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The Impact of Crystal Length on Calorimeter Energy Resolution

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Abstract. Lutetium-yttrium oxyorthosilicate (LYSO) crystal scintillators were originally developed for medical applications. Owing to their high density, small Molière radius, fast response, and high radiation hardness, LYSO crystals have also suitable for future homogeneous electromagnetic calorimeters. Due to these features, LYSO is considered to be used for the electromagnetic calorimeter part of the Turkish Accelerator Center Particle Factory (TAC-PF) detector. In this research, by employing the GEANT4 toolkit program, we simulated a set of crystal, and their energy resolutions were obtained for different lengths at the energy range of 50 MeV - 2 GeV. Depending on the crystal length, contributions to the constant term of the energy resolution were investigated.

INTRODUCTION

Electromagnetic calorimeters, widely used in experimental installations for research in areas of high energy physics, provide not only measurement of energy and particle coordinates, but also particle class identication that is difficult to do with using other traditional methods. When the particle enters the crystal, it initiates a shower of secondary particles, transferring its energy to them. The shower is absorbed in the calorimeter volume, and its energy is measured. High beam energies and luminosity of modern accelerator complexes impose increased requirements on the radiation resistance of materials used in the detectors. In the last decade, mass production capabilities for many crystals were introduced for the medical purposes. Because of high density (7.10 g/cm^3), short decay time (41 ns), high light output (32000 ph/MeV), radiation hardness and stable chemical and physical properties, LYSO crystals are considered ideal for applications that require comparatively better energy resolution, including PET scanner [1]. Therefore, a contemporary era focuses on paying attention to use this crystal in high energy physics experiments such as those SuperB factory [2], Mu2e [3] and the COMET experiment [4]. Turkish Accelerator Center (TAC) project was proposed by group of scientists from Ankara and Gazi University in 2000 as an accelerator based on regional project for fundamental and applied physics research in Turkey due to the lack of accelerator based scientific research in this region. Turkish Accelerator Center Particle Factory (TAC-PF) detector will be used to detect particles from the collision with 4 sub-detectors which are silicon tracker, time of ight, electromagnetic calorimeter and muon calorimeter from inner to outer [5, 6], also LYSO crystal have been proposed for using in electromagnetic calorimeters part of the TAC-PF detector, in addition to PWO and CsI(Tl) crystals [5].

ENERGY RESOLUTION OF ELECTROMAGNETIC CALORIMETERS

Since calorimeters are based on physical processes of statistical nature; the accuracy of calorimetric measurements is determined by fluctuations. In electromagnetic calorimeters, the energy resolution is affected by several factors such as statistical fluctuations in the number of particles in a shower, fluctuations in shower leakage from the calorimeter volume, noise of electronics structural inhomogeneities and sampling fluctuations. The energy resolution of an ideal homogeneous electromagnetic calorimeter of infinite size is determined only by statistical fluctuations in the number of particles and is proportional to $E^{1/2}$. In practice, the energy resolution of a particular calorimeter depends on fluctuations of various types with different energy dependencies. Typically, these effects are uncorrelated, and therefore,

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they should be added in quadrature. In the total resolution of the calorimeter at different energies, various effects may dominate. The energy resolution is expressed by contribution of three terms as shown below:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{\sqrt{E}} \tag{1}$$

Here the symbol “$\oplus$” represents a quadratic sum, “E” the energy of the incident particle. “a” is a stochastic term which includes photoelectron statistics, shower fluctuations and transverse leakages from the crystal. “b” is a constant term which includes the shower losses and this term is one of the terms which does not depend on the energy of the incident particle. The last term “c” represents noise term which includes a contribution from readout electronics cabling and pile-up effects as well.

GEANT4 SIMULATION AND RESULTS

GEANT4 software package [6], developed at CERN, which allows one to simulate the passage of particles through matter. At the beginning of the simulation process, particles and their parameters can be set: energy, direction of beam, and initial position. The materials and the shape of the detector elements from which it is made are also set. For each particle, both initial and produced during the simulation, the probabilities of various physical processes are calculated (for example, the passage without interaction with the substance, ionization of the atoms or bremsstrahlung for charged particles, the probability of the photoelectric effect or pair production for the photons, and so on). Then, a process is randomly selected in accordance with the calculated probabilities. Next, the energy release in the detector is calculated, and new particle parameters are calculated. Also there is a simulation of the birth of new particles in accordance with the process. The "life" of a particle ends when the end of the volume is reached, or if the energy release decreases below a threshold value [7].

A simulation of the EM shower has been made for a 5x5 LYSO crystal calorimeter. In this simulation, the photons at different energies (50 MeV – 2.0 GeV) were assumed to be injected in the center of the central crystal of the matrices. Simulation has been conducted with "$GEANT4.10.04.p01$" version using "$emstandard\_opt1$" physics list. Energy depositions and their fluctuations in the crystals have been obtained for 1x1, 3x3 and 5x5 crystals matrices for different crystal length (195 mm, 200 mm, 205 mm, 210 mm) with cross section 25x25 mm^2. Fig. 1 shows the energy responses to 2 GeV photons observed in the central module and the crystal matrices.

By summing up all the energies deposited in each individual crystal, the energy spectra were obtained for the incident photons at different energies. Novosibirsk function was used to obtain energy resolution because energy deposition spectra have a Gaussian form with an asymmetric tail towards lower energies [8]. For example, Fig. 2 shows the energy spectra and fit results for 1 GeV photons which were sent to the center of 5x5 crystal matrix. It has been seen here as well that the energy deposition increases with increasing the length of the crystal.

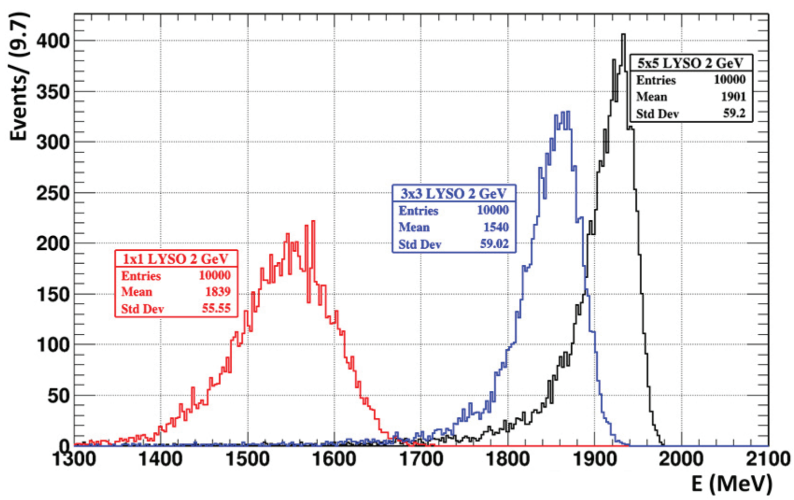
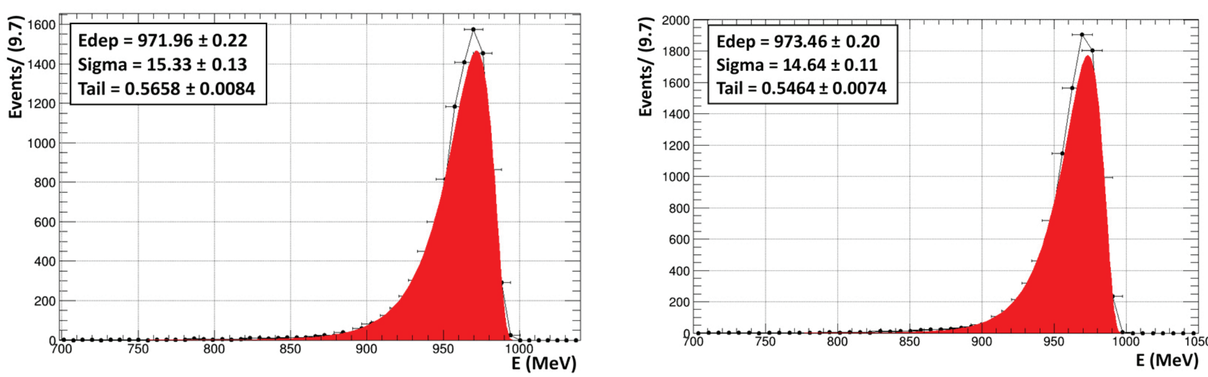


FIGURE 1. Energy deposition spectra in 1x1, 3x3 and 5x5 for 200 *mm* crystal length.



(a) (b)

FIGURE 2. Energy spectra of the 5x5 LYSO crystal matrix for 1 GeV photons for (a) 200 *mm* and (b) 205 *mm* crystal length, filled areas represent the results of the fits.

Energy resolution (σ_E/E) results were fitted using $\sigma_E/E = a/\sqrt{E} \oplus b$. Fig. 3 shows the simulated energy resolutions as a function of incident photon energies for LYSO crystal matrices (3x3 and 5x5) of different crystal lengths. Solid lines are the results of fits. The results are consistent with the simulation studies in ref. [5, 9] for 200 *mm* crystal length. Any expansion in the lateral and longitudinal dimensions of the calorimeter module leads to decrease fluctuations in energy deposition and consequently an improvement in energy resolution.

Table I shows all fit results we calculated for 3x3 and 5x5 matrices for different lengths. Simulated energy resolution includes the shower fluctuations as well as the shower losses (transverse and longitudinal).

Contribution to the stochastic term of the energy resolution comes from shower leakages in the transverse directions outside the crystal matrix and shower fluctuations in the crystals, while the contribution to constant term coming from shower leakages from back and sides of the crystals.

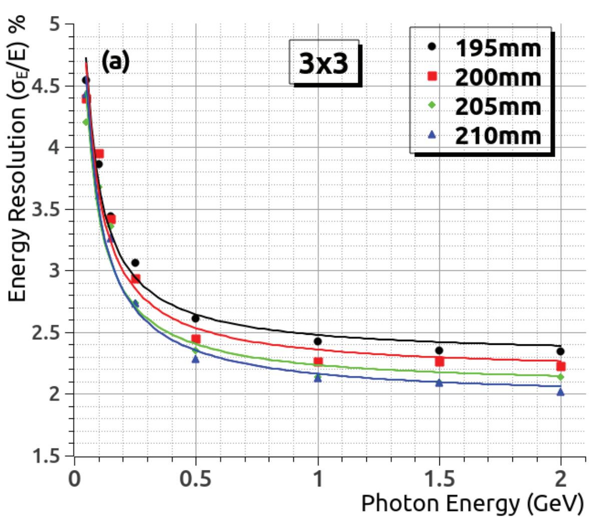


FIGURE 3. Energy resolutions as a function of incident photon energies for different LYSO crystal lengths, (a) 3x3 and (b) 5x5 crystal matrices.

TABLE I. Calculation results of the stochastic "*a*" and constant term "*b*" of the energy resolution for 3x3 and 5x5 matrices for different lengths.

	Stochastic Term a(%)		Constant Term b(%)	
Crystal length(*mm*)	3x3	5x5	3x3	5x5
195	0.94	0.38	2.37	1.73
200	0.95	0.38	2.17	1.60
205	0.95	0.39	2.05	1.54
210	0.95	0.38	1.92	1.45

CONCLUSION

In this work, GEANT4 Monte Carlo simulation study was conducted to investigate the effect of the crystal length on the energy resolution. The results of the simulation study were partitioned according to the crystal lengths as well as crystal matrices (3x3 and 5x5). Increasing lateral dimension of the module signicantly lowers shower fluctuations and the transverse leakage from the crystal. As shown in Table I, with increasing matrix dimensions, the stochastic and constant term of the energy resolution improves. With increasing the crystal length, the stochastic term remains more or less constant while constant term decreases with increasing matrix dimensions. Furthermore, this study can help researchers in detector designing to estimate optimum crystal length in order to gain a good energy resolution.

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