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Cherenkov water calorimeter on the basis of quasispherical modules

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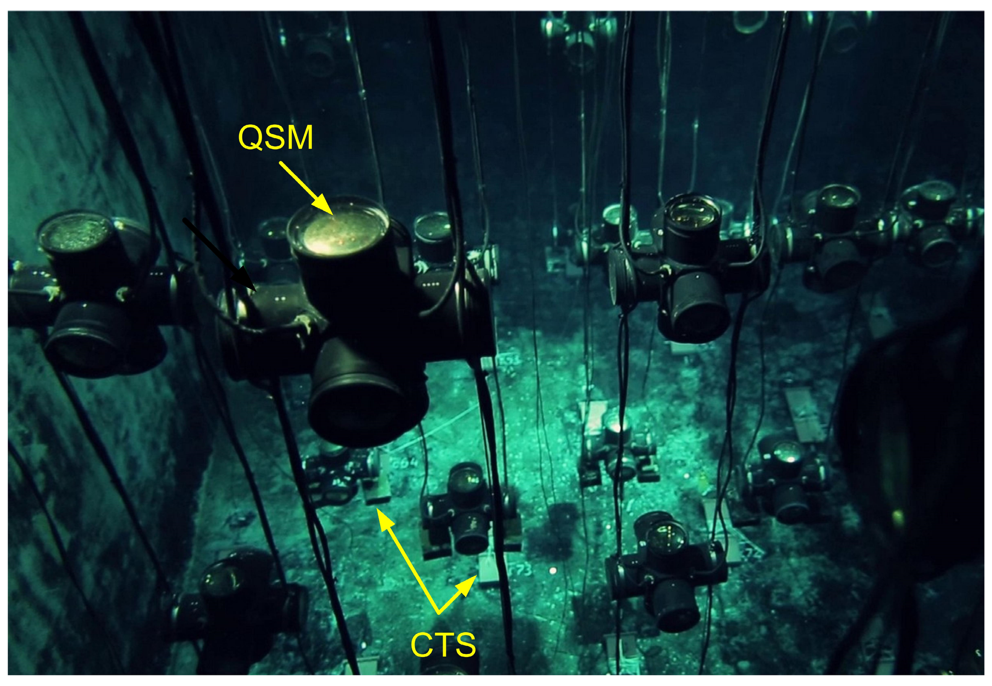
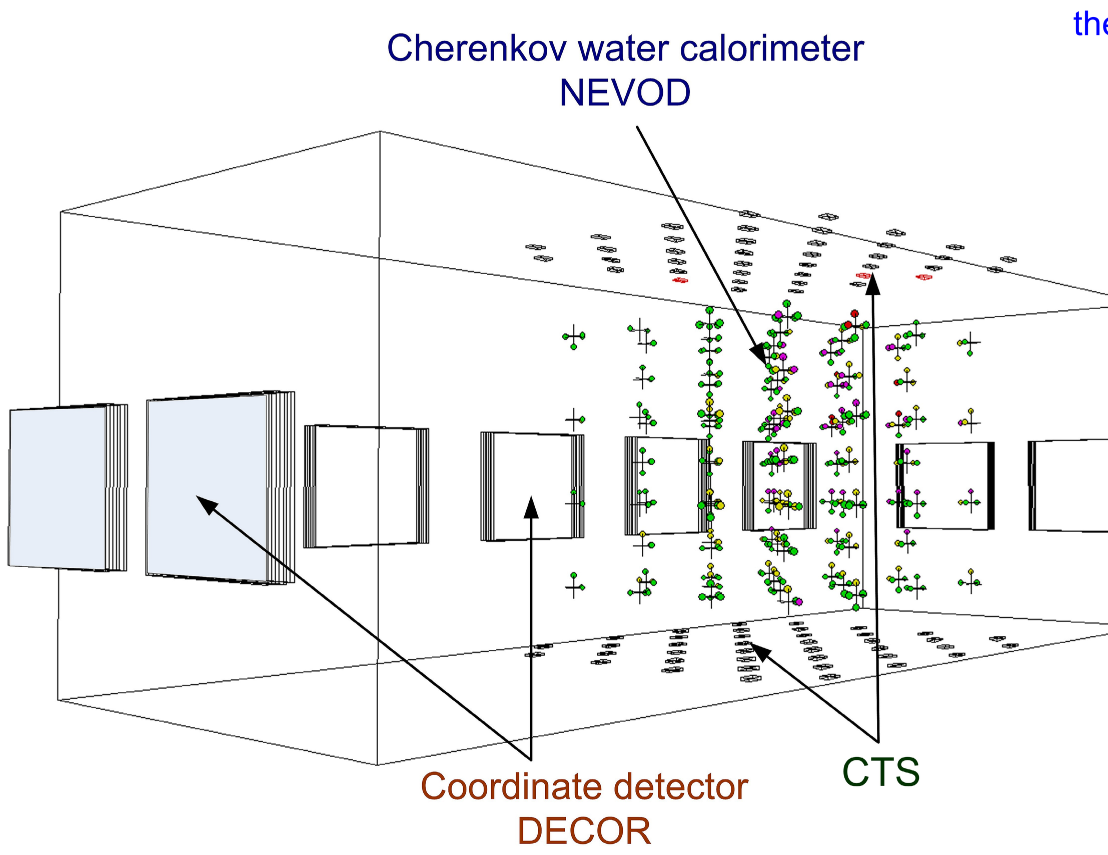
Cherenkov water calorimeter (CWC) NEVOD with volume of 2000 m^3 (9 m depth) is located on the surface of the Earth in the MEPhI campus and is intended for the registration of all major cosmic ray components. Its experimental capabilities are determined by the properties of the detecting spatial lattice with the quasispherical modules (QSM) in its nodes. These modules provide almost the same efficiency of registration of Cherenkov radiation from any direction. The detecting lattice consists of alternating planes: four planes with 16 QSMs and three planes with 9 QSMs each. In turn, each plane is formed with vertical clusters consisting of 3 or 4 QSMs. The distance between the modules is 2.5 m along the water reservoir axis, 2.0 m across it and 2.0 m in the vertical direction. The small distance between the QSMs in the lattice enables to reconstruct the tracks of charged particles and provides the characteristics of 4π-detector. The threshold energy of the detector is up to 7 GeV for horizontally moving muons and 2 GeV for vertical muons.

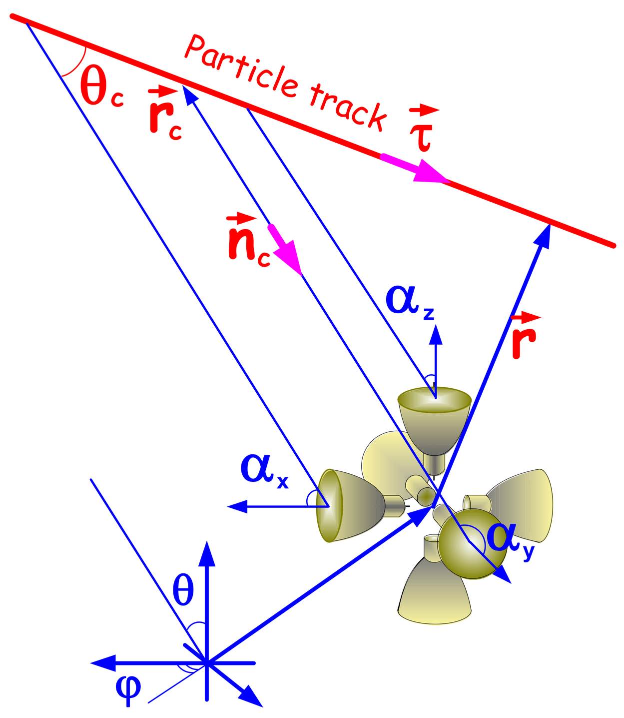
Around the CWC, the coordinate detector DECOR consisting of 8 supermodules (SM) with total area of about ~ 70 m^2 is located. Each SM consists of eight vertical planes of streamer tubes. DECOR allows reconstruction of the tracks of charged particles with high spatial (about 1 cm) and angular (better than 1°) accuracy.

For the calibration of QSM, the calibration telescope system (CTS), which consists of 80 scintillation detectors: 40 are located on the cover and 40 on the bottom of the water reservoir (upper and lower planes), is used. Any pair of detectors from upper and lower planes forms a muon telescope. Telescopes select single muons with accuracy of ~ 2º in the range of zenith angles from 0º to 50º.



For the first time, the idea of a cluster structure of OM was presented at the conference in Kyoto, 1979: *Borog V.V. et al., Proc. 16th ICRC* **10**, 380





Principle of quasispherical construction

In registration of the Cherenkov radiation from charged particles by a photomultiplier with a flat photocathode, the dependence of the response on the angle of radiation incidence on the photocathode exists. For the isotropic response of a optical module consisting of such photomultipliers it was proposed to use symmetrical clusters of several PMT. Amplitude response of the photomultiplier with a flat photocathode is expressed by a following formula:

$$A = \frac{S\cdot N\cdot\cos\alpha}{2\pi\cdot r\cdot\sin\theta_c}\cdot\exp(-r/l\cdot\sin\theta_c)$$

where S is the photocathode area, N is photon flux, l is the light attenuation length in water.
The response of a system of several PMTs has the following form:

$$B = \sqrt{\sum_{i=1}^{n} A_i^2} = \frac{C}{r}\cdot\exp(-r/l\cdot\sin\theta_c)\cdot\sqrt{\sum_{i=1}^{n}\cos^2\alpha_i}$$

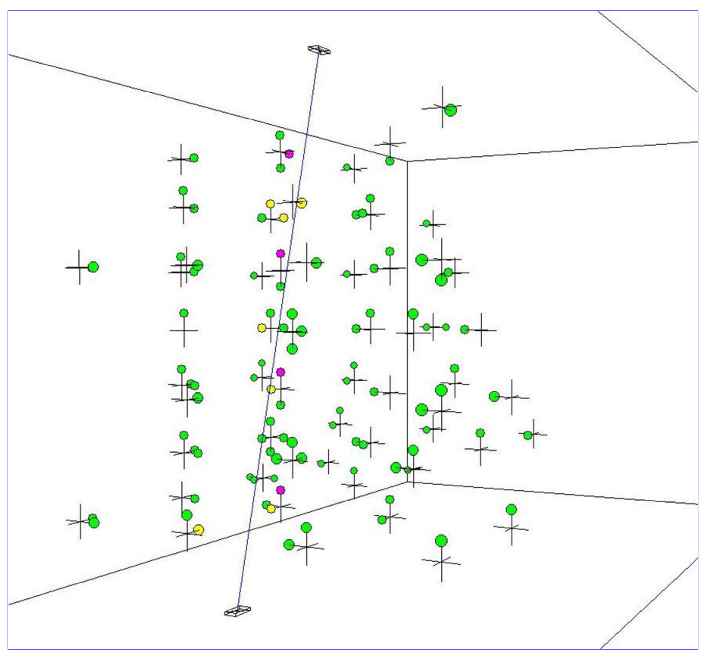
For the system of six PMTs, $\sum_{i=1}^{6}\cos^2\alpha_i = 1$

Characteristics of QSM of the NEVOD calorimeter

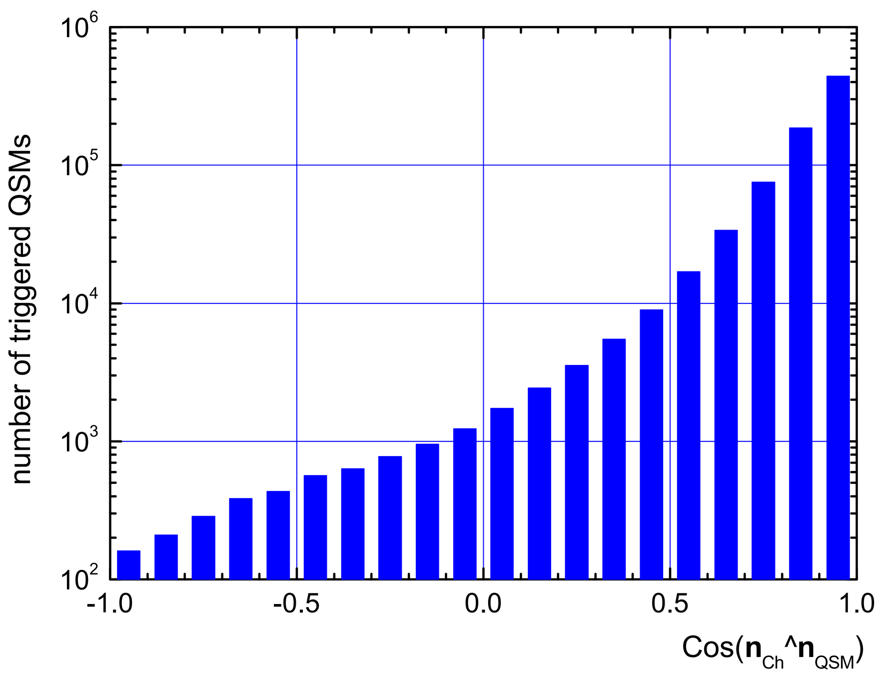
Quasispherical module consists of a waterproof aluminum housing, intra-module electronics and six FEU-200 PMT (flat photocathode with diameter of 15 cm) with plastic protective illuminators. QSM dimensions are 0.56×0.56×0.56 m^3. It includes six flat photocathode photomultipliers oriented along the axes of the orthogonal coordinate system. Such detecting system registers Cherenkov radiation from any direction with almost equal efficiency. A wide dynamic range from 1 to 10^5 photoelectrons is achieved by using signals from the 9th and the 12th dynodes. The gain between the dynodes is ~ 80. For the registration of signals from dynodes, charge-sensitive amplifiers are used. Event selection is performed by the multiplicity of three types of trigger signals for each QSM: "a" (any) – boolean "OR" of six signals from the 12th dynodes of PMT; "b" (bottom) – signal from the PMT No. 5, which photocathode is directed downwards; "c" (coincidence) – coincidence of signals from any two photomultipliers except oppositely directed, within a time gate of 150 ns. Registration threshold is set by software, minimal value is 0.25 ph.e., step is 0.025 ph.e.

Determining the direction of the Cherenkov light with one QSM

The range of directions from the muon track to the QSM is 0.5 to 2 m. For each triggered QSM, the angle between the estimated direction of light and the direction determined according to the CTS data was calculated.

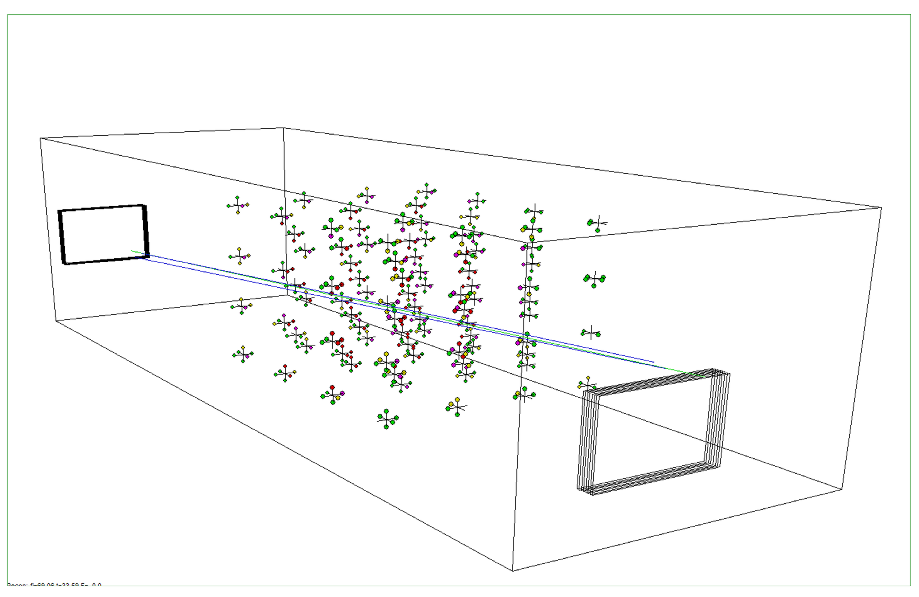


Example of the event detected with CTS: 108 PMTs are triggered (in 57 QSMs), including 31 PMTs oriented upwards, 5 PMTs oriented downwards, the total amplitude response is 0.39×10^3 ph.e.

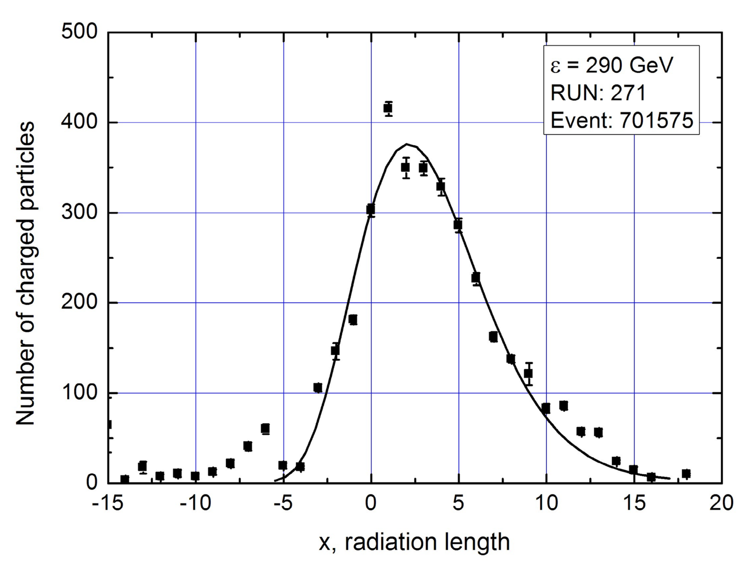


Distribution of the value of the cosine of the angle between the direction of the Cherenkov light determined according to the CTS data and its estimation using QSM responses (~ 9×10^5 events).

Calorimetric properties



Example of the event with cascade shower detected. 91 QSM are triggerd, 445 PMT, the total amplitude of the photomultipliers ~ 2.8×10^4 ph.e.



Reconstructed cascade curve of the shower detected in CWC NEVOD

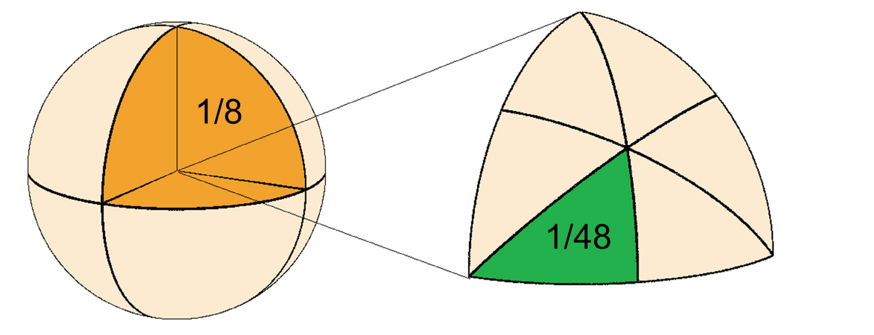
Study of the independence of the QSM response on the direction of Cherenkov light (a characteristics of the sphericity)

The study of the independence of the QSM response on the direction of Cherenkov light (the characteristics of the sphericity) was conducted. The events with single muons, detected with the pair of supermodules of the detector DECOR were used. As the characteristics of QSM response, the value of *B* was used:

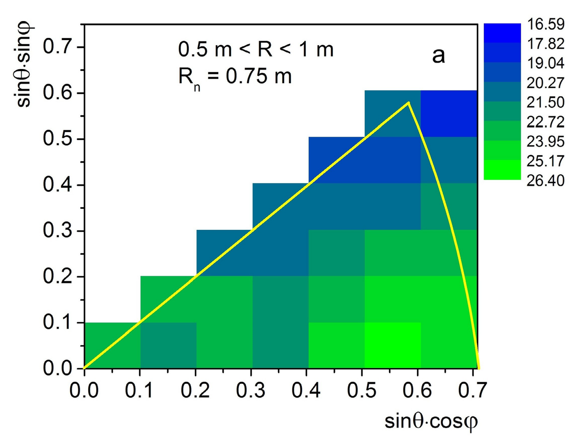
$$B = \frac{R}{R_n}\sqrt{\sum A_i^2},$$

where R_n is some normalization distance.

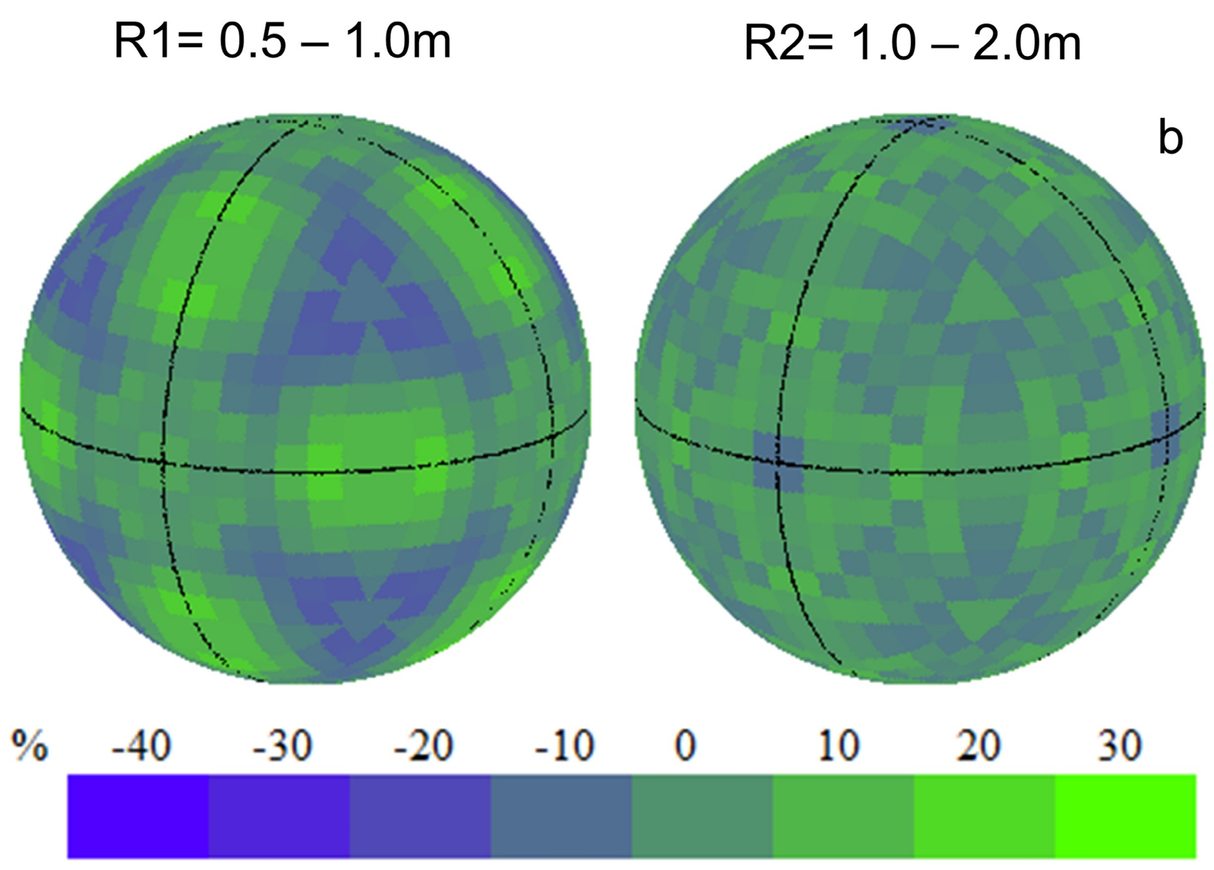
The parameters of the response of each QSM were transferred to the spherical triangle, representing the 1/48 part of the sphere. For QSM with six PMTs it is the smallest space that enables to cover the whole sphere using rotations and mirror reflections to the symmetry planes of the QSM.



The study was conducted for two ranges of distances *R* between the muon track and the center of QSM: 0.5 – 1.0 m and 1.0 – 2.0 m. The middle of each range was used as the value of normalizing distance R_n, for the ranges above these values are 0.75 m and 1.5 m, respectively. The zenith angles of single muons were limited with the range from 86° to 89°. The average values of *B* for various locations on the spherical segment are shown in the Figure (a). The borders of the projection of the spherical segment to the plane are marked with yellow lines.



For each of two ranges, the rms-deviation from the mean value of QSM response averaged over the sphere (Figure b) was calculated. This value shows the deviation from the sphericity of QSM. This value expressed in percentage equals to 8% for the range of 0.5 – 1.0 m and is less than 5% for the range of 1.0 – 2.0 m.



Conclusion

The design of the detecting module with several PMTs with flat photocathodes enables to reach the isotropic apmlitude response. The QSM with six PMTs oriented along the axes of the orthogonal coordinate system, that is used in CWC NEVOD, has good characteristics of the sphericity: for distances more than 0.5 m the rms-deviation from the mean value of QSM response is less than 8%. Besides, the configuration of PMTs with flat photocathodes enables to reconstruct the direction of Cherenkov light arrival with a single quasispherical module. The lattice of such QSMs allows to reconstruct the tracks of single muons with accuracy better than 7° and to estimate the direction and location of the axes of the showers produced in the sensitive volume of the Cherenkov detector. This gives the detector NEVOD both the hodoscopic and the calorimetric properties.

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