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Properties of Silicon PhotoMultipliers measured at LNS - INFN

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The Silicon PhotoMultiplier (SiPM) represents a new generation of photodetectors working in Geiger mode. The high sensitivity, compactness, low power supply, insensitivity to magnetic fields make them a valid alternative to the PMTs in several fields such as particle physics, medicine, space technology. At LNS a complete characterization of samples developed by different companies (Hamamatsu, STM, SensL) have been performed, in order to measure the most significant properties, consisting in the dark noise, cross talk probability, photon detection efficiency, charge and timing resolutions. Measurements have been performed also coupling the SiPMs with small size LYSO scintillators and using gamma sources, in order to investigate a possible application in the PET diagnostics.

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[1] Speaker

1.Introduction

The silicon photomultiplier (SiPM) [1] represents an innovative photodetector sensitive to the single photons. It is constituted by a bidimensional array of single photon avalanche detectors (SPAD), whose number can be as high as 10^4. Each SPAD, here simply called cell, is a small photodiode with square or circular shape, whose size is tipically below 100 μm. Powering each cell with a bias voltage slightly over the breakdown makes it operate in Geiger mode, thus meaning that the cells stay quiescent until an electron-hole pair produced inside the depletion region generates an avalanche process, producing a fast pulse with a rise time below 1ns. Such an avalanche is immediately quenched by means of a feedback resistor integrated in the chip itself and the pulse falls to zero within some tens of nanosecond. It should be noted that an avalanche may be originated by the absorption of a visible photon as well as by a thermally generated e-h pair. In fig. 1a a cell of a SiPM is shown, with the surrounding integrated quenching resistor visible on top of it. The outputs of all the cells are connected together thus making the SiPM a device that can produce a discrete number of values at its output and allowing to deduce how many photons interacted with the detector. An important requirement is obviously that the pulse amplitude of all the cells must be the same. In fig. 1b a charge spectrum acquired by using a weak laser light source (λ=408nm) shows the very high resolution that allows to resolve the peaks produced by a small number of interacting photons.

The dimension of the SiPMs available now on the market are typically from 1x1 mm^2 to 3x3 mm^2 (fig. 2) and they can also be arranged in array configuration of several elements. The typical bias voltage depends on the technology and can roughly vary between 30 and 75V. Such characteristics, together with the insensitivity to magnetic fields, good timing resolution and sensitivity to a few photons, make the SiPM a quite promising photodetector for several applications, both for nuclear physics research and for applicative purposes.

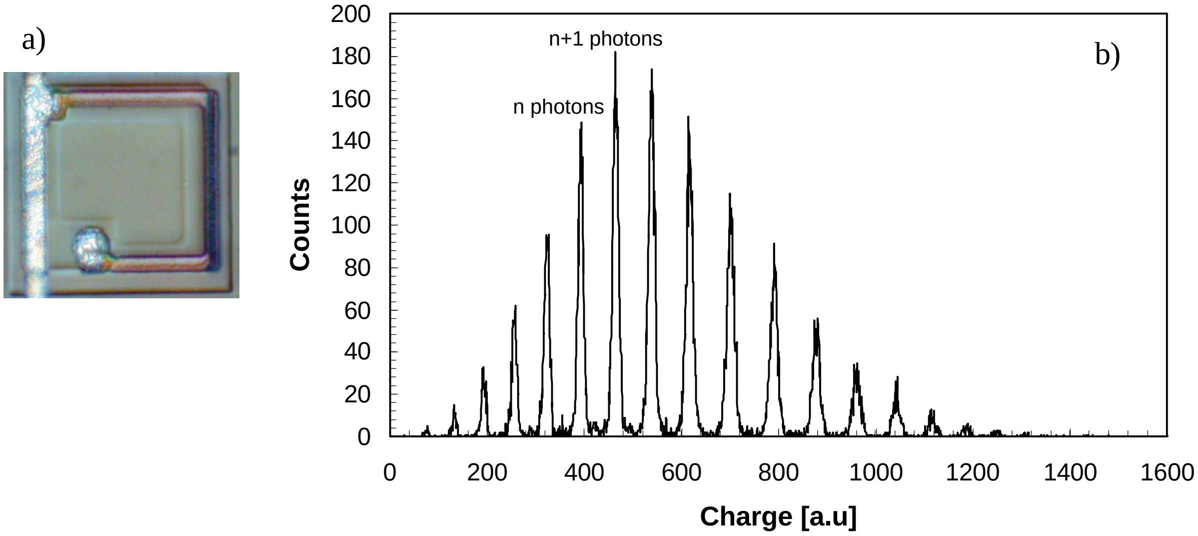

Fig. 1. a) elementary cell of a SiPM; b) charge spectrum generated by a weak light source.

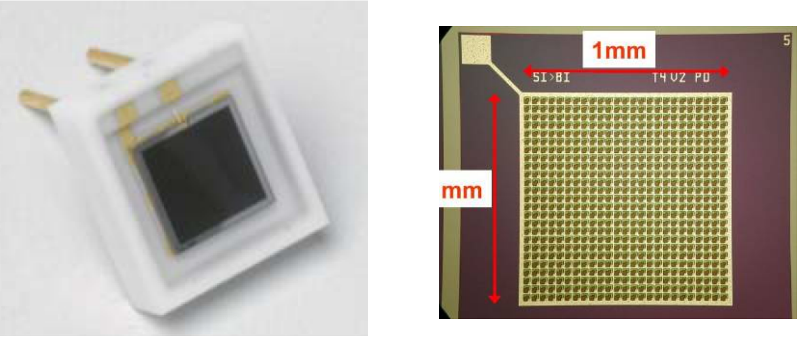

Fig. 2. Two samples of SiPM detectors. The manufacturer is Hamamatsu (left, 3x3 mm^2) and FBK (1x1 mm^2).

2.The measurements

At LNS-INFN in Catania we have tested several kinds of SiPM detectors, in order to study their main properties, with the typical values summarized in the table 1 [2, 3]. The Gain corresponds to the total amount of carriers produced inside the cell as a consequence of the avalanche process. The dark count rate is the number of pulses per second, due to random thermal generation of pairs in the depletion zone that initiate avalanches. The Photon Detection Efficiency (PDE) is the fraction of detected over impinging photons onto the detector window. All of these parameters have been measured at LNS, also allowing to make a comparison between several devices available on the market produced by different manufactures. An estimate of the SiPM quality has been performed by studying in detail the dark noise and in particular the component that is due to correlated events, basically due to the following two physical processes.

Table 1 - Typical Properties of commercial SiPMs

Active Area	up to 10 mm^2
Cell size	25 – 100 micron
Gain	$10^5 – 10^6$
Operating Voltage	30 – 80 V
Dark Count	10^5 - 10^6 cps

The first one consists of spurious afterpulses produced as a consequence of main pulses, due to carriers produced during the avalanche process, trapped inside or near the depletion zone, and exponentially released within a few hundreds of nanoseconds. Such charge carriers can start avalanches giving rise to additional fake pulses. Fortunately the fraction of these events is tipically below 1% and in first approximation can be neglected.

The second source of correlated noise is the cross talk between adjacent cells, mainly because of visible photons produced inside a cell during the avalanche process that can diffuse to the closest cells, be absorbed and thus starting other avalanches. Such a process can be relevant for those devices where no optical insulation has been implemented around each cell.

For all the devices we tested at LNS, the dark noise rate has been measured by using the electronic set-up in fig. 3a. The discriminator threshold has been set in order to have a value corresponding to about half of the single photon pulse amplitude. The measured rates strongly depend on the bias voltage, where the increase of dark noise is due to increasing probability of starting the avalanche as the bias increases.

In order to estimate the amount of crosstalk affecting the SiPMs, we operated by acquiring the dark noise rates for an increasing value of the threshold and calculating the ratio between the rates corresponding to 1.5 and 0.5 photons respectively. This ratio roughly represents the probability of double firing, that in case of pure random noise can be easily calculated to be generally below 1%. In fig. 3b the dark noise profile acquired with a 10x10 cell Hamamatsu SiPM is shown, where the measured ratio dark(1.5 ph)/dark(0.5) is about 20%, thus meaning that a high cross talk is present in such a device. The same profile acquired with a 10x10 cell STM SiPM gave a ratio of 0.5%, a very low value that accounts for the presence of an optical trench around each cell, preventing the light propagation and hence the cross talk effects.

In fig. 4 the dark noise normalized profiles for four SiPMs are shown, allowing to compare the cross talk of such devices by comparing their slopes. In order to quantify the amount of the cross talk in the measured dark noise, we calculated by the difference between the measured noise and the expected value in case of poissonian random noise, and the values are shown in table 2.

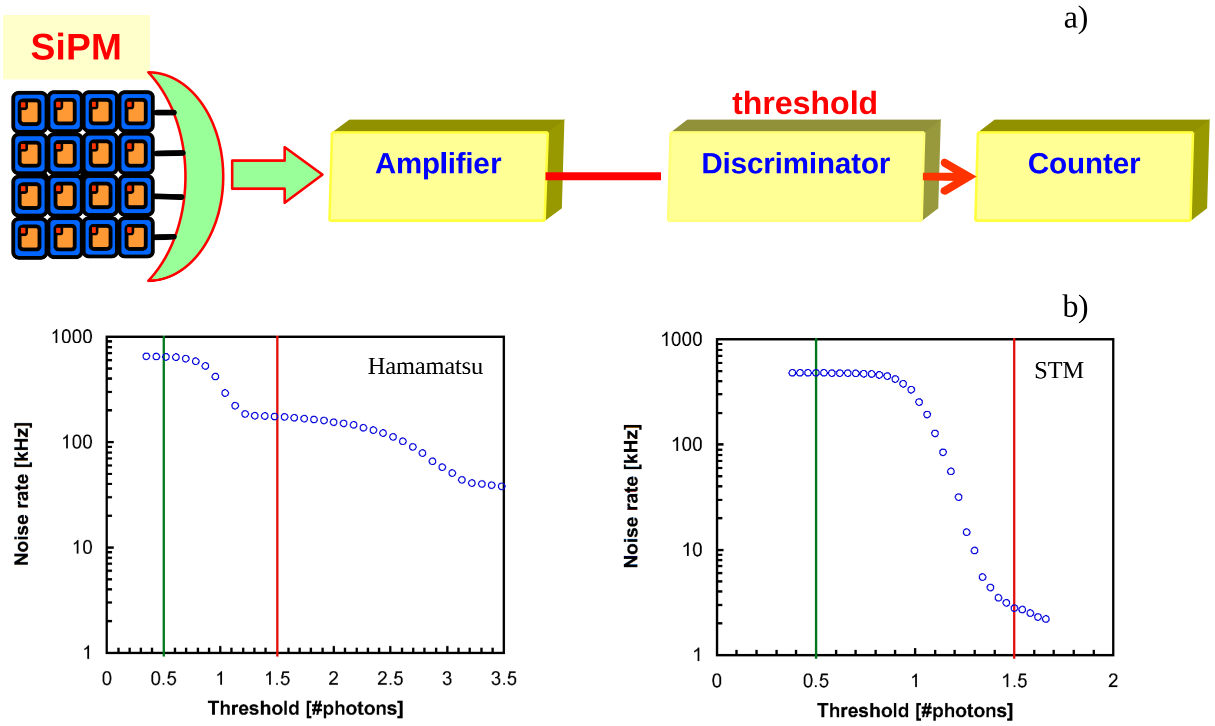

Fig. 3. a) Electronic set-up to acquire the dark noise rate; b) dark rate measured by changing the threshold for Hamamatsu and STM 100 cells.

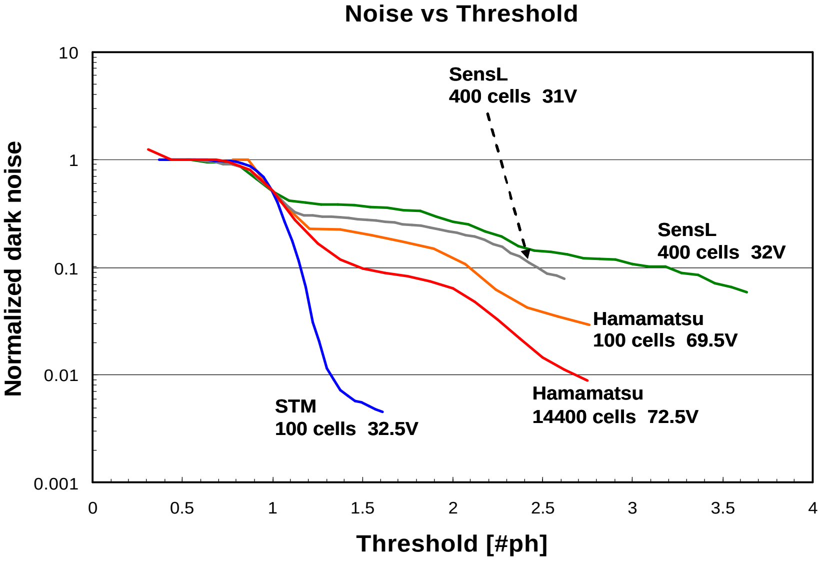

Fig. 4. Profiles of normalized dark noise of four SiPM models.

A further evidence of the effects due to cross talk comes from the analysis of the charge spectra acquired with a weak light source. Such spectra have been fit by using a Poisson multi-gaussian function,

$$F(x) = A\frac{dP}{dx} = A \cdot \sum_{n=1}^{\infty} \mathrm{Poisson}(\mu,n) \cdot \frac{1}{\sigma_{tot}(n)\sqrt{2\pi}} \cdot e^{-\frac{[x-c(n)]^2}{2\sigma_{tot}^2(n)}}$$

with n the number of photons, $\sigma_{tot}^2(n) = \sigma_e^2 + n\sigma_1^2$ and μ the centroid of the poisson curve, corresponding to the average number of photons, fig. 5. Whilst for the STM the function fits the experimental values with a very good agreement, a large discrepancy is present for the Hamamatsu, as we expect because of the high contribution from correlated noise.

For all the devices the gain has been measured constructing the charge spectrum and dividing the charge corresponding to two adjacent peaks by the elementary charge, in order to obtain the number of carriers produced during the avalanche process. Also the dependence of the gain on the bias voltage has been measured, showing an almost linear behaviour, fig. 6.

Table 2 - Probability of correlated noise

SiPM	Probability
SensL 1x1 mm^2 (V$_{bias}$ 31V)	9%
Hamamatsu 1x1 mm^2	10%
Hamamatsu 3x3 mm^2 (new)	1%
STM	<0.5%
FBK 1x1 mm^2	2%

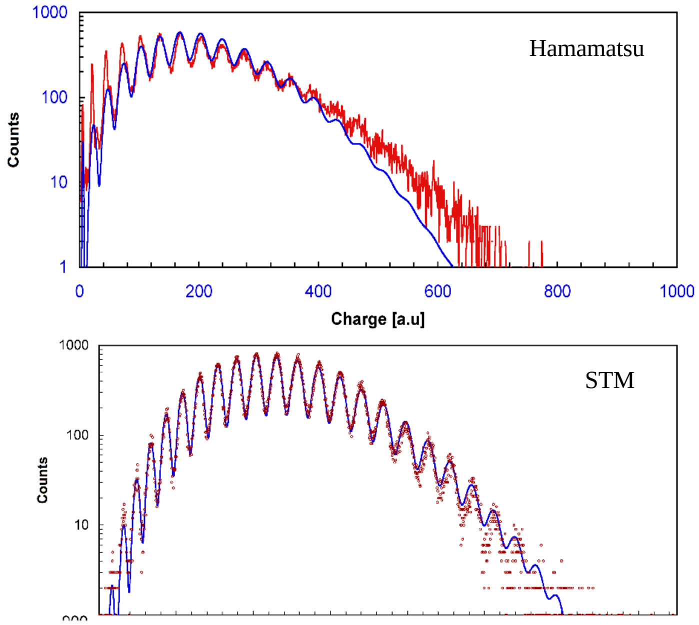

Fig. 5. Charge spectra fitted by a Poisson multi-gaussian function.

One of the most relevant parameters characterizing a SiPM is represented by the PDE, whose value strongly affects the performance of the devices in terms of timing and charge (i.e. energy) resolution. It can be expressed by the following equation PDE=QE x fg x Pa, with QE the quantum efficiency of the single cell, fg the fill factor (i.e. geometrical efficiency) and Pa the avalanche probability, depending on the electric field configuration in the depletion zone. Several procedures can be followed in order to measure such a parameter. All of them make use of a reference detector (typically NIST certified [4]) mounted along with the SiPM onto an integrating sphere, that guarantees the homogeneity of the photon flux on its inner surface. In our first measurements [5, 6] we made use of a xenon lamp that has allowed us to measure the efficiency in the whole visible light spectrum, by means of a grating monochromator. The light is produced continuously and thus we have measured the efficiency by comparing the current intensities read by both photodetectors. The limitation of such a technique is that the contribution of crosstalk and afterpulsing cannot be eliminated. Another technique that we are using now, makes use of pulsed laser light injected into the sphere. It implies that the SiPM must be used in pulse counting mode, in order to count the pulses whatever their amplitude. Maintaining the light intensity of each pulse as low as possible, the probability of double photons at the same time can be made negligible and the number of hitting photons can be easly measured by counting the pulses and subtracting the dark noise rate. If fig. 7 a scheme of the apparatus is shown together with some PDE values measured for SiPM Hamamatsu and STM, where the difference accounts for the fill factor of the Hamamatsu that is twice that of the STM.

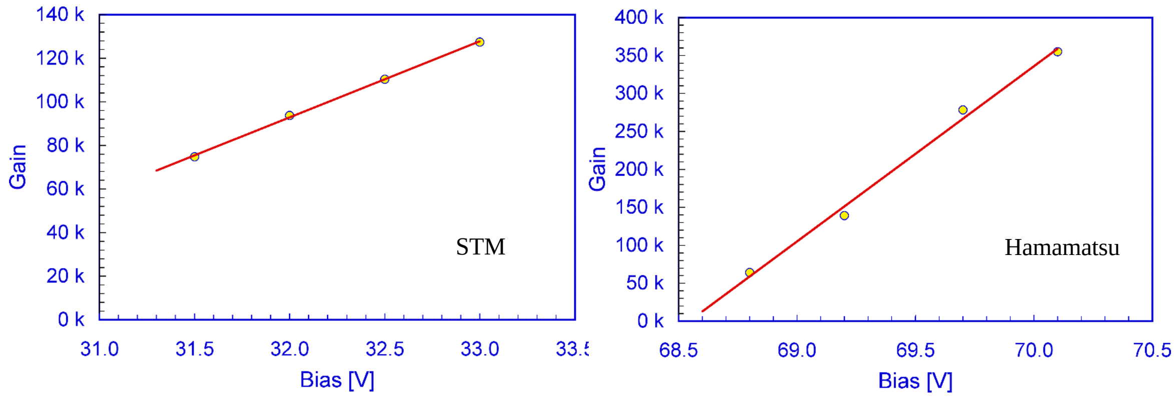

Fig. 6. Gain vs. the bias voltage for the STM and Hamamatsu.

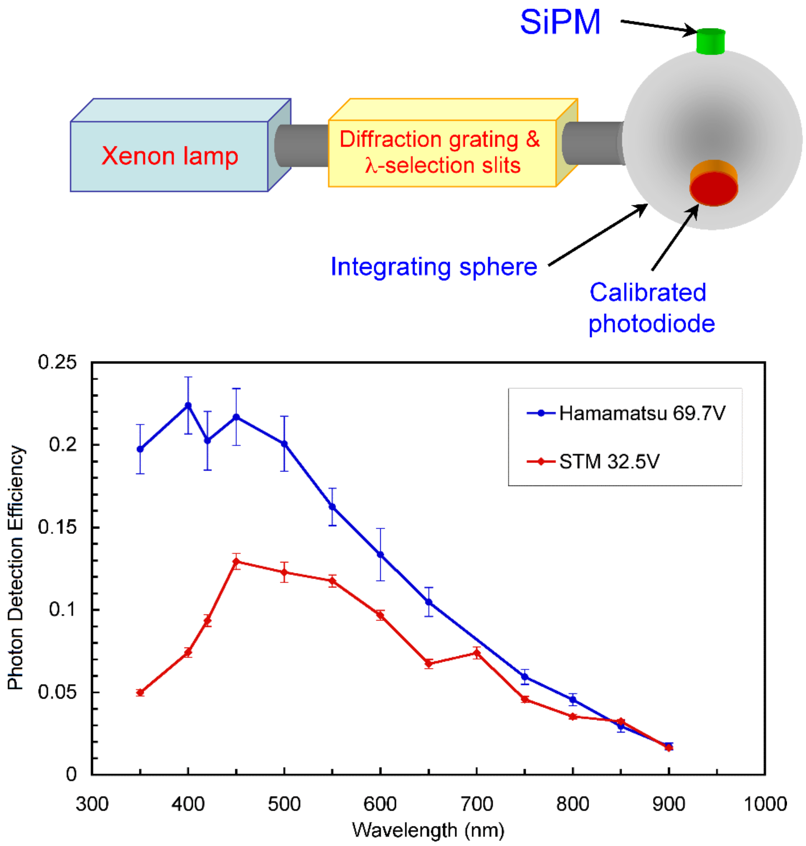

Fig. 7. Sketch of the experimental device for the measurement of the PDE. Values measured for two detectors.

The peculiarity of the SiPM detectors, in particular their small size, the low bias voltage and the high sensitivity, make them very interesting for some applications we are developing at LNS, such as a mesh of counters for radioactive waste monitoring and a small TOF-PET probe for early diagnosis of the prostate cancer [7 - 10]. Within these projects we are pursuing, the SiPMs are coupled with organic or inorganic scintillators, that make them detectors suitable for charged particles, neutrons and gamma rays. A recently developed Hamamatsu SiPM 3x3 mm^2 has been tested by coupling it with a tiny LYSO scintillator 3x3x10 mm^3 (40 ns decay time), in order to measure energy and time resolutions by using radioactive sources. In fig. 8 the spectra of three sources are shown, their resolutions scaling with the energy, as expected. By using a couple of Hamamatsu SiPM coupled with two LYSO crystals, we made coincidence measurements using the two 511 keV gammas produced by a ^{22}Na source, placed in between. The acquired timing spectrum, conditioned with the full energy events in both detectors, is shown in fig. 9. Its FWHM of 350 ps is in agreement with the expectations and can be reduced to 250 by using the similar Hamamatsu device that has twice as large a fill factor and hence twice as large a PDE value, improving the resolution of a factor sqrt(2).

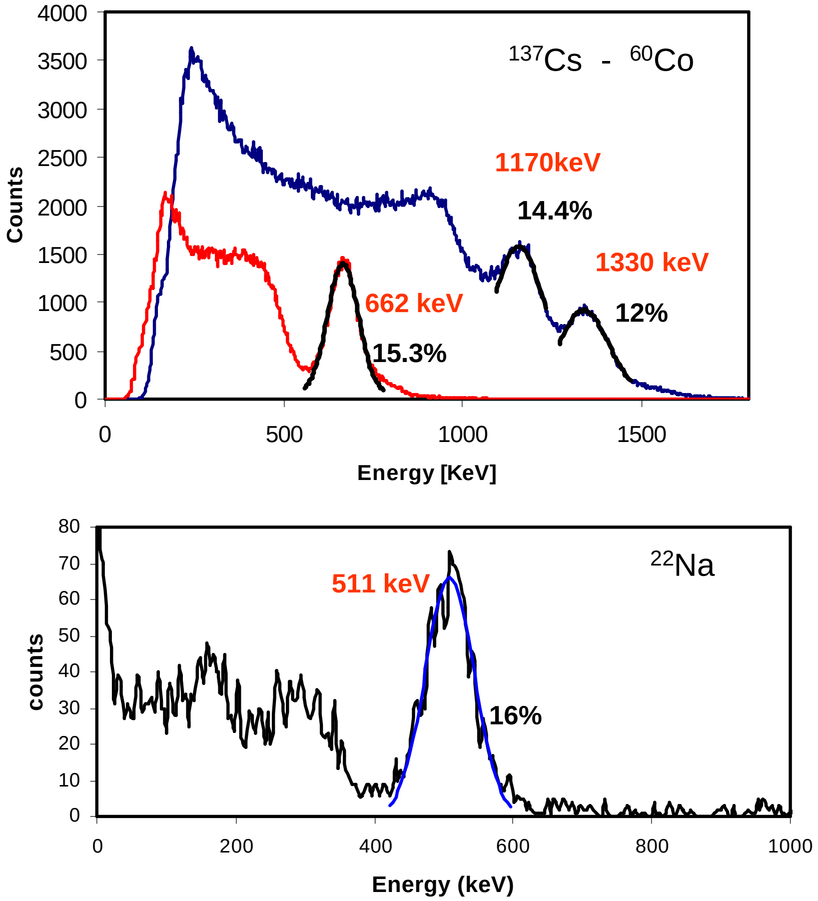

Fig. 8. Radioactive sources energy spectra, acquired with the Hamamatsu SiPM 3x3 mm^2, coupled with a LYSO scintillator.

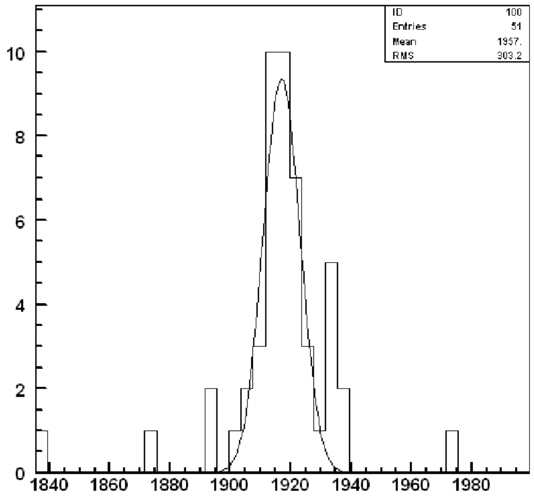

Fig. 9. Timing spectrum of two Hamamatsu coupled with LYSO, acquired by using a ^{22}Na source emitting two 511keV gamma rays in coincidence.

3.Conclusion

We have characterized several samples of SiPM, in order to measure the most significant parameters to be taken into account in order to choose the suitable detectors for specific applications. The measured energy and timing resolution are in good agreement with the data reported in literature and make the SiPMs a very good candidate to substitute the PMT in several applications.

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