Characterization of a SensL C-30035-16P Silicon Photomultiplier array at cryogenic temperature

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1 Introduction

Several experiments have been conducted worldwide, with the aim of studying neutrino interactions with target nuclei in ultra-sensitive, low-background detectors. In the last few decades the technology of the Liquid Argon Time Projection Chamber (LAr TPC), which was first proposed by Professor Carlo Rubbia in 1977, has become the best way to do it. The advantage of LAr TPC detectors is their excellent spatial and calorimetric resolution which makes possible a perfect visualization of tracks of the charged particles. Energy deposited by ionizing radiation is shared equally between free ionization charge and scintillation photons, yielding $2.9 \times 10^4 e^-_{free}/MeV$ and $2.4 \times 10^4 \gamma/MeV$ when an electric field at the typical strength of $500\, V/cm$ is established in the LAr detector volume. Detecting the scintillation light produced in LAr, jointly colleting the ionization charge from TPC, allows to improve the energy resolution of the whole detector sistem. In the biggest detectors hundreds of 3 inch PMTs are used to detect the scintillation light, which in liquid argon has a wavelength of 128 nm shifted to 420 nm.
An actrattive alternative to the traditional PMTs is offered by silicon photomultipliers SiPM.
Actually both two different light collection sistem are mounted in LArIAT experiment. Two UV-sensitive PMTs and three SiPM, with the aim to figure out which of the two have better performance in cryogenics.

1.1 LArIAT: Liquid Argon TPC In A Testbeam

LArIAT is the repurposed ArgoNeuT detector, modified for use in a charged particle beam. It is a small volume Liquid Argon Time Projection Chamber

(LArTPC) dedicated to the calibration and precise characterization of output response of these detectors. The charged particle test beam provides a controlled environment in which to tune simulations and to develop tools for particle identification, calorimetry, and event reconstruction without relying solely on simulation.
In LArIAT, two high-QE cryogenic PMTs as well as three silicon photomultipliers (SiPMs) of different types will be used to collect and read out scintillation light. Adequate photocathodic coverage could be provided by twenty 3-inch diameter PMTs positioned in an array behind the wire planes as in ICARUS and MicroBooNE, or by six hundred $1.2/, cm^2$ SiPMs distributed behind the wire planes and possibly onto the field cage. Electronics for reading out SiPM arrays (groups of 16 SiPM channels combined in a single readout channel) as well as single channel SiPM chips, which include on-board bias voltage filtering and preamp/shaping circuitry.
Our aim is to be able to get a group of 9 arrays of 16 SiPM $1.2\, cm^2$ cells each one, in order to have a device with the same active surface of a PMT.

2 SiPM technology

A silicon photomultiplier (SiPM), is a type of avalanche photodiode operated in Geiger mode, which havs much lower intrinsic radioactive background and smaller mass in addition to unrivalled performances in single photon detection. SiPMs behave linearly with a satisfactory gain of 10^6-10^7 and offer low intrinsic radioactive background, low operating voltage and power consumption, and have possibilities for inexpensive mass production.
SiPM operating in Geiger-Muller mode means that it is inverse polarized: $V_{bias} > V_{bk}$ (bias voltage that came from a power supply must be bigger than the the junction breakdown voltage). When a photon hits the active area of the device (a single pixel Geoger Mode Avalanche Photodiode GM-APD) producing a photoelectron, the latter will trigger an avalanche, while drifting to the electrode and traversing the high-field region.
The single pixel GM-APD capacitance C_d, which depends on the pixel size, discharges from V_{bias} to V_{bk} whit a time costant $\tau_d = R_d C_d$ (rise time), in which R_d is the equivalent diode resistance; at the same time the external currents grows from 0 to $I = \frac{\Delta V}{R_q}$, where $\Delta V = V_{bias} - V_{bd}$ is the junction over-voltage and R_q is the quenching resistor connected in series to the APD. Then, when the number of carriers traversing the high-field region fluctuates to 0, the avalanche is quenched. It is necessary to use a proper quenching resistor to let the internal current decrease to a level such that statistical fluctuations may quench the avalanche (turn-off time).

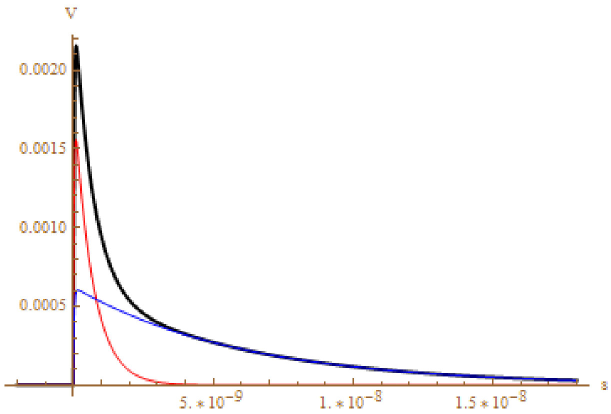

Figura 1: Exemple of a signal from an array of SiPM cells. The red component is the fast and the blu is the slow.

So C_d is charged from V_{bk} to V_{bias} until there is no more current flowing, with a time constant $\tau_q = R_q C_q$. The pixel GM-APD 99% recovery time corresponds to $\approx 5\tau_q$. The leading edge of the signal is much faster than trailing edge: $\tau_d \ll \tau_q$ and turn-off mean time is very short (if R_q is sufficiently high, $I \approx 10 - 20\mu A$).
In addition to this, when we a have an array of SiPM installed on a PC board, come out a further parameter, which the shape of the signal depends from. It is called parrasitic spike. It is a second fall costant of the signal $\tau_{fast(fall)}$, fast because is smaller than the cell recovery time costant. It depends on how many cells are connected together and on how big is the load resistence in which the current flows to discarge the capacity.
For the rise we have a exponential dependence:

$$V_{rise}(t) \sim \left(1 - e^{-\frac{t}{\tau_{rise}}}\right) \qquad \tau_{rise} \sim R_q(C_q + C_d) \tag{1}$$

instead for the fall part we have a dependece from the sum of 2 exponentials

$$V_{fall}(t) = \frac{Q}{C_q + C_d}\left(\frac{C_q}{C_{tot}} e^{-\frac{t}{\tau_{fast}}} + \frac{R_{load}}{R_q}\frac{C_d}{C_q + C_d} e^{-\frac{t}{\tau_{slow}}}\right) \tag{2}$$

$$\tau_{fast} = R_{load} C_{tot} \quad \tau_{slow} = R_q(C_q + C_d)$$

where

$$\tau_{rise} \ll \tau_{fall(fast)} \ll \tau_{fall(slow)} \tag{3}$$

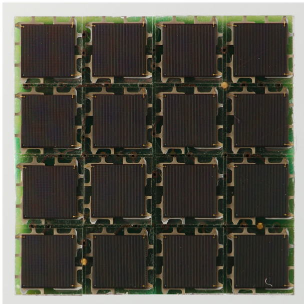

Figura 2: SensL ARRAYC-30035-16P-PCB

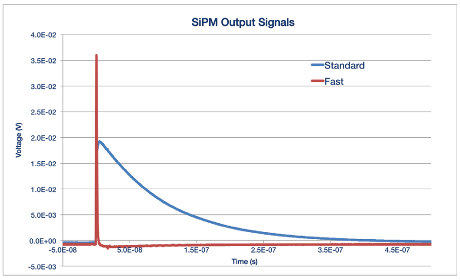

Figura 3: Fast and STD signals

3 Our SiPM and PC boards

The SiPM device on which I have worked is the SensL ARRAYC-30035-16P-PCB (4X4 ARRAY OF 3MM SMT SENSORS) Figura 2.
The ArrayC-30035-16P-PCB is comprised of 16 individual 3mm SMT sensors arranged in a 4x4 array. From the data sheet we know that each 3mm SMT have a total capacity of 850 pF $\rightarrow C_{tot} \sim 13.6nF$.

A feature of our SiPM is to have two output signals, one is the standard singal STD, the other, the Fast signal, come out from the SiPM before the

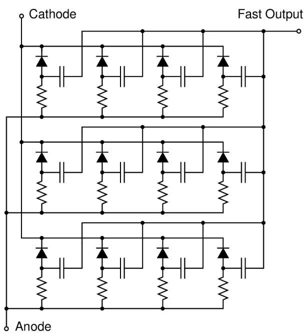

Figura 4: Simplified microcell level schematic of the C-Series SiPM.

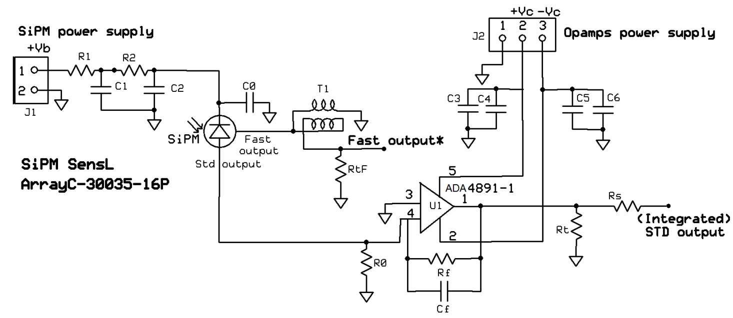

Figura 5: The circuit of the board with only one OpAmp.

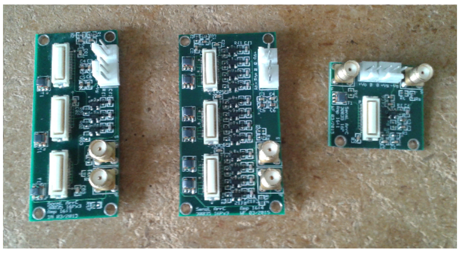

Figura 6: Three of the our boards.

R_q (Figure 4), so it is very short (Figure 3). Even if this Fast signal isn't porportional to the charge of the signal, it could be good to have a timing trigger of the avalanche in the diode.

Regarding the front-end electornics, I have had four boards (Figure 6) with differnet circuit, designed by Irene Nutini INFN (Fermilab summerstudent 2014 and Fermilab graduating 2015) and Will Foreman (Chicago University). Each of this boards have been designed with the idea to can test more different configurations changing some electronic components (Figure 5), in order to find out the best.

They essentilly differ each other for the amplification stage configuration and the number of SiPM array connectors.

Two of them (Figure 7) have only one SiPM array(4x4) connector. The first has a single operational amplifier (OpAmp) place, in which all sixteen channels from the SiPM array(4x4) are connected together, the second has four place for the OpAmps and for each OpAmp there are four of the sixteen channels that came from the SiPM array. The other two boards have essentially the previous configurations replicated three times, therefor they can hold three SiPM array(4x4) each one (Figure 8).

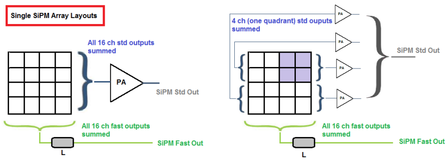

Figura 7: Schematic cells connection on the one connector boards.

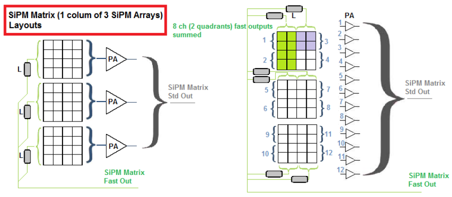

Figura 8: Schematic cells connection on the three connectors boards.

4 The Cryocooler

I have had a great experimental equipment available to do my tests at cryogenic temperature (Figure 9). Placed in the 14th of WH.
It consists in a cylinder vacuum camber (60 cm high, 40 cm diameter) with inside a copper plate, on which the boards are fixed (Figure 10). The copper plate is connected to a cryocooler, that thanks a helium compressor, can reach cryogenic temperatures. I did tests up to $60\,K$ degrees. During this low temperature runs, pressure inside the cylinder was less than $1\,mTorr$, to prevent ice making on the boards. The SiPM surface, inside the cryocooler, is lightened by a pulsed blu LED, driven from outside to inside through an optical fiber. The LED wavelength peak, of $400\,nm$, is in the zone of maximum quantum efficiency of the SiPM light detection. This wavelength is almost the same of the LAr scintillation light (shifted) wavelenght $428\,nm$. So we will expect a similar response, by the SiPM, to the LAr light. The only difference is taht the LED has essentially an impulsive characteristic, the signals are $\sim 1\,ns$ wide, differently in LAr they are few μs long. Finally the other three components of my setup are two power supply, one for the SiPM and one for the OpAmp and a oscilloscope to read out the STD and Fast signals triggered by the LED.
Before to start with my tests I had to set up my equipment. This part took me a lot of time of the first weeks. Because the high sensitivity of our device and the smallness of the signals analyzed (single photoelectron event SPE), I had to deal with anything that could cause noise, from the room light to signals coming from my equipment itself. I changed some connectors with some best, screened all the equipment controller cables and eliminated un-

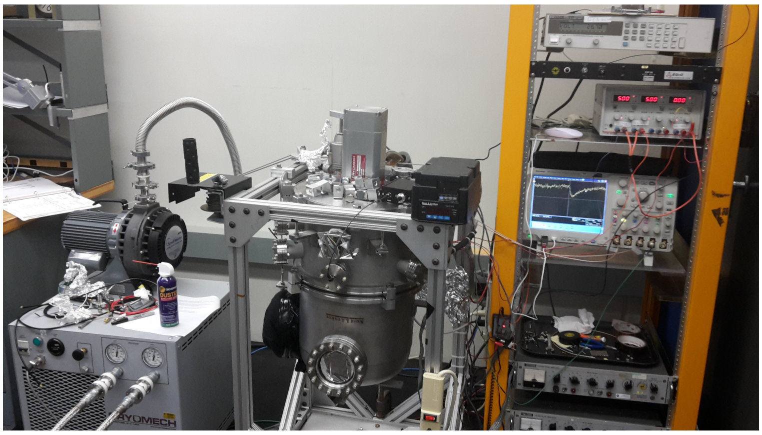

Figura 9: Cryocooler setup.

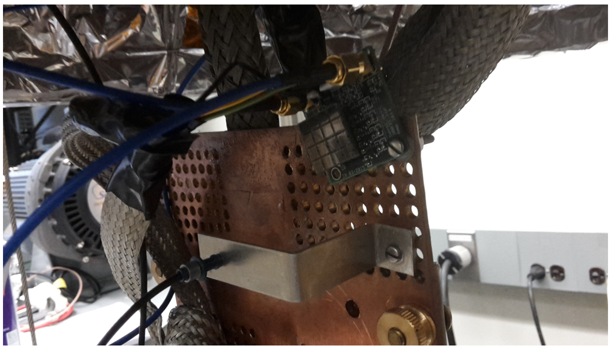

Figura 10: A board fixed on the copper plate inside the cylinder.

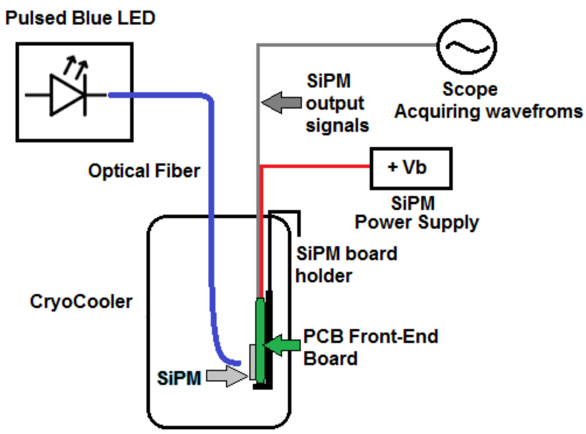

Figura 11: Schematic representation of the experimental setup.

necessary ones.

5 Start with the tests

Before starting with the cryogenic test, we have compared several configurations in order to find the one which will be more suited to our purpose, at room temperature.
First of all, we have taken as reference a SensL evaluation board. On it there is installed a SiPM single cell $3 \times 3\, mm^2$ with the same characteristics of one of our 16 SiPM cells of the Array. Because as final aim we want obtain a surface composed by a lot of SiPM array, I start searching a configuration in which the output signal would't depend on the number of cells connected together. This requirement is due to $\tau_{fast(fall)} \sim C_{tot}$. With our SiPM, where $C_{siglecell}$ (cell of $3 \times 3\, mm^2$) of $850\, pF$, if we want a device of 9 array of 4x4 cells($3 \times 3\, mm^2$), the time fall costant will be 144 times bigger, this means the signal is long and few wide.
With the evluation board we have signals with $\tau_{rise} \sim 3\, ns$ and $\tau_{fallfast} \sim 130\, ns$. As in this case, when the cell is small $\rightarrow C_{tot}$ is small, the discharge structure of the signals can be aproximte with only an exponential. The most of the charge flows trought the parasitic spike and the slow component can be neglected.
Indeed, when I have seen the signal directly from the SiPM in the configuration in Figure 12(configuration 0), with no components except $Rt = 50\, \Omega$, placed in parallel to the oscilloscope internal resistence of $50\, \Omega$, to avoid reflection. In this case, because we have all sexteen cells connected, C_{tot} is big enaugh to allows us to se the two component of the signal discharge part. To solve the τ_{fall} problem we set a new configuration, in which only four channels are connected to a $R0 = 50 Ohm$ as in Figure 13(configuration 1). In this case (as in the evaluation board) the $\tau_{fallslow} \sim \tau_{fallfast}$ and the multiplication factor of the exponential is $\ll$ (), so we can approximate the fall with a unique exponential. This approximation will not cause us any problem at cryogenic temperature because only the $\tau_{fallslow}$ is sensible to T (see Figure). The fast component will be big enough to allow us negletting the slow component.

Once found out that the best way to cennect the cannels together is 4 to 4, I started testing the aplification stage. To do this easlier and faster at the beginning I connected only four channels. For the amplification stage, we have choosen a configuration with Rf and Cf (Figure 14), which ,in addition to amplify, integrates the signal, in order to detect all the charge. This to

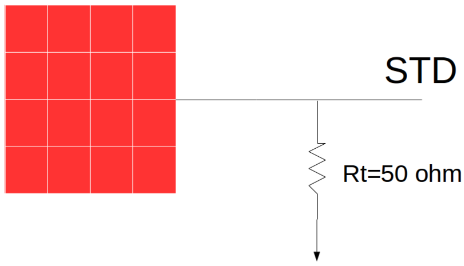

Figura 12: Schematic representation of the board without OpAmp, and all 16 SiPM channels connected together. Configuration 0.

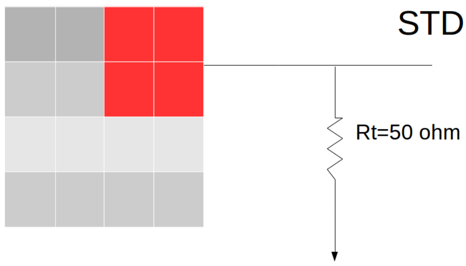

Figura 13: Schematic representation of the board without OpAmp, and only 4 SiPM channels connected together. Configuration 1.

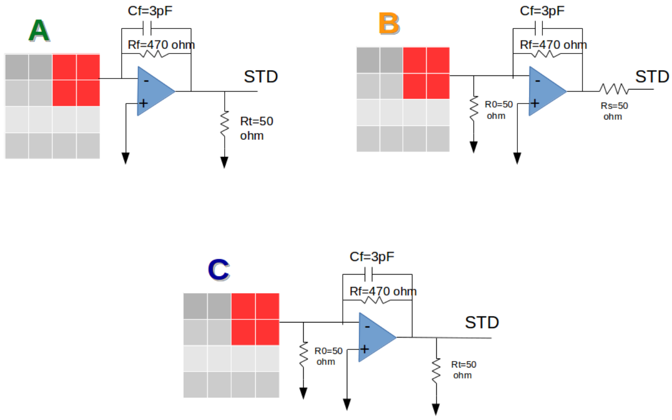

Figura 14: Three configuration tested for the amplification stage. The best is the configuration C.

makes our device able to analyze signals produced by LAr scintillation. I have tested the three configuration in Figure 14. The configuration C has been found the best because: has a R0 connected directly to the 4 cells, that allow to have a recovery time independent from the number of cells connected and independent on $R_{quenching}$; has a good impedence for the oscilloscope reflection $Rt = 50\,\Omega$. The best impedence should be a resistence of $50\,\Omega$ in series, like Rs in conf B, but it can't be possible for the Rf on the OpAmp, which cause an increase of impedence seen by oscilloscope and for the OpAmp that change their resistence when it works.

Now, with the right configuration for the amplification stage and the SiPM cells connection, we can start to test the device at cryogenic temperature. I have done the first cold test with the one connection SiPM array board, with the SiPM cannels connected 4 to 4, with the amplification stage in configuration C: Figure 14. When I did the first run in cold, came out a new noise. I (with Albert's help) have measured each single electronic component in liquid nitrogen (77.35 K) and came out that the capacitances lose half of their value. The resistences are the same ($\Delta R = +2\,\Omega$). So we have replaced $C_0 = 10nF \rightarrow C_0 = 100nF$ to be sure that C_{0SiPM}, this condition need to have a stable SiPM power supply. At this point we have a good configuration for the board which will lodge three SiPM array (4x4).
Now we are testing a device which overall has 48 cells of $3 \times 3\,mm^2$ Figure 16. The results make us thinking that we could have a device with 9 of 4x4

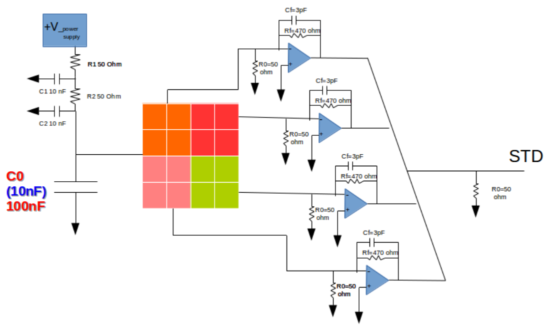

Figura 15: Our best configuration redy for the cold.

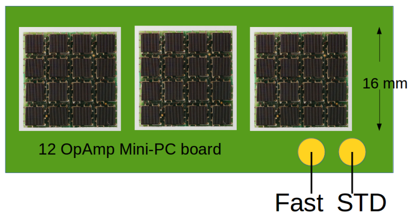

Figura 16: Current device we are testing.

arrays of $3 \times 3\,mm^2$ cells, (144 cells of $3 \times 3\,mm^2$) Figura 17, which will not have more problem than a single cell SiPM device.

6 Our results

How we can see in Figure 18, the signal shape doesn't change a lot from T_{room} (A) to T_{LAr} (C), only τ_{fall} grows a bit, but we expected it. When we amplify the signal, the differences from T_{room} to T_{LAr} are even less, Figure 18 (B) and (D). In the amplified signal we have to note that rise time is longer then in the direct signal. We think that this is due to the OpAmp performance. From the data sheet we know that our OpAmp: ADA4891-1

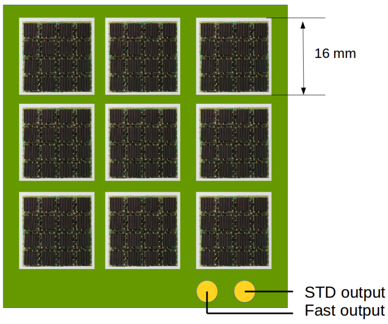

Figura 17: 9 to 9 SiPM array final configuration, which we want to have.

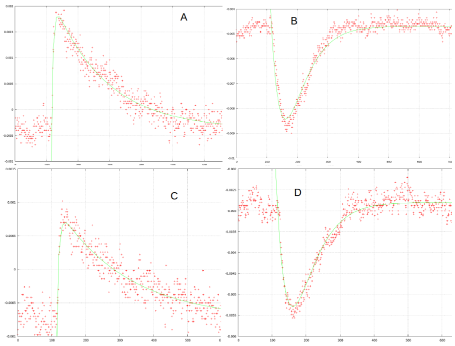

Figura 18: .

has a bandwidth of $220MHz \rightarrow \sim 5\,ns$, for $Gain = 1$, ($25\,Mhz$ for $G = 2$)... in our case $G \sim 3-5 \rightarrow$ bandwidth is $<$ of the rising time of our signals. In the last part of my work I have replaced our OpAmp with someothers faster and at the same time with a good response at cryogenic temperature, I will speak later of it. I have studied a lot of parameters, temeprature dependence, and V_{bias} dependence. In the most case I have found out that the SiPM and the amplification stage have a linear behavior.
In partioular:

- the aplitude of the signal amplified is proportional to the signal before the amplification stage
- the integral of the signal (charge of the signal) is proportional to the amplitude
- both signal amplitude and signal charge have a linear dependence from V_{bias}

For the light intensity dipendence we can't have a good description because the LED intesity isn't linear and our LED device haven't a good data sheet

form which we can understand its trend.
The most important part of my work it has been studying how the SiPM and OpAmp parameters change as a fuction of temperature.
An important result came from the study of τ_{fall} vs Temperature. With our configuration we have a very little dependence of τ_{fall} from the temperature, and in particolura, after that we have stayed at cryogenic temperature for long time, changes in temperature region from 60 kelvin to 150 kelvin, do not cause perceptible changes in the signal shape.
The $V_{breakdown}$, that around room temperature is linear with T, stop to go down linearly (our fit is linear plus quadratic) and slows to make a plate in the cryogenic range (from 100K to 60K).
The hardest part has been to detect and characterize single photoelectron events. I haven't had time to do this for the board with three SiPM placed, but I have had good result from the single SiPM array board. With a oscilloscope function we can see more signal overlapped and in this way, finding the right power supply, light intensity and OpAmp supply, condictions, we can obtein a set of waveform that differs each other for only one photoelectron. So it is possible extract the contribute that each single photonelectron gives to the signal.

7 Graphics and plots