Selection of the optimal parameters of the scintillation hodoscope model for the muonography

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Abstract. This article discusses the problem of selection by modeling the optimal parameters of a new scintillation muon hodoscope created for the development of the muonography method. The muon hodoscope is a scintillation detector consisting of several layers of scintillation strips with fiber optic light collection on silicon photomultipliers (SiPM). Its exact model in the Geant4 software package was developed. With its help, the passage of muons through the detector and the response of the detector to these events are simulated. The reconstruction of the tracks of muons was carried out and the accuracy of their reconstruction was estimated. The obtained distributions of events in the angle between the reconstructed and "real" tracks for various detector parameters and the selection of optimal parameters for the highest accuracy and efficiency of the reconstruction of muon tracks are considered.

1. Introduction

Variations in the muon flux on the Earth's surface arise as a result of the influence of various processes in the heliosphere on the primary cosmic rays flux, as well as during the passage of muons through the atmosphere. A high penetrating ability of muons makes them an attractive tool for muonography of various large objects [1]. The muonography is a new promising research method based on the loss of muon energy in matter. Muonography is a part of the method of muon diagnostics, for the development of which the muon hodoscopes TEMP [2] and URAGAN (MEPhI) [3] were first created. Detectors for research in the field of muonography must have such characteristics as stability of operation and accuracy of reconstruction of muon tracks with a high angular resolution.

Construction of sets of experimental samples is a technologically difficult and resource-intensive process. It is advisable to estimate in advance the optimal parameters of the installation, such as the dimensions of the strips, the dimensions of the supermodule, the distance between the coordinate planes, etc., which provide the necessary accuracy of the reconstruction of tracks by means of mathematical model. In this article, a model of a new scintillation muon hodoscope developed in the Geant4 software package is presented. The basis of the new detector is the scintillation muon hodoscope (ScMH) [4], developed at MEPhI.

2. Scintillation muon hodoscope model

Modeling is carried out with the Geant4 software package version 10.5 [5]. The muon hodoscope model includes four coordinate planes. Each coordinate plane consists of two mutually perpendicular layers of strips (128 strips each), which are located in a light-insulating case that provides structural
rigidity. Fiber optic light collection goes to silicon photomultipliers (SiPM). An individual SiPM is located at the end of each strip. The model contains the real chemical composition and optical properties of the substances of the detector, all the necessary processes of interaction of radiation with the substance are connected.

3. Estimate of the efficiency and accuracy of muons registration
To simulate the response of the muon hodoscope, the spectrum of cosmic ray particles, which was close to the real one, was simulated [6]. The following detector models are considered: with a distance \( d \) between layers of 65 cm, 82 cm and a strip width \( w \) of 17 mm, 20 mm, 23 mm. For all variants, the following values are calculated: zenith \( \theta \) and azimuth \( \phi \) angles for the "real" track (the track obtained by the least squares method by the points of passage of the muon through the detector) and the reconstructed track (the track obtained by the "straight-line" segment search algorithm [7] by the coordinates of the triggered strips), projection angles \( \theta_X \) and \( \theta_Y \) for the same tracks, the angle between the "real" and reconstructed tracks. For all the quantities under consideration, histograms of the number of events falling into the corresponding interval in angle are plotted. For the histogram in the zenith angles, the step is 1 degree, for the azimuth angles the step is 4 degrees. Figures 1, 2 show histograms for zenith \( \theta \) and azimuth \( \phi \) angles of "real" and reconstructed tracks for a scintillation muon hodoscope model with the distance between layers of 65 cm and the strips width of 23 mm (the same in the rest of the figures).

\[ \Delta \theta \]
\[ \Delta \phi \]
\[ \Delta \theta_X \]
\[ \Delta \theta_Y \]

**Figure 1.** Distributions in the zenith angle of "real" and reconstructed tracks.

**Figure 2.** Distribution in the azimuth angle of "real" and reconstructed tracks.

Figures 1 and 2 show that the number of reconstructed tracks practically coincides with the number of "real" tracks. Distributions of events in the difference between azimuth angles \( \Delta \phi \) and zenith angles \( \Delta \theta \) are shown in Figures 3a and 3b and for projection angles \( \Delta \theta_X \) and \( \Delta \theta_Y \) in Figure 4. In the figures, the solid line marks the fitting of the histogram with the Gaussian distribution. The obtained fitting parameters are presented in Table 1.

| Values | Peak height, particles | Average value, degrees | Mean square deviation, degrees |
|--------|------------------------|------------------------|---------------------------|
| \( \Delta \theta \) | 1775 | 0.003±0.009 | 0.332±0.006 |
| \( \Delta \phi \) | 1159 | 0.005±0.009 | 0.837±0.019 |
| \( \Delta \theta_X \) | 1491 | 0.001±0.007 | 0.528±0.009 |
| \( \Delta \theta_Y \) | 1491 | 0.001±0.008 | 0.519±0.005 |
Figure 3. Distribution of the difference between the angles of "real" and reconstructed tracks: a) in the angle azimuth (0.1° step), b) in the zenith angle (0.05° step).

Figure 4. Distribution of the difference between the projection angles of "real" and reconstructed tracks: a) projection angle $\theta_X$ (0.05° step) b) projection angle $\theta_Y$ (0.05° step).

Figure 5 shows the distribution of events in the angle $\alpha$ between the "real" and reconstructed tracks. The resulting histogram has the form of a Rayleigh distribution (solid line in the graph) with fitting parameters: peak height of 4940 particles, average value $0.243° \pm 0.003°$, and mean square deviation $0.271° \pm 0.012°$.

Figure 5. Distribution of events in the angle between "real" and reconstructed tracks.
In order to determine how efficiently the tracks are reconstructed for various model parameters, one can estimate mean square deviations of the difference between the projection angles $\Delta \theta_x$ and $\Delta \theta_y$, the difference between the zenith $\Delta \theta$ and azimuth $\Delta \phi$ angles of the “real” and reconstructed tracks, as well as the angles between the “real” and reconstructed tracks (Table 2). Table 2 shows that the accuracy of the reconstruction of muon tracks is better than one degree for different variants of the parameters of the detector models, the accuracy changes insignificantly, all values satisfy the requirements of the muonography method. Taking this into account, it becomes possible to assemble the detector in any dimensions (in any of the considered combinations of strip width and interplanar distance). The efficiency of the muon hodoscope is estimated as the ratio of the number of reconstructed tracks to the number of "real" ones. According to the data obtained, the efficiency is more than 95%.

Table 2. Mean square deviations (in degrees) of the difference of zenith $\Delta \theta$, azimuth $\Delta \phi$, projection $\Delta \theta_X$ and $\Delta \theta_Y$ angles, and angles $\alpha$ between the “real” and reconstructed tracks.

| $d$     | $w$ | 65 cm, 65 cm, 65 cm, 82 cm, 82 cm, 82 cm, 82 cm, 82 cm, 
|---------|-----|----------------------------------|
| 65 cm,  | 17 mm | 0.276±0.007 0.317±0.008 0.332±0.006 0.239±0.003 0.266±0.005 0.279±0.005  |
| 82 cm,  | 17 mm | 0.276±0.007 0.317±0.008 0.332±0.006 0.239±0.003 0.266±0.005 0.279±0.005  |
| 82 cm,  | 20 mm | 0.735±0.016 0.748±0.016 0.837±0.019 0.698±0.015 0.704±0.016 0.786±0.019  |
| 82 cm,  | 23 mm | 0.462±0.009 0.497±0.009 0.528±0.009 0.261±0.002 0.308±0.004 0.335±0.004  |
| 82 cm,  | 20 mm | 0.462±0.009 0.497±0.009 0.528±0.009 0.261±0.002 0.308±0.004 0.335±0.004  |
| 82 cm,  | 23 mm | 0.459±0.003 0.494±0.004 0.519±0.005 0.264±0.004 0.310±0.004 0.353±0.007  |
| 82 cm,  | 23 mm | 0.459±0.003 0.494±0.004 0.519±0.005 0.264±0.004 0.310±0.004 0.353±0.007  |

4. Conclusion
The reconstruction of the modeled muon tracks has been carried out and the accuracy of their reconstruction has been estimated. It is shown that any combination of detector dimensions with a distance between layers of 65 cm, 82 cm and strip width of 17 mm, 20 mm, 23 mm satisfies the muonography tasks in accuracy and can be used to assemble a real detector. For all considered combinations, the accuracy of the reconstruction of muon tracks is better than one degree, and the efficiency of track reconstruction is more than 95%.

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References
[1] Barbashina N S et al. Method and setup for obtaining of muonographies Patent number 2406919 (Moscow: Applicant and patentee MEPhI)
[2] Borog V V et al. 1996 Nuovo Cimento C 19(6) 1291
[3] Barbashina N S et al. 2008 Instrum Exp Tech 51 180
[4] Ampilogov N V et al. 2015 Phys. Procedia 74 478
[5] Geant4 Collaboration 2019 Book for application developers Release 10.5. URL https://geant4.web.cern.ch/support/user_documentation
[6] Kovylyaeva A A et al. 2013 J. Phys. Conf. Ser. 409 012128
[7] Kovylyaeva A A 2014 International Telecommunication Conference of Young Scientists and Students "Youth and Science" p 27