γ-Ray hit-location in large monolithic crystals with SiPM readout: analytical versus neural-network algorithms

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***Abstract*— The main objective of this research was to achieve an excellent gamma-ray position reconstruction with very large monolithic scintillation crystals coupled to pixelated silicon photosensors. Analyzing the scintillation-light distribution measured along the SiPM-pixels one can get a sub-pixel accuracy for the position reconstruction. The quality of the latter depends on both the characteristics of the crystal-photosensor assembly, and the goodness of the algorithm used to reconstruct the gamma-ray hit location. We have carried out a systematic study for 511 keV gamma-rays using three different crystal thicknesses of 10 mm, 20 mm and 30 mm, all of them with planar geometry and a base size of 50x50 mm^2. To our knowledge, these are the largest monolithic crystals with SiPM readout aimed at gamma-ray imaging reported in the literature thus far. We have optimized state-of-the-art 3D position-reconstruction methods based on the fit of an analytical model for the propagation of the scintillation light distribution, as well as methods based on artificial neural-networks. In all cases the experimental data-set used was a matrix of 35x35 collimated-source positions measured across the transversal xy-plane on a pitch of 1.5 mm. In terms of spatial resolution, a superior performance is obtained with the analytical-fit methods for the 10 mm and 20 mm thick crystals, with results of 1-2 mm FWHM on average across the full field-of-view of nearly 25 cm^2. On the other hand, NN-algorithms perform better for thick crystals (30mm), with average position resolutions of 3 mm FWHM and significantly better S/N-ratio and FoV than analytical approaches. This research is intended for the development of a total-energy detector with gamma-ray imaging capability, so-called i-TED, which is aimed at the measurement of neutron-capture cross sections using the time-of-flight technique. The results reported here are of interest for medical imaging, homeland security and Compton astronomy.**

***Index Terms*— Gamma-ray detectors, Molecular imaging, Neural networks, Nuclear imaging, Position sensitive particle detectors, Spatial resolution.**

I. Introduction and Objectives

We are developing radiation detectors with γ-ray imaging capability aimed for demonstrating a novel technique for time-of-flight (TOF) neutron-capture cross-section measurements in the framework of the HYMNS project [1]. The proposed detection system is based on the combination of several position-sensitive radiation detectors (PSDs) with sufficiently fast time response (<1 ns) and good energy resolution (5-6% at 662 keV) for enabling both neutron-TOF and γ-ray Compton imaging techniques simultaneously. A set-up of five PSDs is operated in time-coincidence mode and arranged into a Compton imaging system, so called i-TED (Total Energy Detector with γ-ray imaging capability) [2]. For the implementation of the Compton technique in i-TED one needs high precision on the reconstructed position for the measured γ-ray interactions; Spatial resolutions of 1-2 mm FWHM and 3-4 mm FWHM are required for scatter- and absorber-PSDs, respectively [2]. In a previous work [3], we studied in detail the energy response of these PSDs. This work is a continuation of the spatial-reconstruction research, that we reported recently in Ref.[4]. Here, we implement different state-of-the-art position-reconstruction algorithms, we optimize them for our set-up and compare the advantages and drawbacks of each approach. Materials and methods used in this study are reported in Sec. II. Sec. III summarizes the main results and conclusions, together with a short perspective on the next research steps.

II. Materials and Methods

We investigate three different PSDs based on encapsulated $LaCl_3$(Ce) monolithic crystals of planar geometry, a base surface of 50x50mm^2 and thicknesses of 10 mm, 20 mm and 30 mm. Each crystal is optically coupled to a 50x50mm^2 SiPM-array (SensL ArrayJ 60035-65P-PCB), which features 8x8 pixels on a pitch of 6.33 mm. Each pixel has 22292 avalanche photodiodes operated in Geiger-regime. Data from the SiPM are acquired by means of the PETsys TOF SiPM readout system [3]. In order to characterize the spatial response of each PSD a characterization apparatus was set-up, consisting of an xy-positioning table and a collimated ^{22}Na positron source of 416 kBq activity. Two PSDs are arranged in opposite directions along the collimated 511 keV γ-beam line. Both detectors are operated in time-coincidence (20 ns coincidence window). One of them is coupled to the collimated source and fixed in position, whereas the other one is displaced in small steps of 1.5 mm, covering a full matrix of 35x35 positions.

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Two radically different position-reconstruction algorithms are investigated. On one hand, a method is implemented, which is based on a least-squares fit of an analytical model for the scintillation light propagation. Hereby two different models have been investigated, the model by Lerche et al.[6], and the somewhat more elaborated parameterization by Li et al.[7] which includes also light-reflection effects in the walls of the crystal.

On the other hand, we have implemented machine-learning artificial neural-network techniques, which are based on a passive input-layer of 64 neurons, an active layer of 64 neurons and a single output layer of one neuron. The latter represents one of the transversal coordinates *x* or *y*.

III. RESULTS AND OUTLOOK

The analysis reported here has been improved with respect to the results reported in Ref.[4] in several aspects. On one hand, a more realistic treatment of the residual scintillation-light background has been made regarding the analytical models. On the other hand, a more sophisticated method has been developed and included for correcting pixel-gain inhomogeneity corrections. Fig.1 shows an illustrative example of the Li-analytical approach.

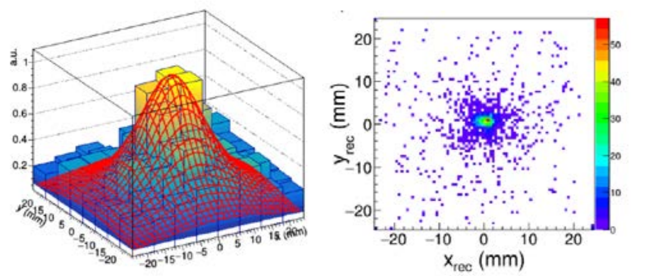

Fig.1 Example of a random individual γ-ray hit-event analyzed with the scintillation model of Li (Left). Cumulative plot of the positions for the center of the 20 mm thick crystal (Right).

The results obtained for each method (Lerche-, Li-analytical or NN) are summarized in Fig.2 for all three crystal thicknesses investigated. In summary, one can conclude that analytical-fit methods have a superior performance in terms of spatial resolution, with results close to 1 mm FWHM. However, the position reconstruction efficiency (not shown in Fig.1) becomes too small with increasing crystal thickness. For the thick crystal (30 mm thickness) better overall performance is obtained with the NN-algorithm, which yields average spatial resolutions of 3 mm FWHM and a linear field-of-view of 18 cm^2.

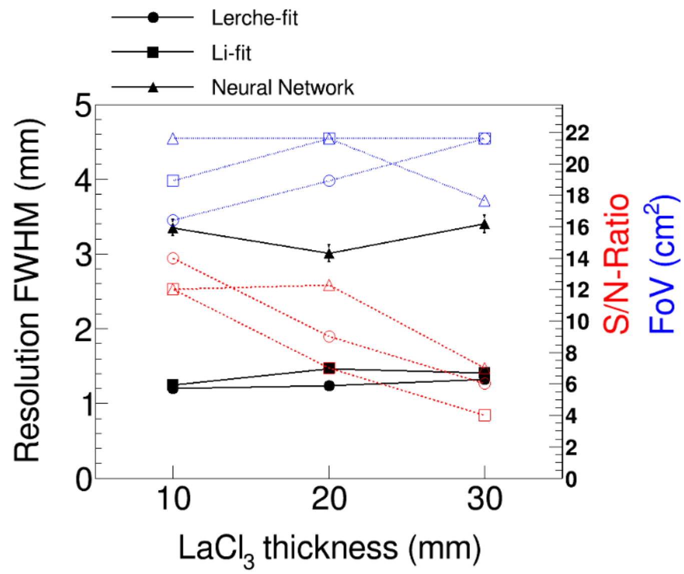

Fig.2: Summary of the results obtained as a function of the crystal thicknesses (horizontal axis). Spatial resolutions (left vertical axis) are shown by solid bold-symbols. Signal-to-noise and field-of-view (empty symbols) are indicated by dashed-red and dotted-blue colors, respectively (right-hand side axis). See figure legend.

The results obtained here are within the specifications required for the i-TED concept [2], of 1-2 mm and 3-4 mm FWHM resolution for the scatter (10 mm thick) and absorber (30 mm thick) crystals. Further improvements can be envisaged for the thick crystals in view of these first results reported here using NNs. In this respect, we have acquired a higher activity (5 MBq) ^{22}Na-source and a more convenient *xy*-scanning table. This will allow us to investigate the impact of a higher matrix-granularity for training and testing the neural network, and the possibility to use more complex NN-schemes, particularly regarding the active intermediate layer(s).

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