

Detection of low-energy X-rays with 1/2 and 1 inch LaBr₃:Ce crystals read by SiPM arrays

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LaBr₃:Ce crystals, with photomultiplier or single SiPM readout (up to 3x3 mm²) have been introduced for radiation imaging in medical physics. An R&D was pursued with 1/2" and 1" LaBr₃:Ce crystals, from different producers, to realize compact large area detectors (up to some cm² area) with SiPM array readout, aiming at high light yields, good energy resolution, good detector linearity and fast time response for low-energy X-rays. The study was triggered by the FAMU experiment at the RIKEN-RAL muon facility, aiming at a precise measurement of the proton Zemach radius to solve the so-called "proton radius puzzle". The goal is the detection of characteristic X-rays around 130 KeV. Other applications may be foreseen for homeland security and γ -ray astronomy. Results were obtained with a direct readout based on a CAEN V1730 FADC, with no need for an amplification stage. At the Cs¹³⁷ peak, energy resolutions up to $\sim 3\%$ were obtained, using a readout with Hamamatsu SiPM arrays. These results compare well with best available results obtained with a PMT readout.

*** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ***

*** 26-30 July 2021 ***

*** Online conference, jointly organized by Universität Hamburg and the research center DESY ***

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1. Introduction

The need of large area, compact crystal detectors, with good linearity and energy resolution, read by SiPM is arising in many fields from fundamental physics experiments, such as FAMU [1, 2], to PET [3], homeland security and γ -ray astronomy. Even if they are hygroscopic, the good light yield (75000 γ/MeV) and short decay time (~ 30 ns) of $\text{LaBr}_3:\text{Ce}$ crystals makes them the best choice, as respect to other crystals as PrLuAg or Ce:GAGG [4]. Our R&D is based on $\text{LaBr}_3:\text{Ce}$ crystals of increasing size (1/2 inches to 1 inches) read by SiPM arrays, whose gain drift with temperature is corrected online by a custom NIM module. The signals from the different cells of the readout array (4 for SENSL arrays, 16 for the other arrays) are summed up and read in parallel, to be later digitized by a fast CAEN V1730 FADC. As the signal is sizeable: ~ 100 mV at the Cs^{137} peak, there is no need for an amplification stage. The crystal and the SiPM array are housed in a 3D ABS printed holder, as shown in the right panel of figure 1. The optical contact between the crystal and the SiPM array is realized through Bicon BC631 silicone optical grease. To correct for the gain drift of SiPM with temperature, an Analog Devices TMP37 sensor is mounted on the back of each SiPM array. The temperature information is then used by a custom made module, based on CAEN A7585D units, to make an online correction (see reference [1, 6] for more details). The effect on the detector response (P.H. in a.u.) between 10°C and 40°C is reduced from 60 (40) % to less than 6 (10) % for 1/2" (1") detectors (see figure 2 for an example). While 1/2" crystals are cubic in shape: $14 \times 14 \times 14$ mm³, 1" crystals are round and 0.5" thick ¹ The used SiPM arrays

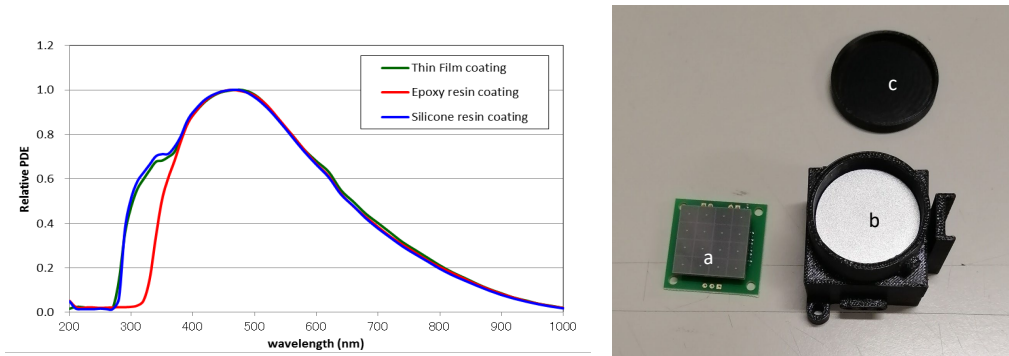


Figure 1: Left panel: response of Hamamatsu S13361 SiPM arrays to incident photons of different wavelengths and with different windows [courtesy of Hamamatsu Italia]. The response in the UV region is enhanced with a Silicone resin coating. Right panel: 1" detector mounting. a) SiPM array mounted on the PCB; b) crystal under test inside the holder; c) cover to ensure light-tightness. Mounting for 1/2" detectors is similar.

are shown, with their main characteristics, in table 1. Operating voltages V_{op} are set to $V_{brk} +$ overvoltage, where the overvoltage is chosen according to manufacturer's specifications.

¹we estimated a 88 % efficiency for 100 (200) keV X-rays with a 0.33 (1.54) cm thickness crystal, from tabulated X-ray mass attenuation coefficients [7]. This estimation has been confirmed by a refined MonteCarlo simulation based on the MNCPC code [8]. Thus for detection of signal X-rays with energy ~ 130 keV in FAMU, a 0.5 inch thickness is adequate.

Table 1: Main characteristics of the SiPM 1/2" and 1" arrays used in the laboratory tests.

	size (inches)	cell dim (mm ²)	V_{op} (V)	$\Delta V_{brk}/T$ mV/C	λ_{peak} (nm)	PDE max (%)	spectral range (nm)
Hamamatsu S14161-6050-AS	1	6x6	41.1	34	450	50	270-900
SENSL Array-J-60035-4P	1/2	6x6	29	21.5	420	50	200-900
Advansid NUV3S-4x4-TD	1/2	3x3	29.5	26	420	43	350-900
Hamamatsu S14161-3050-AS	1/2	3x3	41.1	34	450	50	270-900
Hamamatsu S13161-3050-AS	1/2	3x3	53.8	60	450	35	320-900

2. Results from laboratory tests

Laboratory tests were done putting the detectors under test inside a Memmert IPV-30 climatic chamber, where the temperature could be stabilized with a precision of ~ 0.1 °C. Tests were done mainly at 25 °C in the following. Detectors were powered at their nominal operating voltage V_{op} , as reported in table 1. Different exempt X-rays sources (Cd^{109} , Co^{57} , Ba^{133} , Na^{22} , Cs^{137} , Mn^{54}) were used. The summed analogue signal from the cells of a SiPM array is directly fed into a CAEN V1730

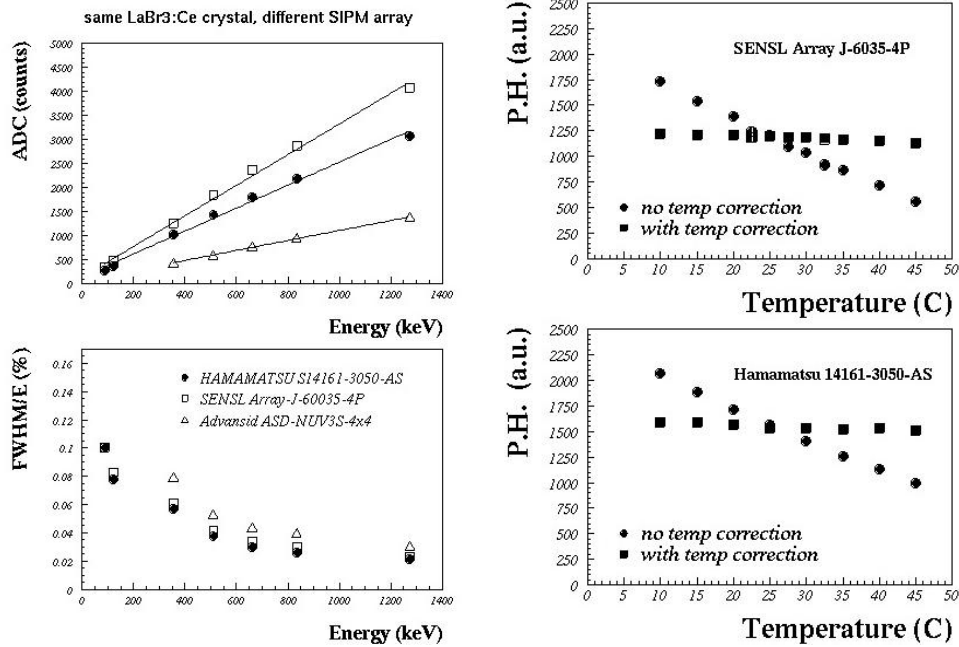


Figure 2: Left panel: linearity (top) and energy resolution (bottom) dependence for a 1/2" $\text{LaBr}_3:\text{Ce}$ crystal read by different SiPM arrays. The same crystal was used in all tests. Right panel: P.H. response in a.u. for a typical 1/2" detector, with and without temperature correction, with different SiPM array readouts.

fast digitizer (500 MHz bandwidth, 14 bit resolution) and is acquired by a custom developed DAQ system [9]. Produced n-tuples are analyzed by the ROOT package [10]. Figure 2 reports linearity and FWHM energy resolution for readout made with different SiPM arrays of the same $\text{LaBr}_3:\text{Ce}$ crystal. Resolutions up to 3% at the Cs^{137} peak are obtained with Hamamatsu or Sensl arrays. They compare well with what obtained with the best PMT readout. Detectors with SiPM array readout have typically longer risetimes (~ 20 ns for 20-80 % risetime) as compared to ones with fast PMT readout. To reduce this problem, due to the used parallel ganging of SiPM cells, an hybrid ganging solution is under study. Figure 3 shows the results obtained with a sample of $\text{LaBr}_3:\text{Ce}$ 1/2" crystals read by Hamamatsu S13161-3050 arrays. Figure 4 reports instead linearity and FWHM energy

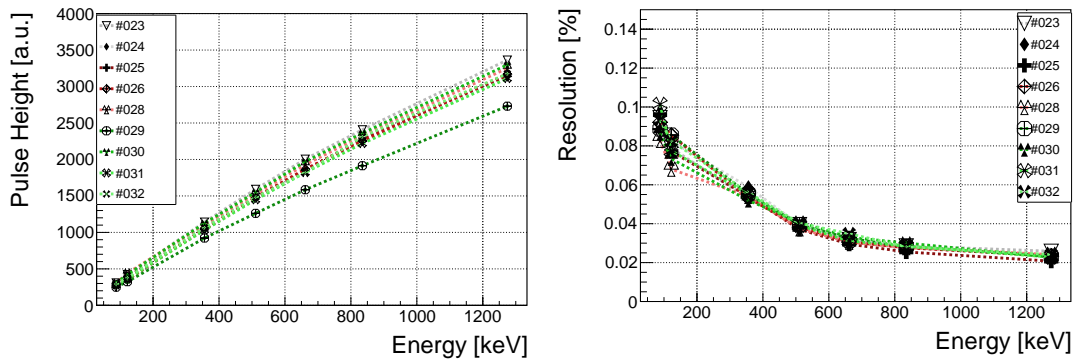


Figure 3: Linearity (left panel) and energy resolution (right panel) dependence for a sample of 1/2" $\text{LaBr}_3:\text{Ce}$ crystals read by Hamamatsu S13161-3050-AS SiPM arrays.

resolution for two typical one inch $\text{LaBr}_3:\text{Ce}$ crystals read by Hamamatsu S14161-6050-AS arrays. In both cases resolutions up to $\sim 3\%$ are obtained at the Cs^{137} peak. At the energies of interest for

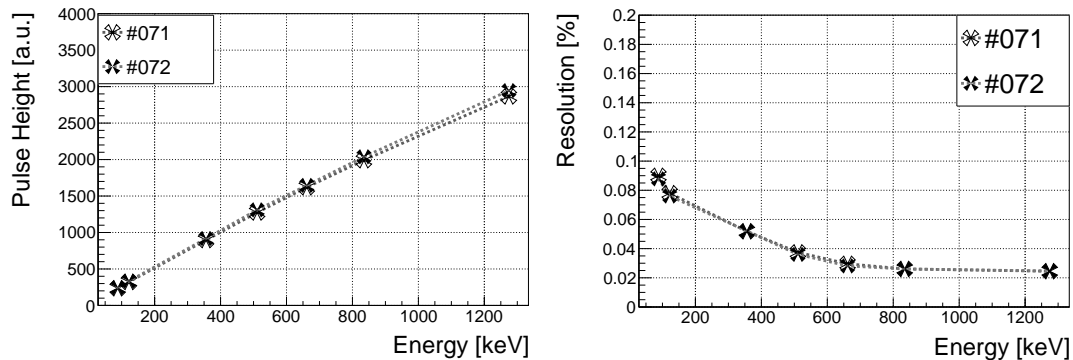


Figure 4: Linearity (left panel) and energy resolution (right panel) dependence for 1" $\text{LaBr}_3:\text{Ce}$ crystal read by Hamamatsu S14161-6050-AS SiPM arrays for two typical crystals.

the FAMU experiment (~ 130 keV) resolution up to $\sim 7\%$ are obtained. This compares well, with what obtained with a conventional PMT readout, as shown in reference [11].

3. Performances in beam

In December 2018, eight 1/2" detectors were used for the FAMU data taking, where the RIKEN-RAL pulsed muon beam impinged on a target filled with a $\text{H}_2 + \text{O}_2(0.3\%)$ mixture at 7 or 11 bar

pressure at 80 °K. After background subtraction (in red), signals corresponding to the Oxygen K_{α} or K_{β}/K_{γ} lines at ~ 130 and 160 keV are clearly visible (in green) in the delayed spectra, reported in figure 5 [12]. The use of two crowns of LaBr₃:Ce crystals read by SiPM arrays is foreseen for the final FAMU data taking in 2022-2023, in addition to one equipped with conventional PMTs.

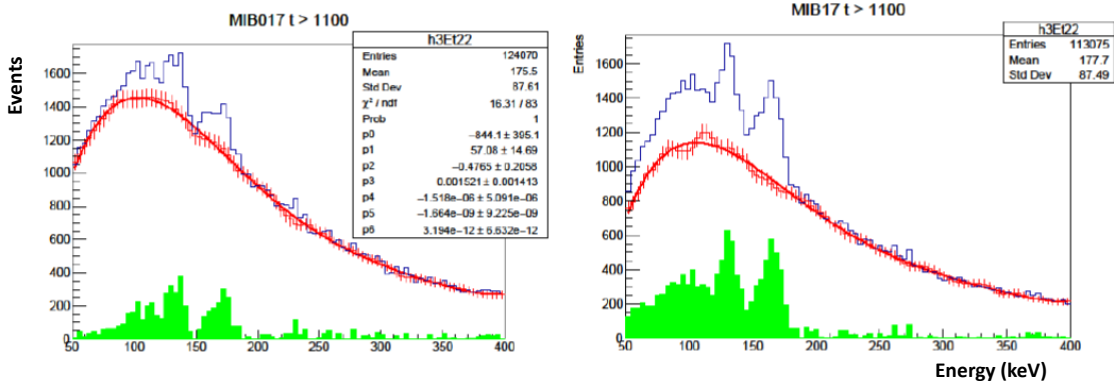


Figure 5: Delayed spectra from a 1/2" LaBr₃:Ce detector on the muon beam at RAL, using a target filled with a H_2+O_2 (0.3 %) mixture at 7 bar (left panel) and 11 bar (right panel), at 80 °K.

4. Conclusions

Good performances and FWHM energy resolution up to 3% have been obtained for both 1/2" and 1" LaBr₃:Ce crystals read by SiPM arrays. The gain drift with temperature was corrected online by a custom developed NIM module, based on CAEN A7585D units.

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