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МЕТОДИКА ФИЗИЧЕСКОГО ЭКСПЕРИМЕНТА

TESTS OF THE MODULE ARRAY OF THE ECAL0 ELECTROMAGNETIC CALORIMETER FOR THE COMPASS EXPERIMENT WITH THE ELECTRON BEAM AT ELSA

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The array of 3×3 modules of the electromagnetic calorimeter ECAL0 of the COMPASS experiment at CERN has been tested with an electron beam of the ELSA (Germany) facility. The dependence of the response and the energy resolution of the calorimeter on the angle of incidence of the electron beam has been studied. A good agreement between the experimental data and the results of Monte Carlo simulation has been obtained. It will significantly expand the use of simulation to optimize event reconstruction algorithms.

На электронном пучке ускорителя ELSA (Германия) была исследована сборка из 3×3 модулей электромагнитного калориметра ECAL0 установки COMPASS (ЦЕРН). Изучались зависимости отклика и энергетического разрешения калориметра от угла падения пучка электронов. Получено хорошее согласие экспериментальных данных с результатами расчетов методом Монте-Карло, что позволит существенно расширить применение моделирования для оптимизации алгоритмов реконструкции событий.

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INTRODUCTION

Measurement of generalized parton distributions (GPD) in the reaction of deeply virtual Compton scattering (DVCS)

$$\mu^+ p \to \mu^+ p\gamma \tag{1}$$

is one of the main goals of the second phase of the COMPASS experiment [1]. Most of the photons born in the reaction (1) are registered by a system of two COMPASS electromagnetic calorimeters ECAL1 and ECAL2. Currently at JINR a large aperture electromagnetic

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calorimeter ECAL0 has been created. Its task is to expand the kinematic range of registering photons in the reaction (1) and to participate in the effective suppression of background processes with π^0 and η with high transverse momentum in the final state. ECAL0 will be located after extensive liquid hydrogen target at the detector of the recoil protons output, and its task will be to register gamma rays with energies ranging from 0.15 to 30 GeV in the polar angle range 0.15–0.6 rad.

The design of the calorimeter ECAL0 was chosen as a result of a series of successful tests of various "shashlyk"-type prototypes of electromagnetic calorimeters readout by micropixel avalanche photodiodes (MAPD) on the beam T9 PS (CERN) in 2008–2009 [2, 3]. ECAL0 is a "shashlyk"-type calorimeter with high granularity (cell size 4×4 cm). Calorimeter module (3×3 cells) consists of the active part — 109 alternating layers of lead (0.8 mm) and scintillator (1.5 mm), and the registration block with MAPD. The total thickness of the active part is 15.3 radiation lengths. Light collection from scintillator plates on MAPD is performed by WLS fibers. Usage of photomultipliers as photodetectors is almost impossible, since the calorimeter will be located in the region of sufficiently strong scattered field of COMPASS spectrometer magnet. Photodiodes of MAPD-3N and MAPD-3A types with ultrahigh-density pixels ($1.5 \cdot 10^4$ mm^{-2}) and an area of 3×3 mm are used in the registration blocks. These photodiodes have a wide dynamic range, providing good linearity of response [2]. Active parts of calorimeter modules are manufactured at the Institute for Scintillation Materials (Kharkov). Detailed calorimeter module construction description is presented in the paper [4]. Note that modules of similar design will be used for electromagnetic calorimeters of the NICA facility.

The array of 3×3 prototypes of ECAL0 modules has been successfully tested at the T9 beam (CERN) in 2011 [5]. ECAL0 calorimeter fragment of 56 modules (about a quarter of the total number) was tested during the test session at the COMPASS facility in 2012. Calibration of the calorimeter cells was performed by using a parallel muon beam and the signal from the π^0 decay. Studies showed that parameters such as energy, spatial, temporal resolution and linearity of response corresponded to the expected and were stable over time.

However, for further optimization of the events reconstruction algorithms, as well as for improving the spatial and energy resolution, etc., it is neccessary to study dependencies of calorimeter characteristics on the angle of incidence of the photons (or electrons). For this purpose, additional studies of 3×3 modules array were performed with electron beam at the ELSA facility (Bonn) in February 2014 [6].

1. STUDY OF THE MODULE ARRAY

1.1. Experiment. Study of the 3×3 module array (81 cells) was carried out on the extracted electron beam of the ELSA accelerator with intensity of $2 \cdot 10^3$ e^-/c for three values of the electron energy: 0.8, 1.6 and 3.2 GeV. The module array was placed on a remotely controlled mobile platform, allowing one to set the vertical and horizontal position of the modules with an accuracy better than 0.2 mm, and the angle of rotation in the horizontal plane — with an accuracy of $0.1°$. Hodoscope consisting of two planes of scintillating fibers with a diameter of 1.0 mm with 0.7 mm pitch had been used to determine the coordinates of the point of incidence of electrons on calorimeter modules, to monitor the beam intensity and also as a trigger. The size of the active region of the hodoscope was 2.3×2.3 cm.

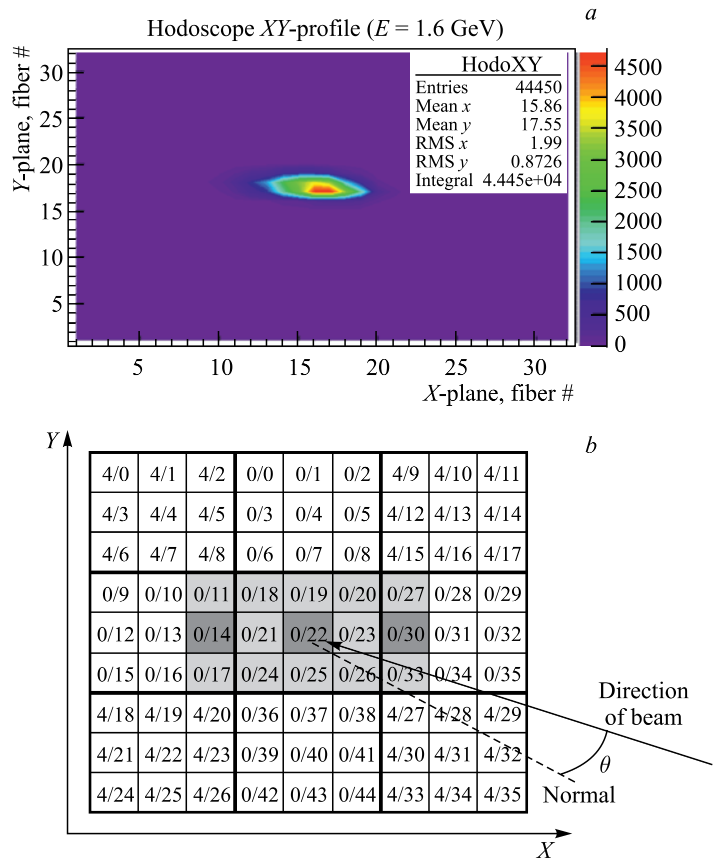

Fig. 1. *a*) A typical profile of the electron beam with an energy of 1.6 GeV: $\sigma_x = 1.4$ mm, $\sigma_y = 0.5$ mm. *b*) Configuration of 3×3 modules array. For gray marked cells the energy and angular dependence of the response was measured. For dark gray marked cells Monte Carlo simulation of the response was performed

Figure 1, *a* shows a typical profile of an electron beam with an energy of 1.6 GeV obtained with the hodoscope. The signals from the calorimeter modules photodetectors were applied to shaping amplifiers and then by twisted pair to the inputs of 12-bit 80-MHz analog-to-digital converters MSADC-COMPASS. Trigger for readout system was produced at the coincidence of signals from two planes of the hodoscope. In the MSADC-COMPASS readout system a digital threshold of about 5 ADC channels (≈ 50 MeV) was set.

Study of calorimeter modules was carried out in two stages. In the first stage, a calibration of response of each cell at the energy 3.2 GeV was performed. In the second stage, the angular dependence of the response of the calorimeter was measured for 15 cells located in the central region of the array.

To carry out energy calibration of cells, the platform with array was moved in the vertical and horizontal directions with 40 mm step so that the electron beam hits the center of each cell. For a few cells a scanning with 10 mm step was performed to study dependence of the response on the point of incidence of electron to the cell.

In order to study the angular dependence of the calorimeter characteristics, the module array was rotated in the horizontal plane at θ angle from 0 to 36° relative to the beam axis with 6° step. The direction of rotation is shown in Fig. 1, *b*. The measurements were performed at electron energies of 0.8, 1.6 and 3.2 GeV for the 15 central cells of array that are shown in gray in Fig. 1, *b*.

1.2. Monte Carlo Simulation. The experimental results were compared with the results of Monte Carlo simulations performed with the Geant4 software package [7]. The model took into account the holes in the lead and scintillator plates, clearances, LEGO locks and WLS fibers in the calorimeter construction. Also the size of the electron beam measured by a scintillation hodoscope was taken into account. Standard set of physical processes QGSP_BERT was used for simulation of the electromagnetic shower in the material. Response of the calorimeter to the passage of the electron was considered proportional to the total energy deposition in the scintillator layers. For each cell the detection threshold was 43 MeV, which corresponds to digital electronics threshold (5 ADC channels). Gaussian dispersion of threshold with $\sigma = 15$ MeV determined from experimental data was further introduced for correct description of the calorimeter response. Also the model took into account the attenuation of light in fibers and statistical fluctuations of the number of photoelectrons generated in MAPD.

2. THE RESULTS OF STUDIES

The measurement results are shown in Figs. 2–5, measurement errors are less than sizes of the points on the graphs.

Figure 2, *a*, *b* shows the measured response and the energy resolution of the calorimeter in case of a normally incident beam. For comparison, the figure also shows the simulation results and the data obtained in 2011 on the T9 channel at CERN [5]. Clearly, the results are in good agreement.

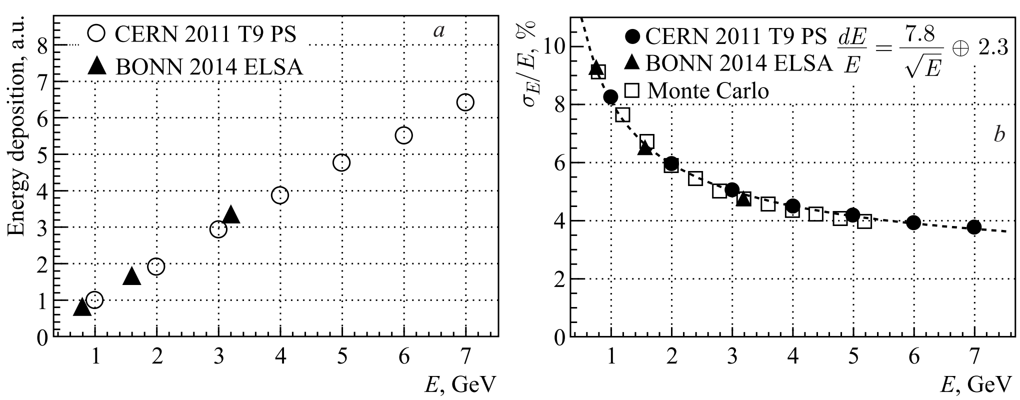

Fig. 2. Dependence of the response (*a*) and energy resolution σ_E/E (*b*) of module array on the energy of electrons, normally hit ($\theta = 0°$) in the center of the cell 0/22. The results of measurements in 2011 at CERN are shown by circles, in 2014 at the ELSA — by triangles, and the results of Monte Carlo simulations — by squares

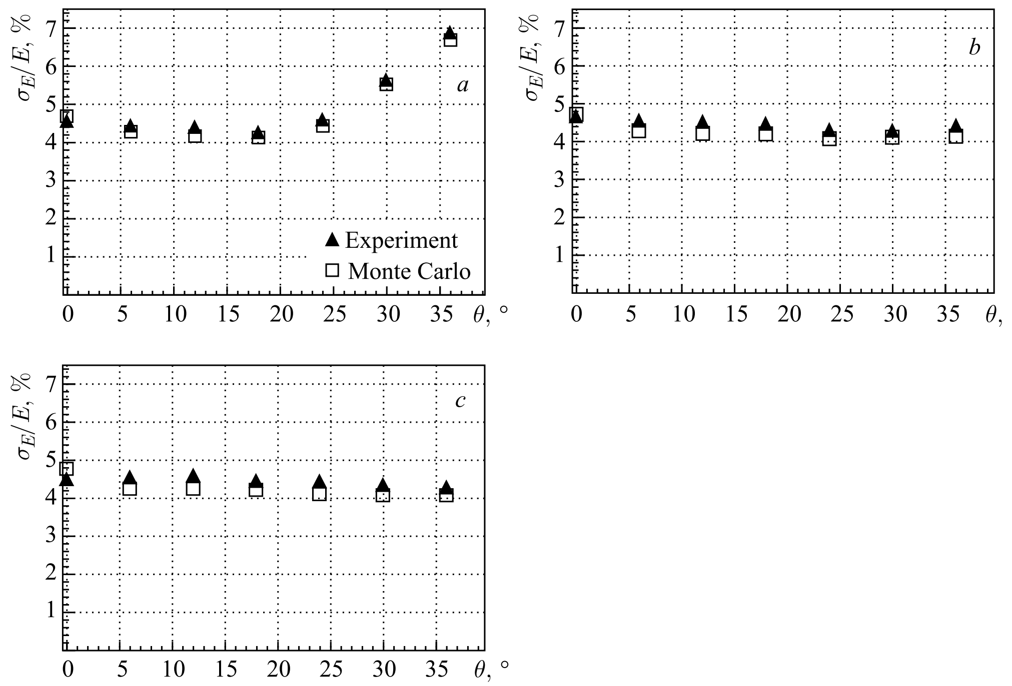

Fig. 3. Dependences of the energy resolution σ_E/E of the array on the angle of incidence of the electron beam with an energy of 3.2 GeV in the centers of cells: *a*) 0/14; *b*) 0/22; *c*) 0/30. The results of the measurements are shown by triangles, simulation results — by squares

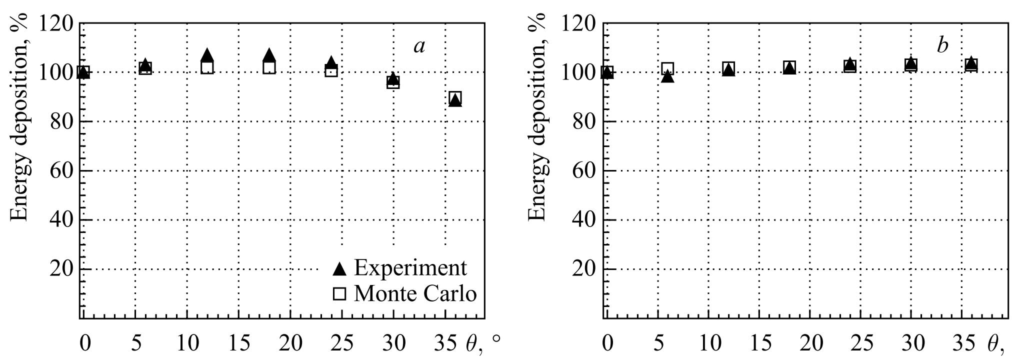

Fig. 4. Dependence of the energy deposition in the array on the angle of incidence of the electron beam with an energy of 3.2 GeV in the edge 0/14 (*a*) and central 0/22 (*b*) cells. The results of measurements are shown by triangles, simulation results — by squares

Figure 3 shows angular dependences of the energy resolution σ_E/E measured and obtained by the simulation when electron beam with an energy of 3.2 GeV hits in the centers of cells 0/14, 0/22 and 0/30. For cells 0/22 and 0/30 one observed expected slight improvement of resolution with increasing of angle as a result of increasing of the effective length of the

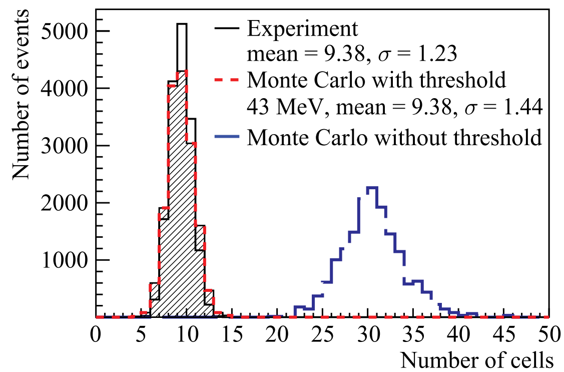

Fig. 5. The distribution of the number of cells in the energy deposition cluster when the electron beam hits the cell 0/30 at angle $\theta = 36°$: experimental, and obtained as the result of simulation — without a threshold on the energy deposition in the cell and with a threshold of 43 MeV

calorimeter active part. For 0/14 cell at angles $\theta \geqslant 20°$ resolution degrades significantly, because of the shower leakages through the lateral surface of the array. Dependences of the energy deposition on the angle of incidence of the beam to the edge 0/14 and the central 0/22 cell at an energy of 3.2 GeV are presented in Fig. 4, *a*, *b*, respectively. It is seen that the Monte-Carlo simulation describes the experimental data.

Simulation used experimentally obtained value of threshold on the energy deposition in a single cell — 43 MeV. To confirm this value, experimental and simulated distributions of the number of cells in the energy deposition cluster were plotted (Fig. 5). As seen from the distributions, simulation using the threshold of 43 MeV is in good agreement with the experimental results.

CONCLUSIONS

Study results have demonstrated the ability of the calorimeter ECAL0 to measure the energy of photons incident at large angles (up to 0.6 rad) with accuracy $\sigma_E/E \leqslant 10\%/\sqrt{E}$ required by the COMPASS experiment. The experimental data show good agreement with the results of Monte Carlo simulation. The results of measurements and Monte Carlo simulation will be used to optimize the cluster reconstruction algorithms, which will take into account both the effects associated with the angle of incidence of photons and boundary effects.

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