NEVOD: A unique scientific facility of Megascience class

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Abstract. The term “Megascience” appeared relatively not long time ago and has no distinct definition. Intuitively, this term is understood as something big and certainly expensive, i.e. a concept of “Megascience” is replaced by a concept of “Megamoney”. In this paper, the unique scientific facility “NEVOD Experimental complex” (USF NEVOD), which satisfies all requirements to Megascience facilities, is described. USF NEVOD provides conduction of basic and applied investigations of cosmic rays in the record energy interval $10^9 – 10^{19}$ eV. Obtained scientific results are considered, and their comparison with other, larger scale detectors is discussed. This comparison shows the advantage of original approach used in the NEVOD complex compared to traditional methods of investigations. Taking into account the location of USF NEVOD in the University, the Scientific and Educational Center was organized on its bases. This allows solve two important tasks: to provide permanent operation of USF NEVOD by envolving students and to ensure their training in frame of real scientific experimental investigations. Some other questions of development and functioning of unique scientific facilities are considered, too.

1. Introduction
The term of "Megascience" is very indefinable. And although attempts to formulate requirements for such scientific facilities both at the government level and at the expert level have been made and are being made, nevertheless, a clear definition of the concept of mega-science has not yet been given. Intuitively, this term is often understood to mean something big and certainly expensive, i.e. the concept of "Megascience" is often replaced by the concept of "Megamoney".

If to summarize the requirements that were put forward for scientific facilities of the "Megascience" class in various documents, they can be reduced to the following:
1. The relevance and importance of the scientific field for research in which the facility is created
2. The uniqueness of the facility and the lack of close analogues in the world both in terms of parameters and the possibilities of solving scientific problems.
3. The relatively high cost and complexity of the facility, the development and creation of which requires the cooperation of different organizations.
4. Participation in the creation and development of the unique scientific facility of members of foreign countries who can make not only intellectual, but also material contributions.
5. Perspectives of using the obtained scientific and scientific-technical results for the development of new and improvement of existing technologies and for other practical purposes.
6. Using the facility in the educational process for preparation of students, scientific and pedagogical cadres, advanced training, etc.
7. The duration of the period of the relevance and demand for facility by existing and potential users.

Currently, six facilities are officially classified as “megascience” in Russia, four of which are at the design stage and only two are at the creation stage (NICA collider and PIK reactor). The class “megascience” can also include some existing unique scientific facilities (USF) which satisfy the listed above requirements, and the further development of which will preserve their uniqueness and relevance for many years. One of such USF is the NEVOD Experimental Complex.

2. Experimental complex NEVOD
The basis of the NEVOD experimental complex is the Cherenkov water detector (CWD) with the same name NEVOD with a volume of 2000 m², created on the basis of quasispherical modules, which provide registration of Cherenkov radiation from any direction with almost the same efficiency [1]. The idea of quasisphericity is based on the fact that the response of certain configurations of photomultipliers in the form of the sum of squares of signals taken from individual PMTs does not depend on the direction of the Cherenkov radiation and is determined only by the distance to the radiation region. Such properties have all configurations of photomultipliers located on the faces, edges, and vertices of regular polyhedra with the exception of the tetrahedron [2]. The first simplest quasispherical module was created at the MEPhI from six PMTs located on the faces of the cube (QSM-6). The spatial lattice of such QSMs is the detecting system of the Cherenkov water detector NEVOD (figure 1). On the other hand, the availability of information from individual PMTs and the total response of all PMTs allows to determine the directional cosines, and thereby the direction of the Cherenkov radiation.

![Figure 1. Inner view of Cherenkov water detector NEVOD.](image)

To verify the quasisphericity and provide the calibration of photomultipliers by Cherenkov radiation, a system of calibration telescopes (SCT) was created, consisting of scintillation detectors with size 40 × 20 cm² and placed on the bottom (40 pcs.) and the top (40 pcs.) of the water tank. The counters are included in the majority coincidence system, which allows one to select 1600 spatial-angular directions, providing control of 83% of all photomultipliers, with the exception of PMTs directed downward. At the first stage, SCT detectors worked in a counter mode and were used only for calibration of PMTs and QSMs. After the modernization, the detectors were equipped with amplitude channels and at present SCT is used to study the electron-photon (upper plane) and muon (lower plane) components of EAS.

The next stage of the development of the experimental complex was the creation of the DECOR coordinate detector with streamer tubes made in Italy and used earlier in the NUSEX experiment in a tunnel under Mont Blanc. From chambers containing 16 streamer tubes each, modules of 16 such...
chambers were created. Eight modules form a super-module with an area of 8.4 m². Total DECOR includes 8 supermodules: two on front ends of the CWD and four from the lateral side [3]. The presence of a large number of points on the muon trajectory (up to eight) provides good spatial (better than 1 cm) and angular (better than 1 degree) resolution of the coordinate detector. The main feature of DECOR is the vertical arrangement of its measuring planes, which provides good conditions for recording of the muon component of EAS (groups of muons) at large zenith angles up to the horizon (figure 2).

![Coordinate-tracking detector DECOR](image)

**Figure 2.** Russian-Italian NEVOD-DECOR complex.

It was originally planned to create an upper coordinate detector DECOR-B for recording near-vertical EAS. However, the high particle density of the electron-photon component did not allow to realize this project and the upper coordinate detector was converted into the Unit for Registration of Atmospheric Giant Anomalies (URAGAN), which is used to solve fundamental and applied problems of the cosmophysical direction of cosmic ray research [4].

Further development of the NEVOD Experimental Complex was associated with the creation of external detectors and facilities for recording various EAS components. Firstly, the PRISMA facility for recording the EAS neutron component was created. It consists of 32 detectors capable of detecting both electronic and neutron EAS components. A neutron scintillator based on lithium-6 is used to detect neutrons, which effectively absorbs neutrons with the formation of an α-particle and a tritium nucleus. Neutron detectors are located on the fourth floor of the experimental complex building around the cover of the water detector on the area of 500 m² [5].

The next facility for detecting the EAS neutron component was the Unit for Registration of Atmospheric Neutrons (URAN), the detectors of which are located on the roofs of two buildings: the NEVOD experimental complex and the neighboring laboratory building. URAN detectors use a scintillator with natural boron-10, which forms an α-particle and a nucleus of lithium-7 upon the capture of a neutron. URAN detectors are combined into 6 clusters containing 12 neutron detectors each. The total area of the URAN facility is 10⁴ m² [6].

To register EAS using the classical method, the central part of the NEVOD-EAS facility was created from scintillation detectors, which were previously used in the EAS-TOP (Italy) and KASCADE-Grande (Germany) installations. The facility consists of 9 clusters of four detection stations in each. The station includes 4 scintillation detectors with an area of 0.64 m². The distance between the detection stations is 15–20 m, and between the clusters ~ 50 m. The total area is 10⁴ m² [7].

3. Main areas of research
The initial goal of research at the Neutrino Water Detector (NEVOD) was to prove the possibility of detecting neutrinos generated in the atmosphere and passing through the Earth, under conditions of a very high background of atmospheric muons. The relevance of solving this problem was due to the simultaneous development of projects for large-scale facilities for detecting neutrinos (at great depths
under water) and gamma-rays (on the Earth's surface). Since both events are quite rare, the possibility of creating a single installation for solving two problems looked very attractive.

At the same time, deployment of such facility on the Earth’s surface opens a wide possibilities for studying other components of cosmic rays reaching the Earth’s surface: electron-photon, muon, and hadron ones. Of course, this requires that the experimental setup must be a $4\pi$ detector capable to detect particles arriving from any direction. The quasispherical module developed for CWD provides this possibility (figure 3).

![Figure 3. Main directions of investigations by means of the Experimental Complex NEVOD.](image3)

After equipping the NEVOD CWD with other detectors and facilities, the created experimental complex gives a possibility to study cosmic ray particles in a record wide energy range from $10^9$ to $10^{19}$ eV (figure 4).

![Figure 4. Energy intervals covered by various detectors and installations.](image4)

The range of tasks presented in figures 3 and 4 includes both fundamental (energy spectrum and mass composition of cosmic rays, their interaction at high and ultrahigh energies, neutrino registration) and applied (solar-terrestrial physics, monitoring and prediction of the state of the heliosphere, magnetosphere and the Earth's atmosphere) areas of research.

Most interesting is the registration of muons groups from the inclined EAS. With an increase in the zenith angle the distance of the point of generation of secondary particles decaying to muons from the
place of their registration on the Earth’s surface increases and the amount of matter that muons must cross in order to get into the detector also increases. These factors lead to an increase in the flight time of pions and kaons in the rarified layers of the atmosphere and, accordingly, to an increase in the probability of their decay and an increase in the muon flux. On the other hand, an increase in the distance leads to an increase in the lateral spread of muons and to a decrease in the number of muons entering the detector.

An additional factor is the influence of the magnetic field on the muon flux. Since in Moscow the lines of force of the Earth’s magnetic field are directed at an angle of about 60 degrees to the surface, for particles flying at large zenith angles the magnetic field separates positively and negatively charged muons. All this leads to the fact that the dimensions of EAS at large zenith angles increase significantly and can reach tens of kilometers. As a result, the number of recorded events is determined not by the size of the facility, but by the size of the EAS. Therefore, with a relatively small setup (~ 100 m²), EAS with energies up to $10^{19}$ eV can be recorded, for the study of which experimental complexes with a size of thousands of square kilometers are created.

The region of low energies from ~ 1 to ~ 100 GeV is of a special interest. In this energy region, the flux of primary particles is strongly influenced by various heliospheric disturbances caused by the solar activity. Naturally, these perturbations are also transmitted to secondary particles, which are formed during the interaction of primary particles with the nuclei of atoms in the atmosphere. Such a dependence opens up the possibility of recording and studying heliospheric disturbances from variations in the muon flux on the Earth's surface. It should be taken into account that the flux of secondary particles, including muons flux, is greatly affected by the state of the atmosphere and various processes and phenomena occurring in it. These studies have a great practical importance, because lay foundations for new methods for monitoring and forecasting space and atmospheric weather.

4. Obtained results
At the first stage (1995 – 2000), the main task was to prove the possibility of detecting neutrinos of cosmic rays passing through the globe under conditions of a very high background of atmospheric muons on the Earth's surface. The rejection factor was $2 \times 10^{10}$. This problem was solved in 1997 – 1998 after careful processing of experimental data obtained in 1995 [8]. Nine muons were recorded that entered the CWD at zenith angle of 115° to 150°, including four at an angle greater than 130°. The probability of imitation of such events by muons from the upper hemisphere is less than $10^{-11}$.

Further studies were carried out taking into account the capabilities of the created coordinate detector DECOR, with which it was possible to register both single and groups of muons at large zenith angles, including muons from below the horizon (up to 94°). These studies are important for determining the critical angle at which the flux of muons from the upper hemisphere scattered through large angles is comparable to the flux of muons generated by neutrinos from the lower hemisphere. This critical angle will determine the interval of zenith angles in which neutrinos passing through the Earth can be studied by means of muons they generate.

The second important result was obtained when registering muons passing through front-end DECOR supermodules (zenith angle range 85° – 90°). The large distance passed by them in the water made it possible to investigate the cascade showers generated by these muons. As a result, for the first time the cascade curve, determined by the Cherenkov emission of electrons and positrons of cascade showers was measured. The obtained muon energy spectrum was in a good agreement with the spectra obtained by other methods [9].

The most interesting results were obtained in the study of the muon groups. The obtained distributions of muon groups by multiplicity and zenith angle were recalculated into local muon density spectra, which were compared with those expected under various assumptions about the spectrum and composition of primary cosmic rays using the interaction models in the well-known CORSIKA program. The obtained results indicate a constant increase in the experimental values of the
local density spectrum in comparison with the calculated ones with an increase in the zenith angle and, accordingly, in the energy of primary particles [10] (figure 5).

![Comparison of experimental data with results of simulations for different models and for two cases of mass composition (pure p and Fe).](image)

**Figure 5.** Comparison of experimental data with results of simulations for different models and for two cases of mass composition (pure p and Fe).

Up to energies of \( \sim 10^{17} \) eV, this increase can be interpreted as an increase of the average mass of primary cosmic rays, but a further increase gives an excess of muons, to explain which a change in the model of particle interaction in the region of ultrahigh energies is necessary. This result was later confirmed at other larger facilities: IceCube (area of 1 sq. km) and Pierre Auger Observatory (area of 3000 sq. km) (figure 6) [11].

![Review of experimental data on EAS muon component.](image)

**Figure 6.** Review of experimental data on EAS muon component.

To solve the problem of an excess of muons, called the “muon puzzle” [12], information on the energies of muons is needed. If the excess of muons is caused by the appearance of heavy nuclei (for example, uranium) in the PCR, then the energy spectrum of muons should practically not change. If the excess of muons is related with the inclusion of a new process of muon generation or the formation
of a new state of matter at energies above some threshold, then such muons should have a higher energy. Two approaches to solving this problem are possible: measuring the inclusive energy muons spectrum in the region of ultrahigh energies or measuring the energy deposit of muon bundles.

 Currently, the NEVOD Experimental Complex is the only facility in the world on which such an experiment can be carried out, since this requires independent measurements of the number of muons and their energy deposit in various detectors, in this case, DECOR and CWD NEVOD. Such an experiment has already been started and preliminary results favor a change in the interaction model.

5. Scientific and Educational Center NEVOD
On the basis of the USF NEVOD, the eponymous Scientific and Educational Center (SEC) was created. Its purpose is ensuring the unity of scientific and educational processes both for fundamental and applied research, as well as the training of highly qualified personnel in real conditions of modern physics experiments. The creation of the Center was awarded in 1997 the Prize of the President of the Russian Federation in the field of education. Currently, SEC NEVOD prepares students of baccalaureate, specialty, magistracy, graduate students and doctoral candidates in a wide range of specialties. At the same time, research works of students, final qualification and diploma works are performed not only by students directly studying at the SEC NEVOD under the programs “Particle Physics of High and Ultra-High Energies” and “Nuclear Physics Methods of Solar-Terrestrial Physics”, but also by students of other departments and faculties. A wide range of research carried out at the SEC NEVOD on a unique scientific facility provides wide opportunities to carry out such work not only in the field of physics, but also in electronics, automation, instrument design, IT technologies, etc.

For all works carried out in SEC NEVOD, a prerequisite is the preparation and submission of reports at special youth and “adult” Russian and international scientific conferences, depending on the level of obtained results. Generally, publications are prepared on these reports. The high level of students and young scientists training is evidenced by the numerous victories of representatives of SEC NEVOD in competitions for the medals and prizes of the RAS for students and young scientists. In the period from 2001 to 2018, 9 student works (10 people) and 6 works of young scientists (8 people) were awarded medals with prizes of the Russian Academy of Sciences.

The employees of SEC NEVOD carry out a great career-oriented work with schoolchildren: they carry out excursions of the unique experimental complex, organize summer practice for pupils of the lyceums of the pre-university of MEPhI, and ensure that schoolchildren become enthusiasts of scientific work. The scale of this work is evidenced by the following facts. Annually from 1000 to 1500 schoolchildren of various classes of schools in Moscow and other regions of the Russian Federation visit the SEC NEVOD. For them, guided excursions, overview lectures and master classes are held, as well as practical classes. In recent years, distant forms of these events have begun to be implemented. The effectiveness of this work is evidenced by the results of scientific work carried out by schoolchildren. As a rule, they are presented at the “Junior” competition, which is annually held at MEPhI, where they win prizes.

SEC NEVOD supports a wide scientific and technical cooperation with Russian and foreign universities and scientific institutes with which agreements have been concluded providing for their participation in work carried out on a unique scientific facility, including material contribution to its development. Currently, there are 13 such organizations, six of them are Russian and seven are foreign. The results of the collaborative work are presented at Russian and international conferences, published in publications listed by WoS and Scopus.

6. Manpower supply
The location of the USF NEVOD directly on the university territory greatly facilitates the solution of a significant part of personnel problems by attracting students who do not need to spend a lot of time to get to the place of work. Many functions associated with the maintenance of the installation, monitoring its operation, ensuring continuous operation are performed with the involvement of
students. At the same time, the early involvement of students into the work in a scientific laboratory enables them to adapt in a timely manner to the real conditions of their future activities in the scientific and technical field. In this way, the existing team of the unique scientific facility and the Scientific and Educational Center NEVOD was formed and continues to develop.

Nevertheless, the general problems of staffing of large scientific facilities, although to a lesser degree, concern USF NEVOD, too. These problems are of multidimensional nature and are associated, first of all, with a change in the attitude of the society, and, accordingly, of young people to science in general and to technical science in particular. And although competitions in technical universities have been growing in recent years, nevertheless, it should be recognized that the most talented children are not motivated to enter technical universities. The second aspect of this change is the unwillingness of university graduates to work in science, where the achievement of tangible life results such as an apartment, a summer residence, a car, etc. is stretched for many years. And most of them want everything and faster.

The problem is aggravated by the existing order of financial support even for successfully working teams and laboratories. A significant part of salary is determined by the availability of contracts, various grants, etc. And their number and volume is very difficult to predict, and as a result, uncertainty about tomorrow.

A serious problem remains housing. Although certain steps are being taken in this direction, nevertheless, for most young and not very young scientists, decent housing (own or rented) remains an unattainable dream for many years.

All these problems are not new and are being actively discussed, measures are being taken, appropriate resources are allocated, but there is still a long way to go to solve them. Today, for unique scientific installations of the megascience class, some solutions can be proposed using, among other things, the experience of USF NEVOD:

1. It is necessary to provide the full participation of specialized educational institutions (preferably closely located) in the creation of “megascience” facilities and in their further operation with the allocation of appropriate funding for this. This will allow access to various categories of students (schoolchildren, students, graduate students) with the aim of their early orientation to work on the corresponding "megascience" facility.

2. It is necessary to ensure normal guaranteed financial support for employers of truly unique scientific facility, which should not depend on grants and other short-term earnings, which only distracts from solving the main problems.

3. Solving the housing problem through the massive housing construction for scientists, including young ones, is hardly feasible in the foreseeable future. This problem can be solved if young scientists, primarily families and with children, are provided with separate boxes in university dormitories. Savings on rental housing will allow them to accumulate funds for several years for initial payment on a mortgage and within a reasonable time to get their own housing.

7. Legal issues

Lack of financing is certainly bad, but the financing two to three months before the end of the reporting year is very bad. The implementation of the procurement of scientific equipment and necessary materials under the current laws on the obligatory tendering, auctions and other similar procedures not only requires a long time, but also poses a great risk of running into unscrupulous suppliers, or even just crooks. Such events become completely meaningless when it comes to unique scientific facilities, which according to the official definition cannot consist of a set of standard equipment.

Therefore, it is necessary for leaders of unique scientific facilities to provide the right to conclude contracts without any competitions and other bureaucratic procedures with those people and organizations who are able to develop and manufacture the necessary equipment and produce the required materials in accordance with the terms of reference and on time. Naturally, such a leader should bear full responsibility for the targeted use of funds.
The second issue is related to advance payment and pre-payment for purchases. Since the development of unique equipment is usually carried out by small firms and organizations, as a rule, their working capital does not allow them to develop and manufacture equipment at their own expense. Therefore, with orders for the development and manufacture of unique scientific equipment and the production of materials with the required characteristics, it is necessary to allow advance payment and prepayment of orders.

On May 1, 2019, the Federal Law No. 71-FZ was adopted, which greatly simplifies the procurement procedures for scientific and educational organizations, but it will take some time to understand how much.

And lastly, it is necessary to reduce (by at least 10 times) the quantity and volume of various securities (applications, reports, certificates, contracts with numerous applications, etc.). It may be recalled that the terms of reference for the development and creation of the atomic bomb were written on one page.

8. Conclusion
Long-term operational experience with the unique scientific facility “NEVOD Experimental Complex” at MEPhI shows that many personnel problems can be solved much easier if the unique scientific complex is located on the territory of the university. The influence of a unique scientific facility on the training of students and graduate students is also important, providing them with the opportunity to work on modern equipment and participate in solving current scientific problems.

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