Study of characteristics of scintillation muon hodoscope

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Abstract: A new muon hodoscope for investigations of the processes in heliosphere and terrestrial atmosphere by means of cosmic ray muons is described. The setup design is based on multi-layer assemblies of narrow long scintillation strips with WLS fiber readout. Features of the hodoscope design are discussed and results of tests of the basic unit of the hodoscope detection system – the module – are presented.

Keywords: muon diagnostics, scintillation muon hodoscope, WLS fiber, multi-anode PMT

1 Introduction

Muon diagnostics is a new and promising direction in the development of the world environmental observation system, based on penetrative ability of cosmic ray muons. Muon flux is formed in the upper atmosphere and is sensitive to the changes of main thermodynamic atmospheric parameters as well as to the processes in the heliosphere and the magnetosphere of the Earth related with the activity of the Sun. The reasons which cause changes in muon flux at the Earth’s surface is the subject of the study of muon diagnostics. Muon diagnostics technique is based on the simultaneous detection of muon flux from all directions of the celestial hemisphere in the hodoscopic mode. Such measurements give possibility to study the processes in the heliosphere and the Earth’s atmosphere and magnetosphere and to follow their dynamics [1].

For practical application of the methods of muon diagnostics, large area precise coordinate-tracking detectors – muon hodoscopes – are required. They must ensure continuous detection of cosmic ray muons from the celestial hemisphere in a real-time mode. Possibilities of muon diagnostics were demonstrated by means of the first generation of the hodoscopes: muon hodoscope TEMP (MEPhI, Russia, constructed in 1995) [2] and muon hodoscope URAGAN (MEPhI, Russia, 2005) [3]. The experience of operation of the first such detectors allowed to formulate main requirements to muon hodoscopes: sensitive area more than 40 m²; angular resolution better than 2°; efficiency of muon track detection about 97%; modular approach for an easier construction; easy handling, maintenance and transportation. However, both setups were created on the basis of unique detectors, which were originally designed for high energy physics tasks, so their detection systems were not optimized to meet the challenges of muon diagnostics. The optimal choice of the detecting system for such muon hodoscope is a multi-channel scintillation detector with wavelength shifting (WLS) optical fiber light collection. This experimental technique is widely used for the construction of a new generation of large area coordinate-tracking detectors in particle physics [4].

2 Scintillation muon hodoscope setup

Currently in MEPhI the new scintillation muon hodoscope (ScMH) with light collection on the basis of wavelength shifting optical fibers is being created [5]. Muon hodoscope has a modular structure and consists of identical units - basic modules (BM), which are constituted by 64 scintillation strips with WLS fibers coupled to one 64-anode PMT. The choice of the detection element of the hodoscope (scintillation strip – WLS fiber – 64-pixel PMT) provides possibility to use a single PMT for simultaneous detection and processing of signals from 64 readout channels of the BM. Moreover, the use of WLS fibers allows us to reduce requirements to the transparency of scintillation strips. All elements of the module are contained in a single housing which has a simple construction and ensures reliable light insulation. Two such modules constitute the detection layer with 3.4 × 3.4 m² sensitive area. Two layers of modules with orthogonally oriented strips form the coordinate plane that provides muon track X–Y coordinate information. Two planes mounted on a common frame form the multi-channel
muon hodoscope (see Fig. 1) which contains eight 64-strip BM (512 detection channels). The distance of 1 m between the planes provides angular accuracy of track reconstruction of about 1.5° (for muon incidence orthogonal to the plane of the module).

![Figure 1](Image)

**Figure 1.** Scheme of a wide-aperture scintillation muon hodoscope.

### 3 Basic module

Each detection channel of the hodoscope represents a narrow long scintillation strip (10.6 × 26.3 × 3460 mm$^3$ size; polystyrene with 2% p-terphenyl and 0.02% POPOP). To improve the light collection, a diffuse reflective compound of polystyrene and TiO$_2$ coextruded with the scintillator surface is used. At the middle of each strip a groove (2 mm deep, 1.6 mm wide) is made for WLS fiber pasted with high-transparency glue BC-600. The end of the fiber of every strip is positioned in front of the corresponding pixel of a 64-anode H7546 PMT by means of an optical connector. At passage of a charged relativistic particle through the strip a scintillation flash is formed, and a part of the primary flash photons enter into the WLS fiber, are re-emitted in the green part of the spectrum and reach the PMT. On the surface of each strip above the groove a silvered polyamide scotch is glued in order to decrease the loss of photons. The PMT H7546 has a very compact geometry (3 × 3 × 7 cm$^3$ including the resistor divider and connectors) with a matrix of 8 × 8 pixels. The average gain of the PMT at 800 V voltage is about 10$^5$. This provides the efficient detection of single photoelectron signals. The channel-to-channel gain difference is compensated by readout electronics which allows to adjust the amplification for each channel. As a whole, the basic module represents a “sandwich-type” structure with elements fixed by means of a double face adhesive film between two aluminum sheets (3460 × 1689 × 0.8 mm$^3$) and unites 64 strips with one photodetector. PMT and front-end electronics box are located near the optical coupling area.

### 4 Study of the characteristics of BM

![Figure 2](Image)

**Figure 2.** Dependence of the light yield on the LED position for WLS fiber.

#### 4.1 WLS fiber

The attenuation length in the optical fiber was estimated from the dependence of the PMT response on the distance to the position of the blue LED illuminating the WLS fiber (Fig. 2). Fitting was performed using the function:

$$y(x) = A_1 \exp(-x/l_1) + A_2 \exp(-x/l_2)$$

which is the sum of two exponents: the first exponent is responsible for the absorption of photons whose wavelength is in the fiber absorption region, the second one - for decrease of the flux of re-emitted photons. The measured attenuation length $l_2$ was obtained as 520 ± 25 cm.

![Figure 3](Image)

**Figure 3.** Dependences of the light yield on the distance between muon telescope and PMT for three strips.

#### 4.2 Scintillation strip

For investigation of the light yield at muon detection, a calibration telescope was used. Dependences of the light yield on the distance between muon telescope and PMT for three strip samples are shown in Fig. 3.
The light yield is always above 4 p.e., even for hits at the far end of the strip. It will correspond to single muon detection efficiency of more than 98% at 1/3 p.e. threshold.

Measurements of the dependence presented in Fig. 3 require long-time because of a low counting rate of the muon telescope. Therefore serial testing of strips by means of muon telescope is not suitable. To decrease the time of measurements, a spectrometer based on β-source ($^{90}$Sr) was used. The electrons with energy about 1.8 MeV were selected from the total flux of electrons by means of the magnetic field. To link the magnitude of the response of strips for detection of electrons from the β-spectrometer ($Q_{\mu}$) to the response from telescope muons ($Q_{\mu}$), the calibration dependence was obtained (Fig. 4).

![Image](image1)

Figure 4. The correlation between signals detected from muons selected by the telescope ($Q_{\mu}$), and the response for β-spectrometer electrons ($Q_{\mu}$). Experimental data are fitted by a straight line with coefficients $K$ and $M$; $R$ is correlation coefficient.

### 4.3 Multi-channel PMT

Hamamatsu H7546 PMT was tested by means of a LED system. As the estimate of amplification coefficients of separate channels of PMT, the $\sigma^2/A$ value which is proportional to the gain of the dynode system has been used.

![Image](image2)

Figure 5. Non-uniformity of H7546 PMT channels; solid line marks the passport data sheet, dotted line – normalised $\sigma^2/A$ values of the measured spectra.

Fig. 5 shows the $\sigma^2/A$ values for 64 channels (in % relative to the maximum value) of a sample of PMT. A good agreement with the data sheet of anode non-uniformity of PMT is observed. The form of a single photoelectron charge distribution for the anode No. 1 of the tested photomultiplier is shown in Fig. 6. To ensure the photomultiplier operation in a single electron mode, the intensity of light from LED was chosen so that the signal detection efficiency was about 10% at a threshold of 0.3 p.e. Frequency of noise pulses of the channel at this threshold did not exceed 1 s$^{-1}$.

![Image](image3)

Figure 6. Single photoelectron spectrum for one of the channels of the H7546 PMT.

### 5 Calibration of the basic module

An assembled basic module was tested using the URAGAN supermodule (SM), registering tracks of muons from different directions.

The URAGAN SM includes eight planes interlaid with 5 cm foam plastic, each composed of 320 streamer tubes with external strips forming a two-dimensional readout system. Total area of one supermodule is about 11.5 m$^2$. The setup provides detection of particles in a wide range of zenith angles (from 0 to 80°) with angular accuracy about 0.7°. The data processing system allows to reconstruct muon tracks in an on-line mode and to register muon flux from the upper hemisphere.

The objectives of the BM testing on URAGAN SM included: testing of operation of all 64 channels; investigation of the efficiency and uniformity of detection over the area of the BM; determination of the level of channel-to-channel crosstalk. Tested BM was located over the upper coordinate plane of URAGAN SM. The area of each strip was divided into fifty 70 mm cells. Trigger system of the muon hodoscope URAGAN selected particle tracks that crossed the effective area of the BM, while the response signals were read from all channels of BM. As a result of the exposure of BM in the muon flux, the following two-dimensional distributions of strips’ cells are obtained: the matrix of the number of muon tracks, selected by URAGAN SM; the matrix of the number of operated strips at the intersection of the cells by reconstructed tracks; the
matrix of charge on the outputs of the PMT channels at the intersection of the cells by reconstructed tracks.

The distribution of detection efficiency for twenty strips is shown in Fig. 7. Shades of gray represent average detection efficiency for each cell of the strip (150 events on the average have been collected in each cell). The strip efficiency at 1 m distance from the nearest to the PMT end of the strip is presented on the top of the figure. The dependence of efficiency on the coordinate for selected strip (№ 17) is presented on the right.

The analysis of Fig. 7 shows that the value of light collection of strips ensures the registration efficiency of muon tracks in cells about 91% (at a threshold of 0.3 p.e.) with a standard deviation of 2.6%. However, visual inspection of events that gave a trigger for the BM in URAGAN SM showed that about 6% of the total statistics are events that mimic muon tracks: curved tracks of low-energy electrons, multiparticle events. Thus, given evaluation of the efficiency is underestimated. The average muon detection efficiency over the entire area of the BM (without partitioning in cells) was equal to 97%.

The described methods of testing the basic modules using the SM of muon hodoscope URAGAN provide quick and efficient BM verification, including finding of possible areas of reduced efficiency of muon detection.

6 Conclusion

For the development of experimental methods of muon diagnostics of heliospheric and atmospheric processes, the new muon hodoscope with fiber optic light collection has been designed. Results of testing of individual elements of the hodoscope and of its basic module show that the solutions used in the module design and technology allow to create the detecting system of the scintillation muon hodoscope for effective registration of tracks of single muons in a wide range of zenith angles.

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8 References