Study of Position Sensitivity of Large $LaBr_3$:Ce Scintillators Readout by SiPMs

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[1] ***Abstract*– Cerium-doped Lanthanum Bromide ($LaBr_3$:Ce) is a very attractive material for scintillation detectors for spectroscopy measurements in nuclear physics thanks to its excellent energy resolution (3% at 662 keV). In some experiments, in order to correct for the Doppler broadening effect, some degree of position sensitivity is required in addition to excellent spectroscopy capability. However, the typical geometry of such crystals, designed to enhance their efficiency (crystal thickness equal of comparable to diameter), and the use of diffuse reflectors on all surfaces but the exit window (to enhance energy resolution), make attaining position sensitivity quite challenging. In this work, we use Monte Carlo simulation to study a reference 3” × 3” $LaBr_3$:Ce scintillator read out by an array of SiPMs to evaluate position sensitivity over the full volume of the crystal. The reconstruction of the 3D interaction coordinates of the gamma-ray in the scintillator is performed by means of maximum likelihood method provided by the recently developed ANTS2 toolkit. The simulation study demonstrated feasibility of reconstructing position of a single gamma ray scatter anywhere in the crystal. The expected spatial resolution is no worse than 10 mm FWHM in the SiPM plane and 15 mm FWHM for the depth of interaction for 662 keV gamma rays.**

I. Introduction

THE energy resolution offered by large Cerium-doped Lanthanum Bromide (LaBr3:Ce) scintillators (3% at 662 keV) makes them very attractive for spectroscopy measurements in nuclear physics experiments. In some of these experiments, for example in those studying radioisotopes at relativistic velocities, scintillation detectors with 3D position sensitivity are highly desirable in order to reduce the energy uncertainty due to Doppler effect [1]. Position sensitivity in large $LaBr_3$:Ce crystals, obtained by means of processing the light distribution pattern on its output window measured with a segmented photodetector, has been already subject of previous studies [2]. However, the adopted reconstruction algorithms did not allow yet to reach the identification of the interaction positions in the full volume of the crystal and 3D event reconstruction.

A typical commercially available $LaBr_3$:Ce scintillator crystal, being optimized for energy resolution and high-energy (up to 15 MeV and beyond) gamma-ray detection efficiency, is usually an encapsulated cylinder with the height equal to its diameter and with all surfaces except the output window covered by a diffuse reflective material (Fig. 1a). In this configuration, due to the large fraction of diffusely reflected photons, the light collection pattern becomes less dependent on the event position. This is beneficial for the energy resolution, but makes the position reconstruction a more challenging task, especially for the events that are farther away from the photodetector array. In a search for the most adequate solution, we decided to use the Maximum Likelihood (ML) position reconstruction as it most efficiently uses all the available information and already have been proven as a powerful tool for 3D reconstruction in scintillator crystals [3].

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II. Rationale

Standard commercial $LaBr_3$:Ce crystals are embedded in highly reflective white paint, except for one base covered by transparent output window, as shown in Fig. 1a. A scintillation photon entering the paint layer (magenta track) undergoes diffuse scattering and loses information on its original direction. This photon is of little use for position reconstruction. However, in a polished crystal, part of the scintillation light is reflected specularly by total internal or Fresnel reflection (red track) from the crystal-paint interface, creating spatial patterns (caustics) on the output window. The fraction of specularly reflected light increases with the ratio between the refractive indices of the crystal material and the paint base. The shape of these light patterns depends on the

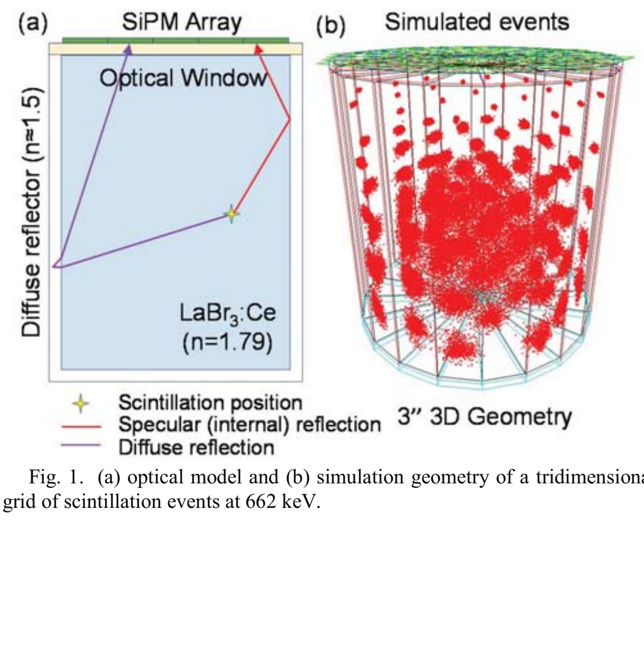

Fig. 1. (a) optical model and (b) simulation geometry of a tridimensional grid of scintillation events at 662 keV.

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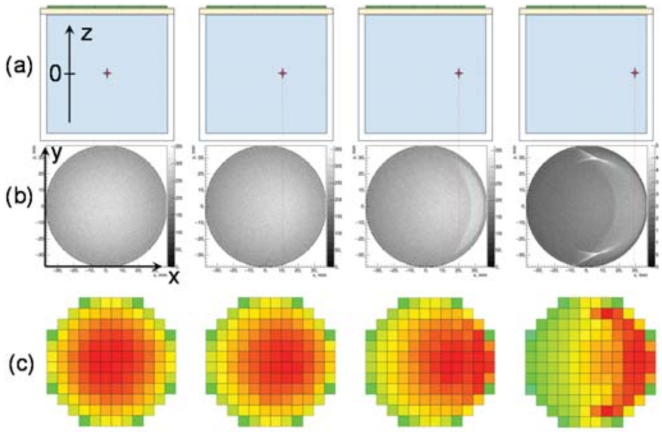

Fig. 2. (a) Scintillation position along the x axis in the middle of the crystal (z = 0), (b) scintillation light distribution across the output window and (c) average signal detected by the elements of a SiPM array composed by 4 tiles of 6 × 6 photodetectors (not fully covered at the corners).

source position as demonstrated by images in Fig. 2, so it can be used to train the position reconstruction algorithm. The training consists in fitting spatial dependence of each SiPM light response with 3D spline functions. Following the training phase, the position of a scintillation event can be reconstructed from the observed SiPM signal by the method of maximum likelihood (ML). Note that while other training and reconstruction methods (for example, neural networks or nearest neighbor) can be employed as well, possibly with similar result techniques, only ML method was tested in this study.

III. Simulation Approach

In this proof-of-the-concept work, we used Monte Carlo simulation in order to evaluate the position sensitivity in the full volume of a reference scintillator detector consisting of a $LaBr_3$:Ce scintillator read out by an array of silicon photomultipliers (SiPM). SiPM readout is a promising alternative with respect to the more conventional PMT readout, as demonstrated recently in measurements also with $LaBr_3$:Ce [4,5].

The model used in the simulations consisted of a cylindrical 3" × 3" $LaBr_3$:Ce crystal (n = 1.79) enveloped (with the exception of the output window) in a thin (0.5 mm) layer of a transparent material with n = 1.5. The outer surface of this transparent envelope, was made diffusely reflective (Lambert scattering, 99% reflectivity) to emulate the effect of the reflective paint. The transparent output window, with thickness of 2mm and n = 1.5, was optically coupled to the square 12 × 12 array of 6 × 6 mm^2 SiPMs. The SiPMs not in contact with the output window (triangular groups of 6 elements in the corners of the array) were excluded from the analysis, making the total number of active SiPMs equal to 120. The SiPM were modeled after FBK NUV-HD series [5] with photon detection efficiency of 38%.

To simplify the analysis, in this study we simulated each scintillation event as an isotropic emission of 42000 optical photons, which corresponds to the average number of scintillation photons produced in $LaBr_3$:Ce by a photocapture of a 662 keV gamma ray. Each photon was traced according to the laws of geometrical optics, taking into account the detector geometry and optical properties of the materials, until its detection by one of the SiPMs or its absorption. The simulation included SiPM saturation effect due to finite

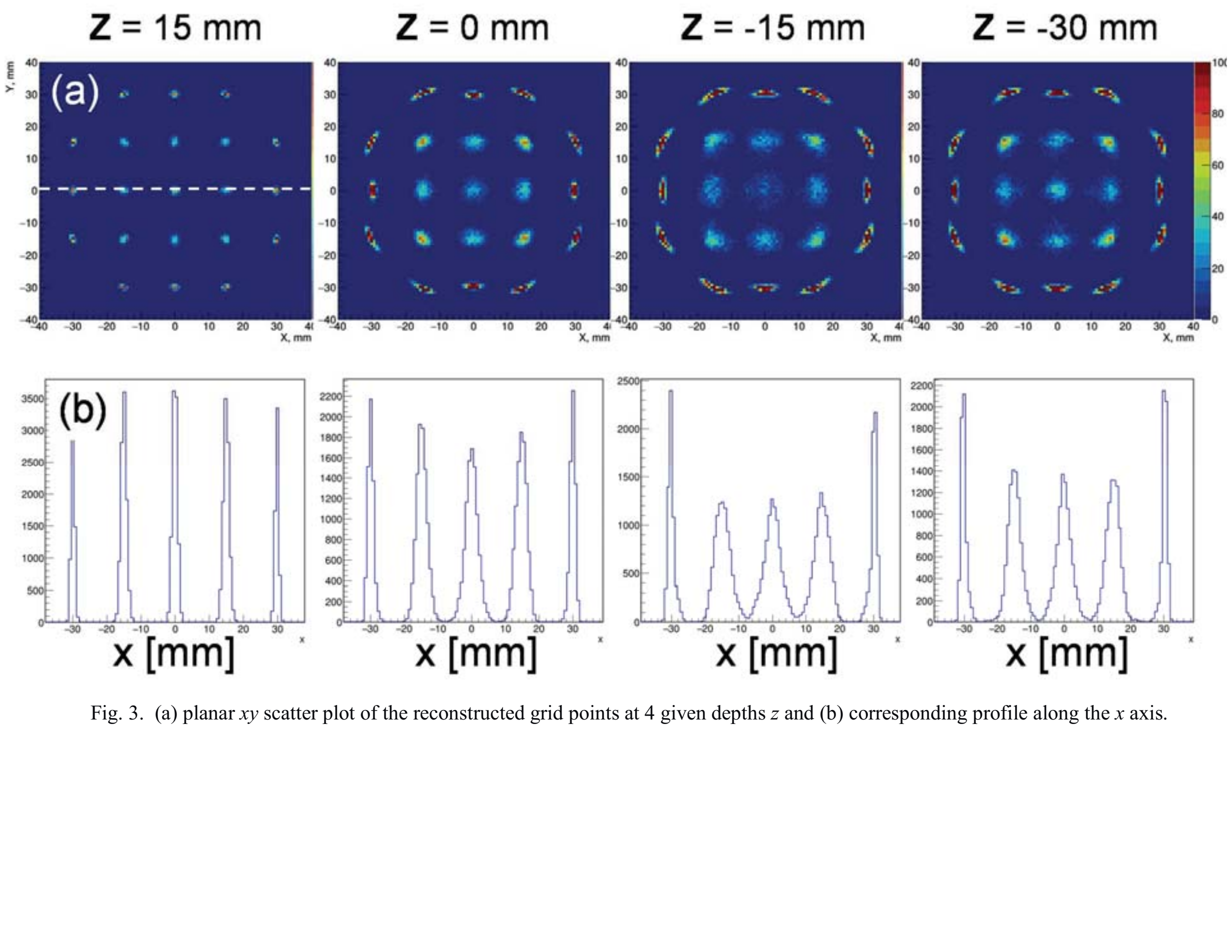

Fig. 3. (a) planar *xy* scatter plot of the reconstructed grid points at 4 given depths *z* and (b) corresponding profile along the *x* axis.

number of microcells.

Simulations were performed in three steps. First, 200000 events were simulated with positions uniformly distributed in the crystal volume. This data was used to determine the spatial dependence of the light response for each SiPM, which was parameterized as a weighted sum of 3D spline functions. Second, the second batch of events was simulated with positions arranged on a rectangular three-dimensional grid aligned with the crystal axis and the SiPM array. The grid pitch was 7.5 mm along the crystal axis (z) and 15 mm along the x- and y-axes, making 21 nodes per slice in z direction and 210 nodes in total. For each grid node, 1000 events were simulated. In the final step, positions of these events were reconstructed by ML method using SiPM light response parameterized in the first step (Fig. 1b), and were compared to the true ones in order to evaluate the correctness of reconstructed position and spatial resolution across the whole crystal volume.

All simulation, reconstruction and analysis work was performed using ANTS2: a simulation and experimental data processing toolkit for position sensitive scintillation detectors [6].

IV. Simulation Results

The typical examples of the reconstructed grid slices are shown in the top row of Fig.3. Here the z axis coincides with the crystal axis and the origin is placed in the middle of the crystal, so that SiPM array lays at $z = 38$ mm and the opposite crystal base – at $z = -38$ mm. For the whole upper half of the crystal ($z > 0$), simulations predict spatial resolution better than 5 mm FWHM for 662 keV events. With increasing depth of the interaction, the resolution degrades, reaching the worst values for z between –20 and –15 mm. Then, somewhat unexpectedly, it improves again for $z = -30$ mm.

As one can see in Fig. 3, the worst spatial resolution is observed near the axis of the crystal, thus the resolution obtained for the axially paced events gives the upper limit for the whole crystal. The plot in Fig. 4 shows simulated spatial resolution along the x (or y) and z directions for such events. This "worst case" resolution is within 10 mm FWHM in the SiPM plane and below 15 mm along the axis for the whole crystal. It was also found that the reconstruction bias (deviation of the average reconstructed position from the true one) is within statistical error for the whole crystal volume, as demonstrated by x-projections shown in the bottom row plots of Fig. 3.

V. Conclusions

The reported simulation study demonstrates the feasibility of reconstruction of all three coordinates of a single scatter scintillation event in an encapsulated cylindrical $LaBr_3$:Ce crystal, read out by a single flat array of SiPM photosensors. For the events equivalent to point-like full energy deposition of 662 keV, the expected spatial resolution is no worse than 10 mm FWHM in the SiPM plane and 15 mm FWHM for the depth of interaction. Such promising results show the potential of this reconstruction technique for both nuclear physics experiments and medical imaging.

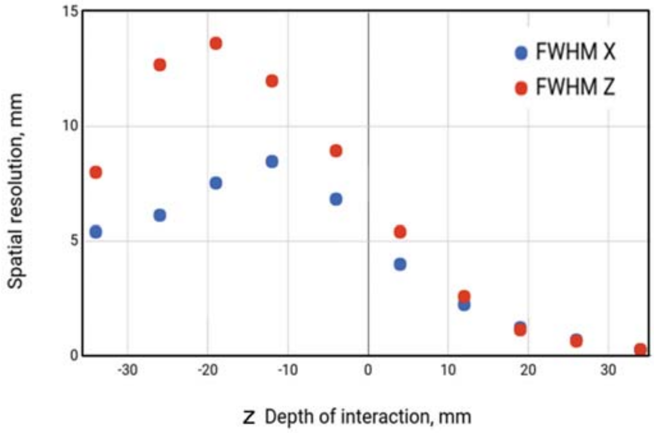

Fig. 4. Simulated spatial resolution (FWHM) along the *x(y)* and *z* directions for the events on the crystal axis.

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