Research Article

Determination of Position Resolution for LYSO Scintillation Crystals Using Geant4 Monte Carlo Code

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LYSO scintillation crystals, due to their significant characteristics such as high light yield, fast decay time, small Molière radius, and good radiation hardness, are proposed to be used for the electromagnetic calorimeter section of the Turkish Accelerator Center Particle Factory (TAC-PF) detector. In this work, the center of gravity technique was used to determine the impact coordinates of an electron initiating an electromagnetic shower in a LYSO array, in a calorimeter module containing nine crystals, each 25 mm × 25 mm in cross-section and 200 mm in length. The response of the calorimeter module has been studied with electrons having energies in the range 0.1 GeV-2 GeV. By using the Monte Carlo simulation based on Geant4, the two-dimensional position resolution of the module is obtained as

$$\sigma_R (\text{mm}) = \left(\frac{(3.95 \pm 0.08)}{\sqrt{E}}\right) \oplus (1.91 \pm 0.11)$$

at the center of the crystal.

1. Introduction

Cerium-doped silicate-based heavy scintillation crystals were initially developed for medical applications. Later, the scintillation characteristics of lutetium oxyorthosilicate (LSO) [1] and lutetium-yttrium oxyorthosilicate (LYSO) [2, 3] were found. LYSO crystals have high stopping power (>7 g/cm³), fast decay time (40 ns) and high light yield (200 times of PWO), and superior radiation hardness against gamma rays, neutrons, and protons [4–6]. Furthermore, the crystal emits light in the wavelength region between 360 nm and 600 nm, reaching a peak at 402 nm. Due to all of the above-mentioned properties, this crystal has also attracted the attention of experimental high energy physics research groups working to improve the performance of electromagnetic calorimeters, such as the proposed SuperB forward parts of the endcap calorimeter [7], the KLOE experiment [8], the COMET experiment at J-PARC [9], and the Muon-to-Electron (Mu2e) experiment [10]. In addition to lead tungstate (PWO) and Thallium-activated Cesium Iodide (CsI(Tl)) crystals, LYSO scintillation crystals may also be studied for the electromagnetic calorimeter (ECAL) section of the proposed Turkish Accelerator Center-Particle Factory (TAC-PF) detector [11]. This paper reports the results of a simulation study carried out with Geant4 to evaluate the position resolution of LYSO scintillation crystals for incident electrons at an energy range from 0.1 GeV to 2 GeV.

2. Position Resolution of Electromagnetic Calorimeters

When a particle is sent to the electromagnetic calorimeter, its energy is deposited in the central crystal as well as the crystals around it. The impact position of the particle can be found from the weighted mean of the position of energy deposits in the crystals. The technique used to find the position of the incident particle is called the center of gravity method and calculated by

$$x_{\text{gravity}} = \frac{\sum_i x_i E_i}{\sum_i E_i}, \quad (1)$$

for the x-coordinate and similarly,
\[ y_{\text{gravity}} = \frac{\sum y_i E_i}{\sum E_i}, \]  

for the \( y \)-coordinate, where \( E_i \) is the energy deposited in the \( i \)-th crystal and \( x_i \) and \( y_i \) are the coordinates of the \( i \)-th crystal [12]. For the ideal position resolution, it is preferable to take the sum over nine crystals due to the effect of large energy fluctuations in the tails of an electromagnetic cascade [13].

3. Geant4 Simulation and Results

Geant4 simulation code [14] was employed to perform the simulation process for the electrons passing the electromagnetic calorimeter module consisting of \( 3 \times 3 \) LYSO scintillator crystals. The electrons were directed perpendicular to the module in the energy range of 0.1 GeV to 2 GeV. The simulation was performed with Geant4.10.04-patch-03 with the QGSP-BERT4.5 physics list. The LYSO crystals have a length of 200 mm \((17.5X_0)\) with a cross-section of \( 25 \times 25 \text{mm}^2 \)\((1.2R_M)\). In the simulation, in order to obtain the distributions of the center of gravity of the deposited energies in the crystals, electrons were injected into the central crystal at fourteen different positions (-1.25 mm, -11 mm, -9 mm, -7 mm, -5 mm, -3 mm, -1 mm, 0, 2 mm, 4 mm, 6 mm, 8 mm, 10 mm, and 12.5 mm), respectively, to scan the entire surface of the crystal. The coordinates of the center of the central crystal were defined to be \( x = 0, y = 0 \). The relation between \( x_{\text{gravity}} \) and \( y_{\text{gravity}} \) in the center of the LYSO matrix for 1 GeV electrons can be seen from Figure 1.

The calculated positions \( (x_{\text{gravity}}, y_{\text{gravity}}) \) versus the true positions \( (x_{\text{true}}, y_{\text{true}}) \) are shown in Figure 2 for 1 GeV electrons (S-curve). If the impact point is at the center of the crystal or near the boundary between different crystals, the particle’s position can be reconstructed correctly, as can be seen from Figure 2. In other cases, since most of the energy in the shower is deposited in the hit crystal and there is an exponential fall in the energy shared among neighboring crystals, the position of the particle is systematically miscalculated from equation (1).

To remove this nonlinear dependence among the true positions \( x_{\text{true}} \) and the calculated positions \( x_{\text{gravity}} \), the S-curve fit function was utilized. This function is an empirical algorithm and given by

\[ x_{\text{gravity}} = c \tan d(x_{\text{true}} - e). \]  

Here, \( x_{\text{gravity}} \) and \( x_{\text{true}} \) are presented in mm. As a result of this fit, the values of \( c \), \( d \), and \( e \) at 1 GeV are found to be 2.669, 0.108, and 0.001, respectively. Table 1 shows the obtained fit results for the incident electron energies between 0.1 and 2 GeV in the X direction. As the Molière radius is loosely dependent on energy, the parameters differ slightly depending on the energy of the incident electron. By employing the values \( c \), \( d \), and \( e \) which are obtained from the fit, the corrected X position \( x_{\text{corrected}} \) is calculated by

\[ x_{\text{corrected}} = \frac{1}{d} \tan^{-1} \frac{x_{\text{gravity}}}{c} + e. \]  

Similar calculations have been also made for the Y direction to obtain the corrected Y position \( y_{\text{corrected}} \). As the corrected position distribution spectra have roughly a Gaussian shape (see Figure 3), they have been fitted using a Gaussian function to obtain the position resolution. The sigmas of these distributions shown in Figure 3 give the calorimeter position resolutions in the X and Y directions for 1 GeV electron energy. Figure 4 shows the corrected position \( x_{\text{corrected}} \) versus the true position \( x_{\text{true}} \) for 1 GeV electrons in the X direction. Figure 5 displays the position resolutions at the center of the central LYSO crystal (at coordinate \( x = y = 0 \)) for the incident electron energies from 0.1 GeV to 2 GeV. The Geant4 simulations indicate that the position resolution improves as the energy of the incident electron.
increases as shown in Figure 5. At the center of the central crystal, the position resolutions depending on the energy of the incident electrons can be parameterized as

$$\sigma_x (\text{mm}) = \frac{(2.77 \pm 0.07)}{\sqrt{E}} \oplus (1.46 \pm 0.10)$$ (5)

for the X direction and

Table 1: Fit parameters for the incident electrons in the X direction.

| Electron energy (GeV) | $c$ (mm) | $d$ (rad/mm) | $e$ (mm) |
|-----------------------|----------|--------------|----------|
| 0.1                   | 2.166    | 0.112        | -0.007   |
| 0.25                  | 2.327    | 0.110        | 0.017    |
| 0.5                   | 2.739    | 0.107        | -0.003   |
| 0.75                  | 2.702    | 0.108        | -0.004   |
| 1                     | 2.669    | 0.108        | 0.001    |
| 1.25                  | 2.637    | 0.108        | -0.023   |
| 1.5                   | 2.651    | 0.108        | -0.003   |
| 1.75                  | 2.654    | 0.108        | 0.003    |
| 2                     | 2.613    | 0.108        | -0.01    |

Figure 3: $x_{\text{corrected}}$ and $y_{\text{corrected}}$ positions after the S-curve correction, for electron energy of 1 GeV.

Figure 4: Dependence of the corrected position ($x_{\text{corrected}}$) in the LYSO crystals on the true coordinate ($x_{\text{true}}$).

Figure 5: Position resolutions in the X and Y directions at the center of the $3 \times 3$ LYSO matrix as a function of the energy. The solid lines represent the fits to the data. The error bars are negligible compared to the symbols shown.
for the \( Y \) direction.

The spatial resolution is not constant on the entire surface of the scintillation crystal and changes depending on the impact position of the incident electron. As can be seen in Figure 6, the simulated position resolution improves towards the edges of the crystal scintillator, and the minimum spatial resolutions are acquired on the edges. This is because the electromagnetic cascade sharing among neighboring crystals starts to become important in that position of the crystal.

One can get the two-dimensional position resolution \( \sigma_R \) by using \( \sigma_x \) and \( \sigma_y \) values:

\[
\sigma_R (\text{mm}) = \sqrt{\sigma_x^2 + \sigma_y^2}.
\] (7)

Figure 7 shows the two-dimensional position resolution as a function of energy at the center of the \( 3 \times 3 \) LYSO matrix.

In addition, in order to check the accuracy of the simulation code, a prototype electromagnetic calorimeter developed for the COMET experiment given in Ref. [9] was simulated with the Geant4 code. The mentioned prototype consists of \( 7 \times 7 \) LYSO crystals with a dimension of \( 2 \times 2 \times 12 \text{ cm}^3 \). The position resolution of the prototype was calculated for the incident electrons using the center of gravity technique mentioned above. The simulation results are well-matched with the experimental data with a slight difference at low energies as can be shown in Figure 8.

4. Conclusion

The simulation of the position resolution of the electromagnetic calorimeter module made of LYSO crystals for the
The two-dimensional position resolution was calculated as
\[ \sigma_X(\text{mm}) = (2.77 \pm 0.07)/\sqrt{E} \oplus (1.46 \pm 0.10) \]
for the \( X \) direction, and a similar result was also obtained for the \( Y \) direction. The position resolution was calculated as
\[ \sigma_X(\text{mm}) = (3.95 \pm 0.08)/\sqrt{E} \oplus (1.91 \pm 0.11) \]
also, by using Function (4) with the fit parameters shown in Table 1 with a minor modification, the impact position of an electron or photon in similar LYSO calorimeters can be deduced from the center of gravity of energy deposits in the crystals.

**Data Availability**

All figures in the paper represent the results obtained by Monte Carlo simulation, and the data used to support the findings of this study are cited at relevant places within the text as references.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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