Megascience projects in modern nuclear physics and personnel training

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Abstract. Modern nuclear physics is impossible without the implementation of projects of the megascience class, for the creation of which the efforts of many organizations and countries are consolidated. The level and complexity of experiments carried out with the use of such facilities is provided by scientific researchers with a wide range of competencies. The education of such researchers is an important task for scientific and educational organizations. These issues were discussed at the 2nd conference "Personnel training and legal support for the implementation of scientific projects of the Mega-science class" organized by National Research Nuclear University MEPhI and Kutafin Moscow State Law University on June 25, 2020. The aim of the Conference was to discuss the policy management issues of implementation of the Mega-science class research projects.

1. Introduction

Today, the solution of scientific problems in the fields of modern nuclear physics and nuclear technologies is practically impossible without the creation of large-scale scientific complexes of the megascience class. Such complexes are, first of all, unique large-scale scientific facilities, the creation of which requires the combined efforts of large teams of scientists from various scientific organizations and countries.

Why are facilities of such class needed? It is known from the history of natural science that the first scientific research and the acquisition of a new knowledge began with the study of the properties and behavior of objects around a human. The further development of the natural sciences was built around the study of not only objects comparable in size to the human himself (~ 1 m), but was aimed at studying the composition of matter and understanding the structure of the Universe. Those studies that were directed deep into matter led to the discovery of molecules, atoms, atomic nuclei and elementary particles. Another part of the research was aimed at studying the starry sky and answered questions about what the Earth, the Sun, the Solar System, the Galaxy, the Universe are and what they are made of. The diagram below (figure 1) demonstrates the ranges of characteristic sizes of objects of research in modern science to the date: the difference is over 45 orders of magnitude: from $10^{-20}$ to $10^{26}$ meters. It is important to note that in the second half of the last century it turned out that the state of matter at extremely small distances is similar to the state of matter in the early Universe, so by studying the physics of elementary particles, we are studying the history of the development of the Universe.
To penetrate deep into matter, scientists use charged particle accelerators, and to study the depths of Space, they use various telescopes (optical, radio, X-ray, gamma, neutrino, gravitational antennas).

![Figure 1. The scale of the objects under study in modern scientific research at megascience-class facilities.](image)

In the previous work of the authors [1], the experience of MEPhI participation in international collaborations and research projects of the Megascience class was considered. This article discusses the features of some modern mega-science projects in the field of fundamental and applied research, as well as the main approaches to training researchers to work at such complexes.

2. Accelerator experiments

Today there are two largest operating accelerators (colliders) in the world: the Ring Heavy Ion Collider RHIC (BNL, USA) and the Large Hadron Collider LHC (CERN, Switzerland). In this century there was also the third large proton-antiproton collider Tevatron at Fermilab (it finished its work on September 30, 2011). Each of these three projects provides several experiments aimed at solving different physics problems. The experience of National Research Nuclear University MEPhI participation in RHIC and LHC research projects is discussed in detail in [1].

From the description of complexes of the megascience class, one can see that the higher the particle energies, the larger the collider should be. This is because it is more difficult to hold and accelerate particles in a ring of a fixed size at higher energies. The RHIC collider has a length of 3.8 km and allows accelerating particles to 0.2 TeV. TEVATRON has a size of 6.3 km and the maximum particle energy of ~ 1 TeV. LHC has a ring size of 27 km, and the maximum energy of accelerated particles is 7 TeV [2-10]. Figure 2 shows the location of facilities in a geographic area.

![Figure 2. Installation layouts on geographic maps.](image)

The importance of creation of such facilities is confirmed by the discoveries made on them. It includes those discoveries marked by Nobel Prizes: the discovery of quark-gluon plasma at the RHIC experiments, the discovery of the top quark at TEVATRON, and one of the most important discoveries in science of the last decade - the discovery of the Higgs Boson at LHC.

It is necessary to point out that the considered experiments operate at high energies, but at a low baryon density of colliding particles and nuclei. At the same time, interest in nucleus-nucleus interactions is growing today. At present, construction of two large experimental megascience complexes, FAIR (Germany) [11] and NICA (Russia) [12], is underway. The NICA collider [13, 14] means to study the phase diagram of highly compressed baryonic matter in laboratory conditions. The accelerator with a fixed target (not a collider!) is being assembled within the FAIR project. In the
CBM experiment [15, 16] at a low temperature (energy), but at an extremely high baryon density, a search will be carried out for a phase transition of hadronic matter into a quark-gluon plasma.

3. Non-accelerating experiments

Accelerators are not the only sources of high-energy particles. Particles of higher energies (thousands and millions of times greater than the capabilities of colliders existing in the world) come to the Earth from outer space, but their flux is rather small and decreases with increasing particle energy. Therefore, large detectors are being developed for their registration. Primarily among such detectors, it is necessary to note the IceCube neutrino detector (Antarctica) with a volume of 1 km³ and the Pierre Auger Observatory (Argentina) for detection of extensive air showers with an area of 3000 square kilometers.

3.1 IceCube

IceCube is a neutrino detector [17-19] located in the Antarctic ice, designed to detect astrophysical neutrinos with energies above $10^{11}$ eV. The IceCube detects Cherenkov radiation from charged particles produced by neutrino interactions using more than 5,000 optical sensors placed on 86 vertical “garlands” in the ice at depths from 1,450 to 2,450 meters. The experimental setup is shown in figure 3.

One of the most important results of the experiment is the detection of astrophysical neutrinos. Since, unlike charged particles, neutrinos are not deflected by electromagnetic fields, determination of the direction of arrival of such a particle makes it possible to accurately determine the direction to its source. Since neutrinos are practically not absorbed on their way, their detection allows to see a source hidden from observation by optical or other electromagnetic radiation. Thus, the detection of astrophysical neutrinos is a fundamentally new instrument for observation of high-energy processes in outer space.

Figure 3. Experimental setup IceCube.
3.2 Pierre Auger observatory
The Pierre Auger Observatory studies particles of the highest energies that come to the Earth from space by using of a “hybrid detector” [20-21]. The detection of particles occurs simultaneously by Cherenkov radiation detectors and registration of ultraviolet light from extensive air showers. The layout of the observatory detectors and the arrangement of the Cherenkov water detector are shown in figure 4.

Figure 4. Layout of detectors at the Pierre Auger Observatory (left) and the design of the Cherenkov water detector (right).

The facility consists of more than 1,600 reservoirs with a volume of 12,000 liters of water, located 1.5 kilometers apart from each other and covering the area of about 3,000 km². The simultaneous detection of flashes of light in several of these detectors indicates the registration of extensive air showers. The difference in response time of the detectors makes it possible to determine the direction of arrival of cosmic ray particles.

4. Fusion, synchrotron research and other applied megascience projects
Accelerator and non-accelerator high-energy experiments are aimed at obtaining new fundamental knowledge about the world around us. However, now a huge range of studies is also being actively carried out aimed at solving applied problems in various spheres of human life. Among such megainstallations, we should mention the ITER project, the first reactor for controlled thermonuclear fusion [22-23]. Today it is one of the most ambitious international energy projects in the world, which aims to implement the concept of controlled thermonuclear fusion. This energy source will be the backbone of the carbon-free energy future.

At present, there is also growing interest in the construction of large-scale facilities – sources of synchrotron and neutron radiation, which can be used for a number of research areas in the field of applied sciences. In Russia, the Program for the Development of Synchrotron and Neutron Research and the Related Research Infrastructure has been launched. Within the framework of the program, it is planned to design, build and operate unique research facilities of the megascience class: a 4+ generation synchrotron radiation source (Novosibirsk region), a prototype of a pulsed neutron source based on a spallation reaction (Protvino, Moscow region), the International Center for Neutron research on the basis of the high-flux reactor PIK (Gatchina, Leningrad region); design of a unique scientific facility of the megascience class (Russky Island) based on structural blocks and assemblies of the Zelenograd synchrotron radiation source; modernization of the Kurchatov specialized source of synchrotron radiation "KCSRN" (Moscow). The development of such a research infrastructure will launch a large-scale campaign to develop applied research in materials science, chemistry, biology, archeology, geology and many other fields of knowledge.
5. Features of a personnel training for megascience

Approaches to the organization of the educational process in personnel training in the interests of megascience projects are determined by the features of the projects themselves and the tasks they are aimed at solving. Most projects of the megascience class are technically complex large-scale installations that are aimed at solving fundamental and applied problems. All such projects have long-term multi-stage work plans, and also use expensive equipment and developed research infrastructure. Megascience projects always attract a large number of researchers: international collaborations that are organized around experiments, have a developed institutionalization and include hundreds of scientific organizations from dozens of countries.

Thus, special requirements for training are manifested at all stages of the life cycle of such projects. At the stage of project selection and the formation of a list of attitudes, all participants in these works must develop communication skills, be able to present a project, get support from fellow researchers, and demonstrate the prospects of work for funding organizations. During preliminary research and long-term planning of experiments (R&D, TDR development, assignment of responsibilities), the ability to work in a team becomes the most important quality of the researcher. At this stage, it is important to understand the general goals of the project and the ability to highlight the main stages in planning, which requires participants to have broad knowledge in many subject areas of science and the ability to establish a creative environment in a team. Within the direct implementation of the project and monitoring of the results of the work the ability to achieve a specific result of a work becomes an important quality for the researcher.

Analyzing the experience of MEPhI in training of researchers for various megascience projects, we can conclude that the basis for the successful development of a young researcher requires continuity and transfer of experience within the framework of established scientific schools. Such a transfer of knowledge is impossible without fundamental physical and mathematical training of students, which should include studying at a deep level of general and theoretical physics, various branches of modern mathematics and engineering disciplines. At the same time, as noted earlier, the work of a researcher in the framework of large research collaborations is impossible without developed soft skills. At MEPhI future researchers develop such skills due to the early involvement of students in research groups or in the implementation of engineering projects. It is also important to note that today the training of researchers is impossible without including computer science and modern digital technologies into the educational process [25].

6. Conclusion

Megascience facilities open a new stage in fundamental and applied research, the basis for the further development of nuclear physics and technology. At the same time, the role of international scientific cooperation has significantly increased both in the creation of megascience facilities and in the training of young researchers.

To ensure the continuity of generations in the development and creation of megascience installations and their subsequent long-term operation, timely training of personnel at a high level is necessary.

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