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Original Article

The design of a scintillation system based on SiPMs integrated with gain correction functionality

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A B S T R A C T

Use of SiPM has been considered as an alternative to PMT, because of its compact size, low-operating voltage, non-sensitive to electromagnetic, low costs and so on. The main limitation for the use of SiPM is due to its small sensitive area compared to PMT that limits the light collection, and therefore the sensor energy resolution. In this article we studied the effect of increasing the number of SiPM by connecting them in parallel to increase the active detection area. This allowed us to compare the different energy resolution measurements. ^{137}Cs has been selected as reference to study the energy resolution for 662 keV gamma-rays. Another investigation was to compare the minimum detectable gamma energy under various SiPM configurations. It has been found that the use of 4 SiPM arrays can greatly improve the energy resolution up to 4% than only one SiPM array, meanwhile use of more than 2 SiPM arrays does not increase the energy resolution significantly. Thus we can conclude that for a large area of cylindrical scintillator (3 $\times$ 3 inches), the use of SiPMs are limited to a certain number or certain active area depending on the commercial SiPMs, and its cost should be less than traditional PMT for the cost-effective and compact size considerations. It is well known that the gain of SiPM varies with temperature. In this article, we also calibrated gain to guarantee the same position of photoelectric peak in response of different temperatures.

1. Introduction

Up to date, various types of radiation detection instruments have been developed. Scintillator system has been considered as the best favorite for real time on site in situ monitoring conditions [1], gamma ray imaging system [2], high energy physics [3], nuclear medicine [4] and so on. Crystalline sodium iodide, doped with thallium [5], is the detector of choice for routine gamma spectroscopy. Gamma-ray spectrometry is a nondestructive passive method for the detection, identification and quantitative determination of radioactivity in the environment. NaI(TI) has an excellent light yield (38,000 photons/MeV), a good linearity for a wide energy range, at a relative low production costs. The crystal is typically coupled to a photomultiplier tube (PMT). PMT, based on vacuum tube technology, has been the most widely used device for the detection and amplification of weak optical signals for decades [6]. However, silicon photo multipliers (SiPMs) can be a good replacement for PMTs, because of its compactness, insensitivity to magnetic field, low costs, low operating-voltage, apart from equivalent gain and quantum efficiency to the PMT [7]. For scintillation system, the efficiency of scintillation photon collection increases with the area of the photon sensor. Nevertheless, the largest single-chip SiPM is still less than 1 cm^2 [8]. In order to increase the SiPM sensitive active area for a large cylindrical scintillator (3 $\times$ 3 inches), we evaluated the effects using multiples SiPM in parallel. Meanwhile, on one hand, increasing the sensitive active area using SiPMs in parallel connections can improve the light collections, on the other hand, it can introduce more noises and the increase of signal rise time and width [9]. Thus one of our interest is focus on the finding the best compromise energy resolution results tested within various number of SiPM ranging from 1 to 4 for a large

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area of detection area. Contrast to PMT, using SiPM system is often required to be measured in cooling conditions, due to its gain sensitivity to temperature [10]. We also developed an approach to stabilize the position of corresponding photoelectric peak at a certain user defined channel when temperature varies. In this article, our objective is to determine the design of a cylindrical NaI (3× 3 inches) scintillation system based on the use of SiPMs integrated with gain correction functionality for the best energy resolution and photoelectric peak stabilization in case of temperature changes.

2. Materials and methods

2.1. Scintillation system design

Generally, a scintillation detection system is composed of one scintillator, it converts the adsorbed energy radiations to a large number of visible photons [11]. In our system, as principally hardware listed in Fig. 1 top left, only the NaI crystal was manufactured exterior, remaining was home designed by us comprising readout electronics, MCU (MicroController Unit) programing. A thin layer of optical grease, 0.1 mm, was sandwiched between the scintillator and the SiPMs for transporting scintillation photons. In order to better collect light, a reflector sheet (Vikuiti ESR) was applied on the crystal surface with an opening adjusted to the SiPM dimensions (Fig. 1 top left). Then a set of classical signal processing (Charge sensitive preamplifier, amplifier, MCA (Multiple Channel Analyser) was performed (Fig. 1 down: Readout electronics). Amplifier output pulse was shaping with a time constant at around 1 us. The energy histograms were monitored with the home-made AXINTDETECT labview software. Signal measurements, using the gamma sensor system, were exploited as an energy histogram distributed along 4096 channels. This energy histogram was reprocessed using a moving average on 10 points (still equivalent to a range ΔE~ 2.2 keV). This provides a smoother and legible signal without changing interpretation given the fact that energy resolution of the sensor is superior to 2.2 keV.

Differ to classical scintillation system design, the novelty from our sensor is that it offered the flexibilities to test the various SiPMs array that were connected. As illustrated in the following figure (Fig. 2 top), various SiPMs were possible to be connected between SiPM bias and system power (+30V could be in connection with BIASX (1,2,3,4)), between SIG and ARRAYX (1,2,3,4). These connections could be activated through mechanical switches (Fig. 2 down). SiPM bias could be controlled by a digital potentiometer (24.5–30V) through SPI communications as well. Temperature sensor (AD7814) [12] was implanted on readout electronics and can be read by PC.

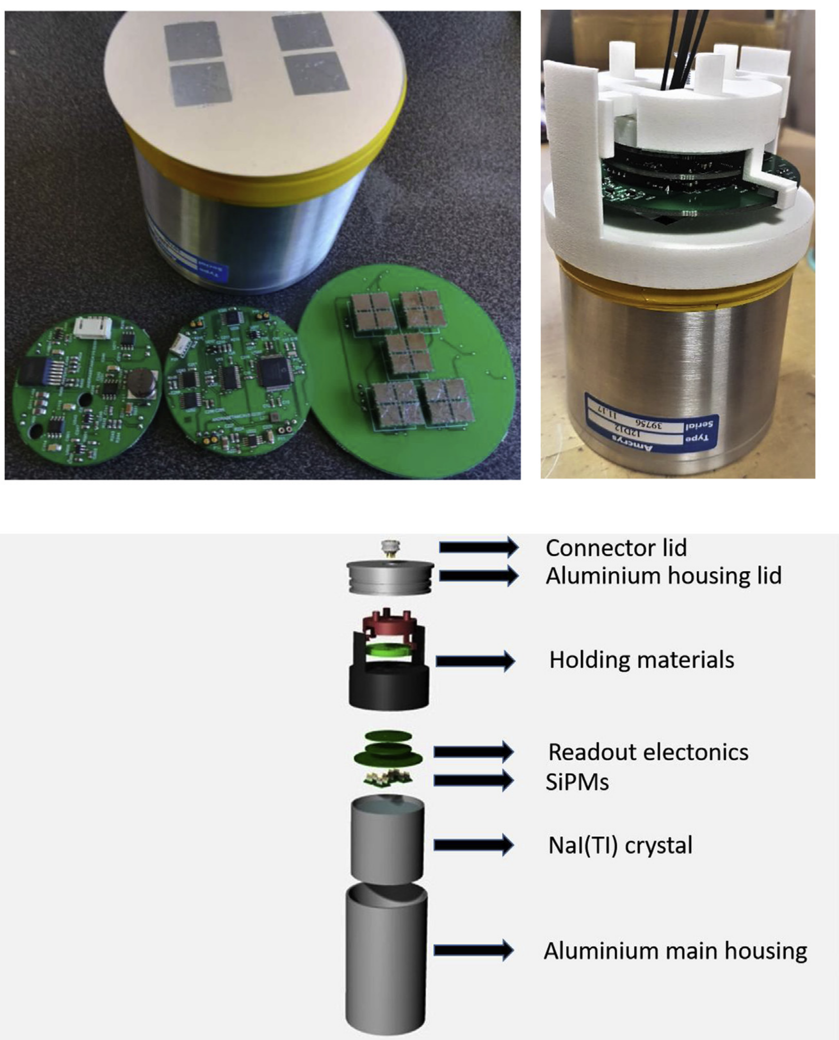

Figure 1. (Top) (Top left) General view of the crystal, reflector sheet, and PCBs (from left to right: power supply board, ADC/MCU board, preamplifier board); (Top right) General view of part of assembly; (Down) CAD view of scintillation system design.

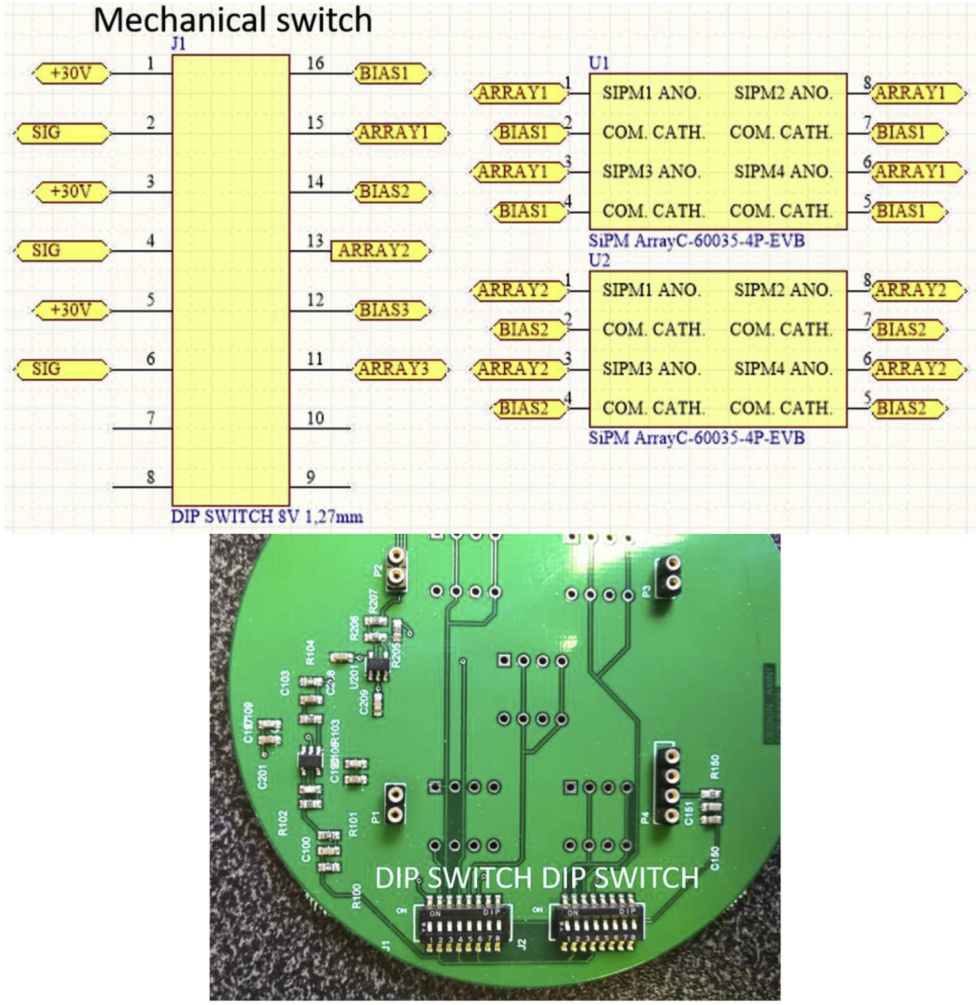

Figure 2. (Top) Electronic schematic view of connections (Down) View of DIP Switches.

2.2. Source information

^{137}Cs, ^{241}Am:

Two radioactive sources have been used, they were considered as point sources (^{137}Cs emitters gamma at 662 keV within 9 KBq, ^{241}Am emitters one of photoelectric peak gamma at 59 keV within 38 KBq) [13]. In our cases, we only analyzed the energy histogram below 1 MeV ^{241}Am is considered to verify the detection limit at low energy range, ^{137}Cs offered the standard reference of energy resolution at 662 keV under different SiPMs configurations.

2.3. Experimental setup procedure

Our experimental measurements were structured as following

1. Estimation of energy resolution under various SiPMs configurations using ^{137}Cs as radioactive sources
2. Energy histogram plotting with ^{241}Am source
3. Measurements of photoelectric peak position and temperature under different temperature milieu
4. Calculations of temperature gain corrections
5. Verification of gain corrections

First of all, we expected to find the best adaptation of SiPMs to obtain the best energy resolution. In this stage, we tested from 1 SiPM array to 4 SiPM arrays in connection. SiPMs used were SensL ArrayC-60035 [14], each SiPM array composed of 4 SiPMs (6 mm × 6 mm) in the form of 2 × 2 array. Thus the sensitive area can be increased from 12 mm × 12 mm–24 mm × 24 mm, this allowed us to create a equivalent solid-state alternative to the 1" PMT. After optimization of SiPMs configurations, a minimum gamma energy detection level has been identified using ^{241}Am sources as low energy gamma emitters. As SiPM is sensible to temperature variations, at this stage we measured the photoelectric peak position in response of different measurements conditions this including measurements at room temperature, in an isothermal bath milieu, in a refrigerator. The temperature was lectured by a digital temperature sensor (AD7814) which is direct connected to readout electronics. After that we established a gain correction formula based on fitting these measurements data. Finally, this formula has been integrated into AXINTDETECT software and for a user defined time base, this new correction gain of SiPM value has been taken into account. This new embedded functionality has been verified as well lastly.

3. Results

3.1. Best SiPMs configurations for a 3 × 3 inches cylindrical NaI scintillator

This part of results gave us indications for the study of SiPMs in response to energy resolution. The energy resolution was measured using ^{137}Cs as reference, it emits gamma energy at 662 keV. In an energy histogram, it was characterized through various interaction phenomena such as Compton edge, back scattering, photoelectric peak and so on [14]. For each configuration, the SiPM bias was adjusted to keep the photoelectric peak at the same position to guarantee the uniform detection amplitude signal of ^{137}Cs. Obviously, as clear identified in Fig. 3, in case of 1 SiPM configuration, the bias voltage has been much increased to 30V due to the lack of light collections. Both bias voltage and light collections were not in the best situation, this gave the lowest energy resolution compared to other configurations.

As plotted in Fig. 4, in each configuration we fixed the target position of the photoelectric peak at around channel 3000. The most interesting observation is the increasing energy resolution while increasing the number of SiPM arrays. Especially, from 1 to 2 arrays, calculated resolution is 3%p better. After that the energy resolution improved very slightly from 10.1% to 8.8%. This improved energy resolution is near to the use of PMT as light readout device with an energy resolution of 7% [15] for the 662 keV gamma ray from ^{137}Cs. Although the use of SiPM system loss a little of energy resolution compared to PMT (7.5%), this is due to its intrinsic property, first of all, commercial SiPM product formed very small sensitive area that limit the light collection face to only one SiPM. Then another perturbation source come from optical crosstalk. The crosstalk is defined as the probability that an avalanching microcell will cause an avalanche in a second microcell. Nevertheless, the use of SiPMs can gain on various aspects. This guarantees a compact size, insensible to electromagnetic perturbations aspect, low voltage operation, typically cost-effective side.

Obviously, the threshold gamma detection level was different under different configurations, this was due to the difference on overvoltage value. Because overvoltage value will decide threshold level of dark count rate (DCR). On the other side, if we regulate breakdown voltage for 1–4 SiPM arrays independently, obviously 1 SiPM array can detect low energy gamma rays as well. The key information is that increasing breakdown voltage will increase the threshold level of DCR.

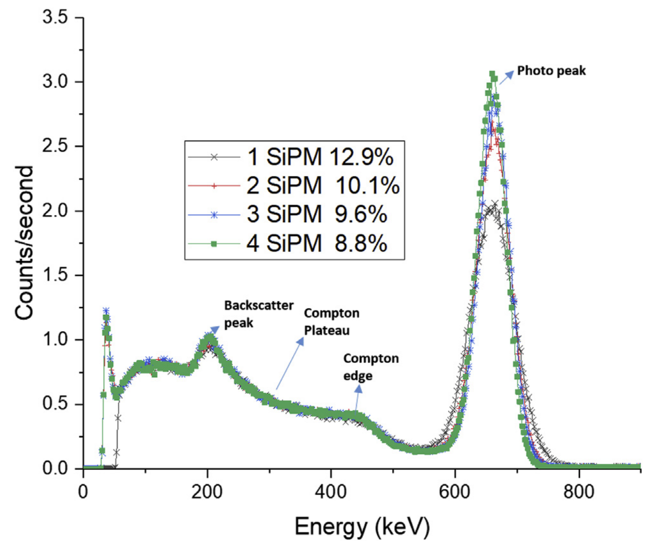

Fig. 4. Energy spectrum of 1–4 SiPM arrays.

After we found the best configuration to achieve the optimize energy resolution. We studied the evolution of energy resolution as a function of the bias voltage (Fig. 5) in the case of best configuration. The best energy resolution of 4 SiPM arrays used in this study was estimated to have a bias voltage of 28.3V. This was almost stabilized with 28.3 ± 0.5V.

For the next set of studies, our logical basis is defined the best SiPM configuration considering the best energy resolution and cost effect compared with PMT at first. Then based on this configuration, we studied the minimum detectable energy and temperature dependency.

3.2. Detection of minimum gamma energy

Although LaBr3 has long time been considered as the best candidate in terms of energy resolution (<3% at 662 keV for a source 137Cs) [16]. Nevertheless, the principal drawback of $LaBr_3$ is

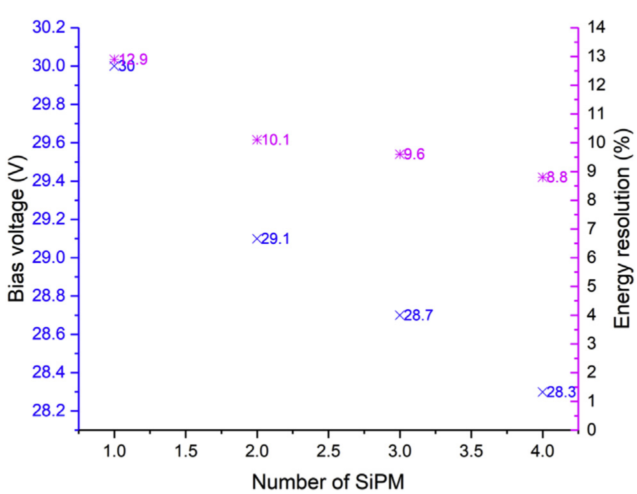

Fig. 3. The SiPM bias voltage and energy resolution results with the use of different number of SiPM arrays.

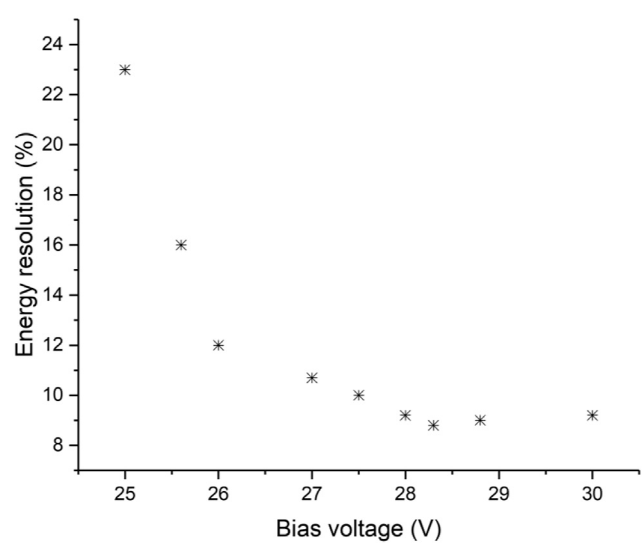

Fig. 5. The variation of energy resolution as a function of bias voltage in case of 4 SiPM arrays in connection.

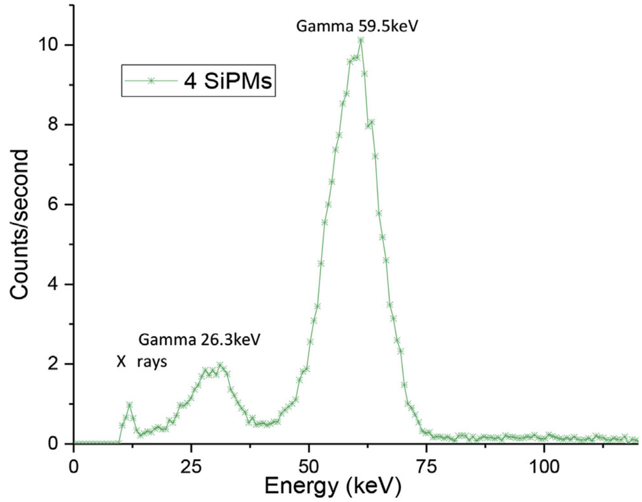

Fig. 6. Low energy gamma detection energy spectrum (^{241}Am source).

due to its internal radioactivity that contributes to spectral counts and a low-energy response that can cause detector resolution to be lower than that of NaI(Tl) below 100 keV. Using a large size of NaI(Tl) coupled with SiPMs, as energy spectrum plotted in Fig. 6, 241Am can be identified easily from energy histogram (photoelectric peak gamma emission at 59.5 keV, 26.3 keV, X ray peaks) [13] and our system was able to detect low gamma energy even at least to 15 keV (threshold). Thus this system offered a very compact, sensible at low gamma energy range, hand-held portable radioisotope identification, cost effective properties.

3.3. *Variations of photoelectric peak positions as a function of temperature*

One of well-known problematic of SiPM is about its temperature dependencies [17], increasing the temperature will reduce the detection signal, thus leading to a decrease of photoelectric peak position.

Before study the temperature influence versus the overvoltage, we studied for each independent temperature the variation of photoelectric peak as a function of Gain.

From Fig. 7 top, it was found that for each gain evolution of ±1 unit, the photoelectric peak varies around 30–35 channel depending on temperature. A linear behavior was observed at different temperature. Nevertheless, at high temperature (36 °C, 41 °C) for the same gain, it was found that its photoelectric peak positions were more away from other photoelectric peak position, this explained a larger gain correction value was necessary at high temperature than at low temperature.

A.Kaplan [17] suggested a first order correction of the effects of temperature. As illustrated in Fig. 7 down, we plotted the relative corrective gain (related to reference gain) as a response of various temperatures. Obviously, no linear relationship between the variation of gain versus the temperature has been observed. From Fig. 7 down, we found the changes on the gain value at high temperature was higher (large slope) than in cold or room temperature (small slope), this had been confirmed in Fig. 7 top as well. We estimated this no linear relationship was due to increase use of multiple SiPMs decrease linear temperature range.

In order to stabilize the photoelectric peak position at different temperature, an intuitive 3-degree polynomial fitting function was applied to auto regulate the gain value at various measured

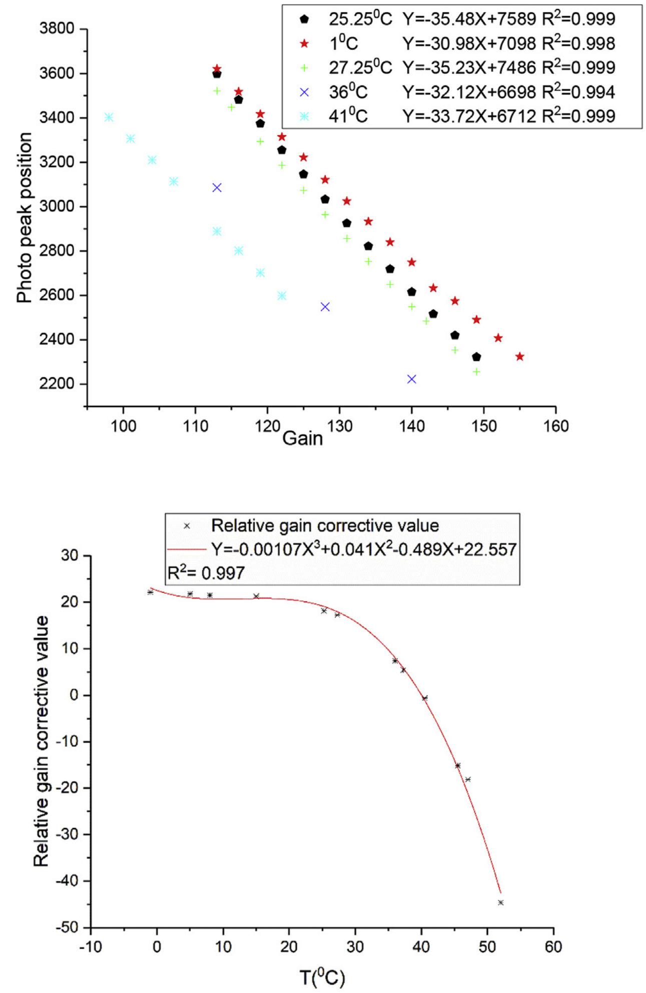

Fig. 7. (Top) Variations of photoelectric peak position in response of gain at different temperature (Down) Determination of relative gain correction value as a function of temperatures.

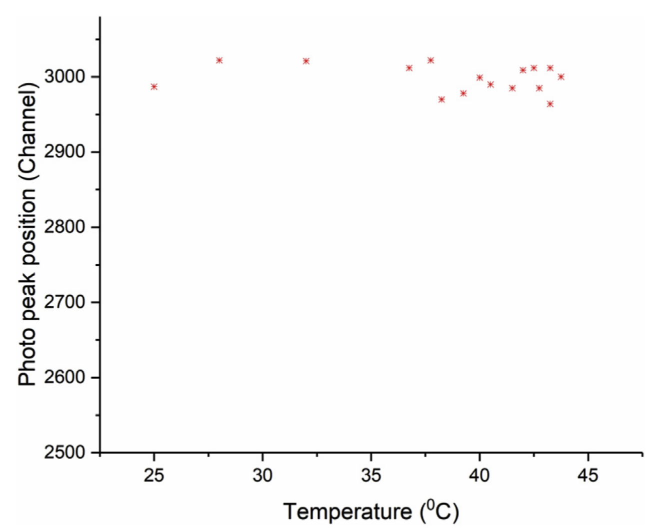

Fig. 8. Variations of photoelectric peak position in response of various temperature using relative gain correction functionality.

temperature. Fig. 8 illustrated for each 20 min the effect of application of relative gain corrective function, now the photoelectric peak was found to be stable at channel 3000 in response of different temperatures, the channel deviation was below the range of ±35 channels. This figure allowed us to validate our corrective fitting functions.

4. Conclusion

We have tested and validated for a 3 × 3 inches cylindrical NaI(TI) crystal the best SiPMs configurations that allowed us to get the optimize energy resolution. Using 4 SensL ArrayC-60035-4P-EVB SiPMs in connections increasing sensitive area up to 24 mm × 24 mm offered the best optimize solutions considered the better energy resolution (8.8%) and costs effective, low operating voltage aspects compared to PMT. A method for the correction of the temperature effects has also been developed and shown to work in our measurements. Differ to a first order correction of the effects of temperature proposed by A. Kaplan et al., a regulate gain shifts value in response of various temperatures has been defined and validated using a three-degree polynomial function rather than a first order correction. Adjustments of the operating voltage are proposed to compensate for temperature fluctuations during data taking. Such an online gain adjustment would minimize the data corrections to be applied offline. Our solutions give a compact, non-sensible to magnetic fields, detectable at very low energy level (15 keV), relative high energy resolution, can be considered as a cost effective portable radionuclides identification device, it can be used for nuclear effluent management, radioactive waste leaching, quality control of nuclear medicine and so on.

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