Large area LaBr$_3$:Ce crystals read by SiPM arrays with improved timing and temperature gain drift control

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Abstract

Compact X-rays detectors made of 1/2” or 1” :LaBr$_3$:Ce crystals of cubic shape with SiPM array readout have been developed for the FAMU experiment at RIKEN-RAL. The aim is a precise measurement of the proton Zemach radius with incoming muons. Additional applications may be found in medical physics, such as PET, homeland security and gamma-ray astronomy. Due to the high photon yield of LaBr$_3$:Ce it was possible to use a simple readout scheme based on CAEN V1730 digitizers. Detectors, using Hamamatsu S13361 or S14161 arrays, have good FWHM energy resolutions up to 3% (8%) at the $^{137}$Cs ($^{57}$Co) peak, comparing well with the best results obtained with a photomultiplier’s readout. Detailed studies were performed to correct online the drift with temperature of SiPM gain and to reduce the risetime/falltime of detectors’ signals, that increased going from 1/2” to 1” detectors, due to the larger capacity of the used SiPM arrays.

Keywords: SiPM; X-rays detectors; temperature gain compensation

1. Introduction

LaBr$_3$:Ce crystals have been introduced for radiation imaging in medical physics, with a readout based on photomultipliers (PMTs) or on Silicon Photomultipliers (SiPM). An R&D was pursued with 1/2” and 1” LaBr$_3$:Ce crystals, from different producers, to realize compact large area detectors (up to some cm$^2$ area) with a SiPM array readout. The aim was to obtain high light yields, good energy resolution, good detector linearity and fast time response for low-energy X-rays. A straightforward application was found inside the FAMU (Fisica degli Atomi Muonici) project $^{[1]}$ at the RIKEN-RAL muon facility. Its scope is a precise measure of the proton Zemach radius to contribute to the assessment of the so-called ”proton radius puzzle”, triggered by the recent measure of the proton charge radius with incoming muons at PSI $^{[2]}$. In FAMU, the detection of characteristic X-rays around 130 keV, with a short falltime of the output signal ($\leq$ 300 – 400 ns), is needed $^{[3]}$. Other applications may be foreseen in medical physics, such as PET, gamma-ray astronomy and homeland security. For these good FWHM energy resolution at higher energies ($\sim 500 – 600$ keV) is needed instead.

The drift of SiPM arrays gain with temperature is a limiting factor, giving a major deterioration of the FWHM detector’s energy resolution. In addition, for large detectors (area $\sim 1”$ square) the increment of the SiPM array capacity increases the falltime, as compared to what obtained with 1/2” detectors. To solve the first problem, a custom NIM module, based on CAEN A7585 digital power supply chips, was developed. Test results of the correction of gain drift with temperature for 1” SiPM arrays from Hamamatsu are reported. Previous results for 1/2” arrays from Hamamatsu, Sensl and Avansid were already presented in references $^{[3]}$ and $^{[4]}$. At the $^{137}$Cs ($^{57}$Co) peak, an energy resolution better than 3%(8%) was obtained for a typical 1” LaBr$_3$:Ce crystal, using Hamamatsu S14161 arrays. This compares well with best available results obtained with a PMT. For the second problem (“timing”) different solutions were studied from hybrid ganging of SiPM powering to the adoption of zero pole circuits, with or without amplification. All solutions, while giving a sensible reduction of timing: up to a factor two, had the drawback of an increase of the FWHM energy resolution: higher in the case of hybrid ganging. A good compromise was obtained by retaining the standard parallel ganging for the powering of the cells of the SiPM arrays, with a suitable zero pole circuit, while improving the used overvoltage by 1-2 V (at the limit of the operating conditions) to compensate for the signal decrease.

2. 1” Crystal detectors with SiPM array readout

The LaBr$_3$ crystals and the readout SiPM arrays are mounted inside an ABS holder, realized with a 3D printer, as reported in reference $^{[5]}$. A parallel ganging for SiPM powering was used. The SiPM temperature is monitored for an online correction of the operating voltage, via a TMP37 temperature sensor. Laboratory tests were done putting the detector under test inside a Memmert IPV-30 climatic chamber, where the temperature...
could be stabilized with a precision of ~ 0.1 °C. Detectors were powered at their nominal operating voltage $V_{op}$. Different exempt X-rays sources (Cd$^{109}$, Co$^{57}$, Ba$^{133}$, Na$^{22}$, Cs$^{137}$, Mn$^{54}$) were used for calibration. The summed analogue signal from the cells of a SiPM array is directly fed into a CAEN V1730 fast digitizer (500 MHz bandwidth, 14 bit resolution) and is acquired by a custom developed DAQ system [6]. Produced results for linearity and FWHM energy resolution obtained for a sample of 1" crystals at the reference temperature of 25 °C inside the climatic chamber. Results for 1/2" crystals has been previously shown in references [3] and [5].

3. Correction of gain drift with temperature

The SiPM’s gain drifts significantly as a function of temperature. This feature prevents their use in conditions with a changing temperature, as homeland security and military applications. The response of a typical 1" detector to a $^{137}$Cs source in the IPV-30 climatic chamber, where the temperature is varying from 20 to 30 °C, is shown in the left panel of figure 2. Without the online correction, the resolution of the photo peak at 662 keV is sensibly degraded. The response, with the online correction for temperature (see below for further details) is shown instead in the right panel of the same figure, where no degradation of the $^{137}$Cs photo-peak is seen. To overcome this problem, SiPMs must be operated at a fixed gain if temperature changes. Thus the operating voltage $V_{op} = V_{bd} + \Delta V$, with $V_{bd}$ breakdown voltage and $\Delta V$ overvoltage, must be modified as a function of temperature according to:

$$V_{bd}(T) = \frac{V_{bd}(T_{ref}) \times (1 + \beta (T - T_{ref}))}{T_{ref}}$$

with $T$ working temperature, $T_{ref}$ reference temperature (typically 25 °C) and $\beta = \Delta V_{bd}/\Delta T$ the differential value of the breakdown voltage to temperature. $\beta$, as explained in references [7] and [8], is independent of temperature.

For an online hardware correction, a custom NIM module, based on CAEN A7585D digital power supplies, with temperature feedback was developed. The SiPM temperature is monitored via a TMP37 sensor from Analog Devices mounted on the PCB where the array socket is soldered. A 3.5 mm stereo jack cable connects the sensor to the custom NIM module for online temperature correction.

Up to eight channels may be powered by a single 2-slots NIM module, as shown in figure 3. The control of the NIM module was implemented via either a FDTI USB-I2C converter or an Arduino Nano chip. Three modules (with which up to 24 channels may be powered) were realized and are linkable in daisy chain, via the I2C protocol.

One inch LaBr$_3$:Ce crystals, read by Hamamatsu S14161 SiPM arrays, were then put inside the IPV-30 climatic chamber for measurement. With a $^{137}$Cs exempt source, tests were done with and without the online temperature corrections. Results on the dependence of the photo peak at 662 keV and the FWHM energy resolution, as a function of temperature, are reported in figure 4. The same crystal is used in all the tests. After correction, the variation in the $^{137}$Cs photo-peak position (up to 33 % in the range 10-30 °C) was reduced to ~ 7%. Similar results with 1/2" LaBr$_3$:Ce crystals, read by Hamamatsu, Advansid or SENSLSiPM arrays, were previously reported in reference [5] in the range 10-45 °C. After the temperature correction, in all cases the variation was reduced to ~ 5%. The online temperature correction for gains seems to work better for the smaller

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Figure 1: Top panel: linearity for a sample of 1" detectors. Bottom panel: FWHM energy resolution for the same 1" detectors. Temperature control is applied.

Figure 2: $^{137}$Cs spectra recorded by a LaBr$_3$:Ce 1" detector read by an Hamamatsu 14461 SiPM array during a temperature scan between 20 °C and 30 °C, inside a climatic chamber. Left panel: is without temperature correction. Right panel: is with online temperature correction. Fits to the 662 keV photo peak, with a simple gaussian, are shown.

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2 ±2 °C accuracy over temperature, ±0.5 °C linearity
1/2" SiPM arrays. As shown in the bottom panel of figure 4, the effect on the FWHM energy resolution is within 1 per mille and is compatible with a zero dependence. Our results confirms previous results as published in references [9] and [10], both obtained with a PMT readout.

4. Improving timing properties

Different schemes may be used for powering the cells of a SiPM array, from parallel ganging, to series ganging or to hybrid ganging, as shown in reference [11]. The standard parallel ganging of SiPMs inside an array provides a good FWHM energy resolution: up to ~ 3%, comparable to what obtained with a conventional PMT readout [12], but with poor timing properties for larger SiPM arrays (e.g. 1 inch array).

Increasing the dimensions of the SiPM arrays, to match the growing detector’s window area, timing properties worsen, due to the increased array capacity. As an example, for S14161 Hamamatsu SiPM arrays the capacity increases from 500 pF to 2 nF, going from 1/2" to 1" size. Figures 5 and 6 report the distribution of risetime and falltime for a sample of 1/2" and 1" detectors. A clear increase in both risetime and falltime is seen. Different solutions were studied for 1" detectors, from hybrid ganging to the use of a zero pole circuit with or without an amplifier stage, to reduce timing. A reduction of risetime/falltime up to a factor 2 was obtained, at the cost of an increased FWHM energy resolution. Results for a typical detector are reported in table 1 and figure 7.

A good compromise is obtained by using conventional parallel ganging, with a 2 or 3.3 nF zero pole circuit increasing the...
Table 1: Timing and energy resolution for a typical (MIB071) 1” LaBr3:Ce crystal, with different solutions for the electronic readout

| circuit                | \( V_{op}(V) \) | risetime (20-80%) (ns) | falltime (10-90%) (ns) | resolution(%) @\(^{57}\)Co | resolution(%) @\(^{137}\)Cs |
|------------------------|-----------------|------------------------|------------------------|----------------------------|----------------------------|
| // ganging             | 41.82           | 46.6 ± 5.3             | 293.3 ± 43.4           | 7.78                       | 2.96                       |
| hybrid ganging         | 41.82           | 16.1 ± 2.4             | 176.8 ± 29.0           | 9.58                       | 6.08                       |
| 0-pole 3.3 nF          | 43.02           | 50.0 ± 16.5            | 145.7 ± 33.2           | 7.0                        | 2.94                       |
| 0-pole 2 nF            | 43.02           | 36.0 ± 7.9             | 123.4 ± 21.7           | -                          | 2.99                       |
| 0-pole 2 nF + Amp      | 40.82           | 29.4 ± 12.6            | 170.8 ± 48.7           | 10.0                       | 3.40                       |

![Figure 6: Distributions of the risetime (20-80 %) and falltime for 1” LaBr3:Ce crystals read by Hamamatsu S14161-6050-AS SiPM arrays. A standard parallel ganging is used.](image1)

![Figure 7: Effects on linearity and FWHM energy resolution for a typical 1” LaBr3:Ce crystals with different readout circuits. The line connects points for the standard parallel ganging of the SiPM cells of the array.](image2)

5. Conclusions

Good FWHM energy resolutions are obtained with 1” LaBr3 crystals read by Hamamatsu S14161-6050-AS SiPM arrays, both at the \(^{137}\)Cs peak and at lower energy at the \(^{57}\)Co peak. Resolutions up to 3 % and 8% were obtained in the two cases. With 1” detectors there is an increase of signal risetime and falltime, due to the increased capacity of the used SiPM arrays, as respect to 1/2” ones. To reduce the falltime of the 1” detectors, different solutions were studied. A simple solution based on a zero pole circuit and a greater overvoltage for the used SiPM arrays gives a reasonable reduction of falltime/risetime at the expense of a minimal increase of FWHM energy resolution. Solutions based on the use of hybrid ganging show a sensible increase of the detectors’ energy resolution and were discarded.

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