

New challenges and approaches in training personnel for research projects of the “MegaScience” class

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Abstract. MegaScience projects are unique scientific experiments and facilities of a large scale that were initiated to allow to go beyond modern knowledge in the field of fundamental sciences and open up new opportunities in the technological development. The implementation of such complex projects requires the combined efforts of many scientists and institutions at national and multinational level. The paper presents an analysis of new trends in the training of researchers in the field of elementary particle physics, high energy physics and cosmophysics for research projects and experiments at MegaScience facilities. The authors consider the vast experience of extensive training of MEPhI students for fundamental science and analyzed new approaches to organizing the individual training of researchers at the university. The result of this work was presented and discussed within the proceedings of the Third 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 17 June 2021.

1. Introduction

The MegaScience projects are unique scientific facilities and experiments on a large scale the implementation of which requires the combined efforts of many scientists, organizations and even countries. Most modern MegaScience projects are usually divided into accelerator and non-accelerator experiments. Among the largest accelerator MegaScience experiments are the following:

- Ring collider of heavy ions RHIC (BNL, USA) [1]: STAR, PHENIX, PHOBOS experiments;
- Large Hadron Collider LHC (CERN, Switzerland) [2]: experiments ATLAS, CMS, ALICE;
- Proton-antiproton collider TEVATRON (Fermilab, USA) [3]: experiments D0, CDF;
- European Center for the Study of Ions and Antiprotons FAIR (GSI, Germany) [4]: experiments NUSTAR, PANDA, CBM, APPA;
- Superconducting accelerator complex NICA (JINR, Russia) [5]: BM@N, MPD, SPD experiments.

The discoveries made on such facilities determine the importance of their operation: the discovery of quark-gluon plasma at the RHIC experiments, the discovery of the top quark at TEVATRON, the



discovery of the Higgs boson at the LHC. All these projects involve a colossal number of researchers to create the facilities themselves and conduct experiments. The scale of each facility and the number of specialists involved are of impressive amount. For example, more than 3000 scientists representing more than 70 organizations are taking part in experiments at the LHC, and about 700 researchers from 70 academic and research institutions work in experiments at the RHIC collider. In particular, National Research Nuclear University MEPhI is an active contributor to all the activities related to personnel training and MegaScience experiments.

Accelerators are not the only sources of high-energy and ultra-high-energy particles, naturally they come to Earth from space. Designers and engineers have been constructing large-scale detectors for particle registration on the ground, and detectors on board spacecraft to registry high-energy particles in outer space. One can mention the following existing and developed large non-accelerator experiments and MegaScience complexes in particle physics and astrophysics:

- IceCube under-ice neutrino telescope (Antarctica) [7];
- The world's largest detector of extensive air showers Pierre Auger (Argentina) [8];
- Gamma Observatory TAIGA (Russia) [9];
- Neutrino water telescope SUPERKAMIOKANDE (Japan) [10];
- BAIKAL GVD neutrino telescope (Russia) [11];
- Experimental complex NEVOD (Russia) [12];
- Magnetic alpha-spectrometer AMS-02 (ISS) [13];
- Apparatus for the study of space radiation PAMELA (Resurs DK-1 Satellite) [14];
- Gamma-astronomical multifunctional modular apparatus GAMMA-400 (Russia) [15].

Similar to accelerator experiments, the operation and maintenance of MegaScience facilities require the collaboration of a large number of researchers and institutions. For example, the IceCube collaboration includes more than 350 participants representing 45 institutions, and the Pierre Auger collaboration comprises about 500 researchers from more than 80 organizations of different countries. A detailed description of some experiments, as well as the specifics of training personnel for accelerator and non-accelerator projects of MegaScience classes are given in the previous work of the authors [16].

2. Peculiarities of personnel training for MegaScience

First of all, the specific nature of every MegaScience project and the tasks it is aimed at solving determine the approaches of the educational process for future personnel of MegaScience projects. The first feature of such projects is a *fundamental problem* that demands from researchers and engineers deep theoretical knowledge and in-depth understanding of fundamental processes. The second feature is the lifecycle *a MegaScience facility* that is extremely expensive and technically complex and concentrates the large amount of resources and technological insights from each institutional participant at all the stages of its operation, in particular with special attention to the operational safety and disposal of a research facility. The third feature of global MegaScience project that makes them complex is its business legal structure: *long terms of project implementation and a large number of participants from different countries* make the choice of organizational and legal model crucial, while the Organizing Committees ensure the distribution of institutional contribution of collaboration members to the final results of experiments. All these features of MegaScience projects lead to the significant advancement of requirements compared to other research projects, particularly for training, international mobility, publication policies, management and decision-making system, distribution of access to research infrastructure, distribution of rights to the results of intellectual property, etc. [17-19].

In order to describe the features of personnel training, we will consider the basic requirements for the qualifications and competencies of future professionals. Most of the researchers who work within international research collaboration can be divided into 4 categories: “*Theorists and*

Phenomenologists”, “*Experimental Methodologists*”, “*Data Analysts*”, and “*Project Administrators*”. Researchers from the first group should have deep theoretical and fundamental knowledge, be able to formulate experiment requirements and be able to constantly update the scientific project goals and tasks. Researchers engaged in the methodology of conducting experiments should be able to carry out mathematical modeling of physical processes, as well as know modern techniques for the development and design of equipment and electronic systems for collecting and primary data processing. Data analysts should have developed skills in the field of modern digital methods of data processing and visualization, be able to analyze the nature of the detected effects and formulate the results through the communication with the public. Project administrators should have experience in preparing, planning, and conducting large experiments, which can only be gained, as a rule, while having maintained one of the previously listed positions. All these features should be reflected in the academic curricula while training future researchers.

Meanwhile, modern trends [20-22] in the industrial and technological development impose new requirements for the personnel training for all high-tech areas. The first to mention is the interdisciplinarity, that will be able to diversify the research agenda and the applicability of products. The second issue is a request for universities to train both highly qualified specialists with a wide range of competencies, and personnel with unique competencies to work in interdisciplinary projects. The latter is the ongoing global transfer of research and engineering to the digital environment, which requires the introduction of various new digital competencies in the study process.

Regarding the personnel training for MegaScience projects in the field of high-energy particle physics, the following trends in education and practical training are of the utmost importance:

1. ***Digitalization*** [23-26]: the emergence of new applied and computational software packages, new visualization methods, etc. This factor makes the academia reflect new methods of mathematical modeling of physical processes and cutting-edge specialized software in the curricula of disciplines and courses.
2. ***Growing volume of data*** [27-31]: big data approach, using machine learning and new data formats that requires strengthening the IT competencies in the curricula of engineering and physics academic programs.
3. ***Growing competition***: global competition between fundamental science, applied science and industry. Fundamental science is no longer an elite area of knowledge; more and more university alumni with advanced research competencies prefer to have jobs in applied research or engineering positions in industrial companies. To satisfy the growing needs for research personnel of international collaborations, universities have to strengthen career guidance significantly and attract talented students to undergo academic programs in fundamental particle physics.

Requirements for soft skills of researchers are growing significantly. Figure 1 shows that for each stage of a project's development, researchers are to develop and possess unique skills that can only be learned empirically.

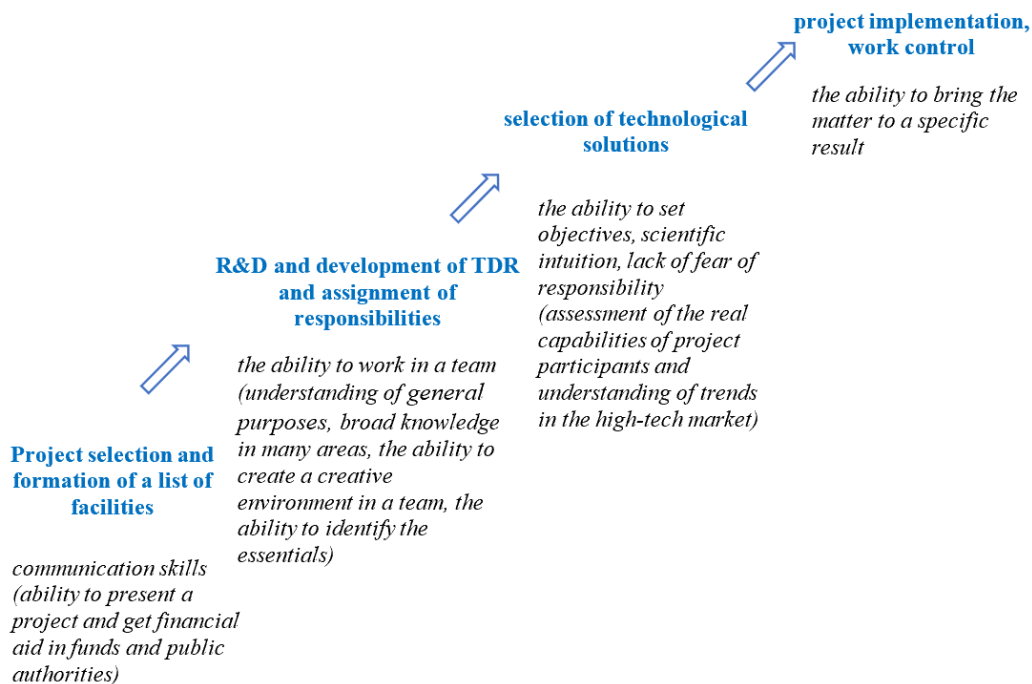


Figure 1. Soft skills requirements at different stages of a research project.

At different stages of the project implementation, one may require different skills and competencies, that in turn means that modern university training should include the formation of such skills.

3. Experience and prospects of training researchers at MEPHI

MEPHI has been training researchers in the field of nuclear physics and elementary particle physics for many years, who then have successfully been working in international collaborations. The University is directly involved in the work of more than 40 international collaborations, including collaborations engaged in nuclear and particle physics research.

Historically, the peculiarity of the MEPHI academic process is based on extensive training of physics and mathematics and in-depth study of engineering subjects. An important part of the training of future scientists is the mandatory participation of each student in research activities in the university laboratories, that can be a starting point for subsequent internships on large experiments.

To solve these challenges, MEPHI professors and officials are constantly improving approaches to organize individual educational paths for the research personnel training. Figure 2 shows the modern educational path for the training of researchers and research engineers within academic programs in nuclear physics and technologies. It is important to emphasize that the full cycle of training of both researchers and engineers is at least 10 years.

While being a freshman and sophomore, a student has more than 10 compulsory disciplines of physics and mathematics and about 5 courses in engineering and basics of IT. It is worth mentioning that practically every academic program is adaptive because each student has several options of elective courses of humanities or those that are aimed at developing soft skills. An important focus in the training of future researchers and engineers is a variety of options within production practical training in the MEPHI laboratories, participation in student competitions and Olympiads in physics and engineering. Taking courses at the first and the second academic years, a student does not have the fixed major or specialization that he chooses as a further study profile when transferring into the next academic year.

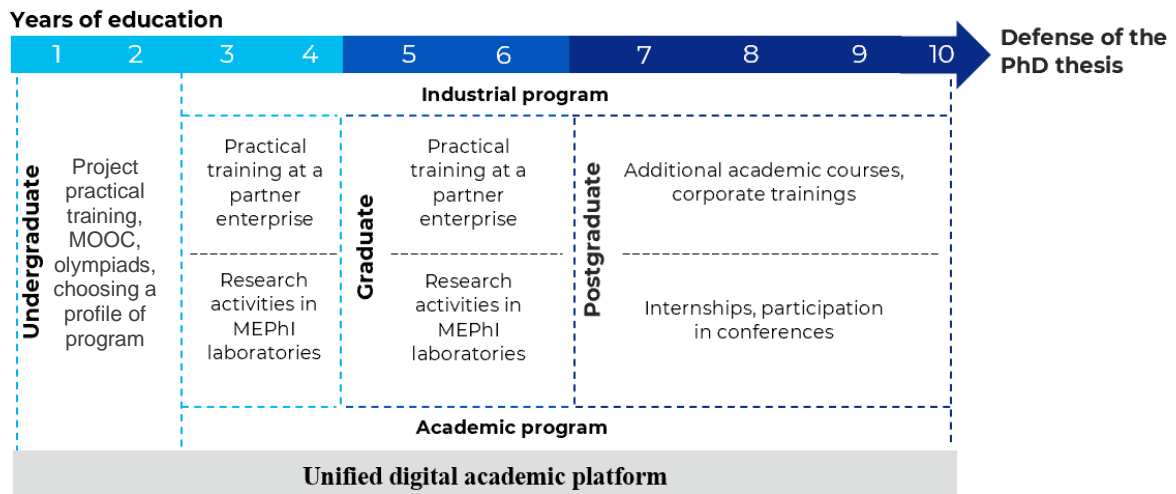


Figure 2. MEPhI educational path in nuclear physics and technologies.

The following third and fourth undergraduate academic years at MEPhI can be roughly divided into two parallel tracks: training programs for engineers for the needs of the nuclear industry (such programs can often be implemented with the collaboration with industrial partners) and training programs for researchers in nuclear physics and technologies (in particular, for MegaScience projects). The MEPhI Institute of Nuclear Physics and Technology, the leading research and educational unit, implements both tracks in its academic life. Taking courses at the third and the fourth academic years, all students determine the major and have an individual scientific supervisor who serves as a mentor of research activities and guides a student at their work under the undergraduate thesis. The curricula comprise advanced and specialized courses in experimental nuclear physics, data processing, physics of nuclear facilities, thermal hydraulics of nuclear reactors or other subjects depending on the chosen research area. A student spends up to 40% of the study time on an individual research project as part of research work in the MEPhI laboratories (in case of an academic program) or production practical training at a partner institution (in case of an industrial program). The best students have the opportunity to participate in MEPhI research projects as part of experiments on MegaScience facilities.

Traditionally, the majority of MEPhI graduates prefer to continue their studies within one of master programs, while about 10-20% of students change their study profile, including moving from an industrial track to an academic track and vice versa. The structure of master programs reflects mostly the structure of the second part of undergraduate academic programs, but the main difference is that much more study time is dedicated to individual research projects. At this stage, each student gains experience of working in research groups on large projects. While preparing the master thesis, most students have experience in presenting their results at conferences and writing scientific papers. Postgraduate studies at MEPhI are entirely devoted to research work, each PhD student is an active participant of the university research, including those that are conducted within the framework of collaborations.

4. Conclusion

Modern trends in the development of science and industry pose new requirements for the training of researchers at the university. Today, the training of researchers for MegaScience projects requires flexible adaptation of the academic process to the requirements of a specific research project, while being based on a broad knowledge of physics, mathematics and engineering disciplines. At each stage of preparation, it is necessary to provide for the possibility of an individual educational path for each student: unique educational courses in IT or engineering; extensive training of basic disciplines;

individual research projects, practical training and internships. This approach will allow the most suitable approach to the training of both researchers and engineers - developers of new technologies.

To implement such approaches in the academic training of researchers, the MEPHI staff takes solid efforts to elaborate and modernize the methodological foundation and digital platforms that will allow to create a student's digital footprint in the academic information space.

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