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Simultaneous Deposited Energy and Interaction Position Determination in Monolithic Scintillators

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A study of several methods to obtain simultaneous measurements of deposited energy and interaction position in monolithic $CeBr_3$ and $LaBr_3$ scintillator crystals using a 12×12 matrix of $3mm^2$ silicon photomultipliers was performed by simulation and experiment. A multistep method for analysis and reconstruction of the data is being implemented. Two data acquisition and analysis systems - from commercially available modules and an in-house design - are being built to validate the simulation results and are currently undergoing calibration and testing. The tested detector system can perform spectroscopy with energy resolution reaching the specification limits of the scintillator crystals. Depending on the chosen sequence of methods, spatial resolution of 0.65mm with $\sigma = 0.88mm$ was achieved after applying the developed event classification and separation algorithms.

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1. Introduction

In high energy and nuclear physics experiments there is a demonstrated need for small-size, robust and reusable detector components and acquisition systems that can be operated in resource-limited environments and provide measurements limited by the physical properties of the available primary detectors. Such components would have applications beyond research [1].

Typically a detector system that needs to measure energy spectrum and position will consist of more than one detector, comprising a position sensitive module and a calorimetric system [1], [5]. Such systems tend to be large and to require complex processing for synchronization and data reconstruction.

The presented research investigates the use of recently developed fast, high yield and resolution crystal scintillators, SiPM-based readouts ([2]) and "edge intelligence"-based analysis system to provide a single-unit detector that can provide fast simultaneous measurements of energy and position. A set of simulations, an analysis framework and two integrated hardware solutions were developed with promising results and are in the process of testing and iterative improvement.

2. Simulation and Modeling

A Geometry Description Markup Language (GDML)-based Geant4 simulation package was developed to allow fast investigation of different geometries, sensor-to-readout couplings and channel readout arrangements [3]. Primary object of investigation were widely available $CeBr_3$ and $LaBr_3$ cylindrical and rectangular prism scintillators, coupled to multi-pixel SiPM matrices, although the framework allows for easy construction and simulation of complex simulations from modular and parametrized templates. A typical simulation target is shown on Figure 1.

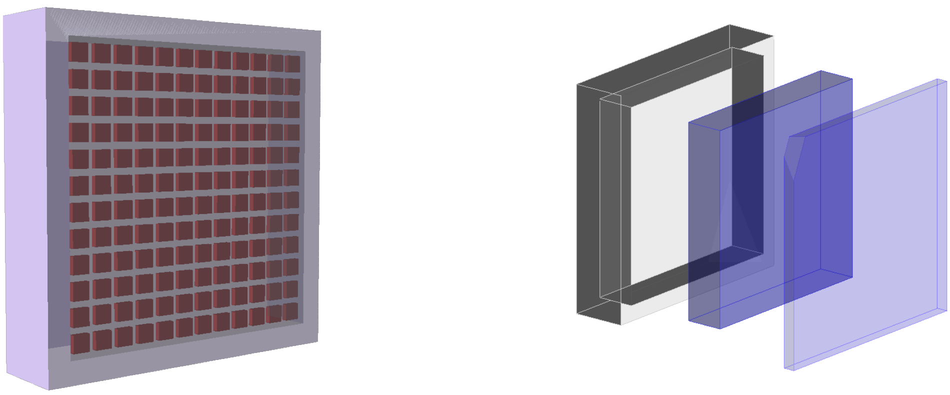

Figure 1: Typical scintillator simulation targets. Left: Scintillator with the attached SiPM sensitive detector matrix. Right: Exploded view of the scintillator - reflective case, crystal, glass cover for hygroscopic protection.

As the goal of the research is to quantify the ability to obtain simultaneously readings for energy as well as interaction position (or its projection onto the sensor matrix plane), both reflective and diffuse enclosure surfaces were modelled and simulated. All planned electronic readout and acquisition systems were simulated by collecting individual SiPM sensitive detector data and aggregating them using the respective readout response functions developed for all hardware under investigation.

3. Scintillators and Photon Counters

For the validation experimental measurements, two $CeBr_3$ crystals with size $51x51$mm^2 and thicknesses of 10 and 25mm, and one $LaBr_3$ cylindrical crystal with D=2.54mm/H=25.4mm are used. The pixel counters are On-Semi (formerly Sensl) 30035 type SiPMs with 35μm cell size, 4774 individual cells per pixel and with total pixel size of 3×3mm^2, assembled in a 12×12 pixel matrix with a pitch of 4.6mm.

4. Readout

Three different readout systems were built and are undergoing testing. Two are based on commercially available modules and are used to test the usability of different channel summation schemes. Additionally, a multi-channel prototype was developed in-house to digitize individual SiPM pixels and enable the application of more advanced event classification algorithms in the data processing stage.

Summating readout was implemented using AiT instruments' 4-channel readout and Row-and-Column readout modules ([6], [7]). Figure 2 shows simplified schematics of the two systems.

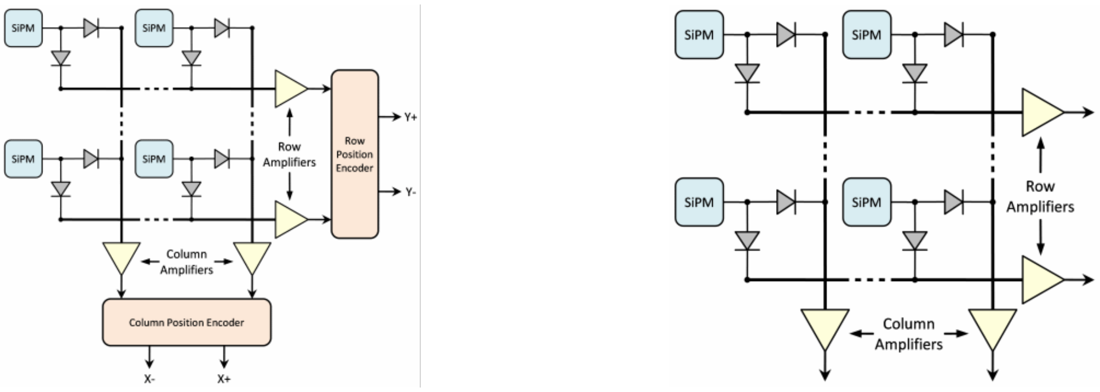

Figure 2: Channel-summing readout schematic of AiT Instruments' modules. Left: 4-channel summation ([6]). Right: Row-and-Column summation. ([7]).

Both solutions allow in principle the construction of a readout system capable of simultaneous estimation of position and energy, their main advantage being the ability to use a smaller number of expensive ADC channels. The readout schematic for the ATI-based approach is shown in Figure 3, left.

The TDC-to-ADC system using delay lines ([4], [5]) developed in-house allows the operation of a large number of ADC channels and therefore processing of individual SiPMs without summation. It therefore allows for the application of smarter data-processing algorithms. Additionally, the implementation of the system on a general-purpose FPGA module allows the migration of data processing complexity from the front-end electronics into the FPGA chip, simplifying the detector analog readout design and enhancing the ability to configure the detector geometry and readout. This readout schematic is shown in Figure 3, right.

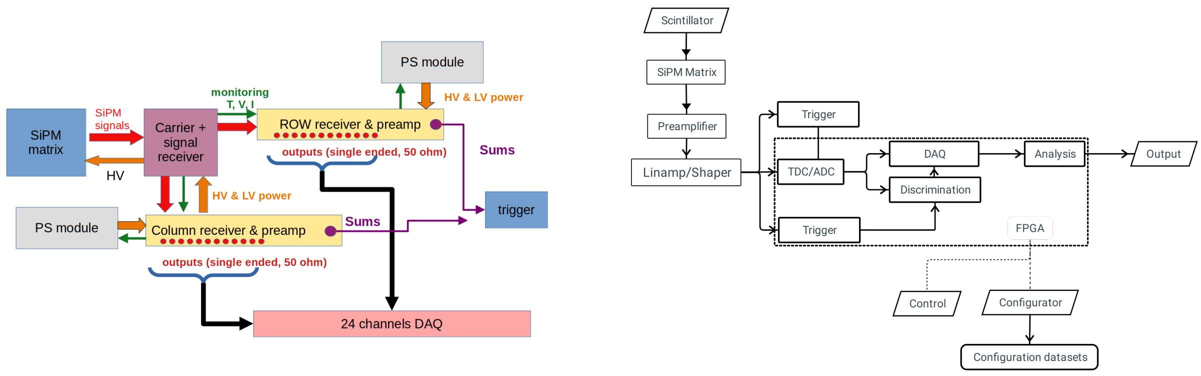

Figure 3: Left: Data acquisition using AiT instruments' channel summing technologies. Right: Schematic of Individual Readout Based on Amplitude-to-Time transformation and measurements of ToT and ToA using an FPGA-based TDA algorithms.

While theoretically the position resolution of the row-column channel summation system is no different from the resolution of an individual readout system using the centroid method, applying a series of steps to categorize data allows the individual SiPM readout system to provide a significant increase in position sensitivity.

The resolution of the 4-channel system was also studied for comparison with a non-segmented scintillator.

5. Preliminary Results

All three systems have been studied by simulation for energy resolution and position resolution, however for positional resolution the focus is on the row/column summation and individual readout systems.

The 4-channel summation system has been tested experimentally and found to provide very low position resolution when used with a monolithic crystal. Work is ongoing to complete and test experimentally the row/column summation and individual readout systems for positional resolution, as shown in Figure 4.

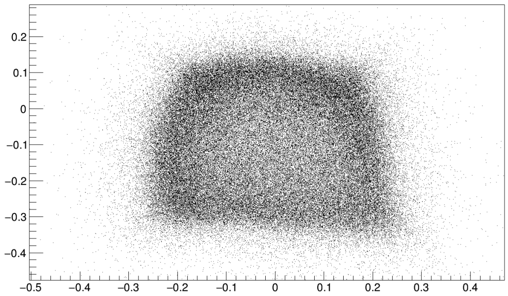

Figure 4: Experimentally measured ^{137}Cs position resolution for the 4-chanel readout from AiT. The position measurements using this summation scheme (shown in units of SiPM pixel size) are too crude to be of experimental value.

The 24-channel summation system and the individual pixel readout systems have been studied by simulations and analysis algorithms have been applied to generated data in expectation of completion of the hardware.

For spectroscopic measurements, the expected energy resolution for the two systems is very much in line with the vendor-provided single PMT measurements (summary of the energy resolution simulations is provided in Table 1).

Energy [keV]	**Experimental [%]**	**Simulation [%]**
122	5.0	6.4
244	4.2	5.6
344	3.7	4.7
778	2.4	3.0
1408	3.0	4.0

Table 1: Selected Spectral Line Resolutions of Simulation and Experiment, $LaBr_3$ Scintillator

The slight increase in the resolution compared to the vendor results can be attributed to differences between the model and the actual crystals and minor effects of the summing electronics. The summary in the table is based on data generated by several simulations and experimental measurements, as shown in Figures 5 and 6.

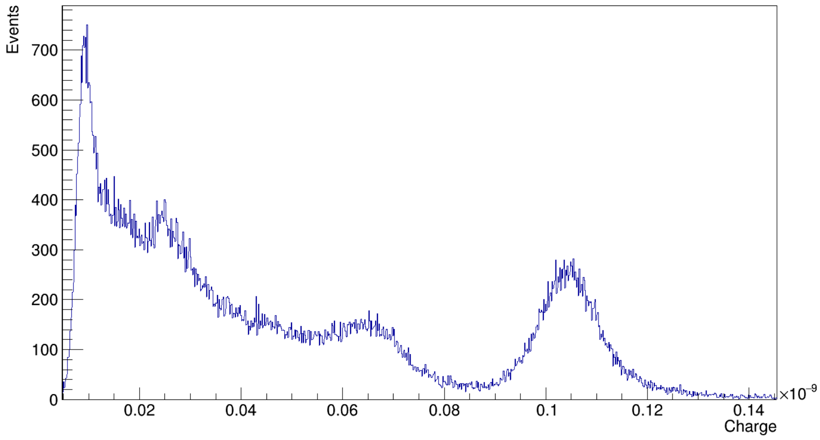

Figure 5: Experimentally measured ^{137}Cs energy spectrum using the 4-column readout from AiT. The spectrum measurements are very close to the expected resolution.

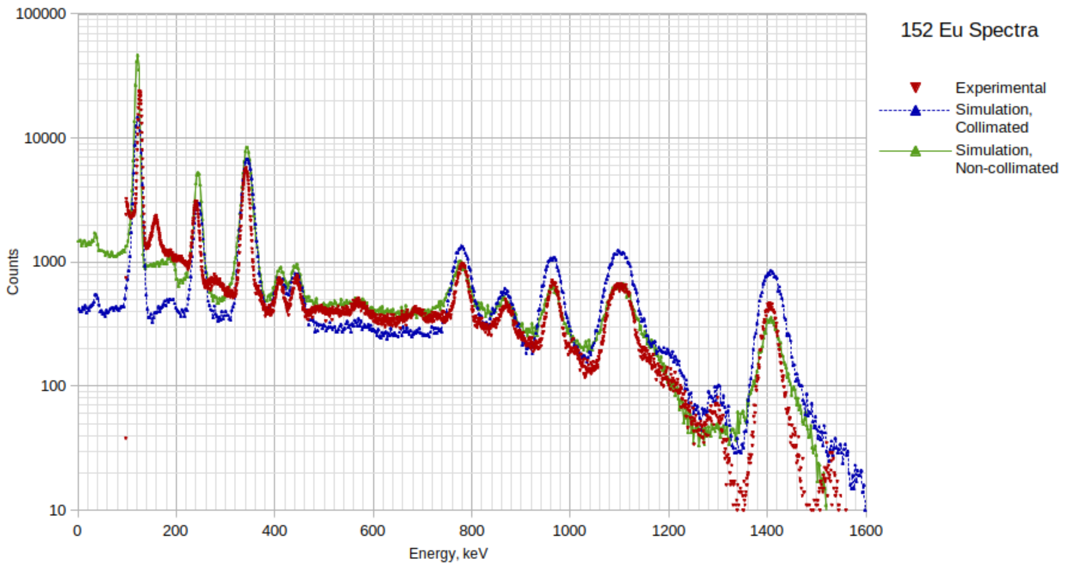

Figure 6: Simulated and experimental data of ^{152}Eu spectra from an in-house readout system for a comparable number of events.

The baseline for the study of determination of position of interaction is the centroid method [5]. It determines the impact point in the plane defined by the SiPM matrix by the weighted average light intensity of the distributed photons produced by the incident particle. This point is calculated by the following equation

$$x_j = s\frac{\sum_{i=1}^{n} iI_i}{\sum_{i=1}^{n} I_i} \quad (1)$$

where x_j is the position of interaction, s is the size of a pixel in the matrix, I_i is the light intensity registered in a pixel and n is the number of pixels on every dimension of the detector.

For the chosen SiPM matrix, the obtained position resolution results for unclassified "pictures" of individual events that include both single and multiple interactions $dx = 1.36mm$ with $\sigma = 1.84mm$ for a set of $100k$ interactions of monochrome gamma rays with energy between $662keV$ and $5MeV$. This is a satisfactory result for the system with channel summation, as it allows position measurements with a limited number of ADC channels, although the information of intensity distribution is lost by the summation.

The largest errors in the position determination with the simple application of the centroid method are appearing unsurprisingly in the frames, where several interactions of the same event happen in different frame locations and have similar deposited energies (Fig. 7, right). The position of interactions where the events are clustered (Fig. 7, middle) or there are single events (Fig. 7, left) is determined with a much better precision.

To reduce the error in position determination due to this error, two approaches were tried with the simulated data for the individual SiPM readout system. The first was to attempt to classify events into multiple and single interactions, and determine position interaction only for the latter class. This approach is easy to implement, however it comes at the cost of losing some detection efficiency and may not be appropriate in all experiments.

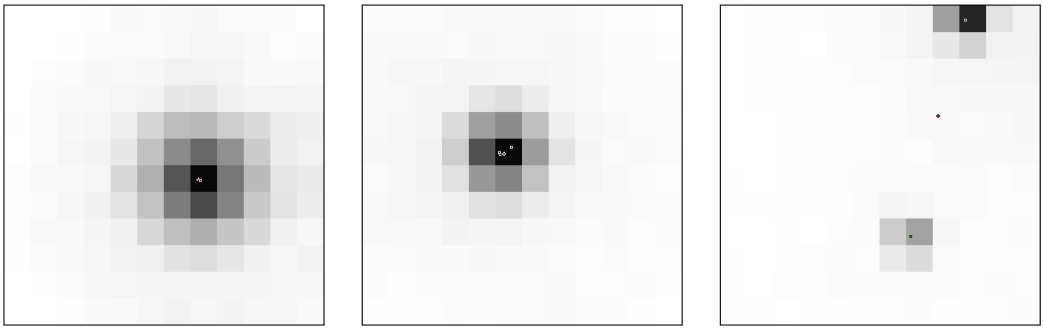

Figure 7: Position estimate simulations for the channel summation/individual readout system without classification. Leftmost: Best case. Middle: median case. Rightmost: Worst case.

To evaluate the increase in position resolution, an image classification algorithm (a convolutional neural network, implemented using Tensorflow [8] and Keras [9] frameworks) was trained to distinguish between one and two or more events using a training set from the simulation of gamma interactions from a centered ^{137}Cs source. Data sets comprising of $\approx 10k$ events were generated for every crystal thickness.

The algorithms were then applied to a generated set of $90k$ events and a position was determined for the frames classified as "single event" frames. The algorithm accuracy for determining a single event was 92%. The observed accuracy of interaction position was ($dx = 0.66mm$, $\sigma = 0.88mm$), resulting in significant increase over the simple application of the centroid method.

The count rates of the two systems are limited by their respective data acquisition subsystems. For the delay line implementation of the in-house digital acquisition system, expected maximum data rates in 12-bit resolution mode are $O(1)$M/s. The commercially available solution is using a CAEN V1751 VME board, which is an 8-channel, 10 bit flash ADC digitizer module with specification data rate of 1 GSps [10]. Data rates in tests did not exceed $O(10)$k/s.

6. Conclusion

A study of several methods to obtain simultaneous measurements of deposited energy and interaction position in monolithic $CeBr_3$ and $LaBr_3$ scintillator crystals using a 12×12 matrix of $3mm^2$ silicon photomultipliers was performed by simulation and experiment. A multistep method for analysis and reconstruction of the data is being implemented. Two data acquisition and analysis systems - from commercially available modules and an in-house design - are being built to validate the simulation results and are currently undergoing calibration and testing. The tested detector system can perform spectroscopy with energy resolution reaching the specification limits of the scintillator crystals. Depending on the chosen sequence of methods, spatial resolution of 0.65mm with $\sigma = 0.88mm$ was achieved after applying the developed event classification and separation algorithms. Further work will focus on improving algorithms for the classification of multiple interactions during a single event and extracting information from the pattern of intensity distribution.

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