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Research of long GSO and LYSO crystals used in the calorimeter developed for the COMET experiment

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Experimental tests have been performed in order to study loss of the light output in length and to improve light collection of photons for long GSO and LYSO crystals. Research of shower development in crystals with non-optimal geometry and losses of light energy in light-reflecting wrapping were performed with the use of SLitrani and Geant4 codes. Obtained results allowed developing the structure of a calorimeter producing the required energy and energy-correlated resolutions in the COMET experiment.
Keywords: Segmented electromagnetic calorimeter, Research of long GSO and LYSO crystals parameters, Geant4 and SLitrani simulation

Проведены экспериментальные исследования с целью изучения потерь световыхода по длине и улучшения светосбора фотонов для длинных кристаллов GSO и LYSO . Изучение развития ливня в кристаллах с неоптимальной геометрией и потерь световой энергии в светоотражающих обертках выполнено с использованием программ SLitrani и Geant4. На основе полученных результатов предложена структура калориметра, позволяющая получить требуемые энергетическое и координатное разрешения в эксперименте COMET.

Дослідження довгих кристалів GSO і LYSO для калориметра експерименту COMET. *В.Калинників, Е.Велічева.*

Виконано експериментальні дослідження з метою вивчення втрат світловиходу за довжиною і поліпшення світлозбору фотонів для довгих кристалів GSO і LYSO. Вивчення розвитку зливи у кристалах з неоптимальною геометрією і втрат світлової енергії в світловідображуючих обгортках виконано з використанням програм Slitrani і Geant4. На основі отриманих результатів запропоновано структуру калориметра, що дозволяє отримати необхідні енергетичний і координатний розподіли в експерименті COMET.

1. Introduction

In the study of elementary particles in physics of high and ultrahigh energies need not just to know which particles are generated, but with great accuracy and to measure their characteristics, such as the trajectory, momentum and energy. All this is done with the help of detectors. Track detectors measure the trajectory and momentum of particles, without any distortion. Calorimeters, which completely absorb particles, are used to measure its energy (the total absorption spectrometer).

In experiments, the electromagnetic calorimeters are used to measure the total energy and particle identification (including neutral). Advantages of calorimeters are as follows: 1) measure the energy of particles in the range from a few MeV up to the maximum attainable; 2) the relative energy resolution of the calorimeter increases with energy as $\sqrt{E}$, where E is the energy of the particles; 3) the detection of both charged and neutral particles in the segmented calorimeter allows to obtain information about the coordinates of particles and electromagnetic shower; 4) help to identify particles, for example, to separate photons, electrons, protons, and other; 5) allow you to create a trigger systems of preselection events (first level trigger).

High-energy electrons and photons passing through matter scintillator generate an electromagnetic shower of electrons, positrons and photons. The number of particles in the shower will grow rapidly, until the average energy of particles not decrease to critical. The required length of the calorimeter depends on the type and maximum energy of a primary particle and is determined by the radiation long (X_0) of the scintillator. For example, the length of the calorimeter, where can absorbed 95 % of the energy of primary particles is equal to $L_{95\%} \approx L_{max} + 0.08Z + 9.6$, where L_{max} is the length of the scintillator, where generated the maximum number of secondary particles ($L_{max} \approx \ln(E_0/E_c)$). The transverse size of the scintillator depends on the electromagnetic shower, which is determined by multiple scattering of electrons and positrons. Therefore, the transverse size of the crystal throughout the depth of the shower is determined by the Moliere radius (R_M). For example in the cylinder with radius $2R_M$ absorbed 95 % of shower energy.

The energy resolution of the ideal homogeneous electromagnetic calorimeter infinite size proportionally $\sqrt{E}$ and depends only on the statistical fluctuations of particles number. In fact, the energy resolution of the electromagnetic calorimeter depends on the fluctuations of different types with different energy dependences and is defined as

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c,$$

where a is the statistical fluctuations of number of photoelectrons in the electromagnetic shower; b is the noise of electronics, c is the fluctuations in leakage of shower from volume of the calorimeter, the structural heterogeneity of a scintillator, heterogeneity of signal and temperature and uncertainty of a calibrations. Typically, these effects are uncorrelated, so it has should be added in quadrature.

Thus, the choice of the scintillator is determined by the type and energy of recorded particles and requirements to parameters of the calorimeter. For example, the calorimeter for the COMET experiment (the search process of the electron-muon conversion in an atom of aluminum [1]) should have an energy resolution of better than 5 %, as events that should be recorded in this experiment lie in a narrow energy region (within 105±0.5 MeV), and an energy-correlated position coordinate accuracy of about 1 cm (rms)). The calorimeter also should solve the following tasks: 1) to measure of electrons energy very exactly; 2) to generate time trigger signal for recording system events; 3) to do the correlation position of electron track and its energy; 4) to identify the electrons, neutrons and low energy gammas [2].

Hence, for the calorimeter two candidates — LYSO and GSO crystals were selected, which have similar optical parameters and satisfy the requirements of the COMET experiment. Moreover, LYSO and GSO crystals should have a minimum length of 12 cm, it is follows from their radiation lengths values ($X_{0-\mathrm{LYSO}} = 1.14$ and $X_{0-\mathrm{GSO}} = 1.39$ cm). While the cross sectional dimensions of the crystals should be greater than 4 cm for complete absorption of electromagnetic shower energy, because the Moliere radius for LYSO and GSO crystals have values $R_{\mathrm{M-LYSO}} = 2.03$ and $R_{M-\mathrm{GSO}} = 2.3$ cm.

It should be noted that the price of crystals with such geometrical dimensions ($4 \times 4 \times 12$ cm^3 for LYSO and $5 \times 5 \times 15$ cm^3 for GSO) is very high and, taking account the total number of crystals (~2000) the production of the COMET experiment calorimeter will amount to a very large sum. In this regard, and in accordance with the requirement of the geometric resolution in the calorimeter were selected crystals with the dimensions of $2 \times 2 \times 12$ cm^3 for LYSO and $2 \times 2 \times 15$ cm^3 for GSO crystals. However, for crystals with such geometry the requirement of the optimal size to reduce the photons losses along the crystal length $L/H \leq 3$ (ratio of length to cross-section size must be less than or equal to 3) is not satisfy [3]. Therefore, in this case, will be a significant the losses of photons along the crystal length, which occur as a result of multiple reflection and absorption of photons at the boundary surface of the crystal, and due to the energy leakage from crystal. It makes the parameters of the calorimeter on the crystals of these types worse.

In this regard, more research is needed to find methods to compensate for the deterioration of calorimeter parameters with

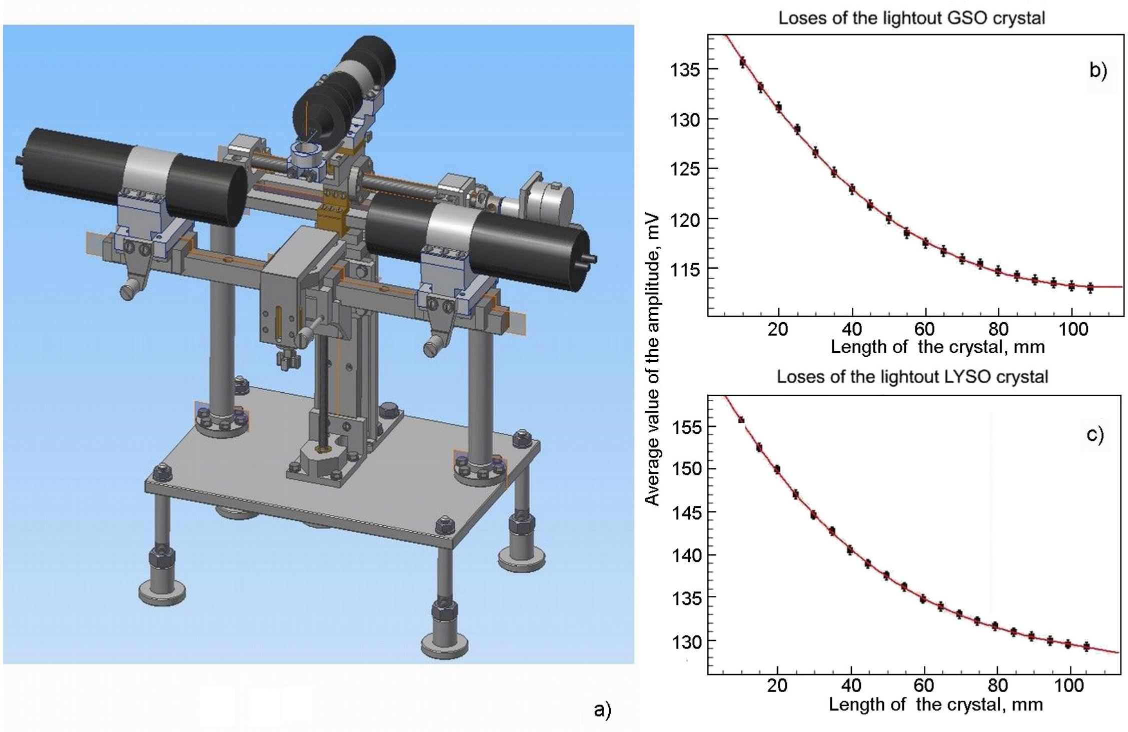

Fig. 1. a) A view of a precision measurement setup; light output losses along the crystal length for GSO (b) and LYSO (c) crystals.

such geometry of crystals, which is a purpose of work. For this aim, the following tasks were solved:

— an experimental study of crystals optical parameters associated with light output losses along the length and losses of photons collection in a crystal;

— a study of the electromagnetic shower in crystals with given geometry and losses of photons along the crystals length on the base of SLitrani code;

— a determining the type and parameters of reflective wrappers to achieve a given geometric resolution of the calorimeter and optimal structure of segmented modules for trigger on base of SLitrani [4] and Geant4 [5] simulation.

2. Experimental study of the optical parameter LYSO and GSO crystals

The crystals for the COMET calorimeter must have a high-energy resolution, large light output, fast decay and rise time and high radiation resistance. The crystals of LYSO and GSO satisfy these requirements [6, 7].

The experimental study and measurement of parameters of LYSO and GSO crystals were made to study the photons losses along the length and optical parameters that affect the improvement of the light collection in a scintillator with $L/H > 3$ geometry. The losses of the light output along the crystal length, heterogeneity, energy resolution were experimentally measured. In addition, a comparative estimate of the light output for these crystals was obtained. The studies were performed by using a precision measuring setup by the made of authors (Fig. 1), the results are published in [8].

Figure 1a shows a view of the setup consisting from: the optical measuring system that was executed on the fast PMT HAMAMATSU H1949-50 with divider H1949-50; the precision mechanical system for moving the radiation source with accuracy 1 μm on the basis of the precision stepmotor; the precision measuring system on the base of the 14 digit 5-GHz digitizer; the trigger system of selection which was made on the NIM modules.

Figure 1b,c show the dependences of light output losses along GSO and LYSO crystals length measured on energy 1274.5 keV (^{22}Na). As seen from Figs. for a given geometry of the crystal, many photons (~20 %) do not reach the APD. It reduces the accuracy of the determination of the energy deposited in crystal and the energy resolution deteriorates, as the fluctuations photons number of the leakage will be to increase. On the magnitude of losses is influenced by the heterogeneity of Ce concentration along the length and also losses of photons inside of crystal material. Reduction of light output losses along the length can be achieved by changing the reflection coefficient at the boundary surface of the crystal (the use of reflective films, which reduces the leakage of photons shower from crystal volume and losses on the scattering and absorption of photons at the boundary surface of a crystal).

In this regard, the experimental study of the influence of different reflective material types on the magnitude of light output losses, energy resolution and energy deposited in the crystal was made. As the processes taking place in wrappers of reflective materials, do not depend on the type of scintillator, and are determined only by the optical properties of films, all further studies are made for GSO crystal. As the reflective materials were used Teflon (AF 1601, a layer of 60 μm thickness) and aluminized Mylar, it is Mylar coated aluminum (a layer of 20 μm thickness).

The results of the experimental research of influence of Teflon and Mylar materials on the optical parameters of GSO crystal are shown in Fig. 2. Namely, the dependence of light output losses along the GSO crystal length for Teflon and Mylar materials is shown in Fig. 2a,b. The coefficient of light output losses along the crystal length is equal to ~2.4 %/cm (Fig. 2a) and ~2.2 %/cm (Fig. 2b) for material of Teflon and Mylar, respectively.

From the analysis of results is seen that the Mylar film increases the collection of photons along the length, although their reflection coefficient has approximately the same as Teflon ($\mathrm{Refl.Coef.}_{TF} \cong 0.98$, $\mathrm{Refl.Coef.}_{Al} \cong 0.94$ [9]). It is because the material of Teflon has a relatively high transmittance of the generated photons, and when we use the Teflon film 60 μm thickness part of the electromagnetic shower get out from crystal [10].

At the same time, from the analysis of uniformity coefficients of the light output along the length seen that it is not depend on the material of the wrapper (by wrapper both as Teflon and Mylar it is the same and equal to ~1.4 %/cm) and is determined mainly by properties of the crystal (Figs. 2c,d). In Fig. 2e,g,f is given the energy spectra of GSO crystal for different type of material wrappers, namely: e) for Teflon, g) for Mylar and f) for crystal without wrapping. In Fig. 2h is shown the peak position of the light output for GSO crystal, wrapped with Mylar, Teflon and crystal without the wrapping, and energy resolution for these cases, obtained from analysis of the spectra of Figs. 2e,f,g.

As follows from the analysis, when the crystal is wrapped with Mylar, the leakage of photons from crystal volume is reduced, and the energy resolution will have the best value equal to 13 % at the energy 1274.5 keV (^{22}Na). The energy resolution under the same conditions for crystal wrapped with Teflon tape and crystal without the wrapper is 14.1 % and 14.3 %, respectively.

Thus, for long crystals with geometry $L/H > 3$ and $H \le R_M$ is needed to use the reflective wrapper with good reflectivity. It will to improve the accuracy of registration of energy and to improve the energy resolution for the segmented calorimeter on long crystals.

3. The study of optical parameters of long crystals using SLitrani and Geant4 codes

For a more detailed study of light output losses along the crystal length with non-optimal geometry, leakage of photons shower from crystal volume, scattering and absorption of photons at the boundary surface crystal the researches were made by using a SLitrani code simulation [4].

The following main tasks were solved using SLitrani simulation:

— the study of the electromagnetic shower in crystals with non-optimal geometry and losses of photons along the crystals length;

— the study of photons losses in materials of reflective wrappers (Teflon, Mylar, and other).

The dependence of losses of photons in the crystal as a function of wavelength, losses of photons in reflective wrappers (Table 1), total losses of photons and quantum efficiency were obtained using the simulation.

The SLitrani simulation of the losses of photons along the crystal length was made under the condition when the energy of the radiation source moves along the crystal length and distance from its surface was the same as in similar experimental measurements. Figure 3 shows the simulated (Fig. 3a) and experimental (Fig. 3b) losses of the

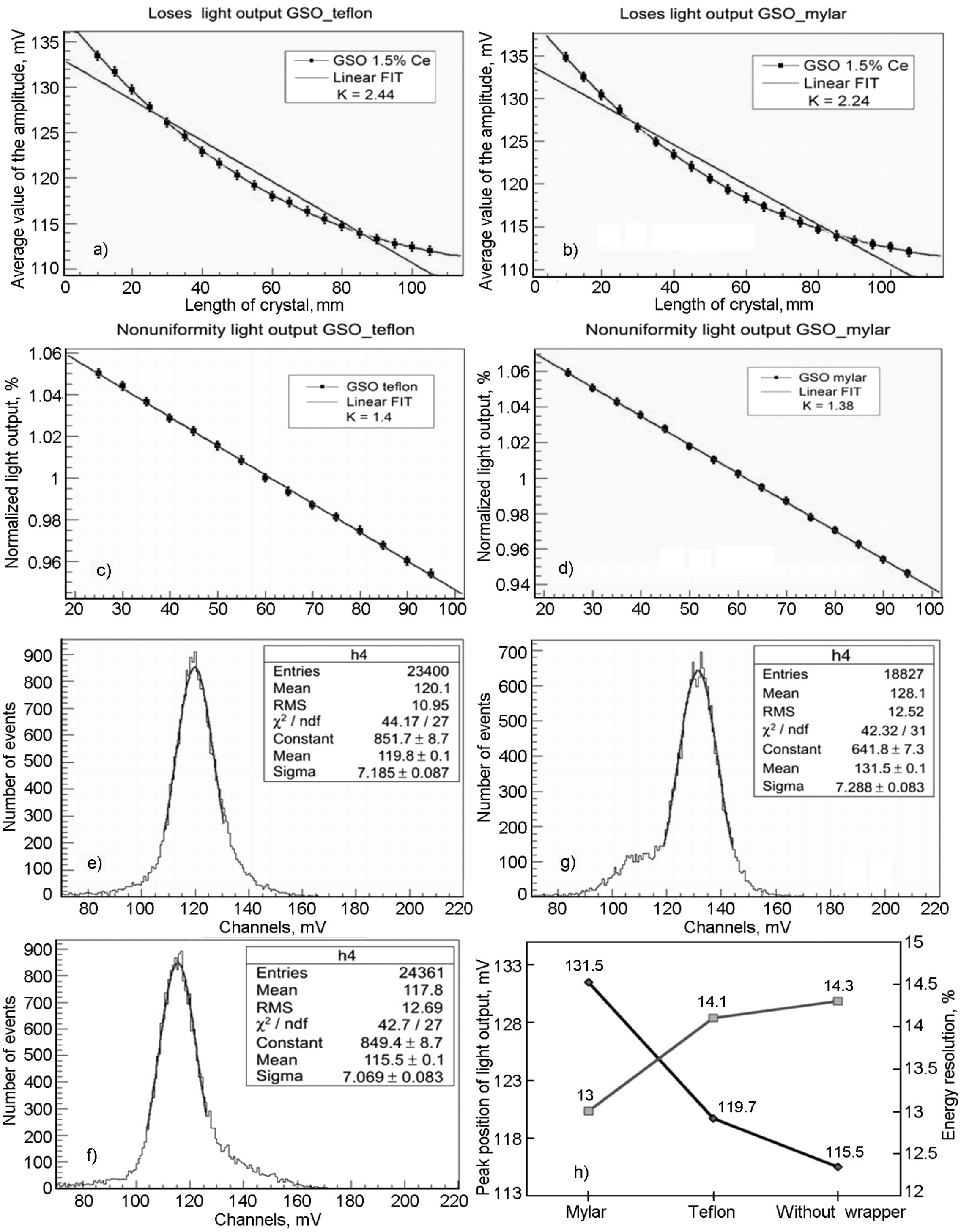

Fig. 2. Experimental study of the influence of reflective materials on optical parameters of GSO crystal: light output losses along the crystal length wrapping of Teflon (a) and Mylar (b); the uniformity coefficient of light output of the crystal, wrapping of Teflon (c) and Mylar (d); the energy spectra obtained for crystals wrapped with Teflon (e) and Mylar (g) without the wrapper (f); (h) the peak position of light output and energy resolution for the crystal wrapped with Mylar, Teflon and without wrapper.

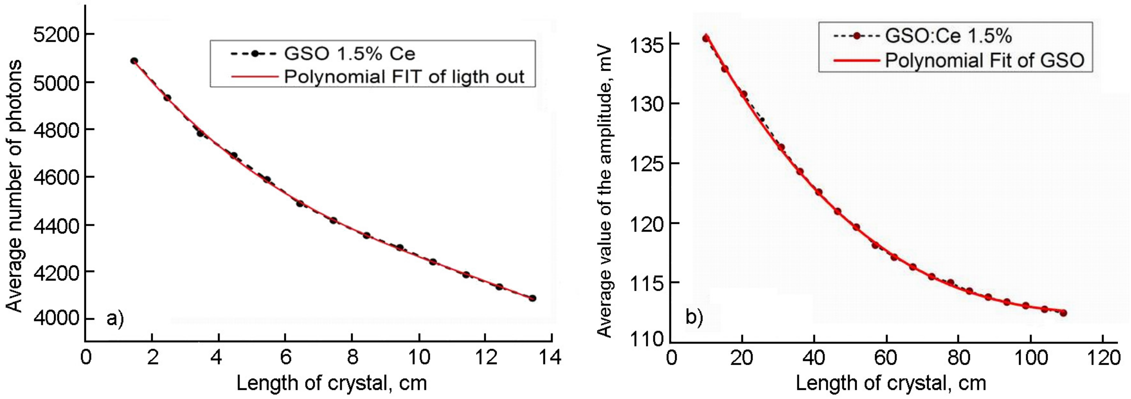

Fig. 3. Dependences of the losses of photons along the GSO crystal length, obtained as a result of simulation using SLitrani code (a) and as a result of experimental measurements (b).

light output along the GSO crystal length. In Table 1 is given the comparative results of the main optical parameters of GSO crystal, obtained by SLitrani simulation and in experimental measurements.

From the analysis of results (Table 1) seen that the difference between the simulated and measured values of light output losses along the crystal length is about 3 %. In addition, the good agreement between the simulated and measured values of decay and rise time was obtained. Thus, the adequacy of the optical model of parameters and real parameters for crystal GSO was obtained.

Figures 4a,b,c show the visualization of the simulation of energy deposition in the crystal on the position of the radiation source at a distance of 13.5, 7.5 and 2 cm from the photomultiplier tube. Figure 4d shows the result of the SLitrani simulation of photons losses along the GSO crystal length wrapped with Teflon. From the simulation is follows that a lots of photons are lost inside material volume of the crystal (~70 %). The losses in the reflective film material are ~ 6 %. The losses of reflection and absorption between the wrapper and the crystal are ~8 % (Fig. 4d).

Table 1. Comparative results of the measured and simulated optical parameters for GSO crystals

Optical parameter	Measured value	Simulated value
Decay time, ns	420±0.5	430
Rise time, ns	17±0.03	15
Losses of light output along length, %	17.9±1.2	16.4

The losses of photons in reflective material depend from the material type, so we simulated the losses of photons for different materials wrappers using SLitrani code. The results of the simulation are shown in Table 2.

From Table 2 it follows that the losses of photons in the material of Teflon less than for a film of Mylar, because Teflon has a relatively high transmittance of the generated photons as we have noted above.

The leakage of the electromagnetic shower can lead to optical cross-interference between crystals, i.e. a higher probability of incorrect identification of the crystal and thus to a deterioration of the spatial resolution of the calorimeter. On the other hand, the specular reflection leads to reduce the efficiency of light collection in the crystal [11].

This is due to the fact that the transfer of light energy in the crystal happens by repeated reflection of photons from the surface in this case. Therefore, the light output of the crystal depends strongly from the angular distribution of reflected light. In this regard, it is necessary to consider the diffusion coefficient of reflector, which determines how many photons are reflected at

Table 2. Photons losses in reflective material

Reflective film material	Losses of photons, %
Teflon(AF1601)	7
Aluminum-backed Mylar (diffusion constant 0.5)	9
Aluminum-backed Mylar (diffusion constant 0.1)	8.85
Bright-finished steel (reflection coefficient 95 %)	8.72

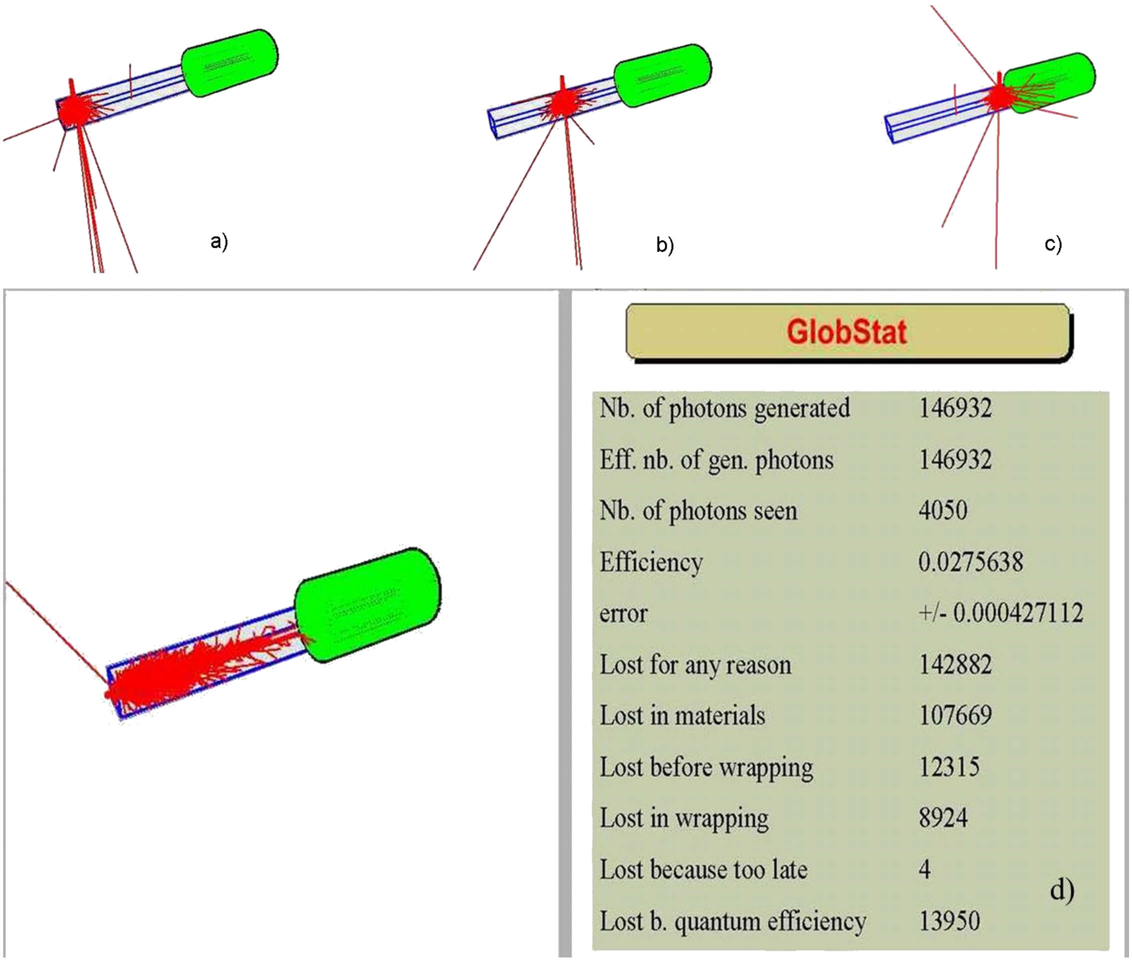

Fig. 4. Visualization of the SLitrani simulation for GSO crystal.

small angles [3]. It is believed that a diffuse reflector gives the best efficiency of accumulation of photons compared to a specular surface [3].

Thus, the choice of the reflective material for wrappers plays an important role to increase the light output of the segmented calorimeter. In addition, the transverse heterogeneity of the collection of photons which depend from reflective material of wrappers will be to influence on the energy resolution of the calorimeter. The study of these problems has been made using the Geant4 code [5].

As noted earlier, a diffuse reflector (Teflon) gives the best efficiency of accumulation of photons compared to the specular reflector (Mylar, Millipor, Tyvek and others). Therefore, the simulation of the calorimeter for the COMET experiment was carried out using the optical model, obtained by using SLitrani code, with the Teflon diffuse reflector. During the simulation, the calorimeter was located in 1 T uniform magnetic field (as it will in the COMET experiment). The beam energy spread was 105±0.5 MeV. The beam spot was 1 cm^2 ± 1 cm. Simulation of the calorimeter was made for the cases when:

— each crystal was wrapped with two layers of Teflon (AF1601, one layer thickness is 60 μm);

— each crystal was wrapped with Teflon, and they are grouped in modules from 4 (2 × 2) or 9 (3 × 3) crystals, wrapped with Mylar to determine the optimal structure of crystals segmentation for the generation of trigger signal.

Figure 5a shows a view of geometry of the calorimeter for the case when each crystal was wrapped with Teflon. Figure 5b shows the spectrum of energy deposited in the calorimeter. As follows from the analysis of results (Figs. 5a,b), the leakage of shower takes place only in neighboring crystals, so the required energy and coordinate resolution of the calorimeter can be ob-

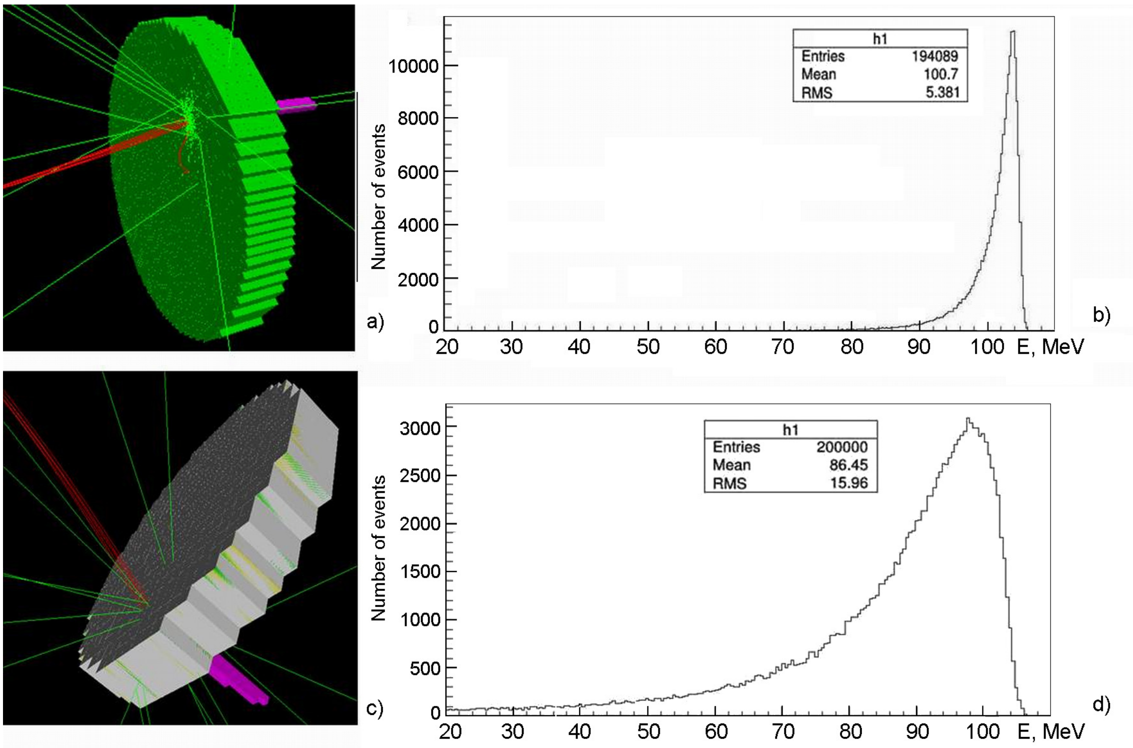

Fig. 5. Results of calorimeter simulation on the crystals wrapped with Teflon: a view of calorimeter geometry (a), the energy spectrum (b); c and d) the similar characteristics as (a) and (b) when the calorimeter segmented in modules, wrapped with Mylar.

tained. The Geant4 simulation of the calorimeter for the COMET experiment where was obtained the energy resolution of 4.8 % for LYSO and 6 % for the GSO at the 105 MeV beam of electrons confirms this conclusion [12]. Crystals were wrapped with two layers of Teflon. The calorimeter was located in 1 T uniform magnetic field.

Figure 5c shows geometry of the segmenting of the COMET calorimeter in modules from 4 (2×2) crystals wrapped with Mylar, and Fig. 5d shows the spectrum of energy deposition in the calorimeter. Combining of the crystals in modules from 4 crystals, wrapped with Mylar, is making the energy resolution of the calorimeter significantly worse (Fig. 5d). In this case, the structure of calorimeter becomes heterogeneous, and the losses of energy (photons) inside the calorimeter depend not only on the processes of scattering and absorption on the material of the crystal and wrappers, but also from electron beam trajectory.

Thus, the optimal structure of the calorimeter can be the following:

— the lateral surfaces of crystals should have a diffuse reflection, i.e., must be wrapped with a double layer of Teflon to improve the efficiency of the accumulation of photons due to diffuse reflection, and the transverse homogeneity of the calorimeter;

— the front surface of crystals should have a specular reflection, i.e., should be wrapped with Mylar, Millipore, Tyvek and others to improve a light collection. It will improve the collection of photons in the calorimeter and as a result, the energy resolution will be better.

Grouping of crystals in modules, wrapped with Mylar, leads to the transverse inhomogeneity of the calorimeter, which is depend from the trajectory of the electron beam. Taken into account that in the calorimeter for COMET experiment all tracks of incident electrons are curved this heterogeneity will lead to large errors in the measurements of electrons energy in the calorimeter, and, as result the energy resolution will be worse. Therefore, the segmentation of the crystals in modules to generate the trigger signal should be carried out at the level of logic signals, i.e. to use the modules from 4 crystals without wrapper of Mylar.

4. Conclusions

The researches have been carried out to find methods to compensate the deterioration of the parameters of the calorimeter, because crystals selected as candidates to create the calorimeter for the COMET experiment have not optimal geometry. Namely, the experimental and SLitrani and Geant4 simulated studies of the losses of photons along the crystal length were made. Parameters and types of the reflective wrapper were studied to achieve a given geometric resolution of the calorimeter and optimal structure of the segmented modules for the trigger system.

As follows from the analysis of results, the required values of the energy and coordinate resolution for the COMET experiment can be obtained for the case when the lateral surfaces of the crystals wrapped with two layers of Teflon, and the front surface has a specular reflection. Combining crystals into modules of four crystals, wrapped with Mylar, leads to the transverse inhomogeneity of the calorimeter, which is, depend from the trajectory of the electron beam. So, for the trigger system, it is needed to use logical signals with modules of crystals without Mylar wrapper.

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