Current-Voltage Characterisation of SiPM

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Abstract

This report summarises my work during the DESY summer programme, in which the main task was to characterise one Silicon Photomultiplier (SiPM), as well as to check the stability of the current obtained as a function of time. The current-voltage curve of the SiPM was measured and the breakdown voltage of the device was determined. In addition, the stability of the measuring device and the influence of the temperature to the measurement was obtained.

Contents

1 Introduction

The Silicon Photomultiplier (SiPM) is made basically to detect photons in the visible range, transforming the light in electric current that we can measure. The SiPM used in this report was the Multi Pixel Photon Counter (MPPC) (figure 1), which is developed by Hamamatsu Photonics [1], with a size of $1 \times 1\,mm^2$ and a pixel size of $50 \times 50\,\mu m^2$ which means 400 pixels in total.

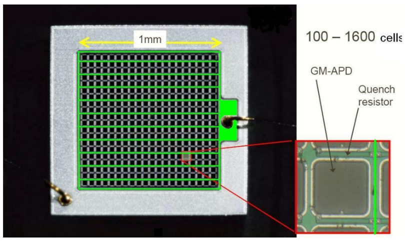


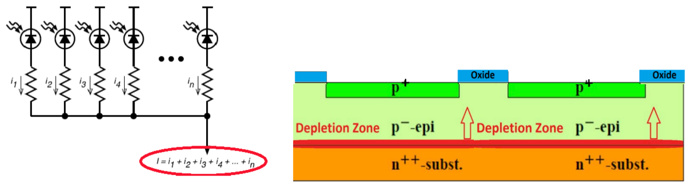
Figure 1: Picture and size of a MPPC

The current-voltage curve (IV curve) of an MPPC was characterised with and without LED illumination. The current as a function of the LED triggering pulse frequency was measured. Also, the influence of temperature variation to the electric current is measured and the breakdown voltage of the SiPM was determined (V_{BD}).

2 Theory

2.1 Basics of the MPPC

The MPPC is made of avalanche photodiodes associated in parallel working in Geiger mode. When operating in reverse bias the depletion zone's width of the diodes increases. Visible photons can pass through $1 - 5\,\mu m$ of silicon before being absorbed. After absorption and due to the photoelectric effect, a pair of free electron and free hole (e^-/h^+) is created. And in reverse bias there is a large electric field, which first separates the electron and the hole and then this field accelerates in different directions the electron and the hole giving them enough energy to create avalanche through impact ionisation. If the bias voltage is above the breakdown voltage, V_{BD}, that is the voltage at which the avalanche is self-sustained, the device is operating in Geiger mode. In this mode the electric current is still flowing after the acceleration of the pair e^-/h^+. This behaviour provides the device gains about 10^5 to 10^7 that make our device very fast detecting light. But the initial conditions have to be restored before the detection of the next photon. A common technique is to place a quenching resistor in series with the photodiode limiting the flow of the current, this technique is called quenching technique.
Each diode of the MPPC only gives us binary information, i.e. the diode fired by one photon produces the same electric current than when it is fired by several photons, so we associate them in parallel, and measuring the current given by the diodes we can know how many diodes have been fired (figure 2(a)). In the figure 2(b) we can see two diodes. The zone which detects the photons is painted dark green and the quenching resistance is the blue oxide, which is silicon oxide.



(a) Diagram of the photodiodes in parallel (b) Plate of photodiodes in parallel

Figure 2: Images from [3]

If we measure the current obtained from the MPPC with applying bias voltage we can obtain the plot showed in figure 3. Where the left part is the forward bias, there the current increases linearly as a function of voltage above the threshold voltage. In the right part below breakdown voltage the current measured is the leakage current. Above the breakdown voltage the current increases dramatically with the voltage and the avalanche pixel discharging dominates.

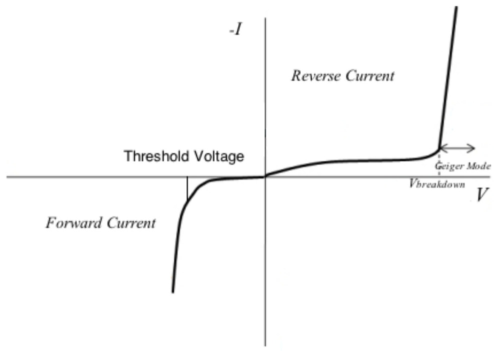


Figure 3: IV curve of the MPPC with the different operation regions

Being a silicon device, the MPPC is able to work under high magnetic fields, so it can be used for the Positron Emission Tomography (PET) imaging working together with the Magnetic Resonance Imaging (MRI), used for cancer detection [2].

2.2 Determination of the Breakdown Voltage

As commented before, the breakdown voltage, V_{BD}, shows the change in MPPC behaviour, and it is possible determine it from IV curves as shown below. The total current measured of the MPPC with LED illumination is:

$$I_{tot} = I_d + I_p \tag{1}$$

Where I_d is the leakage current, which always appears, and is due to the spontaneous pixel firing of electron-hole pair, which happens also in the absence of light.
And I_p is the current due to the pixel firing from photon detection, called photo current, that is a function of voltage:

$$I_p = f \cdot C(V - V_{BD})^{\alpha} \qquad only\ for\ V > V_{BD} \tag{2}$$

Where f is the frequency of the LED triggering rate, V is the bias voltage, V_{BD} is the breakdown voltage, C is a constant and α indicates us the behaviour of the photocurrent above breakdown, it is a number which ideally is one, that means the photocurrent above V_{BD} is linear, but in practise it is usually not one, so the behaviour is not linear. We can say then that this number indicates us the amount of noise that affects the photocurrent above breakdown. Now if we calculate the natural logarithm of I_p, then the derivative with respect to the voltage and the inverse function, we obtain:

$$\left(\frac{d(ln(I_p))}{dV}\right)^{-1} = \frac{1}{\alpha}(V - V_{BD}) \tag{3}$$

And when the left part equals to zero:

$$\left(\frac{d(ln(I_p))}{dV}\right)^{-1} = 0 \Rightarrow V = V_{BD} \tag{4}$$

The corresponding voltage is the breakdown voltage, which is extracted by fitting a linear function to the $\left(\frac{d(ln(I_p))}{dV}\right)^{-1}$ curve.

3 Measurements

3.1 Experimental set up

To measure these curves we used the cold chuck (figure 4), which allowed us to keep the temperature and the humidity under control, the chuck is provided with a black box, inside which there is a tube that provides dry air, reducing the relative humidity of the chuck. The ATT controller controls the chiller to maintain the temperature inside the box.

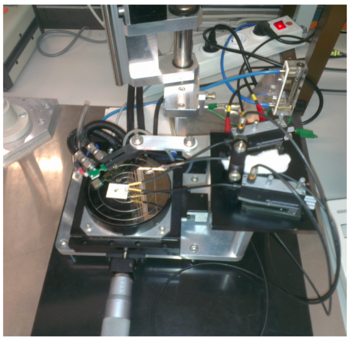


Figure 4: Cold chuck picture

The MPPC was soldered to a ceramic plate and it was placed on a stage, inside the black box. Two probes were connected to the anode and cathode of the MPPC. These probes were connected to a voltage power supply (Keithley 6517B), which is also a current meter, which provided all the information collected by the computer for further analysis. The light source was a blue LED, with wavelength equals to 406 nm, triggered by a pulser (Stanford DG645) with a 3 ns square wave. The trigger width is much less than the recovery time of the MPPC ($\sim 50\,ns$). So the pixels of the MPPC are firing at the same time for each trigger. A sketch of the set-up is shown in figure 5.

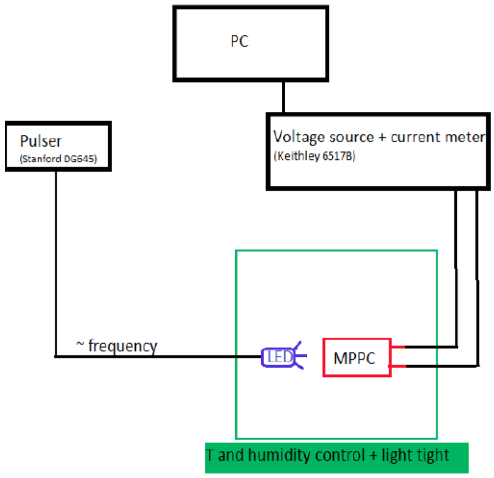


Figure 5: Cold chuck diagram

3.2 Measurement procedure

The measurement procedure was as following:

1. In order to determine if the LED might change the temperature of the chuck and therefore, the temperature of the MPPC, we measured the temperature inside the chuck with the LED turned off and once the thermal equilibrium was reached we turned on the LED and the temperature was measured again.

2. With the purpose of obtaining the IV curves of the MPPC the electric current was measured, varying the bias voltage from low values to values above breakdown voltage. First we measured with the LED turned off, after collecting the data we turned on the LED, and we measured with different triggering frequencies. The frequencies used were 10 kHz, 20 kHz, 30 kHz, 50 kHz, 70 kHz and 100 kHz.

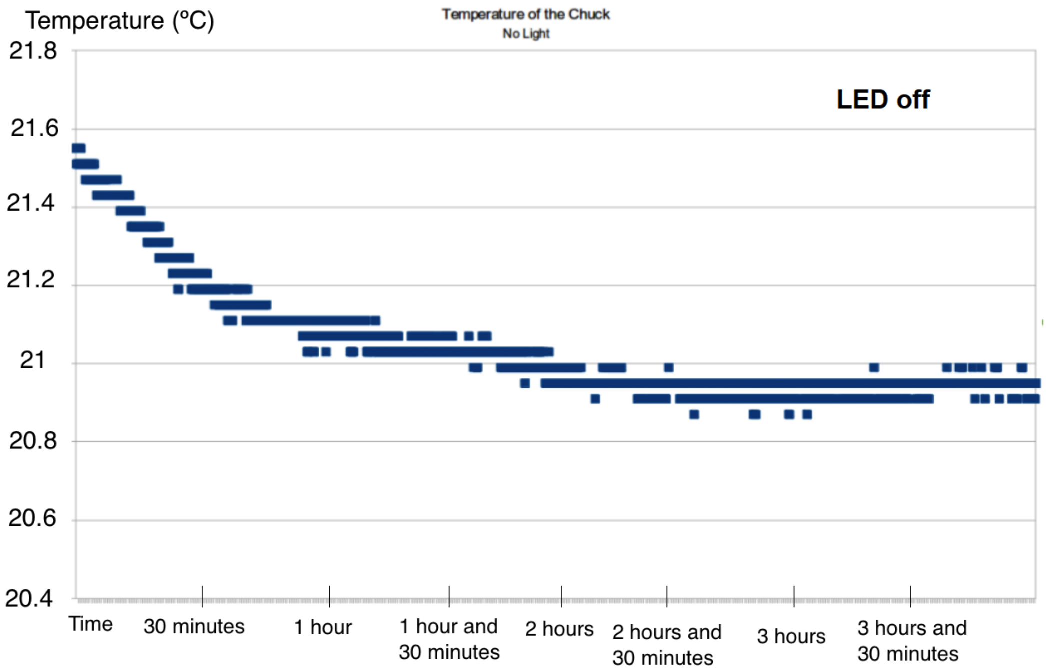
3. In order to check the stability of the current, the IV curves were measured from voltages below the breakdown voltage to voltages above breakdown. After this we went with voltage scanning in the opposite direction for four hours. We did this without illumination and with LED triggered by 20 kHz pulse.

With this procedure we obtained the following results.

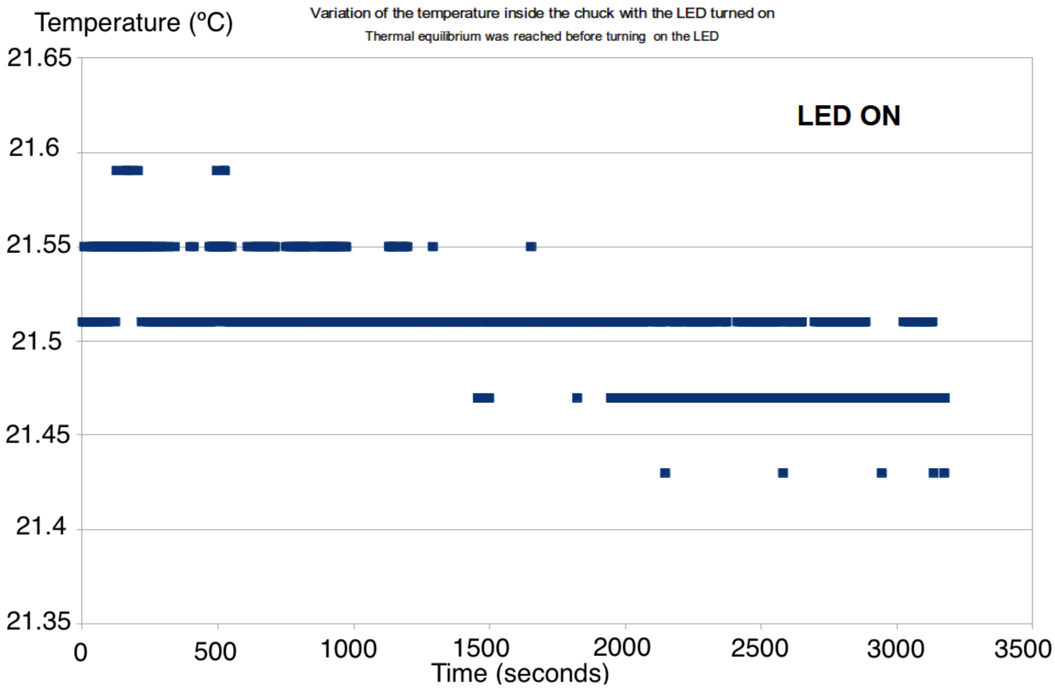
4 Results and discussion

4.1 Temperature of the chuck

The temperature of the chuck was measured, with the LED turned off and then we turned on the LED (see figure 6), it was important because the temperature directly affects the current created by the MPPC.



(a) LED turned off



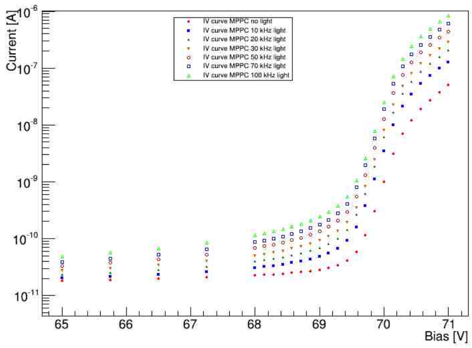
(b) LED turned on

Figure 6: Evolution of the temperature inside the chuck

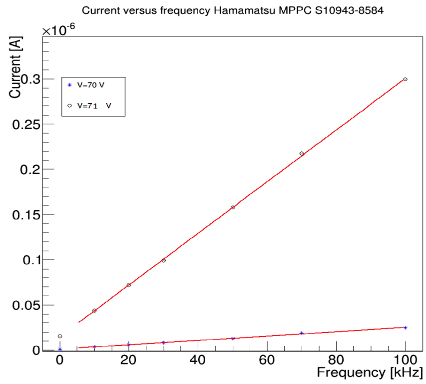
As can be seen, after one hour, the thermal equilibrium was reached in the chuck with the LED turned off, the fluctuation after this point were less than 0.2 degree. And after we turned on the LED the temperature remained stable, with the same value of fluctuation. So we can say the temperature inside the chuck, once the thermal equilibrium is reached, is stable, and it is not affected by the LED.

4.2 IV curves for several frequencies and linear behaviour

In the figure 7(a) we can see the behaviour of the IV curves of the MPPC under illumination with different LED trigger frequencies. Above the breakdown voltage the current for higher frequencies is greater because the triggering period, which is the inverse of the triggering frequency, is lower, and we have more pixels fired per point. Below the breakdown the current is leakage current, which is created by the silicon and if it receives more light, it will increase the leakage current. With the previous data we plotted the current versus frequency, and we obtain, as shown in figure 7(b), straight lines, that show us the linear behaviour of the MPPC. We omit the current value without light, which is the measured leakage current, to see how good our linear fit was, and the results obtained are shown in the Table 1. Where can be seen that the differences between fitted intercept, leakage current predicted by fit, and the values measured for the leakage current are not very large, about 10%.



(a) IV curves



(b) Current versus frequency

Figure 7: Results used to prove the linearity of the MPPC

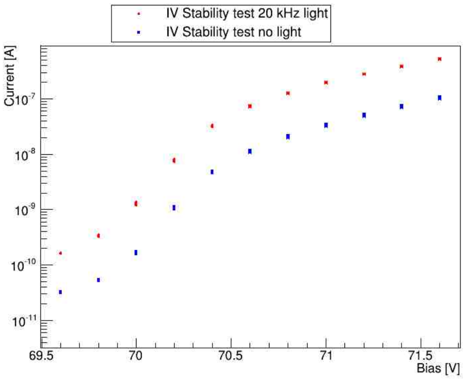
Table 1: Fitting $I = a \cdot f + b$

Voltage	Slope (a)	Intercept (b)	I measured for 0 kHz	$\frac{\lvert Measured \rvert}{Intercept} \times 100$	ρ
70	238.326	1131.15	992.2426	12.28 %	0.995
71	7874.26	47972.3	50316.14	4.89 %	0.987

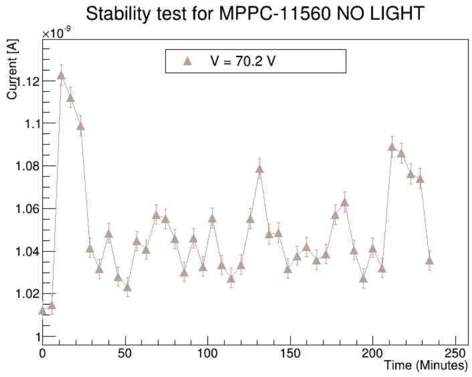
4.3 Stability of the current

With the data obtained measuring the IV curves (figure 8(a)) during four hours without light and with a triggering frequency of 20 kHz, we plotted the current obtained as a function of time for some voltages and the results are shown in figure 8. First of all is to mention that each point from the IV curve is made by 42 current measurements. These values were plotted later as a function of time in order to check the stability of the said current.

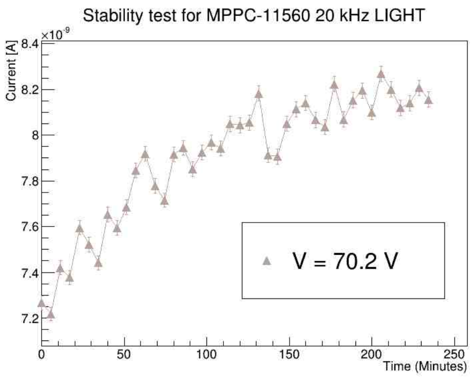
In figure 8(b) we can see the different values for the electric current at 70.2 V and with the LED turned off. We can say that the current shows normal fluctuations, about 10 % between the lowest value and the highest one. In the figure 8(c) the electric current at 70.2 V and 20 kHz triggering pulse versus the time is plotted. We see how the current increases with a total increment of almost 14 % until 200 minutes. This growth in the current value is due to the warming up of the pulser and the LED, that take a long time in stabilise the intensity of the light. After this warming up time can be seen how the current stabilises and only shows fluctuations with a value less than 2 %. So in order to obtain the most stable current is recommended to wait at least 200 minutes (3 hours and 30 minutes).



(a) IV curves during 4 hours



(b) I-time, no light

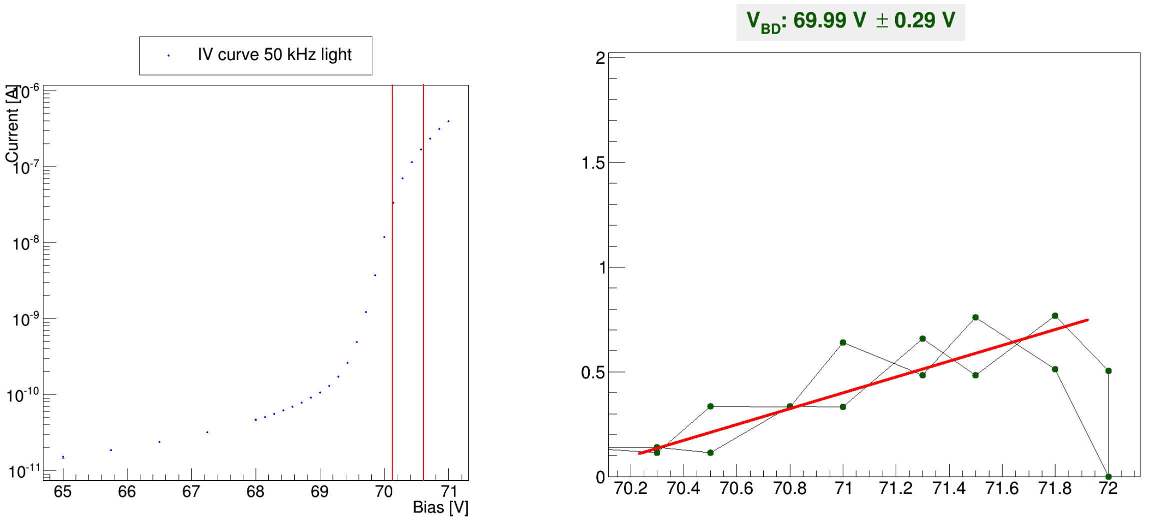


(c) I-time, 20 kHz light

Figure 8: Results from the stability test

4.4 Determination of the breakdown voltage

To determine the breakdown voltage we use the data collected in the previous steps. As was shown in the theory, 2.2, the breakdown voltage is obtained from the IV curves, but before any analysis we had to subtract the dark current, measured obtaining the IV curve for no LED light, to the current obtained with light, in order to work only with the photo current (equation 1). After plotting $\left(\frac{d(lnI_p)}{dV}\right)^{-1}$ versus the bias voltage, we did a linear fit in the indicated region, and where the line cuts the x-axis that was the breakdown voltage (equation 4). The obtained value for 50 kHz light is shown in figure 9(b). The points used to obtain the linear fit correspond to the values between red lines in figure 9(a).



(a) IV curves for 50 kHz light

(b) $\left(\frac{d(lnI_p)}{dV}\right)^{-1}$ versus bias voltage and linear fit

Figure 9: Breakdown voltage for one frequency

The V_{BD} value has got a large error, it may because we only have got a few points. We obtained the values for the others frequencies (table 2) including the value of the slope, which gives us the value of the constant α, remember equation 3.

Table 2: Values of the breakdown voltage for different frequencies

Frequency $[kHz]$	$V_{BD}[V]$	α
10	69.98 ± 0.37	2.5722 ± 0.0092
50	69.70 ± 0.29	2.5773 ± 0.0073
70	69.66 ± 0.27	2.5375 ± 0.0071
100	69.77 ± 0.26	2.5370 ± 0.0064

We can see that the values for the breakdown voltage are very similar, so assuming that the breakdown voltage is not frequency dependant, see equation 3, we plotted all the current values together in order to increase the number of points, thus reducing the error. And the result is shown in figure 10.

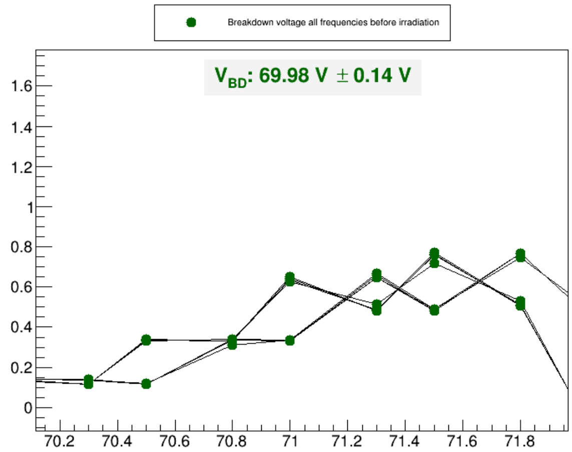


Figure 10: Breakdown voltage calculated plotting all the frequencies

We can see that all the points overlap reasonably well and the error of the value obtained for the V_{BD} is not as large as before. Also the parameter α has got a lower error (see table 3).

Table 3: Value of the breakdown voltage using all the frequencies

V_{BD} [V]	α
69.98 ± 0.14	2.5494 ± 0.0037

As can be seen, the values for the V_{BD} do not vary with the frequency of the trigger, also the photocurrent is not linear, because the constant α introduces noise, since it is not one.

5 Conclusions

We can conclude that the cold chuck used to measure the IV curves is thermally stable once equilibrium is reached. We can conclude that the current measured of the MPPC, with which we have been working during this summer programme, behaves linearly as a function of the frequency of the trigger, this is, if frequency is doubled the current obtained is the double than before. This statement is based in the percentage obtained between the measured current at no light and the intercept obtained with the fit differ about 10 % or even less (Table 1). We can also claim that the current for successive measurements does not differ more than 10 % for LED turned off. In the case of 20 kHz light that growth of the current, could not be due to temperature changes, because we checked the temperature inside the chuck and no significant changes were observed. So the reason of this growth was the warming up that the LED and the pulser took before emitting a stable amount of light.
With regard of the breakdown voltage, we determined that the breakdown voltage is unaffected by the frequency of the incident light, also we could use the data from all the currents to calculate the value of the breakdown voltage more precisely, delimiting then, the operating region of the MPPC.

Acknowledgement

I would thank to our supervisor Chen Xu for giving us all the help we needed, and all the people working with him, who helped us, too. And finally thanks to DESY for letting me join this wonderful programme.

References

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[3] Prof. Dr. Erika Garutti *Silicon Photo-multipliers*