Investigation of muon bundles generated by UHECR by means of the new coordinate-tracking detector

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Abstract. The new coordinate-tracking detector based on drift chambers (CTUDC) is created in MEPhI. The detector represents two planes with total area of 30 m² placed on the opposite sides of Cherenkov water detector of 2000 m³ volume. Each plane consists of 8 large multiwire drift chambers (4000x508x112 mm³). The key advantages of these chambers are a large effective area (1.85 m²) and a good coordinate and angular resolution with a small number of measuring channels. From the beginning of 2017, CTUDC operates as a part of the experimental complex NEVOD. The detector is designed for measuring of high density muon bundles (up to 10 particles per m²) at zenith angles in the range from 30° to 90°. The results of the CTUDC operation during the last year are given, the first distributions of the events in zenith angle, muon bundle multiplicity and density obtained from the detector data are discussed.

1. Introduction
The aim of the large-scale coordinate-tracking detector is to solve the problem of the excess of muon bundles that increases with the energy of the primary cosmic rays [1, 2]. What can be caused by both cosmo- or nuclear-physical reasons [3]. The only characteristics that responds differently to changes in the composition of cosmic rays and the inclusion of new physical processes is the energy of the muon component of extensive air showers [3] which has not been investigated till the present time. Such studies are performed at the experimental complex NEVOD-DECOR [4]. However, the coordinate detector DECOR does not cover the entire aperture of the water Cherenkov detector and does not exclude the possibility of passing of several muons between the individual supermodules of the detector. Besides, the size of its cells limits the possibility of separating two or more particles at small distances (less than 3 cm). The new coordinate-tracking detector [5] based on drift chambers DC will increase the coverage of the side aperture of the Cherenkov water detector (CWD) NEVOD and significantly improve the resolution of close tracks.
2. The experimental setup
The Coordinate-Tracking Unit based on Drift Chambers (CTUDC), which is the first detector of such type implemented in the field of cosmic ray physics, has been developed and included as a part of experimental complex NEVOD. Detector represents 16 drift chambers forming 2 coordinate planes by 8 DC in each deployed at opposite sides of CWD (Figure 1). Effective area of the detector is 29.6 m².

It uses multiwire drift chambers that were developed for neutrino accelerator experiment in Institute of High Energy Physics (IHEP) [6]. They contain an array of field-forming wires located on perimeter, 10 cathode and 4 signal wires in the center of chamber. The signal wires alternately shifted from the center by 0.75 mm to solve left-right ambiguity. According to the DC data it is possible to reconstruct the track on a plane perpendicular to the signal wires. The passage points of the track are determined from the drift time for each signal channel taking into account the constancy of the drift velocity of the electrons.

![Figure 1. The location of the coordinate-tracking setups of the experimental complex NEVOD.](image)

The aim of the CTUDC is to inspect the possibilities of drift chambers in cosmic ray experiment in case of joint operation with large Cherenkov water detector and other setups [7]. The full-scale detector TREK will consist of 264 drift chambers that form two vertical coordinate planes at the same wall of CWD building [8]. Planes differ in the chamber orientation: in outer plane chambers are near-vertical, in another plane DCs are horizontal. TREK will cover entire side aperture of CWD and will allow to count all tracks that passed through its working volume and precisely determine their arrival angle.

3. Event selection and estimation of multiplicity
The main characteristic that is measured by CTUDC is local density that at the first approximation can be counted from:

\[ D \sim \frac{m}{s_{eff}} \]

where \( m \) is the number of muon tracks, \( s_{eff} \) is effective area of the setup [9,10]. The expected integral distribution of events by muon density has the form

\[ F(\geq D) \propto D^{-\beta} \]

where \( \beta \) is the value proportional to the index of the integral distribution of the energy spectrum of primary cosmic rays. Taking into account the power dependence of the density distribution of events the differential spectrum of events in multiplicity (up to constant \( C \)) has the form:
It is necessary to know the zenith and azimuth angle of the bundle to define the effective area. The drift chamber data can provide information only on the projected zenith angle. So the CTUDC data can give only distributions in multiplicity. Muon bundle density can be estimated by means of DECOR data, that provide azimuth angle. Thus, the distribution in this characteristic can be plotted only for joint events.

The primary reconstruction of multi-particle events registered by the CTUDC is performed by three main methods: the sequential search method, the method of finding the straight line and the method of histogram [11]. The last method gives the most relevant reconstruction, but the best result can be reached only by using of combination of the methods that helps to find missed muon tracks and distinguish tracks of secondary particles. For the moment, automatically reconstructed events are not acceptable, so manual selection and corrections of events are needed.

The selection of events includes two stages: program selection and visual analysis of candidates. Due to the presence of after-pulses and right-left ambiguity, it is impossible to fully automate the selection of events. The selection criteria are:

1) For each angle the number of tracks in the plane that shielded by water and that are in the range of ±5 degrees is estimated. The maximum multiplicity defined by this histogram must be greater than 3 tracks.

2) The presence of parallel tracks at both planes of the CTUDC.

3) The portion of hits (signals) on the shielded plane that are involved in reconstruction (each should be putted in compliance to some muon track) must exceed the total number by 11.5% for the method of the straight line and 15% for the method of histogram.

For small multiplicities, the method of finding the straight line is used, since it is less time-consuming. In the multiplicity determination, only tracks shielded by the CWD are considered to exclude the soft components of secondary cosmic rays. The last two criteria are used to exclude events in which mainly electrons and positrons are passing through the setup.

4. Experimental results

Visual analysis of the candidate events adjusts the multiplicity of the bundle and discards the false events. Figure 2 shows the results of the selection of events for the whole 2017 year. At the left plot distribution of events in multiplicity without visual selection is given, the fitting is carried out with the index \( \beta = 2.6 \). The results of the selection can be seen at the right plot: the fitting changed index \( \beta \) to 2. That is close to the expected value. Due to the small number of high-multiplicity events it is impossible to talk about the excess of muon bundles.

![Figure 2](image-url). The distribution of events by multiplicity: without (left) and with (right) visual selection.
The muon bundle density that can be measured in the CTUDC is more than 10 particles per m². Figure 3 shows event with 13 tracks in a single drift chamber, with a respect to the projected zenith angle and without assuming of azimuth angle the muon density in this event is higher than 10 particles per m². These capabilities of the CTUDC are due to the 3 mm two-track resolution of drift chambers that is 10 times better than for the DECOR.

![Figure 3](image)

**Figure 3.** An example of reconstruction of a high-multiplicity event in a single drift chamber.

Figure 4 shows the distribution of events in muon bundle density. The number of particle tracks for this distribution is obtained from the CTUDC data. The zenith and azimuth angles are taken from the DECOR data. This combination allowed to investigate events with density more than 2 tracks per m². Figure 5 shows the distributions in projected zenith angle (left) and azimuthal angle (right) for the events that compose density distribution. The requirement for shielding of the DECOR modules by the CWD limits azimuthal angles. The possibilities of the DC for track registration at small zenith angles limit a corresponding distribution.

The higher density events are rare and possibilities of two-track resolution of the DECOR limit the number of events in which the muon bundle angle can be determined. The key to investigation of the full number of high-density events is the creation of the new full-scale setup TREK that will be able to make full-angle reconstruction of muon bundles.

![Figure 4](image)

**Figure 4.** The distribution of events in muon bundle density according to the CTUDC-DECOR data.
Figure 5. The distribution of events in projected zenith angle (left) and azimuthal angle (right).

5. Conclusion
The new coordinate-tracking setup CTUDC increased possibilities of the experimental complex NEVOD-DECOR in registration of muon bundles of high density and at large zenith angles generated by ultra-high energy primary cosmic rays. Two years of operation of the CTUDC has showed high performance and durability of the drift chambers from accelerator experiment in the field of cosmic ray physics. This result has opened possibilities for the creation of the full-scale setup TREK that will be the largest coordinate-tracking detector for registration of cosmic rays with a high precision and at a high particle density.

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