Particle Physics and High-Energy Heavy-Ion Physics

Scientific research in the field of elementary particle physics and high-energy heavy-ion physics can be classified into four interrelated directions — the energy-increasing accelerator direction (the Energy Frontier), the intensity-increasing accelerator direction (the Intensity Frontier), the accuracy-increasing non-accelerator direction (the Accuracy Frontier), and the particle astrophysics direction (the Cosmic Frontier). In view of these general directions, within the framework of the new Seven-year plan, JINR will focus on the following main topics:

1. Particle physics research, including particle spectroscopy, spin physics, neutrino physics and rare phenomena studies (covering the Energy, Intensity, Accuracy, and Cosmic Frontiers), aimed at extending the Standard Model and discovering new fundamental laws of Nature.

2. High-energy heavy-ion physics research (Energy and Intensity Frontiers) aimed at establishing unique properties of hadronic matter under conditions of phase transitions between quark and hadronic states of matter.

3. Development of new-generation detector systems and accelerator complexes, theoretical support of the current and planned experimental investigations, development and maintenance of high-performance telecommunication links and computing facilities at JINR, aimed at providing a comprehensive support for realization of the scientific tasks envisioned by the seven-year plan.

The new Seven-year plan in the field of particle and high-energy heavy-ion physics will be implemented by efforts of four JINR Laboratories (VBLHEP, DLNP, LIT, and BLTP) both on the JINR in-house facility base — the NICA accelerator complex, and within the framework of international partnership programmes at the world's largest accelerator facilities in the experiments with essential contribution made by JINR staff.

JINR will continue to participate in the development of accelerator subsystems and detectors within the ILC project.

Within the framework of the FLASH and XFEL international projects, JINR physicists participate in the development of diagnostic systems of ultrashort bunches in the linear accelerator, X-ray, large cryogenic systems.

The study of hot and dense baryonic matter and its phase transformations will be performed at the NICA complex, whose basic configuration is planned to be carried out in the second half of the seven-year period. Experiments will be carried out with extracted beams of the Nuclotron at the BM@N set-up and in the collider mode at MPD in heavy-ion collisions at the energy range $\sqrt{s_{NN}} = 4$–11 GeV. The launching of the NICA complex and the mentioned detectors, their final adjusting to the design objectives, and obtaining new experimental results will be the primary tasks for VBLHEP in the next seven years.

The VBLHEP research groups will continue taking part in the study of nuclear matter properties under extreme conditions, in the search for the onset of quark deconfinement and possible phase transitions within common research programmes in the STAR experiment at RHIC, BNL, in the NA6I experiment at CERN's SPS, in the ALICE experiment at CERN's LHC, and in the CBM experiment at FAIR, GSI. The scope of JINR's participation will be assessed and possibly limited depending on the progress in implementing the NICA project as well as on the necessity to consolidate work at the JINR accelerator complex.

Expected results:

I. The start-up of the BM@N first configuration for high-intensity light-ion beams extracted from the Nuclotron. Obtaining first results in the research programme of the BM@N experiment: study of yields of hadrons, hyperons, and light nuclei — 2020–2021.

2. Obtaining results at BM@N using high-intensity heavy-ion beams, including ions of gold. Study of elliptic and directed flows, production of hyperons with $S = 2$ and hypernuclei — 2023–2024.

3. The start-up of the MPD Stage I, obtaining first results in the research programme to study the properties of hot and dense baryonic matter in the central rapidity range, to search for phase transitions (observables - particle yields and spectra) including partial restoration of chiral symmetry (observables - yields of di-leptons), and to search for the critical end-point (observables - event-by-event fluctuations, particle correlations) — 2022–2023.

4. Commissioning of the MPD Stage II. Beginning of the research programme with the MPD detector in the available phase space region — 2025.

5. Obtaining new results in the energy scan programme in the experiments NA61 (SPS) and STAR (RHIC) — 2017–2023.

6. Obtaining new results in the femtoscopy programme in the ALICE experiment (LHC), participation in ALICE upgrade — 2017–2023.

7. Settlement of commitment in the development and commissioning of the CBM set-up under JINR's obligations in accordance with the NICA-FAIR joint research programme — 2017–2023.

The study of nucleon spin structure and other polarization phenomena in nucleon–nucleon and nucleon-nuclei interactions as well as in few-nucleon systems will be carried out at the VBLHEP accelerator complex and at CERN and BNL. Both fixed-target experiments with Nuclotron polarized beams and NICA collider experiments at the SPD detector will be performed at VBLHEP. Construction of SPD is planned to be implemented within the next Seven-year plan according to the technical design project which is to be prepared. The SPD research programme will extend the ongoing programme of hadron structure and spectroscopy investigations with high- intensity muon and hadron beams in the COMPASS experiment (CERN's SPS) as well as with polarized proton beams at STAR (BNL), in which JINR will continue its participation during 2017–2023.

Expected results:

1. Stage-by-stage commissioning of the polarized beam channels at the Nuclotron and of the infrastructure necessary to support the experimental research of polarization phenomena within the framework of an international collaboration — 2017–2023.

2. Carrying out the research programmes of the DSS and ALPOM-2 experiments with Nuclotron polarized beams. Approval and realization of new experiments developed to study nucleon spin structure and other polarization phenomena (both in nucleon-nucleon and nucleon-nuclei interactions and in few-nucleon systems) with Nuclotron beams —2017–2023.

3. Putting the SPD start-up configuration into operation at the NICA collider — 2026.

4. Obtaining new results on nucleon spin structure in the COMPASS (SPS) and STAR (RHIC) experiments in MMTDY, DVCS and SIDIS processes — 2017–2023.

The search for physical phenomena beyond the Standard Model will be continued in the CMS and ATLAS experiments at CERN's LHC.

JINR will take part in the upgrade of detectors during LHC shut-down periods in 2018–2019 and 2022–2024 and will continue analysis of data from the LHC.

The JINR group is supposed to take part in a search for weakly interacting particles of dark matter which is proposed to be conducted at CERN's SPS. JINR will also participate in a search for charged lepton flavor violation in muon-to-electron conversion in the **μ2e** (FNAL) and **COMET** (J-PARC) experiments.

Expected results:

1. Obtaining new experimental results within the framework of the programme aimed at verification of the Standard Model (SM) predictions and a search for physics beyond the SM at CMS and ATLAS. Settlement of commitment on detector upgrades under the JINR contract — 2017–2023.

2. Preparation and launch of the experiment aimed at a search for weakly interacting particles of dark matter using SPS beams — 2017–2023.

3. Achievement of an upper limit for muon-to-electron conversion at a level of $6 \cdot 10^{-17}$ in the μ2e and COMET experiments — 2020–2023.

The JINR team will continue a series **of precise experiments to study kaon decays**, including those with direct CP violation, in the NA62 experiment at CERN's SPS.

Expected results:

1. Obtaining new data on extra rare decays of charged K-mesons in the NA62 experiment – 2017–2023.

2. Precise determination of the SM parameters, obtaining new knowledge about the nature of CP violation and search for the occurrence of new physics beyond the SM.

JINR will continue to participate in the preparation of the physics programme of the **FAIR** complex, which includes a wide range of tasks concerning the key aspects of QCD. The antiproton beam with an energy range from 1 to 15 GeV/s will allow one with the PANDA set-up to take precision measurements on the spectroscopy of charmonium and charmed hadrons, on the search for exotic hadron states and research on the nature of hadron mass modification due to the dense hadron environment. In the PANDA experiment, JINR plans to take part in construction of the muon system, the superconducting solenoid and quartz radiators of the electromagnetic calorimeter. The main part of work will be financed within the Russian contribution to FAIR.

In the field of accelerator physics and technology, in addition to work on the construction of elements for the NICA accelerator facility and participation in the preparation of ILC systems, collaborative effort on the construction of the FAIR complex is planned under the Russia-FAIR and JINR-FAIR programmes.

Neutrino physics and astrophysics offer promising possibilities to study the fundamental, key issues of modern elementary particle physics. Observation of **neutrino oscillations**, which led to the 2015 Nobel Prize in Physics, requires neutrinos to have non-zero mass as well as lepton number non-conservation.

DLNP is taking part in the leading experiments studying neutrino oscillations such as the **Daya Bay** reactor neutrino experiment, which discovered a non-zero value of the mixing angle θ_{13} — a result garnering the 2016 Breakthrough Prize in Fundamental Physics.

At present, neutrino physics has entered a new era of precision measurements and new objectives focusing on studies of neutrino mass hierarchy and CP violation.

The mass hierarchy problem will be addressed by JINR scientists with the help of two complementary techniques using reactor and accelerator neutrinos in the **JUNO** and **NOvA** experiments respectively.

CP violation in the lepton sector will be addressed with help of another accelerator experiment — **DUNE**, in which JINR plans to enhance its participation.

The study of double-beta decay processes is also of high priority at DLNP and is conducted within the framework of the **GERDA-MAJORANA (G&M)** and **SuperNEMO** projects.

DLNP will continue to participate in the study of solar neutrinos in the **BOREXINO** experiment.

DLNP plans an increasing international large-scale participation in the **BAIKAL-GVD** experiment focusing on the detection of ultrahigh-energy cosmic neutrinos. A continuous increase of the observable volume up to 0.4 km^3 in parallel with data taking is foreseen during 2017–2023.

In the next seven-year period, the internationally recognized Neutrino Programme of JINR will be realized in several stages unique for each experiment. In addition to the development of the **BAIKAL-GVD facility**, which was covered in detail in the previous section, the following are the plans concerning the JUNO, NOvA and DUNE experiments:

During 2017–2020, JINR aims to complete its major contribution to the construction of the **JUNO** experiment. In particular, JINR specialists:

– will build a power supply for 20 thousand of JUNO's PMT;

– will build a number of PMT scanning stations developed by JINR for detailed characterization of JUNO's PMT at experimental site;

– will complete part of its financial contribution, in the form of use of scintillation detectors of the OPERA experiment in the JUNO experiment as a veto-system; will develop methods to control these sensors and provide necessary equipment for the installation at the experiment site;

– will develop methods and seek for a hardware contribution in terms of the PMT protection against the Earth's magnetic field;

– will build a computer farm for simulation and analysis, including the development of its own computer database for processing data at JINR.

JINR aims to maintain the **NOvA** remote control room used not only for JINR, but also by some institutions of the Russian Federation (INR, FIAN).

During 2019–2023, JINR specialists plan to conduct R&D work on the calorimetry of the near detector of DUNE and on the construction of the electromagnetic calorimeter, which is based on the unique experience of JINR.

Financing schedule (k$)

	2017	2018	2019	2020	2021	2022	2023	Total
JUNO, NOvA/DUNE projects	1 220.0	1 290.0	3 440.0	930.0	582.7	1 000.0	1 000.0	**9 462.7**

JINR plays a leading role in advanced reactor neutrino experiments in the immediate vicinity of nuclear reactors (DANSS, GEMMA / νGeN). The development of experimental techniques, synergy with other low-background projects of JINR, allows and will allow in the future to carry out new research at the forefront of science. The research results will be:

– search for neutrino oscillations to sterile states on a short baseline with the world's best sensitivity; - search for the neutrino magnetic moment at a level better than 9×10^{-12} μ_B;

– detection of coherent scattering of neutrinos on nuclei (CEνNS) in the zone of complete coherence;

– the use of CEνNS for the precision study of the electroweak sector and the search for New Physics beyond the Standard Model;

– monitoring of in-core processes.

	2017	2018	2019	2020	2021	2022	2023	Total
Experiments at the Nuclotron: DSS, ALPOM-2, HyperNIS, FAZA-3, new projects	150.0	150.0	205.0	205.0	1 005.0	3 005.0	2 905.0	**7 625.0**
VBLHEP: experiments in CERN, BNL, GSI / FAIR	1 566.0	1 736.0	1 879.0	1 709.0	1 629.0	1 649.0	1 649.0	**11 817.0**
Neutrino program	1 880.0	1 934.0	1 993.0	1 533.0	1 574.0	1 617.0	1 662.0	**12 193.0**
DLNP: ATLAS	1 020.0	1 200.0	1 460.0	2 550.0	1 540.0	930.0	960.0	**9 660.0**
DLNP: other projects	820.0	830.0	840.0	850.0	860.0	870.0	880.0	**5 950.0**
Total	**5 436.0**	**5 850.0**	**6 377.0**	**6 847.0**	**6 608.0**	**8 071.0**	**8 056.0**	**47 245.0**