BAIKAL-GVD

Deep underwater muon and neutrino detector on Lake Baikal (Gigaton Volume Detector)

JINR Group

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Dubna 2017

Form No. 24

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BAIKAL-GVD

CODE OF THEME 03-2-1100-2010/2018

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NAMES OF PROJECT LEADERS: I.Belolaptikov

NAME OF PROJECT DEPUTY LEADERS:

DATE OF SUBMISSION OF PROPOSAL OF PROJECT TO SOD _________

DATE OF THE LABORATORY STC _________ DOCUMENT NUMBER _________

STARTING DATE OF PROJECT January 2019 (FOR EXTENSION OF PROJECT — DATE OF ITS FIRST APPROVAL) December 2011

Form No. 25

PROJECT ENDORSEMENT LIST

Deep underwater muon and neutrino detector on Lake Baikal

BAIKAL-GVD

CODE OF THEME 03-2-1100-2010/2018

NAME OF PROJECT LEADER: Igor Belolaptikov

APPROVED BY JINR DIRECTOR	SIGNATURE	DATE

ENDORSED BY

JINR VICE-DIRECTOR	SIGNATURE	DATE
CHIEF SCIENTIFIC SECRETARY	SIGNATURE	DATE
CHIEF ENGINEER	SIGNATURE	DATE
HEAD OF SCIENCE ORGANIZATION DEPARTMENT	SIGNATURE	DATE
LABORATORY DIRECTOR	SIGNATURE	DATE
LABORATORY CHIEF ENGINEER	SIGNATURE	DATE
PROJECT LEADER	SIGNATURE	DATE
PROJECT DEPUTY LEADERS	SIGNATURE	DATE

ENDORSED

RESPECTIVE PAC	SIGNATURE	DATE

Form № 26

Schedule proposal and resources required for the implementation of the Project BAIKAL-GVD

Expenditures, resources, financing sources			Cost of parts (US$), resources needs	Proposals of the Laboratory on the distribution of finances and resources		
				1st year	2nd year	3rd year
Main parts and equipment	1. Underwater optical module elements		8430K	2810K	2810K	2810K
	2. Underwater connectors		2100K	700K	700K	700K
	3. Elements of underwater electronic system of control and data acquisition		1950K	650K	650K	650K
	4. Elements of underwater cable communications		1500K	500K	500K	500K
	5. Elements of the acoustic positioning system		2400K	800K	800K	800K
	6. Infrastructure development and vehicles		2400K	800K	800K	800K
	7. Electro-optical cable and deployment tool		1800K	600K	600K	600K
	Total		**20580K**	**6860K**	**6860K**	**6860K**
Resources	Standard hour	JINR workshop	6000	2000	2000	2000
		DLNP workshop	3300	1100	1100	1100
Financial sources	Budgetary resources	Budget spending	**18000K**	**6000K**	**6000K**	**6000K**
	External resources	Contribution from collaboration(s); Grants; Sponsors; Contracts; Other sources	**3000K**	**1000K**	**1000K**	**1000K**

PROJECT LEADER I.A.BELOLAPTIKOV

Form № 29

Estimate of expenditures for the project BAIKAL-GVD, Deep underwater muon and neutrino detector on Lake Baikal

#	Designation for outlays	Full cost	1st year	2nd year	3rd year
Direct expenses for the project					
1.	Networking	30.0K US$	10.0	10.0	10.0
2	DLNP workshop	3300 h.	1100	1100	1100
3.	JINR workshop	6000 h.	2000	2000	2000
4.	Materials	14280.0K US$	4760.0	4760.0	4760.0
5.	Equipment	6300.0K US$	2100.0	2100.0	2100.0
6.	R&D on a contract base	60.0K US$	20.0	20.0	20.0
7.	Travel expenses	180.0K US$	60.0	60.0	60.0
	Total	**20850.0K US$**	**6950.0K$**	**6950.0K$**	**6950.0K$**

PROJECT LEADER

LABORATORY DIRECTOR

LABORATORY CHIEF ENGINEER-ECONOMIST

Форма № 26

Предлагаемый план-график и необходимые ресурсы для осуществления проекта **BAIKAL-GVD**

Наименования затрат, ресурсов, источников финансирования			Стоимость (тыс. долл.). Потребности в ресурсах	Предложение лаборатории по распределению финансирования и ресурсов		
				1 год	2 год	3 год
Затраты	1. Элементы глубоководного оптического модуля (ФЭУ, стеклосферы, электроника)		8430K	2810K	2810K	2810K
	2. Глубоководные разъемы		2100K	700K	700K	700K
	3. . Элементы подводной электронной системы управления и сбора данных		1950K	650K	650K	650K
	4. Элементы подводных кабельных коммуникаций		1500K	500K	500K	500K
	5. Элементы системы позиционирования		2400K	800K	800K	800K
	6. Транспортные ср-ва и развитие инфраструктуры		2400K	800K	800K	800K
	7. Оптоэлектрический кабель и средства развертывания		1800K	600K	600K	600K
	Итого		**20580K**	**6860K**	**6860K**	**6860K**
Необходимые ресурсы	**Нормо-час**	ОП ОИЯИ	6000	2000	2000	2000
		ООЭП ЛЯП	3300	1100	1100	1100
Источники финансирования	Бюджетные средства	Затраты из бюджета, в том числе инвалютные средства	**18000K**	**6000K**	**6000K**	**6000K**
	Внебюджетные средства	Вклады коллаборантов. Средства по грантам. Вклады спонсоров. Средства по договорам. Другие источники финансирования и т.д	**3000K**	**1000K**	**1000K**	**1000K**

РУКОВОДИТЕЛЬ ПРОЕКТА И.А.Белолаптиков

Form № 29

Смета затрат по проекту BAIKAL-GVD, Глубоководный детектор мюонов и нейтрино на оз. Байкал

NN пп	Наименование статей затрат	Полная стоимость	1 год	2 год	3 год
	Прямые расходы на Проект	.			
1.	Компьютерная связь	30.0K $	10.0	10.0	10.0
2	ООЭП ЛЯП	3300 h.	1100	1100	1100
3.	ОП ОИЯИ	6000 h.	2000	2000	2000
4.	Материалы	14280.0K $	4760.0	4760.0	4760.0
5.	Оборудование	6300.0K $	2100.0	2100.0	2100.0
6.	Оплата НИР, выполняемых по договорам	60.0K $	20.0	20.0	20.0
7.	Командировочные расходы	180.0K $	60.0	60.0	60.0

Итого по прямым расходам **20850.0K $** **6950.0K$** **6950.0K$** **6950.0K$**

РУКОВОДИТЕЛЬ ПРОЕКТА

ДИРЕКТОР ЛАБОРАТОРИИ

ВЕДУЩИЙ ИНЖЕНЕР-ЭКОНОМИСТ ЛАБОРАТОРИИ

1. Abstract

The construction of the Baikal-GVD neutrino telescope is motivated by its discovery potential in astrophysics, cosmology and particle physics. Its primary goal is the detailed study the diffuse flux of high-energy cosmic neutrinos and the search for their sources. It will also search for dark matter candidates (WIMPs), for neutrinos from the decay of super heavy particles, for magnetic monopoles and other exotic particles. It will also be a platform for environmental studies in Lake Baikal. The detector will utilize the deep water of Lake Baikal instrumented with optical modules (OMs) – pressure resistant glass spheres with large photo-multiplier tubes (PMTs), which record the Cherenkov radiation from secondary particles produced in interactions of high-energy neutrinos inside or near the instrumented volume. The Infrastructure will consist of a network of autonomous subdetectors - so-called clusters – each of them with 288 OMs arranged at eight vertical strings attached to the lake floor. The clusters are connected to shore via a network of cables for electrical power and high-bandwidth data communication. The large cubic-kilometer scale detection volume, combined with high angular and energy resolutions and moderate background conditions in fresh lake water allows for efficient study of cosmic neutrinos, muons from charged cosmic rays and exotic particles. It is also an attractive platform for environmental studies.

During the Design Study (2008–2010) and the Preparatory Phase (2011–2015), design, production and comprehensive in-situ tests of all elements and systems of the future detector have been performed. The Preparatory phase was concluded in 2015 with the deployment of a demonstration cluster "Dubna" comprising 192 OMs. The construction of the first phase of Baikal GVD (GVD-I) was started in 2016 by deployment of the first cluster in its baseline configuration. In 2017, the array was upgraded by the deployment of the second GVD cluster. Commissioning of GVD-I (8 clusters, effective volume ~0.4 km3) is envisaged for 2020. The second stage GVD-II with 14 clusters will be completed by 2023.

2. Introduction

The Baikal-GVD neutrino telescope will study the most violent processes in the Universe, which accelerate charged particles to highest energies, far beyond the reach of laboratory experiments on Earth. These processes must be accompanied by the emission of neutrinos. The large detection volume, combined with high angular and energy resolution and moderate background conditions in fresh lake water allows for an efficient study of the diffuse neutrino flux and of neutrinos from individual astrophysical objects, be they steady or transient. Multi-messenger methods will be used to relate our findings with those of classical astronomers and with X-ray or gamma-ray observations. A high-energy diffuse astrophysical neutrino flux has been observed recently by IceCube, using track-like and cascade-like events. GVD-I will have a detection volume for cascades of about 0.4 km^3, which is approximately the same as the fiducial volume of IceCube for this detection mode. That guarantees the detection of astrophysical neutrinos during the GVD's first years of operation. We will scrutinize the IceCube result and study in detail the energy spectrum, the global anisotropy and the neutrino flavor composition of the diffuse neutrino flux. This flux must have been formed by neutrino emission of the entire set of Galactic and extragalactic sources during the period from remote cosmological epochs to the present day. Extragalactic sources make a major contribution to this flux. The neutrinos produced by the interaction of cosmic rays with interstellar matter and, in the case of ultra-high-energy cosmic rays, with electromagnetic radiation from a wide energy range including the cosmic microwave background, do also contribute to the diffuse flux. It should be noted that the neutrinos from the decay of supermassive particles associated, in particular, with Grand Unified Theories (GUT) (top-down scenarios) might account for a certain fraction of the diffuse flux. The high angular resolution of GVD for track-like or cascade-like events (~0.25° for muon tracks and ~2° for cascades, respectively) provides a high capability for identifying point-like cosmic-ray accelerators. The closest (with respect to a terrestrial observer) astrophysical objects that are currently assumed to be capable of emitting high-intensity neutrino fluxes are located mainly in the vicinity of the Galactic center and in the Galactic plane. Supernova remnants, pulsars, the neighborhood of the black hole Sgr A* at the Galactic center, binary systems comprising a black hole or a neutron star, and clusters of molecular clouds are the most promising Galactic sources with respect to the detection of their neutrino emission. The energy of neutrinos from Galactic sources is assumed to span the energy range 10^3 - 10^6 GeV. The long-term priority goal of Baikal-GVD is to find neutrinos from the cosmic-ray accelerators in our Galaxy. The search strategy is to identify upward-moving muons, which unambiguously indicate neutrino reactions since only neutrinos can traverse the Earth without being absorbed. Located in Northern hemisphere, Baikal-GVD is excellently positioned to observe Galactic sources, in contrast to the IceCube detector at the South Pole which is much less sensitive to Galactic sources (at least in the energy range where most of the signal flux is expected). Extragalactic objects — like Active Galactic Nuclei (AGN), Gamma-Ray Bursts (GRB), starburst galaxies and galaxy clusters — are another class of neutrino sources to be targeted by Baikal-GVD. These sources are characterized by a much higher energy release and generate neutrinos in the energy range 10^4-10^8 GeV or higher. Baikal-GVD will substantially contribute to multi-messenger astronomy studies. Multi-messenger astronomy is the combination of observations in cosmic rays, neutrinos, photons of all wavelengths and even gravitational waves. It represents a powerful tool to study the physical processes driving the non-thermal Universe. The alert system of GVD will allow for a fast, on-line reconstruction of neutrino events recorded by GVD and – if predefined conditions are satisfied – for the formation of an alert message to the other communities. By combining information provided by the Baikal-GVD neutrino telescope with that coming from other observatories, the probability of detecting a source is enhanced, leading to the principal possibility to identify a neutrino progenitor from a single detected neutrino event. Another approach within the context of multi-messenger studies is an off-line combined analysis of data of experiments recording different messengers. Combined analyses of cosmic high-energy neutrinos with spatially or temporarily coinciding gamma-rays (or spatially coinciding ultra-high energy cosmic rays) again lead to a higher significance of the combined results.

3. State-of-the-art of the science case proposed

The construction of a large infrastructure is the only way to perform high-energy neutrino astronomy with the necessary sensitivity. Worldwide, three neutrino telescopes are in operation or under construction: IceCube at the South Pole, KM3NeT in the Mediterranean See and GVD in Lake Baikal. IceCube is the first Gigaton neutrino detector ever built and was primarily designed to do high-energy neutrino astronomy. It consists of 5,160 digital optical modules (DOMs), each housing a photomultiplier tube. The DOMs are attached to vertical “strings,” frozen into 86 boreholes, and covering a cubic kilometer of ice. The strings have a horizontal spacing of 125 m and hold 60 DOMs each. The vertical spacing of the DOMs is 17 m. Eight of these strings at the center of the array have a horizontal spacing ~ 70 m and a vertical spacing of 7 m). This denser configuration forms the DeepCore subdetector, which lowers the neutrino energy threshold to about 10 GeV, creating the opportunity to study neutrino oscillations, in addition to the mentioned primary goal.

The KM3NeT Collaboration has started to build a new RI consisting of a network of deep-sea neutrino detectors in the Mediterranean Sea. In its Phase-2 it will consist of three building blocks, each with 115 vertical strings. One string carries 18 DOMs: pressure resistant spheres with 31 photosensors each. Two deep-sea sites are selected according to the optical properties of the water, distance to shore, and local infrastructure. The first KM3NeT building block (“ORCA”) will be densely configured to precisely measure atmospheric neutrino oscillations. Two more KM3NeT building blocks (“ARCA”) will be wider spaced to cover a volume of 0.5-0.6 km^3 each. Like Baikal-GVD, ARCA will address neutrinos of astrophysics origin in the TeV to PeV energy range. To date, only one string with total of 36 optical modules are operating in ORCA site.

Construction of Baikal-GVD was started in 2016. To date, the array comprises a total of 576 optical modules attached to 16 strings (2 clusters) and is taking data. IceCube is not adequate to search for sources close to the Galactic center due to its geographical location. Moreover, it has a moderate angular resolution which limits its capabilities to identify point sources. KM3NeT does not suffer from these limitations, but since high-energy neutrino events are rare, more effective volume is a key for discovery, irrespective whether it is, e.g., a third KM3NeT block in Greece or GVD in Lake Baikal. This makes KM3NeT and GVD, in a sense, “additive”. Also, the different systematics (sea water and fresh water, shallow vs. deep depth, configuration of detectors) make KM3NeT and GVD complementary. Another important aspect is the vulnerability to single point failures. IceCube has the least vulnerability (each DOM independently connected to the surface), Baikal the second least (with each of the 8 clusters of Phase-1 with its own shore cable), while KM3NeT has one shore cable for a full block of 115 strings. Therefore, for GVD the danger to miss neutrinos from a transient event (e.g. a gamma ray burst) is potentially smaller.

The Table below shows foreseen and realized so far plans of KM3NeT and Baikal-GVD implementation.

KM3NeT				
	2015	2016	2017	2020
Foreseen			24 Str. ARCA 7 Str. ORCA	230 Str.(ARCA) 115 Str. (ORCA)
Realized so far	1 DU (36 OMs) ARCA	2 DUs (72 OMs) ARCA	1 DU (36 OMs) ORCA	
Baikal-GVD-1				
Foreseen	*Dubna* 192 OMs	1 Cluster 288 OMs	2 Clusters 576 OMs	8 Clusters 2304 OMs
Realized so far	*Dubna* 192 OMs	1 Cluster 288 OMs	2 Clusters 576 OMs	

In a case of the Baikal-GVD array implementation is realized according to the plans. In a case of KM3NeT, about of 2 years delay comparing to initial schedule is expected now, which is caused by several failures in ARCA and ORCA sites during 2015-2017.

4. Main results for the previous design, preparatory and implementation period

The predecessor of Baikal-GVD, the detector NT200, has been operated for 15 years, proving the ability to construct and operate such detectors in Lake Baikal. The specific innovations that were made for Baikal-GVD have been validated with several prototype strings and engineering arrays which were successfully operated during 2008-2015. New optical modules, FADC readout units, underwater communications and trigger systems have been tested in situ by long-term operating prototype strings integrated in NT200 (2008-2010). The first engineering array which comprised all the key elements of the measuring and communication systems of a GVD cluster was successfully operated since April 2011. It consisted of 24 optical modules (OMs) arranged at 3 strings and was connected to shore by the first GVD electro-optical cable. The objective of this installation was to check the trigger approaches, the time calibration procedures, a new acoustic positioning system, and to compare expected and observed performances of the measuring system. In April 2012, the next version of an engineering array with 36 OMs was deployed in Lake Baikal. This array consisted of two short and one long string. Both short strings carried 6 OMs combined in a “section”. The long string comprised 24 OMs with Hamamatsu-R7081HQE PMTs combined in two sections. The vertical spacing of OMs was 15 m. This string was at the same time the first string of the GVD demonstration cluster from 2015. The next important step was made in 2013 by the deployment of an enlarged engineering array with 72 OMs at three 345 m long strings of the GVD demonstration cluster, as well as an instrumentation string with calibration and environment monitoring equipment. The vertical spacing of OMs was 15 m, the distance between strings ~40 m. In addition to the OMs, each string comprised a communication module (CoM), and two central modules of the sections (CeM), as well as one transmitter and three receivers of the acoustic positioning system. The modified cluster DAQ-center was located at a separate cable station and connected to shore by an electro-optical cable. In 2014, the second stage of the demonstration cluster with 112 OMs on five strings plus an instrumentation string with auxiliary equipment was deployed. It was operated during 2014 in data taking and testing modes.

In April 2015 the Baikal-GVD demonstration cluster named *Dubna* was deployed and started operation, in accordance with the time schedule of the project. The *Dubna* cluster enclosed 1.7 Megatons of water. It comprised a total of 192 OMs at eight 345 m long strings, as well as an acoustic positioning system, accompanied by the instrumentation string. Each string carried 24 OMs at depths of 910 m to 1260 m. The seven side strings were located at a reduced radius of 40 m (instead of the baseline radius of 60 m) around the central one in order to increase the acceptance of low-energy atmospheric muons and neutrinos which are used for array calibration. During 213 days (April 2015 till February 2016), 1.6×10^9 events were recorded (operation efficiency ~72%). The search for high-energy neutrinos with the *Dubna* array was based on the selection of cascade events generated by neutrino interactions in the sensitive volume of array and a corresponding data sample of $4.4\text{x}10^8$ events. After applying several selection cuts and reconstruction of cascades vertex, energy and direction, 1192 events with reconstructed energies $E > 100$ TeV have been selected. With the exception of one event, all events had hit multiplicities <10 OMs and were consistent with expected background events from atmospheric muons. One promising event with 17 hit OMs was reconstructed as downward moving cascade. Results obtained with this analysis demonstrated the high quality of data, as well as the efficiency of the analysis procedures. The deployment and operation of the *Dubna* cluster concluded the Preparatory Phase.

The demonstration cluster "DUBNA"

The construction of the Baikal-GVD Phase-1 (GVD-1) has started in 2016 when the *Dubna* demonstration cluster was upgraded to the baseline configuration of a GVD cluster with 288 OMs. 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 located 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.

The basic structural unit of the data acquisition system of cluster 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 (which was deployed in 2017) 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.

The array took data over 235 days from April 2016 till February 2017 and recorded 4.9×10^{8} events.

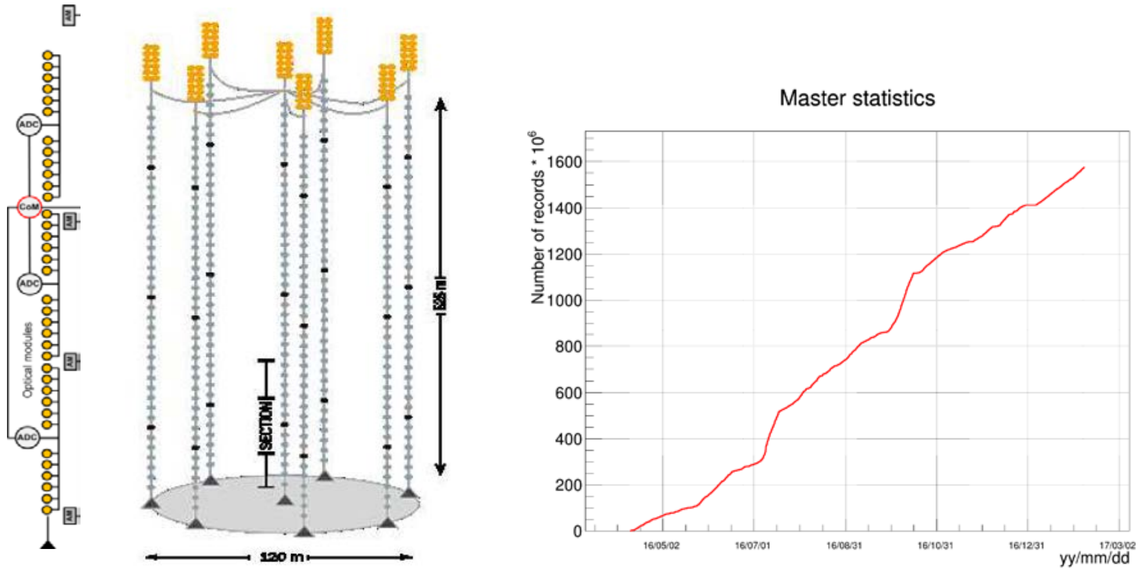


Fig. 1. Block diagram of the string and view of a cluster of Baikal-GVD (left), and cumulative number of the *master records* detected by first cluster (since April 10 to February 16 of 2017).

Muons

The collection of runs demonstrating moderate noise rates and taken in June-July 2016 was selected for the atmospheric muons flux analysis. Reconstruction software has been developed and applied for the atmospheric muon reconstruction. Reconstruction is performed in two distinct stages. First one is the rejection of OM noise and thus selection of OM impulses generated by photons accompanying muon propagation. And the second one is the search for muon track optimal for the collection of found impulses. The developed method of noise rejection allows to reduce fraction of noise impulses to 2%. The optimal muon track is found using minimization function employing impulse time, distance from track and amplitude information. Reconstruction was applied to the data collected by first full-scale cluster deployed in 2016. Monte Carlo (MC) samples with ideal geometry and realistic noise measured in the cluster in these dates were used for the reconstruction performance study and comparison to the data (Figure 1).

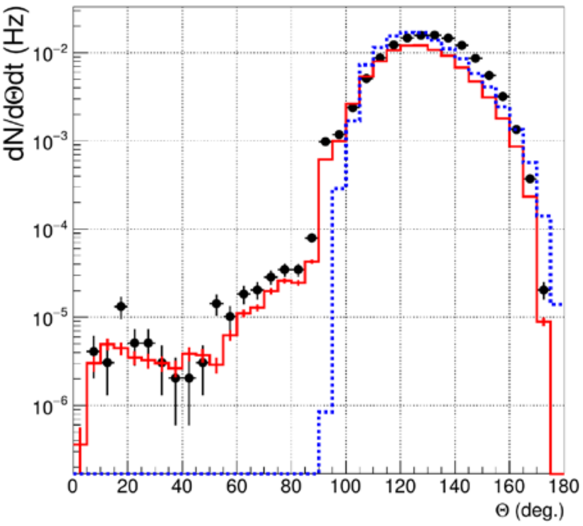


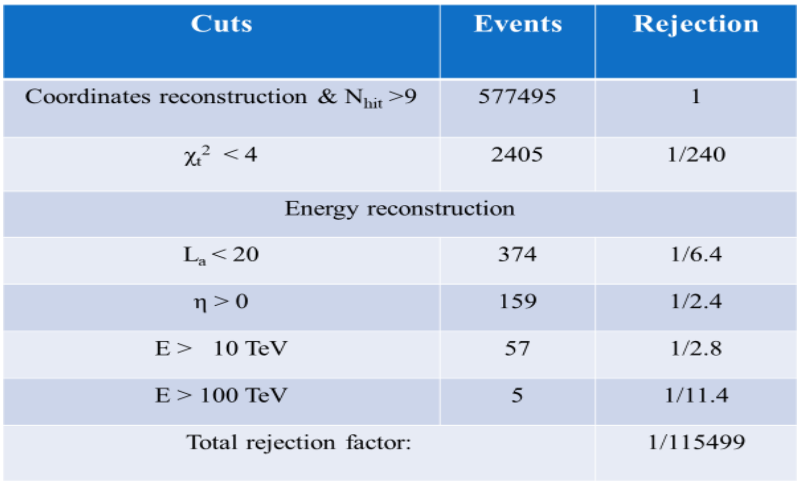
Fig. 1. Polar angle distribution of muons selected with the requirement of at least 6 hit OM's at 3 strings. Data (black dots) is compared to the atmospheric muon flux generated with CORSIKA (dashed histogram) and passed through the detector simulation (histogram).

Reasonable agreement of polar angle distributions in data and MC in shape is observed however total rate of muons in data is 1.5 times larger than in MC. Fraction of misreconstructed as upgoing tracks is 0.2% these tracks constitute background to the upgoing neutrino signal. Rejection of misreconstructed tracks is possible with various quality cuts. The procedure of neutrino selection is under development now.

Cascades

For search for high-energy neutrino flux of astrophysical origin the data collected from 10 April 2016 till 7 January 2017 have been used. A data sample of 4.86×10^{8} events has been accumulated by array trigger and requirement of $N_{hit}>4$ hit OMs with charge higher 1.5 ph.el., which corresponds to 182 array live days. Causality cuts rest about 3.27×10^{8} events for further analysis. After applying an iterative procedure of cascade vertex reconstruction for hits followed by the rejection of hits contradicting the cascade hypothesis on each iteration stage, 577495 events with $N_{hit} >9$ survived as cascade-like events. At the next step of analysis, the cuts were applied on allowed values of the following observables: the quality parameter of shower vertex reconstruction - χ_t^2, the negative log-value of maximum likelihood function of shower energy and direction reconstruction procedure - L_a, quality parameter η which depends on the probability of hit OMs to be hit and non-hit OMs to be non-hit, and estimates the consistency of event with shower hypothesis. Table 1 shows the applied cuts, value of survived events and cut efficiency.

Table 1. Quality cuts, number of survived events and efficiency of cuts.



Cuts	Events	Rejection
Coordinates reconstruction & $N_{hit} >9$	577495	1
$\chi_t^2 < 4$	2405	1/240
Energy reconstruction		
$L_a < 20$	374	1/6.4
$\eta > 0$	159	1/2.4
E > 10 TeV	57	1/2.8
E > 100 TeV	5	1/11.4
Total rejection factor:		1/115499

Hit OM multiplicity distributions of events surviving after cuts, which were described in Table 1, are shown in Fig.2 (left) by different colours from top to bottom of panel. Total of 57 events were selected as showers with energy E > 10 TeV, and 5 events with E >100 TeV. Four events with E > 100 TeV have rather low hit multiplicities $N_{hit} < 15$, as is expected for background events from atmospheric muons. One event was reconstructed as shower-like event with $N_{hit} = 38$ OMs. Reconstructed coordinates in z,ρ-plain (z – vertical coordinate, ρ - distance from central string of cluster) of events with E >10 TeV (blue dots), >30 TeV (green dots) and E >100 TeV (red dots) are shown in Fig.2 (right). Dashed lines indicate an instrumented water volume. Event with high multiplicity is reconstructed as contained event and is indicated by arrows in Fig.2. For more precise reconstruction of cascade parameters, this event was reanalysed including hits with amplitudes lower 1.5 ph.el.. Total of 53 hits are consistent with a cascade hypothesis and reconstructed cascade parameters are following: cascade energy E = 155 TeV, zenith angle θ=57º and azimuthal angle φ=249º, distance from array axis ρ=46 m. This event is promising one to be induced by neutrino of astrophysical nature.

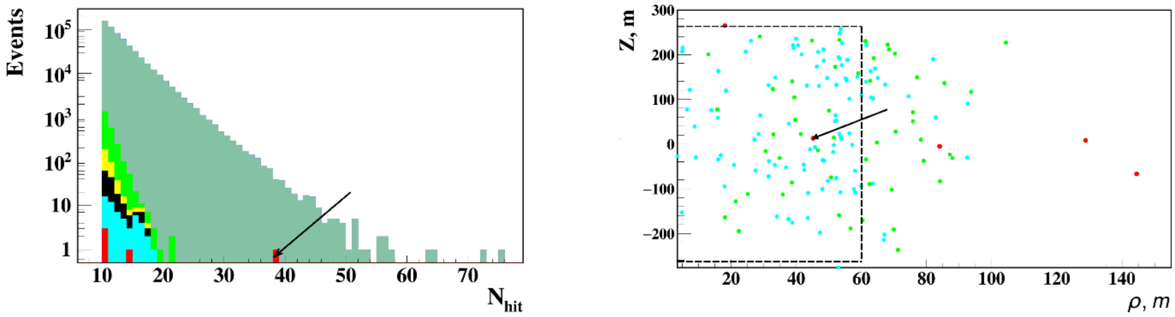


Fig. 2: Left: Hit OM multiplicity distributions of experimental events after continuously applied cuts from Table 1. Right: Reconstructed coordinates in z,ρ-plain (z – vertical coordinate, ρ - distance from central string of cluster) of events with E >10 TeV (blue dots), >30 TeV (green dots) and E >100 TeV (red dots). Dashed lines indicate an instrumented water volume. Arrows indicate promising event with high hit OMs multiplicity.

The second full-scale GVD cluster was installed and commissioned in April 2017. 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. To date, the two GVD clusters about 0.1 km^3 effective volume (about a factor 50 larger than NT200!), with high angular and energy resolution for high-energy neutrino detection are data taking in Lake Baikal. Fig. 3. shows the present layout of the array and the cumulative number of the master records for two clusters.

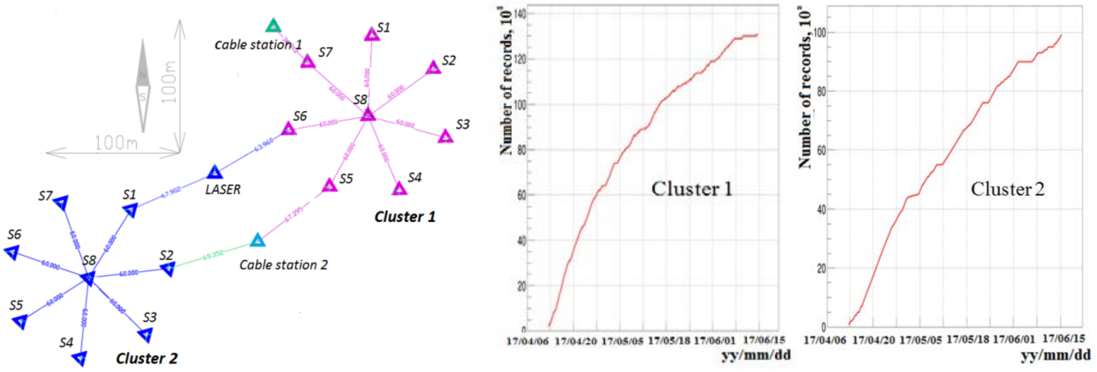


Fig. 3. Layout of the installation and cumulative number of the *master records* detected with two clusters (since April 13 to June 15 of 2017).

Production sites and Infrastructure

The construction of the research infrastructure has already started. The first GVD cluster with 288 OMs was deployed in 2016. The second cluster has been deployed in 2017. Three electro-optical cables leading from the shore station to the deep-sea sites have been installed and two of them are connected to the first two GVD clusters. Production site for optical modules has been set up at DLNP JINR. A sustained rate of 12 optical modules/day, which is needed to meet the goal to finish the GVD-II construction by 2023 has been achieved. This OMs production rate allows construction of two GVD clusters per year. All logistics and storage questions, connected with a number of components and prepared optical modules are resolved on DLNP JINR site.

Production site for cluster electronics has been set up in INR RAS(Moscow). The rate of electronic systems production is adequate to requirements for two clusters construction per year at moment. Installation and deployment of GVD clusters are performed from an ice cover during winter expeditions on Lake Baikal. Also, during winter expeditions deployment of two electro-optical shore cables will be performed. Deployment rate of two clusters per year, starting from 2018, allows to complete the GVD-I phase by 2020 and GVD-II by 2023.

5. Description of the proposed research

GVD Phase-1: 8 clusters with 288 optical modules each. The decision on the necessary investment has been taken in 2014 by the JINR directorate, by Russian Academy of Sciences, by the Federal Agency for Scientific Organizations (FASO) and by the Russian Ministry of Education and Science.

Timeline Phase-1:

2017	**2018**	**2019**	**2020**
2 clusters (deployed)	4 clusters	6 clusters	8 clusters

GVD Phase 2: extension to 14 (possibly technologically upgraded) Timeline Phase-2:

2021	**2022**	**2023**
10 clusters	12 clusters	14 clusters

A further extension of Phase 2 to more 14 clusters will depend on the worldwide physics situation in the 2020s, on additional funding from new partners, and last but not least on the performance and physics output of the BAIKAL-GVD detector.

6. Human resources

Baikal is international collaboration that includes about 60 sciences from Russia, Czech Republic, Slovakia, Romania, Germany and JINR

Work distribution for Phase 1 is as follows:

1) Institute for Nuclear Research, Russian Academy of Sciences (Moscow, Russia):

   Production, tests and assembling of electronics of measuring, power supply, control and monitoring systems of clusters, production of inter-string and inter-cluster power and communication lines, production of calibration units, data analysis, simulation software and MК production.

2) Laboratory of Nuclear Problems, JINR, Dubna, Russia:

   assembly and test of OMs and strings, detector calibration, remote control and monitoring systems of detector, access and security service, data archive processing and analysis, simulation software and MK production, on-line software, data analysis.

3) Irkutsk State University (Irkutsk, Russia)

   Production and assembling of nodes of acoustic positioning system, data analysis.

4) Comenius University (Bratislava, Slovakia)

   detector calibration, data processing and analysis, simulation software and production.

5) Czech Technical University in Prague (Prague, Czech Republic)

   detector calibration, data processing and analysis.

6) Nizhni Novgorod State Technical University (Nizhni Novgorod, Russia):

   production of facilities and equipment for shore cable deployment from the ice.

7) Moscow State University (Moscow, Russia)

   production and test of readout electronics.

8) St.Petersburg State Marine Technical University (St.Petersburg, Russia):
   support of underwater mechanical structures.

9) EvoLogics Gmb, (Berlin, Germany):
   Production acoustic positioning nodes, acoustic data analysis.

All partners: operation shifts at the shore and participation in the winter deployment campaigns.

INR group human resources are

Name	Category	Responsibilities	Time that each participant will give to the work under the Project in relation to its FTE
V. Brudanin	Head of department	Administrative work	0.2
P. Antonov	Engineer	Networking, system administrator	0.3
I. Belolaptikov	Researcher	Administrative work, detector building, MC, data analysis, reconstruction	1.0
I.-A. Caracas	Junior researcher	MC production, data analysis	1.0
A. Doroshenko	Engineer	OM production, detector building	0.5
R. Dvornicky	Researcher	MC, calibration, detector building, data analysis	1.0
K. Golubkov	Engineer	OM calibration, detector network system, synchronization	0.5
N. Gorshkov	Engineer	OM production and testing, detector building	1.0
Z. Hons	Senior Researcher	Detector monitoring	0.1
E. Khramov	Senior Researcher	Data analysis	0.3
M. Kolbin	Engineer	OM production and testing, detector building	1.0
K. Konischev	Researcher	MC production, detector building	1.0
A. Korobchenko	Junior researcher	Monopole system developer, OM production and testing, detector building	1.0
M. Kruglov	Engineer	OM production and testing, detector building	1.0
M. Milenin	Engineer	Hardware detector constructions	0.5
V. Nazari	Researcher	MC production, data analysis	1.0
T. Orazgali	Engineer	Data analysis, calibration	1.0
A. Panfilov	Engineer	Hardware detector	0.5

		constructions, detector building	
D. Petukhov	Engineer	On-line software development, remote detector control	0.5
E. Pliskovsky	Researcher	On-line software development, remote detector control, calibration	1.0
V. Rushay	Engineer	Data analysis, detector building	1.0
G. Safronov	Senior Researcher	Analysis, reconstruction	0.5
B. Shaybonov	Senior Researcher	Data analysis, calibration, reconstruction, detector building	1.0
S. Sinegovski	Senior Researcher	MC analysis	0.3
A. Svistunov	Engineer	OM production and testing, detector building	1.0
Total FTE (Engineers): 8.8, Total FTE (Scientific staff): 8.4, Total FTE: 17.2			

7. SWOT (Strengths, Weaknesses, Opportunities, Threat) analysis

The planning of the Baikal-GVD implementation is based on the long-term operation of GVD's predecessor NT200 and on the operation of GVD prototypes and the demonstration cluster *Dubna*. There is a long-term experience of designers, scientific and engineering stuff involved in the project realization. After the IceCube discovery of cosmic neutrinos, we do not see a general scientific risk (like "no detection of cosmic neutrinos with GVD at all"). Our technical realization has been chosen on the basis of a technical option analysis with the goal of the a) most reliable and b) cost-effective realization with c) high signal sensitivity and low background. The explicit risks for delays will be given in the answer to the next question.

We do not see any realistic risks which make the realization of Baikal-GVD impossible. There are however potential risks to delay the planned schedule of deployments:

a) Bad ice conditions (short period of sufficiently thick and firm ice) during the winter expeditions

b) Failure of underwater equipment. This may require repair activities which delay the deployment of new equipment. The great advantage of GVD, however, is that such repair activities are much easier than in Oceans.

c) Delays in payment schedule or delay in delivery (including those due to embargos!).