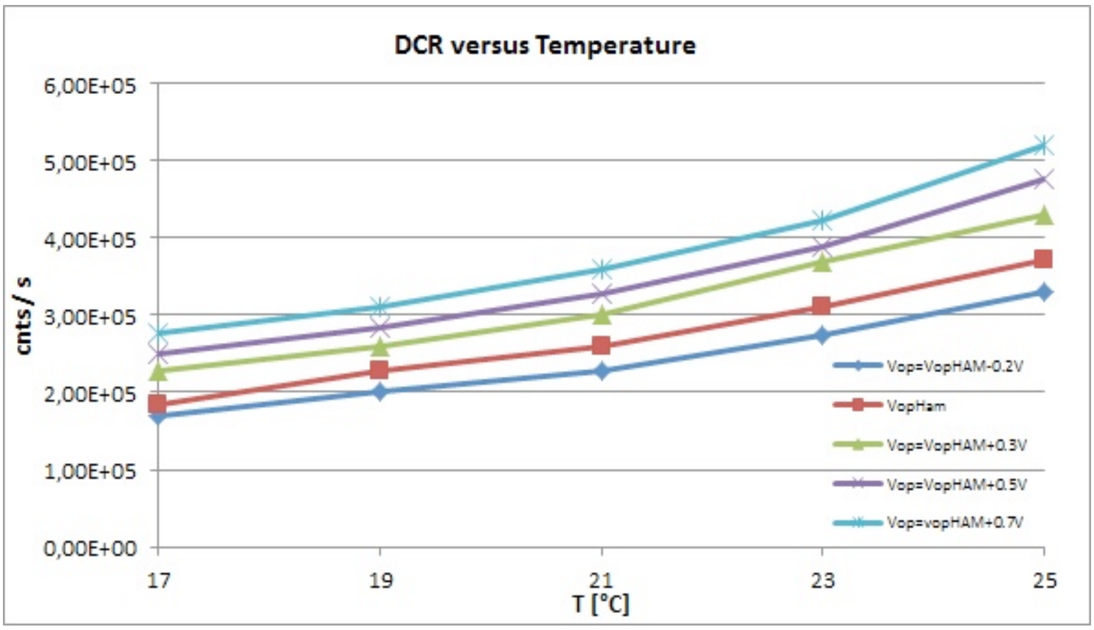



*Fig. 36 - DCR at various Vop and at temperatures ranging from 15°C to 25°C in steps of 2°C.*

Another way to present the data of the plots in fig. 36 is to report the DCR versus the Vop at temperatures ranging from 15°C to 25°C in steps of 2°C as showed in fig. 37.

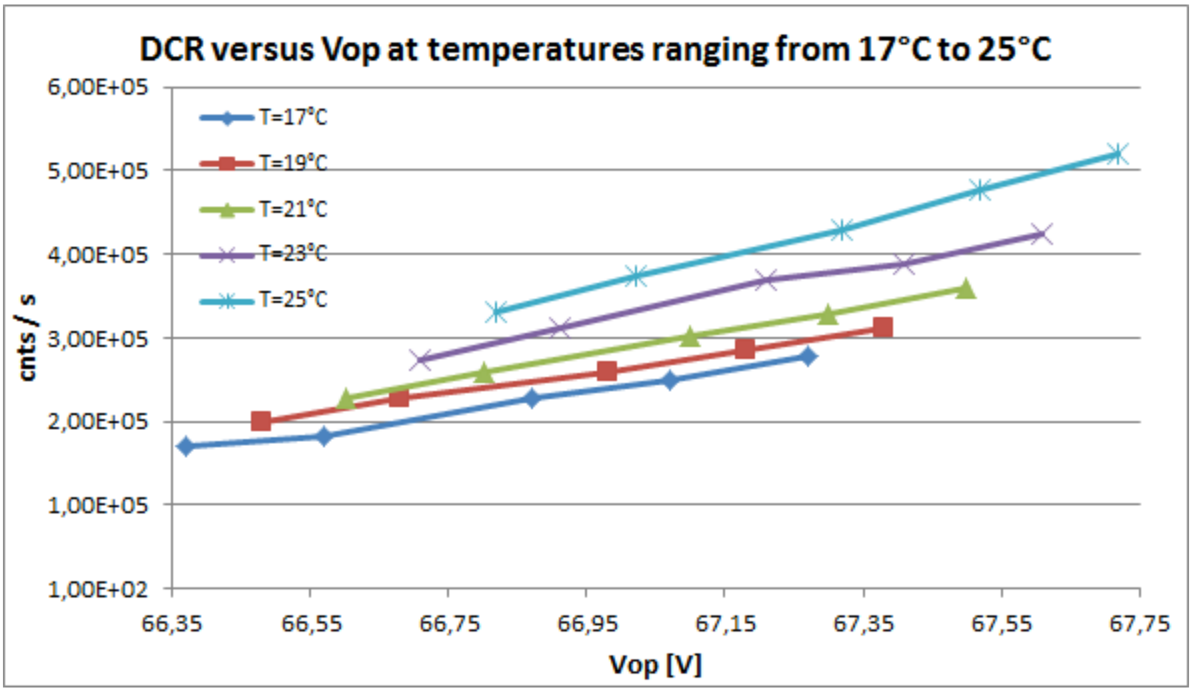



*Fig. 37- DCR versus the operating voltage at temperatures ranging from 15°C to 25°C in steps of 2°C.*

## 9.0 CONCLUSIONS

To be rewrite

As expected the PDE increases with the Operating-Voltage. Good operating conditions are obtained at Vop = 72.30 V where the PDE reaches a maximum of 35 % in the 420 – 500 nm range.

Due to the fact that a grouping of two by two pixel has to be used the Vop of 72.50 has to be discarded to avoid a very high DCR. But if a working temperature lower than 20 °C would be selected than also the case of Vop=72.50 V can be considered.

It will be noted that at Vop greater than 72.50 V the pixel is working near the saturation probably due to the fact that most of the micro-pixels are fired due to the DCR.

The error bars are also reported.

Note also, as above stated, that:

1. the cross-talk doesn't affect the PDE measurements due to the method used for PDE evaluation. In fact the second pulse due to the cross-talk is counted as one because is simultaneous to the primary pulse. And the threshold level is set to 0.5 pe;
2. the after-pulse contribute on the first 70 ns is removed by introducing an hold-off time and correcting for dead time.