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Cherenkov water detector NEVOD: a new stage of development

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Abstract

The new detecting system of the Cherenkov water detector of the Unique Scientific Facility “Experimental complex NEVOD” located at the ground level is described. During the development of the detecting system, two tasks have been solved: providing a hodoscopic mode for registration of single muon tracks in 4\(\pi\)-geometry and a calorimetric mode for measurements of the energy deposit of cascades and high-multiplicity muon bundles.

Keywords: Cherenkov water calorimeter, quasi-spherical module, photomultiplier tube, muon detector

1. Introduction

Since 1994, a multi-purpose Cherenkov water detector (CWD) has been operating in MEPhI. The detector created for effective detection of all cosmic ray components at ground level [1-3] has a volume about 2000 m\(^3\) and is the basis of the Unique Scientific Facility “Experimental complex NEVOD” (Fig. 1).
2. The detecting system

The basis of the detecting system (DS) of the Cherenkov water detector is a quasispherical module (QSM, Fig. 2). The QSM consists of six PMT with flat photocathodes directed along the axes of the orthogonal coordinate system. Photomultipliers and inner-module electronics are placed in the watertight aluminium housing (see Fig. 2, left). Photocathodes are protected against hydrostatic pressure by means of plastic illuminators. The QSM has a practically equal sensitivity of registration of Cherenkov radiation from any direction, since, in general, for three triggered PMTs, the sum of the squares of cosines of the angles of incidence of Cherenkov radiation on the photocathodes is close to the unit (see Fig. 2, right). Three or four modules are combined into strings forming a space-centered lattice. The detecting system on the basis of QSM allows to reconstruct the parameters of charged particle tracks in the $4\pi$-geometry by means of amplitude analysis only.
In the original configuration of the DS, for registration of Cherenkov radiation the PMTs FEU-49B and FEU-125 (“Ekran” factory, Novosibirsk, Russia) were used. The diameter of the sensitive area of multialkali photocathodes of these PMTs is 15 cm. These PMTs had a high rate of the dark noise, and for noise suppression at the level of inner-module electronics the condition of a double coincidence of neighboring PMT signals had been introduced. Unfortunately, this condition greatly limited the volume of effective registration of a single QSM.

As a new photomultiplier for QSM a FEU-200 specially developed by the company “Ekran – Optical Systems” (Novosibirsk) is use for registration of weak flashes of Cherenkov radiation. FEU-200 has the same overall dimensions as FEU-49B, somewhat higher integral sensitivity and a low rate of dark noise (on the average 5×10³ s⁻¹ at the threshold about 0.25 photoelectrons). It allowed us refuse from the condition of double coincidence in the module.

At present, the NEVOD detecting system consists of 91 QSM (NEVOD-91) deployed in the water volume in the form of a lattice with a step of 2.5 m along the longer side of the tank, and 2 m across it and over the depth.

To calibrate the PMTs, the calibration telescope system (CTS) is used. The CTS consists of two planes of scintillation detectors, 40 in each. Detectors are placed at the bottom and at the lid of the Cherenkov water detector. The scintillation detector includes scintillation block and the PMT FEU-85 performing the light collection from the block inside the watertight aluminium container. Any pair of detectors from the top and the bottom plane forms a muon telescope selecting muon tracks with the angular accuracy better than 2 degrees.

To improve the CWD research capability, the coordinate detector DECOR [4] was constructed around the tank of the NEVOD detector (see Fig. 1). The DECOR is a modular multi-layer system of plastic streamer tube chambers. Each chamber contains 16 tubes with resistive cathode coating. The DECOR includes eight vertically arranged eight-layer assemblies (supermodules, SMs) of chambers with a total sensitive area of 70 m². The chamber planes are equipped with a two-coordinate external strip readout system that allows to localize charged particle tracks with accuracy about 1 cm in both coordinates (X, Y). The angular reconstruction accuracy for muon tracks crossing the SM is better than 0.7° and 0.8° for projected zenith and azimuth angles respectively. The experimental complex consisting of coordinate detector DECOR and Cherenkov water detector has no analogues in the world and is able to detect the muon bundles passing through the water detector in the range of zenith angles 30° - 90°. The spatial resolution of the tracks in the coordinate detector is about 3 cm.

During the CWD NEVOD operation, a number of physical and methodical tasks have been successfully solved: the method of atmospheric neutrinos registration on the Earth’s surface using the muons from the lower hemisphere in conditions of an extremely high background of muons from the upper hemisphere has been developed and successfully tested [3, 5]; a new technique for the EAS investigations based on a new variable - local muon density spectra in a wide range of zenith angles – has been developed [5-11]. For the first time, based on this technique, the characteristics of the flux of the primary cosmic rays (PCR) in the energy range of 10^{15} - 5·10^{18} eV have been investigated by means of a single setup. The "second" knee of the PCR energy spectrum at the region of about 10^{17} eV has been discovered. It has been shown that at the energies of about 10^{18} eV the intensity of muon bundles exceeds its expected value even assuming a heavy (pure iron) PCR composition. Also for the first time, the muon intensity in a wide range of zenith angles (20° - 89°) and threshold energies (1.5 - 7.2 GeV) and the albedo muon flux in the range of zenith angles from 90° to 94° have been measured; the influence of the Earth’s magnetic field on the muon bundle spatial characteristics has been studied.

However, over the years of operation the CWD electronics became obsolete and worn-out. To go to a modern hardware and increase the CWD research capabilities, the new QSMs and measuring system have been developed [12, 13].

The purpose of a new detecting system was to ensure the CWD operation in the hodoscopic mode for registration of muon tracks in the whole range of zenith angles (0° - 180°) for the study of muon flux variations in a wide range of threshold energies, as well as in the calorimetric mode for measuring of the energy deposit of multi-particle events (EAS cores, muon bundles and cascade showers). An important task of the new electronics is an effective registration of the events jointly with other detectors of the experimental complex: DECOR [5, 6], URAGAN [14], PRISMA [15-18], NEVOD-EAS [19, 20].
3. The new measuring system of CWD NEVOD

The new measuring system has a two-level structure of DAQ. Modules of each string are combined into a cluster by means of the block of electronics of the cluster (BEC) located above the water level (Fig. 3). BECs generate trigger signals of the first level, perform the amplitude analysis of QSM responses and data communication with the central computer.

The upgraded inner-module electronics (IME) ensures stable operation of FEU-200 PMTs and procedures of their monitoring. The IME includes six PMT boards (PKh-514P), the power supply unit (PNN-382P) and a six-channel monitoring system on the basis of light-emitting diodes.
The boards PKh-514P are mounted directly on the sockets of the photomultipliers and contain HV power supply resistive divider and two pulse-shaper-amplifiers (PSA). PSA converts short signals from the 9th and 12th dynodes of PMT to the signals with a constant value of the front edge (50 ns) and the trailing edge of the pulse (2 μs). The amplitude of output PSA signals is proportional to the charge from a dynode of PMT. The use of the low-noise FEU-200 has made possible to analyze the amplitudes of all triggered PMTs, so the registration efficiency of QSMs was greatly improved. The use of two dynode signals provides the dynamic range of detected signals from 1 to $10^5$ photoelectrons (ph. el.). The spectrometric channel of 12th dynode is linear up to $10^3$ ph. el. The ratio of output signals of PSA from two dynodes is about 100.

Inspection of the stability of the conversion factor of the spectrometric circuit of PMT→PSA→ADC in IME of QSM is provided by a monitoring system on the basis of a six-channel controller of LED drivers. Each driver represents a separate electronic plate with KingBright L-7113NBC LED ($\lambda = 470$ nm), which ensures the exposure of the photocathode by short flashes (FWHM ~ 5 – 7 ns). The control of the monitoring system is performed by I2C bus from the BEC. The monitoring of the measuring system is carried out periodically during the experimental runs. Values of conversion factor of 12th and 9th spectrometric circuits, their ratio and stability are estimated on the basis of parameters of PMTs amplitude spectra.

![Diagram](image)

**Fig. 4.** Scheme of the module of the amplitude analysis.

The power supply of electronics is provided by a unit PNN-382P on the basis of DC/DC converter which converts +12 V voltage into the values of ±12 V and +2000 V.

The blocks of electronics of the cluster are located in water tight stainless steel housings, which are fixed in the space between the water level and the light-insulating cover of the detector basin. All signals of QSM are sent to BEC by means of two deep water cables. The cables are introduced into the QSM via cable glands and are connected to the BEC housing by means of sealed connector (IP67) HUMMEL [21]. BEC contains four modules of the amplitude analysis, a processor plate, a module of interface with the sensor of temperature monitoring, and power units which provide necessary voltage for the elements of BEC and QSM.

The modules of the amplitude analysis (Fig. 4) perform the digitizing of analog signals of 9th and 12th dynodes of six PMTs with the 12-bit 2-channel ADC Texas Instruments ADS7862YB.

The ADS7862YB has a fast device of track-and-hold that allows to record the amplitude value of the sloping peak of the input signal. To start the signal-processing circuit and to generate logical signals, the MAA contains discriminators with a software-controlled threshold. The accuracy of the threshold value is 0.1 mV. The control logic
and the scheme of the trigger signal formation is realized on the basis of FPGA Xilinx XC2S50-6PQ208C. The FPGA provides the communication between the units of the board, performs blocking of spectrometric circuit by a software-controlled keys, and communicates with the processor board of BEC. The important function of the FPGA is measuring of PMT noise and generation of three types of trigger signals for each QSM: "a" (any), logical "OR" of six signals from 12th dynodes of PMTs; "b" (bottom), signal from downward directed PMT; "c" (coincidence), the coincidence of signals from any two PMT (except those oppositely directed) within 150 ns time gate.

The MAA board has two modes of operation: the monitoring and the exposition modes. The monitoring mode was designed for the test of the working capacity of channels of the measuring system. The exposition mode provides the registration of physical events caused by Cherenkov radiation in the volume of CWD. Timing diagrams of MAA operations in two modes are presented in Fig. 5.

![Fig. 5. Timing diagrams of MAA operations: monitoring mode (left) and exposition mode(right).](image)

During the monitoring mode, discriminators of MAA boards are blocked. The measuring process is synchronized with the startup signal of IME LEDs. After 250 ns from the generation of the startup signals of LED, the track-and-hold device is started. The sampling time of the track-and-hold device coincides with the sloping peak of the input signal from the PKh-514P board. After the digitizing of a signal, ADC readout and the transfer of data to the central computer follow.

At the exposition mode, when the PMT signal exceeds the discriminating threshold, the logical signal is transferred to the block of the trigger generation and to the noise counter. 100 ns after generation of the logical signal, the track-and-hold and the digitizing are produced. During the digitizing, the spectrometric circuit of PMT is blocked. Also at the logical signal generation, after a software-controlled TD delay the gate of waiting of the “Storage” signal from the external triggering system of the detector is opened. If “Storage” signal arrives within the gate of 250 ns, then the fixing of data in registers of hit channels, the readout of ADC and the transfer of data to the central computer are performed. Otherwise, the data are discarded and ADC is switched to the waiting mode.

All four modules of the amplitude analysis are connected with the WAVER-C400E2VN-RS Celeron 400 MHz processor by means of PC/104 bus. The processor implements the control of the measurement regime, performs the data readout from the modules of amplitude analysis in the case of the arrival of “Storage” signal, and ensures their transfer to the central computer via Ethernet. The FPGA of MAA produces trigger signals in the standard TTL, that are converted into standard RS422 for transmission over long lines at the BEC by means of the interface module.
4. Conclusion

The new detecting and measuring systems of the CWD NEVOD allow to increase capabilities of the experimental complex on the registration of cosmic rays at the Earth's surface both in the hodoscopic and in the calorimetric modes. The cluster organization of the detection system allows not only effectively detect events in $4\pi$-geometry and to measure their energy deposit in a wide dynamic range, but also to easy increase the sensitive volume of the detector by installing additional clusters.

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