PROCEEDINGS OF SCIENCE

One inch LaBr3:Ce detectors, with temperature control and improved time resolution for low energy X-rays spectroscopy

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Large area $LaBr_3$:Ce detectors with a SiPM array readout have been developed for the FAMU experiment at RAL. The aim was to have a good energy resolution for low energy X-rays detection (~ 100 keV) and good timing properties of the signal pulse. Sixteen 1" detectors and twelve 1/2" detectors have been presently installed in the FAMU experiment and are taking data since March 2023, at RIKEN RAL Port 1.

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1. Introduction

$LaBr_3$:Ce crystals, with Photomultiplier (PMT) or SiPM readout, have applications in many fields from medical imaging, to homeland security and gamma-ray astronomy [1]. A readout based on SiPMs or SiPM arrays, instead of PMTs, allows the construction of compact detector, that may be used in external magnetic fields, avoiding the use of complicate shielding [2]. Good energy resolutions: around 3% at the Cs^{137} peak (661.7 keV), comparable with the ones obtained with PMTs [3], have been recently obtained for large detectors (area > 1 cm^2) with a SiPM array readout [4], [5], [6]. Our efforts aimed at the development of detectors with large area (initially 1/2") with both a good energy resolution, down to 100 keV, and good timing properties, as shown in reference [7]. The purpose was to contribute to the X-rays detection system of the FAMU experiment [8] at the RIKEN-RAL muon facility. The experimental target of FAMU is the precision measurement of the hyperfine splitting (HFS) of the μp ground state and thus of the proton Zemach radius, with impinging muons.

2. Detectors' construction

The developed detectors are based on 1" round $LaBr_3$:Ce crystals (0.5 " thick) read by Hamamatsu S14161-6050AS-04 square 1" SiPM array and are shown in figure 1.

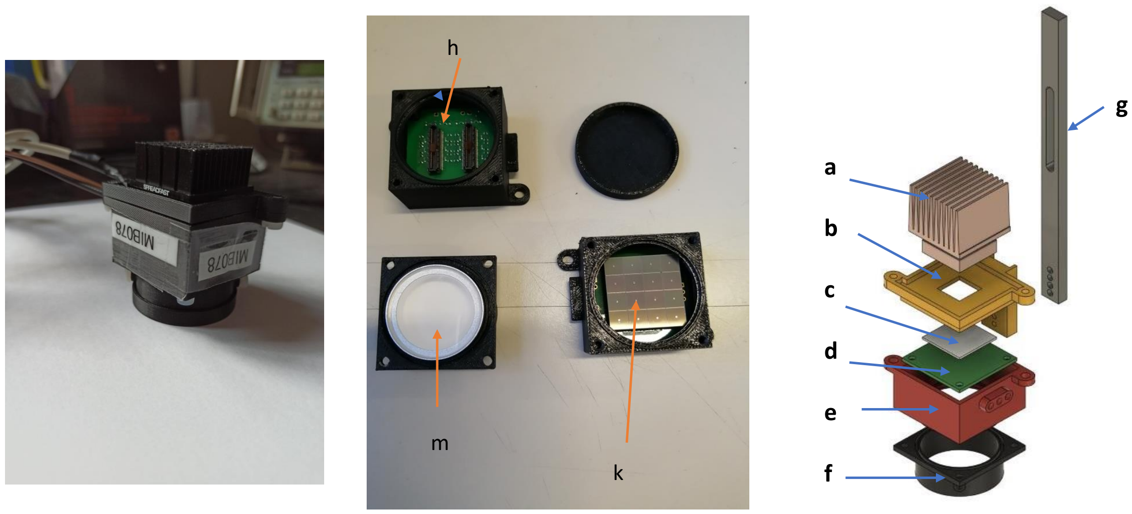

Figure 1: Left panel: image of a complete detector. Middle panel: images of some details of the crystal holder; h) with PCB inside. The two SAMTEC connectors for SiPM array mounting are shown. k) with mounted SiPM array; m) with crystal inside. Right panel: exploded view of a 1" detector. From top to bottom: a) heat dissipator, b) detector base; c) gap filler, d) PCB , e) PCB holder, f) crystal holder, g) support to hang a detector's base (b) from the $LaBr_3$:Ce crown support.

All the needed mechanics items for the detector mounting were realized with a 3D printer. Further details are reported in references [7] and [10]. The ouput signals of four nearby 6x6 mm^2

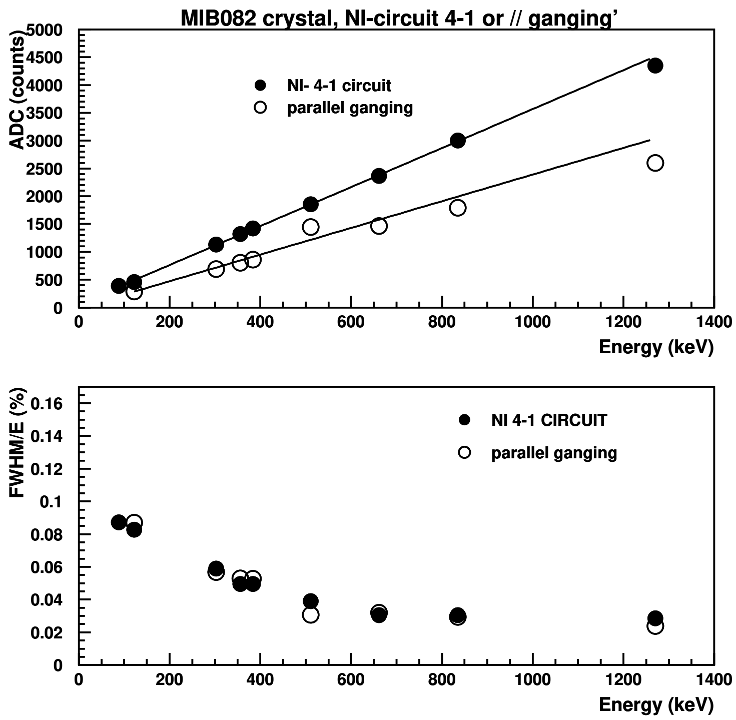

Figure 2: Linearity (top panel) and FWHM energy resolution (bottom panel) for a typical 1" detector both with parallel ganging and the new 4-1 circuit from Nuclear Instruments.

SiPM are grouped together and for them an individual pole-zero compensation and amplification is applied. Afterwords, the four signals of the sub-arrays (2x2 cells) are summed together and inverted, to give a positive output. All is realized with a custom circuit realized with Nuclear Instruments srl, see reference [9] for additional details. In this way a good energy resolution is obtained and pulse timing (risetime/falltime) is reduced by a factor 2X. Figure 2 shows the FWHM energy resolution and the linearity for a typical 1" detector, both with the standard parallel ganging for the 16 cells of the used SiPM array and with the custom 4-1 circuit from Nuclear Instruments srl. No deterioration of FWHM energy resolution is evident. The well-known drift of the SiPM gain with temperature is corrected online via a NIM custom module, based on CAEN A7585D power supply modules, with temperature feedback. In the range 10-35 °C the effect on pulse height (P.H.) variation at the ^{137}Cs photo-peak is reduced from 40 % to 7 %, see references [10], [11] for additional details.

3. Experimental Results

Laboratory tests were performed at INFN MIB with exempt sources from Spectrum Techniques, covering the energy range 80-1274.5 keV (^{109}Cd - ^{22}Na). Detectors under test were put inside a Memmert IPV30 climatic chamber, with a precision of ±0.1°C on the temperature control. Detectors' signals were then fed into a CAEN VME V1730 FADC and then acquired by the FAMU custom DAQ, via a CAEN V2718 interface. Output ROOT ntuples are then processed for data analysis.

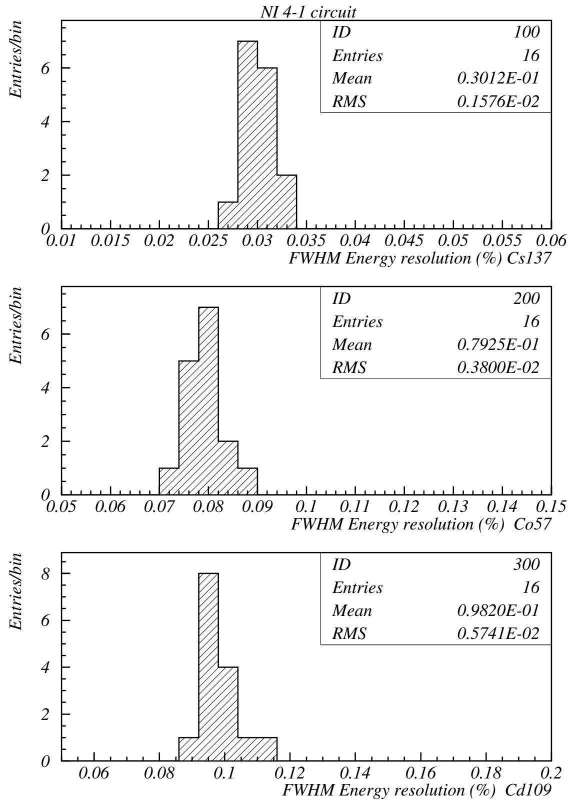

Figure 3: Distribution of FWHM energy resolution for the used 1" detectors at the ^{137}Cs peak (top panel), at the ^{57}Co peak (middle panel) and at the ^{109}Cd peak (bottom panel).

FWHM energy resolution (in %) and 10-90 % risetime/falltime for the sixteen 1" detectors used in the FAMU experiment are shown in figure 3 and 4. The main experimental challenge in the FAMU experiment is the detection of low-energy X-rays around 130 keV separating a "delayed" signal component (after 600 ns) from a prompt one. The reported results: especially the $\sim$ 8% energy resolution at the ^{57}Co peak and the signal falltime ($\sim$ 150 ns) show that the required target may be reached [7], [9]. Prelimary data taken at RIKEN RAL with 55 MeV muons from March 2023 confirm this assumption.

3.1 Installation at RIKEN RAL

In the 2023 run configuration for the FAMU experiment at RIKEN-RAL, sixteen 1" and twelve 1/2" detectors, with SiPM readout, were installed at RAL in the X-ray detection system. They are arranged in three crowns : upstream (ten 1" detectors), central (six 1" detectors) and downstream (twelve 1/2" detectors), as shown in figure 5. In addition six old 1" detectors with a PMT readout [12] are used in the central crown.

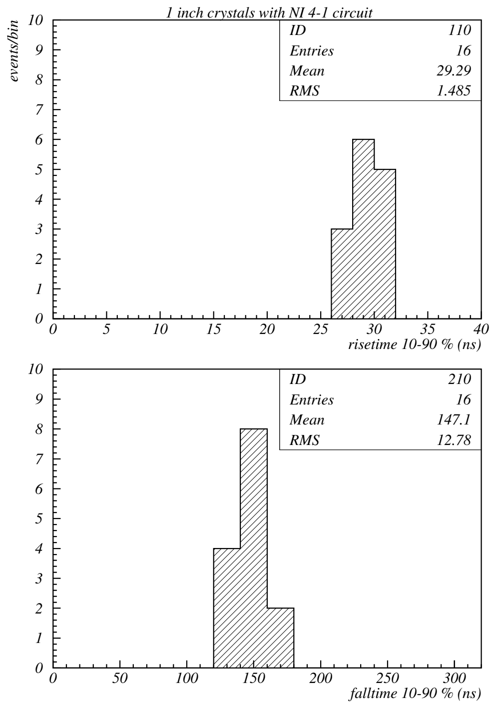

Figure 4: Distribution of the 10-90 % risetime-falltime for the used 1" detectors.

With the 4-1 innovative circuit from Nuclear Instruments srl, that divide the readout of a 1" SiPM array into four, a good compromise in the optimisation of energy resolution and pulse timing is obtained. The major drawback of this solution is the increase of heat dissipation, due to the introduction of several Texas Instruments OPA695 amplifiers: about 1 W. As the working environment at RIKEN-RAL is kept at constant temperature (20 °C) by air-conditioning, a simple passive heat dissipation is enough for proper operations.

The main characteristics of the Ce:LaBr$_3$ detectors used in the FAMU experiment, as obtained from laboratory measurements, are resumed in table 1. 10-90 % risetime (falltime) are measured with a Cs^{137} source, using a Lecroy 1 GHZ scope.

Table 1: FWHM energy resolution and timing characteristics of the Ce:LaBr$_3$ detectors used in the FAMU experiment at RIKEN-RAL

	risetime (ns)	**falltime (ns)**	**resolution %** Cs^{137} (662 keV)	**resolution %** Co^{57} (122 keV)	**resolution %** Ce^{109} (88 keV)
1/2" detectors	42.8 ± 4.7	372.4 ± 17.4	3.27 ± 0.11	8.44 ± 0.63	10.63 ± 1.16
1" detectors	29.3 ± 1.5	147.1 ± 12.8	3.01 ± 0.16	7.93 ± 0.38	9.82 ± 0.54

The worse timing properties of the 1/2" detectors, as compared to the 1" ones, are mainly due to the adoption of a standard parallel ganging instead of the 4-1 solution from Nuclear Instruments

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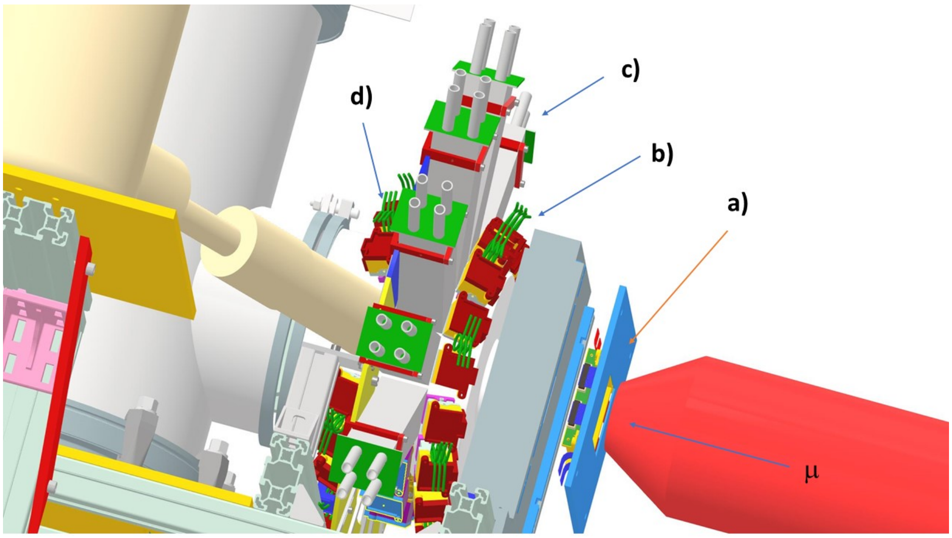

Figure 5: Drawing of the FAMU X-rays system, used in the 2023 run, with (a) the beam hodoscope in front of a Pb collimator, (b) the upstream crown of 1" $LaBr_3$:Ce detectors; (c) the central crown of detectors: based on six old detectors read by PMTs [12] and six detectors read by SiPM arrays (visible near the bottom). All are of 1" size. (d) the downstream crown of 1/2" Ce:$LaBr_3$ detectors.

and probably to a different Ce concentration. Data were taken since March 2023 with a 55 MeV/c muon beam at Port 1 at RIKEN RAL and a preliminary analysis is under way. No major issues have been encountered up to now. Preliminary results on the reconstructed muonic Ag peak (~ 142 keV) confirm our laboratory ones.

4. Conclusions

Good FWHM energy resolution is obtained with 1" $LaBr_3$:Ce crystals read by Hamamatsu S14161-6050AS-04 SiPM arrays. Resolutions better than 3%(8%) are obtained at the Cs^{137} (Co^{57}) peak in laboratory tests. The use of the innovative 4-1 circuit from Nuclear Instruments allowed a factor two reduction of signal risetime (falltime), as respect to the conventional solution with parallel ganging. Detectors are presently installed in the FAMU apparatus at RIKEN RAL.

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