Status of the Baikal-GVD experiment - 2017

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Baikal-GVD is a kilometer-scale neutrino telescope under construction in Lake Baikal, which will be formed by multi-megaton subarrays – clusters of strings. A first demonstration cluster "Dubna" has been deployed in 2015 and comprises 192 optical modules (OMs). In 2016 this cluster was upgraded to the baseline configuration which comprises 288 OMs arranged at eight strings. The second full-scale GVD-cluster was deployed and put in operation in 2017. We review the present activity towards the GVD implementation and discuss some selected results obtained with the "Dubna" cluster.

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[1]Speaker

1.   Introduction

The deep underwater neutrino telescope Baikal-GVD [1] is designed to detect astrophysical neutrino fluxes at energies from a few TeV up to the highest energies of 10^6 TeV and particularly for mapping the high-energy neutrino sky in the Southern Hemisphere, including the region of the galactic center. The site chosen for the experiment is in the southern basin of Lake Baikal. Here, the combination of hydrological, hydro-physical, and landscape factors is optimal for deployment and operation of the neutrino telescope. The water depth is about 1360 m at distances beginning from about three kilometers from the shore. The water transparency is characterized by an absorption length of about 20 - 25 m and a scattering length of 30 - 50 m. The water luminescence is moderate at the detector site.

The development of the km³-scale neutrino telescope Baikal-GVD is carried out on the basis of long-term experience of operating the detector NT200 in Lake Baikal [2]. The first field tests of a new registration system of the Baikal-GVD were started in 2008 as a combined operation with the NT200. Various versions of autonomous strings of Baikal-GVD were tested and fine-tuned in the period 2009 – 2012 [3]. The design of Baikal-GVD was substantially completed in 2013 [4] and a phased deployment of the detector was launched. To date, the Baikal neutrino telescope includes the spatial structure of the 576 optical modules with an effective volume for high energy cascades of about 0.1 km³.

2.   The Neutrino telescope Baikal-GVD

The concept of Baikal-GVD is based on a number of evident requirements for the design and organization of the measuring system of the new detector: the utmost use of the advantages of mounting the telescope from the ice cover of Lake Baikal, the expandability of the system and ensure its effective operation already at the first stages of deployment, and the possibility of implementing different versions of arrangement and spatial density of photodetector location within the same measurement system.

The main detection units of the Baikal-GVD are the optical modules (OMs) [5] equipped with photomultiplier tubes Hamamatsu R7081-100 with photocathode diameter of 10" and a quantum efficiency of ~35%. The OMs are mounted on vertical load-carrying cables, forming strings which are fixed to the bottom with anchors. The choice of this approach to construction of measuring system is fit to the method of deployment of the installation from the ice surface. The strings are grouped into clusters. Each cluster is a fully functional detector which is capable of detecting a physical event both in standalone mode, and as part of a full-scale installation. Underwater modules with the electronics that manages the cluster operation (*Cluster DAQ Center*) are located close to the water surface (depth ~25 m). The *Cluster DAQ Center* is connected to the *Shore DAQ Center* by a hybrid electro-optical cable.

The full-scale neutrino telescope Baikal-GVD will be an array of about 10^4 OMs with an instrumented volume of about ~2 km³. The first phase of the installation (GVD-1) is planned to be completed by 2020. GVD-1 will comprise 8 clusters with about 2.3×10^3 OMs in total. Figure 2.1 shows the block diagram of the string, the view of Baikal-GVD cluster, and the layout of GVD-1. The triangles on the plan show the deep-water stations of the strings, circles indicate the cable stations installed to date.

Each cluster of Baikal-GVD consists of 8 strings comprising 36 optical modules each. The distance between OMs along a string is 15 meters. The bottom optical module of the string is placed at a depth of 1275 meters (about 100 m above the bottom of the lake), the top OMs are 750 meters below the lake surface. The distances between the strings in the cluster are 60 m, the distances between the centers of the clusters are 300 m.
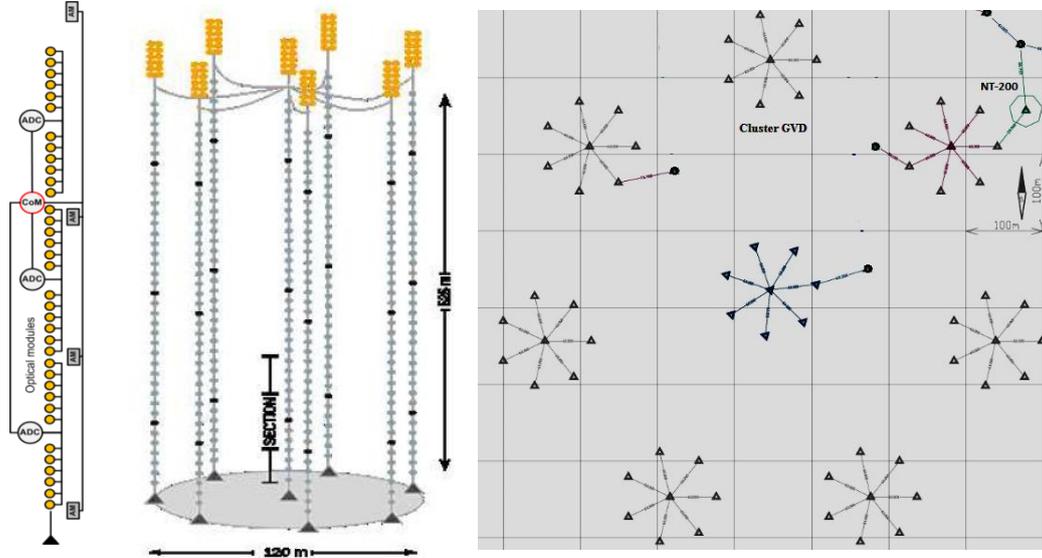

Fig. 2.1. Block diagram of the string and view of a cluster of Baikal-GVD (left), and layout of eight clusters of GVD-1 (right).

The neutrino telescope Baikal-GVD is intended to register the products of neutrino interaction, muons and cascade showers in the energy range from ~1 TeV up to 10^6 TeV. Figure 2.2 shows the effective volume for cascades and the effective area for muons of the installation for two configurations of the telescope: GVD-1 and the full-scale neutrino telescope Baikal-GVD (GVD-4).
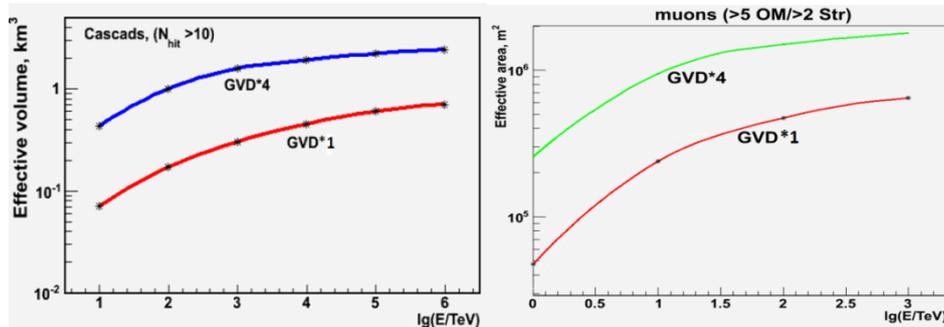

Fig. 2.2. The effective volume for the registration of cascades (left) and the effective area for muons (right) depending on the energy for GVD-1 and full-scale neutrino telescope Baikal-GVD (GVD-4).

3. Data acquisition system

The basic structural unit of the data acquisition system of Baikal-GVD [6, 7] is a *section* of OMs. A section is a functionally complete unit that includes systems of registration of radiation, calibration systems, and control electronics for the formation of trigger, the signal processing, and data transfer. Three sections of optical modules reside on the same carrying cable and form

a string. The configuration of a section, which is currently the basis for the creation of the telescope, includes 12 optical modules with analog outputs, and a Central section Module (CM), which converts analog signals into a digital code. The CM is located in the middle of the section, to minimize the lengths of cables connecting it to OMs. Each measuring channel of a section consists of PMT, preamplifier and 12-bit ADC with a sampling frequency of 200 MHz and an amplitude resolution of 1.6 mV. The conversion coefficients of the channels are leveled off at about 10^8 by adjusting the high voltage of a PMT in the range from 1100 to 1800 Volts. This provides an average single-photoelectron amplitude of the channels of ~25 ADC counts.

Grouping OMs into separate sections allows to organize inter-module coincidences for suppression of the background glow of Baikal water. Coincidences of signals from any pairs of neighboring OMs with low threshold (0.5 - 1.5 p.e.) and high threshold (3 - 4 p.e.) are used as a local trigger of the section (signal *request*). Average frequencies of the section *request* signals are about 2 - 10 Hz, in dependence of thresholds and water luminescence.

The *request* signals from three sections are combined in the Control Module of the string (CoM) and transferred to the cluster *DAQ center*, where a global trigger is formed (signal *acknowledge*). Signal *acknowledge*, returning to each section of the cluster, stops the ADCs and initiates the formation of a *master record* of the sections and data transmitting to the Cluster *DAQ center*. Each *master record* comprises the time of the trigger, the state of the counter of the acknowledge signals (used to merge records of the same event from different sections), and waveforms for all 12 channels recorded in a time window of 5 μs (1024 ADC time counts). The full length of a master record is 12×2048 bytes. The total frequency of *acknowledge* signals is 50 - 250 Hz (the sum of the frequencies of *requests* signals all sections of the cluster). Master records are transmitted to the *Cluster DAQ center* by the Ethernet network on the basis of Ethernet extenders with a transfer rate of up to 10 Mbit/s. A relatively low bandwidth of network does not allow transferring *master records* with full record size. So, *master records* are converted: a part of the records are selected in which ADC data exceeds a pedestal of the magnitude of ~0.3 single-photoelectron signal. The conversion process is implemented at the hardware level. The average size of the converted *master record* is approximately 300 bytes for the basic mode of detector operation (muon detection). This ensures reliable transmission of the full event flow.

In addition to the electronic units directly engaged in the registration process, the data acquisition system includes a number of auxiliary subsystems: control of power supply, calibration of the detector, measuring of the coordinates of the optical modules. The system of power control allows disabling, if necessary, any of the underwater modules of the installation. Managed power switches, installed in the center of the cluster, in each string and in each section are used for these purposes. The calibration setup comprises LED light sources installed in each optical module (for amplitude and time calibration of the channels) and separate underwater modules with LEDs (for time calibration of the sections). The laser light source is used for the calibration of the cluster as a whole.

The coordinates of the optical modules are determined using an acoustic positioning system. Acoustic positioning system of the cluster comprises 32 acoustic modems (AM). Four AMs are mounted on each string on the distances from of the string bottom 1, 181, 346, and 538 meters. The coordinates of the AMs are measured with an accuracy of ~2 cm. Linear

interpolation is used to determine the coordinates of the optical modules located between acoustic modems

4.   The configuration of Baikal-GVD 2017

The modular structure of the neutrino telescope Baikal-GVD provides the ability to conduct physical research in the early stages of the detector construction using different configurations of the installation. The stages of deployment the neutrino telescope Baikal-GVD and the corresponding configuration of the measuring system are presented in Table 4.1. The first cluster consisting of 8 strings with 24 OMs on each (two sections) was put into operation in 2015 [8]. The first cluster was upgraded to baseline configuration (three sections on the string) in 2016. The second cluster Baikal-GVD was commissioned in April 2017.

Table 4.1. Stages of deployment of the Baikal-GVD

Configuration of the detector	2015	2016	2017
Number of optical modules	192	288	576
Geometrical sizes	$\varnothing$80m×345m	$\varnothing$120m×525m	2×$\varnothing$120m×525m
Effective volume ($E_{sh} > 1$ PeV)	0.03 km^3	0.05 km^3	0.1 km^3

Two full-scale clusters of Baikal-GVD were installed in Lake Baikal and are successfully operating now. Figure 4.1 shows the present layout of the installation and the cumulative number of the master records for two clusters.
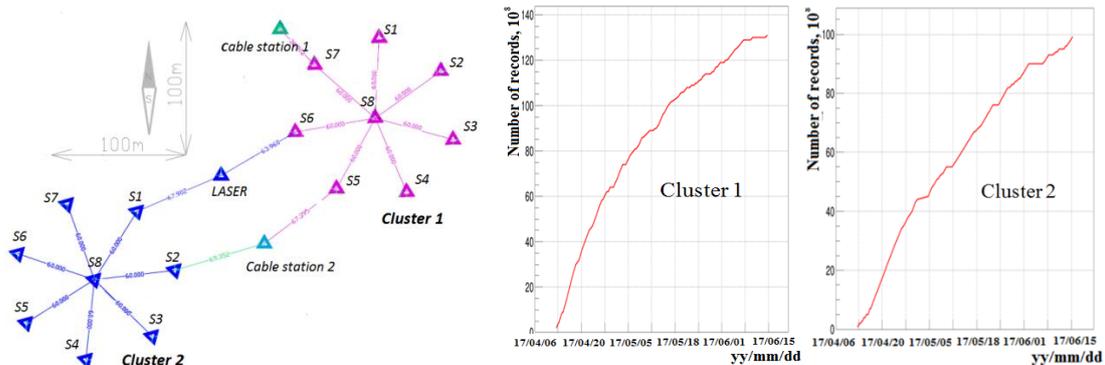

Fig. 4.1. Layout of the installation and cumulative number of the *master records* detected with two clusters (since April 13 to June 15 of 2017).

Each cluster consists of 8 *Strings* (*S1 ... S8*) and the cluster *DAQ center*, located on the central string (*S8*). The cluster *DAQ centers* are connected to the *Shore center* by hybrid opto-electrical cables providing power supply (300 VDC) and data transmission. Additional cable stations are installed to guide the cables to the desired level from the lake bottom to ~25 meters below the lake surface and to connect them to the *Cluster DAQ centers* (see Fig. 4.1). The laser calibration source is mounted on a separate station (*Laser string*) between two clusters. Two additional acoustic modems are installed on the *Laser string* to measure its coordinates.

The deployment of the first cluster of Baikal-GVD was carried out in stages, simultaneously with the debugging and upgrading of the equipment of the data acquisition system. In particular, it includes different versions of the ADC boards. Currently, two ADC boards of the first version work unstable, which led to the need to exclude 24 channels from the

configuration. All ADC boards of the second version, which used in the second cluster, are operating reliably now.

Table 4.2 shows the statistics of the cluster operation in the period from April 13 to June 15, 2017. About 10^7 events containing more than 3×10^8 *master records* were detected within two months. The efficiency of the detector operation was about 85%.

Table 4.2. Statistic of two clusters operation since April 13 up to June 15 of 2017.

Number of RUNs	Duration of the work, days	Efficiency, %	Master records
Cluster-1: 130	64.3	84.4	1.87×10^8
Cluster-2: 117	64.0	87.6	1.45×10^8

The first tests of a new laser calibration source were carried out during this period. The laser emits at a wavelength of 532 nm, the pulse energy reaches a value of 0.37 mJ (~10^{15} photons), the flash duration is about 1 ns. A light diffuser is installed at the output of the laser beam.

The laser is installed at about the same depth as the center of the lower sections. An example of a laser event detected with Cluster-1 is presented in Fig. 4.2. The dots show the time of registration of the laser pulse by the detector channels. Time calibration of the channels was provided by an independent method using LED calibration sources of the cluster. The numbering of the channels starts with the bottom OM of the first string: from 1 to 288. The solid lines show the expected times obtained from calculating the light propagation from the laser to the strings. Laser flashes are reliably detected by all channels of the lower and middle sections of the strings. The lack of data on the second section is due to the fact that two sections were excluded from the configuration.
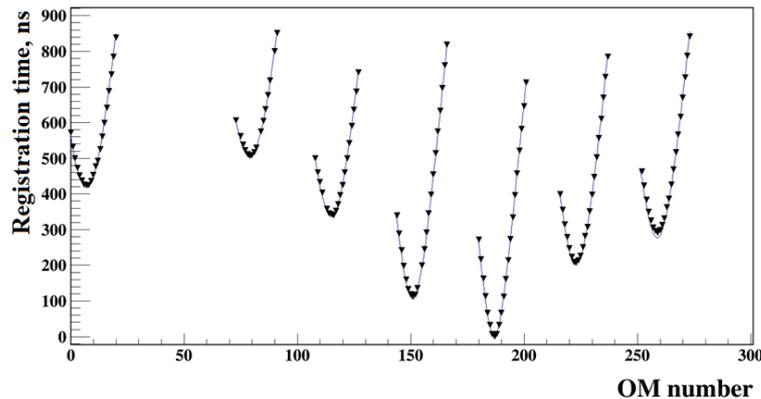

Fig. 4.2. An example of a laser event detected with the cluster of Baikal-GVD.

The expected time of the signals were calculated using the information about string and laser positions that have been provided by the acoustic positioning system. It should be noted that while the bottom of the strings is rigidly fixed at the lake bed by anchors, the top remains not fixed. This leads to significant deviations of the strings from the vertical position due to the impact of currents of Lake Baikal. Fig. 4.3 shows the results of measurements of *x* and *y* coordinates by acoustic modems for different distances *z* to the anchors. The measurements were performed continuously with a period of about 2 minutes during the whole time of the detector operation in 2017. The figure shows that with increasing height of the location of the

modem, the maximum deviation of the positions in the *X-Y* plane increases from ~1 m to ~10 m.
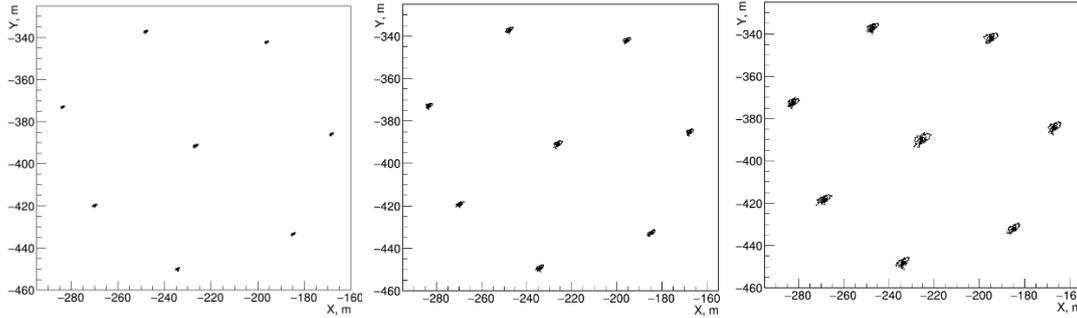

Fig. 4.3. The results of the measurement of the position of the acoustic modems (AMs) installed on the eight strings of the cluster for different distances from AM to the string bottom: *z* = 181 m (left), *z* = 346 (center), *z* = 538 m (right).

The good agreement between measured and expected time of registration of the laser flashes (see Fig. 4.2) indicates the correctness of the channel calibration and a sufficiently high positioning accuracy of the optical modules measured by the acoustic system.

5.   Cascade shower detection

The registration of neutrinos with Baikal-GVD is carried out by detecting the products of their interactions which appear as muon tracks and cascade showers. A data sample obtained with the first cluster of Baikal-GVD in the period 24 Oct to 17 Dec 2015 was used for investigating and checking the methods of the selection from background events and reconstruction of the cascade showers (41.6 days of the detector live time). About 4.4×10^8 triggered events were detected by the array during this time period. After applying several selection cuts and reconstruction of cascades vertex, energy and direction, 1192 events with reconstructed energies E >100 TeV have been selected. Fig. 5.1 shows the distribution of these events with respect to the multiplicity of triggered channels. The experimental distribution is consistent with the expectation from atmospheric muons for multiplicities N_{hit} < 10. The expected N_{hit} distributions for events induced by atmospheric neutrinos and neutrinos of astrophysical nature (IceCube $E^{-2.46}$ neutrino spectrum) are also shown in Fig. 5.1.
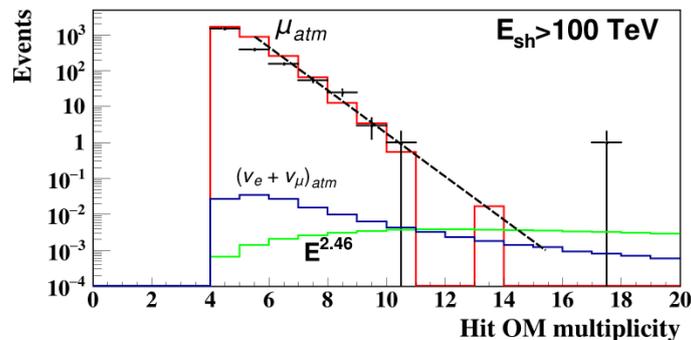

Fig. 5.1. The multiplicity distribution of hit channels for cascade-like events with energies above 100 TeV; points - experiment, red line - background of atmospheric muons, blue line - background of atmospheric neutrinos, green line - expected signal from astrophysical neutrinos. One eye-catching event with N_{hit} = 17 was found in the selected data sample. This event was reconstructed as high-energy cascade with an energy of 107 TeV and a zenith angle of 56.6°. The expected

probability of an event with N_{hit} >16 is about 5% for astrophysical neutrino flux, and less than 1% for atmospheric neutrinos. More MC-simulation statistics is required for a precise estimation of the expected probability of such events for atmospheric muons. The presented methods of selection of the high energy cascades are currently used for the analysis of data recorded by the Baikal-GVD during 2016.

6. Conclusion

The ambition of the Baikal collaboration is to construct a km^3-scale neutrino telescope: the Gigaton Volume Detector in Lake Baikal, with implementation of about ten thousand photo-detectors. The stage of prototyping of the GVD project has been performed since April 2011 and aimed at comprehensive in situ tests of all elements and systems of the future detector. This phase was concluded in 2015 with the deployment and operation of the first demonstration cluster "Dubna". In 2016 this array was upgraded to the baseline configuration of a GVD cluster with 288 OMs arranged on eight vertical strings. The second full-scale GVD cluster was installed and commissioned in April 2017. The operation of both clusters has been successfully tested with the use of a new laser calibration source that was mounted in this year. The effective volume of a present GVD configuration for high energy cascades is about 0.1 km^3. The commissioning of the first stage of the Baikal neutrino telescope GVD-1 with an effective volume 0.4 km^3 is envisaged for 2020.

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